University College of Southeast Norway

Mechanical Engineering
2016 - 07

Orbital Motion Simulator
Bachelor Thesis

Haytham Ali

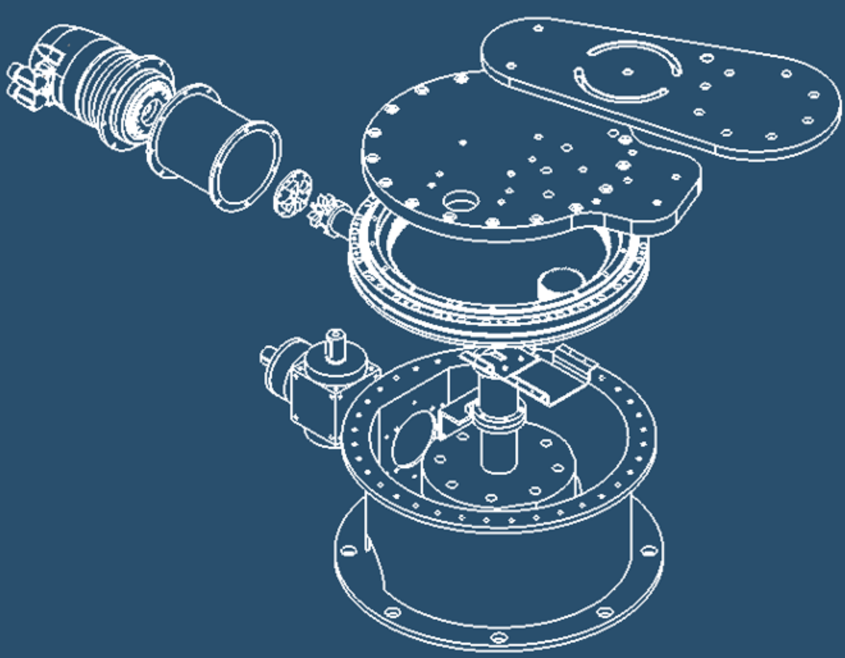
Kjetil Fjeld

Anders Gunbjørnsen

Heidi Kallerud

Martin Sandberg

Fredrik Thoresen



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Høgskolen i Sørøst-Norge

Project Abstract

Aim: The aim of the project was to design a system that will support rotation of a remote weapon station (RWS) in isolation, and in parallel axes off-set, to a rotating turret. The project was provided by Kongsberg Protech Systems (KPS), who intend to implement the system in a test simulation laboratory.

Background: KPS have numerous customers that request to have the RWS mounted onto a turret-carrying vehicle. This significantly increases the complexity of integration between the systems. The great level of complexity of design, integration, testing and verification requires a "demo system" that simulates how the system will respond in real operational environments. KPS works on projects aimed at integrating the input from the two rotating systems; the turret and the RWS. Some of the integrated functions can be simulated in software, but simulating accurate data is challenging. The possibility to adjust the centre of the RWS away from the centre of the turret in the Turret Simulator is necessary in order to acquire specific data and develop software that supports the various set-ups required by customers. Getting access to a full turret has proven difficult and costly. Hence, a low-cost physical Turret Simulator that can be adapted to simulate input data from various RWS placements on the turret is therefore needed.

Method: The Project Plan provided guidelines for execution of the project that aimed to ensure satisfactory delivery of the by the set deadline. The CAFCR+ model was used to structure the systems engineering and development process. Through nine iterations a step-wise, well reasoned development process was ensured; from generation of an understanding of the desired system, through conceptual development and feasibility assessment, to final design development. Frequent view hopping in the CAFR+ model ensures that the needs of all the system stakeholders at different stages of the system's life cycle were considered, ranging from usage to manufacture and service. An extensive Requirements Traceability Matrix was developed to ensure traceability between requirement originator, breakdown of requirements, corresponding tests and status. The complex load scenario that the system will be exposed to includes both rotation of a high load combined with the movement of a motion table involving 6 degrees of freedom, affirmed the need for a structured engineering model to uncover the forces and loads imposed on the system. By starting with a simple Free Body Diagram and progressively expanding the included variables a comprehensive dynamic model of the system was developed in SimuLink, through the use of differential equations and vector analysis. The model uses a custom-made Matlab function block to calculate the torque needed to satisfy the given input conditions. The function block could be changed to calculate different motion and load scenarios, and provided indispensable data for the calculations of total system torque. A "worst case" load scenario was defined, which formed the basis for evaluation and selection of components, as well as structural optimisation of the design. When designing structural components care was taken to ensure that manufacture was feasible, ultimately forming the Production Manual which

will be delivered to the manufacturers. An Incremental Test method was applied to facilitate structured, step-wise testing that would make it easy to identify which component or interface that is the source of any failed test. At termination of the project a system was designed that by verification fulfills more than 94 percent of all the system requirements. This included numerous requirements that were listed as *should* requirements, which introduce additional functional freedom to the stakeholders. In addition to acquiring in-depth experience in mechanical engineering design, numerous lessons were learnt with regards to project management, including requirement identification methods, goal setting and team work.

Conclusion: A mechanical system that supports parallel axis rotation of the RWS at offsets up to 40 cm was designed. Offset increments of 10 cm intervals is enabled and the assembled system can support rotational speed and acceleration beyond the minimum requirements of the stakeholder. A life span of 5 years is verified, provided that service is ensured as according to the developed user manual for the system. The project team has proved able to rapidly rearrange tasks and schedules when exposure to unexpected challenges occurred, and have acquired experience in mechanical engineering that will prove to be of significant value when entering into a career in engineering.

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Project Plan
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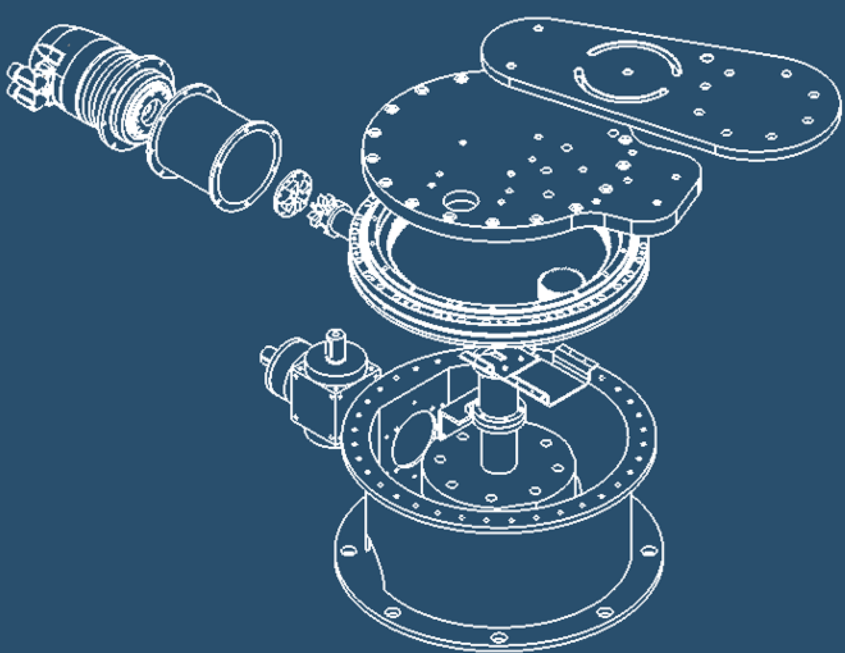

Abbreviations

Abbreviation	Explanation
KPS	Kongsberg Protech Systems
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
MBT	Main Battle Tank
IFV	Infantry Fighting Vehicle
CAD	Computer-Aided Design
DDMM	Day, Month

Revision History

Date	Version Number	Comment	Approved by
22.01.16	1.0	Scope and organisation done.	Fredrik Thoresen
29.01.16	2.0	Background, System Engineering Model, Management and Risk Management done.	Heidi Kallerud
07.02.16	3.0	Appendixes integrated and revised.	Fredrik Thoresen
07.03.16	3.1	Iteration log 3 - 7, Activity list updated and GANTT in appendix B	Kjetil Fjeld
09.03.16	4.0	Revision.	Fredrik Thoresen
15.04.16	4.1	Activity list updated and GANTT in appendix B.	Martin Sandberg
16.04.16	4.2	Revision.	Heidi Kallerud
15.05.16	4.3	Abstract added.	Heidi Kallerud
22.05.16	4.4	Document approved	Fredrik Thoresen

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Abstract

The purpose of the present project is to design a system, on request by Kongsberg Protech Systems, that will enable rotation of a remote weapon station in isolation to, and in parallel axes offset to, a rotating turret in a test simulation laboratory. The project plan aims to describe the approach that will be used to deliver the intended product.

KPS have numerous customers that request to have the RWS mounted onto a turret-carrying vehicle. The possibility to adjust the centre of the RWS away from the centre of the turret in the Turret Simulator is necessary in order to acquire specific data and develop software that supports the various set-ups required by customers.

The scope is delimited to include mechanics and mechatronics, while computational control and electronics is intended to be developed in future projects.

The needs of the primary stakeholders; mainly HSN and KPS; are presented, along with the proposed method of decomposing the requirements and ensuring traceability. The major milestones and an estimate of the time schedule required for various activities are concisely presented, while the extensive Gantt chart provides time frames for each activity that must be held in order to deliver the product as planned. The CAFCR+ model will be used to guide the system development through structured steps from basic understanding of stakeholder needs, concept development and detailed design. Nine iterations are planned, of which the content is planned to ensure well reasoned system development through multiple viewpoints.

Numerous risks pertain to the planning, execution and finalisation of larger projects. An extensive set of risks has been identified, along with accompanying mitigation strategies. The most critical risks pertain largely to requirement identification and management, which are to be addressed by numerous measures in planned iterations. The developed Risk Matrix is planned to be revisited throughout the project period, to ensure that execution of the project runs as according to that stated in the Project Plan.

1.1 Introduction

Kongsberg Protech Systems (KPS) is a world leading supplier of Remote Weapon Stations (RWS). Through innovative, high-tech and flexible solutions KPS aim to deliver systems that improve situational awareness and protection of the operators of the system in high-risk areas. The PROTECTOR RWS is designed to be installed on any type of platform and to provide stabilized input to the system operator under any condition.

Kongsberg Protech Systems have in the last years had an increase in the number of requests from customers to have the RWS mounted onto a turret-carrying vehicle. The required level of integration between the RWS and the main turret significantly increases the complexity of the design, interface management and testing. KPS is working on projects aimed at integrating the input from the two rotating systems; the turret and the RWS. Some of the integrated functions can be simulated in software, but simulating data that highly resembles real life movement in the terrain is challenging. Getting access to a variety of full turrets is difficult and costly, because it involves significant traveling. Hence, a low-cost physical Turret Simulator that can be adapted to simulate input data from various RWS placements on the turret is needed.

1.2 Background

Kongsberg Protech Systems delivers weapon control systems and have gained international recognition for their high-tech, reliable remote weapon system solutions. A Remote Weapon Station (RWS) is a weapon control system that allows the operator to control the weapon from within the safety of the vehicle, which greatly improves the safety of military personnel as well as the civilians. The PROTECTOR RWS is one of KPS' most successful products, both in terms of adoption rate amongst customers, but also in mitigating the severity of combats.

Since the first world war, light armored vehicles with mounted weapon systems have been used in conflict areas to improve safety and accuracy. However, until recently the gunner of the vehicle has held a very vulnerable position without any proper safety. The reason for this is that the mounted weapon systems needed the gunner to be on top of the vehicle to control it. This problem hasn't been solved until now with the PROTECTOR.

The PROTECTOR consists of a remote control unit that is integrated into the vehicle with an associated screen that provides live imaging from the cameras attached to the turret and the mounted weapon

Figure I.2.1: Humvee with mounted weapon system[7]

system. The PROTECTOR stabilises the input image during movement to significantly improve sight and specificity of target attack. The PROTECTOR lets the operator maneuver and fine tune the sight towards a suspicious distant area while sitting protected within the vehicle. This provides the operator and gunner with both the equipment and safety required to undertake more reasoned decisions, as opposed to; as a gunner on top of a vehicle; being under constant fear of being struck and hence potentially firing prematurely at unidentified targets. After the PROTECTOR was widely adopted into the market the number of shots fired has significantly decreased due to these high-tech integrated solutions. The safety of civilians has been improved, because the operators have "bought themselves" more time to monitor areas and identify their true enemies. Furthermore, the accuracy of firing has increased, which reduces the likelihood of hitting unintended targets.

KPS have numerous customers that request to have the RWS mounted onto a turret-carrying vehicle, such as the Infantry Fighting Vehicle (IFV; figure I.2.1) and the Main Battle Tank (MBT; figure I.2.2). This significantly increases the complexity of integration between the systems. The great level of complexity of design, integration and testing requires a "demo system" that simulates how the system will respond in real operational environments. KPS is working on projects aimed at integrating the input from the two rotating systems; the turret and the RWS. Some of the integrated functions can be simulated by software, but simulating accurate gyroscope data from movement in uneven terrain is challenging. Getting access to a variety of full turrets is difficult and costly as it involves significant traveling. Hence, a low-cost physical Turret Simulator that can be adapted to simulate input data from various RWS placements on the turret is needed.

The purpose of the Turret Simulator is to facilitate and simplify testing of RWS functionality that relies on turret interaction. As per se, KPS does not have a test system that allows the RWS to rotate independently of the rotating turret. Customers also request different set-ups of alignment between the RWS and the turret. Hence, the possibility to adjust the center of the RWS away from the center of the turret in the Turret Simulator is necessary. This will help acquire relevant data and develop software that supports the

Figure I.2.2: M1A2 Abrams Main Battle Tank with Remote Weapon Station[8]

various set-ups. The primary use is during the development and early integration test phases. Formal systems integration testing and verification is not expected to be done using the Turret Simulator. This will still be performed with an actual turret and vehicle. The Turret Simulator will primarily be used in conjunction with development and testing of various features, as well as for optimisation of software and different operational modes.

The lab set-up of the Turret Simulator consists of the motion table and the RWS, and in the future the integration of the current system that is to be designed to allow rotation of the RWS on top of the motion table. The motion table is a hydraulic, electric simulation table that allows six degrees of freedom to accelerate and displaced the mounted object. Mounting the RWS on top of the motion table will simulate how the RWS moves when mounted on top of a vehicle that moves in uneven terrain. In real, operational situations the RWS can rotate on top of the vehicle. Simulation of this has been difficult in the lab. The motion table can tilt and elevate the RWS simulating the vehicle driving in terrain. The motion table runs a predefined program. There is no data exchange between the motion table and the rest of the simulator.

I.2.1 The problem to be addressed

The problem to be addressed in this project is to design a system that will support rotation of the RWS in isolation to, and in parallel axes offset to, the rotating turret.

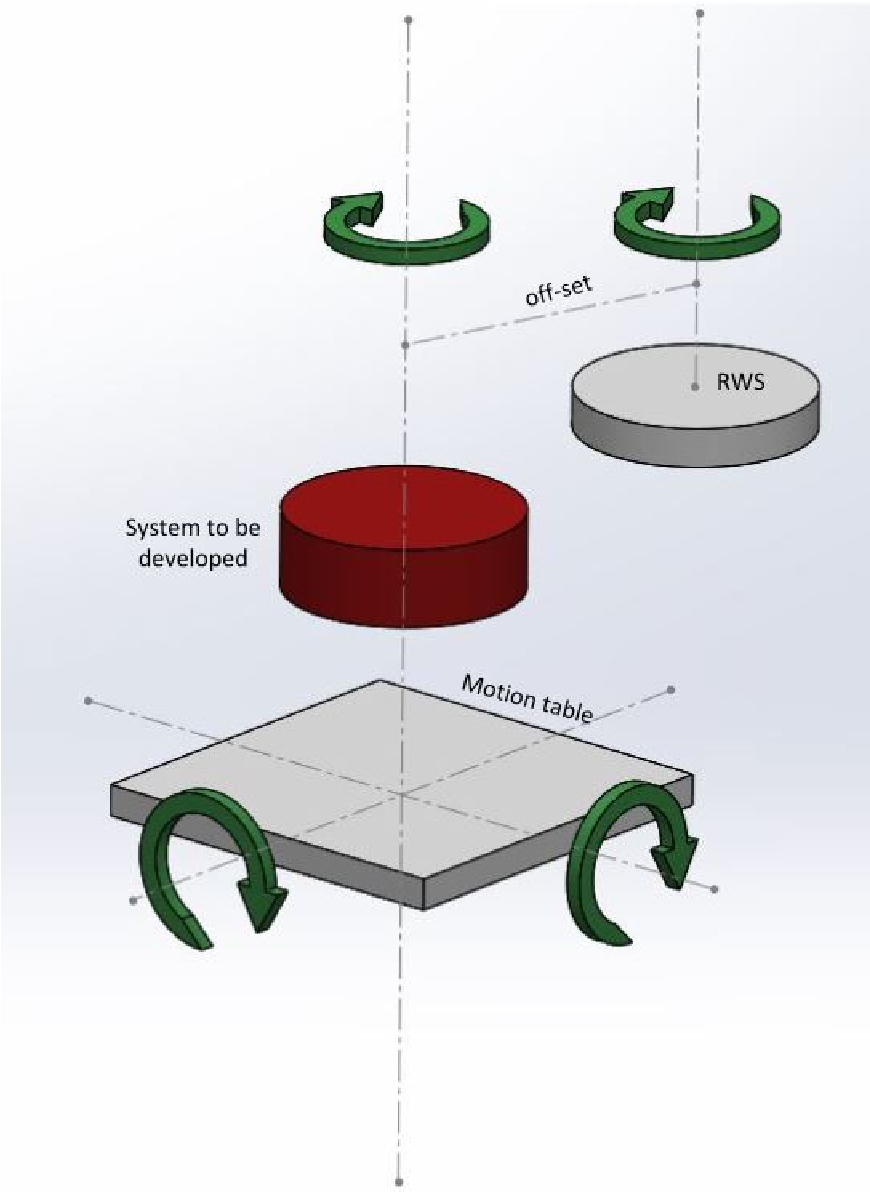


Figure I.2.3: Initial outline of problem

I.2.2 System Boundaries

The system of interest forms part of a larger existing system, consisting of the motion table and the RWS, which form the immediate technical boundaries of the system. The environmental boundaries of the system was already predefined to the KPS test lab. The global boundaries of the system comprise KPS and HSN. However, a clear information boundary also exists between the environmental and global boundaries, as discretion of information is of particular importance in this project.

I.2.3 Scope

The system of interest is part of a larger mechatronic system, which is comprised of mechanical, electric, computational and control components. Figure I.2.4 shows the various disciplines of engineering that exists in a mechatronic system. The problem to be addressed will evolve around aspects of Mechanical CAD, Mechanical Systems and Mechatronics, as shown in the figure below. As the project group only consist of mechanical engineering students, the scope of this project will only include aspects related to mechanical engineering and its main overlapping areas to other disciplines; as agreed upon with the stakeholders before commencing the project. The project will be undertaken in the time period spanning from 04.01.2016 to 10.06.2016. The project will result in a thesis that is to be handed in 19.05.2016.

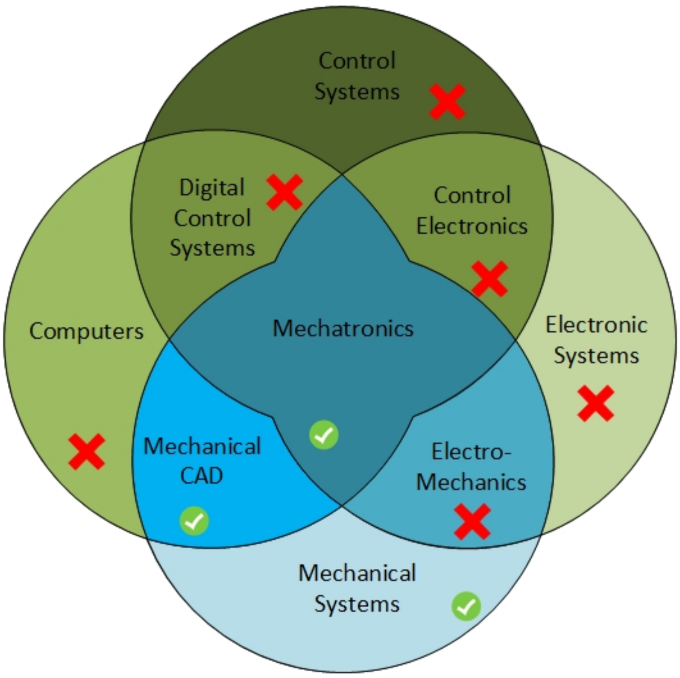


Figure I.2.4: Technical scope of project

I.3 Systems Engineering Model

Complex systems consist of numerous interactive parts that collectively perform a function [3]. Design of complex systems requires both in-depth engineering specific knowledge as well as a complete understanding of the system and its environment as a whole. Systems Engineering models are a means of bridging the various engineering disciplines and providing a guidance path through the complexity of a system. This project is concerned with the design of a complex mechatronic system, involving aspects of both computer, electric and mechanical engineering. Additionally, the system of interest was clearly defined as being part of a larger mechatronic system. Hence, due to the complexity of the system, a systems engineering approach using a suitable model is especially appropriate. Due to the nature and scope of the current project the CAFCR+ project model by Gerrit Muller was chosen.

I.3.1 CAFCR+

The CAFCR+ model is a two-way decomposition models of a system's architecture [1]. The name is composed of the initial letters of the five domains of the model; Customer Objectives, Application, Functional, Conceptual, and Realisation. The Customer Objectives and Application captures the "why" from the customer. The Functional view captures the "what" of the sought system, while the more stable Conceptual and rapidly changing Realization views describes the "hows" of the sought system. To best capture the customers needs and integrate all the information into the optimal system solution the model changes frequently between different viewpoint to sample problems and solutions from many different angles. The aim of this viewpoint hopping is to build a thorough and wide understanding of the system, its dependencies and influencing partners. The "+" sign in the CAFCR+ model represents the life-cycle aspect of the system. The life-cycle aspect addresses how the use-phase, resilience, longevity and termination of the system will be dealt with.

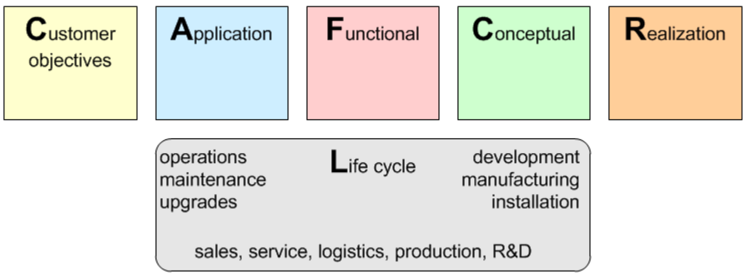


Figure I.3.1: CAFCR+ model

The CAFCR+ model was considered the most suitable model for this project as the system sought by the main stakeholder was unknown to the group members and the iterative nature of the model allows for frequent reevaluation, redesign, and confirmation of work and chosen solution. Furthermore, the CAFCR+ model comes with a range of suggested tables, figures and diagrams that serve as tools in order to get an understanding of the system, its inter-dependencies and environment. A set of tools used can easily be selected to best fit the type of project that is being undertaken; e.g. purely mechanical design or computer programming, mechatronic project combining both electric, mechanic and computer disciplines. E.g. storytelling and use case diagrams are frequently used for programming in order to understand the steps a user and computer will go through to reach their target, while diagrams unveiling the critical components for functional behaviour might be more relevant for mechanical disciplines [1].

The first iteration quickly gets the project going through brainstorming, getting a basic understanding of the system and initial ideas for how and what. The second iteration builds on the knowledge acquired in the first iteration and either extends and builds into further detail or declines previous ideas on the expense of new and more informed ideas. Through numerous iterations more detailed understanding and knowledge based decisions are promoted. This prevents the risk of working on a premature concept throughout an extensive part of the project period before verification against requirements set at a very early stage is made.

The CAFCR+ model is described in more detail in the dedicated "CAFCR+" document. In addition to describing in further detail how the model works, this document also provides an overview of how the project team used the model throughout the project period to arrive at the final product, it provides a discussion of the usefulness of the model, and finally some recommendations for future users. The content and outcome of all the planned iterations are provided in an "Iteration Log" in the "CAFCR+" document, where all the resulting figures and conclusions in each iteration is documented.

I.3.2 Stakeholder Analysis

Stakeholders anyone or anything that can affect or be affected by the objectives of the system [4]. Numerous methods exist for identifying and categorising stakeholders [4], and four categories were chosen for the identification of stakeholders based on the nature of the project:

1. Stakeholders involved in the design and development of the system;
2. Stakeholders with a financial interest in the project and/or an interest in successful finish and sale of the system;
3. Stakeholders who have an interest in the use of the system;
4. Stakeholders responsible for the introduction, maintenance and repair, and termination of the system; so-called life-cycle stakeholders.

The stakeholders that were identified from these categories are shown in figure I.3.2.

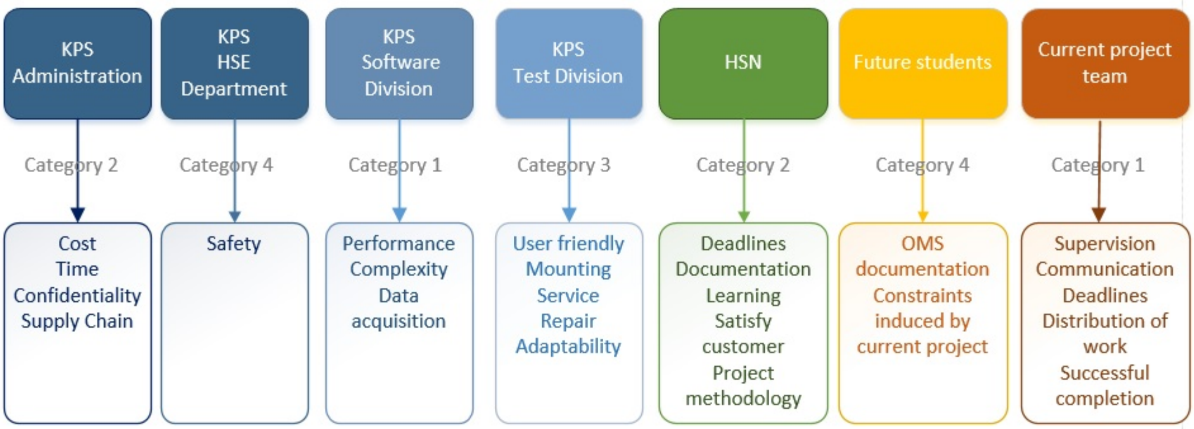


Figure I.3.2: Concerns of the System Stakeholders

Three different stakeholders from KPS were identified, as many people within the organisation have different concerns depending on where in the life-cycle the system is seen. For the sake of traceability into other documents, e.g. into the Requirements Traceability Matrix and the requirements identification boxes, each stakeholder was given an ID. The ID of each stakeholder is given in table I.3.1:

Stakeholder name	Stakeholder ID
KPS Administration	KPS A
KPS HSE Department	KPS H
KPS Software Division	KPS S
KPS Test Division	KPS T
HSN	HSN
Future students	FSTUD
Project team	OMS

Table I.3.1: Stakeholder IDs

All stakeholders have their own concerns regarding the system and they may have different concerns at different stages of the development phase and life-cycle of the system. In figure I.3.2 the major concerns of each stakeholder are listed. These concerns were further translated into stakeholder requirements, either through information supplied directly by the stakeholders (HSN and KPS), or through an interview with the stakeholder directly (KPS). A list of initial stakeholder requirements was also provided by the KPS. Many of those stakeholder requirements were formulated directly into system requirements. This is not uncommen in projects where the project owner (KPS) is an engineering business with high knowledge of the desired system that they want designed. The translation of concerns into stakeholder requirements is shown in Appendix D. A requirement represents a functionality that is requested by the stakeholders (Sols 2014). The requirements stated by the stakeholders are what the customer will evaluate the final product up against. These criteria, or requirements, are hence the criteria that the developed system must fulfill in order to ensure customer satisfaction. However, the nature of this project involves stakeholders that have concerns that are not directly related to the designed system, but rather the processes surrounding the project; e.g. HSN. Thus, some stakeholder requirements could not be translated into system requirements, but had to be formally dealt with in other ways that could also be documented, in order to verify that also these requirements were fulfilled. Appendix D addresses how all the stakeholder requirements were dealt with. This table also serves a purpose of traceability, to show which stakeholder requirement that led to various system requirements. If the project team finds it necessary to make any alterations or have difficulty finding an adequate solution to a system requirement, the stakeholder that was the origin for that system requirement can easily be traced and consulted.

All stakeholders have different levels of interest and influence on the system [4]. Awareness of how each stakeholder scores on these aspects helps the project team to know which stakeholder to pay close attention to and who can be satisfied by information mostly. All the identified stakeholders of this project were plotted on an "Interest-Influence chart" as shown in figure I.3.3.

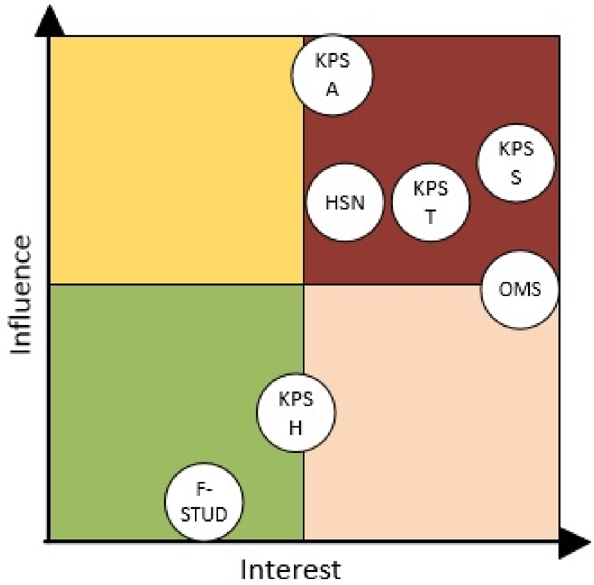


Figure I.3.3: Interest-Influence chart of stakeholders

Stakeholder and hence system requirements may change over time, e.g. when taking the entire life-cycle into account, so the project team should always revisit the requirements of highest rank often to ensure that the product is still progressing in the right direction [5]. Being open to requirement changes is necessary to uncover hidden, forgotten or unnecessary requirements [6]. System requirements are defined, derived and revised continuously throughout the systems engineering life cycle because the stakeholders may change their requirements, or due to the project team having to do trade-offs in the design [6]. To address this dynamic behaviour of requirements through the design phase of the system, numerous iterations where the requirements were revisited throughout the project were planned.

I.4 Management and Organisation

A daily "stand up meeting" is scheduled every working day at 8 am. At this meeting the group will briefly discuss and evaluate the current status of the project compared to the project schedule. A plan for the day will be made and work tasks will be distributed on either an individual or group level.

All meetings, accompanied with a brief description of the meeting's agenda, will be announced in Google Calendar at least 24 hours before actual start-up time. A commentary summarising the content of the meetings, the main decisions made and the plans for further work shall be available in the online Minutes of Meeting folder on ShareLatex. The template named “Minutes of Meetings DDMM” shall be used for all commentaries, with the correct date (two digit day and month) replacing the DDMM in the document name. Group members take turns in writing commentaries. The “Weekly Follow-up” document shall be filled in and sent to the HSN supervisor 24 hours prior to the weekly meeting (Wednesdays at 10 am). Semi-weekly follow-up meetings with KPS shall take place every 2nd Friday (odd numbered weeks).

The software "LaTex" will be used for composition of the project report. The software allows all group members to work on the same document simultaneously while also opening up for the opportunity of helping each other or cooperating "live" within the document from different geographical sites. Google Drive will be used for storage of back-up material, articles, figures, pictures, tables etc. A "Storage and Layout" manual was produced in order to organise in a structured manner where documents go and to ensure consistency of layout, referencing and writing style.

I.4.1 Schedule

Presentations

As a part of the bachelor project it is required that all groups hold three presentations. The purpose of these presentations are to give HSN and KPS an overview of the progress of the project, as well as the group’s knowledge and understanding of the system and system engineering processes. In this paragraph the content of the presentations will be described.

- 10.02.16 - 1st.Presentation
  The first presentation will last 20 minutes. This presentations is meant to give the audience an insight into the project plan and an understanding of *what* and *how* the project is going to be solved. The project model, time schedule and the background for the project will be central points from the project plan, which will show *how* the project will be solved. The requirement specifications and test specifications will also be presented and is meant to give an understanding of *what* in the project that needs solving.
- 11.03.16 - 2nd.Presentation
  The second presentation will last 20 minutes and shall give the audience a technical overview of the project. Concepts and design will be presented, as well as an updated test plan for how these design requirements will be tested. Also, a critical review of the project plan shall be present in this presentation.
- 02.06.16 - 3rd.Presentation
  This is the final presentation; it will last 1 hour and will consist of three parts. 20 minutes for marketing and business, 20 minutes for a technical presentation and 20 minutes of questions.

The marketing and business part shall compare the product to other similar products and review the positive aspects of the product. The technical part shall give insight into time consumption, technical solutions and more. The question segment is open for everyone to ask question that they find relevant.

I.4.2 Milestones

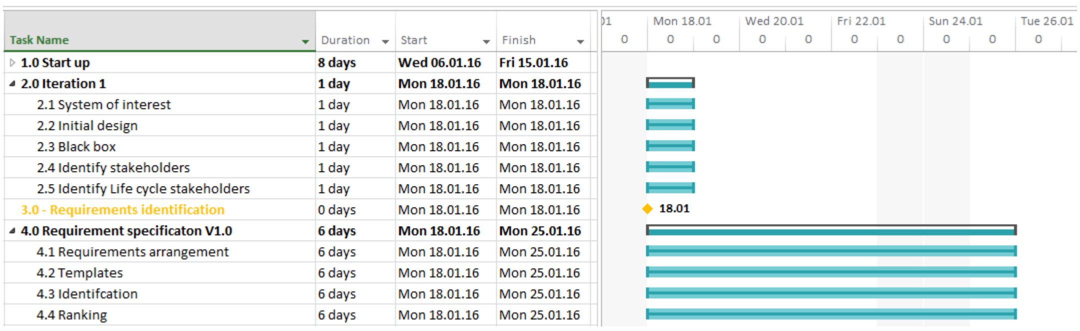
Milestones are used to show important events during a project. The milestones provide a way of tracking how the project is progressing compared to the plan. While the Gantt diagram provides an extensive and detailed overview of all the planned processes of a project, the milestones give clear dates for when major achievements should be finished by. The milestones are defined time points in a project and hence have zero duration. They are points of control that act as a clear goal for the project group, while they also serve to provide information for the stakeholders about when they can expect completion of various stages. The milestones of the project are as follows:

- 18.01.16 - Requirement identification
- 02.02.16 - Project plan finished
- 29.02.16 - Test plan finished
- 14.03.16 - Requirements specification finished
- 16.03.16 - ~~Prototype alpha~~
  - Preliminary Design Decision
- 20.04.16 - ~~Prototype beta~~
  - 3D print Prototype
- 11.05.16 - ~~Test verification and validation finished~~
  - Test verification finished

I.4.3 Gantt Chart

The Gantt chart is a frequently used tool in project management. It serves the cause of providing a good overview of activities and time. The left part of the Gantt chart represents the activities or tasks that the project consists of. Each activity is then represented as a bar on the right side, giving the viewer a good overview of the progress as it shows the start date, duration and end date of the task. This visualisation allows the user to get a good overview of what the different tasks are, when they are supposed to start and end and if any activities are alleged to be done in parallel.

The software Microsoft Project was chosen to construct the Gantt chart for this project. The software is a logical choice since it allows the user to set up the chart as desired. Summaries of tasks that are connected can easily be established, as well as milestones and other important events. A reference ID was also made for every activity so referencing to the activity list is established.
An extraction from the Gantt chart is shown in figure I.4.1, the whole Gantt chart is attached in Appendix B.



Task Name	Duration	Start	Finish
1.0 Start up	8 days	Wed 06.01.16	Fri 15.01.16
2.0 Iteration 1	1 day	Mon 18.01.16	Mon 18.01.16
2.1 System of interest	1 day	Mon 18.01.16	Mon 18.01.16
2.2 Initial design	1 day	Mon 18.01.16	Mon 18.01.16
2.3 Black box	1 day	Mon 18.01.16	Mon 18.01.16
2.4 Identify stakeholders	1 day	Mon 18.01.16	Mon 18.01.16
2.5 Identify Life cycle stakeholders	1 day	Mon 18.01.16	Mon 18.01.16
3.0 - Requirements identification	0 days	Mon 18.01.16	Mon 18.01.16
4.0 Requirement specificaton V1.0	6 days	Mon 18.01.16	Mon 25.01.16
4.1 Requirements arrangement	6 days	Mon 18.01.16	Mon 25.01.16
4.2 Templates	6 days	Mon 18.01.16	Mon 25.01.16
4.3 Identifcation	6 days	Mon 18.01.16	Mon 25.01.16
4.4 Ranking	6 days	Mon 18.01.16	Mon 25.01.16

Figure I.4.1: Extraction from Gantt chart

A valuable feature of Microsoft Project is its ability to create a timeline. The timeline can be designed as desired and the user can select which activities that will be displayed on it. Commonly, the most important activities and the milestones are represented here. This is a good way of visualising the projects' different phases for both the internal parties as well as the external.
The timeline for this project is shown in figure I.4.2.

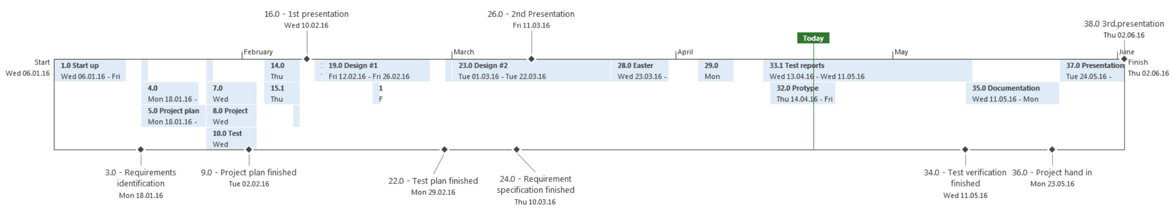


Figure I.4.2: Timeline from Microsoft Project

I.4.4 Activity List

As a part of the project planning an activity list is used as a tool to get control of the time estimation aspect of a project and especially the time consumption. Therefore it is mainly used as a guideline as time consumption is known to commonly fluctuate and being somewhat unpredictable. The purpose of the table used in this project is to make a clear connection between the activity, the start date of the activity, the duration of the activity, a reference to the GANTT chart and a phase reference.

Start up date	Activity	Estimated Hours (h)	Reference ID	Phase
xx.01.16	Internal meetings	150	xx	x
xx.01.16	External meetings	60	xx	x
xx.01.16	Guidance meetings	120	xx	x
06.01.16	Administrative start up period	280	1.0	1
18.01.16	First iteration	7	2.0	2
18.01.16	Requirement specification V1.0	126	4.0	2
18.01.16	Project plan V1.0	196	5.0	3
27.01.16	Second iteration	8	6.0	3
27.01.16	Requirement specification V2.0	105	7.0	3
27.01.16	Project plan V2.0	175	8.0	4
27.01.16	Test plan V1.0	70	10.0	4
03.02.16	First presentation preparation	105	12.0	5
04.02.16	Requirement specification V3.0	63	13.0	3
04.02.16	Project plan V3.0	63	14.0	4
04.02.16	Test plan V2.0	63	15.0	4
08.02.16	Third iteration	10	11.0	5

Table I.4.1: Activity list

.

Start up date	Activity	Estimated Hours (h)	Reference ID	Phase
11.02.16	Fourth iteration	12	17.0	5
12.02.16	Test plan V3.0	231	18.0	5
12.02.16	First design cycle	240	19.0	6
19.02.16	Fifth iteration	15	19.3	6
26.02.16	Requirement specification V4.0	42	20.0	6
29.02.16	Sixth iteration	15	21.0	6
01.03.16	Second design cycle	280	23.0	6
01.03.16	Seventh iteration	12	23.1	6
07.03.16	Second presentation preparation	63	2.0	6
17.03.16	Eight iteration	12	27.0	7
23.03.16	Easter holidays	0	28.0	7
04.04.16	Exam period	0	29.0	7
11.04.16	Third design cycle	300	30.0	7
13.04.16	Ninth iteration	12	31.0	7
13.04.16	Test reports	350	33.1	8
14.04.16	Prototype print preparation	150	32.0	7
11.05.16	Finish all documentation	300	35.0	9
23.05.16	Third Presentation preparation	210	37.0	10

Table I.4.2: Activity list continued

To get a simple overview of the project period, the activity list was divided into ten phases (Table I.4.3). These phases also served a purpose for risk management, where each risk was assigned to the phase where it is most likely to occur. The ten phases are as follows:

Phase #	Phase content
1	Start-up
2	Requirements and stakeholder identification
3	Project plan and requirements specification
4	Project plan and test specification
5	Concept Development and Presentation 1
6	Design and Presentation 2
7	Design
8	Verification and testing
9	Documentation
10	Presentation 3 and thesis hand-in

Table I.4.3: Project phases

I.4.5 Iteration planning

Due to the choice of CAFCR+ as the project model, iterations will play a big role in the progress of this project. An "iteration" as seen from the CAFCR+ model is used as an initiator for a new phase or work cycle. An iteration is meant to provide a manifestation of where in the project cycle the team needs to be in order to be able to finish the whole project as planned. During the iteration identified issues and unknowns are discussed and brainstormed, in order to generate ideas and knowledge of the uncertainties that needs to be addressed in order to initiate the phase following the iteration.

Iterations are scheduled into the project's main schedule. Shorter iterations will be performed more often in the initial phase of the project. As the project progresses the frequency of iterations decreases, while the level of detail and time spent for each constituent step of the iteration increases gradually. The overarching themes for each iteration will be planned according to the CAFCR+ model, while also leaving room to make note of areas where further work, clarification or alteration is needed. These areas will be addressed promptly after finishing the iteration. Ultimately, the need to make changes to the designed system will converge towards a minimum and the iterations serve mainly as a verification of the designed system up against the stakeholder and system requirements [1]. An overview of the iterations that have been planned for this project is shown below in figure I.4.3.

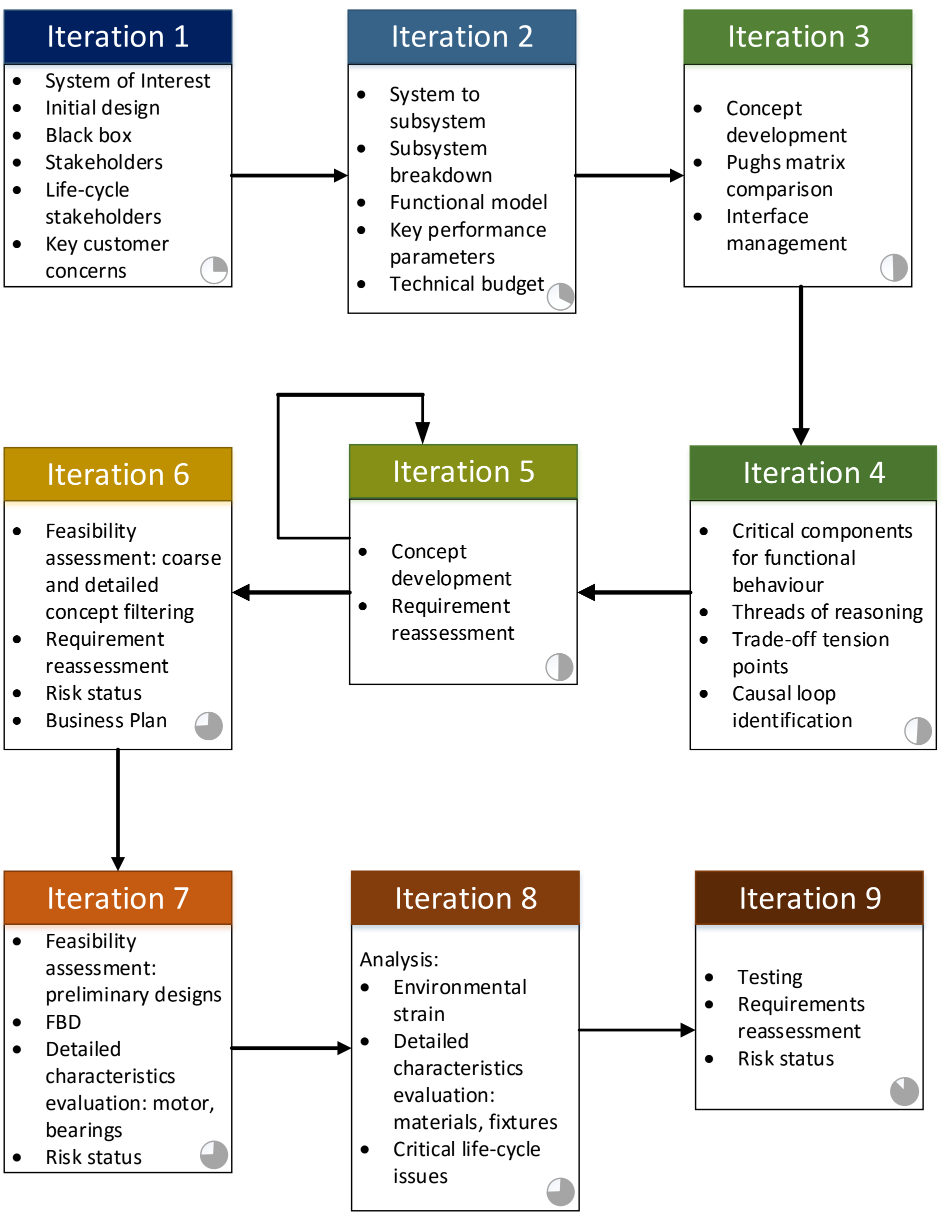


Figure I.4.3: Content of iterations

I.4.6 Roles and Responsibilities

A group contract was collectively formulated by the group. The group contract confirms that all group members share an equal responsibility for planning, conducting and satisfactorily completing the group project throughout the planned project period. All members have read and signed the Contract of Confidentiality (“taushetsplikt”) distributed by both HSN and KPS. All members understand the consequences any nonconformity will have for the parties involved, as well as the ripple effect that their actions might have on the other group members.

A set of "Codes of Conduct" was formulated by the group. The Codes of Conduct serve as guidelines for moral responsibilities of each group member for the companionship of the group. Areas such as deadlines, meeting hours, late arrivals and plagiarism are covered. Consequences for numerous violations of codes were formulated.

Although the responsibility for ensuring progress of work and ultimately successful completion of the progress was equally shared between the group members, each member was given dedicated areas of responsibility both within administrative issues and engineering specific or systems engineering topics. The purpose was to have one group member that would have the major overview of that issue, as well as in-depth knowledge on the topic. Each group members areas of responsibility is listed below:

Group Member	Roles	Areas of responsibility
Fredrik Thoresen	Group Leader	Group management
Anders Gunbjørnsen	Test engineer	Testing, Requirements
Martin Sandberg	Document Controller	Analytics, FEM
Haytham Ali	Graphic Design	Analytics
Kjetil Fjeld	Backup and electronic documentation	Requirements, CAD
Heidi Kallerud	Documentation	Systems Engineering

I.5 Risk Management

I.5.1 Risk Identification and Assessment

Risks are anything that can have a negative impact on the fulfillment of the stakeholders' objectives [2]. Risks can be the result of wrong decisions made or factors outside the control of the systems engineers. Risks can interrupt the progress of the project and ultimately the outcome of the project Thus, it is important to identify and assess risks, and either eliminate or develop strategies that mitigate their consequences [2]. Figure I.5.1 from Sols 2014 [2] was used as a starting point for making a risk management strategy.

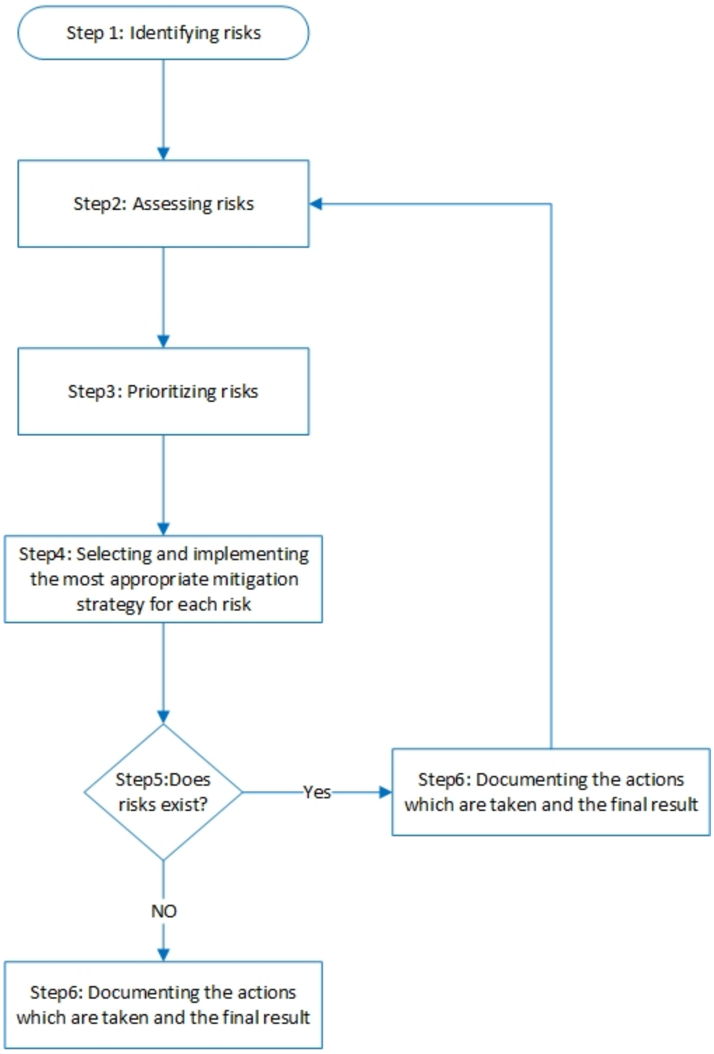


Figure I.5.1: The risk management process

Firstly, the risks associated with the project were identified with the help of the categories listed by Sols 2014 [2]; technical, financial, human, environmental and life-cycle risks. Three categories were used to assess each identified risk:

1. Likelihood of occurrence
2. Severity of consequences
3. Detectability (how easy is it to detect the risk)

Each risk was given a score from A to C in each of these categories, according to table I.5.1.

Assessment category	Rating A	Rating B	Rating C
Likelihood of Occurrence	High	Medium	Low
Severity of Consequences	High	Medium	Low
Detectability	Low	Medium	High

Table I.5.1: Risk assessment categories

All risks which score A on Detectability are hard to identify and are unlikely to be apparent to the project team. A risk that has low detectability as well as scoring A or B on Severity of Consequences might have a considerably negative impact on the successful completion of the project. Hence, these risk require a mitigation strategy to be set up immediately. The risks with the highest score (2 or more A's) were lack of electro competence, lack of knowledge to validate computational control of the system, customer being dissatisfied with the outcome and mechanical failure of the system during usage or testing. Risks might also change over the time of the project, both as more knowledge is attained and due to Murphy's Law. Therefore, to monitor high risks and any changes in the status of other risks, it was decided to include a run-through of risk status in two of the later iterations in the project period.

I.5.2 Risk Management Strategies

Strategies of Action are any actions that can reduce or eliminate the possibility of a risk appearing, or actions that can mitigate the severity of the consequences.

The following three Strategies of Actions were used for risk management in this project:

1. Accept: The risks which has only low probability of occurrence and low severity of consequences can be accepted. Risks which can be accepted needs no action to be taken to prevent them or to mitigate theme's effect.
2. Protect: a strategy is developed in order to reduce the likelihood of the risk occurring, or to mitigate its consequences.
3. Avoid: Actions are taken to eliminate, to the greatest possible extent, the likelihood of the risk occurring, or develop strategies that eliminate severe consequences occurring.

A mitigation strategy was developed for each identified risk. Although the risk strategy "Accept" was applied to a few risks, meaning that there is limited aids available to avoid the risk (e.g. illness), a mitigation strategy was still developed in order to manage the risk as much as possible. Risks with the "Avoid" strategy were given more attention and more stringent, comprehensive mitigation strategies. A risk management matrix E was made in order to keep a record of all data. The list of the ten project phases, shown in the Activity List section, was used to identify where each risk most likely to occur. This will raise particular focus on the most critical risks of each phase of the project. Lastly, each risk was given an ID that was plotted on a Likelihood-Severity chart (I.5.2), to provide an easy, visual aid to identify the most critical risks. The ID is given in Appendix E.

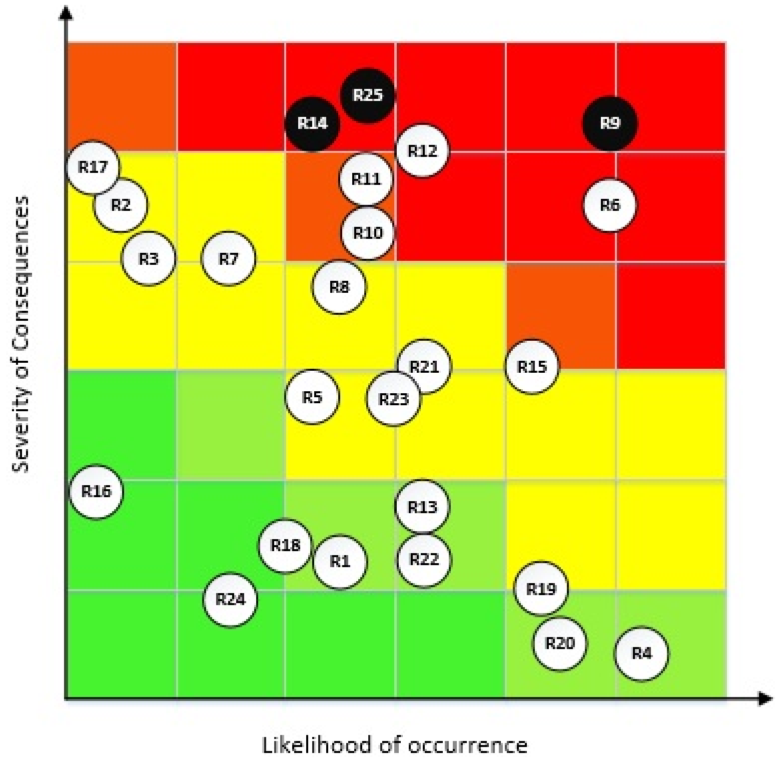


Figure I.5.2: Likelihood-Consequence chart of project risks

The chart shows a cluster of risks related to requirement identification (either lack of identification, misinterpretation or occurrence of new requirements) in the upper, middle area. This means that these risks are both likely to occur and the consequences of occurrence can be extensive. This further supported the decision to revisit and re-validate the requirements in later iterations throughout the project period.

University College of Southeast Norway

Mechanical Engineering
2016 - 07

CAFCR+
Orbital Motion Simulator

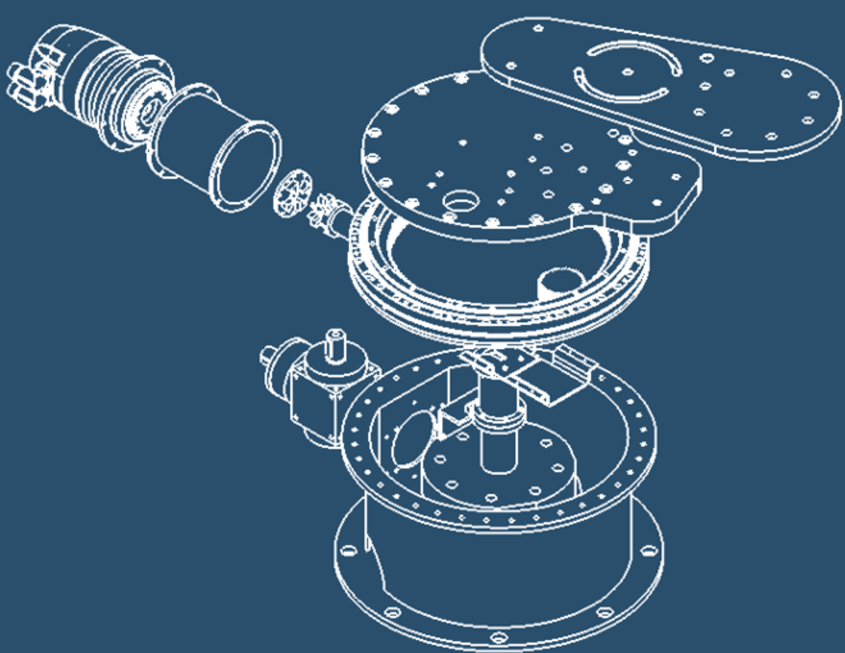


Table of Contents

Abstract

The CAFCR+ model is a two-way decomposition model that promotes system development through frequent shifting views of a systems architecture and desired functions. The CAFCR+ model was successfully applied in the current project, which is thoroughly documented in this report. A general description of the CAFCR+ model is provided. Along follows a description of how the model was used, as well as the order and content of each iteration that was undertaken to arrive at the final product. The model proved particularly useful at jump starting the project and quickly provide the project team with a progressively better understanding of the desired system. The CAFCR+ model is highly flexible and can easily be adapted to fit various types of projects, and the extensive iteration log provided here shows, through a great range of figures, how the model was applied to develop a complex mechanical system. A discussion of why the model is particularly useful to relatively unexperienced students is provided in the Discussion section. The chapter concludes with a chapter listing the lessons learnt and recommendations for future students who consider using this model in their projects is also provided.

II.1 The CAFCR+ model

The CAFCR model is a two-way decomposition models of a system's architecture [1]. The basic CAFCR model is shown in figure II.1.1. The name is composed of the initial letters of the five domains of the model; Customer Objectives, Application, Functional, Conceptual, and Realisation. The Customer Objectives and Application captures the "why" from the customer. The Functional view captures the "what" of the sought system, while the more stable Conceptual and rapidly changing Realization views describes the "hows" of the sought system. To best capture the customers needs and integrate all the information into the optimal system solution the model changes frequently between different viewpoint to sample problems and solutions from many different angles. The aim of this viewpoint hopping is to build a thorough and wide understanding of the system, its dependencies and influencing partners. The top row of the five steps are a top-down approach which is used to understand the intention and context, while a knowledge based bottom-up view is used in the lower part steps to identify constraints and opportunities. Numerous iterations promotes integration of new knowledge that appears throughout the phases, optimisation of design and reassurance of fulfillment of stakeholder needs [1].

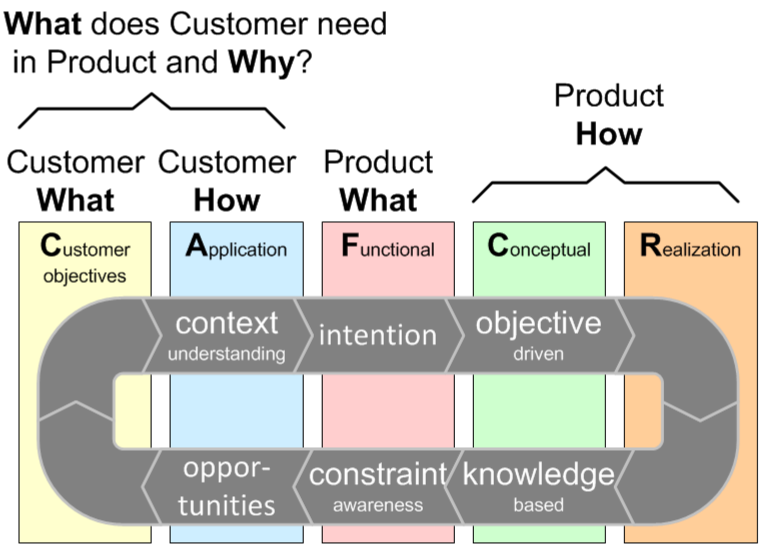


Figure II.1.1: CAFCR model

The extended CAFCR+ model includes a life-cycle aspect of the system [1]; shown in figure II.1.2. The life-cycle aspect addresses how the use-phase, resilience, longevity and termination of the system will be dealt with. The life-cycle aspect will be integrated into the project model and included in the iterative nature of the basic CAFCR model figure II.1.1. The CAFCR+ model was considered the most suitable model for this project as the system sought by the main stakeholder was unknown to the group members and the iterative nature of the model allows for frequent reevaluation, redesign, and confirmation of work and chosen solution. Furthermore, the CAFCR+ model comes with a range of suggested tables, figures and diagrams that serve as tools in order to get an understanding of the system, its inter-dependencies and environment. A set of tools used can easily be selected to best fit the type of project that is being undertaken; e.g. purely mechanical design or computer programming, mechatronic project combining both electric, mechanic and computer disciplines. E.g. storytelling and use case diagrams are frequently used for programming in order to understand the steps a user and computer will go through to reach their target, while diagrams unveiling the critical components for functional behaviour might be more relevant for mechanical disciplines [1].

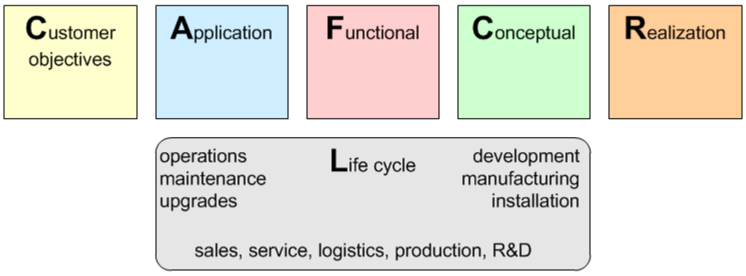


Figure II.1.2: CAFCR+ model

The first iteration quickly gets the project going through brainstorming, getting a basic understanding of the system and initial ideas for how and what. The second iteration builds on the knowledge acquired in the first iteration and either extends and builds into further detail or declines previous ideas on the expense of new and more informed ideas. Through numerous iterations more detailed understanding and knowledge based decisions are promoted. This prevents the risk of working on a premature concept throughout an extensive part of the project period before verification against requirements set at a very early stage is made, which is the risk e.g. in the Vee model [2].

The first five iterations in the current project were planned according to the steps made by Muller (2015) in the presentation "Bachelor Course Systems Engineering: Architectural Reasoning" [12] and "Architectural Reasoning and Integration" [13]. The content of the iterations was planned in the Project Plan. As the project evolved and new "knowns" and "unknowns" appeared, it was deemed necessary to add two more iterations; to duplicate iteration 5, and to add iteration 4 and 7. The resulting iterations and their content are shown in figure II.1.3 below. An "iteration", as seen from the CAFCR+ model, was used as an initiator for a new phase or work cycle. An iteration is meant to provide a manifestation of where in the project cycle the team needs to be in order to be able to finish the whole project as planned. During the iteration identified issues and unknowns are discussed and brainstormed, in order to generate ideas and knowledge of the uncertainties that needs to be addressed in order to initiate the phase following the iteration.

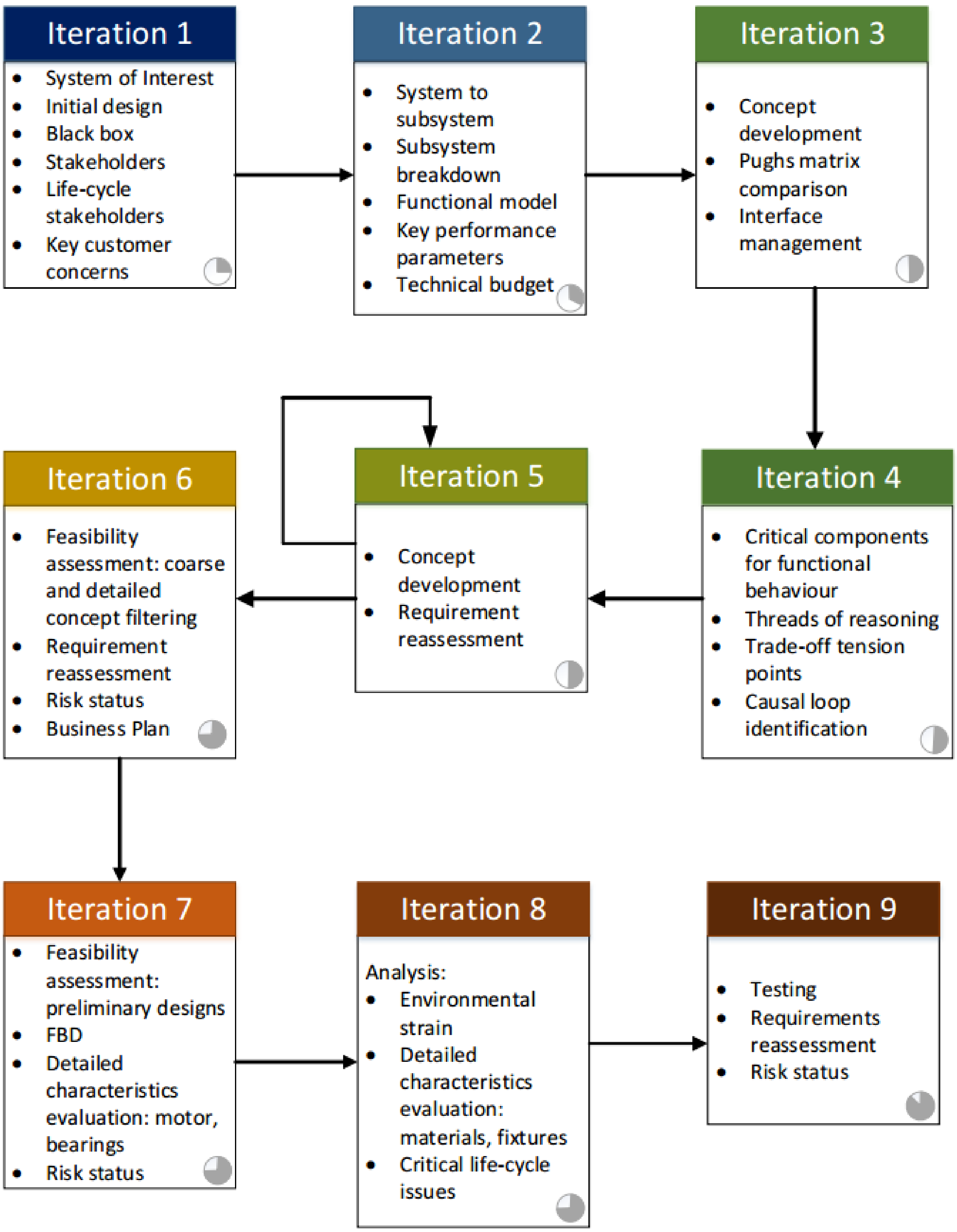


Figure II.1.3: Content of iterations

During the early phases of a project the emphasis is placed on generating an understanding of the system, it's stakeholders and accompanying requirements, the required system functions and capabilities. In the CAFCR+ model this phase is mostly represented by the Customer Objectives, Application and Functional domains. Hence, in the early phases the emphasis of the iterations are clearly left scewed as seen relative to the CAFCR+ model. As the project progresses to the design development and analysis phase, the emphasis of the iterations shift towards the right; through the Functional and Conceptual domains, to the Realisation and Life-Cycle domains. When prototyping, testing and usage commences the emphasis shifts to the Life-Cycle domain and back to the Customer Objectives and Application domain. The shift in domain emphasis throughout the iterations are clearly shown in figure II.1.4 below.

Most of the domains in the CAFCR+ model are reviewed within an iteration; meaning that throughout the project period numerous smaller turns through the model are made. However, throughout the project period one major overall turn through the domains are made, as emphasis of the project changes from initiation to realization. When the major shift throughout the domains return back to the Customer-Objectives and Application domains via in-vivo testing, usage and system termination major CAFCR+ loop is closed and the project can be considered to be finished.

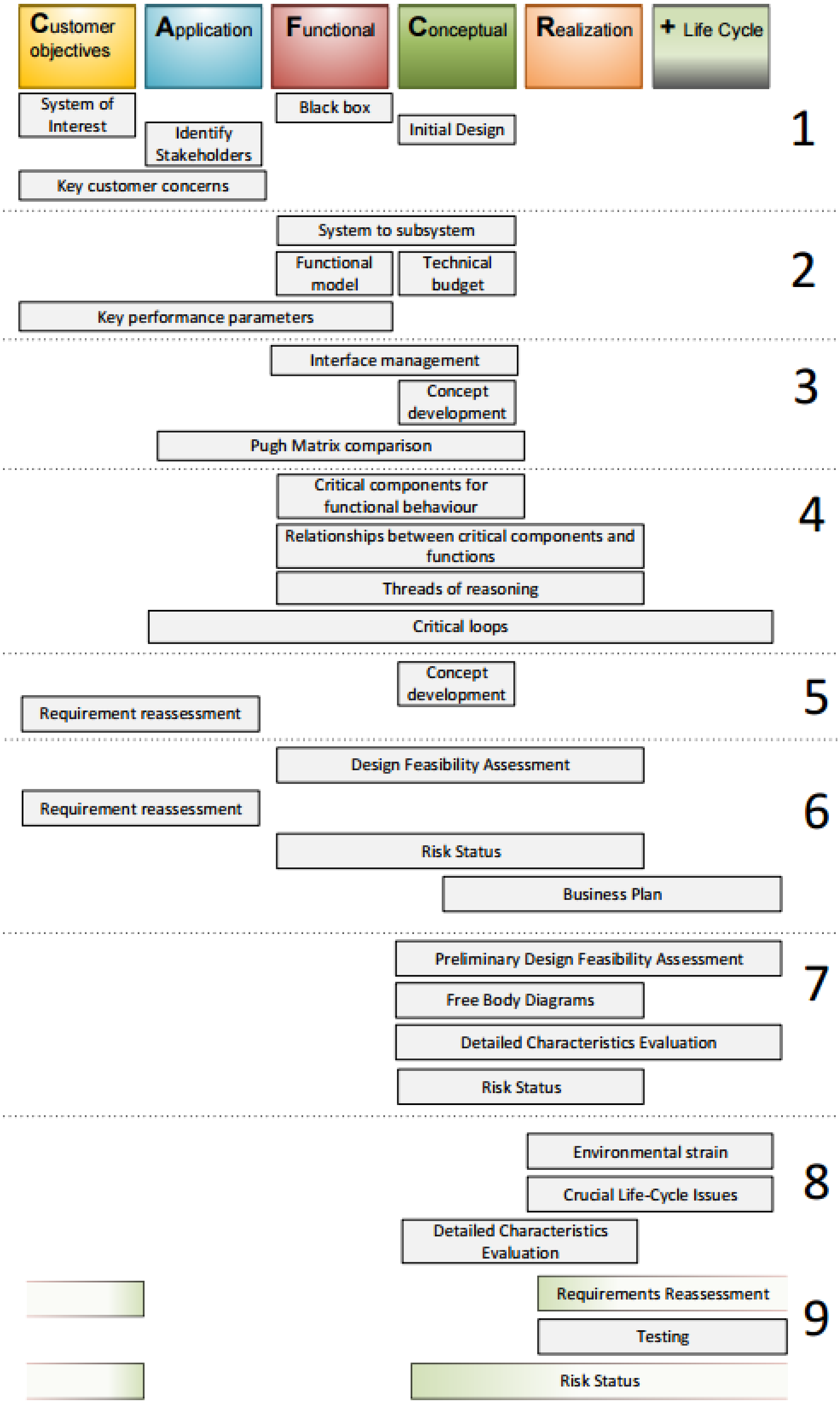


Figure II.1.4: Overview of iterations in context of the CAFCR+ model

II.2 Iteration Log

II.2.1 Iteration 1

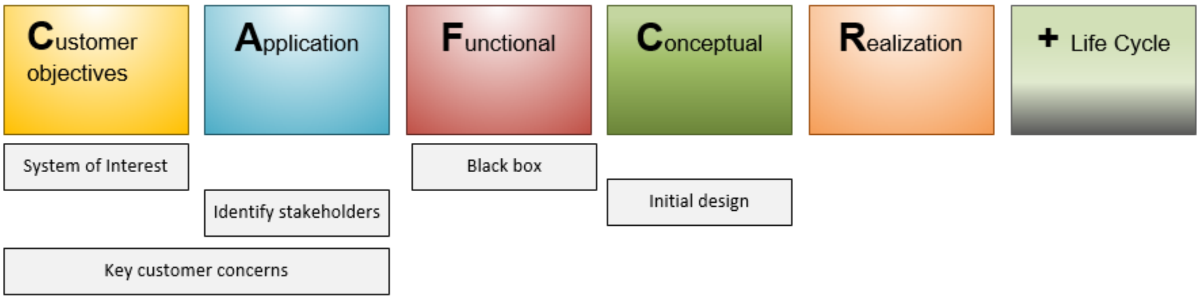


Figure II.2.1: Content viewed in CAFCR+ model

Info

- Date:18.01.2016
- Duration of time boxes: 15 minutes

Plan

- System of Interest
- Initial design
- Black box
- Identify stakeholders
- Identify life-cycle stakeholders
- Key Customer Concerns

Content of iteration 1

Fifteen minute bouts were dedicated to each item. A timer was used and ideas were drawn onto paperboards. A box diagram of the System of Interest was drawn and the general function of each constituent was discussed. Three different initial designs for the OMS were drawn, as well as three different designs for the mounting surface. A black box diagram which defined the input, output, controls/interfaces and constraints was drawn. Stakeholders and life-cycle stakeholders were identified and categorised according to four categories (described in the section "Stakeholder Analysis" in the Project Plan). The key concerns of each identified stakeholder/customer was then identified and listed beneath their names. The purpose of identifying each stakeholder's key concerns at such an early stage is to develop requirements that will ensure that these concerns are looked after and integrated into the project.

Resulting figures

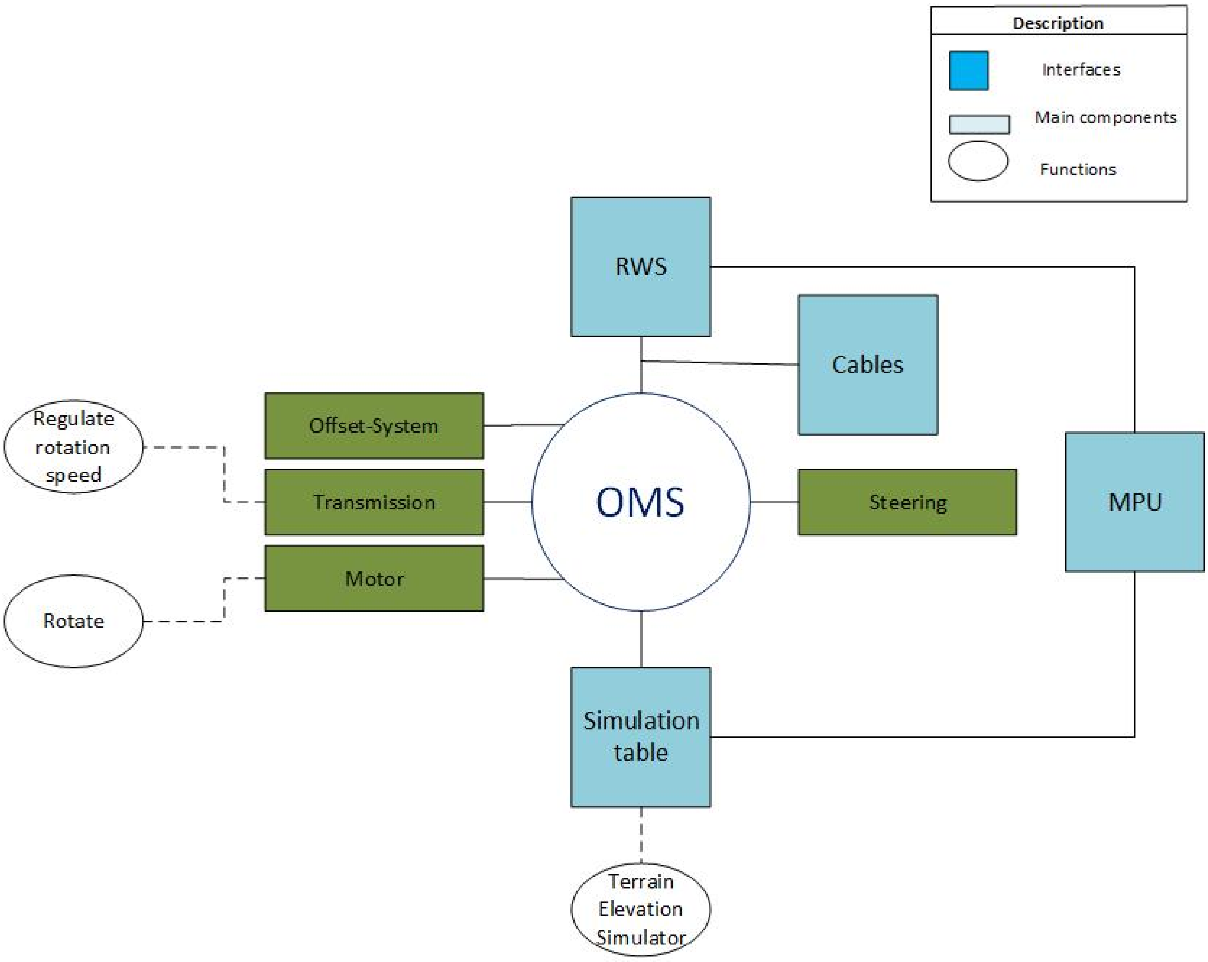


Figure II.2.2: System of Interest

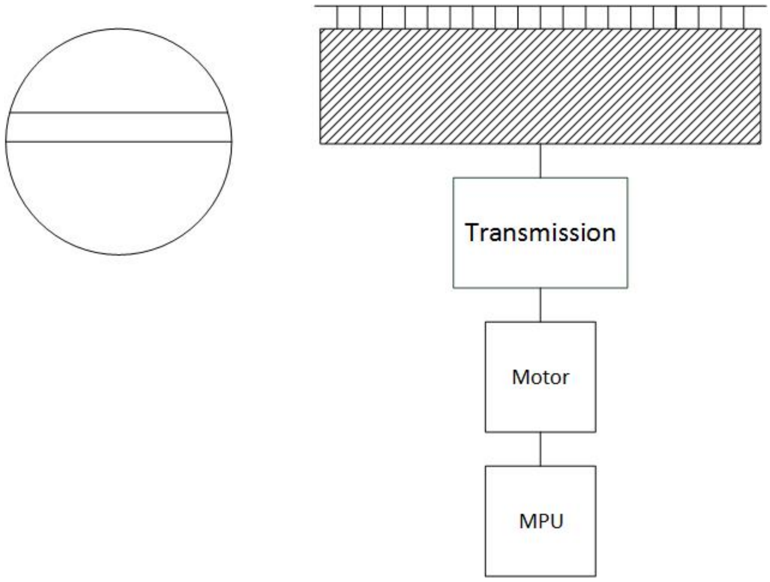


Figure II.2.3: Initial design 1

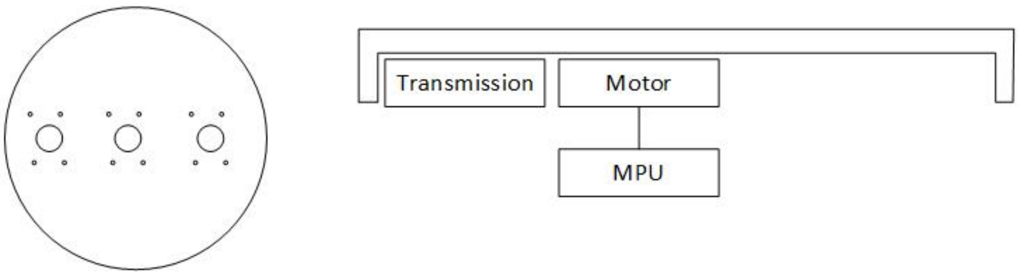


Figure II.2.4: Initial design 2

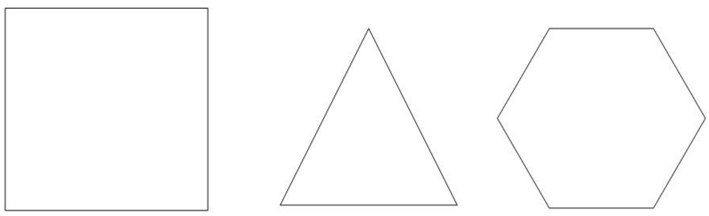


Figure II.2.5: Initial design 3

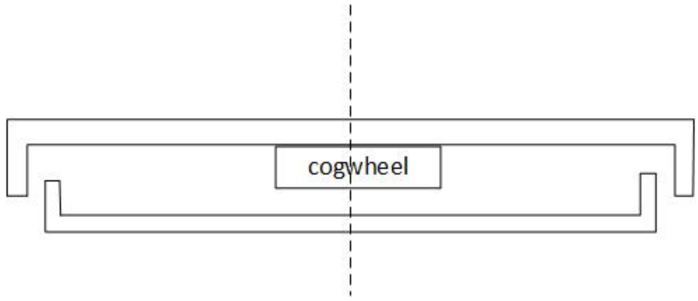


Figure II.2.6: Initial design 4

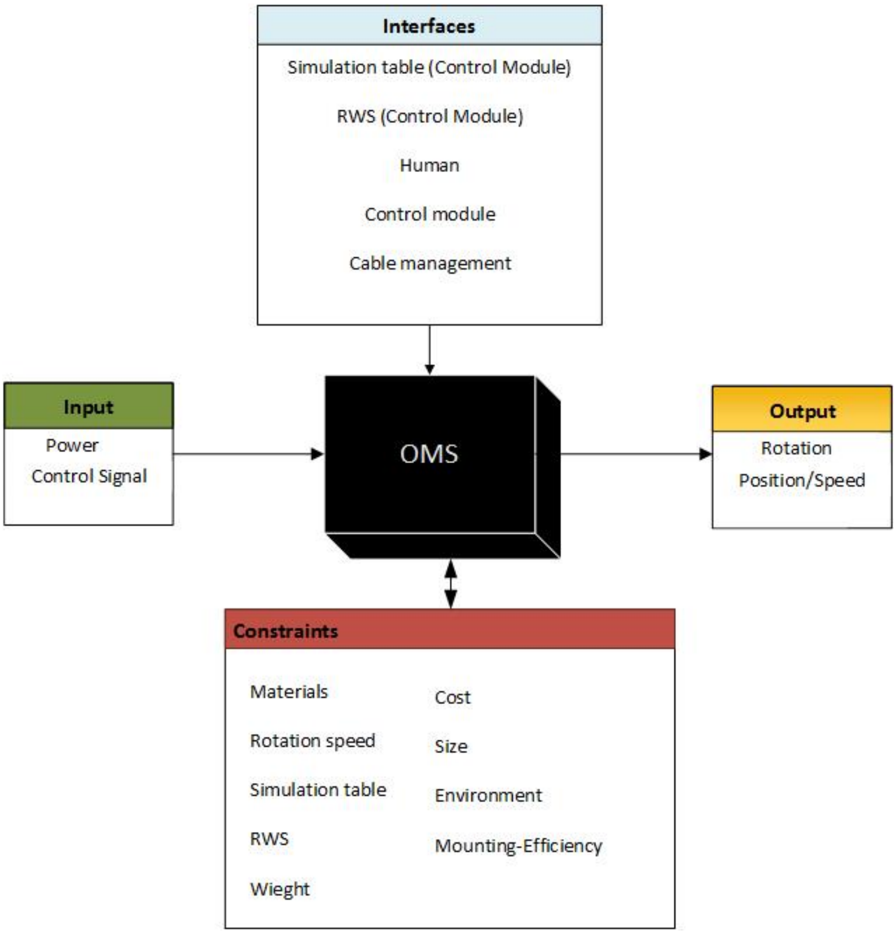


Figure II.2.7: Black box

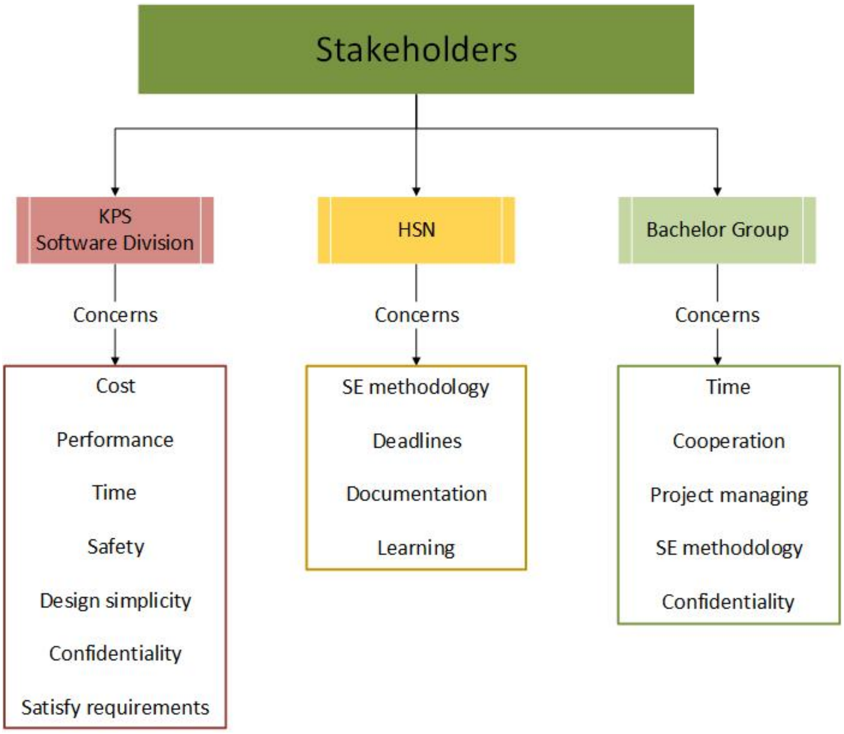


Figure II.2.8: Stakeholders

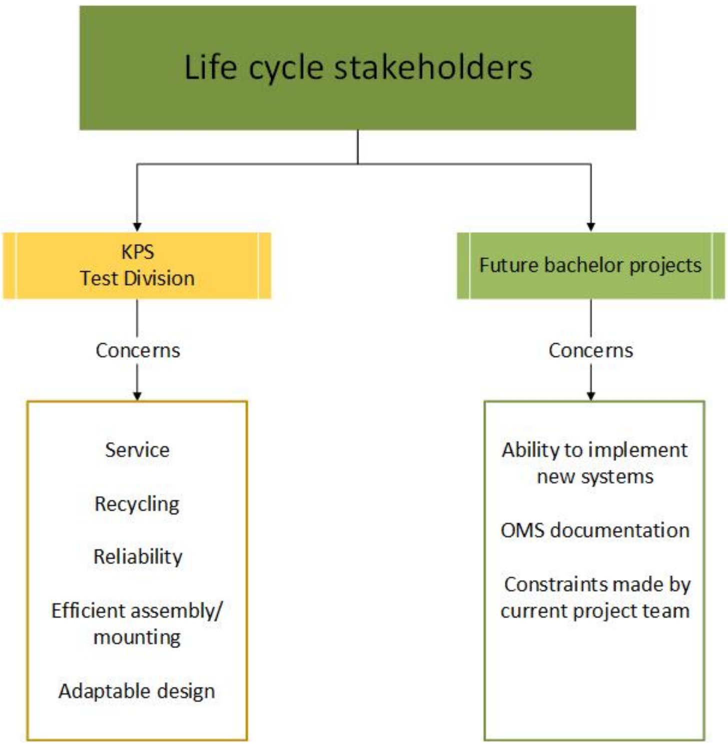


Figure II.2.9: Life-cycle stakeholders

Conclusions from Iteration 1

The major components of the system was defined. An understanding of how the system will integrate with, and move in relation to, existing components was established. Decided to ask for a demonstration of the existing systems in the two labs at KPS, to enhance our understanding of the systems. Initial designs shed light on the issues regarding where to put wires and other equipment without causing disruption to signal or movement of system. Black-box figure identified the main interfaces, but the group decided that more information and knowledge about the electronic interfaces must be sought. During identification of stakeholders it was questioned whether the group itself was a stakeholder; KPS confirmed that we indeed were and further work on stakeholders will be corrected accordingly.

II.2.2 Iteration 2

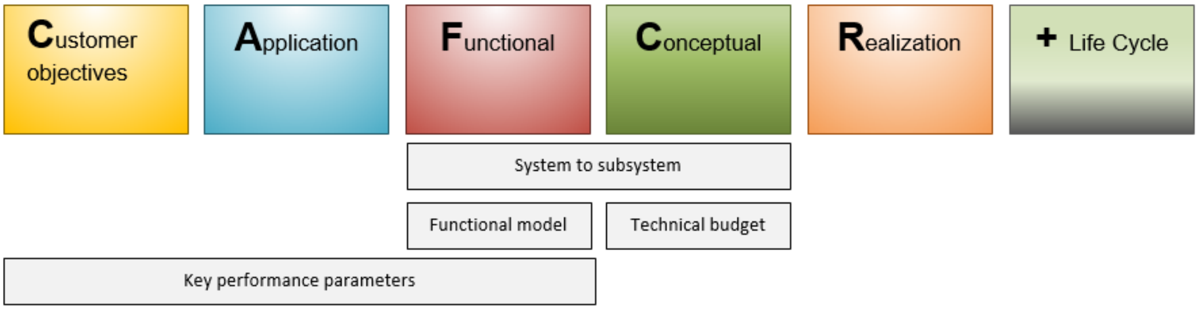


Figure II.2.10: Content viewed in CAFCR+ model

Info

- Date:27.01.2016
- Duration of time boxes: 20 minutes

Plan

- System to Subsystem
- Functional model
- Key Performance Parameters
- Technical budget
- Review and Making a Plan

Content of iteration 2

In the System to Subsystem part the OMS was broken down into its components and connecting interfaces. The braking system was then chosen for a detailed identification of components and broken into subsubsystems. Two functional flow diagrams were made; one for when the user wants to start a test and make the system rotate, and one diagram for the sequence of functions that occur when using the emergency brakes. A table of Key Performance Parameters was made. Nine key performance parameters were identified, as well as a defined value and metric of the required performance. Due to uncertainty of how much the system is likely to weigh and given a requirement regarding total weight, it was chosen to go into detail of the weight budget of the system. Hence, the technical budget chart was made for the total weight and individual weight of subsystem components was made. Lastly, the schedule for future work and progress was discussed, which helped finalise the Gantt diagram and List of Activities.

Resulting figures

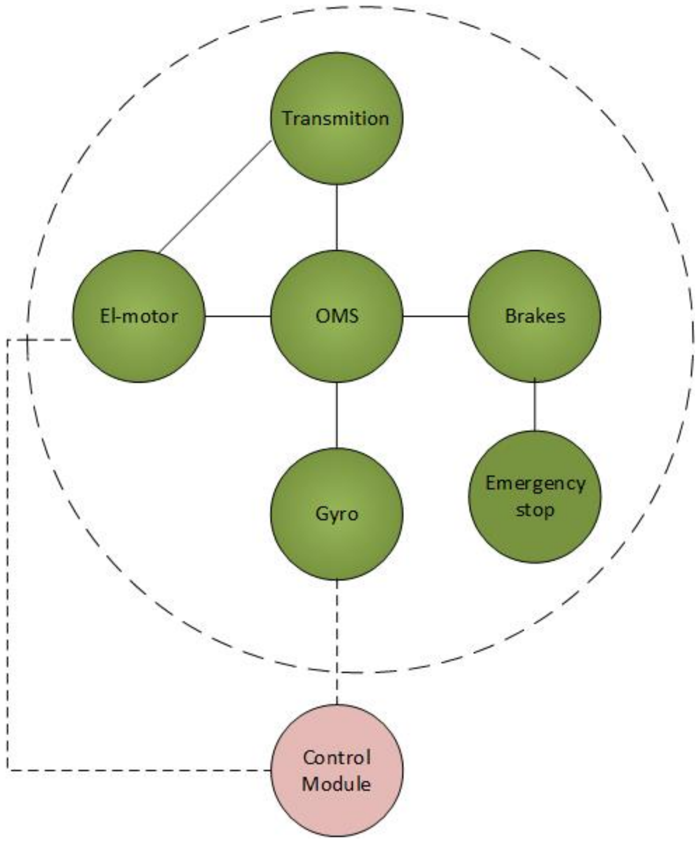


Figure II.2.11: System to subsystem breakdown

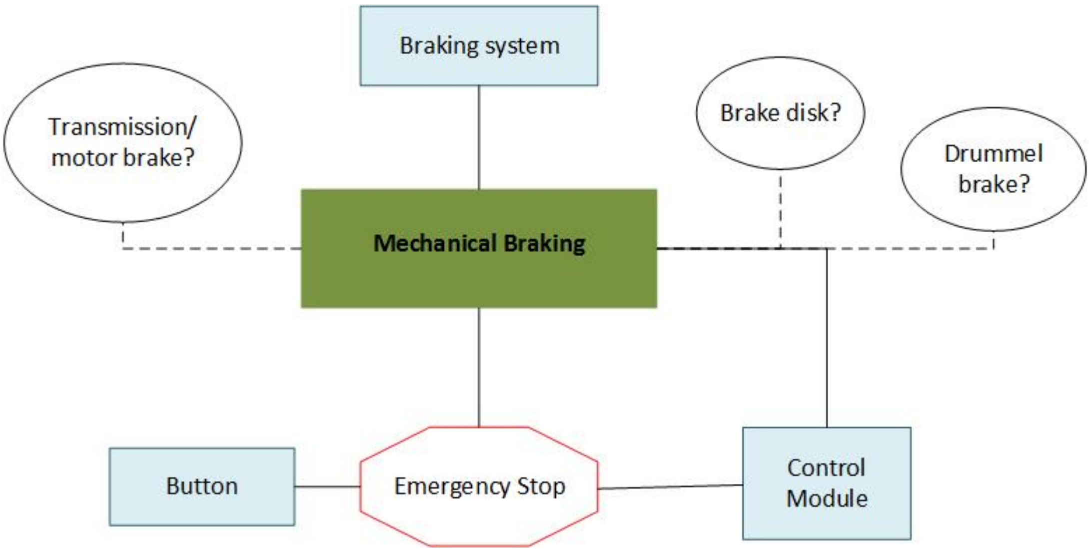


Figure II.2.12: Breakdown of subsystem: braking system breakdown

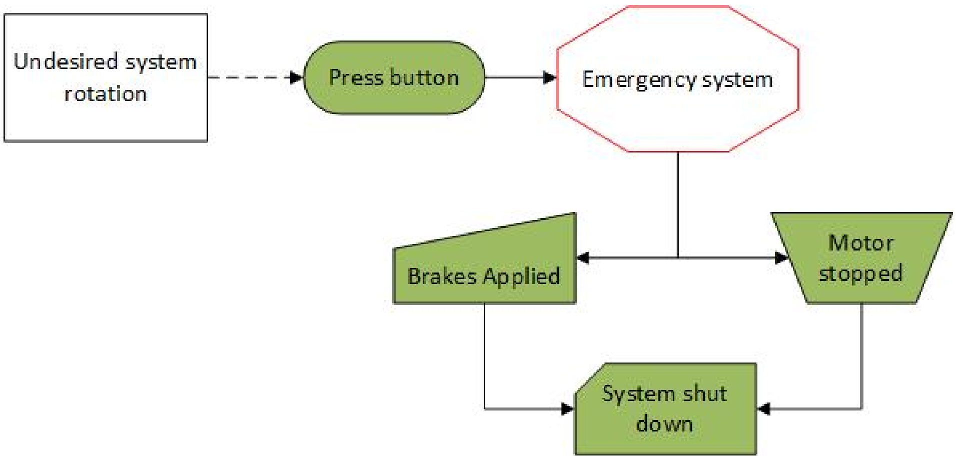


Figure II.2.13: Breakdown of subsystem: Functional model of emergency brake usage

Criteria	Performance parameter
Azimuth movement speed	more or equal to 60 degrees/sec
Azimuth movement range	-90 degrees to +90 degrees
Load capacity	more or equal to 250 kg
Total weight	50 kg
Roof stiffness	20 Hz
Emergency stop	Full stop
Temperature	-40 to +100 degrees celsius
Preload torque on mounting interface to RWS	130 Nm
Preload torque on mounting interface to motion table	200 Nm

Table II.2.1: Key Performance Parameters

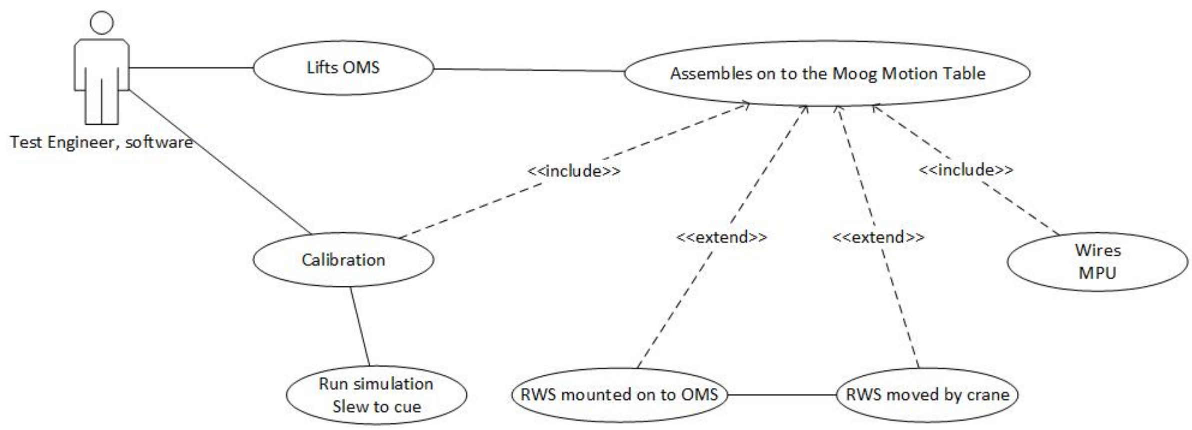


Figure II.2.14: Use case diagram: Mounting of system in test-lab

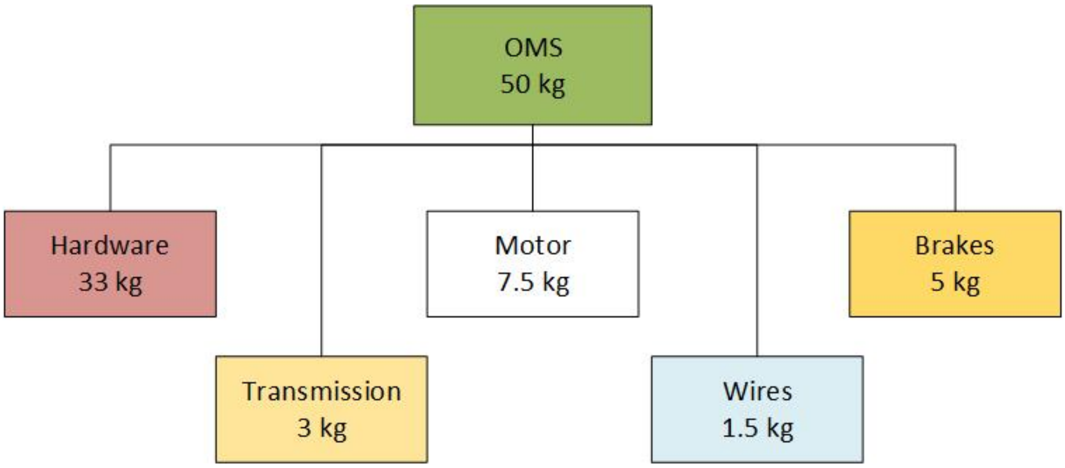


Figure II.2.15: Technical budget: weight

Conclusions from Iteration 2

Throughout iteration 2 the requirements identified so far was discussed with regards to each activity. Numerous instances where further detail was needed in order to formulate an adequate system requirement was identified. Furthermore, our Requirement Specification document needed to distinguish stakeholder and system requirements more clearly. Breakdown of the breaking subsystem awoke a discussion about what sort of brakes to use. This was noted and will be addressed in the design part of iteration 3. Various types of emergency stops were discussed during the functional model, and it was decided that the requirement regarding emergency stop needed to be broken further down. The use case diagram further highlighted the importance of considering the electrical and electronic interfaces, which needs special awareness when designing the system. Interface management is brought forward to consecutive iterations. The requirement from KPS states that the system shall be mountable by one person, so a technical weight budget gave an indication of how much each component could/should weigh. Addressing and solving the identified issues with requirement specification will be the main focus until iteration 3.

II.2.3 Iteration 3

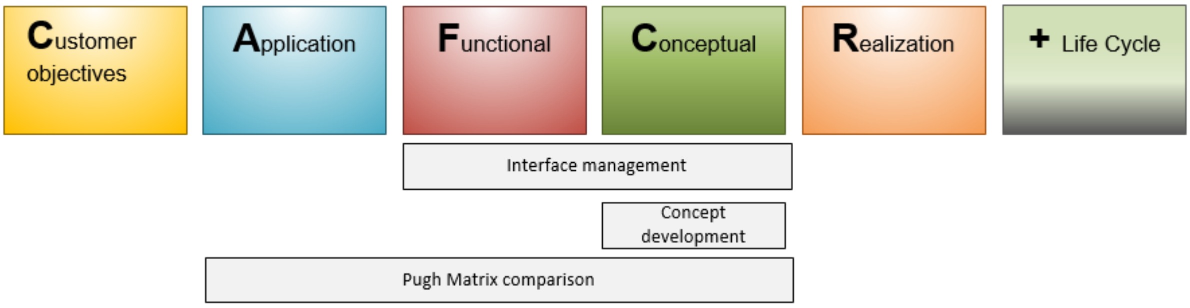


Figure II.2.16: Content viewed in CAFCR+ model

Info

- Date:08.02.2016
- Duration of time boxes: 30 minutes

Plan

- Concept development
- Interface management
- Pugh matrix comparison

Content of iteration 3

45 minute time boxes were used for each topic. For the concept development all ideas, regardless of feasibility, were written down. Approximately five different concepts were scribbled down and Lego was used to demonstrate thoughts and concepts where it was difficult to draw the idea, movement of the system and solutions. The various concepts were discussed and a few more concepts were developed that emerged from putting together pieces from the first concepts. The concepts seemed to fit into three general concept branches: one with two circular, hallow discs mounted on top of each other, one with a center core with a supported external arm for mounting of the RWS, and one branch of hydraulic/electric glider solutions.

Two separate time boxes were used to address interface management; one for the mounting surface between the system and the RWS, and one for wire solutions. The wire solutions opened up for a number of questions and it was identified that more knowledge on different solutions were needed since the group does not hold any electronic engineering students. After some initial searches a Pugh Matrix comparison of the different wire solutions was undertaken. Seven different categories for comparison were identified. Each solution was rated on a scale from 1-5 (5 being the best) in each category. Furthermore, each category was weighted according to how important each category was.

The initial concepts are to be presented at KPS on Friday 12th of February.

Resulting figures

PUGHS MATRIX										
		Slip ring		Alternative slip ring		Spool		Minimum required movement	
	Weight	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score
Cost	0,3	1	0,3	3	0,9	4	1,2	5	1,5
Complexity	0,2	4	0,8	3	0,6	3	0,6	5	1
Range of motion	0,3	5	1,5	5	1,5	3	0,9	1	0,3
Software addition	0,05	5	0,25	5	0,25	2	0,1	2	0,1
Acquisition	0,05	4	0,2	2	0,1	1	0,05	5	0,25
Life span	0,05	5	0,25	3	0,15	3	0,15	4	0,2
Service / repair	0,05	5	0,25	5	0,25	3	0,15	4	0,2
	1,00	29	**3,55**	26	**3,75**	19	**3,15**	26	**3,55**

Figure II.2.17: Pugh Matrix of wire solutions

Conclusions from Iteration 3

All together 10 different designs were scribbled down. The initial designs will be presented at KPS in order to assess whether the project team are on the right track. During this meeting a discussion regarding the feasibility of the various concepts will be undertaken. An indication of the budget of the project will also be provided by KPS, which will help the group further evaluate the various concepts. CAD drawings of the concepts will be made by Fredrik and Kjetil until Friday, while Heidi will make the Pugh Matrix. Each group member will do some internet searches for the alternative wire solution that was suggested. The results of these searches will be discussed on Thursday 11th of February. The meeting at KPS on Friday will provide an indication of whether a new concept iteration is needed.

II.2.4 Iteration 4

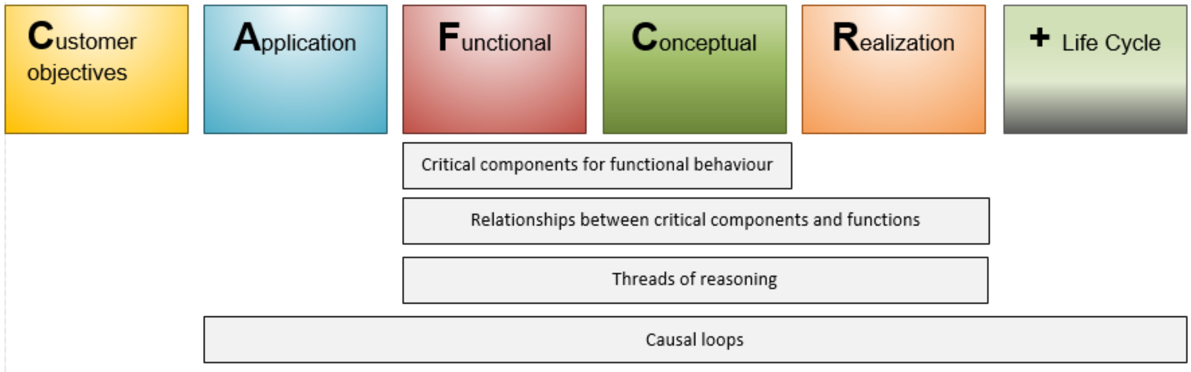


Figure II.2.18: Content viewed in CAFCR+ model

Info

- Date:08.02.2016
- Duration of time boxes: 30 minutes

Plan

- Critical components for functional behaviour
- Threads of reasoning
- Relations between critical components and functions
- Trade-off tension points
- Causal loops

Content of iteration 4

Slide number 50 from Gerrit Mullers presentation "Architectural Reasoning Threads and Integration" was used for this iteration. This iteration is closely connected to iteration 3 here initial designs and concepts were developed, while this iteration goes one step further into a detail. The purpose of this iteration was to get a deeper understanding of the components needed in the system in order to perform the essential functions.

Four essential functions were defined: rotate, emergency stop, mounting and data transmission. For each of these functions all general components needed in order to perform these functions were identified. For each component a list of traits was defined. The purpose was not do completely define the design or specifications of the components, but to analyse what traits that needs to be considered when choosing a specific component. E.g. for the essential function "rotate" a critical component is the motor. Critical traits to take into consideration when choosing a motor were power, regulation mechanism, wiring, weight and size.

For the "Threads of reasoning" part the 5 most critical (stakeholder) concerns, the 4 most important specification issues, the 5 most critical life-cycle issues and the 4 most critical design aspects were identified. Where relationships existed between the 18 different identified issues lines representing positive (green) and negative (red) relationships were drawn. The resulting map of interconnecting issues were used to identify areas where tension between trade-offs will exist. E.g. the map clearly showed a trade-off tension point between motor and price, between geometry and weight, and between material and geometry. Critical loops that show how a change in one issue might cause a circular effect, e.g. the fixtures-moveability-service-lifetime-wear-fixtures loop.

Resulting figures

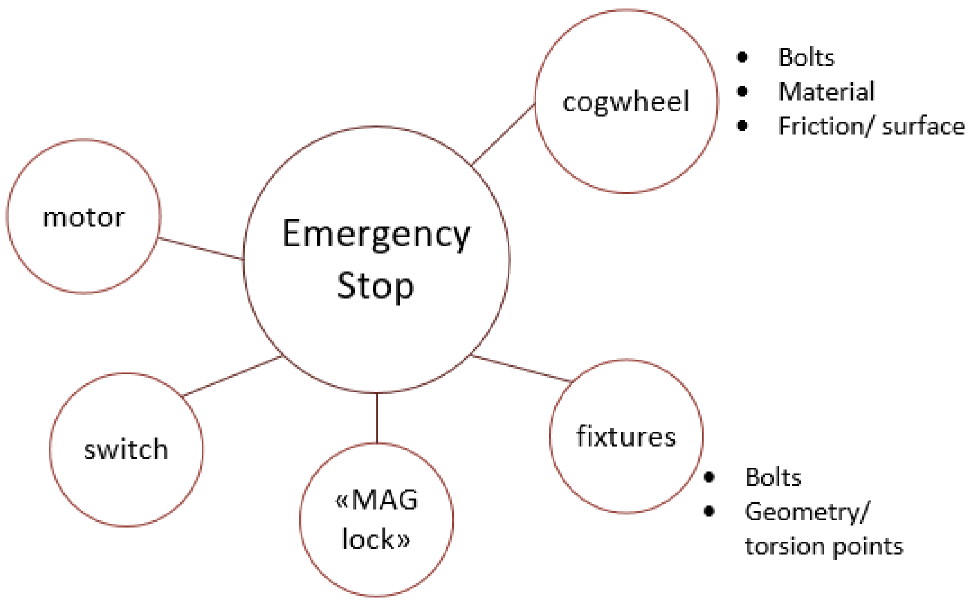


Figure II.2.19: Critical Components for Emergency Stop

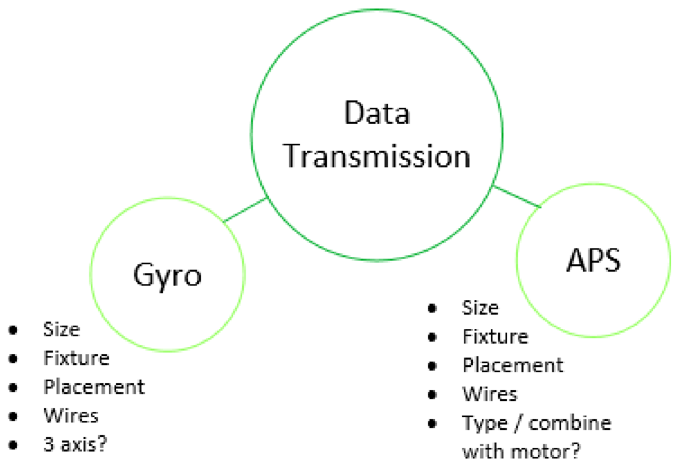


Figure II.2.20: Critical Components for Data Transmission

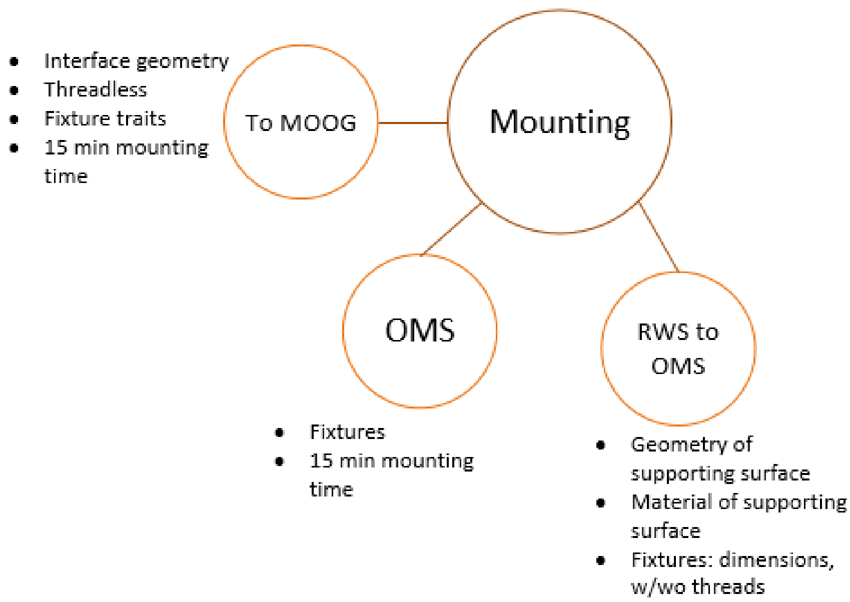


Figure II.2.21: Critical Components for Mounting

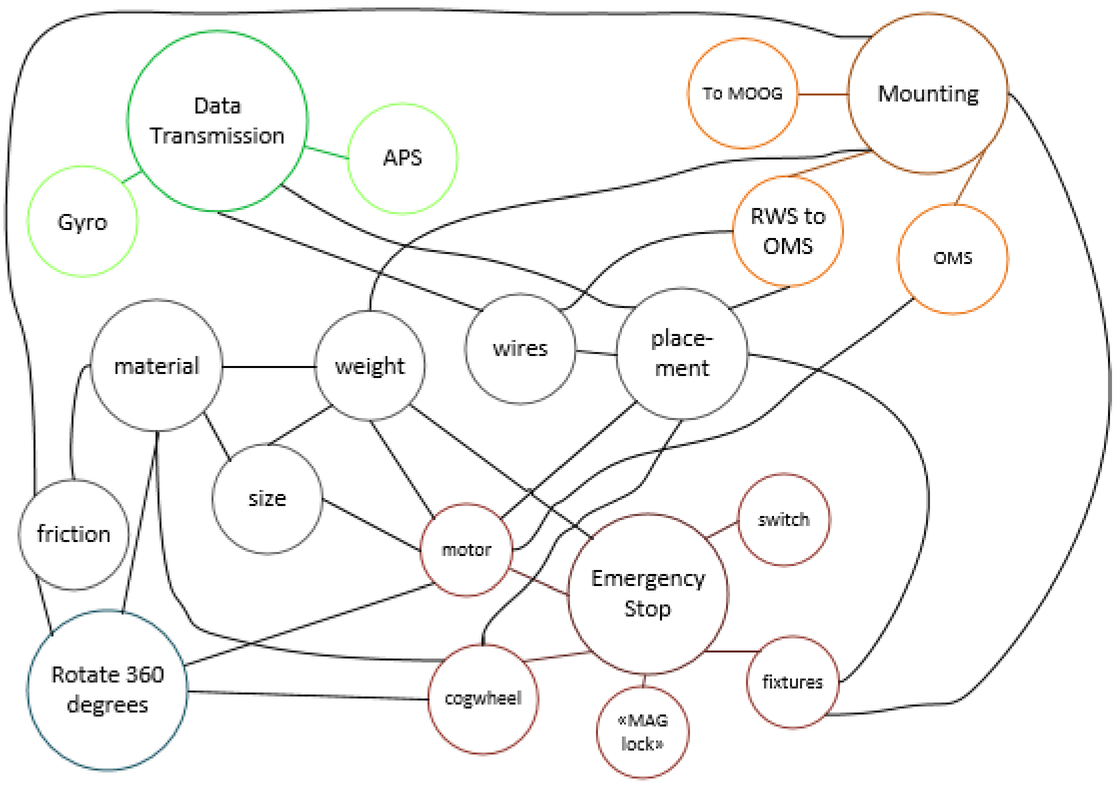


Figure II.2.22: Relationships between Critical Components and Functions

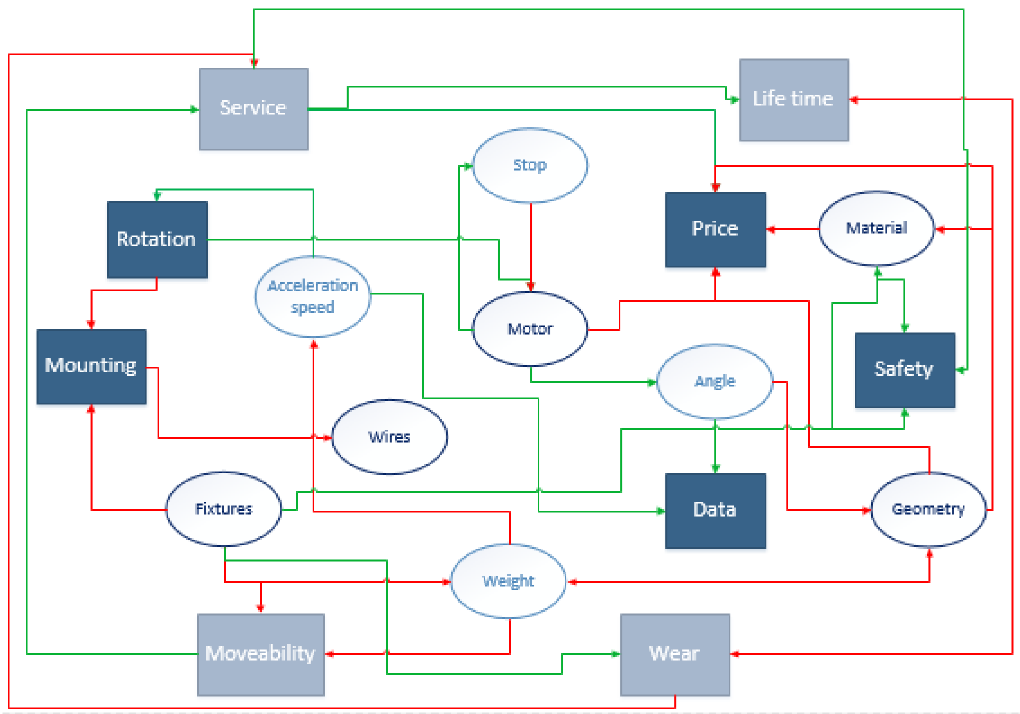


Figure II.2.23: Threads of Reasoning

Conclusions from Iteration 4

The most trade-offs holding the most tensions that we are likely to meet in the design of the system are weight versus geometry, geometry versus material, and material versus weight. A critical loop was identified that shows how the design of fixtures can have ripple effects throughout the lifetime and usage of the system. Hence, special attention must be exerted when choosing a specific type of fixture, as this might also affect wear, moveability and service of the system.

II.2.5 Iteration 5

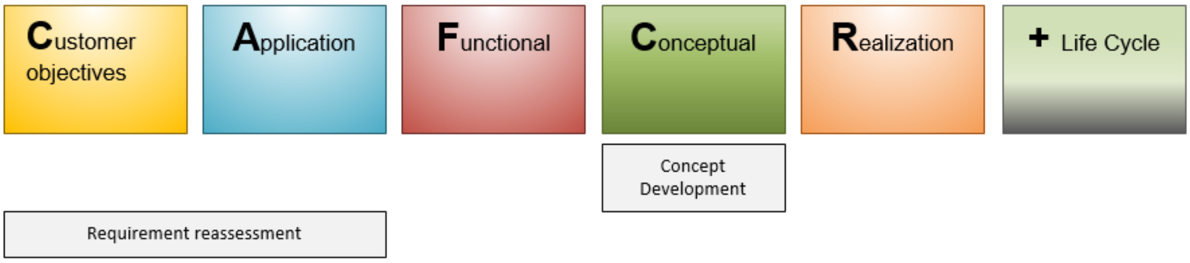


Figure II.2.24: Content viewed in CAFCR+ model

Info

- Date:12.02.2016
- Duration of time boxes: 30 minutes

Plan

- Concept Development
- Requirement Reassessment

Content of iteration 5

With the knowledge obtained through iteration 4 in mind, brainstorming of concepts and various solutions within each concept continued. It was decided to undertake two separate bouts of brainstorming over 2 separate days, as fatigue might cause the creativity and evolution of new ideas to reach a stand still prematurely. Through the brainstorming sessions in Iteration 4 and 5 combined a total of 14 design concepts were obtained; all of which are presented in the Design document. The concepts included everything from crazy, less feasible ideas to simple, more realistic concepts. A brief selection of the brainstormed ideas are presented below under "Resulting figures".

The purpose of the requirement reassessment at this stage was to evaluate if the system we intend to make will fit the objectives, needs and context of the customer, as well as check if new requirements had appeared. When developing concepts the key customer concerns identified in iteration 1 was particularly kept in mind. New requirements were identified through the period stretching from Iteration 4 to Iteration 5. These included system requirements related to the additional forces and strains that will be exerted on the system as the motion table moves through its six degrees of freedom. Pitch, roll, yaw, heave, surge and sway are factors that we need to add into system dynamics calculations and analysis of the system. Twenty new requirements were stated on the background of this finding.

Resulting figures

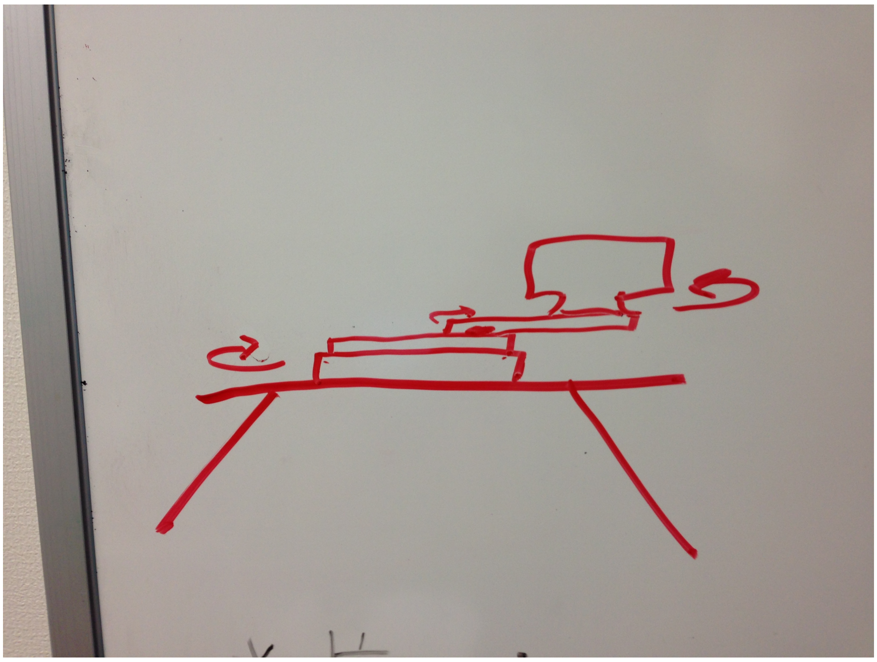


Figure II.2.25: Early concept 1

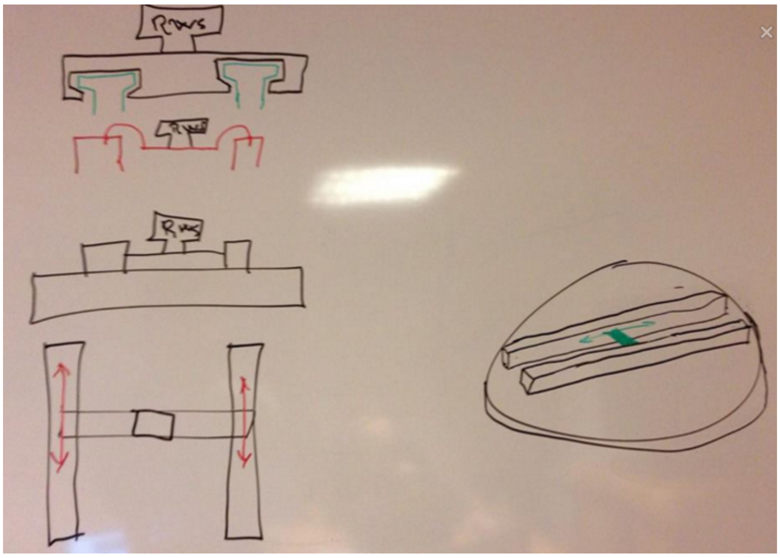


Figure II.2.26: Early concept 2

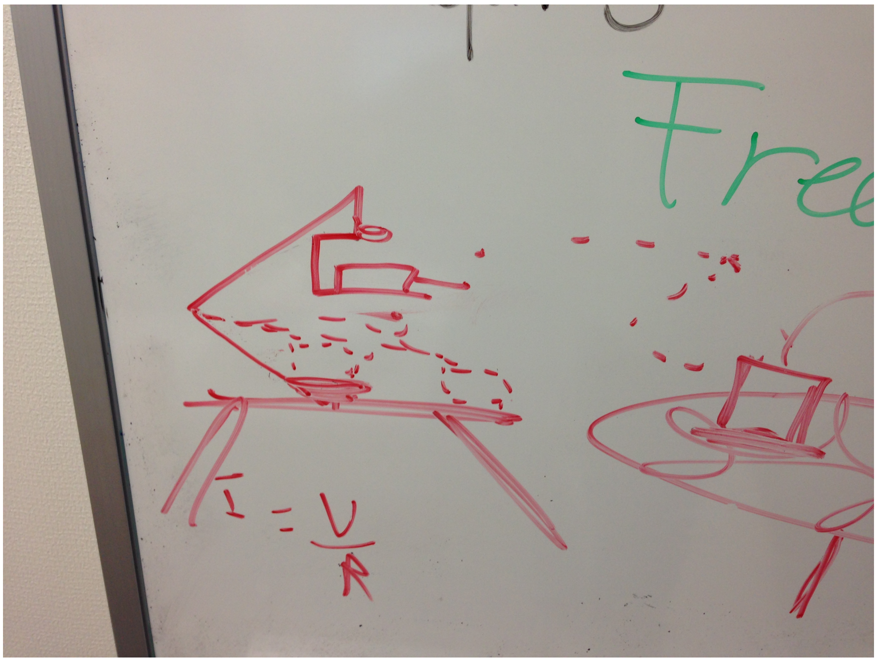


Figure II.2.27: Early concept 3

Conclusions from Iteration 5

Numerous concepts were developed, some of which will be modelled in further detail in order to get a better understanding of the concept, as well as providing models of initial designs that can be presented to KPS. The project team split into three groups where pairs will continue working on one of the following; concept modelling, preparatory reading for analysis, and test specification.

II.2.6 Iteration 6

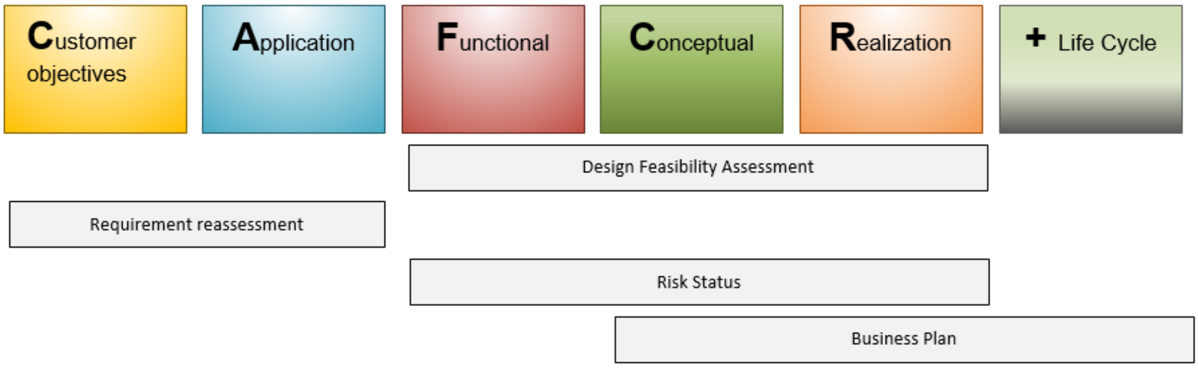


Figure II.2.28: Content viewed in CAFCR+ model

Info

- Date:29.02.2016
- Duration of time boxes: 45 minutes

Plan

- Design feasibility assessment: coarse filtering
- Design feasibility assessment: detailed filtering
- Requirement Reassessment
- Risk Status
- Business Plan

Content of iteration 6

During the two parts of Iteration 5 the group had come up with 5 more design ideas, adding up to a total of 15 design concepts. The concepts included everything from crazy, less feasible ideas to simple, more realistic concepts. Firstly, the concepts were to go through a coarse filtering. The filtering criteria were selected from the the "threads of reasoning" concerns in Iteration 4, where the most important specification issues, life-cycle issues and design aspects were identified. The criteria used for detailed filtering were derived from the stakeholder requirements; both KPS and the project team.The coarse filtering criteria judged the overall feasibility of the concepts and filters out the concepts that are unrealistic for the scope of the project. The five criteria were cost, function, complexity, user friendliness and maturity of technology. Each design concept were simply given either a smiley face, a neutral face or a unhappy face on each of the five criteria. Those with 3 smiley faces and two neutral faces qualified for more detailed evaluation. Five design concepts were filtered out in the first round, leaving a shortlist of 10 more realistic design concepts that deserved more detailed evaluation of feasibility. The criteria used for detailed filtering were derived from the stakeholder requirements; both KPS and the project team. The criteria were as follows: manufacturing cost, weight, design complexity, adjustability and risk. A score from 1 (worst) to 5 (best) were given for each of the five detailed filtering criteria. With the aim of reducing subjectivity and peer pressure, and to increase inter-rater reliability the project team split into two teams who separately evaluated all the design concepts. Lastly, each criteria was weighted. The total sum of weighted scores were added up for each concept.

The concept filtering did not point out a clear best alternative. The project team identified the three best concepts and looked for a hybrid solution amongst those. This encourages further idea generation where one attempts to mix and match the best parts from each of the strongest concepts. The three concepts with the best score after the detailed filtering; "Havnekran", "Dobbel Discus" and "Hamburger 2" respectively; were put next to each other and an idea brief as to any possible hybrid solutions was undertaken. The generated hybrid solution was then lastly subjected to the same detailed briefing as the other concepts. The detailed results of both the coarse and detailed filtering are presented in the Design Evaluation Matrix.

The hybrid solution received the highest score on the detailed filtering. However, the concept "Dobbel Discus" stood out as a more innovative and less intricate solution, whereas the hybrid appeared as more of a "safe" solution. The conceptual design phase often does not provide sufficient detail for full evaluation of the concepts. To bridge the gap between conceptual design and detailed design preliminary designs can be developed. Preliminary designs challenges the designers to address the more detailed feasibility of the solutions within the conceptual design. As two concepts appeared viable at fulfilling the system requirements it was decided to make preliminary designs of the two concepts, with the purpose of providing a better foundation for making a robust final concept selection.

The risk status showed that the most critical risk were as follows:

- Lack of electro competence
- Lack of knowledge to validate computational control of system
- Budget fails to support design
- Lack of knowledge about budgeting and prices
- Incongurency of technical trade-offs

It was decided that the latter three risks were under control as KPS have given clear indications of a rather generous budget if they consider the concept to be of good quality. KPS will provide further discussion of the budget when the concept filtering process is undertaken and the final concepts with life-cycle implications are presented. The two former risks will be addressed when design of a final concept is initiated, as more clear questions will emerge. Any suggestions to wire solutions, electrical and electronic interfaces will be discussed with the appropriate lecturers at HSN for assurance of approach and choices taken.

No new requirements had emerged from previously, but the group was made aware the RWS has to be fixed from underneath, which has an impact on the design of the systems.

Iteration 6 included giving thought to a business plan. A business plan is related to the economical aspect of the project. Traditionally, it includes a strategy for selling the product, and also an estimation of how much the product will cost. However a strategy for selling the product is more or less irrelevant in this case, given that this is an internal product, made specifically for one application and only one firm. Furthermore it is only planned for making one unit. This makes it so that to formulate a business plan is more or less irrelevant, given that the buyer is already lined up.

However the estimation of cost is still largely relevant. The cost estimation is a brief estimation of costs made on the basis of a preliminary design. The preliminary budget includes only what is called a technical budget. A technical budget is related only to the parts and manufacturing of prats in conjunction with the product.

The costs of each individual procurement/aspect is given in table II.2.2, and the distribution is shown in the pie chart, figure II.2.29. It has been decided that to divide the costs in to seven different aspects is expedient. The following aspects is the main estimated costs of the technical budget.

Part	**NOK**
Machining	15 000
Material	9000
Wiring	6000
Motor	20 000
Offset Solution	15 000
Rotational equipment	35 000
Cable Solution	60 000
Sum	160000

Table II.2.2: Preliminary Budget in NOK

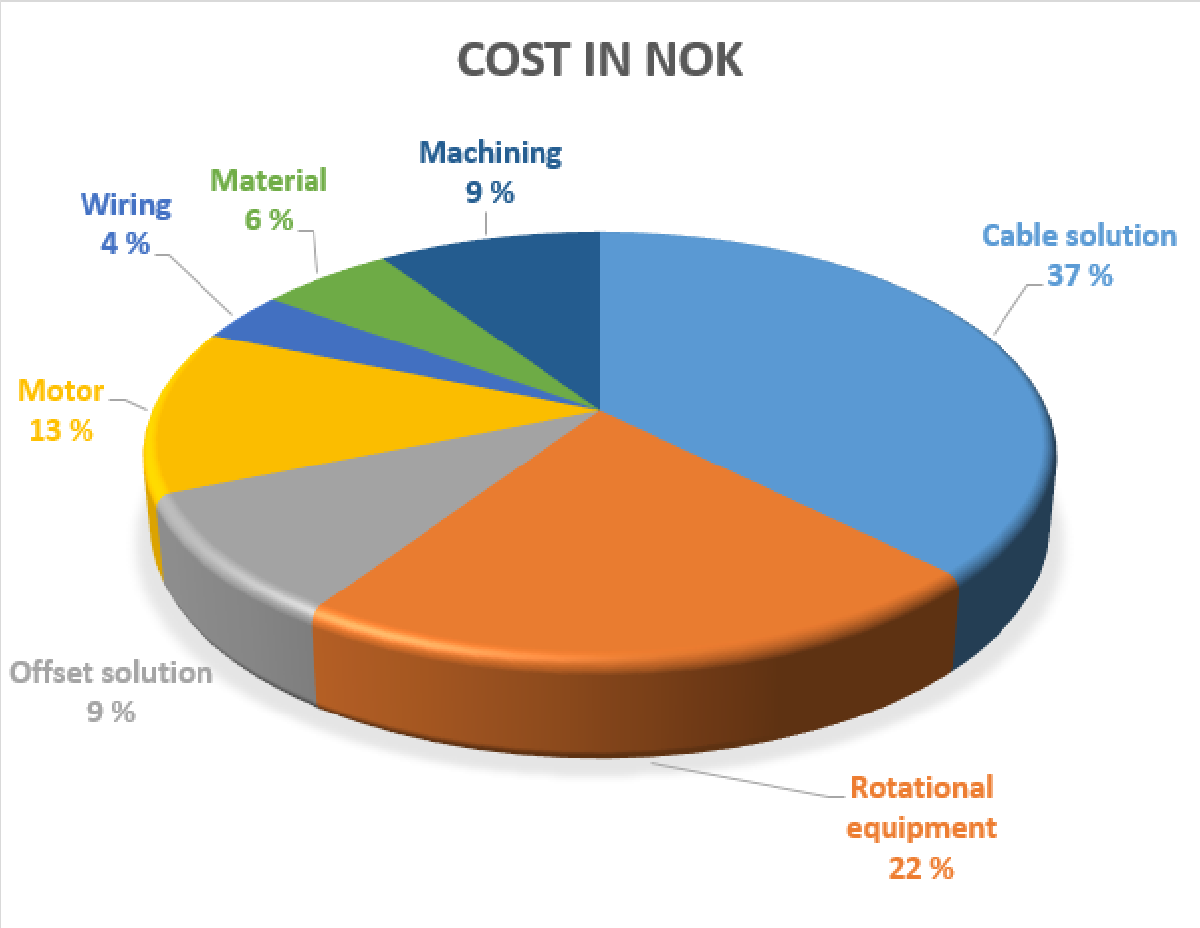


Figure II.2.29: Pie Chart of the Preliminary Budget

It should be added that this is a preliminary budget in every seance of the word. There are a lot of uncertainties when formulating a budget in such an early stage of the project, but nevertheless it is a necessity in order to get a good overview of any restrictions relating to cost. Conclusively, this is only a rough estimate that will serve as an indication on how much investment is expected of the costumer.

Resulting figures

A design evaluation matrix that gathered all the data and corresponding comments was developed. This can be found in the Design Evaluation Log.

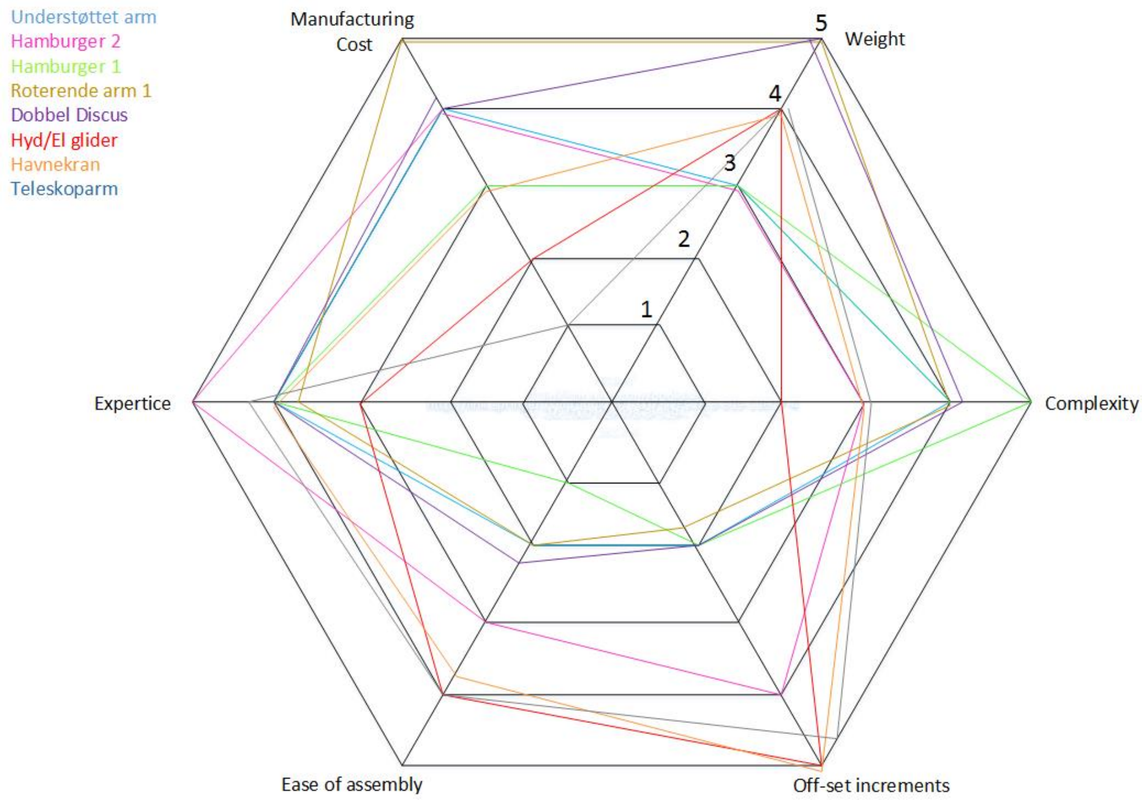


Figure II.2.30: Radar Chart for visualisation of concept scores

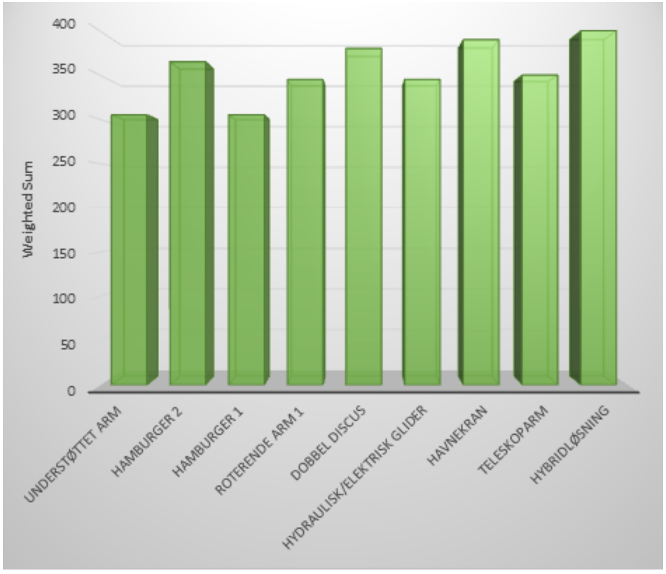


Figure II.2.31: Detailed Weighted Score of Concepts

Conclusions from Iteration 6

Coarse filtering of concepts ruled out some of the less feasible concepts. The detailed filtering left the project team with three design concepts of fairly similar, yet not equal, scores. The concepts, together with the detailed evaluation, are to be presented at KPS three days after the current iteration. Through detailed filtering two of the concepts came out with similar scores. It was decided to split the project team into two groups, each of which goes into further detail for one of the concepts in order to get a deeper understanding of the feasibility of the concept and the associated solutions. The more detailed preliminary designs will be evaluated again, after which the final design will be chosen. The user implications of choosing one design over another will be presented to KPS, in order to allow them to provide feedback on what they would rather prefer.

II.2.7 Iteration 7

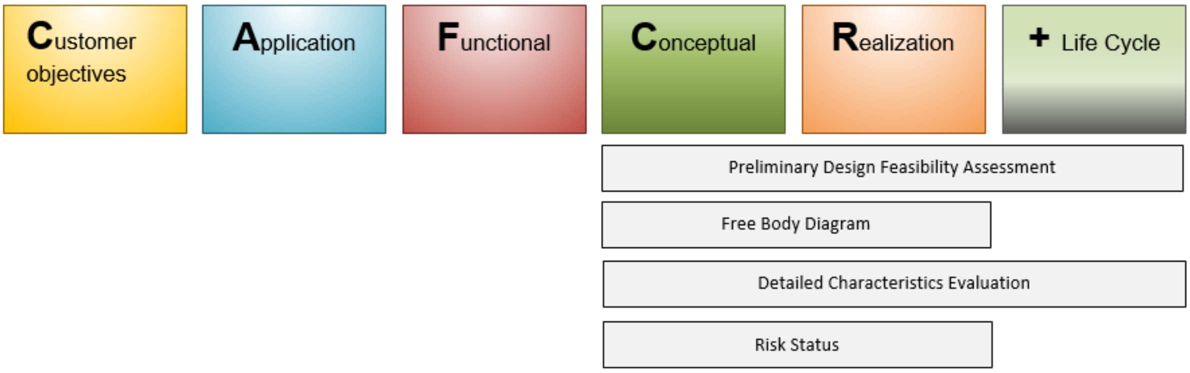


Figure II.2.32: Content viewed in CAFCR+ model

Info

- Date:03.03.2016
- Duration of time boxes: 45 minutes

Plan

- Design feasibility assessment: Preliminary Designs
- Free Body Diagram (FBD)
- Detailed Characteristics Evaluation
- Risk Status

Content of iteration 7

The detailed preliminary designs for Dobbel Discus and Hybrid were presented by their representative group members. The pros and cons of each design were discussed. The designs were then further discussed according to the stakeholder requirements as well as the criteria they were evaluated against in the Design Evaluation Matrix. It was decided that after more detailed modelling some of the scores the Hybrid had obtained in the earlier evaluation was no longer valid, as e.g. weight had increased and ease of mounting was easier in the Dobbel Discus. Hence, the Dobbel Discus appeared as the most feasible solution, both due to having a simpler design with less subsystems and unsure factors, as well as choosing a simpler mechanical design would let the project team focus in more detail on academic risks such as lack of electronics knowledge and learn more on this topic.

The Risk Management Matrix was revisited and the notable risks for this phase of the project was discussed. The risks were the same as for the previous period:

- Lack of competence regarding electronics
- Lack of knowledge to validate computational control of system
- Budget fails to support design
- Lack of knowledge about budgeting and prices
- Incongurency of technical trade-offs

As decided in the last iteration the latter three risks were under control as KPS have given clear indications of a rather generous budget if they consider the concept to be of good quality. The project team felt that the two former risks were slightly mitigated after acquiring more knowledge about electronics as well as discussions with several electronic professors at HSN.

Resulting figures

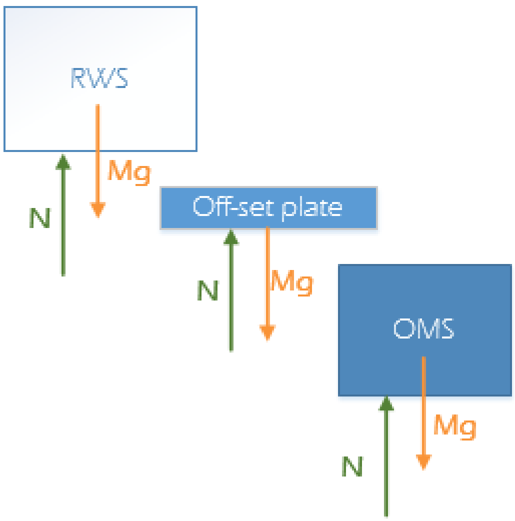


Figure II.2.33: Simple Free Body Diagram sketch of system

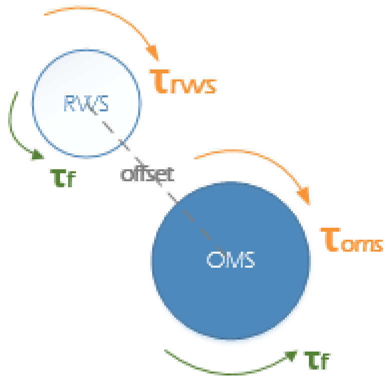


Figure II.2.34: Simple Free Body Diagram sketch of system

Conclusion from iteration 7

On the basis of more detailed information about the two preliminary design concepts a decision was made as to which concept that will be developed further into a final product. The Dobbel Discus was chosen as the most feasible concept and the project will proceed into the analysis phase with this design. The analysis phase was initiated by drawing Free Body Diagrams to engage a discussion as to what we need to think about when analysing and designing the system. Electric motors were discussed and some knowledge has already been gained. However, it was determined that some calculations of the physical properties of the design is necessary in order to further evaluate what electric motor that is most viable.

II.2.8 Iteration 8

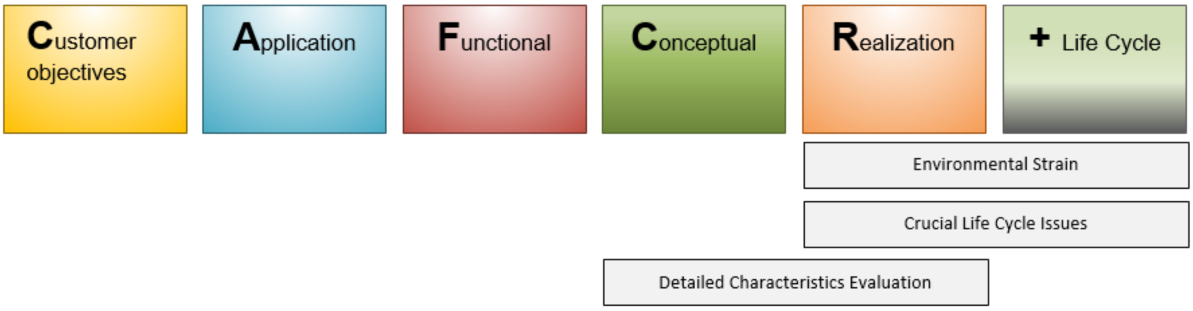


Figure II.2.35: Content viewed in CAFCR+ model

Info

- Date:17.03.2016
- Duration of time boxes: 45 minutes

Plan

- Environmental Strain
- Crucial Life Cycle Issues
- Detailed Characteristics Evaluation: materials, fixtures

Content of iteration 8

The overall purpose of the iteration was to identify factors and issues that might affect the life-cycle of the system and that should hence be considered in the design of the system. Firstly, environmental strains were identified. Environmental strain was defined as any influences that may impact on the system in the environment that it is meant to exist and operate within. Climate, including temperature and humidity, was discussed and it was agreed upon that this would not be a critical factor as the climate in the lab can be considered stable within as the system will not be exposed to neither very high nor low temperature, or large variations in humidity. The system is likely to be moved, either manually or by crane, multiple times within its environment. Also, storage of the system should be thought about. The system needs to be designed and manufactured without any sharp edges and loose parts, to allow safe and easy moving of the system. Furthermore, it could be purposeful to either make or find a dedicated box for storage. The box should include e.g. a moulded polystyrene shape, loose polystyrene or likewise to make sure no parts of the system gets damaged during potential transportation or storage.

During the life-cycle of the system there are several issues that might appear, that needs to be considered when designing the system. The life-cycle issues where split into two categories: maintenance and design. The former comprises access and availability of spare parts and what parts that are likely to need regular maintenance; motor, offset disc and bearing. The latter comprises issues that need particular attention when designing the OMS, such as ease of access to motor, slip ring and bearing, design of the internal space for all the parts we wish to install within it, fatigue on fixtures and bearings from e.g. vibration, and ventilation to prevent overheating of the motor and internals.

Fixtures for the offset disc has during the last phase from iteration 7 been identified as needing further brainstorming and concept development as the fixtures for the offset disc and the fixtures for the RWS interfere with each other, as well as the offset disc fixtures needing further strength/support to ensure that it will be able to withstand the strains experienced during operational life. Due to this the group and plan for further work was reorganised slightly to focus on the two most critical components that are vital in order to progress further in the project; offset solutions including modelling and simulation, and motor selection.

Resulting figures

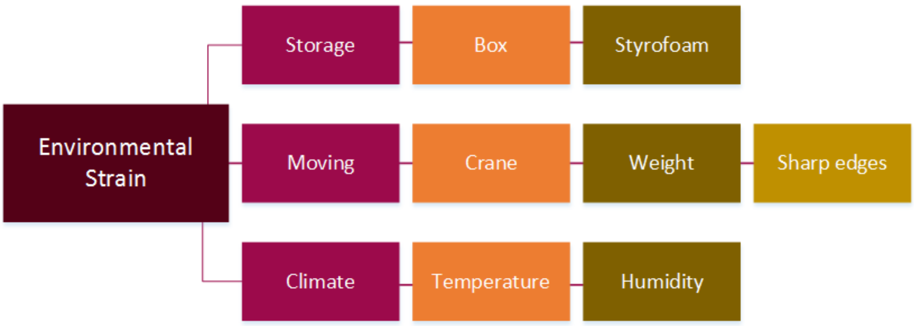


Figure II.2.36: Environmental Strains

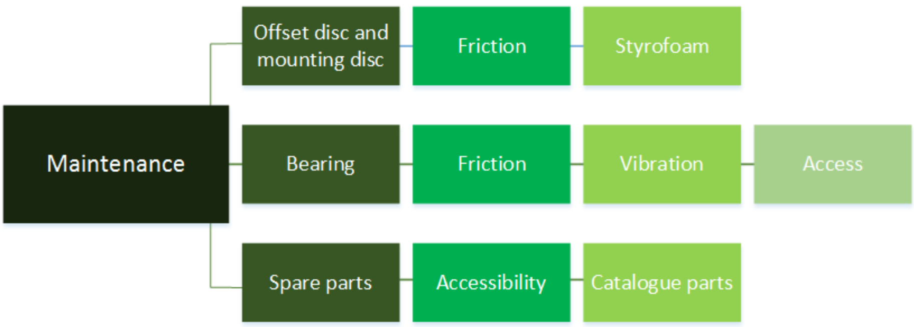


Figure II.2.37: Crucial Life Cycle Issues

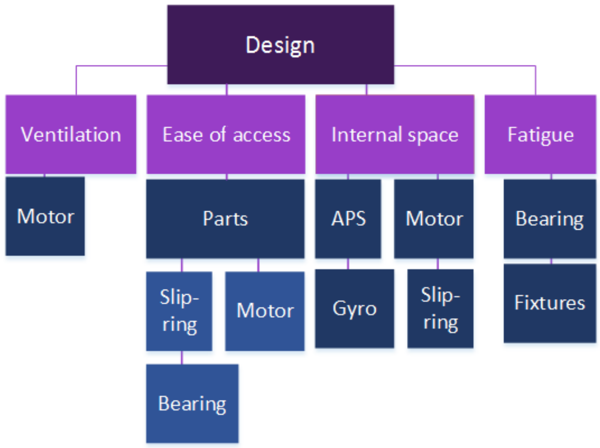


Figure II.2.38: Crucial Life Cycle Issues for Design Development

Conclusion from iteration 8

The environmental strains identified are easy to design for by including sufficient fillets and no loose parts that are likely to move during transportation or moving. The crucial life-cycle issues identified will receive further attention in the upcoming work on design and characteristics. Ease of access to parts and internal space will be considered when designing the arrangement of the internals of the OMS. Fatigue will be considered both through optimisation of design via simulations and vibrational analysis, and through velocity and torque curve analysis for consideration of heat generation when choosing an electric motor.

II.2.9 Iteration 9

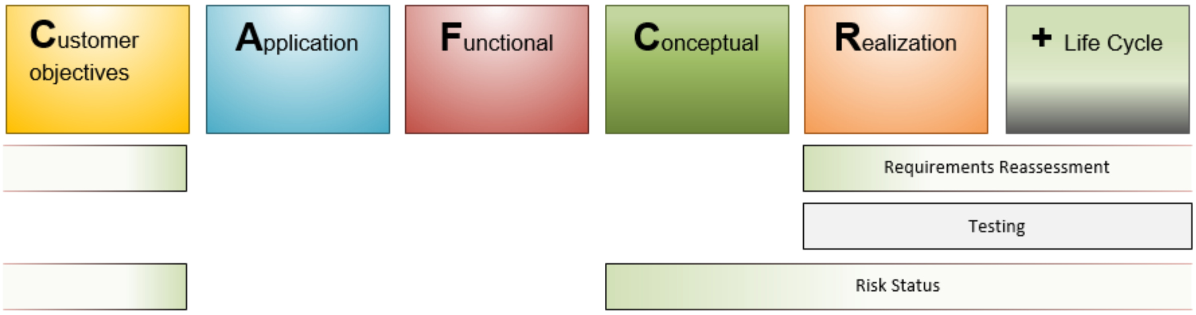


Figure II.2.39: Content viewed in CAFCR+ model

Info

- Date:13.04.2016
- Duration of time boxes: 55 minutes

Plan

- Requirements Reassessment
- Testing
- Risk Status

Content of iteration 9

The purpose of the ninth iteration was to review all the requirements and assess which ones that were ready to be tested and plan the upcoming test period. The requirement reassessment also served the purpose to assure that the developed design will realize the stakeholder- and system requirements. All the requirements in the Stakeholder Analysis Matrix and Requirement Traceability Matrix were discussed and given a status. The status was marked as either a green, orange or red box in a column after the requirement description; indicating "fulfilled", "in progress" or "needs urgent attention" respectively. It was identified that 1/3 of the stakeholder requirements were already fulfilled. The system requirements that were marked as red pertained to the emergency stop function. The definition of what is meant by an emergency function has throughout the project been discussed with the stakeholder several times, and it appeared that the need for an emergency stop function meant a mechanism that cuts the power to the motor in order to prevent overheating. Thus it was decided that this requirement needed to be reformulated. Work was distributed with regards to the other orange and red requirements, in order to ensure that all requirements will be worked on in the upcoming phase.

The Test Specification document was reviewed and discussed before starting to plan the testing that will receive a central position in the upcoming phase. At initiation of the project the goal was to produce a physical prototype that could be tested in the systems intended operating environment. However, along the way it was found that this goal was too ambitious for the scope of this project within the time given. Thus, a number of tests would no longer be relevant to the current project team. It was decided to develop a more extensive set of verification tests in order to be able to verify all system requirements. The validation tests will still be stated in the test specification document, as this will help potential future project teams in validating the stakeholder requirements to the main stakeholder.

The risks that were most critical for the past phase that the team has recently gone through were that the budget will not support the concept, customer being dissatisfied with the product, incongurency of technical trade-offs, lack of knowledge to validate the computational control of the system and lack of electro competence. The most costly parts of the system are the slew bearing and the motor. The team have investigated several options and suppliers and have a couple of alternatives for each. Work with the slew bearing is still in progress; however the project team are confident that a solution that will fit the budget can be provided. Technical trade-offs have evolved mostly around weight, power versus size, and motor versus height. These trade-offs have been solved by providing flexible solutions that easily can be adjusted with minor design alterations by the stakeholder when they in the future plan to manufacture the system and their new lab is finished. The project team does however design and present what they consider the most optimal solution with the requirements they have been given. Lack of electro competence has been particularly challenging when opting to choose an electric motor that will be suitable for the system. Extensive work has been put into getting a theoretical understanding of how electric motors work and what characteristics are important when designing and choosing such a motor. The team have found it necessary to consult both the KPS supervisor as well as specialised lecturers at HSN in order to safeguard against choosing an unsuitable motor, as this will have large consequences for potential future project teams.

Other risks for the upcoming phase include risk of not meeting deadlines, acquisition of parts being challenging and customer being dissatisfied with the product. The team deemed these risks to be under control. Other risks are no longer relevant as no physical prototype will be made; these included long delivery time of parts and wrong parts being delivered.

II.3 Discussion

As described in the Project Plan the CAFCR model as a two-way decomposition models of a system's architecture [1]. Central in the model is the frequent viewhopping between domains that builds a thorough and wide understanding of the system, and sample problems and solutions from many different angles. At initiation of the project the CAFCR+ model was considered the most suitable model for this project as the system sought by the main stakeholder was unknown to the group members and; to the knowledge of the team members; a similar system do per se not exist. The model encourages frequent shorter iterations in the initial phase, which promoted the extensive discussions from different domain viewpoints that generated understanding and knowledge of the system in a rapid pace. Following the content suggested by Muller [1] for the first 4-5 iterations assured thorough and stepwise integration of new knowledge as it appeared throughout the phases, which promoted frequent reevaluation, redesign, and confirmation of work and chosen solution. An example of this stepwise knowledge integration can be followed from starting with defining the "system of interest" in Iteration 1, progressing to "breakdown of subsystems" and next "initial concept development" in Iteration 3. From there "critical components for functional behaviour" were identified and next "causal loops" were worked out which identified what aspects that might cause conflicts in design trade-offs in the next detailed design phase. Lastly, based on the knowledge and experience gained throughout the first 1-6 iterations several design feasibility assessments and preliminary designs were developed.

Seven iterations were planned at the initiation of the project. However, as the project evolved and new "knowns" and "unknowns" appeared, it was deemed necessary to add two more iterations; to duplicate iteration 5, and to add iteration 4 and 7. The CAFCR+ is a highly flexible model with regards to going back and revisiting all domains if needed, or adding in iterations when needed. This is a particularly important trait when choosing a model for a project team consisting of inexperienced members, or when developing a system that is completely new or contain a large amount of uncertainties and "unknowns" to the project team. Iteration 4 was added to gain a more detailed understanding of the dependencies between components and functions within the system, and to map what technical trade-offs we were likely to meet. Iteration 5 was added because a more detailed evaluation of the preliminary designs were needed, in order to be confident of our final design decision. Lastly, iteration 7 was added to initiate the analysis phase of the project. This iteration helped get a rough overview of the forces acting on the system and provided a path for how to move forth into detailed analysis in a more structured, step-wise manner. Choosing this flexible project model allowed the project team to take the time they needed to ensure that proper understanding was gained before moving forth into the next step. A more rigid model could in this instance have led to premature decisions being made and important aspects of understanding could have been lost. It is clearly visible through the preliminary design decision progress that a premature decision would have fallen on choosing a design that later was found to be suboptimal when viewed in more detail.

The justification of choosing the CAFCR+ model proved to be even more appropriate when reaching the design development phase, where two more iterations were added to ensure that as many plausible designs as possible came up. Furthermore, extending the preliminary design phase by one week and including an even more extensive design feasibility assessment brought to light the deeper benefits and challenges of the two preliminary designs; ultimately showing that the design that initially was not considered the most optimal one actually proved to be the most feasible.

In this project an "iteration" was used as an initiator for a new phase or work cycle. The content of the iteration was planned such that all the aspects that needed to be clarified or brainstormed before progressing with the project where discussed. E.g. functional behaviour and necessary architecture was discussed in iteration 3, from which numerous questions arose regarding the stakeholder requirements. These were then clarified, which ensured that work with specifying and prioritising system requirements in the following phase could commence without large questions or disagreements emerging once the requirements matrix was finished. Using the iteration as a kick-off where all project team members were present stimulated brainstorming and discussion, ensured that everyone's viewpoint got heard, clarified numerous uncertainties, and assured that everyone was "on the same page" with regards to development of the system. The kick-off use of the iterations also provided a manifestation of where in the project cycle the team currently was and how the team needed to work in the upcoming phase in order to be able to finish the whole project as planned.

The CAFCR+ model comes with an extensive set of suggested figures that will help the users understand the system, its context and life-cycle. However, development of these figures also greatly stimulates group discussions and brainstorming. Many figures are not directly visible in the resulting product or report; however, figures such as e.g. the "Critical Components for Functional Behaviour" from iteration 4 not only helped the team members understand what components would be needed in the system in order to perform the desired functions, but also raised numerous questions with regards to design geometry, handling of wires, power transfer solutions etc. that were beneficial for future design development. The group members found that working on these figures helped everyone describe their views and ideas better, it clarified numerous misunderstandings with regards to what people were thinking for the designs, solutions and use. Furthermore, figures also stimulated creativity and brought out ideas and challenges that might not otherwise have been thought of until later in the design stages, which could have much larger consequences with regards to meeting the planned deadline.

As visible in the figure II.1.4 most of the domains in the CAFCR+ model were reviewed within an iteration. This helped keep an overview of what aspects of the system that are considered important from all the different viewpoints. meaning that throughout the project period numerous smaller turns through the model are made. However, throughout the project period one major overall turn through the domains are made, as emphasis of the project changes from initiation to realization. As clearly visible in the Iteration Overview figure provided in the Iteration Log the iterations gradually took the project team through all the domains of the CAFCR+ model. Eventually, the project had progressed through an entire cycle of the model and returned back to the first domain. At this stage the major CAFCR+ loop is closed and the project can be considered to be finished if all requirements are deemed fulfilled [13].

Lastly, the CAFCR+ model also has some limitations. First of all, the model does at first glance not seems as intuitive to follow as other models such as the V-model that has very clear steps to follow. However, investing time in the beginning of the project to understand and plan the model well, allows much more flexibility with regards to going back and revisiting all domains if needed. This is a particularly important trait when choosing a model for a project team consisting of inexperienced members or when developing a system that is completely new or contain a large amount of uncertainties and "unknowns" to the project team. The CAFCR+ model was in this project supplemented with tables for structuring large amounts of data, such as requirements and risks, as suggestions for this is lacking in the model. Potential future users of the model might therefore benefit from consulting dedicated Systems Engineering literature for suggestions on how to systematise larger quanta of data.

II.4 Recommendations

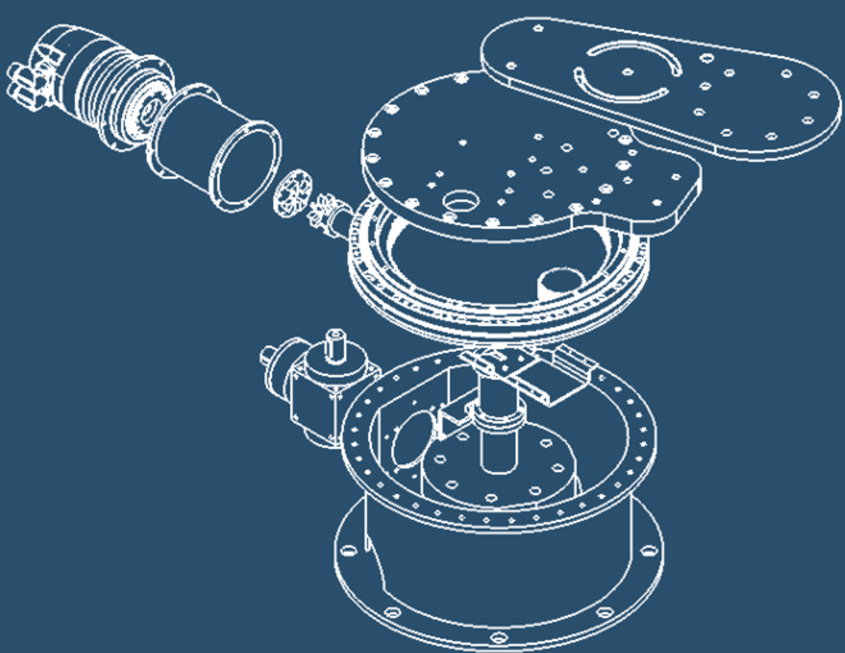
- Plan short and frequent iterations in the early phase of the project. This allows recurrent brainstorming and brings to light numerous questions that will help the participants understand the system of interest.
- From the start; plan iterations with the systematic aim of gradually shifting right towards the latter domains of the model, to ensure progress and increase the likelihood of finishing at the planned deadline.
- In the early phase follow the iterations as outlined by Gerrit Muller [12] to ensure continuous progress and gain understanding of the system from multiple views. These iterations helps kick off the project and guide the participants in the early phase dominated by "unknowns".
- Plan frequent iterations that revisit requirements and risks. New requirements emerge and others change throughout the project, while repeatedly making all participants aware of the risks associated with a particular phase increases focus on avoiding harmful consequences.
- Allow content of iterations to be altered slightly if needed as the project advances. Some aspects might require more focus than originally thought.
- Use an iteration as a kick-off where all participants are gathered to brainstorm and discuss the topics pertaining to the upcoming phase. This brings out numerous questions and relevant discussions, and it ensures that all participants know where in the project they current are and what to focus on next.
- Use time boxes and stick to them! Accept that the results obtained within the planned time are "good enough" and distribute the work. If the upcoming phase reveals that something critical still requires further attention and discussion add this onto the next iteration.
- Actively use the figures and tables suggested by Gerrit Muller [12] [13] and draw them onto large paper sheets to keep. Participants' ideas and points can be more clearly described with these tools, as verbal description might be difficult and can easily be misunderstood. Use of graphics promotes unanimous understanding.

II.5 Conclusion

As visible in the Iteration Overview; figure II.1.4; the iterations have gradually and progressively taken the project team through all the domains of the CAFCR+ model and eventually back to the first domain at the terminal phase of the project. The CAFCR+ model has successively guided the project team through all the different phases of systems design; from planning and getting an understanding of the sought system, through design development, analysis and optimisation, an eventually to verification. The model provided suggestions to valuable figures and charts that promoted understanding and brainstorming, and helped ensure that all aspects of the system was considered through frequent view-hopping between the different domains in each iteration. The iteration log has served as documentation of many central discussions and decisions that have been made through the project period. Furthermore, the log also serves a purpose of documenting to all stakeholders how the team has worked, how they brainstormed, reasoned and made decisions; providing some level of reliability and reproducibility to the process. The CAFCR+ model did in this project prove to be successful in guiding fresh engineers through a complex systems engineering task.

University College
of Southeast Norway
Mechanical Engineering
2016 - 07

Requirement Specification
Orbital Motion Simulator



Abbreviations

Abbreviation	Explanation
STRQ	Stakeholder Requirement
SRQ	System Requirement
DRQ	Design Requirement
CRQ	Component Requirement
KPS	Kongsberg Protech Systems
HSN	Høgskolen i Sørøst-Norge
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
MPU	Main Processing Unit

Revision History

Date	Version Number	Comment	Approved by
27.01.16	1.0	Stakeholder requirements identified.	Fredrik Thoresen
03.02.16	2.0	System- and a few design requirements identified.	Fredrik Thoresen
07.02.16	3.0	STRQ017 and SRQ036 added, document revised.	Fredrik Thoresen
18.02.16	3.1	STRQ037, STRQ038 and SRQ039 added.	Fredrik Thoresen
19.02.16	3.2	STRQ040-STRQ054 added.	Martin Sandberg
07.03.16	3.3	DRQ008-DRQ018 added.	Fredrik Thoresen
09.03.16	3.4	DRQ001, DRQ002, DRQ003, DRQ007 was updated. DRQ008 was reallocated to SRQ055.	Anders Gunbjørnsen
09.03.16	4.0	Requirements relating to MOOG added.	Fredrik Thoresen
18.04.16	4.1	Revised.	Heidi Kallerud
22.05.16	4.2	Document approved	Martin Sandberg

Table of Contents

Abstract

The Requirements Specification document presents all the identified requirements relating to the project. Firstly, the method used to identify requirements are presented. Next, the planned method of ensuring traceability of requirements is presented. A Requirements Traceability Matrix was developed to ensure traceability and overview of all the requirements, their status and a full path of their breakdown. The requirements in this project are mainly based on the stakeholder requirements prepared in the project description provided by Kongsberg Protech Systems (KPS). The requirements pertaining to HSN as a stakeholder are also represented. Stakeholder requirements are into system requirements, and later indexed and given attributes relating to priority, risk, complexity and cost. System requirements are further broken down into design requirements, and in a few selected cases, these are further broken down into component requirements. Each requirement is in this document listed in boxes that concisely present their content and corresponding data.

III.1 Requirements Setup

In terms of the requirement setup there is some very basic guidelines that has to be addressed. The requirements in this requirement specification is divided in to three main categories; Stakeholder Requirements (STRQ), System Requirements(SRQ), Design Requirements(DRQ) and, in some selected instances, Component Requirements (CRQ). The highest, most parent level of the requirement is the stakeholder requirement. The STRQ is then broken down into SRQ, SRQ is broken down into DRQ, and lastly DRQ into CRQ. Stakeholder requirements are the stakeholders' needs and wishes for the final product. These requirements are "high order" requirements that should contain no suggestions to the type of solution. The accompanying system requirements state the functions that the system needs to deliver in order to fulfil the needs of the stakeholders. The system requirements are in most cases broken further down into design requirements that describe in more detail the specific features or characteristic that are needed in order to fulfil the system requirement. The design requirements greatly dictate the design, the selected solutions, physical characteristics of e.g. materials and dimensions. Lastly, with complex components where great consideration of interfaces are needed, detailed component requirements that stated the needed characteristics of the components are formulated by decomposition of a design requirement. The various levels of breakdown of requirements are shown in figure III.1.1.

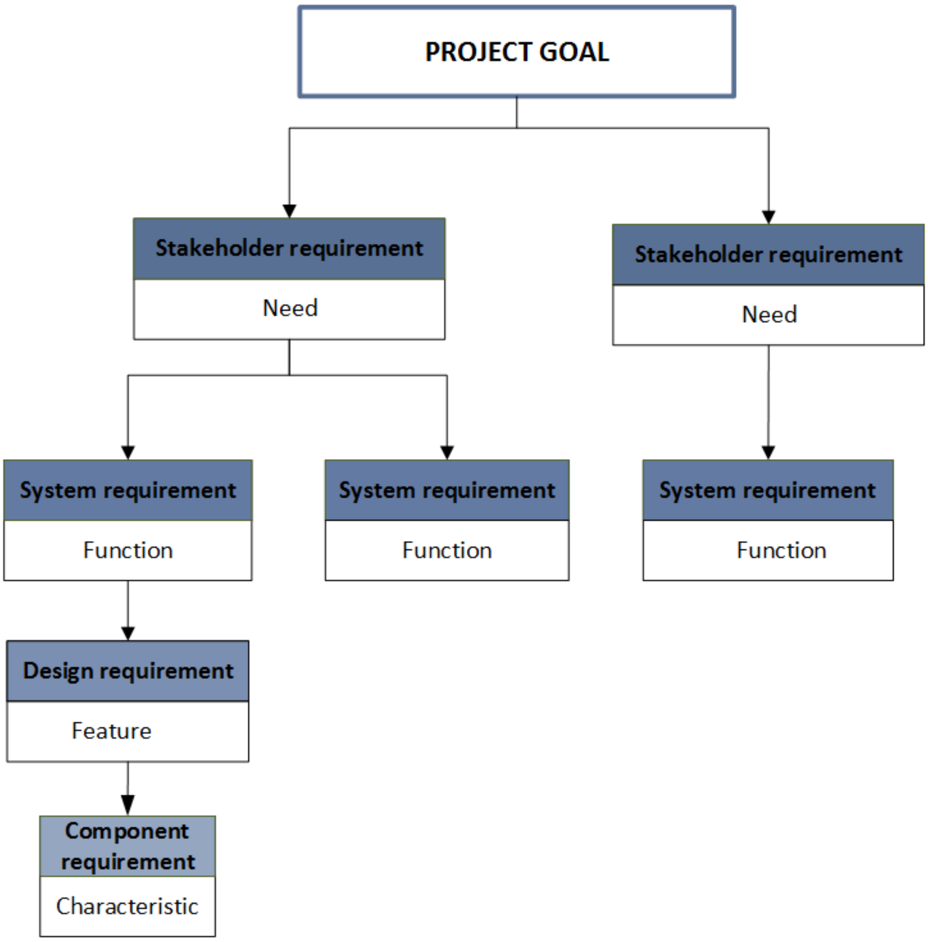


Figure III.1.1: Levels of requirement breakdown

A brief description of the planned process of designing a system based on the requirements follows. Firstly, a top-down method is used to break down the stakeholder requirements to requirements that dictate design and development. The stakeholders' needs and wishes are uncovered and formulated as high-level, more "vague" stakeholder requirements. The team translates the stakeholder requirements into functions that a system must provide in order to fulfill the stated needs and wishes. Feature characteristics and components that can assure delivery of these functions are then decided on and formulated as design requirements. Choice of a specific component is based on the component requirements that are formulated from knowledge of specific interfaces to the boundaries of the system. To assess if a requirement is fulfilled a bottom-up method will be used. The need for a particular component is uncovered by the design requirement and chosen based on the specific component requirements. A component has to fulfil all the component requirements before being eligible to be checked against the design requirement. If the component fulfills all the component requirements it also fulfills the design requirement. Fulfilling all the design requirements that pertain to a specific system requirement means that the desired function described in the system requirement can be delivered. Ultimately, the stakeholder requirement is fulfilled if all its corresponding system requirements are fulfilled through delivery of the stated functions.

The table setup used for each individual requirement is shown below.

		Requirement ID
Description	**Status**	
Test ID(s)	**Ranking**	**Origin**
Note(s)		

Each requirement has an ID, composed of the 3 or 4 letters that make up the abbreviated name of the requirement (e.g. SRQ) and a number. This is a unique serial number, which sole purpose is to separate the requirements from each other. The description explains or states the requirement. Every requirement is ranked in terms of the following categories:

- Priority
- Risk
- Complexity
- Economic estimate

The origin of each requirement is listed, meaning where the requirement came from and who issued it. The origin of the requirement can also refer to another requirement; this will be applicable when it comes to the decomposition of stakeholder requirements into system requirements and further into design requirements. So the origin can relate to three things; either the stakeholder that issued it, the stakeholder requirement (code STRQ) or a system requirement (code SRQ). This will create good traceability between the stakeholder, system- and design requirements.

Three different stakeholders from KPS were identified, as many people within the organisation have different concerns depending on where in the life-cycle the system is seen. For the sake of traceability into other documents, e.g. into the Requirements Traceability Matrix and the Requirements identification boxes, each stakeholder was given an ID number. The ID of each stakeholder is given in the table **III.1.1**.

Next is the status of the requirement. The status of the requirement indicates what state the requirement is in at any point in time. The states of implementation includes the following:

Stakeholder name	Stakeholder ID
KPS Administration	KPS A
KPS HSE Department	KPS H
KPS Software Division	KPS S
KPS Test Division	KPS T
HSN	HSN
Future students	FSTUD
Project team	OMS

Table III.1.1: Stakeholder IDs

- **Identified** - Meaning the requirement has been documented and approved
- **In progress** - The requirement is under implementation
- **In test** - The requirement is under testing
- **Accepted** - The requirement is tested, and approved
- **Rejected** - The requirement was not fulfilled during testing
- **Deleted** - The requirement has been deleted

Then there is the “note(s)”, where "special" information about the requirement is listed. If a requirement is modified, or made invalid it will be stated in the note section.

III.2 Ranking System

The ranking system is taking four factors into account. Priority, risk, complexity and cost, which are four key factors to consider in the evaluation of a requirement. These four factors are graded by letters, combining the grades gives a four letter rank. Having a four letter ranking system, that can be sorted alphabetically helps identifying the most crucial requirements.

The first factor is the priority factor is classified from A to C, whereas A means an absolute necessity and C is not that important. The priority indicates the importance of the requirement.

A	Vital
B	Important
C	Desirable

The second one is risk. Risk is also analysed and put in to the rankings. The risk is ranked from A to C, whereas A is very high risk, and C is very low risk. Risk means what impact the consequences will have, should the requirement not be fulfilled.

A	High risk
B	Moderate risk
C	Low risk

The third factor is complexity. Complexity means how hard it is to implement, this is also graded from A to C where A is the most complex, and C not that complex.

A	High Complexity
B	Moderate Complexity
C	Low Complexity

The last factor of the ranking-system is the economical estimation. The estimated cost of the requirement is graded from A to C, where A is very expensive, and C is the most advantageous in terms of cost.

A	Very costly
B	Moderate cost
C	Low cost

III.3 Requirements Engineering

Requirement engineering is the foundation of any systems engineering project and aims to translate stakeholder requirements to system requirements. In other words, it transforms the often vague needs of the costumer into quantitative system requirements.

III.3.1 Formulating Requirements

The process of formulating the requirements started with a meeting with the customers in KPS where two engineers: one represents software division and the other represents test division; were available for questions. The purpose of the meeting was to get a better understanding of what the system is, why KPS needed this system and how it interfaced with the rest of the simulator. A SWOT diagram was used as an aid to formulate a set of initial questions regarding the system, seen from different perspectives. The SWOT diagram can be seen in Appendix F, figure F.1. Questions regarding system requirements and boundaries were also answered. KPS agreed to provide a concept of operation, along with a draft of their stakeholder requirements.

A first iteration using CAFCR+ was done in order to put the information gathered during the meeting in context with system requirements. During this iteration stakeholder requirements for KPS and secondary stakeholders were identified. Functional diagrams, early concepts drawings and the draft of stakeholder requirements for KPS, would provide the basis form for the first draft of system requirements. Requirements were then ranked and categorized into functional and physical. All requirements were also given an acceptance criteria that would determine if the requirement was met; as stated in section III.1.

III.3.2 Traceability

Traceability is often viewed as an association between two or more logical entities such as requirements, system elements, verification, validation or tasks. Making a requirements database enables a quick way to verify and validate that all requirements have been met. Requirements should also be traceable bidirectionally, which helps analyse how the system is impacted by any change in a requirement. A requirement analysis matrix will track a requirement from inception to allocation, and finally through verification and validation. Every requirement will be associated with possible interfaces, acceptance criteria and unique test number(s).

Firstly, a Stakeholder Matrix was developed, which lists each stakeholder with their unique ID and their requirements. An extensive Requirement Traceability Matrix was developed for the purpose of organising requirements in a database with their corresponding data, such as originating stakeholder, accompanying system-, design- and component requirements, tests and acceptance criteria. An excerpt of the Requirement Traceability Matrix is provided below in figure III.3.1. In the event of one or more requirements being made invalid or changed, they still keep their respective requirement ID in case they were to become active again and to provide traceability of decisions made during the project.

REQUIREMENTS TRACEABILITY MATRIX								
Requirement								
SH ID	STRQ	SRQ	Status	SRQ Description	Type	RPCE Ranking	Allocation	DRQ
KPS S	STRQ001	SRQ001		The system shall have an azimuth movement range from -90 to+90 degrees.	Functional	AAAB	Bearing, Mounting Disc	
KPS S	STRQ001,STRQ002, STRQ003,STRQ004	SRQ002		The system shall have a motor.	Functional	AACB	Mounting Disc, Power Train Disc	DRQ001, DRQ002, DRQ003
KPS S	STRQ001,STRQ014	SRQ003		The system shall have a solution that limits the friction coefficient to a maximum value of 0.010.	Functional	AABB	Bearing	DRQ005
KPS S	STRQ002	SRQ004		The system shall have a minimum azimuth speed of 1mrad/sec.	Functional	AAAB	Motor	DRQ004
KPS S	STRQ003	SRQ005		The system shall have a maximum azimuth speed of at least 60degrees/sec.	Functional	AAAB	Motor	DRQ002
KPS S	STRQ004	SRQ006		The system shall provide an azimuth acceleration of 1 rad/s^2.	Functional	AAAB	Motor	DRQ006
KPS T	STRQ005	SRQ007		The system shall be able to decelerate from the maximum azimuthspeed to a full stop in 1 second.	Functional	AABB	Motor	

Figure III.3.1: Extraction of the Requirement Traceability Matrix

III.4 Stakeholder Requirements

III.4.1 Functional Requirements

		STRQ001
Description	**Status**	**Ranking**
The system shall have an azimuth movement range from -90 to +90 degrees.	Identified	AAAB
Note(s)		**Origin**
		KPS S

		STRQ002
Description	**Status**	**Ranking**
The system shall have a minimum azimuth speed of 1mrad/sec.	Identified	AAAB
Note(s)		**Origin**
		KPS S

STRQ003

Description	Status	Ranking
The system shall have a maximum azimuth speed of at least 60 degrees/sec.	Identified	AAAB
Note(s)		**Origin**
		KPS S

STRQ004

Description	Status	Ranking
The system shall provide an azimuth acceleration of 1 rad/sec^2.	Identified	AAAB
Note(s)		**Origin**
		KPS S

STRQ005

Description	Status	Ranking
The system shall have an emergency stop function.	Identified	AAAB
Note(s)		**Origin**
		KPS T

STRQ006

Description	Status	Ranking
The system shall be operable in the lab used by KPS.	Identified	AABC
Note(s)		**Origin**
		KPS T

STRQ007

Description	Status	Ranking
The system components shall comply with the KPS supply chain requirements.	Identified	ABBB
Note(s)		**Origin**
		KPS A

STRQ008

Description	Status	Ranking
The system shall be mountable onto the motion table without any permanent change to motion table.	Identified	ABCB
Note(s)		**Origin**
		KPS T

STRQ009

Description	Status	Ranking
The system shall be mountable onto the motion table with the equipment available in the current lab.	Identified	ABCC
Note(s)		**Origin**
		KPS T

STRQ010

Description	Status	Ranking
The system shall be possible to mount onto a pedestal with the equipment available in the current lab.	Identified	ABCC
Note(s)		**Origin**
		KPS T

STRQ011

Description	Status	Ranking
The system shall be possible to mount onto the existing pedestal without any permanent change to the pedestal.	Identified	ABCC
Note(s)		**Origin**
		KPS T

STRQ012

Description	Status	Ranking
The system should have an azimuth speed of at least 120 degrees/sec.	Identified	ABCC
Note(s)		**Origin**
		KPS S

STRQ013

Description	Status	Ranking
The system should be able to offset the RWS' center from the motion table center with at least 30 cm at 10 cm intervals in any direction.	Identified	BACC
Note(s)		**Origin**
		KPS S

STRQ014

Description	Status	Ranking
The system should have a free 360 degree azimuth movement range.	Identified	BCAA
Note(s)		**Origin**
		KPS S

STRQ015

Description	Status	Ranking
The system should provide an azimuth acceleration of 6 rad/s^2.	Identified	BCAA
Note(s)		**Origin**
		KPS S

STRQ016

Description	Status	Ranking
The Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0.1 mrad.	Identified	ABCB
Note(s)		**Origin**
		KPS S

		STRQ017
Description	**Status**	**Ranking**
The system shall have a life span of 5 to 10 years.	Identified	ABCB
Note(s)		**Origin**
		KPS A

III.4.2 Physical Requirements

		STRQ018
Description	**Status**	**Ranking**
The system shall consider 30Hz Roof Stiffness.	Identified	AAAB
Note(s)		**Origin**
		KPS T

		STRQ019
Description	**Status**	**Ranking**
All fixtures used for the system shall comply with KPS standards.	Identified	AABC
Note(s)		**Origin**
		KPS A

STRQ020

Description	Status	Ranking
The system mounting interface to the RWS shall withstand a preload torque of 130Nm.	Identified	AABC
Note(s)		**Origin**
		KPS T

STRQ021

Description	Status	Ranking
The system shall have a threadless mounting interface to the motion table according to highlighted holes and information in Appendix A.	Identified	AABC
Note(s)		**Origin**
		KPS T

STRQ022

Description	Status	Ranking
The system shall be able to withstand being mounted to the motion table using a preload torque of 200Nm.	Identified	AABC
Note(s)		**Origin**
		KPS T

STRQ023

Description	Status	Ranking
The system shall be able to withstand, without damage to itself or interfaced units, a 250kg RWS rotating at speeds exceeding 90º/second and suddenly stopping.	Identified	AACB
Note(s)		**Origin**
		KPS T

		STRQ024
Description	**Status**	**Ranking**
The system shall be able to withstand, without damage to itself or interfaced units, a sudden and complete stop of both itself and the RWS at all supported speeds.	Identified	AACB
Note(s)		**Origin**
		KPS T

		STRQ025
Description	**Status**	**Ranking**
The system shall be movable by one person as specified in MIL-STD-1472G.	Identified	AACB
Note(s)		**Origin**
		KPS T

STRQ026

Description	Status	Ranking
The system shall have a maximum weight of 50 kg.	Identified	AACB
Note(s)		**Origin**
		KPS T

STRQ027

Description	Status	Ranking
The system shall have a physical mounting interface to the RWS according to the 2d drawings supplied by KPS.	Identified	AACB
Note(s)		**Origin**
		KPS T

STRQ028

Description	**Status**	**Ranking**
~~The system shall have a maximum diameter of XX mm.~~	Deleted	AACC
Note(s)		**Origin**
Not considered a STRQ, but a SRQ. Resultingly defined as SRQ026 decomposed from STRQ025.		KPS T

STRQ029

Description	**Status**	**Ranking**
~~The system shall have a maximum height of XX mm.~~	Deleted	AACC
Note(s)		**Origin**
Not considered a STRQ, but a SRQ. Resultingly defined as SRQ027 decomposed from STRQ025.		KPS T

STRQ030

Description	Status	Ranking
The system shall be prepared for 3-axis gyroscope.	Identified	ABBC
Note(s)		**Origin**
		KPS S

STRQ031

Description	Status	Ranking
The system should have a maximum cost of 350000 NOK.	Identified	BBBB
Note(s)		**Origin**
		KPS A

STRQ032

Description	Status	Ranking
The system shall be easy to assemble.	Identified	BBBB
Note(s)		**Origin**
		KPS T

STRQ033

Description	Status	Ranking
The system shall be withstand the additional stresses imposed by the movements from the motion table.	Identified	AACB
Note(s)		**Origin**
		OMS

		STRQ034
Description	**Status**	**Ranking**
Spare parts must be easy to acquire.	Identified	BBCB
Note(s)		**Origin**
		OMS

III.5 System Requirements

III.5.1 Functional System Requirements

SRQ001		
Description	**Status**	
The system shall have an azimuth movement range from -90 to+90 degrees.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT018 VAT011	AAAB	STRQ001
Note(s)		
Solved through the integration of a slew bearing.		

SRQ002		
Description	**Status**	
The system shall have a motor.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT019 VAT010	AACB	STRQ001, STRQ002, STRQ003, STRQ004, STRQ012, STRQ014, STRQ015
Note(s)		
An electric actuator chosen based on detailed calculations and component requirements, and fitted into assembly.		

		SRQ003
Description	**Status**	
~~The system shall have a solution that limits the friction coefficient in the bearing to a maximum value of 0.010.~~	Deleted	
Test ID(s)	**Ranking**	**Origin**
VAT003	AABB	STRQ001, STRQ014
Note(s)		
Changed to SRQ055(09.05.2016).		

		SRQ004
Description	**Status**	
The system shall have a minimum azimuth speed of 1mrad/sec.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT019 VAT012	AAAB	STRQ002
Note(s)		
The selected motor has a torque profile that provides peak output torque down to 0 mrad/sec.		

SRQ005

Description	Status	
The system shall have a maximum azimuth speed of at least 60 degrees/sec.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT019 VAT013	AAAB	STRQ003
Note(s)		
The selected motor has a torque profile that provides peak output torque up to 222 degrees/sec.		

SRQ006

Description	Status	
The system shall provide an azimuth acceleration of 1 rad/s^2.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT003 VAT034	AAAB	STRQ004
Note(s)		
The motor was selected based on detailed calculations of required torque under "worst case scenario" load.		

SRQ007		
Description	**Status**	
~~The system shall be able to decelerate from the maximum azimuth speed to a full stop in 1 second.~~	Deleted	
Test ID(s)	**Ranking**	**Origin**
VAT014	AABB	STRQ005
Note(s)		
Changed to SRQ056 (20.04.2016).		

SRQ008		
Description	**Status**	
The emergency stop system shall be an independent system.	Identified	
Test ID(s)	**Ranking**	**Origin**
VAT001	AACB	STRQ005
Note(s)		

SRQ009

Description	Status	
The system should have an azimuth speed of at least 120 degrees/sec.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT019 VAT015	BBBB	STRQ012
Note(s)		
The selected motor has a torque profile that provides peak output torque up to 222 degrees/sec.		

SRQ010

Description	Status	
The system should be able to offset the RWS' center from the motion table center with at least 30 cm at 10 cm increments.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT020 VAT002	BACC	STRQ013
Note(s)		
Design allows offsets at 10 cm increments up to 40 cm total offset.		

		SRQ011
Description	**Status**	
The system should have a free 360 degree azimuth movement range.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT018 VAT004	BCAA	STRQ014
Note(s)		
Solved through the integration of a slew bearing.		

		SRQ012
Description	**Status**	
The system should provide an azimuth acceleration of 6 rad/ s^2.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT004 VAT035	BCAA	STRQ015
Note(s)		
The motor was selected based on detailed calculations of required torque under "worst case scenario" load.		

SRQ013

Description	Status	
The Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0,1 mrad.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT017 VAT005	ABCB	STRQ016
Note(s)		

SRQ036

Description	Status	
The system shall have a minimum life span of 5 years.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT005	ABCB	STRQ017
Note(s)		
Verified in TR005.		

			SRQ037
Description	**Status**		
The system shall withstand a pitch displacement combination motion of the motion table of +25/-23 degrees.	Fulfilled		
Test ID(s)	**Ranking**	**Origin**	
VT021 VAT023	AACB	OMS	
Note(s)			
Verified in TR003.			

			SRQ038
Description	**Status**		
The system shall withstand a pitch velocity from the motion table of $\pm$ 30 deg/s .	Fulfilled		
Test ID(s)	**Ranking**	**Origin**	
VT021 VAT023	AACB	OMS	
Note(s)			
Verified in TR003.			

SRQ039

Description	Status	
The system shall withstand a pitch acceleration from the motion table of ± 500 deg/s^2 .	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT021 VAT023	AACB	OMS

Note(s)

Verified in TR003.

SRQ040

Description	Status	
The system shall withstand a roll displacement combination motion of the motion table of ± 22 degrees.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT022 VAT024	AACB	OMS

Note(s)

Verified in TR003.

		SRQ041
Description	**Status**	
The system shall withstand a roll velocity from the motion table of ± 30 deg/s .	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT022 VAT024	AACB	OMS
Note(s)		
Verified in TR003.		

		SRQ042
Description	**Status**	
The system shall withstand a roll acceleration from the motion table of ± 500 deg/s^2.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT022 VAT024	AACB	OMS
Note(s)		
Verified in TR003.		

SRQ043

Description	Status	
The system shall withstand a yaw displacement combination motion of the motion table of $\pm$ 23 degrees.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT023 VAT025	AACB	OMS
Note(s)		
Verified in TR003.		

SRQ044

Description	Status	
The system shall withstand a yaw velocity from the motion table of $\pm$ 40 deg/s.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT023 VAT025	AACB	OMS
Note(s)		
Verified in TR003.		

SRQ045

Description	Status	
The system shall withstand a yaw acceleration from the motion table of ± 400 deg/s^2.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT023 VAT025	AACB	OMS
Note(s)		
Verified in TR003.		

SRQ046

Description	Status	
The system shall withstand a heave displacement combination motion of the motion table of ± 0,18m.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT024 VAT026	AACB	OMS
Note(s)		
Verified in TR001.		

SRQ047

Description	Status	
The system shall withstand a heave velocity from the motion table of ± 0,30 m/s.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT024 VAT026	AACB	OMS
Note(s)		

SRQ048

Description	Status	
The system shall withstand a heave acceleration from the motion table of ± 0,5 g.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT024 VAT026	AACB	OMS
Note(s)		
Verified in TR001.		

SRQ049

Description	Status	
The system shall withstand a surge displacement combination motion of the motion table of $\pm$ 0,27m.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT025 VAT027	AACB	OMS
Note(s)		
Verified in TR001.		

SRQ050

Description	Status	
The system shall withstand a surge velocity from the motion table of $\pm$ 0,50 m/s.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT025 VAT027	AACB	OMS
Note(s)		
Verified in TR001.		

SRQ051

Description	**Status**	
The system shall withstand a surge acceleration from the motion table of ± 0,6 g .	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT025 VAT027	AACB	OMS
Note(s)		
Verified in TR001.		

SRQ052

Description	**Status**	
The system shall withstand a sway displacement combination motion of the motion table of ± 0,26m.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT026 VAT028	AACB	OMS
Note(s)		
Verified in TR001.		

		SRQ053
Description	**Status**	
The system shall withstand a sway velocity from the motion table of ± 0,50 m/s.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT026 VAT028	AACB	OMS
Note(s)		
Verified in TR001.		

		SRQ054
Description	**Status**	
The system shall withstand a sway acceleration from the motion table of ± 0,6 g.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT026 VAT028	AACB	OMS
Note(s)		
Verified in TR001.		

III.5.2 Physical System Requirements

			SRQ014
Description	**Status**		
The system shall be operable in a temperature range from 0 to 40 degrees Celsius.	Fulfilled		
Test ID(s)	**Ranking**	**Origin**	
VT032 VAT016	ABBC	STRQ006	
Note(s)			
Operability of critical components is verified through supplier technical catalogues. Friction moment of slew bearing at relevant temperature range is included in calculations. Consideration of material properties with regards to temperature has been assured in calculations			

			SRQ015
Description	**Status**		
The system shall consider a roof stiffness of 30 Hz.	Fulfilled		
Test ID(s)	**Ranking**	**Origin**	
VT027	AAAB	STRQ018	
Note(s)			
Verified in TR004.			

SRQ016

Description	Status	
The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT006 VAT006	AABC	STRQ020
Note(s)		
Verified in TR001 and TR003.		

SRQ017

Description	Status	
The system shall have a thread less mounting interface to the motion table according to highlighted holes and information in Appendix B.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT001 VAT031	AABC	STRQ008 STRQ009 STRQ010 STRQ011 STRQ021
Note(s)		
Correspondence in 2D drawings, tolerances for machining defined.		

SRQ018

Description	Status	
The system shall be able to withstand being mounted to the motion table using a preload torque of 200 Nm.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT007 VAT007	AABC	STRQ022
Note(s)		
Verified in TR001 and TR003.		

SRQ019

Description	Status	
The system with the 250 kg RWS mounted on top shall be able to withstand, without damage to itself or interfacing units, rotating at speeds exceeding 90 degrees/second and suddenly stopping.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT008 VAT030	AACB	STRQ023
Note(s)		
Rephrased to improve clarity of content (14.04.16)		

SRQ020

Description	Status	
The system with the 250 kg RWS mounted on top should be able to withstand, without damage to itself or interfacing units, a full stop within 1 second from a speed of 120 degrees/sec.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT009 VAT029	AABB	STRQ024
Note(s)		
Rephrased to improve clarify of content (14.04.16).		

SRQ021

Description	Status	
~~The system shall be movable by one person as specified in MIL-STD-1472G~~	Deleted	
Test ID(s)	**Ranking**	**Origin**
VT010	AACB	STRQ025
Note(s)		
Decomposed into SRQ022, SRQ023, SRQ026 and SRQ027 from STRQ025.		

			SRQ022
Description	**Status**		
Each individual part of the system shall have a maximum weight of no more than 39,5 kg.	Fulfilled		
Test ID(s)	**Ranking**	**Origin**	
VT010 VAT033	ABCB	STRQ025	
Note(s)			
Verified in TR002.			

			SRQ023
Description	**Status**		
The system should have a maximum weight of 50 kg.	Rejected		
Test ID(s)	**Ranking**	**Origin**	
VT011	BBAB	STRQ026	
Note(s)			
Changed from "shall" to "should" status, because STRQ025 dictates the maximum weight the components can have with regards to health and safety regulations. This requirement will solely be used as a goal towards keeping the total weight as low as possible (31.03.16). Verified in TR002.			

		SRQ024
Description	**Status**	
The system shall have a physical mounting interface to the RWS with the hole pattern according to Appendix A.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT002 VAT032	AACB	STRQ027
Note(s)		
Correspondence in 2D drawings, tolerances for machining defined.		

		SRQ025
Description	**Status**	
The system shall have a solution for the guidance of the wiring to the RWS.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT030 VAT008	AABB	STRQ027 STRQ001
Note(s)		
Slip ring integrated into design.		

SRQ026

Description	Status	
The system shall have a maximum diameter of 470 mm.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT012 VAT021	AACC	STRQ025
Note(s)		
Verified in TR002.		

SRQ027

Description	Status	
The system shall have a maximum height of 400 mm.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT013 VAT021	AACC	STRQ025
Note(s)		
Verified in TR002.		

		SRQ028
Description	**Status**	
The system shall have a free space of 60*50*40 mm^3.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT015 VAT020	AACC	STRQ030
Note(s)		

		SRQ029
Description	**Status**	
The system shall be prepared for the wiring of a 3-axis gyroscope.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT016 VAT020	AABC	STRQ030
Note(s)		
Verified in TR002.		

		SRQ030
Description	**Status**	
~~No part of the system shall exceed 100000 NOK.~~	Deleted	
Test ID(s)	**Ranking**	**Origin**
Not applicable	BBBB	STRQ031
Note(s)		
Considered obsolete, only total cost relevant(18.02.2016). See SRQ031.		

		SRQ031
Description	**Status**	
The system shall have a maximum cost of 350000 NOK.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT014 VAT022	BBBB	STRQ031
Note(s)		
Total estimated cost $\approx$ 200 000 NOK.		

SRQ032		
Description	**Status**	
The system shall put zero strain on the wires connected to the OMS.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT028 VAT017	AABB	STRQ014
Note(s)		

SRQ033		
Description	**Status**	
The system shall put zero strain on the wires connected to the RWS.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT029 VAT018	AABB	STRQ014
Note(s)		

		SRQ034
Description	**Status**	
The system shall be assembled in a maximum time of 15 minutes.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VAT009	ABBC	STRQ032
Note(s)		

		SRQ035
Description	**Status**	
~~The system shall have a free space of 15*15*10 mm^3.~~	Deleted	
Test ID(s)	**Ranking**	**Origin**
Not applicable	AACC	STRQ016
Note(s)		
Changed to DRQ017 as a decomposition of system requirement SRQ013 (09.05.2016).		

			SRQ055
Description		**Status**	
The system shall have a solution that allows free azimuth movement range.		Fulfilled	
Test ID(s)		**Ranking**	**Origin**
VT018 VAT004		AABB	STRQ001 STRQ014
Note(s)			
Slew bearing integrated into design.			

			SRQ056
Description		**Status**	
The system shall be able to cut off the power to the motor.		Identified	
Test ID(s)		**Ranking**	**Origin**
VAT019		AABB	STRQ005
Note(s)			

SRQ057

Description	Status	
All suggested suppliers shall be approved by the project supervisor at KPS.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
	BBCB	STRQ007 STRQ034
Note(s)		
Accepted after discussion with KPS supervisor per 14.05.16.		

SRQ058

Description	Status	
Standard supply metric bolts shall be used on all applications.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT031	BBCC	STRQ019 STRQ034
Note(s)		

III.6 Design Requirements

DRQ001		
Description	**Status**	**Origin**
~~The motor shall be adaptable with a 220 V power outtake.~~	Deleted	SRQ002
Note(s)		
Wrong "level", changed to CRQ015.		

DRQ002		
Description	**Status**	**Origin**
The motor shall be able to rotate the OMS with a 250 kg RWS, placed up to 30 cm away from center at 60 deg/sec.	Fulfilled	SRQ005 SRQ002
Note(s)		

DRQ003		
Description	**Status**	**Origin**
The motor should be able to rotate the OMS with a 250 kg RWS, placed up to 30 cm away from center at 120 deg/sec.	Fulfilled	SRQ009 SRQ002
Note(s)		

DRQ004

Description	Status	Origin
The motor shall be able to regulate the rotational speed of the OMS to 1 mrad/s.	Fulfilled	SRQ004

Note(s)

DRQ005

Description	Status	Origin
The system shall be fitted with a slew bearing.	Fulfilled	SRQ055 SRQ011

Note(s)

DRQ006

Description	Status	Origin
The motor shall have a peak torque output of minimum 120 Nm.	Fulfilled	SRQ006

Note(s)

Requirement expressed in terms of torque instead of power.

DRQ007

Description	Status	Origin
The motor should be able to rotate the OMS,with a 250 kg RWS, placed up to 30 cm away from center with an acceleration of $6 rad/s^2$.	Fulfilled	SRQ012

Note(s)

DRQ008

Description	Status	Origin
The system shall have a slip ring.	Fulfilled	SRQ001 SRQ032 SRQ033 SRQ055 SRQ011

Note(s)

DRQ009

Description	Status	Origin
The bolts connecting the power train disc to the offset disc shall have a safety factor of at least 2.	Fulfilled	SRQ019 SRQ020

Note(s)

DRQ010

Description	Status	Origin
The bolts connecting the bearing to the bottom part of the OMS shall have a safety factor of at least 2.	Fulfilled	SRQ019 SRQ020

Note(s)

DRQ011

Description	Status	Origin
The system shall have a switch that cuts off the power from the motor to the OMS drive train within one second.	Fulfilled	SRQ008

Note(s)

DRQ012

Description	Status	Origin
The system shall have an offset disc that allows for an offset of at least 30 cm at 10 cm increments.	Fulfilled	SRQ010

Note(s)

DRQ013

Description	Status	Origin
The main material of the OMS system should be the following Aluminium alloy: 6082-T6-T651.	Fulfilled	SRQ014 SRQ015 SRQ019 SRQ020

Note(s)

DRQ014

Description	Status	Origin
Dimensions, design factors and qualities for standard metric bolts shall be taken from "Tingstad" technical catalogues [14].	Fulfilled	SRQ014 SRQ019 SRQ020 SRQ058

Note(s)

DRQ015

Description	Status	Origin
The general factor of safety used for components in the system shall be no less than 2.	Fulfilled	SRQ016 SRQ018 SRQ019 SRQ020 SRQ037- SRQ058

Note(s)

DRQ016

Description	Status	Origin
The system shall have an entry opening for the wiring to the absolute position sensor.	Fulfilled	SRQ013

Note(s)

DRQ017

Description	Status	Origin
The system shall have a free space of 15*15*10 mm^3.	Fulfilled	SRQ013

Note(s)

DRQ018

Description	Status	Origin
The offset disc shall be able to withstand; with a safety factor of minimum 2; the stresses imposed by bolts holding a preload torque of 130 Nm.	Fulfilled	SRQ016

Note(s)

DRQ019

Description	Status	Origin
The flange of the OMS base shall be able to withstand; with a safety factor of minimum 2; the stresses imposed by bolts holding a preload torque of 200 Nm.	Fulfilled	SRQ018

Note(s)

DRQ020

Description	Status	Origin
The bending radius of any wire shall be no less than 5 times the diameter of the wire.	Fulfilled	SRQ032 SRQ033

Note(s)

III.7 Component Requirements

CRQ001		
Description	**Status**	**Origin**
The system shall have a physical mounting interface to the slip ring with the hole pattern according to Appendix A.	Fulfilled	DRQ008
Note(s)		

CRQ002		
Description	**Status**	**Origin**
The slip ring shall have a power voltage of 36 VDC.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplier		

CRQ003		
Description	**Status**	**Origin**
The slip ring shall have a power current of 40 A.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplie.r		

		CRQ004
Description	**Status**	**Origin**
The slip ring shall have a power resistance < 2.5 mΩ.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplier.		

		CRQ005
Description	**Status**	**Origin**
The slip ring shall have a signal voltage of 36 VDC.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplier.		

		CRQ006
Description	**Status**	**Origin**
The slip ring shall have a signal current of <5 A.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplier.		

CRQ007

Description	Status	Origin
The slip ring shall have a signal resistance < 2.5 mΩ.	Fulfilled	DRQ008

Note(s)

Verified through technical data from supplier.

CRQ008

Description	Status	Origin
The slip ring shall have a data voltage of 5 VDC.	Fulfilled	DRQ008

Note(s)

Verified through technical data from supplier.

CRQ009

Description	Status	Origin
The slip ring shall have a data current of <1 A.	Fulfilled	DRQ008

Note(s)

Verified through technical data from supplier.

		CRQ010
Description	**Status**	**Origin**
The slip ring shall have a data resistance < 2.5 mΩ.	Fulfilled	DRQ008
Note(s)		
Verified through technical data from supplier.		

		CRQ011
Description	**Status**	**Origin**
The motor shall have be able to deliver a peak torque output of 120 Nm up to a speed of minimum 120 deg/sec.	Fulfilled	DRQ003
Note(s)		
Verified through calculations and accompanying technical data from supplier.		

		CRQ012
Description	**Status**	**Origin**
The motor shall have a torque curve that assures that a peak torque output of 120 Nm can be delivered at very low speeds down to 0 deg/sec.	Fulfilled	DRQ004
Note(s)		
Verified through torque-velocity curve in technical catalogue from supplier.		

		CRQ013
Description	**Status**	**Origin**
The motor should have a weight less than 10 kg	Fulfilled	DRQ004
Note(s)		
Selected motor weighs 8.5 kg. Verified through technical data from supplier.		

		CRQ014
Description	**Status**	**Origin**
The motor shall have an output speed of minimum 600 deg/sec.	Fulfilled	DRQ004
Note(s)		
Verified through technical data from supplier. Selected motor has a maximum output speed of approximately 1700 deg/sec.		

		CRQ015
Description	**Status**	**Origin**
Selected motor should provide a reflected inertia of less than 1:20.	Rejected	DRQ004
Note(s)		
Reflected inertia exceeds 1:20 after design optimisation. Inertia ratio deemed not as critical as the system rarely or never operates at constant speed.		

		CRQ016
Description	**Status**	**Origin**
The slew bearing should weigh less than 30 kg.	Fulfilled	DRQ005
Note(s)		
Selected slew bearing weighs 9 kg. Verified through technical data from supplier.		

		CRQ017
Description	**Status**	**Origin**
The slew bearing shall have a maximum module of 4.	Fulfilled	DRQ005
Note(s)		
The selected slew bearing has a module of 1.5. Verified through technical data from supplier.		

		CRQ017
Description	**Status**	**Origin**
The slew bearing teeth must support a static axial load of minimum 2800 N.	Fulfilled	DRQ005
Note(s)		
Verified through calculations and accompanying guarantee from supplier.		

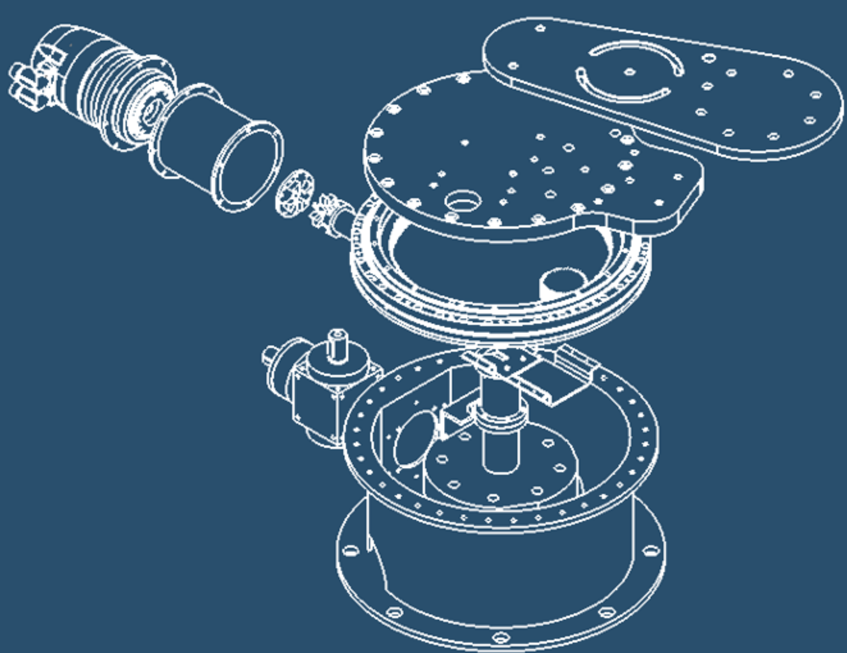
CRQ018		
Description	**Status**	**Origin**
The slew bearing teeth must support a dynamic axial load of minimum 2570 N.	Fulfilled	DRQ005
Note(s)		
Verified through calculations and accompanying guarantee from supplier.		

CRQ019		
Description	**Status**	**Origin**
The slew bearing teeth must support a dynamic radial load of minimum 1200 N.	Fulfilled	DRQ005
Note(s)		
Verified through calculations and accompanying guarantee from supplier.		

CRQ020		
Description	**Status**	**Origin**
The OMS base shall have an entry opening of minimum 32mm x 32 mm for wires to the slip ring.	Fulfilled	DRQ008
Note(s)		
The OMS has an entry opening of 35 x 50 mm^2.		

HSN University College of Southeast Norway
Mechanical Engineering
2016 - 07

Design
Orbital Motion Simulator



Abbreviations

Abbreviation	Explanation
KPS	Kongsberg Protech Systems
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
MBT	Main Battle Tank
IFV	Infantry Fighting Vehicle
CAD	Computer-Aided Design
DOF	Degrees of Freedom
DDMM	Day, Month
FOS	Factor of Safety

Revision History

Date	Version Number	Comment	Approved by
04.03.16	0.1	Introduction, Procedure and Initial concepts done	Martin Sandberg
07.03.16	0.2	Design and analysis chapters revised	Fredrik Thorseen
09.03.16	1.0	Revised	Fredrik Thoresen
29.04.16	2.0	Components, calculations and Matlab scripts added	Martin Sandberg
03.05.16	2.1	Calculations	Kjetil Fjeld
15.05.16	2.2	Revised	Heidi Kallerud
04.05.16	2.3	Budget and manufacturing methods added	Martin Sandberg
22.05.16	2.4	Document approved	Heidi Kallerud

Table of Contents

Abstract

The engineering design process consists of a series of steps for creating functional systems that fulfill the stakeholder requirements. The design process must be based on a thorough understanding of the system objectives and required functions, and must integrate mathematics, physics and engineering sciences to undertake well informed decisions. The following document presents the work undertaken in each of the general phases of the engineering design process; background research and understanding, conceptualisation, feasibility assessment, preliminary design, detailed design, analysis and testing.

Chapter 1 opens with a presentation of the functional analysis and methods used to uncover the system architecture, which comprise the "background research" phase. The process of developing conceptual designs was comprehensive and thorough, involving numerous brainstorming sessions and preliminary design development to ensure that final concept selection was well reasoned. The system is required to carry and rotate a high load during complex motion. Chapter 2 presents the engineering model used to stepwise build an understanding for the forces and loads acting on the system, which formed the foundation for the computational models and simulations. These were indispensable for development of a worst case load scenario that selection and dimensioning of components and features was based on.

Selection of components was based on both custom-made decision matrices, applicability with regards to the load scenario, as well as consideration of the life cycle usage and service of the system. Each individual component and its selection process is described in detail in chapter 3. Chapter 4 presents the final design in its entirety and how the design was optimised when exposed to the load scenarios as an assembly. Component development is incomplete without consideration of how manufacturing can be enabled, as ignorance of manufacturing methods can lead to design of parts that are close to impossible to make or more costly than necessary. Manufacturing methods for the mechanical component developed by the project team is presented in chapter 5, closely followed by a chapter presenting the project and system budget. Lastly, an appendix providing further detail of the designs that were not selected are presented, followed by MatLab and SimuLink scripts used for calculations and modelling.

IV.1 Concept Development

In the Design and Development phase the emphasis of the iterations; as seen from the CAFCR+ model; will shift from being mainly left side oriented towards the right side, which holds the Conceptual and Realisation domains. This right shift is clearly visible in the figure "Iteration Summary" (II.1.4), in the Iteration log (chapter II.1). Conceptual design is regarded the most crucial task in product development, as choosing an incorrect design may prolong the project cost and schedule considerably due to an increased number of iterations needed to complete the design [15]. Robustness of the chosen concept is vital, as the system should be resilient to any changes to the customer demands or changes in the supply chain [15].

IV.1.1 Method

Before conceptual designs can be developed a thorough understanding of the functions that the system must provide in order to fulfill the stakeholder requirements is needed [2]. Identification of system requirements is part of the operational analysis that focuses on what functions the system needs to provide [2]. The next step towards system design is to perform a functional analysis. Here, the system requirements are broken down into design requirements that reveal the elements and architecture that are needed in the system in order to deliver the required functionalities. According to Sols (2014) [2] it is also recommendable to consider if grouping of elements or functions is possible, in order to reduce the complexity and number of interfaces of the designed system.

The system that will bring the needed solution to the stakeholders will emerge through the design and development phase [2]. After all system requirements have been identified and formulated, the next stage is to identify all potential solutions that are considered capable of delivering to the customer all the needed functionalities. All potential solutions that emerge on the basis of the stakeholder requirements are considered design concepts. With a profound consideration of the functionalities needed without any restrictions as to what solutions are feasible, an extensive list of potential design concepts will emerge. In brainstorming design concepts the key question is to answer "in what ways can the needed functionalities be delivered?". Several barriers may hinder individuals' creative ability; e.g. cultural, emotional and professional blocks [16]. Al-Ghamdi 2004 [16] therefore recommends complying to the following four rules:

- No criticism of generated ideas is allowed
- Include all ideas regardless of how wild they might seem
- Quantity over quality of ideas

- Combine and improve ideas

Through this, numerous ideas and solutions are likely to emerge, which can later be filtered out, or parts of them can be integrated into more feasible solutions. When the rate of idea generation slows down during a brainstorming session it is hard to judge whether the project team has thought of all solutions or if they have fatigued [16]. Therefore, several shorter brainstorming sessions on separate days is recommended. The resulting list of concepts will later be filtered with regards to technical, operational and financial concerns. Discarding of concepts may arise due to e.g. lack of maturity of technology, high uncertainty and risk, high cost or complexity of usage [2].

A shortlist containing only the most feasible concepts that are likely to satisfy all stakeholder requirements will result from the filtering process. The remaining design concepts in the filtered shortlist will then be subjected to a detailed evaluation based on several discriminating criteria. These discrimination criteria are elaborated from the stakeholder requirements and represent the key concerns pertaining to the system [2]. Each criteria should furthermore be weighted according to their relative importance. The total sum of weighted criteria for each design concept is then gathered and compared relative to the other concepts. If this discrimination process does not reveal one clear optimal design choice, it might be appropriate to present the remaining list of evaluated concepts to the stakeholder, in order to reveal if new requirements have emerged or if existing requirements might have been misinterpreted [2].

IV.1.2 Procedure

IV.1.2.1 Functional Analysis

The CAFCR+ model contains several tools for functional analysis and identification of system interdependencies; examples of which can be seen in the project's Iteration Log in the CAFCR+ chapter II.2 [1]. Through Iteration 2, 3 and 4 the functional structure of the system was recognised. Initially, the critical functions whose performance are required were identified, without any bias as to what elements can deliver them [2]. Based on the key performance parameters identified in Iteration 2 the critical functions were stated as "rotate 360 degrees", "emergency stop", "mounting" and "data transmission". The general elements needed in order to perform these functions were listed, without bias as to the specific characteristics of the elements. E.g. "motor" was identified as an element, without specifying what sort of motor should be used. An evaluation of the characteristics the elements should hold and how the choice of a specific characteristic will influence overall performance is to be undertaken after a final design concept has been chosen [2].

The greatest challenges with regards to trade-offs in system characteristics were identified in Iteration 4. A trade-off is a situation in which gaining quality or quantity of one variable might result in a loss in an other interrelated variable [1]. The major trade-off challenges that is likely to be faced in the design of the system are weight versus material, material versus geometry, and geometry versus weight. Trade-offs might impose a risk to fulfilling the stakeholder requirements. Hence, in the case of incompatibility between wanted qualities the stakeholders should be made aware of the trade-off challenges in order to reveal which variable that in fact weigh the most. Critical loop diagrams further visualise the interrelations between functions, application and design of the system [1]. A causal loop is a situation in which changes to one variable might cause ripple effects throughout a cycle of variables. A noticeable loop in the OMS system is the "fixture-loop". The loop highlights that caution must be exerted when designing fixtures for the system, as this design aspect will have implications for both the usage and application of the system, as well as life-cycle wear. The reader is advised to review the resulting figures from Iteration 4 in the Iteration Log for details of the discussed figures.

IV.1.2.2 System Architecture

The system architecture describes the structure and general components needed in the system to provide the required functions [2]. Before conceptual design can take place it is necessary to define the system architecture in order to not overlook any critical components or interfaces. A basic understanding of the system architecture was gained in Iteration 1 through development of the "System of Interest" figures. This architecture was elaborated further in Iteration 2 with the breakdown into subsystems. During Iteration 4 the critical components for functional behaviour were identified. Without any bias to specific component characteristics, the components needed for the system to provide the critical functions; "rotate 360 degrees", "emergency stop", "mounting" and "data transmission"; were listed.

IV.1.2.3 Robustness of Concept Selection

Robust product design is defined as making a product that is insensitive to internal and external variations [17]. Internal variation comes from deterioration such as wear and aging of materials. External variation is due to fluctuations in environmental factors, such as temperature, humidity and pollution [17]. A conceptual solution should be viewed as a set of solutions, holding room for future adjustments related to changing customer needs, either in the design phase or during the system's life-cycle [15]. A robust concept should have the potential to excite the customer; not just satisfy them [17]. Stakeholders might not initially be aware of all the requirements they have. Furthermore, they may also become aware of new requirements when being presented to the conceptual designs [2]. Of this reason the shortlist of design concepts was presented to the customer, accompanied by a brief explanation of the usage and life-cycle implications the selection of a particular concept would have. This gives the customer an opportunity to add or revise their requirements, as well as it might provide more clarity to the system designers as to which requirements are more flexible and where room for future adaptation should be ensured [15].

IV.1.2.4 Concept Selection

Through three brainstorming sessions a total of 14 design concepts were developed; all of which are presented in the Initial Offset Concepts (ref: appendix G). The concepts included everything from crazy, less feasible ideas to simple, more realistic concepts. First the concepts were "coarse filtered". The filtering criteria were selected from the "threads of reasoning" concerns in Iteration 4, where the most important specification issues, life-cycle issues and design aspects were identified. The coarse filtering criteria judged the overall feasibility of the concepts and filtered out concepts that were unrealistic for the scope of the project. The criteria were: cost, function, complexity, user friendliness and maturity of technology. Each design was simply given a smiley face, a neutral face or a sour face on each of these five coarse filtering criteria. Designs given three smiley faces or a combination of two smiley faces with two neutral faces qualified to go forth into detailed filtering. A Design Development Matrix was developed to ensure traceability of scoring and decisions made during this process. This matrix can be found in appendix G.8. Five design concepts were filtered out in the first round, leaving a shortlist of 8 more realistic design concepts that were subjected to detailed evaluation. The criteria used for detailed filtering were derived from the stakeholder requirements; both KPS and the project team. The criteria were: cost, weight, complexity, adjustability and risk. Each concepts received a score between 1 (worst) and 5 (best) for each of the criteria. With the aim of increasing the robustness of the concept selection, and to increase inter-rater reliability, the project team split into two teams that separately evaluated all the design concepts. Afterwards the two teams met up to discuss and compare scores and come to an agreement. The scored designs were then plotted on a radar chart (figure IV.1.1), in order to visualise the overall scores of each concept compared to the others.

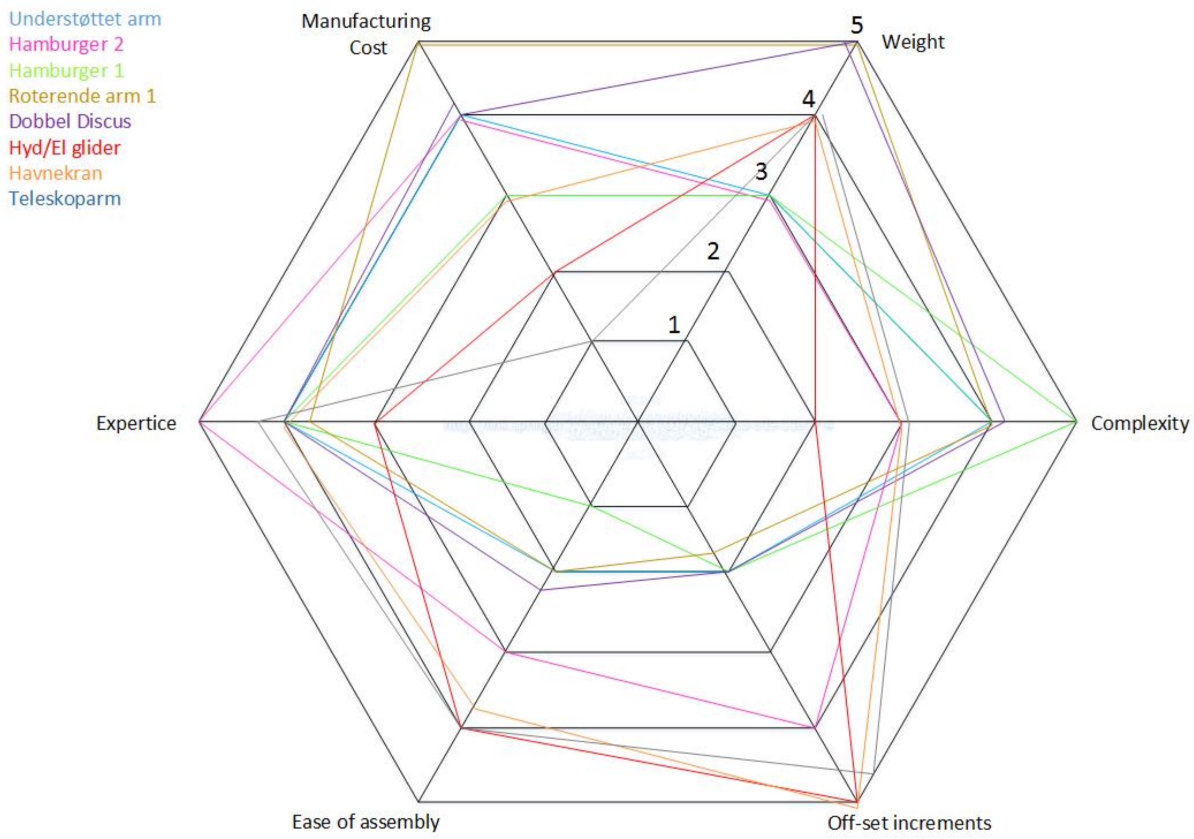


Figure IV.1.1: Radar Chart for visualisation of concept scores

It is often the case that concept filtering does not point out a clear best alternative [18]. This was also the case in the described situation, which is evident from the Radar Chart in figure IV.1.1. The chart visualises that neither of the concepts stands out as holding mainly the high (outer layer) scores. Berkey (2008) [18] recommends identifying the two or three best concepts and look for a hybrid solution amongst those. This encourages further idea generation where one attempts to mix and match the best parts from each of the strongest concepts. Furthermore, selecting evaluation criteria that either does not reflect the most critical requirements or selecting criteria that correlate with each other can result in poor discriminating capability [18]. Hence, a reassessment of the detailed criteria was undertaken. It was found that the previous criteria "adjustability" would inevitably increase "complexity". To enhance clarity this criteria was split into "complexity"; involving analysis; and "offset increments"; the number of steps in which offsets would be offered. The criteria "risk" was renamed "expertise"; comprising the level of knowledge the project team as a whole holds for developing each concept. Lastly, "ease of assembly" was added as an important discriminating criteria after a meeting with the stakeholder. These six criteria then received a weighting factors. Lastly, each concept was evaluated and scored again according to each of these criteria, in the manner as previously described.

A correlation analysis within both sets of old and new criteria was undertaken to objectively assess whether the new criteria were better; in terms of less correlated to each other; than the old set. Correlation analysis showed that on average the old set of criteria had a moderate-strong correlation, while the new set of criteria had a moderate-weak correlation. The details of the correlation analysis is provided in the Design Evaluation Matrix. When looking into more details of the correlation analysis, four correlations up to and above 0.7 existed between several of the variables in the old set of evaluation criteria. In the new set of criteria only one correlation was above 0.7. This strengthens the rationale for changing the evaluation criteria, and shows that the six new criteria distinguishes and evaluates different qualities of the system.

As recommended by Berkey (2008) [18] the three concepts with the best score after the detailed filtering; "Havnekran", "Double Discus" and "Hamburger 2" respectively; were put next to each other and an idea brief as to any possible hybrid solutions was undertaken. The generated hybrid solution was then lastly subjected to the same detailed briefing as the other concepts. The detailed results of both the coarse and detailed filtering are presented in the Design Evaluation Matrix in appendix G.8. Lastly, the total scores were visualised through the column diagram in figure IV.1.2.

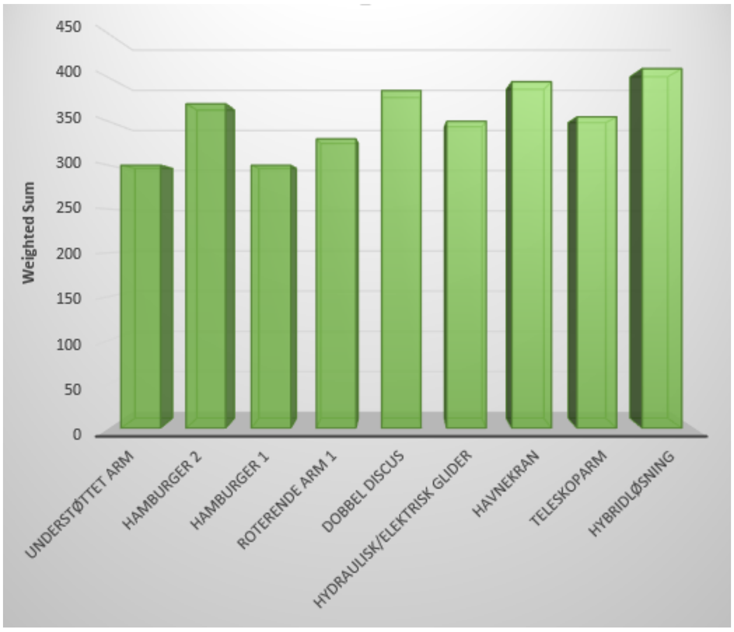


Figure IV.1.2: Detailed Weighted Score of Concepts

The hybrid solution received the highest score on the detailed filtering. However, the concept "Double Discus" stood out as a more innovative and less intricate solution, whereas the hybrid appeared as more of a "safe" solution. The conceptual design phase often does not provide sufficient detail for full evaluation of the concepts. To bridge the gap between conceptual design and detailed design it was decided to develop the two designs into more detailed preliminary designs. Preliminary designs challenge the designers to address feasibility of the solutions in more detail. As two concepts appeared viable at fulfilling the system requirements it was decided to make preliminary designs of the two concepts, with the purpose of providing a better foundation for making a robust final concept selection.

IV.1.2.5 Preliminary Designs

Two preliminary designs were compiled from a long evaluation process. This evaluation process transformed the costumers requirements in to important aspects and functions. These aspects where then in turn rated, and two preliminary designs was isolated. These two preliminary designs are described in the following segment.

IV.1.2.5.1 Double Discus

The first of the two preliminary design to be discussed is the Double Discus. The Double Discus is based on rotation of the mounting plate for the RWS in order to provide an offset from center. The offset will not be linear, however this will not matter because of the fact that the system rotates.

The Double Discus system consists of two main parts relating to the offset system; the mounting plate for the RWS and the plate/top to which the mounting plate is attached.

The amount of degrees that the RWS mounting plate is rotated will be the factor that dictates the offset from center. The mechanical fixture from the mounting plate to the OMS comes in the form of bolts. The mounting plate is bolted in to a position that will give the desired offset from center.

Figure IV.1.3: Preliminary design: Double Discus

The advantages of the design include:

- Simplicity of design
- Easy mounting of RWS from underneath
- Easy access to internals for service
- Fixed offsets might increase inter-day test reliability
- Minimum stress and strain on wire
- Easy to repair or replace offset disk
- Possibility to insert other custom-made offset discs in the future

IV.1.2.5.2 Hybrid

The second of the two preliminary designs is the hybrid solution. This option is a strictly mechanical option which mainly relies on a simple ball screw system to move a plate either further away from or closer to the center of the OMS plate. This option provides the costumer with a simple yet effective system that will make it possible to adjust the offset from center up to 300mm.

Like stated earlier the hybrid option is based on simple mechanics, which will provide the ability to displace the RWS from center without having to disassemble the RWS from the OMS. The system consists of one rail on each side of the RWS, these rails provide free movement back and forth, that is away from and closer to the center.

In the middle of the two rails it is a ball screw, that will ensure the mechanical movement. The purpose of the ball screw is to both provide movement of the RWS of center, and also restrict the movement of the RWS during operation. The restriction of movement is partly done by the rails as well.

The offset system is driven by torque, which is applied to the ball screw, which will then rotate and move the RWS. The torque is applied using either a drill or some other kind of simple devise.

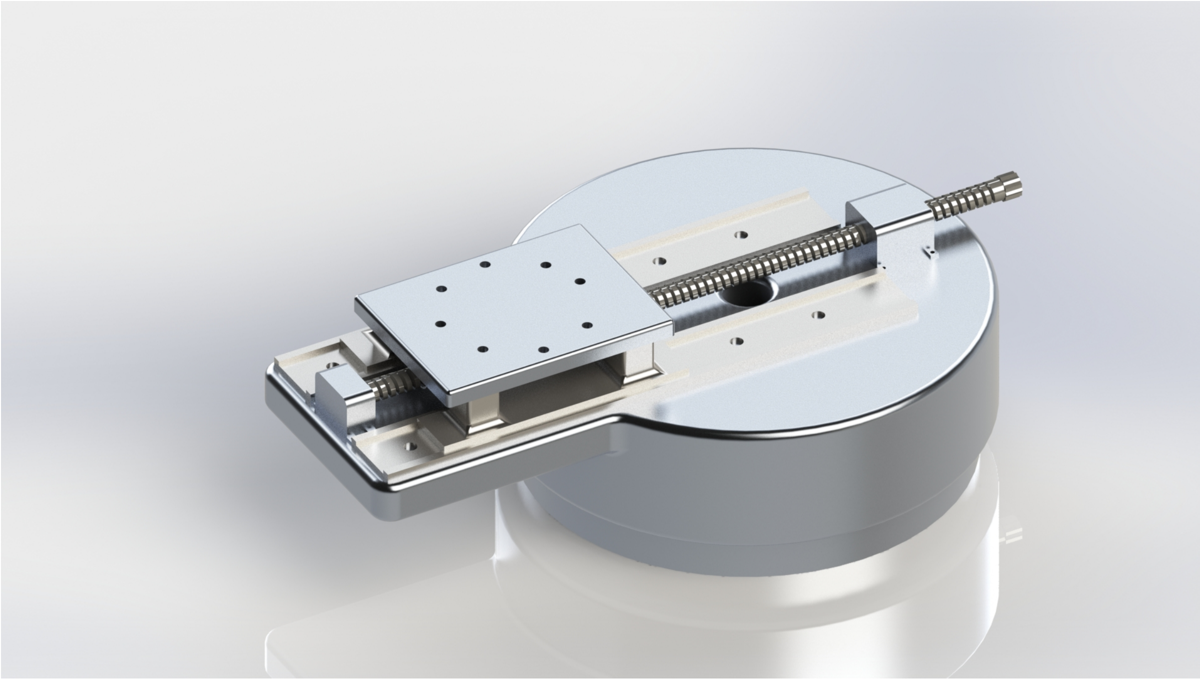


Figure IV.1.4: Preliminary design: Hybrid

The advantages of this design include:

- Free adjustment of the offset, within the range of the rails
- Easy mounting to the RWS
- Possible for further development of design
- No strain on cables
- Simple and intuitive adjustment of the offset
- Relatively low in price
- Easy to replace damaged or outdated parts

IV.1.3 Concept Selection

After a long evaluation process with several iterations, which include several Pugh matrix modifications and careful evaluation of each concept, a decision to go forth with the Double Discus was made. The details for the evaluation process, criteria and scores are presented in the the Concept Evaluation Matrix. The last evaluation of the two preliminary designs was undertaken in two rounds, each of which can be classified as a discussion. The first discussion was a neutral discussion with the customer, where advantages and disadvantages for both concepts were pointed out and discussed. The second part was an internal meeting within the group where both concepts were discussed in detail, and every individual group member where asked to give their personal opinion on which concept will be the most feasible and provide the best solution for all stakeholders.

The concept that was considered to be the most optimal solution was the Double Discus; a decision that was unanimous. In the detailed design evaluation the Hybrid solution received a slightly higher score than the Double Discus. However, modelling and development of the more detailed preliminary designs revealed more detailed design aspects that previously had been based on assumptions only. Example given; the weight of the hybrid was initially thought to be lower than the Double Discus. Yet, preliminary design development showed that the Double Discus was likely to weigh less. Presentation of the two preliminary designs to the customer revealed that their rated importance of weight and number of offset increments were lower than what the project team had assumed. Also, ease of assembly were more important to the customer than the weight that criteria had initially received in the detailed evaluation.

Another reason why the Double Discus was deemed a better solution over the Hybrid solution was simplicity of design. This simplicity manifests itself through fewer subsystems and hence fewer uncertainties and risks. The Hybrid solution would require more complex parts for the offset regulating mechanism, hence more calculations and not to mention more expenditure. Furthermore, the design of the offset mechanism would result in finer architecture which imposes a risk for fatigue and weaknesses in several aspects of the design. With it's more simple design the Double Discus would allow for more time for optimising the design and controlling uncertainties due to a lower quantity. Hence, the Double Discus was deemed superior both in terms of cost and feasibility. In conclusion, with the factors mentioned above in mind, the Double Discus was deemed the most feasible solution that was most likely to fulfill the stakeholder requirements. The Double Discus was therefore chosen as the concept to go forth with into development of the desired system; the OMS. From this point onwards, further development and discussion of the system (Double Discus) will be called OMS (Orbital Motion System).

IV.2 Analysis and Calculations

The OMS system will consist of several subsystems, each of which are to function individually and as a unity, under a wide range of complex movements in 6 dimensions. Being a mechatronic system with several mechanical and electronic components further adds to the complexity of both the mechanical design, calculations, analysis and testing. The analysis phase will hence consist of several segments where the system is broken down into subsets to simplify initial analysis. Components are then added and the system as a whole is then analysed under progressively more advanced movements. The following chapter will describe the steps undertaken to analyse the system in enough detail to provide the information needed for optimisation of the design according to the requirements.

IV.2.1 Method

To analyse the complex dynamic motion and accompanying impacts on the OMS a "system dynamics" method of approach was chosen. System dynamics is the study of power variables within an energetic system [20]. The OMS will interact with a power source which makes the energy flow across the OMS' boundaries, before it dissipates as either friction, electrical resistance or heat. The system dynamics approach was deemed suitable because the OMS will be a mechanical design where it is possible to predict the transient and steady state responses to any arbitrary input imposed on the system. Furthermore, the system dynamics approach will also allow creation of engineering models which can be used to determine the critical loading of the system through prediction of how the power variables vary with time.

The OMS system will consist of many individual subsystems, each of which will be modelled and analysed separately before combining the subsystems into a model that represents the entire system. Decomposition of the OMS involves breaking down the system into basic components that easily can be characterized. This helps and facilitates modelling and mathematical representation. The complexity of the different models will depend on the accuracy needed to predict the dynamic response.

A closed form solutions will be used to analyse the OMS' response to various inputs. Closed form solution equations solve a given problem in terms of functions and mathematical equations, and returns a finite number of solutions [21]. This makes it possible to isolate and understand the effect of the most important parameters and avoiding unnecessary complexity. The goal of OMS modelling is to reduce or eliminate the need to build an expensive prototype and/or tedious computational model. A challenge in modelling is to balance having enough details to make a model meaningful, without including too much detail that will make it impossible to solve analytically. The goal of the system dynamics approach is to predict the dynamic response of the system by putting together the mechanical and electric elements, and ultimately analyse them as a whole.

The design tools used for developing the OMS system includes analytical and numerical modelling, computer 3D modelling and simulation, as well as physical prototyping. The analytical approach to OMS design presented itself firstly in the design process. At that stage it gave a quick assessment of feasibility, as well as a rough estimate of the range of the critical design parameters. In this analysis phase numerical models are used to derive detailed numerical quantities for the critical design parameters that will ensure fulfilment of the system requirements. Numerical calculations, computational modelling and simulation will run in parallel to each other throughout the analysis phase. Results from computational modelling can be used to ensure that the handwritten calculations that are made hold ground. Vice versa, the handwritten calculations will be used as input to the computational modelling for optimising the design according to loads that are challenging or impossible to simulate. Lastly, a prototype can be built and tested if the time schedule allows it.

IV.2.1.1 Engineering Models

In general, an engineering model is a simplified representation of the real entity. The level of realism needed will vary with the intended use, which is dictated by what stage of the design process the model is used in. Initially, a simplified model is created, such as the Free Body Diagrams (FBD) developed in Iteration 7. These can be found in the Iteration Log(appendix G). In FBDs assumption and simplification are made in order to provide a basis for further engineering computations and design decisions. These decisions yield uncertainties in the design, especially in the early stage. As understanding and knowledge of the system evolves, the model is made more and more complex and each simplification is investigated in more detail. Finally the details are added together to assess the system as a whole under the environmental conditions it is required to function in.

IV.2.1.2 Mathematical Models

A mathematical model is an equation or set of equations which form an input-output relationship. As shown in the following figure IV.2.1, the input variables are known and the output variables contain the desired information. Mathematical models are based on engineering models as they are simplifications based on certain assumptions.

The different attributes and proprieties of the modelled system can be described by simplified mathematical statements that describe physical aspects of the model. A set of equations are listed, after which the

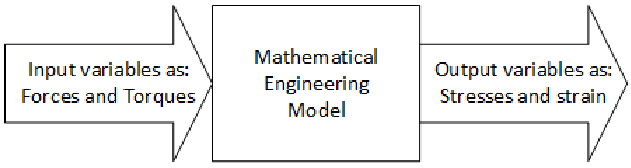


Figure IV.2.1: Mathematical engineering model

equations are condensed to eliminate the unwanted variables by substitution; leaving the input we want, the output we are interested in calculating and the independent variables of time and position. Engineering modelling and analysis is divided into four steps: defining the model by drawing a picture of what is going to be analysed, and defining all of the variables and parameters in the model. Then, mathematical statements of relevant physical truths are written. Further, all unknown variables in these mathematical statements are reduced before solving the equation for the desired output. Finally, the soundness of the solution is evaluated in context of other known characteristics and engineering knowledge.

IV.2.2 Calculations

The central requirements for the OMS is to provide rotation of a 250 kg load with an offset of 30 cm from the OMS center of rotation. The requirements state that the OMS shall supply a angular acceleration between 1 and 6 rad/s^2, and an angular velocity between 60 and 120°/s.

The calculations regarding the rotation of the OMS system are based on Newton's second law. The sum of all torques affecting the system is equal to the systems inertia (I) times its angular acceleration (α).

$$\sum \tau = I \cdot \alpha \tag{E.2.1}$$

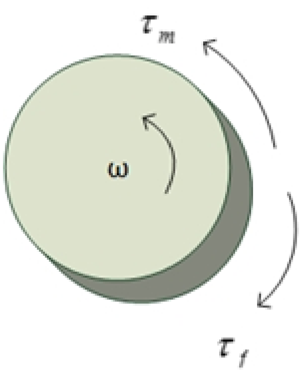


Figure IV.2.2: Simple model of the OMS rotational system.

Since $\sum \tau$ = NET Torque, equation E.2.1 can be modified to this:

$$\tau_{motor} - \tau_{friction} = I \cdot \alpha \qquad \equiv \qquad \tau_{motor} = I \cdot \alpha + \tau_{friction} \tag{E.2.2}$$

The motor power can then be calculated by multiplying motor torque(τ_m) with angular velocity for OMS (ω).

$$P = \tau_m \cdot \omega \tag{E.2.3}$$

IV.2.3 Free Body Diagram

The initial analysis were done by drawing a free body diagram (FBD). Assumption and simplifications were made to show the main forces and loads affecting the system. FBD establish the basis for further engineering computations and design decisions, especially in the early stage. Each simplification is investigated in more detail as more understanding and knowledge of the system is obtained. Finally, details will be added together to evaluate the system as a whole under the conditions it is required to function in. Figure IV.2.3, shows the simplified FBD of the OMS which analysis and modelling of the system is based off.

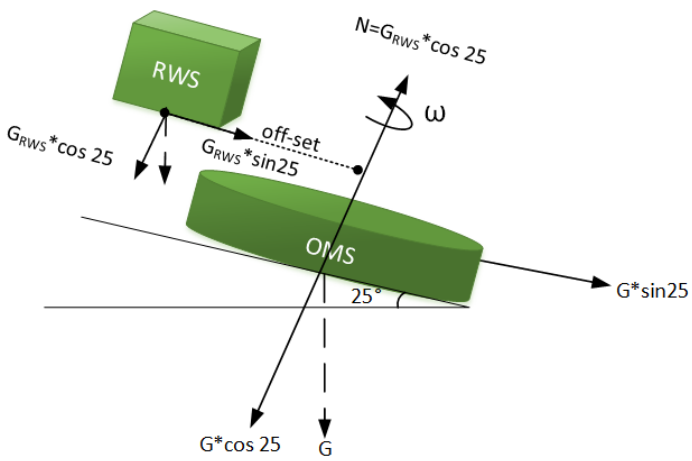


Figure IV.2.3: Simplified Free-Body Diagram of OMS

IV.2.4 Moment of Inertia

The moment of inertia (MOI) of an object is a measure of it's distribution of mass around a given axis. The MOI determines the torque needed to rotate an object with a given angular acceleration about an axis. A higher mass or a more distally distributed mass with regards to the rotational axis will increase the MOI, and hence increase the torque needed to accelerate the mass. The purpose of the designed system is rotate a high load; thus MOI plays a central part of the initial calculations for the design of the system. The formula for MOI is:

$$I_{OMS} = \frac{1}{2}mr^2 \tag{E.2.4}$$

By using volume and density to express mass, the equation can be expressed as:

$$I_{OMS} = \frac{1}{2}\rho H \pi r^4 \tag{E.2.5}$$

The system shall be able to rotate the RWS when the load is placed at an offset of 30 cm away from the system's center of rotation. The parallel axis theorem was thus used to determine the MOI of the RWS when rotated about the OMS's center of rotation. The parallel axis equation used states:

$$I_{PA} = I_{OMS} + m_{RWS}r^2 \tag{E.2.6}$$

The total MOI of the system was found by adding the MOI of the power train disc, the slew bearing, the body used to fixate the bearing and the parallel axis MOI of the RWS at an given offset; x mm. The total MOI of the system was found to be 24 kgm^2. A MatLab script was developed in order to alleviate the extent of calculations that needed to be done if one or more input values changed. The script can be found in Appendix H, section "Moment of Inertia Script".

IV.2.5 Forces and Loads

The mathematical analysis is based on Newton's second law for rotation (see eq. E.2.1). Only forces that have a contribution tangential to the circular motion, will generate torque. Forces working perpendicular to the rotation will not generate any torque. In order to calculate what amount of torque the motor needs to supply in order to accelerate the system, one need to know the other torques affecting the system.

Friction from the bearing will require additional torque from the motor in order to accelerate the system. In the standard model for friction it is assumed that the friction is independent of the velocity. There are however exceptions; one being fluid lubricants. When fluid lubricants are involved, the system encounters viscous resistance, and it is dependent on velocity. Also when making a dynamic model of the system, having a constant friction would not be optimal. This is because if the system is stationary, the constant friction would still give a torque that the motor would need to counter in order to keep the system stationary. There is also air resistance that contribute to the dampening of the system, which is also dependant on the velocity.

As stated, the forces working perpendicular to the motion will not provide any torque that the system would have to counteract. Meaning that the gravitational forces will not generate any additional torque as long as the motion table is leveled. This does not however mean that the system performance is independent of the weight of the system. Remember that the inertia is dependent on the weight. However when the motion table is tilted, the gravitational forces will no longer always be perpendicular to the rotation (see figure IV.2.4). In other words the the gravity will have a force contribution in the same direction as the motion, and will create a torque. Gravitational torque will now refer to this torque, and will be dependant on both angular position and the tilt of the motion table.

As more of the forces working on the system are identified, one can derive how much torque the motor needs to supply in order to keep the system at the desired acceleration, as a function of multiple parameters. Expanding equation E.2.1 to include the known torques affecting the system.

$$I \cdot \alpha - \tau_f - \tau_g - \tau_m = 0 \tag{E.2.7}$$

The gravitational torque is dependant on angular position. And the frictional torque is dependant on velocity as no torque will be generated from the friction when the system is stationary and not being accelerated. As a result of these dependencies, the torques in equation E.2.7 can be written as a function of different derivatives of angular position.

$$I \cdot \ddot{\theta}(t) - \tau_f(\dot{\theta}(t)) - \tau_g(\theta(t)) - \tau_m(t) = 0 \tag{E.2.8}$$

Equation E.2.8 can compute motor torque as a function of time in relation to angular position and it's derivatives as a function of time. This equation also serves as the basis for simulation of different load situations of the system in Matlab.

IV.2.5.1 Gravitational Torque

As seen in figure IV.2.4, gravitational forces will come into effect when rotating the system around an inclined plane. While traveling uphill the gravitational contributions in the direction of rotation will work against the system. Meaning more work for the motor. And when traveling downhill these contributions will accelerate the system. Gravitational torque implies what torque the system needs to supply to overcome the gravitational force.

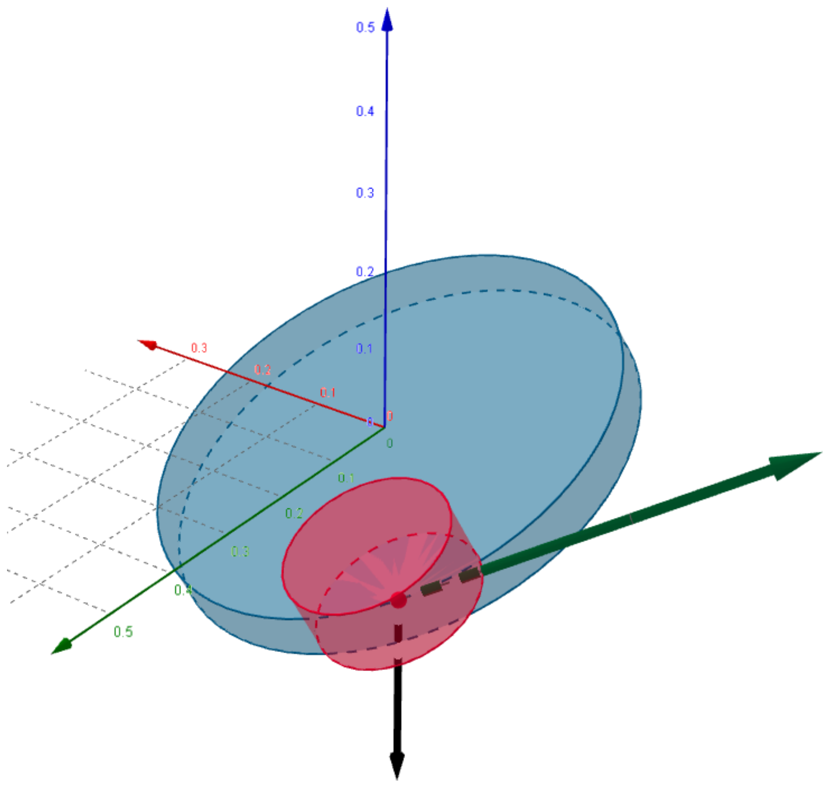


Figure IV.2.4: Gravitational pull.

The manual of the motion table states that the table can be rotated around three axis. The z axis is the normal vector of the tilted table and OMS. Mounting the OMS so that the axis of rotation of both OMS and table align, will eliminate one degree of freedom. Since rotation of table and OMS is around the same axis, it can be combined and simplified to one rotation.

In order to calculate the force contribution from gravity, we need to know the tangential vector of rotation and the position of the RWS in space. According to Euler's rotation theorem, any rotation can be described by three angles. A simple way to track position of an object being rotated around three different axis is using rotation matrices. If we define the tilt of the motion table with angles θ and ϕ and the rotation around the new z axis as ψ, we get the following rotation matrices.

$$R_X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(\theta) & -sin(\theta) \\ 0 & sin(\theta) & cos(\theta) \end{pmatrix} R_Y = \begin{pmatrix} cos(\phi) & 0 & sin(\phi) \\ 0 & 1 & 0 \\ -sin(\phi) & 0 & cos(\phi) \end{pmatrix} R_Z = \begin{pmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The three rotation matrices can be combined in a resulting matrix $R_R = R_X \cdot R_Y \cdot R_Z$

$$R_R = \begin{pmatrix} cos(\phi)cos(\psi) & -cos(\phi)sin(\psi) & sin(\phi) \\ sin(\theta)sin(\phi)cos(\psi) + cos(\theta)sin(\psi) & -sin(\theta)sin(\phi)sin(\psi) + cos(\theta)cos(\psi) & -sin(\theta)cos(\phi) \\ -cos(\theta)sin(\phi)cos(\psi) + sin(\theta)sin(\psi) & cos(\theta)sin(\phi)sin(\psi) + sin(\theta)cos(\psi) & cos(\theta)cos(\phi) \end{pmatrix}$$

In order to find the new position of a point or vector in space after being rotated simply multiply R_R with the column matrix of the point or vector.

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = R_R \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

As a result the unit vectors for the new axis' will be the following.

$$\vec{X'} = \begin{pmatrix} cos(\phi)cos(\psi) \\ sin(\theta)sin(\phi)cos(\psi) + cos(\theta)sin(\psi) \\ -cos(\theta)sin(\phi)cos(\psi) + sin(\theta)sin(\psi) \end{pmatrix} \vec{Y'} = \begin{pmatrix} -cos(\phi)sin(\psi) \\ -sin(\theta)sin(\phi)sin(\psi) + cos(\theta)cos(\psi) \\ cos(\theta)sin(\phi)sin(\psi) + sin(\theta)cos(\psi) \end{pmatrix}$$

$$\vec{Z'} = \begin{pmatrix} sin(\phi) \\ \\ -sin(\theta)cos(\phi) \\ \\ cos(\theta)cos(\phi) \end{pmatrix}$$

Defining the $\vec{X'}$ as the direction from center of rotation to the RWS makes a lot of sense. Since $R\vec{W}S$ =offset$*\vec{X'}$ will then be the vector from origo to the RWS with magnitude equal to the offset. As origo is situated at (0, 0, 0), $R\vec{W}S$ will also be the point in space of the RWS. As an added bonus $\vec{Y'}$ will be the tangential vector of rotation without magnitude. This is because $\vec{Y'}$ is always equal to to the cross product of $\vec{X'}$ and $\vec{Z'}$.

$$\vec{G} = M \cdot g \cdot \begin{pmatrix} 0 \\ \\ 0 \\ \\ -1 \end{pmatrix}$$

To find the contribution of $\vec{G}$ in the same direction as $\vec{Y'}$, one can project vector $\vec{G}$ onto $\vec{Y'}$ as shown below.

$$\vec{F_g} = Proj_{\vec{Y'}} \cdot \vec{G} = \frac{\vec{Y'} \cdot \vec{G}}{||\vec{Y'}||^2} \cdot \vec{Y'}$$

The final torque will be the length of $\vec{F_g}$ times the offset.

$$\tau_g = ||\vec{F_g}|| \cdot \text{offset}$$

τ_g will vary depending on multiple parameters such as the incline, angular position and offset. In terms of dimensioning the system, the interest lies in the maximum value of the gravitational torque and when it occurs. Distribution of maximal gravitational torque as a function of angles θ and ϕ were plotted with the help of Matlab.

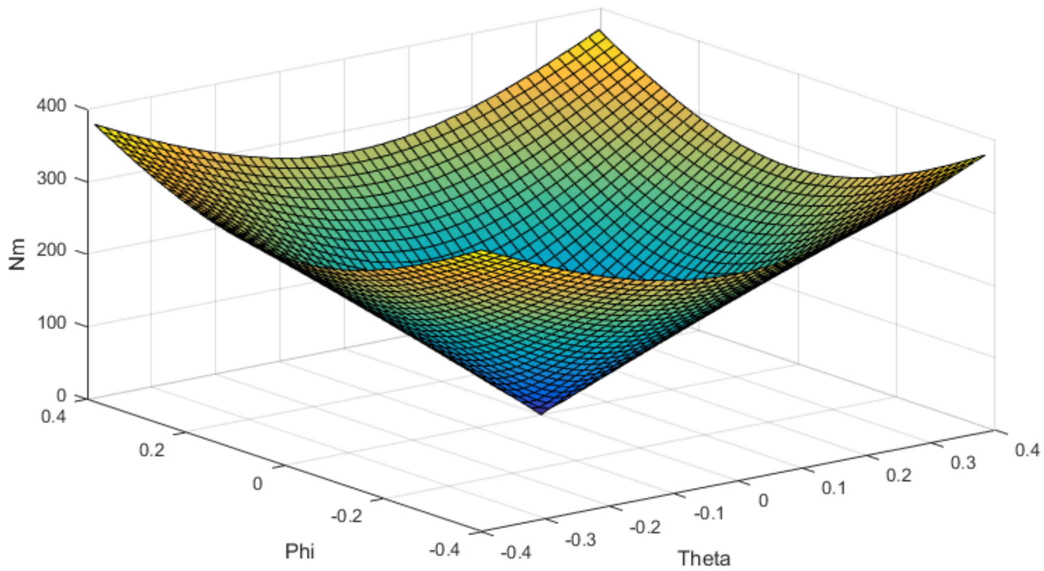


Figure IV.2.5: Distribution of maximal gravitational torque.

The Matlab calculation shows that the maximal gravitational torque occurs when the two rotation angles of the motion table is either at maximum or minimum at the same time. At these four points the gravitational torque is 520 Nm.

IV.2.5.2 Friction Torque

Section IV.3.3 presents the bearing selection process and why the bearing from SKF was chosen. SKF would not provide details about the frictional moment of the bearing, as that would cause problems with licensing. Therefore a estimation of the frictional moment was needed.

Estimating the frictional moment in the slew bearing is not an exact science; the frictional moment depends on many variables. Load conditions, lubrication and raceway diameter are just some of these variables. Testing has been done by KPS on a bigger version of same kind of slew bearing used in this project. The test measured the frictional moment at different temperatures.

The diameter of the bearing planned for the OMS is less than half of the one used at KPS. Diameter and frictional moment is often viewed as proportional when estimating frictional moment in bearings [55]. However having loads placed away from the center of the bearing creates a bending moment in the bearing. Moment loads in the bearing contributes more to the frictional moment than axial and radial loads [56]. At KPS the mass center of the loads was placed closer to the center. The offset disc will place the load of the RWS outside of the bearing.

Temp(Celsius)	Average(Nm)
-46	320
-40	193
20	55
65	37

Table IV.2.1: Frictional moment

The bearing Rollix suggested had a frictional moment of 80 Nm given the load conditions and diameter. Seeing as the SKF bearing has steel wire inserts in the raceway to prevent jamming as a result of dynamic loads. Setting the estimated frictional moment of the OMS at 55 Nm.

IV.2.6 Computer model and simulation

The mathematical model was implemented in different computer software, to make the model dynamic. Meaning that calculations does not have to be redone for different scenarios. Computer models discussed in this section is used primarily to calculate required motor power and torque in relation to the requirement specification.

IV.2.6.1 Geogebra

A graphic representation of the load conditions was made using Geogebra. Geogebra uses points and vectors to make constructions in an interactive 2D or 3D environment. The ability to do symbolic calculations makes Geogebra very useful in this application. The program can define most dimensions as variables, meaning that there is no need to redo the calculations every time a variable changes. Since Geogebra can do operations on matrices, most of the calculations in section IV.2.5.1 could be used directly.

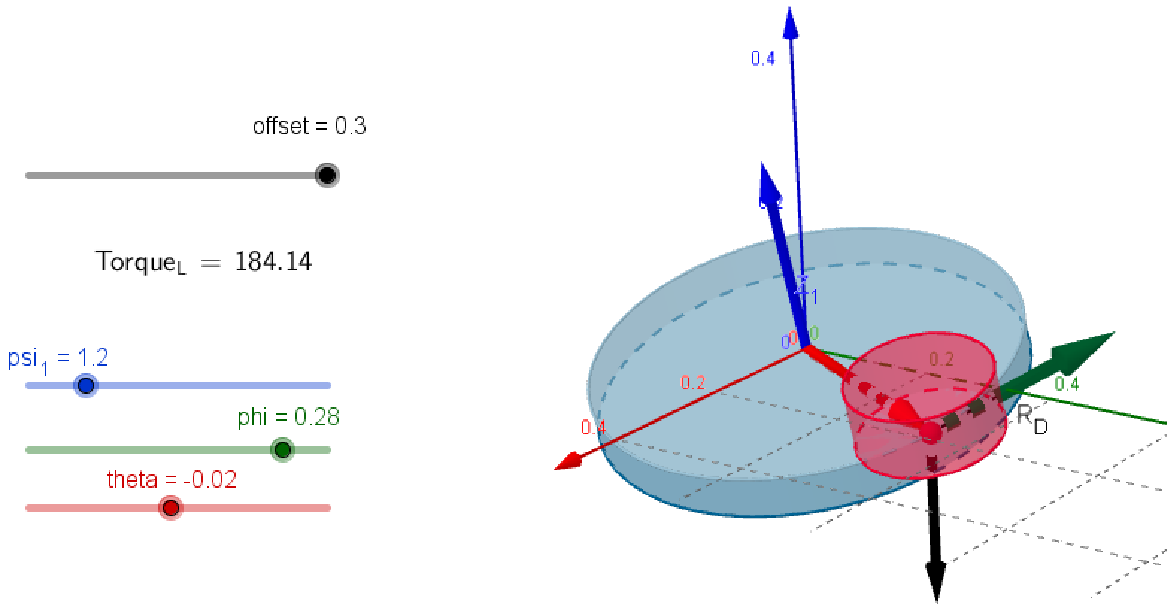


Figure IV.2.6: Geogebra model

The main purpose of a Geogebra model in this project was to verify the math. Verifying that each force vector's direction is correct was an important step before moving on to more advanced simulation of the problem. Geogebra also supports animation through the ability to let the computer vary variables as a function of time. As seen in figure IV.2.6 the green arrow represents the torque the motor needs to supply in order to counteract gravitational forces.

IV.2.6.2 Simulink

A simulation of the system was made using Simulink. This model served as a tool when dimensioning the motor. Its important to note that the model only calculates the amount of torque the motor needs to supply at any position, given a set velocity and acceleration. It does not model how the system responds to torque from the motor.

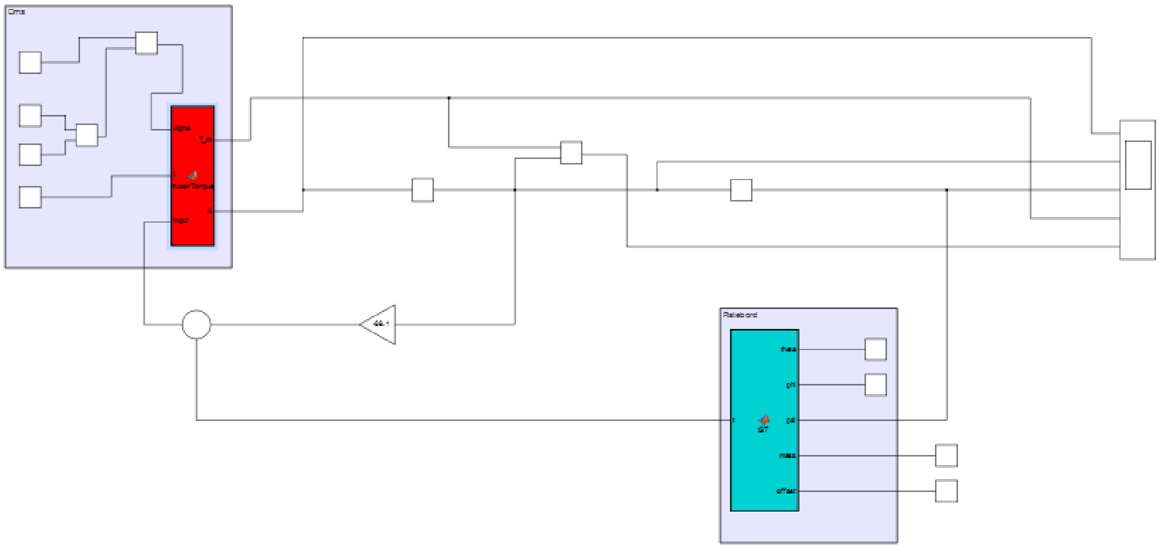


Figure IV.2.7: Overview of the Simulink model

The Simulink model is based on the differential equation E.2.8. The model uses a Matlab function block with different inputs in order to calculate the amount of torque needed to satisfy the input conditions. This function block can changed in order to calculate different scenarios. An example of this block is included in appendix I.2. In this example the system is accelerated with 6 rad/s^2 until it reaches a velocity of $2/3\pi$ rad/s. This velocity is maintained for five seconds, afterwards the motor is disconnected. The output acceleration is then integrated two times, and the two integrals forms feedback loops back to the motor torque function block.

The position feedback loop gives input to another Matlab function block that calculates the gravitational torque. This block also takes input from constants such a offset, mass and the incline of the motion table. The code can be found in appendix I.1. Velocity feedback is multiplied by a dampening factor. The incline of the table can either be static or follow a sine function.

The simulation outputs system acceleration, velocity, position. Along with required motor torque and power required for that motion. An example of the resulting graphs is included below.

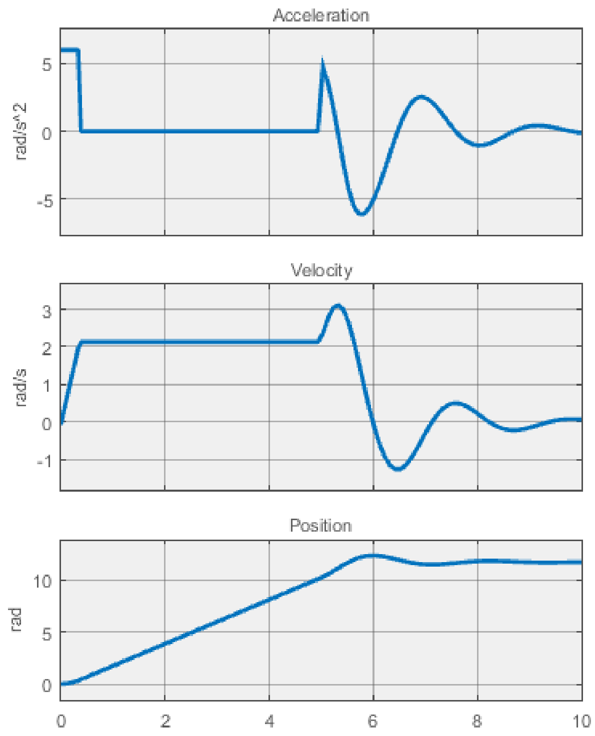


Figure IV.2.8: Example of results from Simulink model

IV.2.7 Worst Case Load

When designing a system it's important to identify what loads the system will have to withstand while operating. The system needs to be able to withstand all loads scenarios, and especially the worst case scenario it could be subjected to. The design needs to withstand the worst case load, making it very important to identify and calculate.

The OMS will be subjected to both static and dynamic loads. Another important aspect is that all these loads are not acting on the system at the same time. The motion table is not able to output max pitch and roll acceleration at the same time, because the same actuators is needed for both rotations. Because of this relation the need to define worst case scenarios is important. If the system was dimensioned considering all loads at their maximum, it would be over dimensioned.

This section will discuss and identify worst case load scenarios. These scenarios will be used and considered during design and testing phase of the project.

IV.2.7.1 Loads

The static load working on the system is primarily the weight of the RWS. The offset from centre is another size that needs to be considered, as the weight of the RWS on the offset plate will result in a bending moment. The maximum weight of the RWS that the deign needs to consider is 250kg. The requirement specification also list 30 cm as the maximal offset.

IV.2.7.2 Motion Table

The motion table is operated by six linear actuators, mounted pairwise to the three short sides of the top plate. Performance parameters of the table is included below. The table show the acceleration the table can supply with one degree of freedom. The question is what the maximum acceleration the table can supply in a combined motion scenario.

Degree of Freedom	Displacement Comb. Motion	Displacement Single DOF	Velocity	Acceleration
Pitch	+25/-23 deg	± 22 deg	± 30 deg/s	± 500 deg/s^2
Roll	± 22 deg	± 21 deg	± 30 deg/s	± 500 deg/s^2
Yaw	± 23 deg	± 22 deg	± 40 deg/s	± 400 deg/s^2
Heave	± 0.18 m	± 0.18 m	± 0.30 m/s	+0.5g
Surge	± 0.27 m	± 0.25 m	± 0.50 m/s	±0.6g
Sway	± 0.26 m	± 0.25 m	± 0.50 m/s	±0.6g

Table IV.2.2: Datasheet: typical motion table specifications

Since the actuators are mounted pairwise facing each other, force components from their respective displacement will work in opposite direction. Meaning that some of the forces will balance each other out (see figure IV.2.9). This effect can be seen in table IV.2.2 in relation to the heave displacement and yaw rotation. During heave or yaw, all actuators will be active and used only to displace or rotate the table along or around Z-axis. Note that the acceleration of heave and yaw are smaller compared to what the table can supply in the other directions.

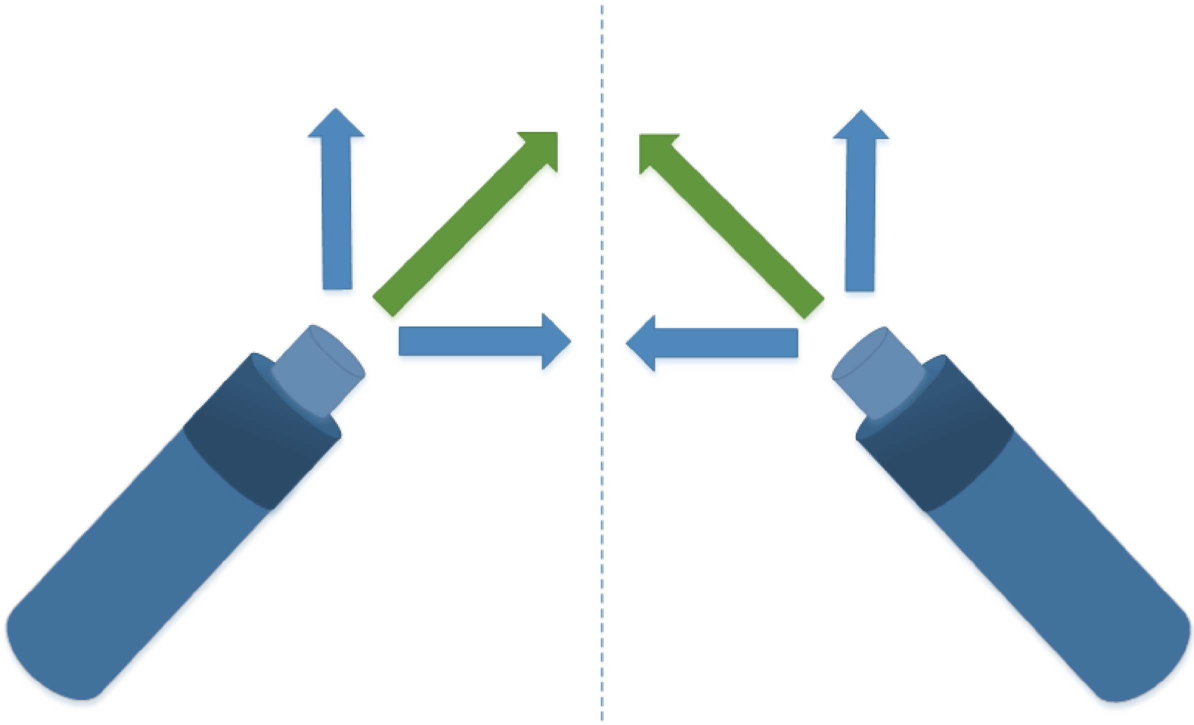


Figure IV.2.9: Forces applied by two actuators.

As most of the motions the table can perform uses all actuators to some degree, a combined motion would not supply their respective one DOF acceleration at the same time. As a simplification one could view the one DOF acceleration, as what the table can supply when all actuators are working together to move the system. This means that a combined motion could not exceeded an acceleration of 500 deg/s^2. Another consequence of this is that the table cannot accelerate translation and rotation at the same time. KPS has mounted a thick aluminium plate that serves as the mounting interface between the table and RWS or OMS. According to a past bachelor project [59] concerning the control interface of the motion table, acceleration is limited by the extra weight added by this plate. This makes sense from a physical view as each actuator can supply a certain force, and the sum of forces equals mass times acceleration. Since the force supplied stays the same, the acceleration has to decrees as a result of the added weight. The past project found that the system could supply 400 deg/s^2 with the added weight from the plate. The OMS will add even more weight, resulting in an uncertainty that serves as a factor of safety.

IV.2.7.3 Incline and Shear Forces

The incline of the motion table will change the load situation. As less of the gravitational forces from the RWS will work normal to the offset-plate, more will work as shear forces in the bolted interface between RWS and OMS. Bolts are most vulnerable to shear forces. The offset-plate is most vulnerable to normal forces because of its geometry, having a small thickness compared to width and length.

IV.2.7.4 Acceleration and Deceleration of OMS

Acceleration and deceleration of the OMS is independent of any other motion of the system. Meaning that the OMS can supply maximal angular acceleration regardless of how the motion table accelerates the system.

IV.2.7.5 Resulting Forces

Because the motion table cannot fully accelerate both translation and rotation at the same time, it was decided to design after two worst case scenarios. One where the table accelerating results in translation, and another were acceleration results in rotation.

IV.2.7.5.1 Rotation

Resulting force from pitch and roll will work normal to the offset-plate. Calculation of said force to be equal to the angular acceleration in radians times the offset times the mass of the RWS.

$$F_{rot} = \frac{25}{9}\pi \frac{rad}{s^2} \cdot 0.4m \cdot 250kg \approx 875N$$

Forces from the rotation of the OMS will work parallel to the rotation. The magnitude of said forces be equal to the angular acceleration in radians times the offset times the mass of the RWS.

$$F_{oms} = 6\frac{rad}{s^2} \cdot 0.4m \cdot 250kg = 600N$$

Since the bolted connection is most vulnerable to shear forces it was decided to use max tilt as worst case scenario. Meaning that gravity will result in two different force component, working parallel and perpendicular to the offset-plate.

$$F_{gy} = 9.81\frac{m}{s^2} \cdot cos25^\circ \cdot 250kg \approx 2225N$$
$$F_{gx} = 9.81\frac{m}{s^2} \cdot sin25^\circ \cdot 250kg \approx 1050N$$

IV.2.7.5.2 Translation

The resulting forces of sway and surge will work perpendicular to the OMS as shear between the bolted connections. The magnitude of the resulting force will be the linear acceleration times the mass of the RWS.

$$F_{trans} = 0.6 \cdot 9.81\frac{m}{s^2} \cdot 250kg \approx 1475N$$

Force components from rotation of the OMS and the incline of the table stays the same in this scenario.

IV.2.7.6 Discussion

These worst case scenarios rely the simplification that the acceleration of a combined motion cannot exceed 500 deg/s^2 or 0.6g. Since the table's acceleration decreases with the added weight, adding a safety factor on the loads did not seem appropriate. As the tables acceleration in realty is 400 deg/s^2, as a result of added weight of the aluminium plate. Meaning that the resulting acceleration of could 25% higher than the number used in this simplification. Giving a sufficient margin of error for this problem.

IV.2.8 Safety Factor

Strength of a structure is defined as the ability of the material and the construction to resist loads [43]. The applied forces and loads must not exceed the strength of the structure. Integration of a safety factor into the design calculations helps to safeguard the structure against failure arising from unexpected loads, accidental overloading, fatigue failure, degradation of materials and fatigue failure. The risk of structural failure increases if the safety factor is too low; however, designing for a very high safety factor increases the weight and dimensions of the structure [43]. Safety factor, n, is defined as:

$$n = \frac{\text{structural capacity}}{\text{applied load}} \tag{E.2.9}$$

To design a durable construction it is important to keep the material of the structure within its elastic region to prevent permanent deformation. Thus, the yield stress of the material and the theoretical stresses are used to calculate the safety factor.The equation states as follows:

$$n = \frac{\text{yield stress}}{\text{applied stress}} = \frac{\sigma_y}{\sigma_a} \tag{E.2.10}$$

Note that for brittle materials the ultimate stress should be used instead of yield stress [43]. The choice of safety factor depends on the material properties, the desired reliability of the structure and the failure analysis. Accurate analysis of a well known load situation, in addition to using a material with well known properties, can allow use of a safety factor close to 1. A larger safety factor is required if either the material or load situation is unknown, and in the case of dynamic loads. No clear guidelines for choice of safety factor exists and recommendations vary greatly across literature.

The following rules-of-thumb were in the current project applied for choosing the safety factor [43]:

- **n= 1-1.5**: Well known material properties and well understood load scenarios. Static loads.
- **n= 1.5-2**: Ductile materials. Well analysed operating scenarios.
- **n= 2-4**: Brittle materials. Dynamic loads. Complex operating scenarios that is challenging to analyse.
- **n= > 4**: Uncertain stresses and load scenarios. Dynamic loads with repeated change of direction from compression to tension. Repeated shock loading.

In the current project a design requirement for choice of safety factor was formulated on the basis of the above mentioned rules. Design requirement DRQ015 states that "The general factor of safety used for components in the system shall be no less than 2". The materials used in the system are ductile and great efforts are made to analyse the operating scenarios. However, the load situation is highly dynamic and the test scenarios performed in the lab involves more complex movements than what can be analysed in sequence. Thus, a safety factor of no less than 2 was considered necessary. The components to which integration of a safety factor for design and dimensioning were as following:

- **Bolts**:
  the bolts are exposed to highly dynamic, varying loads involving both shear and tension stresses, as described in detail in section IV.3.9. A safety factor of 4 was applied for calculation and dimensioning of bolt connections.
- **Pinion**:
  A safety factor of 2 was applied for determination of the material needed for the pinion, as shown in equation E.3.11. Furthermore, calculations of the stress imposed on the teeth were calculated with the assumption that all the force transferred would be applied on one tooth, as shown in equation E.3.5.
- **Material**:
  A safety factor of 2 was applied for all solid materials of the OMS main components (base, power train disc and offset disc).

IV.3 Component Design

The OMS is based on rotation of the mounting plate for the RWS in order to provide an offset from center. The OMS consists of three main subsystems; the offset mounting disc for the RWS, the power train disc which the offset disc will be mounted onto, and base which will mount the whole OMS onto the motion table. Figure IV.3.1 indicates the terminology that will be used for the separate parts of the system. The number of degrees that the RWS offset disc is rotated will dictate the offset distance from center. The offset disc will be fixed to the OMS with bolts; one of which provides rotation around an axis and while the other bolts are moved according to the desired offset distance.

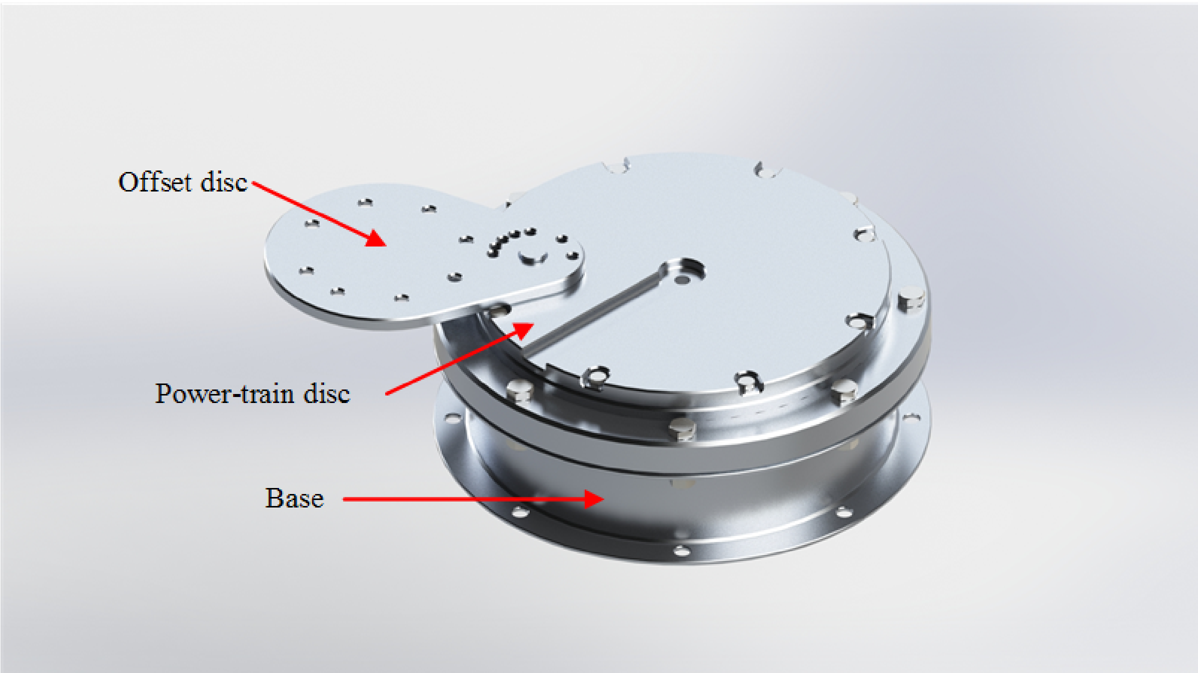


Figure IV.3.1: Naming of the separate parts of the OMS

A concept evaluation was undertaken for all the system components and traits, such as material, fixtures and motor. In Iteration 4 all the general components needed in order to perform the critical functions were identified. For each component a list of traits was defined, which represent aspects of the detailed conceptual design that needed to be evaluated. E.g. for the critical function "rotate 360 degrees" a critical component is the motor. Critical traits to take into consideration when choosing a motor were power, regulation mechanism, wiring, weight and size. An evaluation will be undertaken for the following components and traits: motor, material, fixtures/bolts, data and power transmission, and bearing.

IV.3.1 Motion Transfer Selection

Table IV.3.1 shows the various forms of motion transfer from the motor to the system that were considered. The advantages (pros) and disadvantages (cons) of each type of solution are also listed in order to assist decision making. The decision fell on a peripheral slew bearing that will be mounted onto the perimeter of the OMS base, as this will simplify cable guidance, reduce need for extra stabilisation, as well as it is more likely than the other options to provide higher accuracy which is needed for the requirement of minimum azimuth velocity.

Motion Transfer Solutions		
Solution	**Pros:**	**Cons:**
Centered Slew bearing (internal)	• Low weight • Possible to choose gear ratio	• High weight • Loss of space for wires • Likely need for further stabilisation
Peripheral slew bearing (internal)	• Higher gear ratio • High no. of teeth • Easy to mount • Simplifies wire guidance • Easy to disassemble for service/repair • No need for further bearing	• Large size • High cost
External cogwheel and motor	• More internal space	• Safety • Requires more external space • Risk of interference with RWS
Chain-/beltdriven (external)	• More internal space	• Complicated offset adjustment • Safety • Requires more external space • Risk of interference with RWS

Table IV.3.1: Concept evaluation for transfer solutions

IV.3.2 Motor Selection

A decision was made that some kind of servo system would be suitable as the drive mechanism for the OMS. A servo system is a universal term for automated motion control systems [23], which has the ability to accurately control the position of the load by regulating the movement. They have high dynamic performance, and comes in power ranges from fractional kW up to well above 100 kW[23]. This proves that the choice of a servo system as drive mechanism for the OMS is good and reasonable. Servo systems are often categorised into three sections with regard to their nature of operation: pneumatic, hydraulic and electric servos [23].

Table IV.3.2 shows these three options and lists the advantages and disadvantages for each type of servo motor. From this, an electric motor was chosen. The decision was based on the facts that the electric motor has a high dynamic performance, the positioning and speed are easy to regulate, and the technology is widely used in similar applications.

Servo System Solution		
Solution	**Pros:**	**Cons:**
Hydraulic motor	• High force density • Instant power • High torque	• Difficult to accurately regulate speed • Risk of liquid leakage • Frequent maintenance • Risk of fire • Limited range of motion • Audible noise
Electric motor	• High dynamic performance • Large ranges of speeds possible • Numerous suppliers • Widely used technology • Easy positioning • Excellent availability of options for numerous traits	• High cost • More complex computerised control • Torque-heat generation dependency
Pneumatic motor	• Low cost • Use friendly • Low maintenance	• Difficult to accurately regulate speed • High audible noise • Arrangement of pressurised network • Poor efficiency

Table IV.3.2: Concept evaluation for motion servo systems

IV.3.2.1 Electric Motor Selection

As visible in figure 2.4 in the Project Plan where the scope of the project is specified, electric and electronic systems are beyond the defined scope, because all the members of the project team are mechanical engineering students. This was clarified with KPS at initiation of the project. However, numerous aspects of the design of the OMS were co-dependent on the motor that would drive the system. It was therefore deemed necessary to take the challenge and broaden the scope slightly to investigate electric motors and ensure that it would be possible for future project teams to find a motor that could be integrated into the system; both with regards to physical design and fulfillment of speed and acceleration requirements.

Following the decision to use an electric motor some specific characteristics that are important to the selection of a particular electric motor were identified. In use the system will be exposed to rapid accelerations in alternating directions with only short, or even no, periods of constant velocity in between. Rapid accelerations involve high and frequent torque development, while constant speed only requires comparably low torque. High precision and high torque development at low speed if also an important system requirement. An electric servomotor allows precise control of position, velocity and acceleration in closed-loop systems. The servomotor is coupled with an encoder that will provide feedback on position and speed. In the closed-loop feedback system the output is compared to the input control command and any required adjustments to output is read from the error signal.

The general methodology for selecting a motor from a systems perspective begins by determining the appropriate size of a directly coupled motor [25]. If the required torque, speed and load-to-motor inertia ratio advocates an unacceptably large motor, one should move forth to consider integrating a gear head. The process from there is iterative; trying to find the best combination for your system, while keeping in mind issues related to speed, torque and inertia.

The ratio between load inertia to motor inertia is important in systems where motion control and high dynamic performance are required [23]. Appropriate interplay between mechanical and electrical properties of the system is necessary to allow optimal electrical control of performance [25]. High inertia mismatch between the motor inertia and load inertia can cause significant mechanical resonance that will have a deteriorating effect on system performance. Servo systems can deliver high dynamic performance through electronic control and closed-loop feedback. The encoder will quantify the magnitude and frequency of the error that is introduced due to mechanical errors and external force. Based on this feedback the motor output is adjusted to optimise performance. Mechanical issues can affect this control if the inertia of the load is too high compared to the inertia of the motor. Too high a load can either cause the rotor to lag or introduce resonance; or even anti-resonance; that heavily changes the force applied by the motor. This mechanical resonance will degrade motion and limit the usable bandwidth that the system can operate at. An inertia ratio between 1:1 to 1:15 between motor and load is considered the "rule of thumb" to ensure optimal performance. A possible inertia mismatch can be addressed by increasing motor size, reducing the load inertia, increasing material stiffness or through gearing [25].

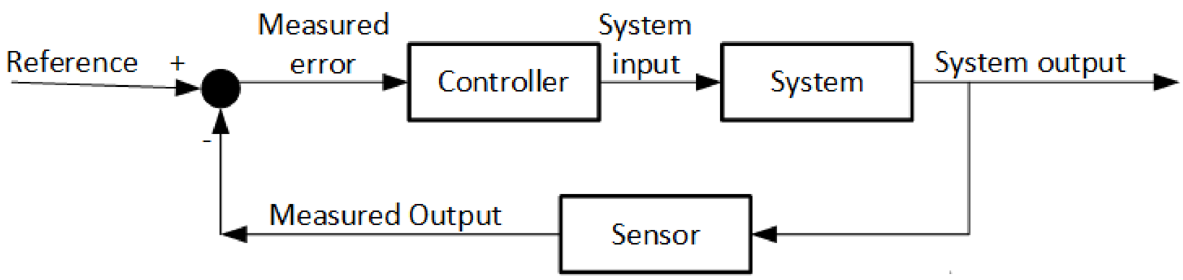


Figure IV.3.2: Closed Loop Feedback System for Improved System Performance

Two main categories of electric motors exist; namely AC and DC. DC motors are increasingly being replaced by AC motors in applications where high dynamic performance is needed, as great advantages in the technology of AC motors have taken place over the last century [23]. The power density and acceleration characteristics are superior in the AC motor compared to that of DC motors. Furthermore, DC motors have a more complex structure, lower efficiency, requires more regular maintenance and have a lower overloading capability due to the mechanical commutator [23]. Based on the conversations with university staff and the article by Puranen [23] a permanent magnet synchronous motor (PMSM) or an induction motor (IM) seemed most viable for use in the OMS. A table listing the advantages and disadvantages of the two types of motors was developed and is presented below.

Electric Motor Selection		
Solution	**Pros:**	**Cons:**
Permanent Magnet (PMSM)	• Smooth torque • High efficiency • Good heat dissipation • High current-to-torque ratio • Compact	• High cost • Risk of demagnetisation
Induction (asynchronous AC)	• High dynamic performance • Low cost • Simple construction	• Lower current-to-torque ratio • Low efficiency • Large size • Complicated control

Table IV.3.3: Electric motor selection

Due to the nature of the movement pattern of the system, as well as the space available for placement of a

Figure IV.3.3: PMSM torque-velocity curve

motor, it was decided to go forth with looking for a PMSM motor due to their higher current-to-torque ratio and smaller size compared to IM. The torque-velocity curve of a PMSM motor is shown in figure IV.3.3. The torque output remains constant at lower speeds up to a certain point where the torque output decreases by a nearly proportional rate to the increase in speed. The ability of holding a constant, high torque output at low speeds is an important characteristic with regards to the OMS, as the system is required to develop relatively high torque at low rotational speed down to 1 mrad/sec.

The torque and power required to drive the system at the desired maximum acceleration under the conditions imposed by the motion table was obtained through the development of the mathematical and engineering models presented in chapter IV.2. Calculations of the total moment of inertia (MOI) of the system were used to find the torque required to rotate the system at the desired maximum acceleration. The calculations of inertia involved both calculating the inertia of the different components of the system, as well as the parallel axis inertia of the offset plate and RWS set at the maximum offset distance. Details of the MOI calculations can be found in section IV.2.4. However, the system was also required to rotate the load while being tilted and translated in a combination of directions; all with their own acceleration; caused by the motion table. The additional torque required to overcome the gravitational forces that come into effect when rotating the system around inclined planes was found through complex vector analysis and development of relevant transfer functions, with the aids of MatLab, SimuLink and Geogebra. Details of the vector analysis can be found in subsection IV.2.5.1. Details of the mathematical modelling and simulations can be found in section IV.2.6.

Results of the mathematical models and simulations showed that a torque of 600 Nm and a power of around 2 kW would be required to drive the system at an output speed of 2.09 rad/sec and an acceleration of 6 rad/sec^2. It was deemed desirable to design for the *should* requirements, as this would give more freedom of choice to the stakeholders; being the KPS test division. With these data as a starting point motors in the 2kW range were identified from several suppliers. A power-balance equation was to evaluate if the motors' rated speed and torque will provide the needed output torque for the system at a given speed. The following data and formulas were used:

$Speed_{min}$: 0.001 rad/sec = 0.00955 RPM
$Speed_{max}$: 2.09 rad/sec = 20 RPM
$Torque \approx 600$ Nm
$Power \approx 2$ KW
$Acceleration : 1 - 6 rad/sec^2$
$Diameter_{oms}$: 325 mm

$Radius_{inner}$: 162.5 mm
$d_{drive} \approx \frac{1}{5} \cdot Radius_{inner}$
$Inertia_{system}$: 24 kg m^2
$Bearing-to-driveratio$: $\frac{N_{oms}}{N_{drive}} \approx 5$
$Power-balance-equation$: $\frac{T_0}{T_i} = \frac{V_i}{V_0}$
$Inertia-ratio$: $\frac{Inertia_{motor}}{Inertia_{load}}$

The resultant inertia ratios found with a selection of motors that were deemed suitable exceeded the recommended inertia ratio severely, if direct coupling was to be used. However, mechanical resonance caused by inertia mismatch appears to most commonly be an issue when rotating at a constant speed. The test profiles used in the KPS lab rarely involves constant velocity rotation, hence the inertia mismatch might not be a large challenge. However, due to the technical competence of the project team it was decided to safe-guard the design to these potential challenge and thus look for a means of reducing the inertia ratio. The addition of a gear head significantly reduces the load inertia, as seen from the motor shaft, by the gear ratio squared:

$$Inertia_{reflected} : \frac{Inertia_{load}}{(Gear\ ratio)^2}$$

A cogwheel is necessary in order to transfer power from the motor onto the teeth of the slew bearing. As a starting point it was approximated that the internal design and geometry of the power train disc and base would allow a cogwheel with a size that was one fifth of the internal diameter of the OMS. This equals a reduction ratio of 5 between the motor and the power train disc. The typical rated speed of the considered motors needed to be geared down by a ratio of around 20 in order to give an output speed on the power train disc that fulfilled the system requirements. These numbers were used as a starting point to assess to what extent the inertia mismatch could be reduced through gearing. As shown below, the reflected inertia would be reduced by a factor of 625:

$$Inertia_{reflected} : \frac{Inertia\,ratio}{(5+20)^2}$$

For the selection of motors that were deemed suitable it was found that the reduction ratio achieved by gearing would give a suitable inertia ratio. Arriving at this ratio made the project team confident that future project teams that are likely to be responsible for deciding on a motor will likely not meet challenges related to speed and inertia mismatch that are impossible to solve.

Following calculations on torque, speed and inertia ratio a few alternatives for motors from different suppliers were presented to KPS, with an accompanying discussion of the calculations and qualities of the motors. This was deemed necessary in order to ensure that the selection was valid as electrical components is slightly beyond the defined scope of the project. Two options were suggested: a motor from Kollmorgen coupled with a Neugart right angled gear head, or an actuator from Wittenstein. The characteristics of the two different motors are provided in table IV.3.4 below. The more compact design of the Wittenstein actuator allows for internal mounting within the OMS base, while also weighing less, and was thus selected for the current system.

Motor Supplier Selection		
Motor (gearhead)	Wittenstein TPM+ dynamic 025S	Kollmorgen AKM-53M (Neugart WPLE120-020)
Peak torque (*Nm*)**:**	239 (at output)	29.7 (416)
Gear ratio:	1 : 21	1:1 (1:16)
Inertia (kgm^2)	0.000216	0.0012 ($\approx$ 0.0002)
Weight (*kg*)	8.5	7.4 (12)
Max speed (*RPM*)	286	3000
Dimensions (*mm*)	Ø144,L 183	L250,h108,w108 (L277, h $\approx$ 156)
Price (€)	3900 net	1000 net (897 net)
Backlash	$\leq$ 3 arcmin	Unknown
Ambient temperature	0-40 degrees Celsius	5-40 degrees Celsius (-25-90 degrees Celsius)
Pros:	• Compact • Lightweight • Internal mounting possible • Fewer parts and interfaces	• Lower cost • Solution is more adaptable for future teams • 230 V power supply
Cons:	• High cost	• Partial external mounting • Height of gearhead increase OMS' total height

Table IV.3.4: Motor Supplier Selection

Figure IV.3.4 below shows the torque-velocity curve of the Wittenstein TPM 025S actuator. With the suggested actuator model a peak torque output of 239 Nm (T_{2B}) can be achieved from speeds ranging from 0 rpm up to 185 rpm (n_{2B}). This is sufficient since a pinion is going to be implemented, with a gear ratio of 5. The pinion will rotate at the given motor speed (100 RPM) and transfer the power to the power-train disc that will rotate at 20 RPM, through the bearing. This reduction in RPM is favorable since the output torque of the motor then only has to be 1/5 of the required torque on the power-train disc. This comes by the fact that the power is always constant, and one can "trade" RPM for torque.

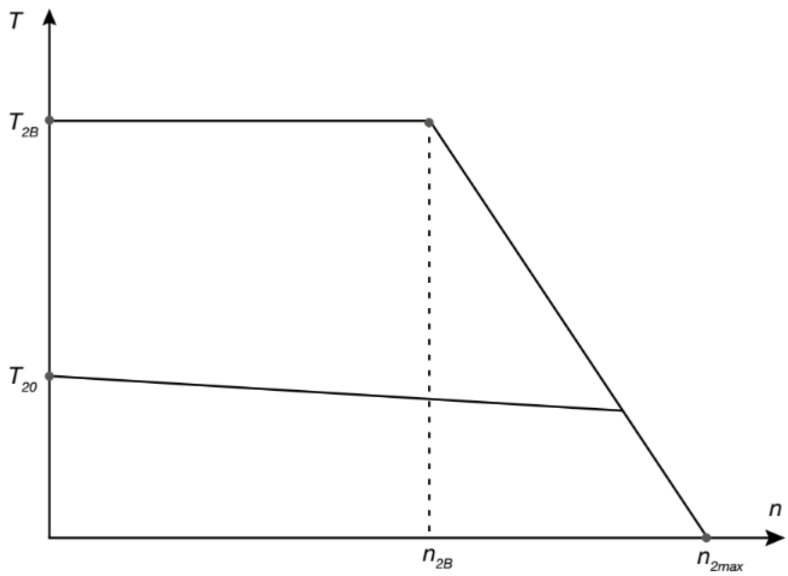


Figure IV.3.4: Torque-velocity curve of the Wittenstein TPM 025S actuator

IV.3.2.2 Motor Placement

The electromagnetic torque that is developed in an electric motor is proportional to current [23]. This is an important issue in electric motors as heat generation is proportional to the square of the current. Thus, for the system of interest where there is a requirement for frequent torque development thermal failure can be a risk. In the detailed conceptual design of the system placement of the motor in the inside of the system was considered an alternative, as well as the option of placing the motor on the outside. In short, internal mounting would make the system more compact and take up less space on the surrounding surface of the motion table. However, risk of overheating would be much higher and a ventilation mechanism either in the form of a fan or perforated bottom discus would likely be necessary. Access to the motor for service would also involve detachment of the OMS power train disc. External mounting allows easy access to the motor and ventilation would be ensured through normal monitoring of the surrounding temperature. An angled gear head would be required; a solution which introduces slightly more complexity due to calculations that will have to be performed in order to dimension and design these parts in accordance to the load situation. However, it was deemed most viable to place the motor outside the system for numerous reasons; limited internal OMS space made internal mounting challenging, particularly if room for future adaptations was to be left available; external space on motion table was available, ventilation and prevention of overheating was more safeguarded with external mounting, and service, maintenance and exchange to other motors in the systems life-cycle would be easier.

IV.3.2.3 Implication of Design Optimisation for Motor Selection

Calculations undertaken for the selection of an electric motor were performed before the design optimisation and FEA analysis commenced. This is because the choice of motor and gear head could have great implications for the design. When all components had been chosen based on calculations and subsequently integrated into the design, the final design emerged and analysis of the assembly as an entirety commenced. Through the detailed design development phase it emerged as necessary to change the rotation and fixture region for the offset disc in order to avoid structural weakness and interference with the RWS attachment region. The solution to this was to make the offset disc longer, giving a maximum offset of 40 cm. An increase in offset distance affects the parallel axis inertia, as well as the additional torque required to overcome the gravitational forces that come into effect when rotating the system around inclined planes. Also, the optimisation and analysis phase revealed that changes to the offset plate had to be done in order to fulfil the requirement pertaining to resonance frequency (SRQ015). The total system inertia increased from 24 kg m^2 to 42 kg m^2, the additional torque increased from 400 Nm to 520 Nm. Lastly, after much effort, a more accurate value for the friction torque of the bearing was obtained. The input friction torque to the calculations then increased from 40 Nm to 50 Nm. In total, the required torque and power after design optimisation and analysis had been undertaken was 827 Nm. The MatLab script with the changed input is shown in Appendix H in the "Optimised Inertia" script.

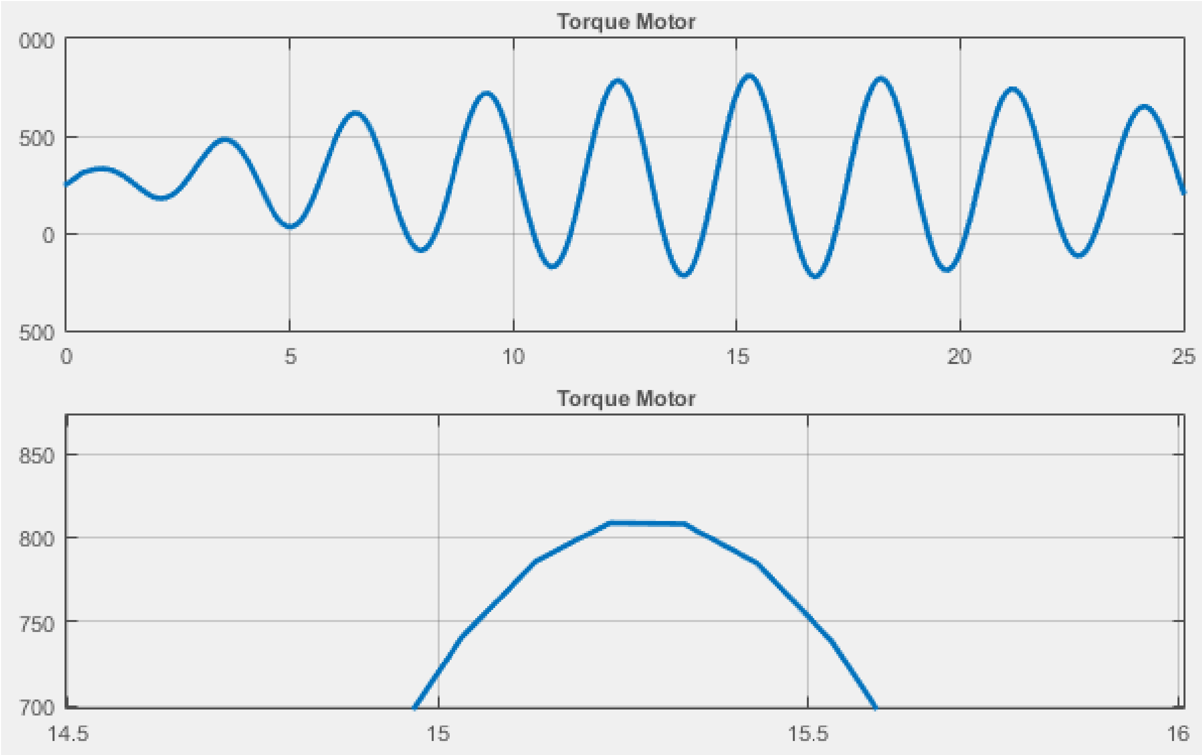


Figure IV.3.5: Torque curve from Simulink model

An analysis with the new inertia and offset values was done using the Simulink model. The Simulink model is described in section IV.2.6.2. The model accelerated (6 rad/s^2) the RWS to a constant velocity of 120 deg/s. The motion table oscillated between -0.4 and 0.4 rad in pitch and roll. Motor torque graph from the simulation can be found in figure IV.3.5. The maximum motor torque identified by the Simulink model was slightly above 800 Nm. The complete Simulink model is included in the project USB drive.

Enough safety margin was taken when choosing an electric motor that the required torque output after optimisation could still be delivered with the Wittenstein actuator. Furthermore, the final design with the motor placed outside the system with an adaptor to the gear box, left great flexibility for choosing a different motor if this would have been found necessary. The adaptor insert could have easily been adjusted slightly to fit in a more powerful motor.

IV.3.3 Bearing Selection

The whole basis of the product's application is rotation. Providing rotation of the RWS at different offsets is the key element in the design and for test application. The purpose of the final product is to simulate rotation and also elevation as the vehicle is moving in an uneven terrain. A solution that allows free rotation bidirectionally and that can withstand substantial loading is required. Thus, a bearing was a natural choice. A bearing is a mechanical component that constraints relative motion between two parts to allow only the desired rotation. A bearing significantly reduces friction between the two moving parts, which is desirable in the current system in order to reduce the torque and thus energy required to rotate the system.

IV.3.3.1 Comparison between alternatives

Numerous different types of bearings exist and choosing the right one must take into account the load that is to be supported, direction of loading and load pattern, space, weight and cost. In the current application the system also needed to be fitted with a cogwheel that would transmit rotation of the motor axle into rotary motion of the OMS. As shown in table IV.3.1 an assessment of the best solution for a bearing and cogwheel solution was undertaken. It was decided that a peripheral slew bearing was the best option, as it would provide a solution for both bearing and cogwheel in one application. This simplifies design and service, and a higher gear ratio and number of teeth is possible. The latter is important due to the high precision of motion required by the stakeholders (down to 1 mrad/sec).

The slew bearing provides free azimuth movement, while also supporting the upper structure of the OMS that holds the 250 kg RWS. The principle behind the bearing is based on one part being fixed to the part that is required to rotate, while the other part is mounted on to a stationary plate. Normally, bolts are used as fixtures, as maintenance such as lubrication might be regularly required, which would not be possible if welding is used. Between the stationary part and the moving part of the bearing there are small spherically shaped balls that allow for one part to be moving and one part to be stationary, and thus providing the desired rotation. The movement in azimuth direction is based on a motor that drives a gear which in this case is on the inside of the of the slew bearing, as seen in case b in figure IV.3.6.

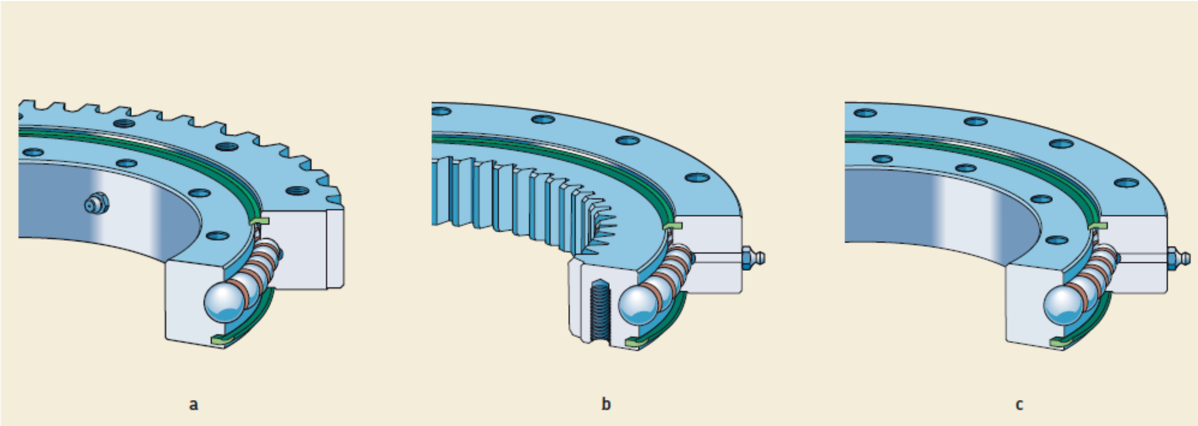


Figure IV.3.6: The principle of a slew bearing[24]

IV.3.3.2 Selection of a slew bearing

When it comes to the selection of a slew bearing no clearly defined approach exists due to involvement of several factors. However, some general guidelines are formulated that aid in the process of selecting the appropriate bearing [26]. The factors to take into consideration are:

- Accuracy of motion
- Direction and magnitude of load
- Operating temperature
- Vibration
- Operating speed
- Sealing

In the case of the OMS, accurate positioning is key since the system shall be able to rotate the OMS down to a speed of 1 mrad/sec (STRQ002). This requirement places particular demands on the accuracy of the system's rotation in azimuth direction. This is also a requirement that is considered to be a "shall" requirement, meaning that it must be fulfilled in order for the system to function properly.

The magnitude and direction of the loads are normally used to determine the size of the bearing [26]. However, the size is not only dictated by this factor alone, but also decided from the other interacting geometry. In the case of the current application the decision process involved both load analysis and consideration of existing, or desired, surrounding geometry. The OMS has two specific stakeholder requirements in relation to magnitude of load; STRQ023 states that *the system shall be able to withstand, without damage to itself or interfaced units, a 250kg RWS rotating at speeds exceeding 90º/second and suddenly stopping*. STRQ024 states that *the system shall be able to withstand, without damage to itself or interfaced units, a sudden and complete stop of both itself and the RWS at all supported speeds* . The magnitude of the loads will also largely influence the dimensions of the bearing and what material the bearing can be made from. These factors directly affects the weight of the bearing.

Permitted operating temperature is not too relevant in the case of the OMS. It is a given that this system is to operate in room tempered environment. System requirement SRQ014 states that *the system shall be operable in a temperature range from 0-40 degrees Celsius*. Given this requirement, the environmental operating temperature will not reach any wear near critical temperatures for bearings. The permissible operating temperature of a common type slew bearing typically ranges from –25 to +70 °C [26], which is more than enough for a system operating in a lab at room temperature. So for the OMS this is not a deciding factor.

Vibration is an important factor that has to be taken in to a count. The OMS also have a specific requirement in relation to the vibration in the system; to consider a roof stiffness of 30 HZ (STRQ018). Vibration typically comes from variable loads, and this can interfere with the natural frequency of the material and could in a worst case scenario compromise the device's ability to maintain accuracy and withstand the external loads that it is subjected to. Vibration can occur from bearings due to imperfections in the manufacturing process or defects on the rolling surface.

When it comes to the operating speed, the issue is not the speed itself, but rather the friction that is created during rotation. The OMS has two requirements relating to speed. The first one states a required azimuth speed of 60 degrees/sec (STRQ003), which is a *shall* requirement that thus has to be fulfilled. The second requirement is a *should* requirement; meaning that it is desirable; and it states that the azimuth speed should be 120 degrees/sec (STRQ012). This will influence the friction in the bearing, which again will manifest itself in other calculations; for instance when calculating the required motor power. So the operational speed is a central factor both in terms of the power calculation, but also in relation to lubricant and heat exchange [26].

Sealing of the bearing is to some degree always relevant, but it really becomes more of an issue when the bearing is subjected to extreme environments. The purpose of the seal is to prevent moisture from getting in, and to prevent contamination of the lubricant [26]. Like stated earlier the OMS will not be subjected to extreme conditions, it will only be operating in a lab, and a standard seal will be sufficient, given its environment. In other words this has not been the key focus, when deciding a slew bearing.

Figure IV.3.7 shows the principle behind a basic sealing for a slew bearing.

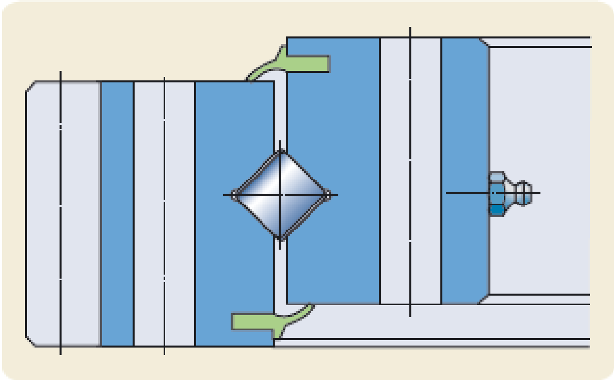


Figure IV.3.7: The sealing of a slew bearing[24]

IV.3.3.3 The process of finding a bearing

When it comes to the selection process of a specific bearing it was a process involving several different and challenging aspects. The decision of a specific bearing was done on the basis of a number of requirements. These requirements involve mostly stakeholder requirements, but also some limitations in terms of free space. The decision of a specific bearing will greatly influence the progress of further design development. The properties of the bearing will manifest itself in the specific pinion that is used. Also, the motor and gears will depend on which type of slewing bearing that is implemented. In short, everything that has to do with the rotation of the upper part of the system is in some way intangled with the slewing bearing. That is why it is important to have a well documented and well thought through solution to the bearing problem.

The first stage of the bearing selection was manifested in a mathematical model. The purpose of this model is to predict how the system is going to act in different situations, and from there get some numerical values of the torque needed, the axial and radial loads and moment of inertia. In short, the different forces acting on the OMS system. The forces that was relevant to the slew bearing was isolated and expedient calculations were undertaken, which are presented in the "calculations" subsection of this chapter. On the basis of the results from these calculations a proposal for a bearing was made. However, the specific values needed for some of the detailed bearing calculations could not be obtained from the supplier, because this information was considered confidential. Thus, the team had to expertise from professionals at SKF and Rollix to get an assessment of the feasibility of various models of the slew bearings for our application. This was however considered as a wise choice, given that this is such a critical component.

Two suppliers; SKF and Rollix; were contacted in order to get several approaches to the problem, and to ultimately get more alternatives for models with regards to weight and dimensions, and to request an estimation of price. Offers from both suppliers were given, after providing information about the loads and load situation. It is important to emphasise that the information exported to the external supplier was on a need to know basis. This is an important detail, given the confidential nature of our contracting entity.

The options were compared on the basis of price, functionality and weight. The functionality requirement is a requirement that had to be safeguarded at all costs. The functionality requirement is not a formal requirement stated by the stakeholders, but a design requirement stating that the bearing is operable in a worst case scenario IV.2.7. The fact that this bearing can withstand the forces that will act on the system in a worst case scenario, is the main priority. Stakeholder requirements STRQ025 and STRQ026 pertains to weight and ease of assembly, which are related to each other. Thus, the weight of the different bearing models were an important evaluation factor. Lastly, price estimates were obtained. However, this factor was less of a limitations, because slew bearings are not that expensive relative to the customers expectations.

The first offer was from Rollix, and included a 30 kg slew bearing, that they deemed appropriate for application in the worst case scenario. However, this would make the total weight of the system to high, which forced the team to put considerable efforts into finding a lighter option. Rollix then suggested a light series version, which had a mass of about 20 kg, but they where not able to guarantee that the bearing would hold up under the given conditions, and some lack in stability would not be unlikely. Based on this information the light series version was considered an unsatisfactory option. SKF suggested a bearing that had a mass of about 9kg, making it the lightest alternative. Furthermore, this specific bearing had been used in similar applications before, and SKF could assure that this bearing would hold up under the worst case scenario IV.2.7. Both weight and accuracy will be greatly improved, but at the expense of price. However like discussed earlier, functionality and weight has a higher priority then price, and therefore the alternative from SKF is the most attractive.

IV.3.3.4 Operational life of the bearing

Integration and functioning of the bearing during it's operational life also requires considerable consideration, as bearing failure; e.g. in the form of loosening; can damage the supporting equipment and the lab environment, and expose the people who operate the equipment to danger [29]. Thus, the mounting, supporting structure and installation of the bearing needs to be thoroughly analysed, e.g. with the help of SolidWorks. The following aspects presents the factors that has been considered and analysed in order to reduce the risks associated with implementation of the bearing:

- Design factors for slew bearings: technical product catalogues contain most of the required information needed to select a slew bearing, but each application has it's own need and specification which require integration of specific design factors (numbers) in the calculations. Slew bearing suppliers SKF and Rollix were contacted to attain these design factors and the load situation was discussed.
- Strength of bolt fixtures: the bolts that are recommended by the manufacture needs to be check with regards to ability to withstand the given load situation for any application. In the case of the current project hand calculation and Finite Element Method (FEM) will be used to verify that the recommended bolts can withstand the loads that they are exposed to.
- Uniformity of bolt hole pattern: the bolt holes should be evenly distributed along the perimeter of the support surface, not just in the maximum load area. This is because substantial forces exist even in the unloaded sections of the bearing. Uniformity of bolt pattern will distribute the load better in the bearing, the bolts and the underlying structure.
- Sufficient bolt preload: bolts need to be tensioned with a sufficiently high preload torque in order to withstand the occuring loads, regardless of the strength and dimensions of the bolts themselves. The bolts used in the bearing application will be analysed through handwritten calculations and verification of the assembly through FEM analysis in SolidWorks. .

IV.3.3.5 Force analysis for bearing

The calculations performed for the bearing are somewhat simplified. The calculations needed to select a bearing from a supplier basically comes down to the axial and radial forces acting on the member.The calculations of the radial and axial loads where done on the basis of the free body diagram, portrayed in the analysis chapter IV.2.3.

This load situation combined with the following physical properties gave the axial and radial loads:

- Mass(RWS)= 250kg
- Mass(OMS)= 50kg
- Offset= (0.00m-0.04m)
- Angular velocity= 120 deg/sec = 2.1 rad/sec
- Angular acceleration= 6rad/sec^2

The axial and radial loads are presented table IV.3.5.

	Static loads		Dynamic loads	
Type of load	**Nominal**	**Maximum**	**Nominal**	**Maximum**
Axial (KN)	2.65	2.8	2.4	2.57
Radial (KN)	0	0	1.12	1.2
Moment (KNm)	0.74	-	0.67	-

Table IV.3.5: Axial and radial loads.

These calculations where then redirected to the supplier who proceeded to propose a bearing that could:

- Withstand the load given in the FBD IV.2.3.
- Contribute to as little weight increase as possible
- Maintain sufficient accuracy in accordance with (REQid:STRQ002).

IV.3.3.6 Final decision

The final decision on which bearing was implemented had its origin in the calculation of the axial and radial loads. However most of the grounds for the final decision is based on expertise from the supplier, which happened to become SKF.

SKF is a recognized supplier of bearings, and claims to be world leading in rotational equipment. SKF is a known supplier for our contracting entity which makes them an acquaintance. SKF provided both the best alternative, and also seems to be the best choice of supplier, both in terms of offer and professionalism.

It can be concluded that the calculations provided by the group where expedient to isolate which bearing was suitable, but since deciding bearings for given applications is a craft in itself and the engineers at SKF specialise in just this field it is deemed acceptable to base the choice of bearing on the expertise of this firm. The choice of bearing is thereby based on consultation with the supplier. Furthermore the details surrounding the bearing is of confidential nature. These "details" include certain factors like friction torque, damping factor and load capacity .This confidentiality stems from the bearings prior application, which is allegedly associated with military applications.

A proposed bearing was then presented by SKF, and documentation containing dimensions was sent to the group. All dimensions of the bearing are given in the appendix provided by SKF J.1. The model is an official unit from the SKF‘s production line, and it has the following serial number: RKS 95223.

Specifications for the final bearing in Appendix J.1 is shown in table IV.3.6. The values for friction moment at the various temperatures were not given by SKF, as this was considered confidential information. The values were extrapolated from information about the slew bearing that is in use at KPS.

Specifications	Value
Mass	9 kg
Exterior diameter	429 mm
Inner diameter	350 mm
Reference diameter	316.5 mm
Number of teeth	211
Pressure angle	20 °
Price	25 000 NOK
Material	Aluminum 7075-T6 (Ref: tableIV.3.7)
Specific model	RKS 95223
Friction moment (0 - 20 degrees Celsius)	47 - 101 Nm

Table IV.3.6: Specification for RKS 95223

IV.3.4 Pinion Selection

When selecting a pinion there are several aspects that needs to be considered. This includes the gear mesh between the pinion and the gear wheel, the torque transmitted through it and the material of the pinion. In the case of the OMS the gear mesh is the interaction between the slew bearing and the pinion. The geometry for the bearing is already given and the relationship between the bearing and pinion is proportional according to the ratio. With this said, calculating the dimensions of the pinion is not difficult. The efficiency in the power transmission (i.e. the motor, to the angled gear, to the pinion) is 98 % [38], but since the project team want to stay conservative and have more margin related to the calculations, the torque applied to the pinion will be the same as the output torque from the motor, i.e η =1. This will be used to calculate the stresses on the gear teeth and conclusively be the foundation for the material choice.

IV.3.4.1 Dimensioning

STRQ003 states that *The system shall have a maximum azimuth speed of at least 60 degrees/sec*. This is a shall requirement meaning that the OMS has to perform this as a minimum. However, the project team has decided to proceed the design with focus on STRQ012 which is the should requirement stated below.

STRQ012 states that *The system should have an azimuth speed of at least 120 degrees/sec*.
This can be converted into RPM using equation E.3.1:

$$RPM = \frac{120 \cdot 60}{360} = \mathbf{20}$$

$$RPM = (\frac{\cancel{degrees}}{\cancel{sec}})(\frac{60\cancel{sec}}{min})(\frac{\cancel{2\pi}}{360\,\cancel{degrees}})(\frac{1\;rev}{\cancel{2\pi}\;rad}) \tag{E.3.1}$$

As stated in subsection IV.3.3.6, the module (m) of the slewing bearing is 1,5 mm and the pressure angle (α) is 20°. In order to achieve a good gear mesh between the bearing and the pinion, these values have to match [11], i.e. $m_{Pinion} = 1,5\,mm$ and $\alpha_{Pinion} = 20°$

The gear ratio, i, which describes the ratio between the rotational speed of the bearing and the pinion, can be found by either using equation E.3.2 or equation E.3.3 [11].

As stated in table IV.3.4, the maximum rotational speed of the actuator is 286 RPM. However, this type of actuator is equipped with a regulation system that is able to regulate the rotational speed. Since the output torque stays constant from a given value of RPM and down, as illustrated in figure IV.3.3, a decision was made that the optimal rotational speed of the actuator was to be 100 RPM. This would generate a gear ratio between the pinion connected to the 1:1 bevel gearbox and the slew bearing of 5, as desired in subsection IV.3.2.1.

Since the rotational speeds for both the bearing and the pinion are known, the obvious approach is to use E.3.2 to find the gear ratio:

$$i = \frac{100}{20} = \mathbf{5}$$

$$i = \frac{n_1}{n_2} \tag{E.3.2}$$

The selected bearing, RKS 95223, has a reference diameter of 316.5 mm, which is equal to a radius of 158.25 mm and it is equipped with 211 teeth. Equation E.3.3 is used to calculate the number of teeth of the pinion [11], Z_1:

$$Z_1 = \frac{211}{5} = \mathbf{42.2}$$

$$i = \frac{Z_2}{Z_1} \qquad \equiv \qquad Z_1 = \frac{Z_2}{i} \tag{E.3.3}$$

Equation E.3.4 is used to find the radius of the pinion. Since the rotational speeds and the radius of the bearing are know, the numerical values of these are inserted into equation E.3.4 to find the radius of the pinion:

$$r_1 = \frac{158.25\,mm \cdot 20\,min^{-1}}{100\,min^{-1}} = \mathbf{31.65\,mm}$$

$$r_1 \cdot n_1 = r_2 \cdot n_2 \qquad \equiv \qquad r_1 = \frac{r_2 \cdot n_2}{n_1} \tag{E.3.4}$$

The calculations conducted in this section states that a suitable pinion for this application has the following specifications:

Reference diameter, d = 63 mm

Number of teeth, Z_1 = 42

Modul, m = 1.5

Pressure angle, α = 20°

IV.3.4.2 Material Selection for the Pinion

The material selection process started with an analyses of the teeth force on the pinion.

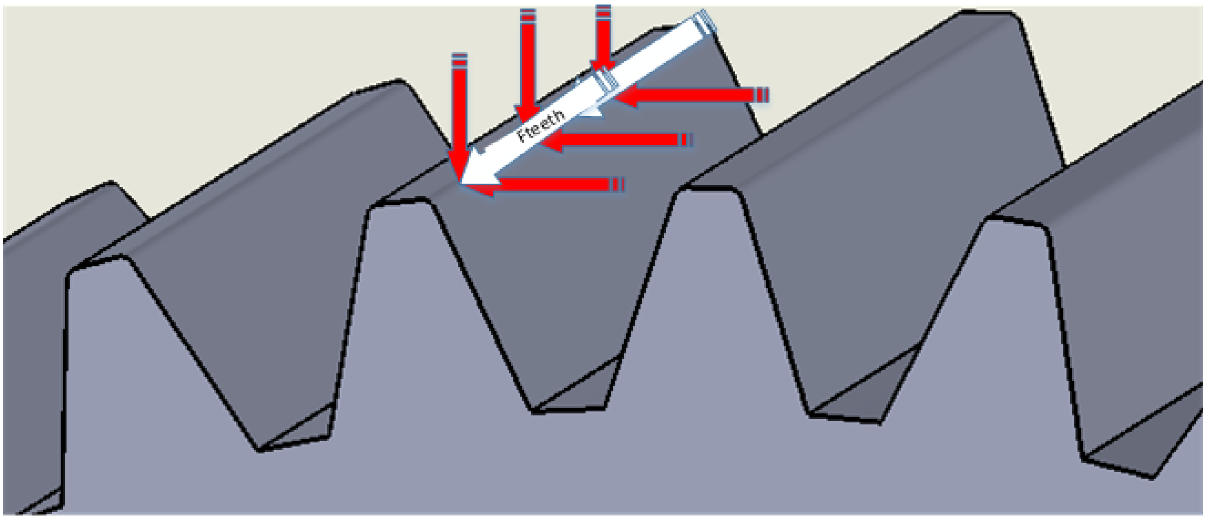


Figure IV.3.8: Teeth force

To acquire the teeth force equation E.3.5 is applied [11]. The force derives from the torque applied to the pinion from the motor, this force is then calculated on one teeth. This acts as a safety factor for the pinion as there will always be at least two teeth in contact with the bearing.

$$F_{teeth} = \frac{2 \cdot 166\, N_m}{42 \cdot 1{,}5\, mm \cdot cos\, 20°} = \mathbf{5608\ \ N}$$

$$F_{teeth} = \frac{2 \cdot M_v}{Z_2 \cdot m \cdot cos\, \alpha} \tag{E.3.5}$$

M_v = Motor torque $\qquad$ m = module

Z_1 = Number of teeth, pinion $\qquad$ α = pressure angle

When the teeth force is known, the bending stress on the teeth can be calculated by using the Lewis formula [32], E.3.6.

$$\sigma_{bending} = \frac{5608\, N}{25\, mm \cdot 1.5\, mm \cdot 0.393} = \mathbf{380.53\ \ N/mm^2}$$

$$\sigma_{bending} = \frac{F_1}{b_a \cdot m \cdot Y} \tag{E.3.6}$$

Y = Lewis form factor, collected from *Table of lewis form factors for different tooth forms and pressure angles* [32].
b_a = Face width
m = module

With the bending stress calculated from the Lewis equation the minimal yield strength of the pinion material is identified. In all gear solutions there are some degree of backlash that results in impact stresses. To make sure the material chosen for the pinion can withstand this impact, a velocity factor is added as shown in equation E.3.9.

$$\omega = \frac{2\pi \cdot 100}{60} = \mathbf{10.47\ rad/s}$$

$$\omega = \frac{2\pi n}{60} \tag{E.3.7}$$

$$V = 0.0633\,m \cdot \frac{10.47\,rad/s}{2} = \mathbf{0.3314\ \ m/s}$$

$$V = d \cdot \frac{\omega}{2} \tag{E.3.8}$$

$$K_v = \frac{6.1 + 0.3314}{6.1} = \mathbf{1.05}$$

The velocity factor for gears is calculated from the method of manufacturing [32] and since the pinion for the OMS will be cut or milled the E.3.9 equation will be used.

$$K_v = \frac{6.1 + V}{6.1} \tag{E.3.9}$$

With the velocity factor identified the impact stress is easily determined by using the Barth equation E.3.10 [32].

$$\sigma_{impact} = 1.05 \cdot 380.53 = \mathbf{399.56\ \ N/mm^2}$$

$$\sigma_{impact} = K_v \cdot \sigma_{bending} \tag{E.3.10}$$

The minimum required yield strength of the material is determined by using the safety factor equation E.3.11:

$$\text{Yield strength} \geq 399.56\, N/mm^2 \cdot 2 \quad \equiv \quad \text{Yield strength} \geq \mathbf{799.12}\, N/mm^2$$

$$\text{Yield strength} \geq \sigma_{impact} \cdot N \tag{E.3.11}$$

With the yield strength calculated, a material can be chosen. To find a standard pinion with material strong enough to this relatively small diameter and module shown to be difficult. The standard options from various pinion suppliers did not meet the material requirements in terms of hardness and yield strength. Therefore, the project team has, in correspondence with KPS, decided to design and manufacture a suitable pinion for this application.

An important aspect to keep in mind at this point is the machinability of the pinion. Since there will only be made one pinion, it will be cut or milled in a CNC machine [11]. This implies that the material should be soft enough to be machined without using too expensive tools. With this said the machinability of the material should not affect the strength of the pinion. A high alloy special steel is therefore an applicable option.

Two suitable alternatives were found and evaluated:

- **17-7 PH Stainless steel**
  This alloy provides high strength, hardness, has good fatigue properties and formability. Application varies from aerospace application, because of it's good corrosion resistance, to flat springs operating at 310°.
  Material properties to consider:
  - Yield strength = 1310 MPa
  - Tensile strength = 1517 MPa
  - Elastic modulus = 200 GPa

- **Steel SS-EN 10083**

  This alloy has a high toughness, great ability to obtain high strengths and a very good fatigue resistance. It is used in several applications, such as military aircraft, automotive systems and tools. Material properties to consider:

  - Yield strength = 800 MPa
  - Tensile strength = 1280 MPa
  - Elastic modulus = 210 GPa

Based on the calculations and the information given above, Steel SS-EN 10083 was chosen for the pinion. The decision was based on the safety factor for the system. As calculated using equation E.3.11 , to achieve a factor of safety equal to 2, the yield strength of the material has to be ≈ 800 MPa. Steel SS-EN 10083 has a yield strength of 800 MPa. This is to be considered sufficient.

Table IV.3.7 presents more detailed properties of Steel SS-EN 10083.

Material Selection		
Property	**Pinion** **Steel SS-EN 10083**	**Slew Bearing** **Aluminium 7075-T6**
Density (1000 Kg/m^3)	7.8	2.8
Elastic modulus (GPa)	210	72
Yield Strength (MPa)	800	510
Tensile Strength (MPa)	1280	580
Poisson's ratio,v	0.32	0.33
Hardness (HB)	250	150
Machinability	Medium	Easy
Galvanic corrosion risk	Lower (Cathodic)	High (Anodic)
Life cycle rating	• 80-90 % recycling ratio • Long life span	• 100 % recyclable - without quality loss • Excellent life span
Corrosion resistance	High	Excellent

Table IV.3.7: Material properties for pinion and bearing [33], [34], [35].

A compressive stress calculation was conducted to make sure that the surface durability of the pinion and the bearing endure the stresses.

In order to conduct this calculation, the Elastic constant, Z_E has to be identified. This can be done by using equation E.3.12 [32]. The factors needed for the equation can be found in table IV.3.7.

$$Z_E = \sqrt{\left[\frac{1}{\pi(\frac{1-0.32^2}{205000} + \frac{1-0.33^2}{72000})}\right]} = \mathbf{137.8}\sqrt{N/mm^2}$$

$$Z_E = \sqrt{\left[\frac{1}{\pi(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2})}\right]} \quad \text{(E.3.12)}$$

With the elastic constant identified, the compressive stress can be calculated using equation E.3.13 [32].

Velocity factor, K_v = 1,05

Teeth face, W = 25 mm

Teeth force, F_t = 5608 N

Pressure angle, α = 20°

$$\sigma_c = -137.8\sqrt{N/mm^2} \cdot \sqrt{\left[\frac{1.05 \cdot 5608\,N}{25\,mm \cdot cos\,20^\circ}(\frac{1}{31.5\,mm} + \frac{1}{158.25\,mm})\right]} = \mathbf{-425.65}\,N/mm^2$$

$$\sigma_c = -Z_E\sqrt{\left[\frac{K_v \cdot F_t}{W \cdot cos\,\alpha}(\frac{1}{r_1} + \frac{1}{r_2})\right]} \quad \text{(E.3.13)}$$

The compressive stress, σ_c, is not permitted to exceed the allowable endurance stress S_e [32], the allowable endurance stress for Steel SS-EN 10083 is 1180 N/mm^2 [40]. With a calculated compressive stress value of 425.65 N/mm^2, the factor of safety in regards to surface durability is 2.77. This is well above the set margin of 2, and it is beneficial to have a high factor of safety since the surface of the pinion is exposed to rapid torque- and rotational changes.

IV.3.4.3 Backlash

To account for the accuracy of the system, backlash must be calculated. Backlash is "the amount by which a tooth space exceeds the thickness of a gear tooth engaged in mesh" [41]. This clearance between the teeth is what causes the inaccuracies.

Circumferential backlash [41]:

Is the length of the arc on the reference diameter. This length is the distance the pinion is rotated until it makes contact with the bearing, while the bearing is held stationary.

$$j_t = \frac{0.150\,mm}{cos\,20° \cdot cos\,0°} = \mathbf{0.159}\,mm$$

$$j_t = \frac{j_n}{cos\,\alpha \cdot cos\,\beta} \tag{E.3.14}$$

Normal backlash, j_n = 0,150mm, collected from "Table 6.2 Spur and Helical Gear Mesh" [41]

Pressure angle, α = 20°

Spiral angle, β = 0°

Angular backlash [41]:

Is the angle a teeth of the pinion is allowed to move inbetween two teeth of the bearing, while the bearing is held stationary.

$$j_\theta = \frac{360° \cdot 0.159\,mm}{\pi \cdot 63\,mm} = \mathbf{0.29}°\,(17.4\,arcmin)$$

$$j_\theta = \frac{360° \cdot j_t}{\pi \cdot d} \tag{E.3.15}$$

Radial backlash [41]:

Is the displacement the pinion has to move in towards the bearing, when the center distances of the bearing and pinion is aligned, for the teeth to make contact.

$$j_r = \frac{0.150\,mm}{2 \cdot sin\,20°} = \mathbf{0.219}\,mm$$

$$j_r = \frac{j_n}{2 \cdot sin\,\alpha} \tag{E.3.16}$$

To accurately determine the accuracy of the system the backlash of the angled gear must be calculated. Because ultimately the backlash of the motor, angled gear and pinion working together will give the biggest error in accuracy. Therefor the final accuracy calculation will be determined in the angled gear chapter IV.3.5.

IV.3.5 Angled Gear

In order to reduce the height of the system a decision was made to have the motor mounted horizontally on the outside of the base. This solution required some kind of 90° angled gear in order to transfer the power from the motor to the vertically positioned pinion and bearing.

The ratio between the motor, pinion and bearing had been decided by calculations in an earlier stage. Due to this an angled gear with a ratio of 1:1 was considered to be the best choice, since it would not change anything in regards of rotational speed of the components.

As stated in table IV.3.4 the maximum output torque from the motor is 239 Nm. It is important that the angled gear can withstand and deliver the same amount of torque, in order to get the OMS to perform as desired. The need of an angled gear arise fairly late in the design process. Due to this fact a decision was made that the project team would not put all of the resources on allocating this issue. The key element here was to find an angled gear that could perform under the given scenarios.

After some research, the Power gear X90L was seen as an applicable option. As stated in table IV.3.8, the maximum output torque of the Power gear X90L is 203 Nm, which is sufficient in terms of the torque comming from the motor to reach the desired rotational speed and acceleration of the OMS.

The Power gear X90L is a suitable choice since it has a ratio of 1:1, can handle the torque from the motor, compact design and is essentially maintenance-free while subjected to normal operation conditions [53].

Specifications for the selected angled gear, The Power Gear X090L from MS-Graessner GmbH & Co. KG are presented in table IV.3.8.

Specification	Value
Nominal output torque	135 Nm
Maximum output acceleration torque	203 Nm
Output backlash	$\leq$ 14 arcmin
Efficiency at max load	> 98 %
Ratio	1:1
Weight	8.5 kg

Table IV.3.8: Specifications of Power Gear X90L [53].

Figure IV.3.9: The X-version angled gear with configuration L [54]

IV.3.5.1 Connections to Other Components

The Drive shaft and Pinion will be mounted to the angled gear using press fits. This is a well known fitting type which is consider to be the standard in applications like this [11]. As seen on the 2d drawings in the Production Manual, the shafts have the tolerance k6, and the holes H7.

IV.3.5.2 Backlash

The maximum backlash in the angled gear is set to be 14 arcmin, since the supplier states that the total backlash is $\leq$ 14 arcmin [53]. As mention in subsection IV.3.4.3, the angular backlash between the pinion and the bearing is calculated to be 0.29°, or 17.4 arcmin. The motors backlash is set to be 3 arcmin, since the supplier states it to be $\leq$ 3 arcmin, as shown in table IV.3.4 in subsection IV.3.2.1.

When calculating the backlash for the whole system, some simplifications are done. All the components contributing to backlash are supposed to be positioned in its "worst" position, giving that the total backlash is as high as it theoretically can be. This makes it possible to add the backlashes for each component in order to get the total backlash.

$$\textbf{Total backlash}: 14\,arcmin + 17.4\,arcmin + 3\,arcmin = 34.4\,arcmin$$

IV.3.6 Slip Ring

A slip ring is an electromechanical device mounted on a rotating part that will allow transmission of power and electrical signals without the obstructing and twisting the wires. The signals from the input wires are transmitted through brushes on the stationary contacts to wires at the outlet of the slip ring. The application of brushes allows unlimited and unrestricted rotary motion of the system.

Various options for transmission of electrical signals in the system were evaluated through iterations 3 and 8. A Pugh matrix was developed in order to evaluate the different wire solutions. This Pugh matrix can be founded in fig 2.17 in iteration 3 in CAFCR+ document. It was decided that a slip ring was the most desired solution for wire management in the OMS, since it allows transmission of signals during free 360 degree rotation. This safeguards fulfilment of a stakeholder requirement that was listed as a *should* requirement. In iteration 8 the implications of integrating a slip ring with regards to the life cycle of the system was discussed. Slip ring can improve mechanical performance, simplify system operation and eliminate strain on the wires hanging from the movable joints; RWS for the OMS system.

The results of detailed design evaluations with accompanying Pugh matrices were presented to the supervisor at KPS. It appeared that it was possible that KPS already had a "spare" slip ring that could be used in the current project. This would significantly reduce the cost and supplier management, as well as simplifying maintenance and service as the employees at KPS already have knowledge and experience with that specific slip ring. Furthermore, from experience KPS already know that this slip ring would be suitable for the military applications that are simulated in the test lab. Compatibility with the RWS that is to be mounted onto the OMS is also assured. This made the selection of a specific model quite straight forward. The specifications of this slip ring are confidential, so no further details regarding the slip ring will be given in this document.

IV.3.7 Material Selection

The material selection process started with identification of constraints introduced by the requirement specification. This process takes multiple factors into account, such as material properties, cost, availability and machinability. Selecting materials in the context of product design is about minimising weight and cost while still meeting the requirements pertaining to performance. The most critical constraints related to material selection were as following:

1. STRQ023 states that *the system shall be able to withstand, without damage to itself or interfaced units, a 250kg RWS rotating at speeds exceeding 90°/second and suddenly stopping.* This requirement is a performance goal that the system must fulfill.
2. STRQ026 places weight constraints on the system. As the OMS shall be mountable by just one person, it is important that each part does not exceed the weight that one person is allowed to lift alone according to HSE regulations. The weight aspect has been a concern from KPS; however the lab is equipped with a crane that is easily and frequently used, which alleviates the emphasize of the weight requirement. Components shall also comply with KPS' supply chain as stated in STRQ019.
3. The material must tolerate all the forces and stresses applied from the motion table, the RWS and the rotation of the system as stated in STRQ020, STRQ022, SRQ037-SRQ054. An aspect of material selection that was not included in the stakeholder requirements from KPS was the price. Although it was not a written requirement, KPS firmly stated that the price should not be unnecessary high.

IV.3.7.1 Selection Process

Critical constraint item number 3 states that the selected material must be able to withstand the forces and stressed imposed by the load of the RWS combined with the motion of the motion table. Yield strength is the level at which the material starts to permanently deform [28]. Deformation of the material up to this level is elastic, so the material will return to its original geometry when the forces are alleviated. A material's yield strength is often considered more important than the tensile strength; the level at which the material tears; in design situations. Permanent deformation during the life cycle of the system is unwanted, so the selected material should have a yield strength that is significantly above the calculated experienced stresses [28].

Another important design factor to take into consideration with regards to material selection is corrosion. STRQ0017 states that *the system shall have a life span of 5 to 10 years*, which was further interpreted into a minimum life span of 5 years in SRQ036. Over time, a material or its properties deteriorate due to reactions with the surrounding environment [28]. Making a product that is insensitive to internal and external variations during its life cycle is essential for the design to be robust, as discussed in "Robustness of Concept Selection", subsection IV.1.2.3. The OMS is to operate in a relatively stable indoor environment; however, the risk of corrosion must still not be underestimated, as all environments can cause corrosion. A normal indoor climate is likely to corrode most steels, which will affect the serviceability and life span of the system. Stainless steel alloys was thus considered an option for the OMS. Stainless steels are alloys containing a minimum of 10.5 percent chromium that display passivity in oxidizing environments [28].

Galvanic corrosion may occur in areas with metallic contact and presence of an electrolytic bridge between different metals [28]. In this situation the least noble metal in the combination will become the anode and consequently corrode. The more noble metal will become the cathode and is protected against corrosion. In most combinations of metals, aluminium is usually the least noble and thus has a higher risk of being subject to galvanic corrosion. In the current design there is a hypothetical risk of galvanic corrosion in the interface between the offset disc (alloy steel) and the power train disc (aluminium). This risk can however be minimized by ensuring that the anode has a larger surface area than the cathode, which spread out of the flow of electrons over a larger area and consequently slows down the rate of the anode's corrosion [28]. In the current design the power train disc (the anode) has a much larger surface area than the offset disc (cathode), thus protecting the design against galvanic corrosion.

As mentioned in the identified constraints an important concern was the weight and geometry of the OMS. Materials of high density will significantly increase the weight of the system, which further impacts assembly, serviceability and transportation of the system. Furthermore, the motion characteristics of the motion table; velocity and acceleration; are compromised by high loads. Thus, it is desirable to keep the total weight of the systems placed upon the motion table as low as possible to not compromise the maximum speed and acceleration output. Thus, a somewhat lightweight material was deemed desirable.

Stainless steel and aluminium were both considered viable material options for the system, as they both hold high yield strength and high general corrosion resistance. The material properties of the two were then compared to each other based on the data presented in table IV.3.9 below.

Material Selection		
Property	**Stainless steel**	**Aluminium**
Density (1000 Kg/m^3)	7.75-8.1	2.6-2.8
Elastic modulus (GPa)	190-210	70-79
Yield Strength (MPa)	207-552	215-505
Tensile Strength (MPa)	515-827	230-570
Corrosion resistance	High	Excellent
Machinability	• Medium/Hard	• Easy • Low input energy
Galvanic corrosion risk	Lower (Cathodic)	High (Anodic)
Life cycle rating	• 80-90 % recycling ratio • Long life span	• 100 % recyclable - without quality loss • Excellent life span

Table IV.3.9: Properties of Eligible Materials [30], [31]

As visible through table IV.3.9 aluminium alloy can have roughly the same properties as a stainless steel alloys. Aluminium has high yield strength as well as higher machinability than stainless steel, which is an important factor for the manufacturing of the system, especially with regards to cost. Maybe most importantly; aluminium has a density that is 2-3 times lower than stainless steel, which would mean significant weight savings. Based on these characteristics it was decided that aluminium would be the most suitable material for this application.

For high stress applications, e.g. cranes, type 6082-t6 aluminium is typically applied. The aluminium alloy has high strength with excellent corrosion resistance. It is a commercial alloy that is easily accessible and has high machinability.

Material Property	Value
Density	2.70 g/cm^3
Modulus of Elasticity	70 GPa
Tensile Strength	$\approx$ 300 MPa
Yield Strength	240 MPa

Table IV.3.10: Properties of Aluminium 6082-t6

IV.3.8 Other Technical Specifications

The motion table can tilt and elevate the RWS simulating the vehicle driving in terrain. The motion table runs a predefined program. There is no data exchange between the motion table and the rest of the simulator. The second part of the simulator will be the turret simulator mounted onto the motion table. It will exchange data with the rest of the simulator. The turret simulator will have to be fitted with a gyroscope in order to capture the rotation speed and acceleration of the turret. However gyroscopes are not optimal to measure position, as they can start to drift after exposure to motion. Therefore there is also a need for an absolute position sensor, to relay the position of the turret accurately to the simulator. It will also be operated by the main processing unit (MPU). The RWS is operated by the MPU, and fitted with both gyro and absolute position sensor.

Stakeholder requirement STRQ016 with accompanying system requirement SRQ013 states that *the Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0,1 mrad.* An incremental encoder system from Renishaw with a TD (dual resolution) interface was selected for this purpose [57]. An encoder with a nominal external diameter of 75 mm is designed to be fitted at the perimeter of the sensor mount part of the OMS. Accompanying reader head T2011 will be used. The encoder has an accuracy of 0.014 mrad.

Stakeholder requirement STRQ030 with accompanying system requirements SRQ029 and DRQ016 states that the system shall be prepared for integration of a 3-axis accelerometer. The multi-axis gyroscope from Sensonor; SIMU202 [58], is suggested as it compact and will fit within the internal space of the OMS base. This gyroscope holds high performance under highly dynamic movements involving vibrations and shock; making it particularly suitable for the conditions under which the system will be used. The bottom internal surface of the OMS base is designed with a free space that allows for mounting of the gyroscope either by bolts or glue.

Both the incremental encoder and gyroscope have an operating temperature which are well within the limits of the required system operating temperature. System requirement SRQ014 states that *the system shall be operable in a temperature range from 0-40 degrees Celsius*. The gyroscope is operable between -40 to +85 Celsius, while the encoder is operable between 0 to +70 Celsius.

IV.3.9 Bolt and Fixtures

To choose the right fastening method for the OMS several aspects was considered. Price, ease of assembly, manufacturing time and attachment force. Obviously, in order for the offset disc to be locked into different offsets it could not be welded to the power train disc. However, as substantial attachment force between the two parts would be needed, a bolt connection was the obvious choice.

The fastening method between the slew bearing and base might not be so obvious. These two parts are not necessary to disassemble from each other, and it might therefore be argued that a welding interface would be a good choice. For instance, a continuous weld between the slew bearing and the top flange of the base would distribute the stress much better than bolt connections. However, as slew bearings are in need of a almost perfectly straight surface to function properly, the chance of irregularities in the material due to welding it is not desirable. The price for a weld with the required accuracy would also be to substantial. Therefore, a bolt connection was chosen here as well.

IV.3.9.1 Bolt Theory

Bolts are used in fixture applications in order to support or transmit an externally applied load [27]. In engineering structures bolts are the critical for providing non-permanent fixture and mounting of everything from smaller parts to structures carrying extremely high loads, such as cranes and bridges [45]. Bolt failure can have fatal consequences and might also involve considerable financial losses. Designing a bolted connection needs to take into consideration bolt dimensions and material, thread engagement, preload, load pattern (static or dynamic), vibration, fatigue and corrosion [45].

A bolt is normally tensioned by a preload applied by a torque. The preload is the clamping force of the bolt, which is the force that clamps two or more surfaces together in a bolt connection, as in figure IV.3.10.

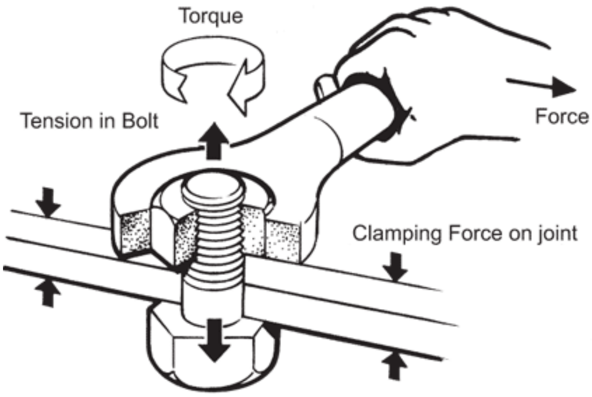


Figure IV.3.10: Schematic of Preload And Resulting Clamping Force. [46]

The applied preload torque is determined by the applied preload force, the bolt's dimension and geometry, and the friction between the bolt threads and under the bolt head. The equation for preload torque is as follows:

$$\tau = F(r_m tan(\varepsilon + \theta) + \mu' r'_m) \tag{E.3.17}$$

F = applied force

r_m = bolt middle radius

ε = friction angle

θ = pitch angle

μ'= coefficient of friction

τ = preload torque

$r'_m = \frac{s+d_h}{4}$

s = key width

d_h = hole diameter

A proof load is commonly defined for all bolts, which represents the tensile load that the threaded portion of the bolt must be able to support without risking permanent deformation [47]. The proof load is commonly set to 85-95 percent of the yield strength. For structural applications the recommended preload of the bolt should be at least 75 percent of the bolt's proof load (Figure IV.3.11).

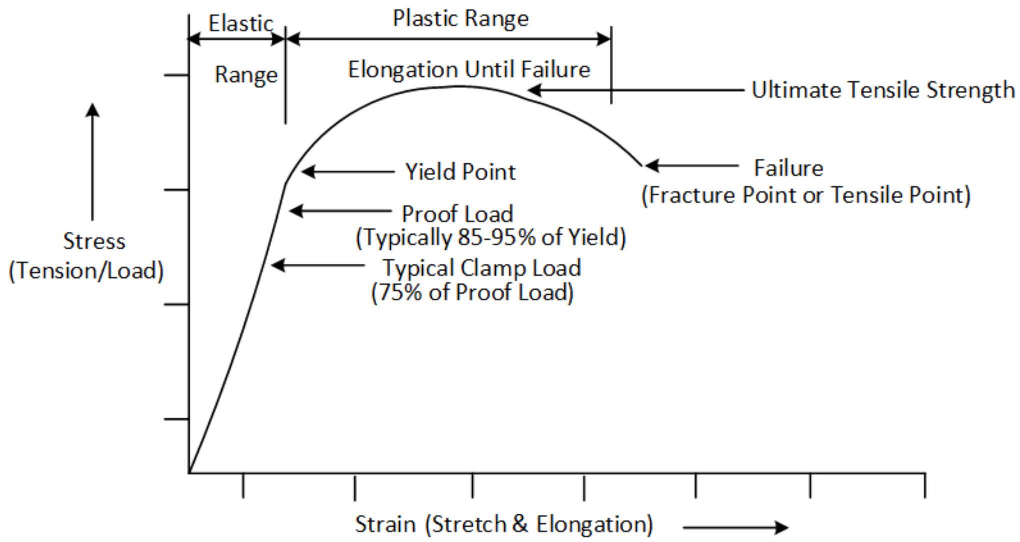


Figure IV.3.11: Proof load and preload of bolts [27]

The most common cause of fracture in bolt connectors is fatigue [45]. Fatigue fractures results from crack initiation and growth that occurs when cyclic stresses causes the material to weaken due to the repeatedly applied load. The preload applied on a bolt greatly affects the amplitude of cyclic stress that acts on a bolt used in application involving complex movement patterns [45]. Fatigue fractures are caused by insufficient preload or a high reduction in preload torque during loading. Increasing the preload reduces the experienced cyclic stress amplitude in the bolt and reduces the risk for bolt loosening. Thus, higher preloads increases the fatigue performance of the bolt [45]. The OMS is required to support a high load under movements of rapid directional change, which puts high demands on the bolts that are used to fix the various parts of the system to each other or other interfaces. Thus, calculation and evaluation of the preloads required for the various applications of bolts in the system is of high importance.

The preload is intended to cause the bolt to elongate elastically [48]. This ensures that the preload stays close to constant under complex movement patterns. Longer bolts results in a longer relative elongation, which is often hard to achieve with shorter bolts [48]. Selecting the appropriate length of the bolt is also affected by the required thread engagement, which is the number of threads that are engaged between the bolt and the hole. A bolted connection should be designed such that the bolt shank fails before the threads fail. To ensure this, a minimum thread engagement length is required. Thread engagement length is calculated from the formula:

$$L_e = \frac{2 \cdot A_t}{0.5 \cdot 3.14 \cdot (D - 0.649p)} \tag{E.3.18}$$

L_e = minimum thread engagement length
D = bolt major diameter
A_t = stress area
p = pitch

Additionally, if the bolt and the female threads have different materials, then the calculated L_e should be multiplied with the factor J:

$$J = \frac{\text{Bolt tensile strength}}{\text{Female thread tensile strength}} \tag{E.3.19}$$

IV.3.9.2 Friction

Friction is an important aspect of the interface between the discs. There are several models of friction. The most popular and simple friction model is the first order approximation model to how friction actually works, as described in E.3.20. Friction force according to this model can be described by the following equation.

$$f_s = \mu_s N. \tag{E.3.20}$$

As stated in equation E.3.20, friction force is a function of both the normal force and the friction coefficient, where the latter depends upon the surfaces interacting on each other. Friction is based on two theories; adhesion theory, and abrasion theory [37]. Friction between the discs is a result of these two theories. Weight and pressure of the RWS causes local plastic deformation on the surfaces, which creates an adhesive effect between the discs; adhesion friction. Interaction of the discs results in abrasive friction. Abrasive friction will tear off particles between the two discs, which can increase the risk of wear. The following equation explains the relation between the two mentioned theories.

$$\text{Friction} = \text{Material coefficient} \times \text{Pressure} \times \text{Contact Area} \tag{E.3.21}$$

It can be noticed that friction is independent of the contact area. But the contact area between the offset disc and power-train disc increasing the resistance to start the offset disc in motion. This resistance is a result of the mechanical deformation. As area increases, applied force per unit area decreases, but there is more contact surface to resist motion as E.3.21 explains below.

Where the material coefficient is a measure of the penetration of the material, the pressure applied to the surface and the area of the surfaces in contact. The area in the pressure term cancels the third term in E.3.21

IV.3.9.3 Load Scenario

The loads working on the interface between the offset disc and the power train disc occurs as a result of acceleration and gravity of the RWS. When the RWS is placed at an offset, the weight of the RWS will cause a bending moment in the offset disc. The forces normal to the discs will create a bending moment, that will pull the discs apart and reduce the clamping force caused by the bolts between the discs. This will in turn reduce the amount of friction the bolted connection can provide. Loads discussed in this section occurs at the interface between RWS/ OMS, see figure IV.3.15.

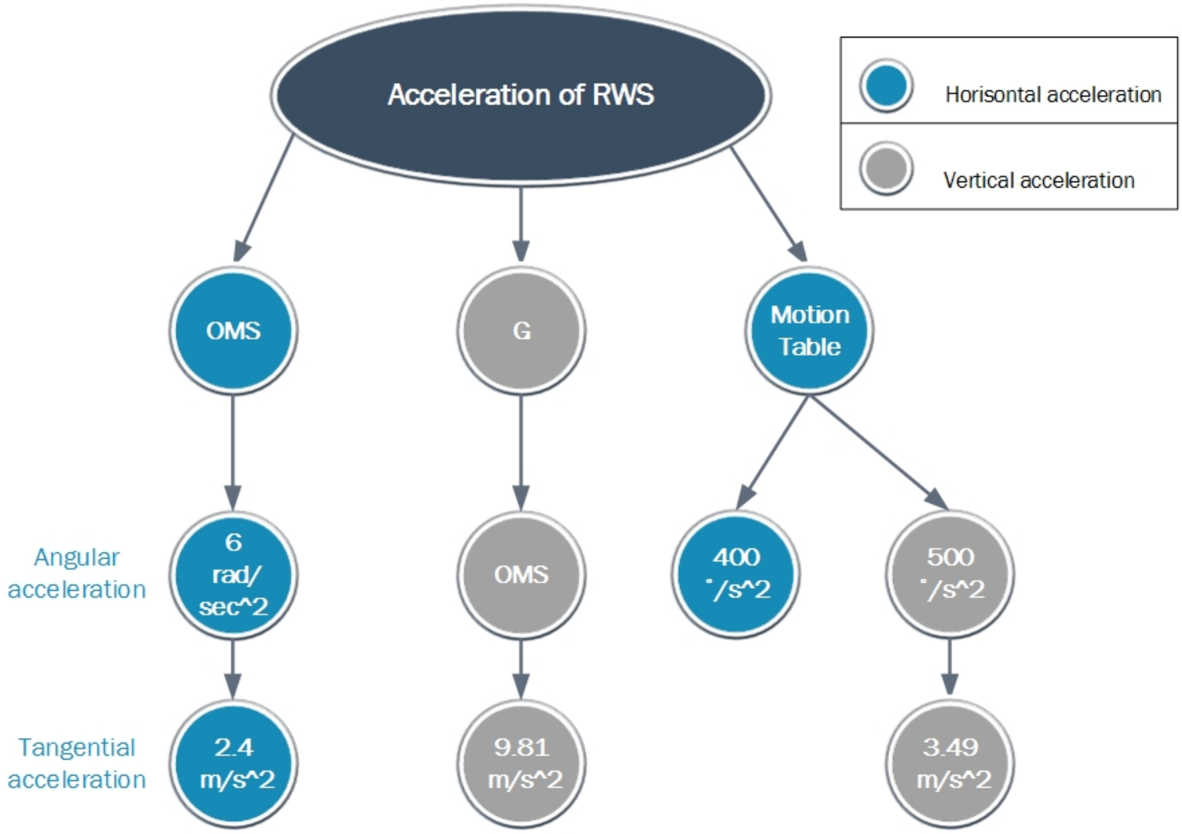


Figure IV.3.12: Acceleration of RWS decomposed.

Figure IV.3.12 shows how the total acceleration of the RWS can be decomposed. These acceleration components will subject the bolted to both static and dynamic loads. Gravity will create a load that will be close to constant. At the maximum tilt of 25 degrees, gravity's force component normal to the discs will be 2225 N, which is within 90% of its original value. Gravity will at 25 degrees tilt create a shear load on the interface of around 1050 N (see section IV.2.7). It was decided to view the static gravitational load as 2225 N, normal to the discs. Dynamic load from gravity will be defined as 1050N parallel with the discs.

Angular acceleration of the OMS will always be parallel to the two discs, creating a dynamic shear force of 600 N in the interface. The bolted connection must always provide enough friction through clamping force, to counteract this shear force. Pitch and roll acceleration of the motion table at 400mm offset, will result in a dynamic load of 875 N normal to the discs.

		Normal (N)	Shear (N)
Gravity	Static	2225	0
	Dynamic	0-230	0-1050
OMS	Static	0	0
	Dynamic	0	0-600
Motion table	Static	0	0
	Dynamic	0-875	0

Table IV.3.11: Bolt interface load situation

IV.3.9.4 Simplifications

The analysis aims to identify the amount of shear and normal contact forces between the discs that the interface has to counteract as a result of the load scenario. Any normal force will pull the discs apart, and shear forces will try to rotate the offset disc. Preloading the bolts will counteract the normal forces that try to pull the discs apart. This preload will also create friction between the two discs that will lessen the bearing stress on the bolts. Friction forces will prevent the discs from slipping by absorbing shear forces from the load situation. As demonstrated in figure IV.3.13

The simplest way to approach the problem is identifying the forces that pull the discs apart. It was decided to simplify the problem to only one resulting force. The mass of the discs compared to the RWS is very small. Therefore it was decided to drop the forces working on these parts as a result of their acceleration in the analysis. The primary force working on the interface comes from the acceleration of the mass center of the RWS. In order to calculate the needed clamping force of the bolt interface, one would need to identify the largest resulting acceleration of the RWS.

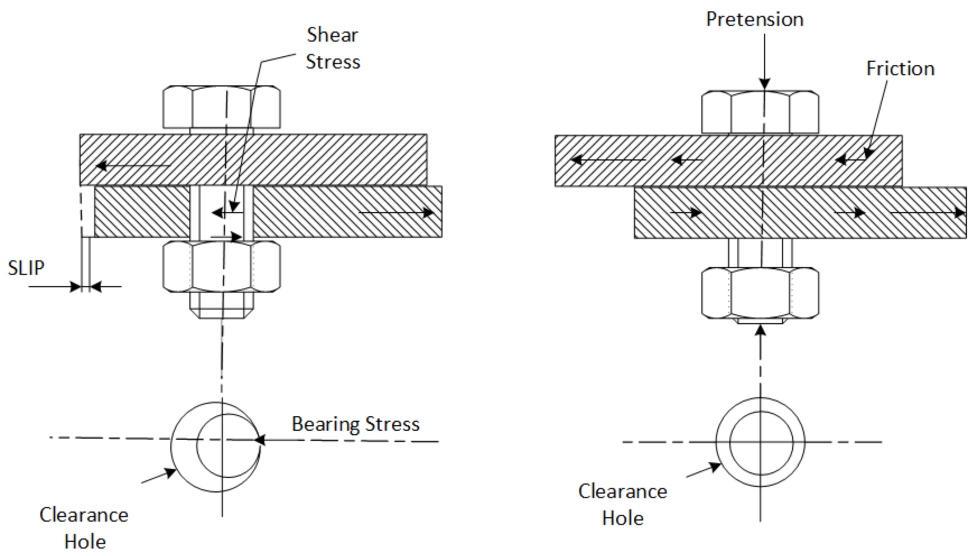


Figure IV.3.13: Shear stress in bolts as a result of preload. [44]

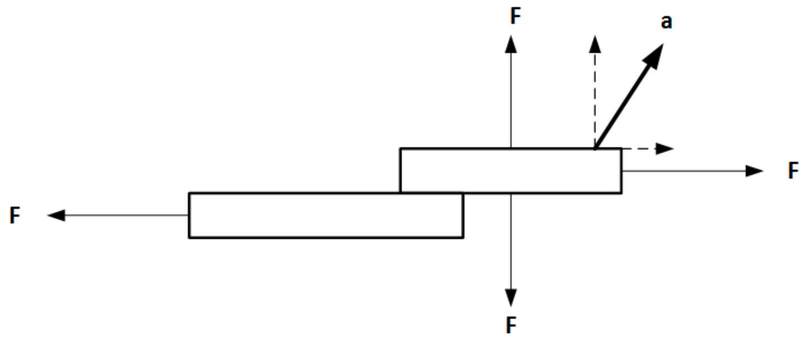


Figure IV.3.14: Simplified load scenario.

The bolted interface is viewed as a single fixture in the simplification. This is incorrect as the load on the offset disc will create a bending moment in the disc. This bending moment would create an unequal load on the bolts. Since a more in depth mathematical analysis proved too complex, it was decided to view the interface as one fixture. Solidworks will be used to verify and argue for this simplification.

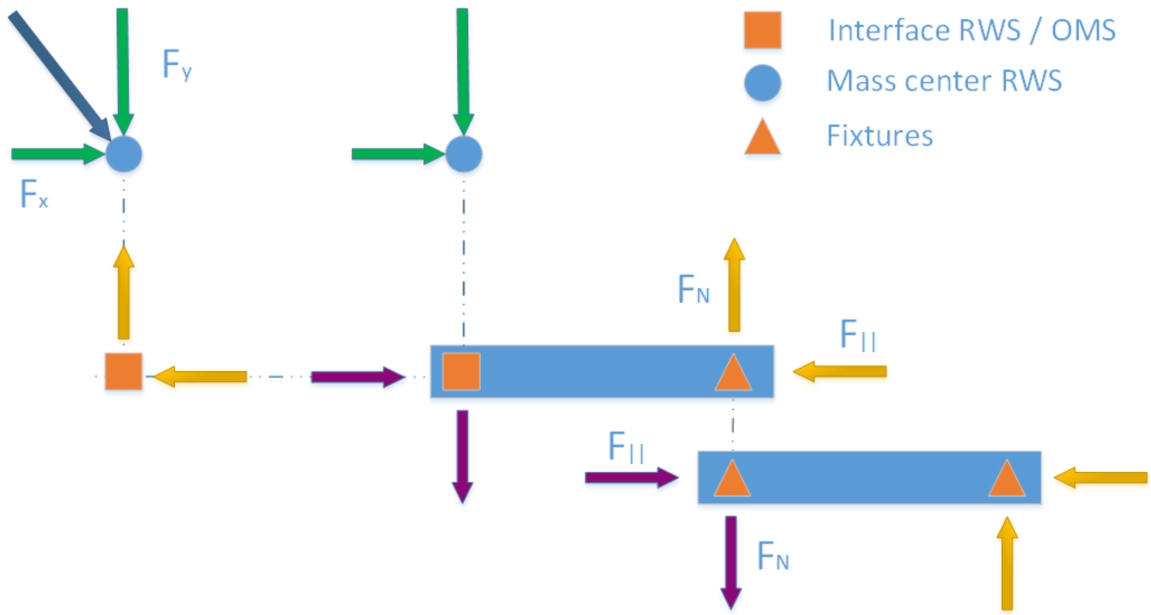


Figure IV.3.15: FBD of bolt interface.

The FBD in figure IV.3.15 shows that the forces working in the bolted interface are equal to the forces working on the mass center of the RWS. In reality these bodies will not be rigid, meaning that the material will absorb forces because of their elasticity. This means that the forces in the bolted interface will be less than the forces working on the mass center. In this simplification $F_{||}$ and F_N will be defined as following.

$$F_N \leq F_Y \qquad F_{||} \leq F_X \tag{E.3.22}$$

IV.3.9.5 Preload Analysis

The bolt connection between the offset disc and power train disc is composed of seven M10 bolts. The bolts will all use the same preload to distribute the clamping force between the discs evenly. The bolts must always retain enough clamping force (F_c) to get the required friction to counteract the dynamic shear loads ($F_{||}$). The clamping force that the interface need to supply in order to get the required friction is shown in the equation below.

$$F_c \geq \frac{F_{||}}{\mu} \quad \equiv \quad F_c \geq \frac{1050+600N}{1.05} \quad \equiv \quad F_c \geq 1571N \tag{E.3.23}$$

Minimum clamping force (F_c) of the bolted interface has to be greater than 1571 N, in order to prevent bearing stresses on the bolts. The greatest dynamic load normal to the disc is 1105 N; the sum of the dynamic loads; as explained in table IV.3.11. Applied force (F_L) on the interface is 2225 N and comes the only static load. Since the bolts are exposed to dynamic and varying loads, and the calculations is based on simplifications a higher factor of safety is needed. It was decided that each bolt should be dimensioned to withstand the loads alone, resulting in a FOS of 7.

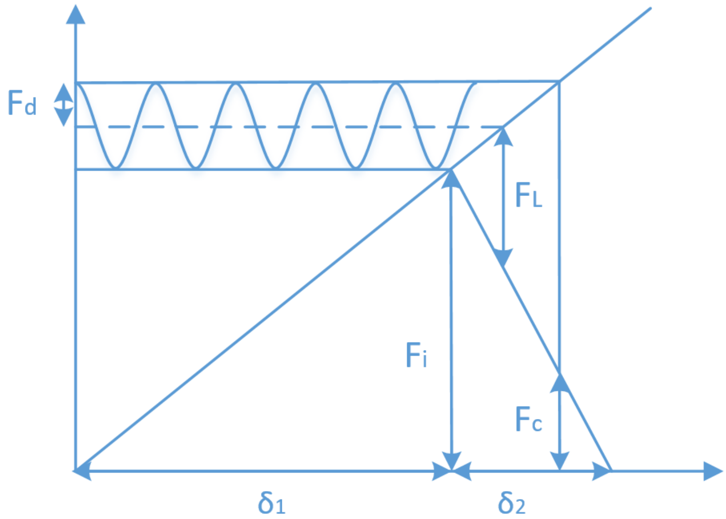


Figure IV.3.16: Bolt diagram.

A bolt diagram was made to help with deciding preload, see figure IV.3.16. The first step was finding the ratio between bolt elongation (δ_1) and material compression (δ_2). All bolts fastening the discs have washers, to help distribute the forces. Equation E.3.24 computes this ratio.

$$\frac{\delta_1}{\delta_2} = \frac{A_w \cdot E_{Al}}{A_b \cdot E_S} = 3.25 \tag{E.3.24}$$

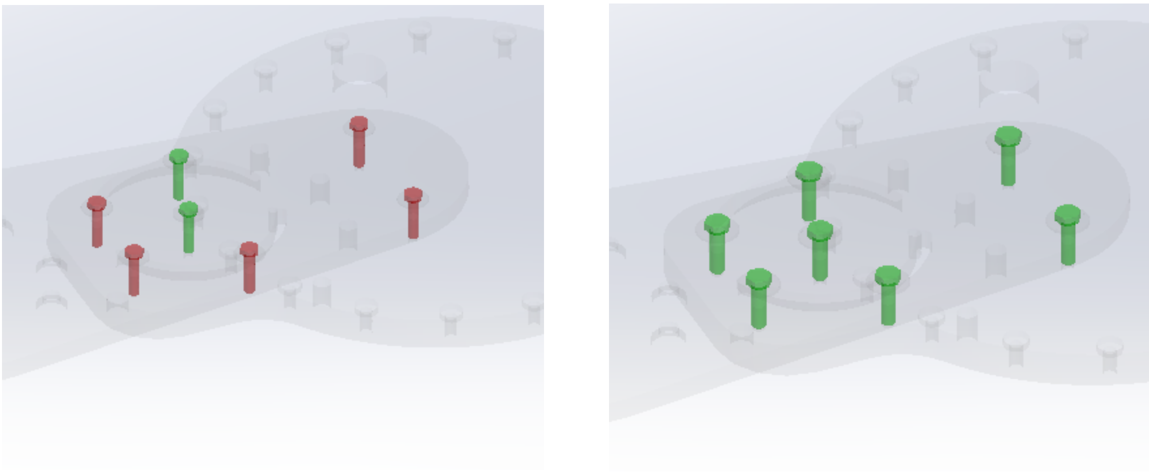
$A_w = 557$ mm^2 (Area under washer) $E_S = 2.1 \cdot 10^{11}$ Pa (Elastic modulus of steel)

$A_b = 57$ mm^2 (Area of bolt shaft) $E_{Al} = 7 \cdot 10^{10}$ Pa (Elastic modulus of Al.)

By plotting F_c, F_d, δ_1 andδ_2 into bolt diagram in figure IV.3.16, a suitable preload was found. With a preload of 10 kN a bolt withstand a static load of 5.5 kN (F_L) a dynamic load (F_d) up to 1.3 kN. and still retain the minimum amount of clamping force (F_c) required of the interface. It was decided that each bolt was to be preloaded with 10 kN.

IV.3.9.5.1 Bolt Dimension

Requirment DRQ009 states, *The bolts connecting the top plate to the offset plate shall have a safety factor of at least 2.* A few simulations in Solidworks was done to establish what bolt size would satisfy the requirement. The simulations with M8 and M10 ran the two worst case scenarios as described in section IV.2.7, with a bolt preload of 10 kN.



(a) M8

(b) M10

Figure IV.3.17: Bolt FOS

The simulation of M8 bolts, resulted in 5 of 7 bolts with a factor of safety less than 2. The bolt with the lowest FOS had 1.6. The bolts in the M10 simulation the most loaded bolt had a FOS of 2.5.

IV.3.9.6 Thread Engagement

The formula for finding thread engagement discussed in section IV.3.9.1, returns the required thread length to ensure that the bolt fails before threads of the material. ISO 965/1-1980 [50] lists required thread engagement of metric screws. A M10 bolt require a tread engagement from 5 mm and up to 15 mm. An M10 bolt with standard pitch would require a thread length of 19.8 mm, according to equations E.3.18 and E.3.18. This sets some design limitations on the power-train disc as it has to support the thread engagement of the M10 bolts.

IV.3.9.7 Verification with Solidworks

Solidworks was used to verify the bolted interface. Figure IV.3.17 shows that the bolts can handle the load situations. The same simulations also looked at contact forces between the discs. In both cases the normal force on the offset disc was over 70 kN, creating much greater friction forces than needed to prevent slipping of the discs. Stress on surface area under washers did not exceed 100 MPa, confirming that the preload did not overstress the material.

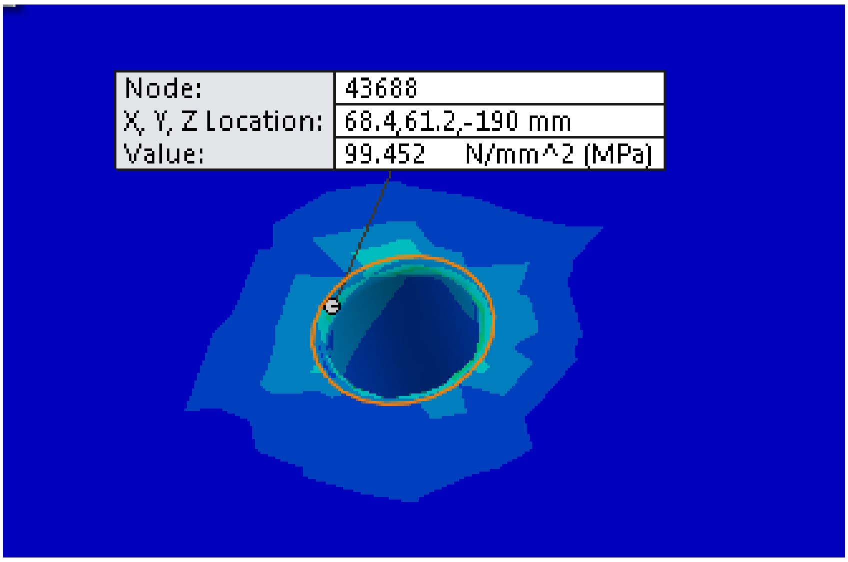


Figure IV.3.18: Stress plot of the surface under the washers.

IV.3.9.7.1 Other Bolt Interfaces

The bolts that fix the system to the motion table and the RWS were defined by KPS, hence no dimensional analysis was required for these bolts. Calculations were undertaken to assess if the system could withstand, without permanent deformation, the required pre-torques as stated in requirements STRQ022 with accompanying SRQ018, and STRQ020 with accompanying SRQ016. The pre-torque formula E.3.17 was used to find the axial force applied on the bolt by the required pre-torque. Input data regarding the bolt geometry, apart from the input torque, were obtained from standard technical catalogues.

The output axial force was used to determine the resultant stress that would appear in the flange and offset plate from the force transmitted by the bolts. The resultant stresses were well below the yield strength for Al 6082 T6 at 260 MPa. The calculations, and thus stated requirements, were further verified in the Translation FEA test; details of which can be found in the Test Report (Ref chapter: VI.1). The MatLab script that was developed to make repeated bolt calculations run smoothly can be found in Appendix H.3.

IV.4 Design

The design phase happened in parallel with the component selection design. Because dimensions such as height of the system is dependant on the size and geometry of the internal components. This chapter will discuss, and justify in detail the design process. Including how the requirements affected the design of each part.

IV.4.1 Model

Design of the OMS is based on the double discus concept as discussed in section IV.1.3. The preliminary design was further developed in accordance with calculations and analysis found in chapter IV.2. The preliminary design did not take into account interfaces between OMS and procured parts such as motor. New parts had to be designed in order to fit procured components to the OMS.

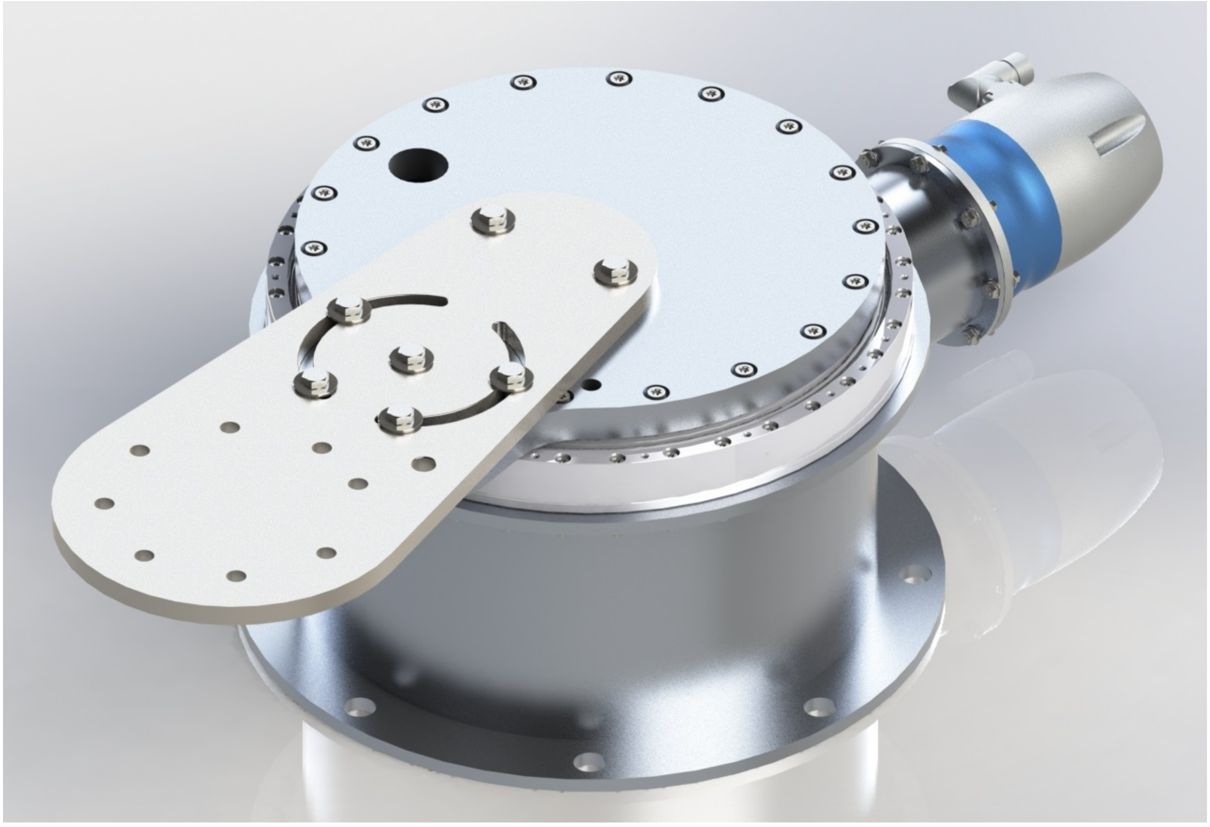
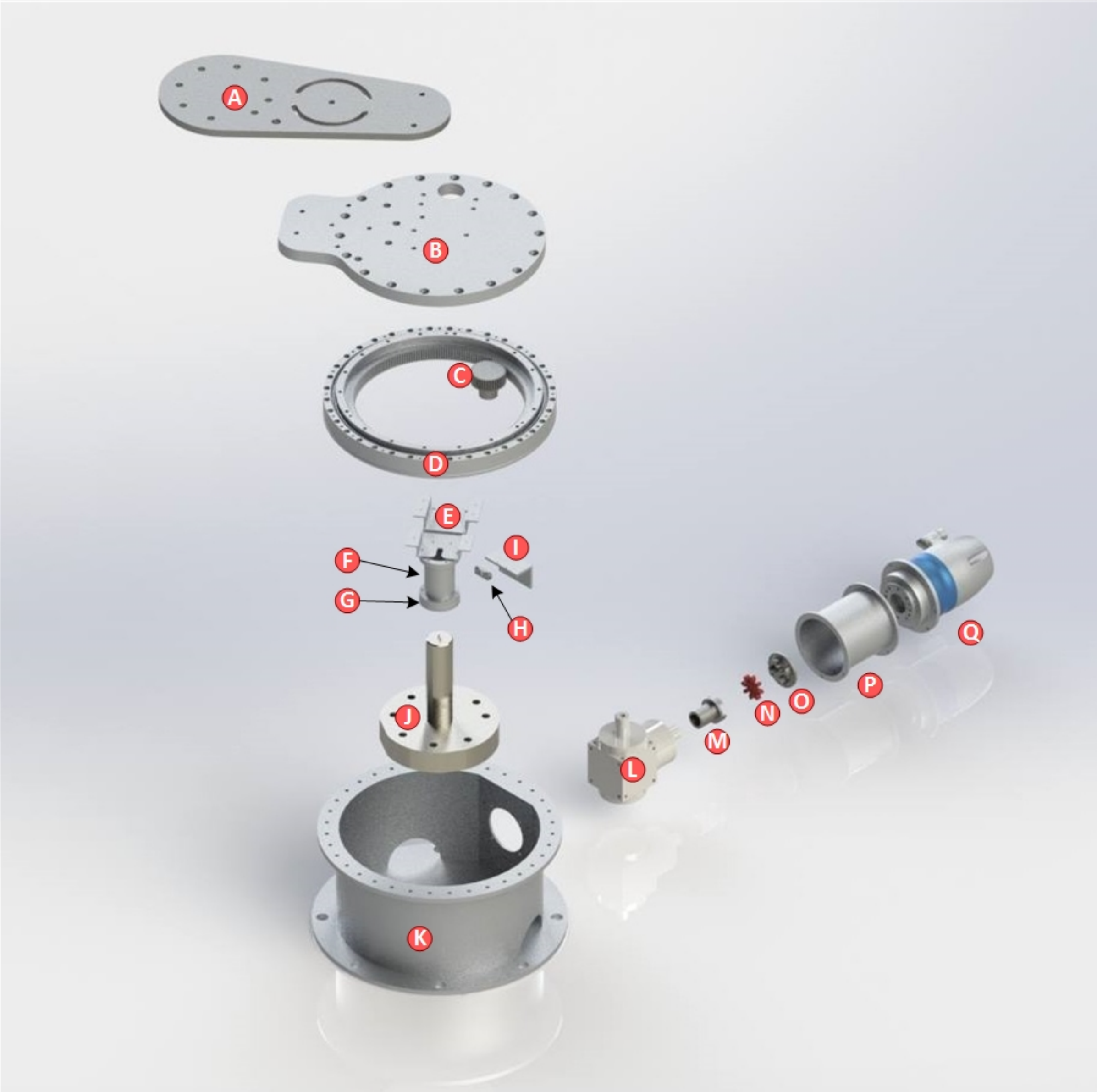


Figure IV.4.1: OMS.



- A Offset Disc
- B Power-train Disc
- C Pinion
- D Slew bearing
- E Cable bridge
- F Sensor mount
- G Encoder ring
- H Reader head
- I Reader head bracket
- J Slip ring
- K Base
- L Angled gear
- M Drive shaft
- N Rubber gasket
- O Motor adapter
- P Motor bracket
- Q Motor

Figure IV.4.2: Exploded view of the assembly.

Since the geometry of the procured parts was not known at the start phase of the design process. Design of parts was done sequentially, meaning starting design of parts that does not depend on other parts. The design of the offset disc was only constrained by the bolted interface to the RWS. Because of this independence, design process started with offset disc. Design of parts that depended on component selection and interfaces, could be started after the selection of interfaced components.

IV.4.1.1 List of Parts

The OMS consists of parts designed specifically for the system, and parts procured from different suppliers. An exploded view of the OMS is shown in figure IV.4.2. Parts will be refereed to in accordance with table IV.4.1 and figure IV.4.2. From this point onwards, all parts and components will be refereed to these names.

OMS parts		Procured parts	
Offset Disc	A	Slew bearing	D
Power-train Disc	B	Encoder ring	G
Pinion	C	Reader head	H
Cable bridge	E	Slip ring	J
Sensor mount	F	Angled gear	L
Reader head bracket	I	Motor	Q
Base	K		
Drive shaft	M		
Rubber gasket	N		
Motor adapter	O		
Motor Bracket	P		

Table IV.4.1: List of Parts

IV.4.2 Offset Disc

The offset disc provides the offset functionality as the name explains. It has interfaces to the RWS and the power train disc. The total length of the disc is 540 mm, and a maximum width of 240 mm. The main concern when dimensioning this part was bending moments as a result of the weight of the RWS. Because the disc's thickness compared to it's other dimensions is small the disc becomes very vulnerable to bending moments. A thick disc is desirable in order to withstand the bending moments, but at the same time there are weight constraints set by the requirements. This dilemma was solved by using a FEA design study, to find the optimal dimensions.

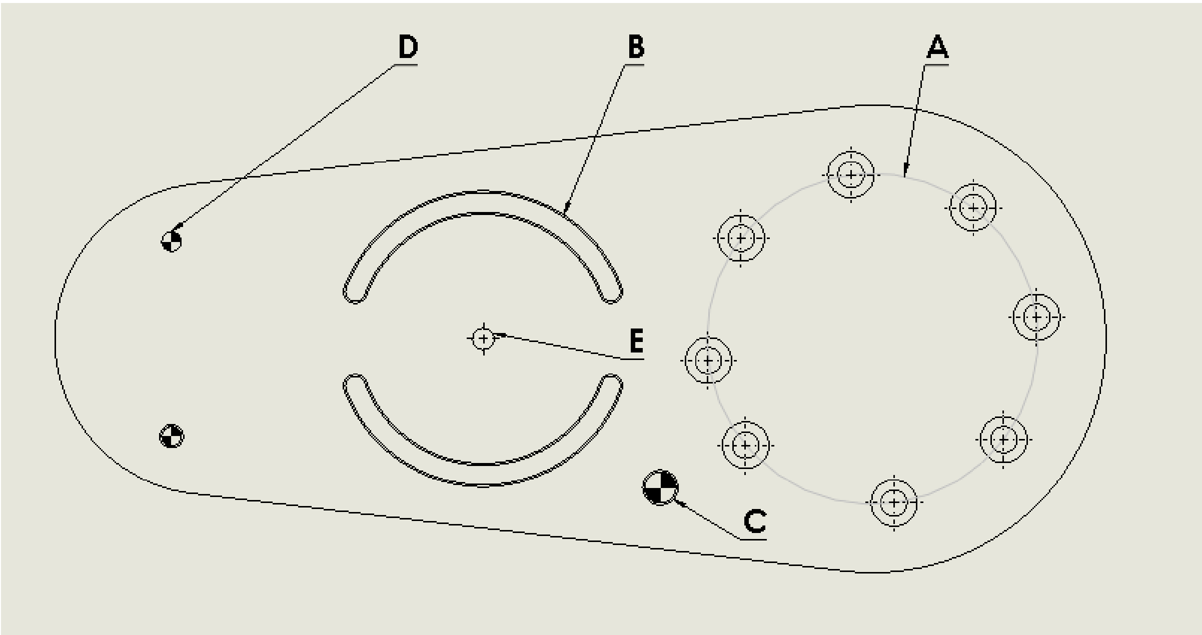


Figure IV.4.3: Offset disc with notations.

When designing the offset disc, the following requirements were considered:

- **SRQ016:** *The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.*
- **SRQ023:** *The system shall have a maximum weight of 50 kg.*
- **SRQ024:** *The system shall have a physical mounting interface to the RWS with the hole pattern according to Appendix A.*
- **DRQ09:** *The bolts connecting the top disc to the offset disc shall have a safety factor of at least 2.*
- **DRQ012:** *The system shall have an offset disc that allows for an offset of at least 30 cm at 10 cm increments.*
- **DRQ015:** *The general factor of safety used for components in the system shall be no less than 2.*

The interface to the RWS is shown on figure IV.4.3 with notation A. The hole pattern is in accordance with SRQ024, the center of the pattern has a distance to the pivot point E of 200mm. This distance will one half of the maximum offset the OMS can provide. The RWS is mounted to the disc with eight M12 bolts with a preload of 130 Nm. Bolt holes on the RWS are threaded and all holes on the offset disc are thread-less. These holes are counter-bored so that the bolt heads will not collide with the power train disc when the offset is small.

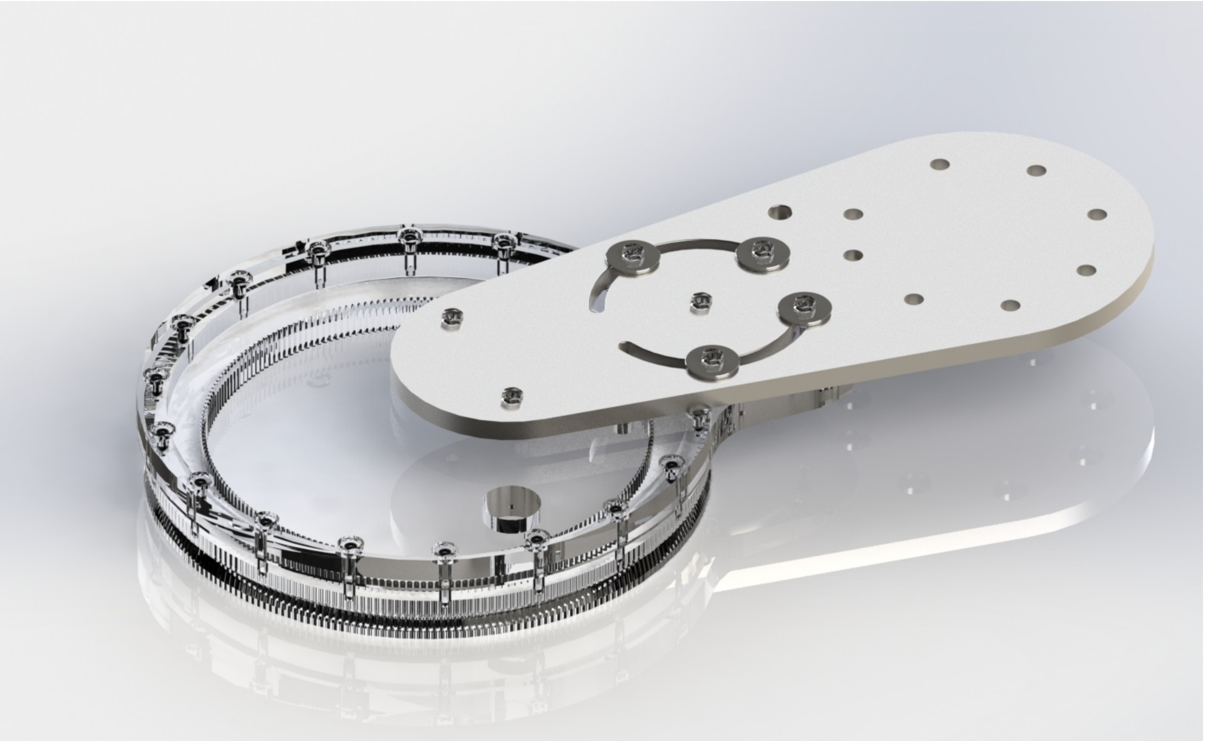


Figure IV.4.4: Render of Offset disc.

The offset disc is mounted onto the power train disc by one M10 bolt see notation E in figure IV.4.3. The offset disc pivots around this bolt. Two M10 bolts at D and four M10 bolts at B prevents the offset-disc from moving during operation. The preloading of these bolts counteracts the bending moment that the offset disc is exposed to.

When the offset is less than 400 mm, holes D will no longer overlap the power train disc. Resulting in less fixtures for the offset disc. Therefore, hole C is used when the offset is less than 400 mm, to compensate the loss of two fixture points. This hole also provides a reference when choosing an offset, enabled by a hole-pattern on the power train disc.

Instead of making multiple four holes for every offset, for the M10 bolts at B, two semi-circle slides B was made. By using slides instead holes, the bolts does not have to be completely unscrewed in order to change offset. In terms of assembly, this solution is superior. Because the operator does not have to identify the correct holes used for a certain offset. The disc will also be more aesthetically pleasing as there is no need for multiple holes without any symmetry. To distribute the load evenly washers are placed between bolt-heads and disc.

IV.4.2.1 Design Study

A design study of the disc thickness was done on the offset disc to compare weight of the part against occurring stresses in material and bolts. The load situation is in accordance with the two worst case scenarios described in section IV.2.7. The goal of this study is to find the optimal thickness that satisfies the given requirements. The study monitors maximal stress, average stress, displacement and bolt forces. The results of the study is presented in table IV.4.2.

Thickness (mm)	Max. stress(MPa)	Displacement(mm)
10	175,54	2,072
12,5	146,71	1,531
15	155,44	1,072
17,5	128,99	0,872
20	129,60	0,710

Table IV.4.2: Results from design study for offset disc

The results shows that the offset disc can be as thin as 15mm, and still be within 70% of the materials yield strength. The study also take into consideration the FOS of the bolts. The FOS for the material with a thickness of 15mm is slightly lower than two. The maximal stress is situated within a few nodes at the edge of one of the bolt holes. As mentioned in section IV.2.7 the loads applied in this study is likely higher than in reality. Therefore a FOS of 2.44 is found acceptable.

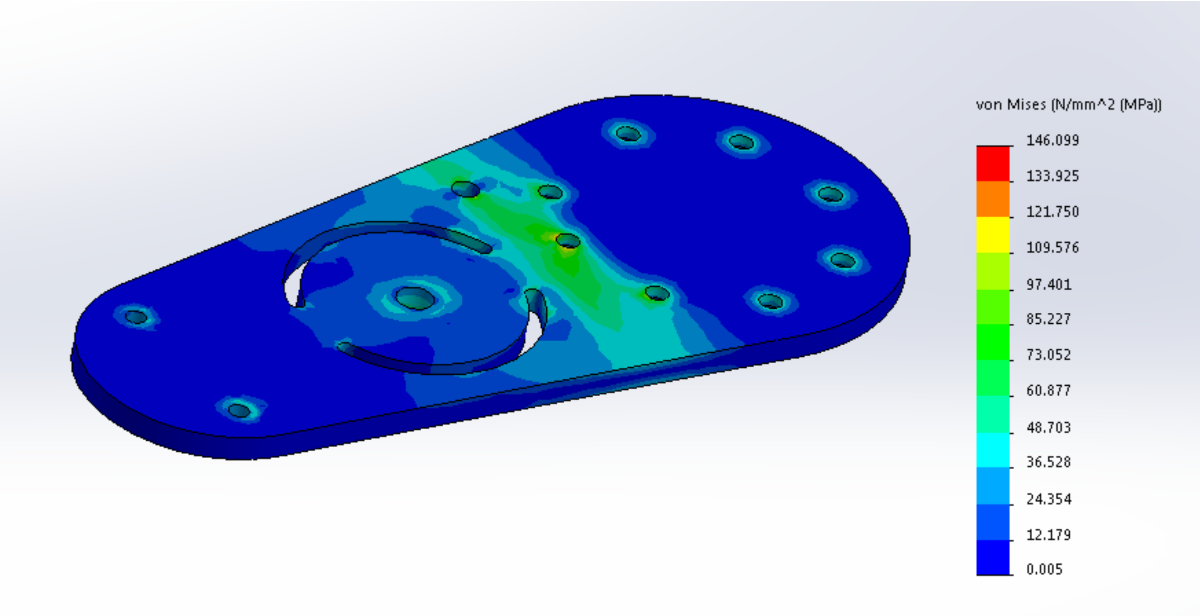


Figure IV.4.5: FEA Offset disc.

Figure IV.4.6 shows a plot of the FOS of the bolt with the highest load. Which also confirms that that a thickness of 15mm satisfy the requirement *(DRQ009)* concerning the bolted interface.

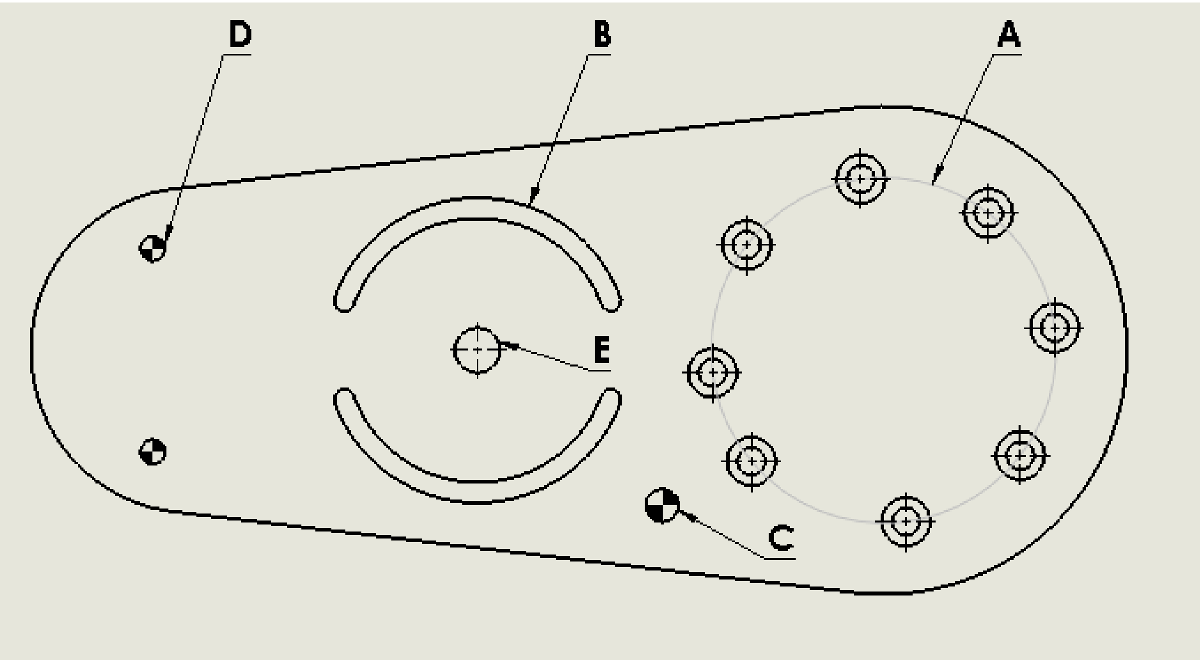


Figure IV.4.6: Design study: Bolt FOS

IV.4.3 Power-train Disc

The power-train disc is the interface between offset disc and the power transmission trough the slew bearing. The disc has a diameter of 390 mm. The disc is not completely circular, it has a lateral extrusion used to increase the pivot point's radius in order to reach the requested offset. The power-train disc is fitted with a hole on the top side, so the cables from the internals can reach the RWS.

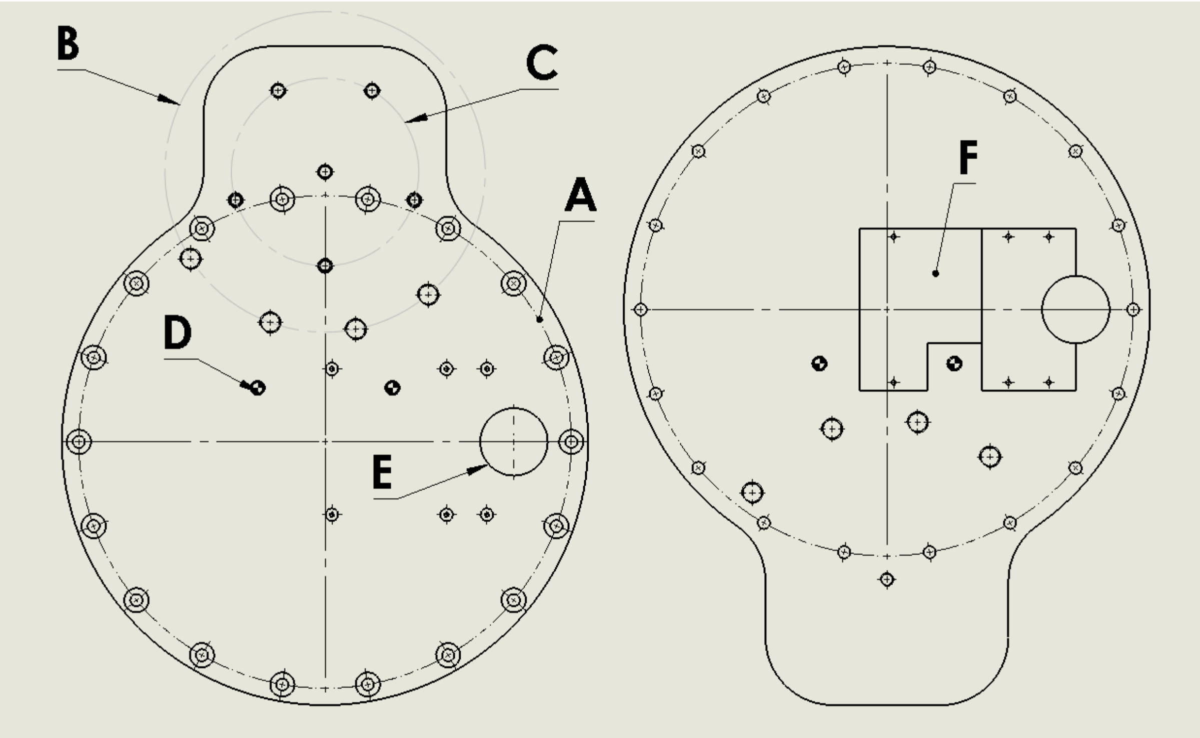


Figure IV.4.7: Power-train disc with notations.

When designing the power-train disc, the following requirements was considered.

- **SRQ023:***The system shall have a maximum weight of 50 kg.*
- **SRQ033:***The system shall put zero strain on the wires connected to the RWS.*
- **DRQ009:***The bolts connecting the top disc to the offset disc shall have a safety factor of at least 2.*
- **DRQ015:***The general factor of safety used for components in the system shall be no less than 2.*

Figure IV.4.7 shows a top view 2D drawing with notations for design features of the power-train disc. These notations will be used when referring to design features in this section. The bolted interface to the slew-bearing **(A)** uses 18 M8 bolts. The hole pattern is in accordance with 2D drawing of the slew-bearing included in appendix J.1.

Holes **(B)** serves as a reference for the different offset. The holes also provides an extra fixture point, when the offset is less than 400 mm. Holes **(D)** is used to fasten the offset disc to the power-disc when the offset is less than 400 mm. Holes situated at **(C)** is where the four M10 bolts from the slides of the offset disc is connected. Hole **(E)** is where the cables from the base goes trough in order to reach the RWS. The hole is situated in a way that the offset disc never cover it. On the underside of the power train disc there are some holes to mount the cable interface, that ensures that there is zero strain on the cables during rotation.

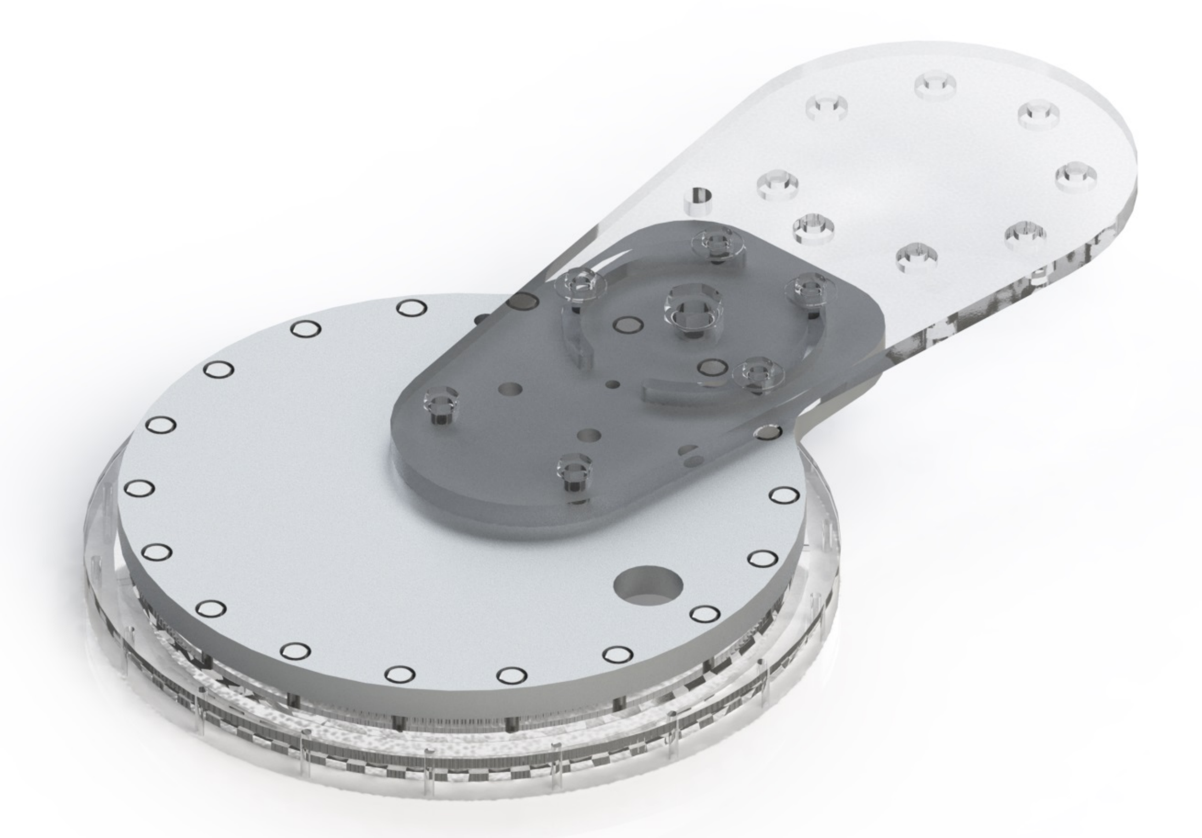


Figure IV.4.8: Render of power-train disc.

The bolts connecting offset and power-train discs has a minimum thread engagement, that needs to be considered. A 8.8 M10 bolt will require a thread length of 19.8 mm when fastened in aluminium. [42] Setting the thickness of the offset disc to 25 mm.

IV.4.4 Base

The main concern when designing the base, is to provide support and rigidity to the slew bearing. Because of it's small cross sectional height compared to its diameter the slew bearing is very little rigidity. The supporting structure must therefore be designed to provide both axial and radial rigidity. The cylindrical shape coupled with it's flanges, is what gives the base its rigidity.

The following requirements was considered, when designing the base.

- **SRQ018:***The system shall be able to withstand being mounted to the motion table using a preload torque of 200 Nm.*
- **CRQ001:***The system shall have a physical mounting interface to the slip ring with the hole pattern according to Appendix A.*
- **SRQ017:***The system shall have a thread less mounting interface to the motion table according to highlighted holes and information in Appendix B.*

The base serves as a interface hub, as most of the other parts and components are connected to the base using bolts. The base is designed to provide a stable interface between the motor and the slew bearing. As seen in figure IV.4.9, the top flange of the base has 36 holes (B) that will fix the slew bearing to the base using bolts and nuts. To prevent any relative movement between bearing pinion, that might damage either components.

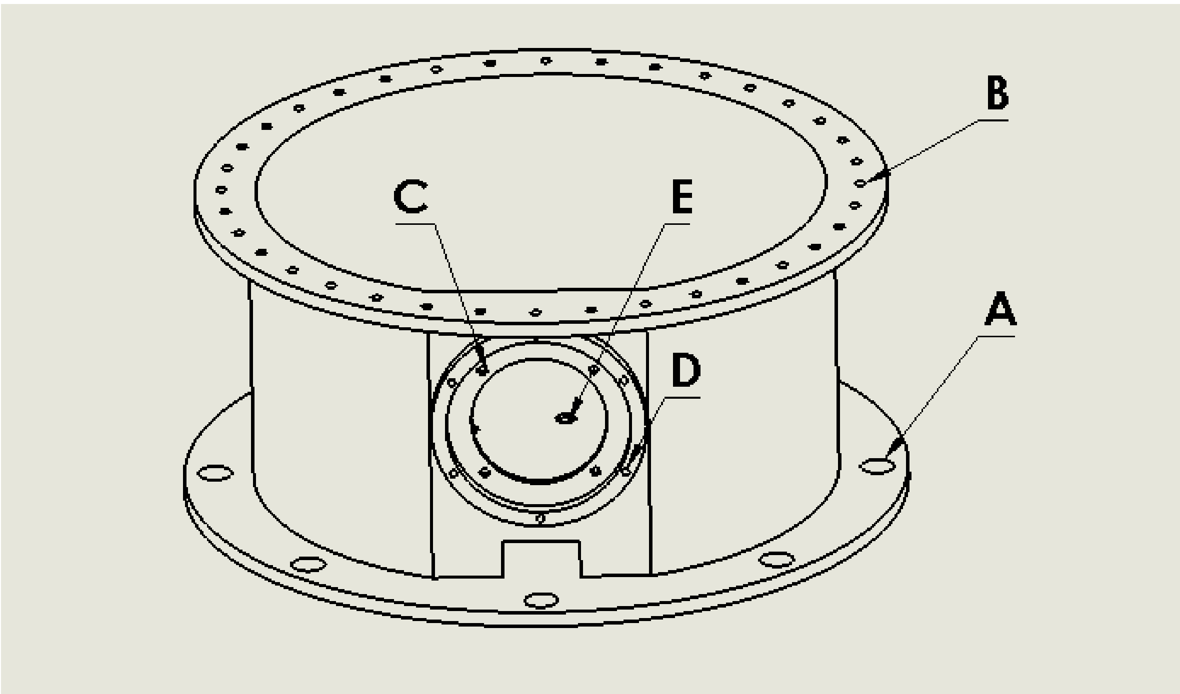


Figure IV.4.9: Base with notations.

The bottom flange has has a hole pattern (A) that consists of eight M20 thread-less holes used to fix the OMS to the motion table, as specified by SRQ017. The preload on these bolts was specified by KPS trough SRQ018 to be 200 Nm. The bottom flange needs to be thick enough to withstand the resulting stresses from this preload. Interface between motor and gearbox is found on the base's front side. Four M6 bolts (C) fix the gearbox to the wall of the base. Bolts are fitted from the outside of the base into threaded holes on the gearbox. Holes D will connect a motor bracket to the base using six M6 bolts. The base has to have a interface to the chosen slip ring as CRQ001 specifies. The hole pattern specified in this requirement is placed on the floor (E) of the base as shown in figure IV.4.9.

IV.4.5 Motor Connector

The connector between motor and gearbox, consists of multiple parts. The motor can not be fitted directly on the axle from the gearbox. The motor's output flange is made to directly attach drive components such as pinion or belt pulley with bolts. Figure IV.4.10, shows how power from the motor's output flange is transferred to the axle of the gearbox.

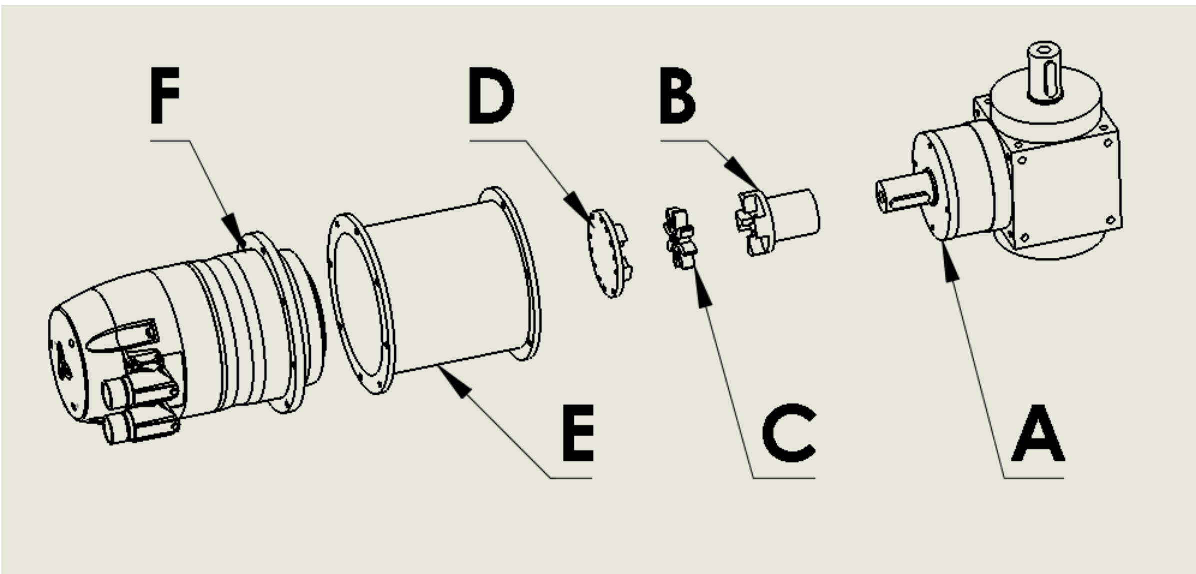


Figure IV.4.10: Exploded view of motor interface.

The drive shaft (B) will be press fitted on the gearbox input axle (A). Slipping between drive shaft and input axle (A) will will wear down the material and weaken the interface. Between drive shaft (B) and motor adaptor (D) there is a elastic gasket (C). There was multiple reasons to split the drive shaft and motor adaptor instead of having one part connection motor and gearbox. Number one is that it opens for easier assembly and dis-assembly of the system, as one would not need to disengage the press pass between axle and drive shaft. The gasket will also prevent wear and tear between the drive shaft and motor adaptor.

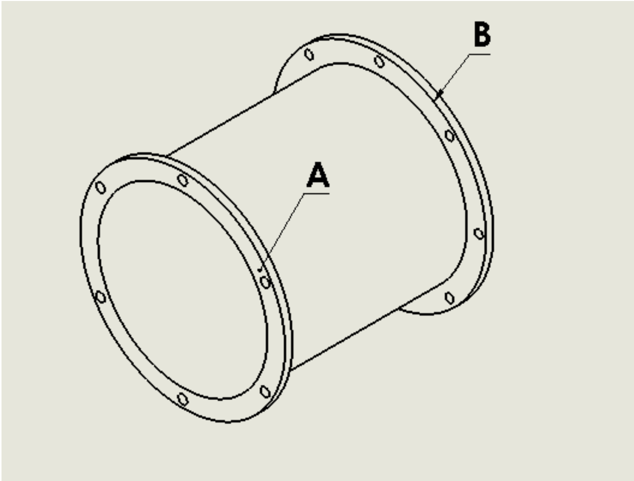


Figure IV.4.11: Motor bracket.

The main functions of the motor bracket (E), are to move the motor away from the gearbox in order to make space for the drive shaft and to protect both the drive shaft and external objects from damage during its rotational movement. The bracket has two flanges with hole patterns to connect it to the motor and the base. Hole pattern (A) in figure IV.4.11 matches hole pattern (D) on the base as seen in figure IV.4.9. Hole pattern (B) is matching the hole pattern on the mounting flange on the motor.

IV.4.6 Positioning System

The OMS incorporates a positioning system that enables proper test interaction between turret and RWS. The position system is compromised of multiple parts as shown in figure IV.4.12. An incremental encoder system from Renishaw (see section IV.3.8) includes the encoder ring (D) and reader head (G). The reader head bracket (F) will be attached to the mounting interface on the backside of the gearbox (B). The bracket for the encoder ring will be connected to the lower surface of the power train disc, and keep the encoder ring concentric with the slip ring. The encoder ring will rotate with the power train disc, while the reader head will stay stationary while reading the angular position off the encoder ring.

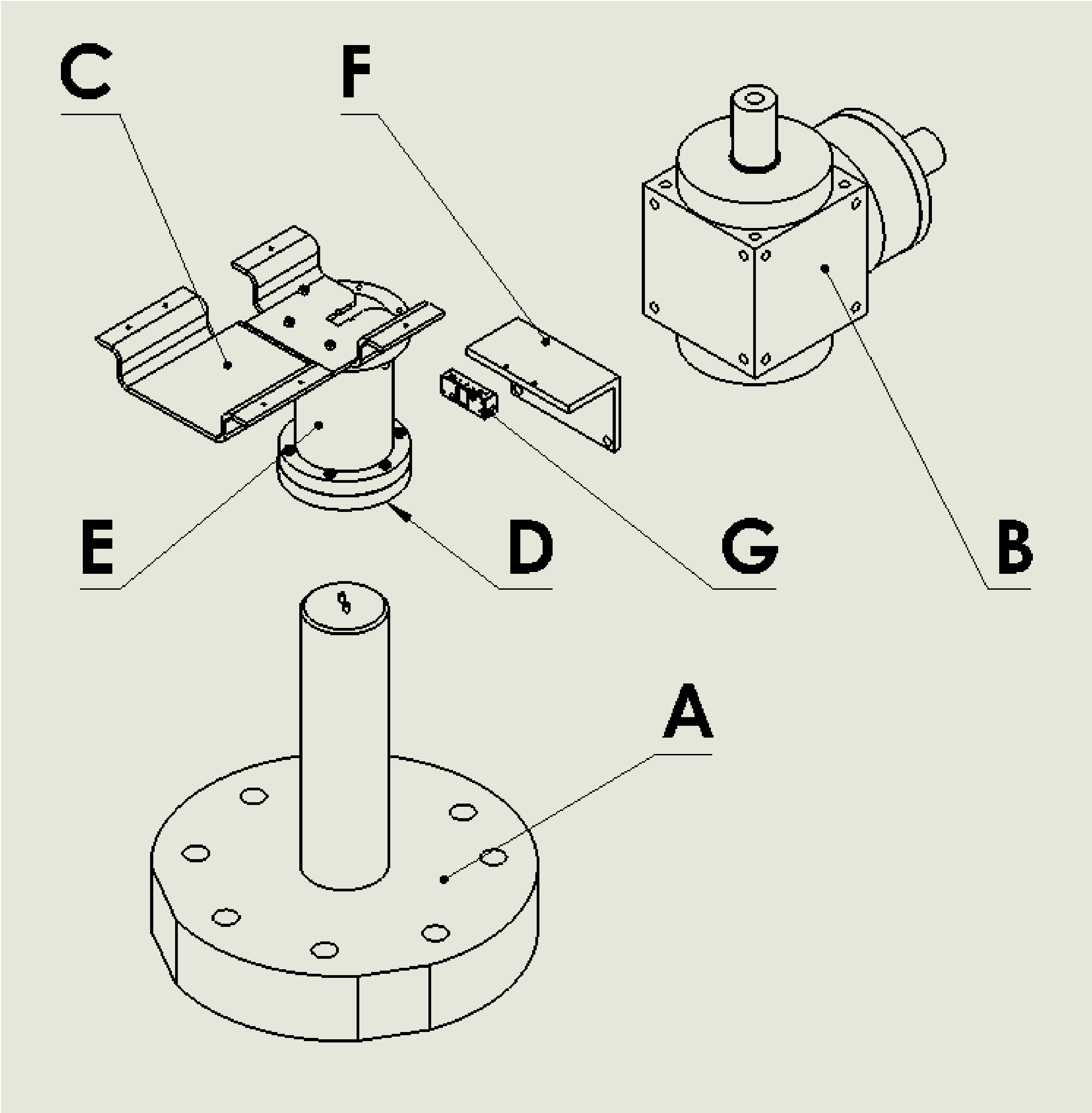


Figure IV.4.12: Positioning System.

The encoder bracket is comprised of two parts: a cable bridge (C) and a sensor mount (E). The cable bridge is mounted to the lower surface of the power train disc using screws and nuts. The bridge will guide the cables from the slip ring (A) to the output cable hole of the power train disc, thus preventing strain on the cables that might occur during rotation of the system. Holes are made on the bridge that coincides with the guide pins on the slip ring. This ensures that the rotation of the power train disc will be transferred to the slip ring and the encoder. The sensor mount is connected to the cable bridge and lowers the encoder disc so that it is leveled with the reader head. The encoder ring is then connected to the lower surface of the sensor mount. The reader head bracket is designed to position the reader within the parameters set by its supplier.The reader head has be within 2.1 ± 0.15 mm while facing the encoder ring directly.

IV.5 Manufacturing Methods

When designing a product, it should be expected that the product is going to be built physically. In order for this to be possible one or more manufacturing methods have to be applied. Manufacturing in this application is defined as making a product from raw materials, using various operations. The type of manufacturing method can differ depending on which component is in question. There are some parts of the main assembly that have special applications, and other material properties, which will dictate what manufacturing method that is the most expedient in accordance with cost and functionality.

When choosing a manufacturing method there are several factors that need to be taken in to account, however the key aspects is not complicated. The manufacturing method has to be efficient in terms of cost, time and functionality. The last point regarding functionality is the most important. The product needs to have its desired functionality otherwise the manufacturing would be redundant.

Secondly comes cost and time, these two are essentially the same thing. As the time of manufacturing increases so does the price. So in essence what the project team needs to define is a manufacturing method, for each individual part that first an foremost safeguards that components functionality, but at the same time is the most cost efficient alternative.

The OMS is planned to be manufactured, however the amount of units is very limited. It is planned to manufacture one unit, because this is a product intended for one specific test rig in the lab at KPS. This will play an essential role when picking a method for manufacturing, because there will be no mass production.

The main manufacturing method that will be applied in the case of the OMS is machining. Machining is a controlled material-removal process, which does includes some loss inn material, but this is already calculated and accounted for in the budget, section IV.6.5. This is also a small price to pay in comparison with the alternatives.

The OMS consists of several different parts, as displayed in figure IV.4.2, which can be differentiated into two groups. Group one is the procurements, meaning the purchased parts. These parts are something that the project team will not be responsible for, because they are purchased from a supplier who has their own manufacturing line. Group two consists of eight different parts that the project team has to facilitate manufacturing for, that being the following:

- **Base**
  The base includes the bottom part of the OMS, and is also the largest component in the assembly.

- **Offset Disc**
  The offset disc provides the offset function for the RWS, and is one of the main components of the assembly.
- **Power-Train Disc**
  The power-train disc could also be referred to as the top plate of the assembly, connecting the bottom part with the offset disc.
- **Pinion**
  The pinion is somewhat of a subcomponent. It is used to drive the bearing in to a rotational motion, meaning it is the component responsible for transmission of motion.
- **Motor Adapter**
  The motor adapter functions as an interface between the drive shaft and the motor. Since the output/input connections on the motor and the angled gear is not the same, the project team had to design an adapter that makes sure that they can be connected.
- **Drive Shaft**
  The drive shaft is an essential part regarding power transmission. It transfers mechanical power from the motor to the angled gear.
- **Rubber Gasket**
  The rubber gasket provides damping to the system and eliminates the metal-to-metal contact between the drive shaft and motor adapter.
- **Motor Bracket**
  The Motor Bracket functions as a cover for the drive shaft.

It should also be mentioned that the project team has constantly modelled the design with the production in mind, resulting in efficient manufacturing. This means that the product is first an for most possible to manufacture. The manufacturing method was thought of in parallel with the modelling, so that the design can be shaped in to something that is easy and cheap to manufacture, and at the same time have the desired functionality.

Conclusion With Semcon Devotek AS

The project team was in contact with an external manufacturing firm in order to get a price estimate regarding the manufacturing, and at the same time get some information as to the appropriate manufacturing method. 2D drawings were exported and an estimate of both cost and method where projected. in common with the project team, Devoteks initial thought was machining, this would cost somewhere around 40 500 NOK, however if water cutting was an appropriate option some discount where to be expected. There are essentially two different parts that are eligible for water cutting, that being the power-train disc and the offset disc. Conclusively, Devotek's estimate for manufacturing method was in close correlation with what the project team envisioned, however water-cutting is something to consider.

IV.5.1 Base

The base of the OMS does not consist of very complex geometry. It has a cylindrical shape with a hollowing in the middle and a flange for fastening.

For this part there is no extra ordinary functions that it has to perform, it needs no abnormal material properties, such as enhanced hardness in the surface. When considering the fact that this is a one unit production and the cost aspect is important, machining is recommended [11].

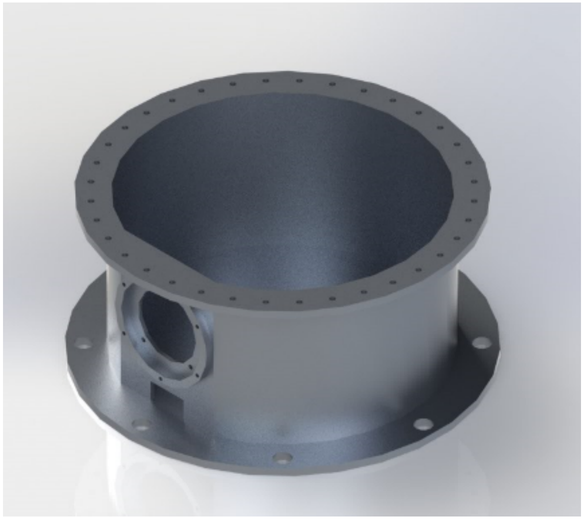


Figure IV.5.1: The Base

The thought behind this is to reduce cost and also maintaining proper functionality. Machining is a well known and used manufacturing method for our contracting entity. Methods like casting and extrusion are not appropriate alternatives, because of the lack of mass production.

The base will be manufactures in two steps. The first step includes the use of a lathe. This process removes the excessive material on the exterior face, creating desired shape. The second step involves the use of a CNC machine. The CNC machine removes the excessive material on the inside of the base creating the hollowing, as well as drilling the holes.

Conclusively, machining is the appropriate choice because it is cost efficient, quick and it does not compromise the parts ability to function properly.

IV.5.2 Offset Disc

The offset disc has quite low complexity and machining using a CNC machine is the appropriate choice [49]. The CNC machine will create both the hole pattern and the main shape of the disc. This is a part that is adapted for machining, and like stated earlier the project team has put countless effort in to making the design more adaptable to the appropriate manufacturing method, meaning this is no coincidence.

Part of the reason for the usage of the CNC machine is the amount of material removed being quite low in comparison to, for instance the base. This will in fact make the offset disc more cost efficient and quicker to manufacture. The geometric shape of the Offset Disc is very basic which makes the manufacturing process easy for the CNC machine to handle.

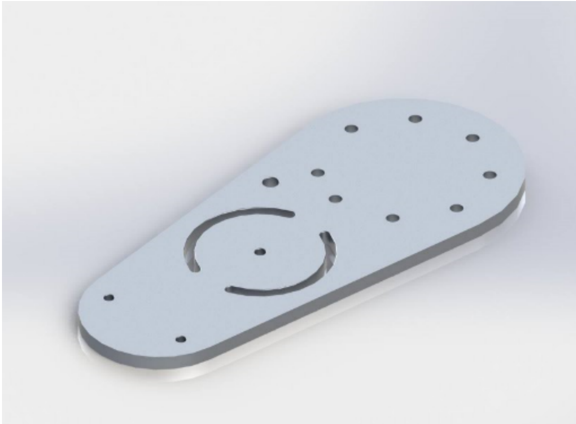


Figure IV.5.2: The Offset Disc

IV.5.3 Power-Train Disc

The Power-train disc is in the same category as the offset disc in section IV.5.2. Both will incorporate the same manufacturing method, given that they are similar in terms of complexity, and also not to different in shape. This makes it so that machining using a CNC machine is going to be the appropriate manufacturing method.

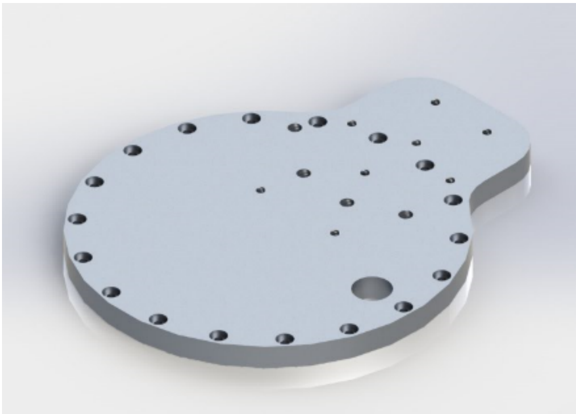


Figure IV.5.3: The Power-Train Disc

The part starts of as a rectangular shaped block, the CNC machine will go on to remove excessive material, and thus creating the desired shape. The last step of the process is to drill the submerged holes, this is also done by the CNC machine. This is a significant advantage since it will only require one machine for production.

IV.5.4 Pinion

As mention in subsection IV.3.4.2, the pinion will be milled using a CNC machine. This is due to the fact that it will only be made one pinion. If this component would be mass produced, casting could be an option, but in the case of the OMS this method is not a good choice in terms of cost. The CNC machines today are very accurate and can create components in almost any shapes.

The pinion will be formed from a round bar. The CNC machine will cut out the teeth with high accuracy [49]. A hole is drilled in the center, along with the key slide, providing it to connect to the angled gear output. This connection will be a press fit, and it is therefor important to make sure that the dimensions and tolerances are correct.

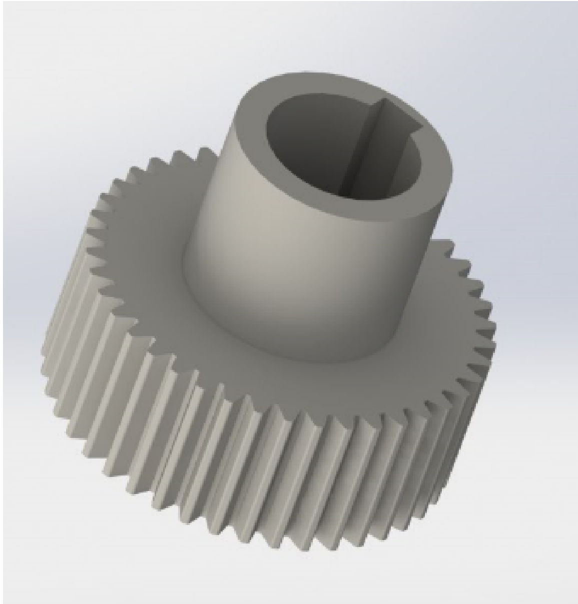


Figure IV.5.4: The Pinion

Since the pinion is exposed to relatively high stresses, it is wise to apply some kind of surface finishing on it. Surface finishing is conducted for several reasons depending on the application. In this specific application, the purpose is to enhance the hardness and wear resistance [49]. This can be achieved using heat treatment and abrasive blasting [11].

IV.5.5 Motor Adapter

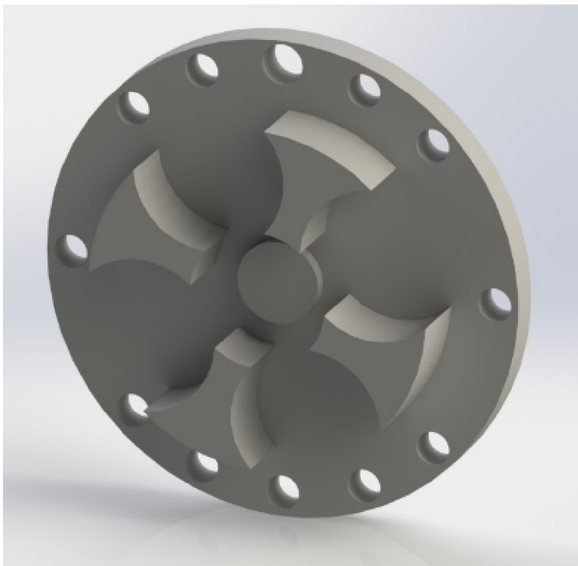


Figure IV.5.5: The Motor Adapter

The Motor Adapter is a relatively small round part, but the geometry demands CNC machining. This is a result of the 4 profiles that arise from the side. These profiles are there in order to create a place for the Rubber Gasket to lie in, and to establish an interface to the drive shaft.

This part will start off as a round bar and the CNC machine will remove the material around the profiles. Holes will then be drilled by either the CNC machine itself or in an external drilling machine. Since the geometric tolerances regarding hole alignment are strict, a CNC machine is recommended.

IV.5.6 Drive Shaft

The purpose of the drive shaft is to transfer rotational motion from the motor to the angled gear. The geometrical shape is considered to have a low degree of complexity, which results in a fairly simple manufacturing process.

The Drive shaft starts off as a circular rod, and will be manufactured in 2 steps [49]. The first step is to use a lathe to create the circular dimensions and shapes. After this step 2 initiates, which includes the use of a CNC machine. The CNC machine will cut out the profiles needed to connect the Drive Shaft to the motor adapter, on the end of the shaft.

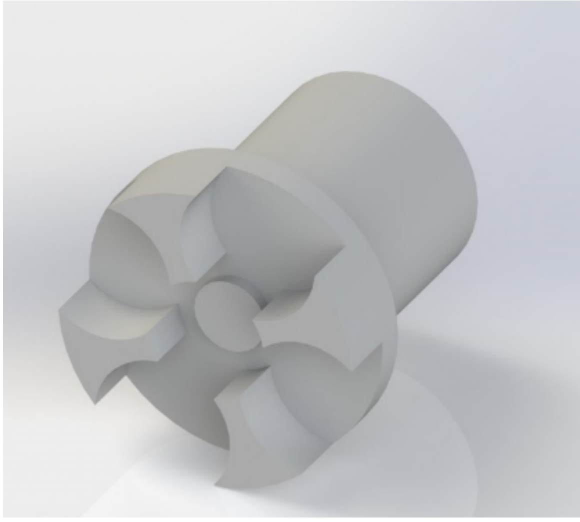


Figure IV.5.6: The Drive Shaft

IV.5.7 Rubber Gasket

The function of the rubber gasket is to be a link between the motor adapter and the drive shaft, providing damping to the system and making sure that there is no metal-to-metal contact.

The Rubber Gasket will be manufactured by casting. The mold will be designed in Solidworks, and a 3D printer will be used to manufacture it. A liquid rubber solution will then be infused into the mold, creating the component. This process is fairly simple and cost effective.

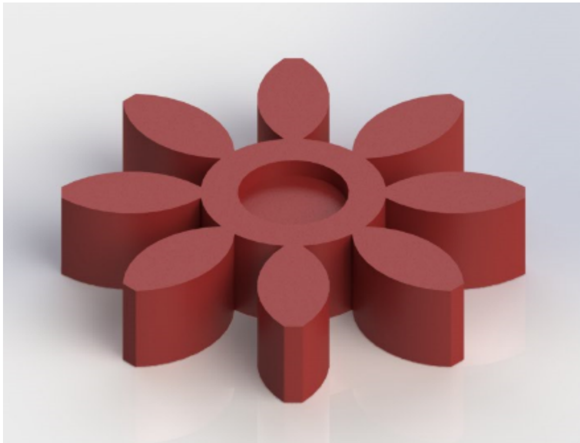


Figure IV.5.7: The Rubber Gasket

It should be emphasised that this is just an option for our contracting entity. If they where to produce it for themselves this would be an option. However seen from an industrial perspective this part is considered a procurement. The project team recognises that our contracting entity is no rubber producer, and that this part most likely would be bought from an external firm.

IV.5.8 Motor Bracket

The purpose of the motor bracket is to protect the drive shaft. This is important in regards of safety, since the drive shaft is a rotating part.

It will be machined from an aluminium tube. A lathe will manufacture this part into the designed dimensions, leaving the "flanges" on the ends with a larger diameter then the center part. Holes will then be driller by either a drilling machine or a CNC machine. The tolerances and properties of this component is not that strict since it will not be a load-bearing part.

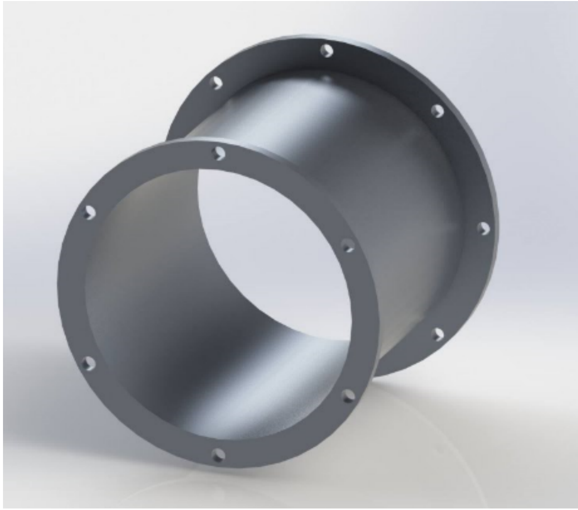


Figure IV.5.8: The Motor Bracket

IV.5.9 Cable Bridge

The purpose of the Cable Bridge is to guide the cables, and shield them from the pinion during rotation. The Cable Bridge is made of sheet metal aluminium, with limited thickness. The manufacturing method involves bending the plate in to the desired shape. Some hole drilling is required.

Additionally the part will be subjected to water-cutting for the small grooves in the part.

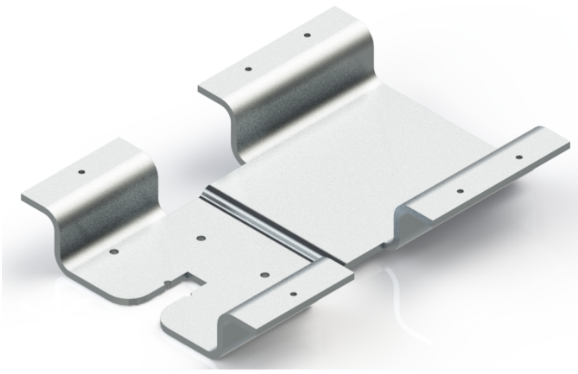


Figure IV.5.9: The Cable Bridge

IV.5.10 Sensor Mount

The purpose of the sensor mount lies somewhat in the name. Its soul purpose is to mount the absolute positioning sensor, at the same time it will aid stability to the cable bridge, through proper fastening.

It will be machined from an aluminium tube. A lathe will manufacture this part into the designed dimensions, leaving the "flanges" on the ends with a larger diameter then the center part. Holes will then be driller by either a drilling machine or a CNC machine.

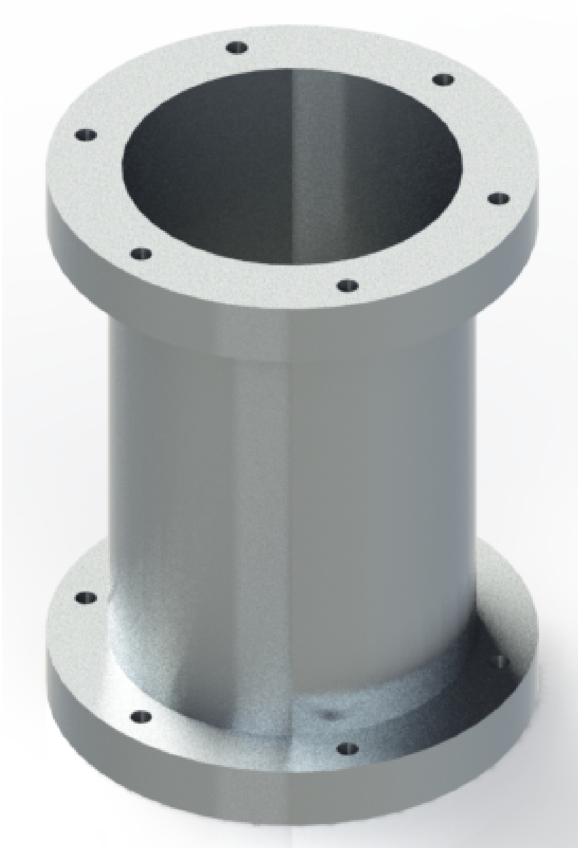


Figure IV.5.10: The Sensor Mount

IV.5.11 Reader Head Bracket

The purpose of the Reader Head Bracket is to mount the reader head in a position that enables it to

The Reader Head Bracket is made of sheet metal aluminium, with limited thickness. The manufacturing method involves bending the plate in to the desired shape. Some hole drilling is required.

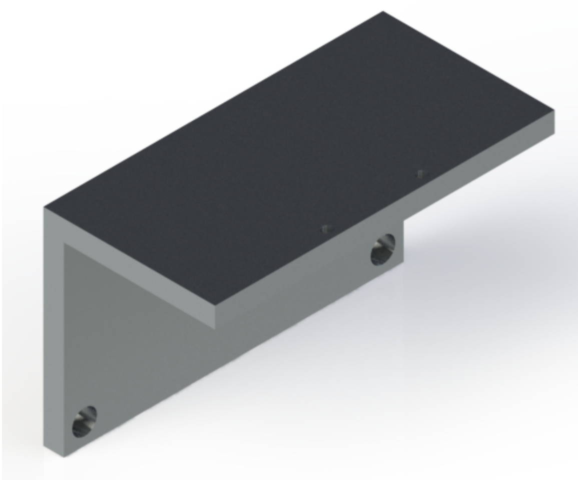


Figure IV.5.11: The Reader Head Bracket

IV.6 Budget

Economy is an important issue in any project and there will always be restrictions in terms of cost. The ultimate goal of any project is for it to be profitable, and a contributing factor to this is having an intuitive structure to the budget. Budgeting and cost estimation is important topics in order to get an abstract overview of expenses and restrictions in the project. This is beneficial for both the project team and the costumer, because it creates an expedient overview, which in turn will help identify boundaries relating to the economic aspect in the design.

In the case of the OMS, it has been decided that to divide the budget into two main subdivisions is appropriate. Practically this means that two different budgets has been worded. One budget will address the procurements of parts, material costs, and so forth, a so-called technical budget. The latter will address "parent" costs, meaning expenses relating to anything other than the parts of the OMS. This is often called administrative costs, meaning a budget that will account for expenses surrounding the project. For instance books, software programs, consultations and so on, essentially anything our external contractor has to take into account.

The main reason for why the two budgets was drafted is to identify relevant boundaries in the project, and to make sure that the costumers demands are met. The two budgets that was formulated will provide a great bit of help when it comes to the boundary of the design, and will also give a nice overview regarding the resources available to the group. At the same time it will provide a structured overview to the contracting entity.

The budget has a lot of interfering factors. Obvious aspects that will interfere with the budget is the choice of supplier, material selection and choice of manufacturing method. That mainly covers the technical budget. The parent budget incorporates everything relating to the progress of the project.

The customer has previously stated that the budget will depend on the solution provided by the group. This creates a loop that is rather hard to brake. On one hand there is the costumer who is pending the solution, on the other hand there is the design group that has to be informed of the restrictions of the project. Essentially, there was no requirement stating an upper price limit. This "problem" was solved by making trade offs, and an efficient design was prioritized over the cost of the solution. However, the aspect of cost was also a heavy influence in the design-process, this might seem like contradicting statement, but it all relates back to the loop that needs to be broken in some way.

IV.6.1 Technical Budget

The technical budget is useful because it will set clear boundaries on the appropriate solution. It will ensure that the costumer is satisfied with regards to the economic aspect. However, the project has not been subjected to any limitations in terms of cost. That is, the limitations are there, just not defined by the customer. The technical budget of the OMS incorporates all manufacturing costs. That includes all the procurements and the cost of machining. The relevant procurements are as follows:

- The Material cost in NOK/Kilogram
- Manufacturing costs
- Slip ring
- Bearing
- Motor
- Angled Gear
- Rubber gasket
- Wiring

All of this will add up to a sum which is considered to be the total cost of the system; the technical budget. This budget revolves around reducing the cost of the system as much as possible, and at the same time ensuring that the appropriate performance requirements are met.

Description	**NOK**
Materials	7 300
Manufacturing	47 500
Slip Ring	50 000
Bearing	25 000
Motor	35 950
Angled Gear	12 000
Wiring	6 000
Fixtures	3 000
Encoder	10 000
Sum	196 750

Table IV.6.1: Technical budget in NOK

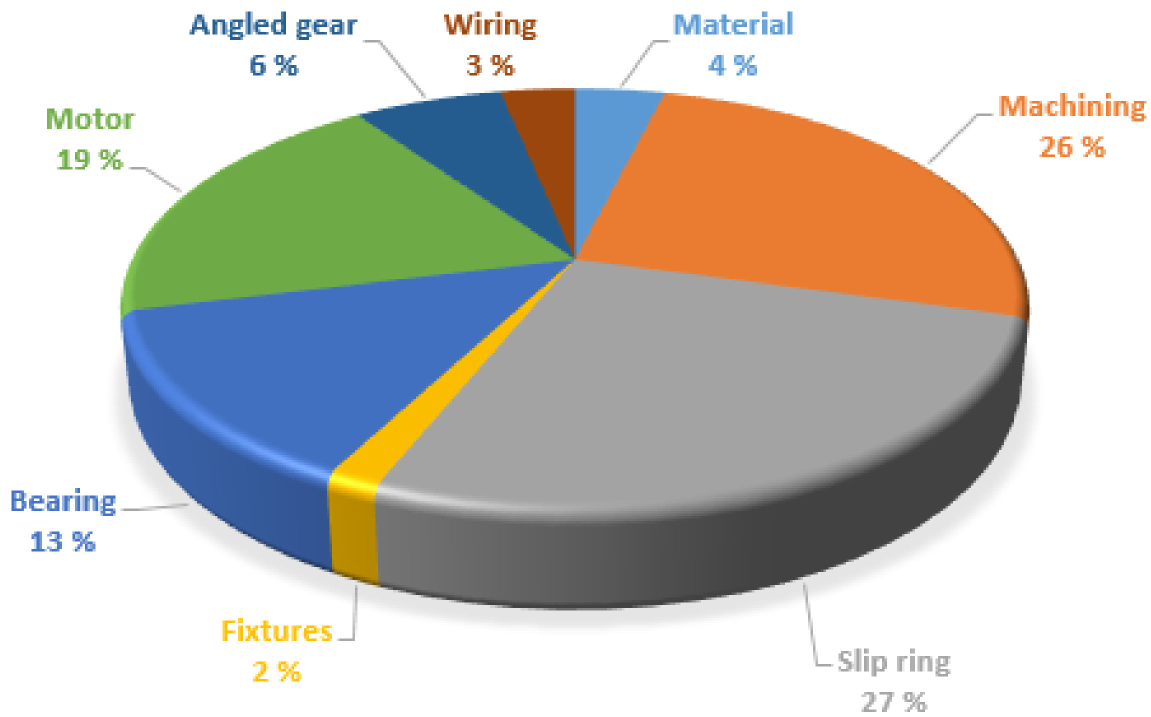


Figure IV.6.1: Pie Chart of the technical budget

It should also be noted that in some instances an official priced offer was not received by the supplier. This is the case for the bearing and also the wiring. This is something that was discussed with the contracting entity, and in instances like this it was deemed sufficient to make a price estimate on behalf of the supplier. This estimate was done by the contracting entity, and not the project team.

There are also some components in the assembly that are to be decided by either future groups or the costumer. This is the case regarding the cables. The outline for the cable design is not designed at this point in time. The solution to this problem is to inquire an estimate based on expertise from KPS.

IV.6.2 Administrative Budget

The administrative budget for the OMS involves like stated earlier an estimate for everything surrounding the project. The factors that are taken into account when estimating the administrative budget are as follows:

- Encyclopedia: books/access to information
- Consultation: payed engineers/constructors for consultations
- Prototype: Includes Lego models and 3D-printing
- Required software

This will add up to a sum, which is considered to be the total cost of the immediate investment for the contracting entity. This budget is mainly for the costumer, so that he knows what investment is expected in the immediate future.

Description	**NOK**
Encyclopedia	2 000
Consultation	5 000
Required software	2 000
Prototype	2 000
Details for presentation	2 500
Sum	**13 500**

Table IV.6.2: Administrative budget in NOK

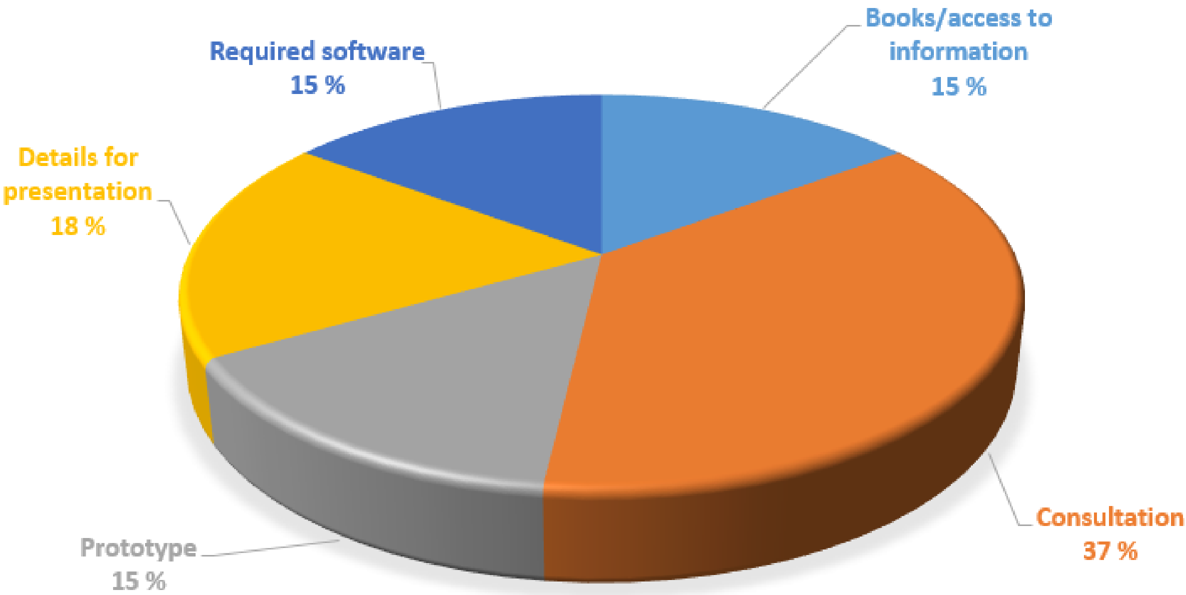


Figure IV.6.2: Pie chart of the administrative budget

IV.6.3 Efforts to Reduce Costs

An important aspect to address in relation to the budget and economy is how the group has made countermeasures to reduce the cost of the product. The product is to be as cheap as possible, but at the same time maintain a given level of compliancy with the stakeholders requirements. That is why efforts to reduce cost is thought of and implemented consecutively throughout the design process.

- **Manufacturing Costs**
  Some of the things that the group has actively worked towards in order to reduce the cost of the project is to be aware of the manufacturing method that is to be implemented. This is one of the aspects that was put a lot of thought into, and is one of the key elements to reducing the cost of the project. The manufacturing costs mainly incorporates the cost of machining, that includes use of CNC machines and so on, more information regarding manufacturing is found in chapter IV.5.In many ways the right manufacturing method can be very time and money saving. For instance casting is not an applicable manufacturing method, and would be a lot more costly compared to machining.
  Furthermore, a rough estimate for the manufacturing costs where requested from Semcon Devotek AS. They are a well known manufacturer and is considered to be qualified to offer a realistic estimate. Semcon Devotek AS's estimated cost for manufacturing the parts is presented in table IV.6.3. It should also be mentioned that the price of manufacturing will vary depending on the appropriate geometric tolerances. Water cutting was also a suitable option, in some cases of the manufacturing, the use of this method will decrease the cost to some extent.
- **Avoid Complex Geometry**
  Another money saving element that has been actively thought of is the aspect of complex geometry in the design. The increase in complexity relating to the geometry is proportional with the manufacturing costs. This means that it was a relevant topic to consider in order to make a cost efficient product.
- **Management of Size**
  Oversizing was also something that was thought of, and countermeasures where put into place in order to prevent this from happening. There was in many ways a balance to maintain. On one side the factor of safety is always going to be 2, so every part is designed to withstand twice the load it is subjected to in a worst case scenario. On the other hand, a factor of safety of more than 2.5 is considered to be unnecessary in this applications. So to find a balance between the factor of safety and money saving countermeasures is crucial

Further information about efforts to reduce cost is discussed in chapter IV.5, named Manufacturing Methods.

IV.6.4 Cost Estimation

This section examines the calculations made in order to make a proper budget. This ensures both the costumer and the project group that the budget is set up in a sufficient way, and everything is soberly estimated.

One of the main calculations when it comes to cost estimation is the material costs. Not all parts are subjects to detailed material estimation. The parts that the group has to manufacture is estimated in terms of material. The procurements is outside of that domain, because of the fact that a price estimation has already been done, since they are products from another manufacturer. The relevant parts for cost estimation in the OMS assembly is the base, the power-train disc, the offset disc, the pinion, the motor adapter, the motor bracket and the drive shaft. These seven parts are variable in size, and the cost will vary accordingly. The parts will be evaluated in terms of manufacturing and material costs.

All parts have the same manufacturing method, that being machining. This is the most cost efficient method for the product. There are many reasons for this, but the main reason is that it is quick and the fact that it is only planned for one unit to be manufactured makes the decision of going for machining justifiable. There is no production line to be established here.

When ordering parts for machining it is typically bought in two geometrical shapes, that is circular rods or rectangular plates. The price of the material will depend on the volume of the "block" that is ordered.

Each part of the OMS that is subject to machining was made a material block for, in order to estimate the amount of material, and thereby the weight which will ultimately give a price. The cost of the relevant material (6082 T6 aluminium) varies from 2000-4000 dollars/ton, according to Alibaba trading site [39]. For the sake of simplicity and safety the price used is 4000 dollars/ton. The same thing was done for the steel used in some parts of the assembly (Steel SS-EN10083), here the material cost was at maximum 3000 dollar/ton, according to Alibaba trading site [51]. The highest possible price is used in order to give a proper and safe estimate. This will ensure that embezzlement is not going to be the case, and the costumer will not get any unforeseen surprises.

In addition to material estimation, it is also expedient to estimate the cost of manufacturing. Yet again the scope will serve as an important restriction. The only relevant parts to estimate manufacturing costs for are the ones designed by the group, as discussed prior in the document.

When it comes to cost estimation in this sense it is imperative to get in contact with professionals. So the way the cost estimation for manufacturing was done is through sending a request to a workshop, and getting an offer in return. The only way to give a proper and realistic estimate to the costs related to manufacturing is by contacting the manufacturer, and request a price as to how much racecourses they need to make the product.

A cost estimate regarding machining of the parts from Semcon Devotek AS is provided in table IV.6.3.

Part	NOK
Base	10 000
Pinion	10 000
Offset disc	3 500
Power-train disc	4 000
Drive shaft	5 000
Motor bracket	4 000
Motor adapter	4 000
Sensor mount	4 000
Reader head bracket	500
Cable Bridge	2 500
Sum	**47 500**

Table IV.6.3: Machining cost in NOK

IV.6.5 Material Estimation

The blocks made for the material estimation were made slightly bigger then the actual size of the parts, this being because of machining. Machining is in fact a process where large solid bodies are cut down to more complex geometrical shapes. That means that some excessive material has to be calculated. However, this will give all the necessary factors for the cost estimation in relation to the material used. They are as follows:

Raw material price:

Aluminium 6082 T6 : ((4000 dollar/ton)/(1000 kg/ton)) · 8.13751 NOK = 32.55 NOK/kg [39].

Steel SS-EN10083 : ((3000 dollar/ton)/(1000 kg/ton)) · 8.13751 NOK= 24.41 NOK/kg [51].

Steel AISI 316 : ((2700 dollar/ton)/(1000 kg/ton)) · 8.13751 NOK= 21.97 NOK/kg [52].

8.13751 is the currency for one US dollar eg. 1 US dollar $\approx$ 8.13751 NOK [10]

Part	Shape	Diameter	Height	Weight	Material	Cost (NOK)
Base	Circular	580 mm	230 mm	165 kg	Al 6082 T6	5380
Drive-Train Disc	Circular	640 mm	40 mm	35 kg	Al 6082 T6	1140
Pinion	Circular	75 mm	35 mm	1.2 kg	SS-EN 10083	30
Drive Shaft	Circular	60 mm	60 mm	1.3 kg	SS-EN 10083	35
Motor Adapter	Circular	75 mm	20 mm	0.7 kg	SS-EN 10083	20
Motor Bracket	Circular	150 mm	140 mm	3 kg	Al 6082 T6	100
Sensor Mount	Circular	80 mm	100 mm	1.35 kg	Al 6082 T6	45

Table IV.6.4: Material cost for the circular shaped parts.

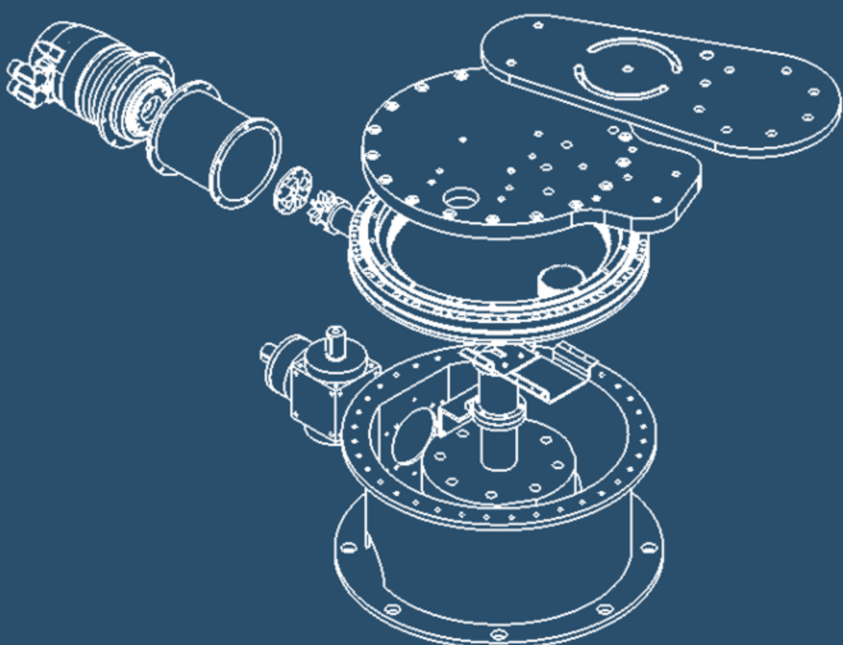
Part	Shape	Length	Width	Height	Weight	Material	Cost (NOK)
Offset Disc	Rectangular	560 mm	260 mm	20 mm	23.3 kg	AISI 316	512
Cable Bridge	Rectangular	170 mm	170 mm	3 mm	0.17 kg	Al 6082 T6	6
Reader Head Bracket	Rectangular	82 mm	82 mm	5 mm	0.1 kg	Al 6082 T6	4

Table IV.6.5: Material cost for the rectangular shaped part.

This adds up to a total sum of 7 272 NOK $\approx$ **7 300 NOK**.

University College of Southeast Norway
Mechanical Engineering
2016 - 07

Test Specification
Orbital Motion Simulator



Abbreviations

Abbreviation	Explanation
VAT	Validation Test
VT	Verfication Test
STRQ	Stakeholder Requirement
SRQ	System Requirement
DRQ	Design Requirement
KPS	Kongsberg Protech Systems
HSN	Høgskolen i Sørøst-Norge
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
CAD	Computer-Aided Design
PUT	Parts Under Test

Revision History

Date	Version Number	Comment	Approved by
02.02.16	1.0	First test specification identified.	Martin Sandberg
07.02.16	2.0	VAT004, VAT005, VT006, VT007 VT008 and strategy added.	Martin Sandberg
17.02.16	2.1	VAT006, VAT007, VAT008, VT009, VT010, VT011, VT012, VT013 added.	Anders Gunbjørnsen
18.02.16	2.2	VAT009-VAT014, VT014-VT021 added.	Martin Sandberg
19.02.16	2.3	VT022-VT027 added.	Fredrik Thoresen
08.03.16	2.4	VT028-VT029,VAT015-VAT018 added.	Anders Gunbjørnsen
09.03.16	3.0	Revised.	Anders Gunbjørnsen
13.04.16	3.1	Definitions and content revised.	Heidi Kallerud
16.05.16	3.2	Abstract added. Introduction revised.	Heidi Kallerud
18.05.16	3.3	Tests edited.	Heidi Kallerud
22.05.16	3.4	Document approved.	Kjetil Fjeld

Table of Contents

Abstract

The test plan aims to provide a guideline for execution of tests on complex systems. A test strategy can prove useful to ensure that all components and interfaces are tested in a purposeful matter than promotes transparency and make it easy to detect where any potential failure occurs. The Incremental Test Methods was chosen for this project, and two incremental test pathways were developed to ensure step-wise and structured testing within the two major branches of testing in this project; *Finite Element Analysis* and *interfaces*. Every requirement has an accompanying test, in which an acceptance criteria has to be met in order to fulfil the requirement. Each verification and validation test is concisely listed in the in chapter V.7 and V.8. Next follows the test reports, which provide details of the methods used to verify requirements; e.g. finite element analysis; and the accompanying results.

V.1 Introduction

The following document contains the test specifications for the Orbital Motion Simulator (OMS). The overarching method that will be used to structure the test procedure is presented. Each requirement stated in the Requirement Specification document has an accompanying test that will be used to certify that the requirement has been fulfilled. This document concisely presents each test, which system requirement it belongs to and ultimately its dependent the stakeholder requirement.

The level to which the OMS fulfills the defined system requirements (SRQ) will firstly be verified through verification tests; after which the corresponding stakeholder requirements(STRQ) will be validated through appropriate validation tests. In the event of the OMS successfully passing both the verification and validation tests it will be defined as having fulfilled the stakeholder-requirements.

The test specification setup template is shown below. The template consists of the requirement identification, a description and also the ranking of the requirement. Each test has a unique ID that is used to promote traceability between documents and makes it easy to refer to a given test within text. An acceptance criteria is stated for each test. An acceptance criteria is the results the system needs to obtain in that specific test in order to fulfill the requirement that the test originates from. In the box named "testing procedure" a brief summary of the test that will be performed is stated. The full test procedure is presented in detail in the test report document.

Test ID	**Description**	**Ranking**	**Req. ID**
Test ID	Status	Description	SXX
Acceptance Criteria			
Testing Procedure			
Testing Equipment			
Note			
Performed by			

V.2 Strategy

For the purpose of the current project an Incremental Test Method will be used as the strategy for testing. The Incremental Test Method is a combination of Top-Down and Bottom-Up testing, and is especially well suited for incremental development of systems through numerous iterations [60]. Each step in an incremental testing procedure will consist of either verification or validation of a component. During this approach the most critical components is tested first, after which components are added a few at a time and then tested in compound. Trying to integrate and test all or many components at a time make it difficult to identify problematic components and interfaces [60].

In incremental testing the revealed failures are most likely to stem from the component that was most recently added. However, the sequence of component testing must be carefully considered. Therefore, an iteration has been dedicated to causal-loop analysis and identification of critical components. This iteration will show how different variables in the system are interrelated, and how failure to fulfill one requirement will affect other requirements and system traits. Each system requirement has been associated with a dedicated test, as shown in the Requirements Traceability Matrix in Appendix C, in order to ensure that all stated requirements can actually be tested. However, the order in which these tests should be performed is not straight forward. A thorough understanding of the system, its components and traits is needed in order to assess their interoperability. Early iterations develop an understanding of the system and various concepts of system design. A latter iterations in this project aim at expanding on an in-depth knowledge. This iteration will help determine the major and minor increments of component testing [60].

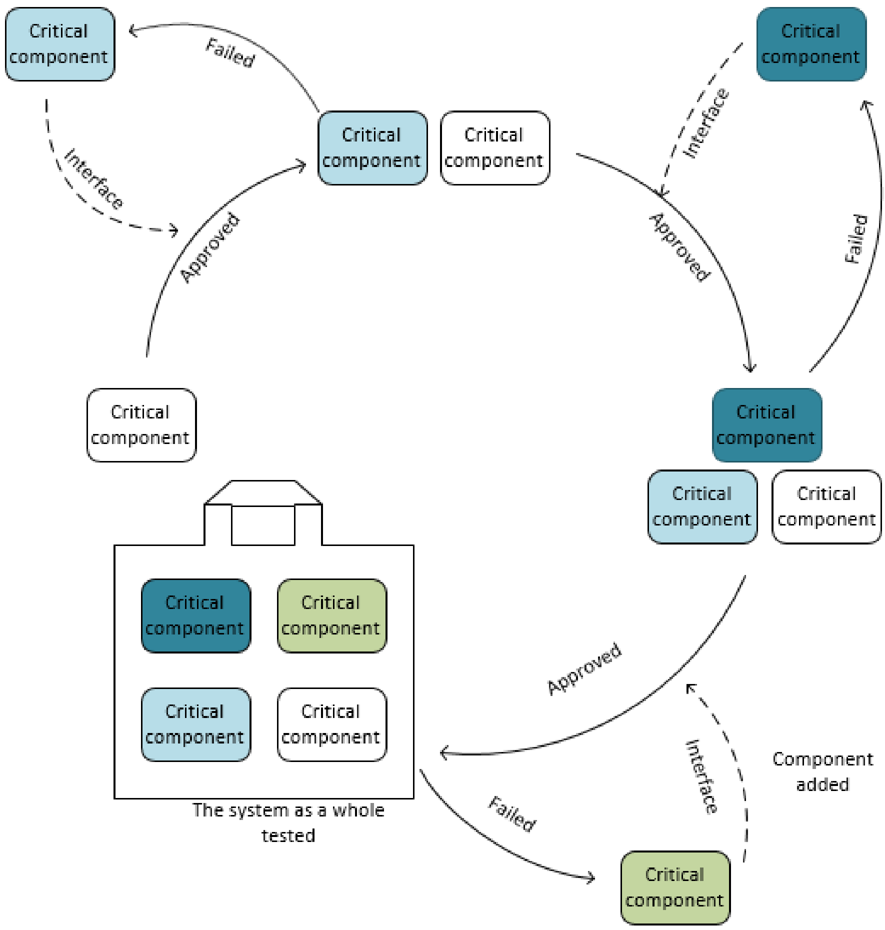


Figure V.2.1: OMS Incremental Testing Strategy

An in-depth analysis of any failed tests is necessary in order to reveal whether the issues stems from traits related to the component or interfaces. In these instances a "Black-box" approach will be used, where the expected test result serve as input, the actual test result is the output. All known constraints and controls, example given material traits, interfaces etc, are identified and will be tested systematically in order to reveal the origin of the problem.

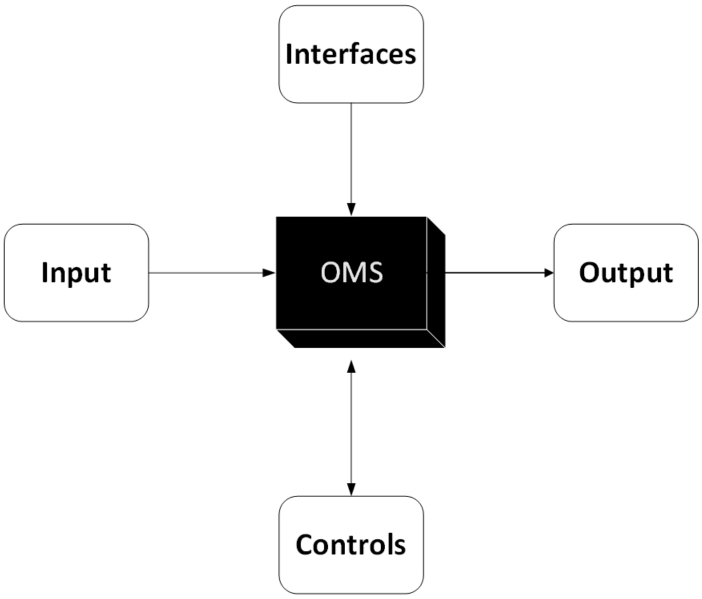


Figure V.2.2: OMS Black-Box Testing Approach

V.3 Method

A number of requirements where issued by Kongsberg Protech Systems (KPS), which where then formulated into specific stakeholder requirements. The stakeholder requirements(STRQ) are then broken down into more detailed system requirements(SRQ), after which the system requirements(SRQ) are further broken down into design requirements(DRQ). The SRQ and the DRQ will be allocated to a specific part of the system. This allocation is clearly visible in the Requirement Traceability Matrix which easily gives an overview of all the requirements that pertain to a specific part of the system.

Furthermore it should be added that all tests, that includes both VAT and VT tests, are tested on a superior system level. Meaning that the tests will not relate to something to specific, and at the same time not test the stakeholder requirements, which is considered to be to broad. This is some of the reasoning for why the stakeholder requirements are broken down into system requirements, so that they are eligible for testing.

V.3.1 Verification and Validation Testing

When it comes to testing method, a number of different test methods exists that correspond to the different stages of the system's life cycle. Basically there are two main categories of tests which relate to the assessment of the system.

- Verification tests

  Verification tests are there to attest fulfilment of the system requirements [2]. All system requirements are stated in terms of traits that can be quantified. Verification tests assess whether these requirements are fulfilled through measurements or calculations on simplified models. Handwritten calculations, FEM simulations, basic prototypes and samples can serve as verification tests [2]. The test results aim to provide sufficient evidence that one or more system requirements are verified and the design can progress into e.g. more detailed design or manufacturing.
- Validation tests

  Validation tests are used to ensure that the system works as intended [2]. The concept of validation focus a lot on the costumer, it is often said that the validation process is there to ensure that the right product is built. It is therefore performed on a real system in its intended environment. Validation tests resemble field test, which are aimed at assessing the operational life of the system. In order to make sure that the right product is built, techniques like demonstrations are utilised. Demonstration is a physical assessment, which can either be done on the true system or a prototype. Validation tests are used to certify to the stakeholders that the delivered system fulfills their stated stakeholder requirements. Hence, fulfilling all stakeholder requirements should be confirmed through a validation test. In the case of the OMS it is unlikely that validation tests can be performed on the final, manufactured system in its intended environment, due to the restricted amount of time available for the project. However, validation tests are formulated where applicable for most of the requirements, because a requirement can only fully be certified by a stakeholder through proper validation tests such as demonstrations [2].

To summarize, the test method that is the most applicable for the OMS within the scope of this project is the verification, which is often done in the design phase of the systems life cycle. The time scope of the project does not allow for a full scale prototype to be machined and assembled; hence, validation tests can not be performed. However, the OMS test specifications are worked out with the intention of being able to perform both verification and validation tests at some point in time to fully certify fulfilment of the stakeholder requirements.

V.4 Basic description of the system

KPS have numerous customers that request to have the RWS mounted onto a turret-carrying vehicle. This significantly increases the complexity of integration between the systems. The great level of complexity of design, integration, testing and verification requires a "demo system" that simulates how the system will respond in real operational environments. The KPS Software Division and the KPS Testing Division works on projects aimed at integrating the input from the two rotating systems; the turret and the RWS. Some of the integrated functions can be simulated in software, but simulating accurate data is challenging. The possibility to adjust the centre of the RWS away from the centre of the turret in the Turret Simulator is necessary in order to acquire specific data and develop software that supports the various set-ups required by customers. Getting access to a full turret has proven difficult and costly as it involves significant traveling. Hence, a low-cost physical Turret Simulator that can be adapted to simulate input data from various RWS placements on the turret is therefore needed. The purpose of the present project is to design a system that will support rotation of the RWS in isolation to, and in parallel axes off-set to, the rotating turret.

V.5 Parts under test (PUT)

The PUT section aims to define what parts of the system that need to be tested, dividing it into different subsections or "subsystems for test". The PUT section function as a scope for what parts of the system that can be tested internally, and which tests that are only going to be facilitated for the future. Another important function of the PUT section is to give a general overview of what parts of the system that needs to be tested, and in what way.

The PUT will define what needs to be tested, directly related to the product and its key functions. This also corresponds with the incremental test strategy that was chosen. This will be divided into the system as an entirety, and also in to different subsystems, that needs to be tested individually.

Practically the tests conducted on the OMS are divided in to verification tests and validation tests. As stated earlier there is a distinct difference between the two. In relation to the bachelor project it is expedient to bend the definition of what a verification test and a validation test is.

When it comes to the definition of verification in an industrial context it is based on the ideology that in order for something to be verified it has to be tested physically, with numerical measurements, and also have expedient calculations to back it up. However, given that this is a bachelor project, some simplifications are in order. The definition of a verification test; called a VT test in this project; is strictly defined to relate to calculations and simulations, as that this is the only realistic type of verification that can be provided in the short amount of time available. Usually a mathematical calculation or a CAD simulation is not sufficient evidence that the requirement is verified. However, what the group define as verification is calculations and simulations through mathematical models and CAD programs, because this is the only form of indication that a requirement is verified that can be provided without a physical prototype.

The definition of a validation test is also to some degree bent. The project team has decided that a validation test or a VAT test is strictly restricted to apply to physical tests. This include demonstrations, but also physical tests that has numerical measurements, which is what normally is defined as a type of verification, but after the simplification a more tidy structure will emerge, and at the same time it will prevent "double" verification tests. Meaning that a requirement has two tests both relating to the verification of the requirement.

With these definitions in place it is intuitive what tests that can be conducted by the group itself, and what tests that just have to be facilitated for. Because of the fact that a prototype is unrealistic, the only tests that is to be performed by the group are the VT-tests. The VAT-tests are just to be facilitated for, and is to be performed some time in the future.

It is expedient to divide the testing in to more categories. The further categorical division that the tests are divided in to is tests relating to the system as an entirety and the tests relating only to a subsystem in the OMS‘s assembly. This is an important subdivision that will set the testing in to a more tidy test setup, and it will help structure the practical testing.

V.5.1 The system as an entirety

The system as an entirety needs to be tested through validation and verification tests so that it can properly certify that the system can be used for its intended purpose in the intended environment. Different subsystems will be tested in isolation before adding more subsystems and testing how these subsystems interact with each other; as described in the Incremental Testing strategy.

However, VAT-tests have to be tested with the whole system being operable, and in full assembly. With a starting point in the Incremental Testing strategy the parts that needed to be tested in isolation before integration into the assembly were listed. The hierarchy and logical architecture of the system then dictated in which order the components should be added to the assembly. Two Incremental Testing pathways were developed; one for a logistic order of Finite Element Analysis and one for testing of components and their corresponding interfaces. In both cases the input loads are the "worst case scenario" as defined in the Design chapter.

V.5.1.1 Finite Element Analysis

The Finite Element Analysis (FEA) aims to uncover if the components and fixtures will be able to hold the components in place during an operational worst case scenario. By starting with one component and incrementally adding more the FEA will uncover overloading of parts, plastic deformation and failure of components. The test pathway is outlined in figure V.5.1 below. Each individual component is verified against their associated design requirements by handwritten calculations, modelling or FEA prior to being added into the assembly. Lastly, in order to get an accurate load scenario the force analysis has to be done on the system as an entirety in order to portray the real operational scenario.

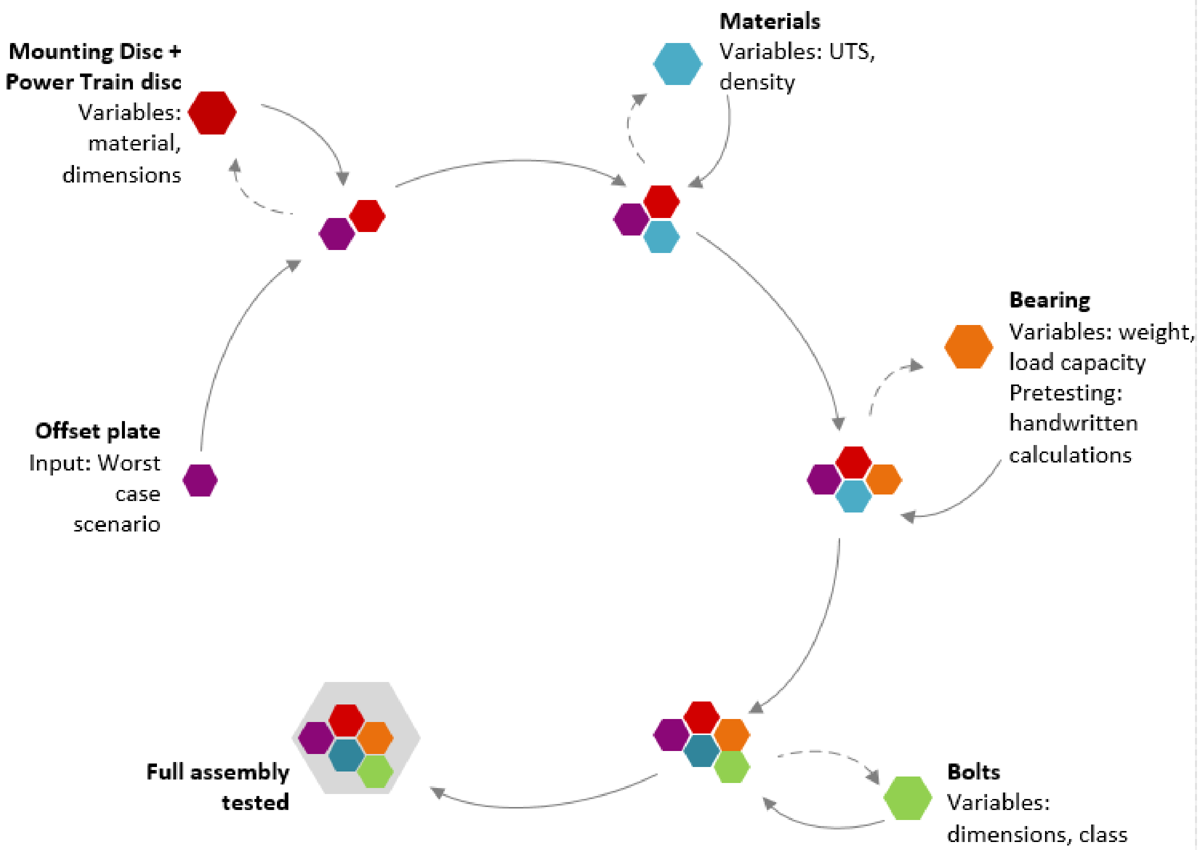


Figure V.5.1: Incremental Testing Pathway: Finite Element Analysis

V.5.1.2 Component traits and Interfaces

The pathway shown in figure V.5.2 below shows the planned order in which separate components and their corresponding interfaces will be tested. The traits of each component will be assesses with regards to the design requirements and verified by calculations and/or modelling where appropriate.

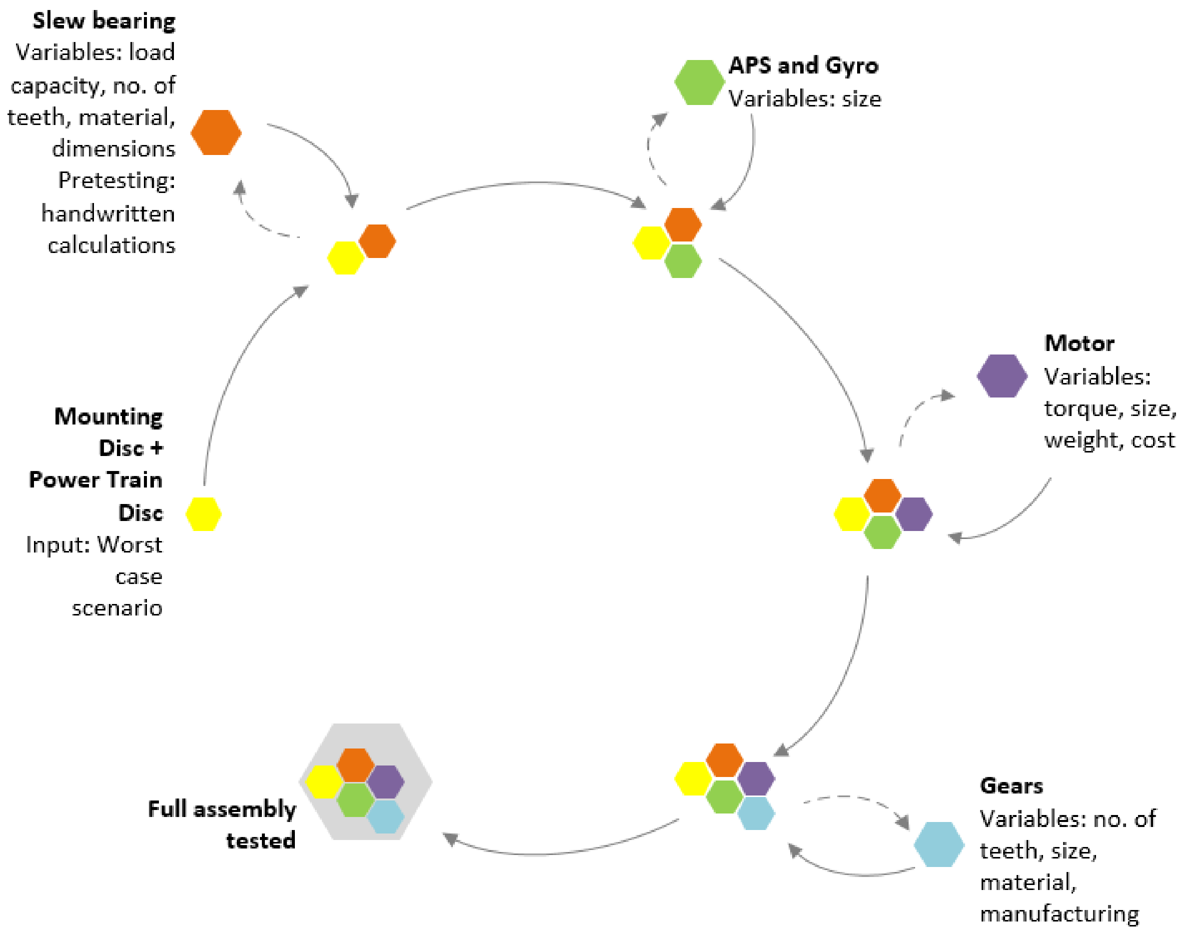


Figure V.5.2: Incremental Testing Pathway: Components and Interfaces

V.5.2 Subsystems for test

In order to properly define what tests that need to be conducted on the system, it is expedient that the system is divided in to subsystems that can be verified separately before adding them into the assembly. The aim of subsystem testing is to uncover issues and design parameters that can most easily be identified and solved when looked upon in isolation. The subsystems are tested by handwritten calculations, modelling and FEA. In the application of the OMS the identified subsystems that need to be tested individually are shown in the pathways figures above (figure V.5.1 and V.5.2), and were defined as:

- Motor
- Bearing
- Mechanical fixtures/bolts
- Slew bearing
- Gears
- Power Train Disc
- Mounting Disc
- Offset disc
- Absolute Position Sensor and Gyroscope

All these components serve their own purpose and function, making them individual subsystems. It is appropriate to test all these subsystem individually, otherwise the complexity of the test would be too much and it would be challenging to identify the source of the problem if the system fails a test. Verification of the traits as stated in the supplier catalogues are typically done by the supplier; however, the project team must be able to confirm to the contracting entity that, example given, the motor can provide sufficient output torque under the required load situation. As mentioned earlier this will be done through mathematical calculations and tables form the supplier.

V.6 Test equipment

This segment of the test specification aims to provide an overview of the equipment needed in order to conduct the verification and validation tests. The purpose is to provide an overview of the resources and equipment that will likely be needed in order to fully certify that the requirements are met. The list also serves as a check list for equipment that needs to be in place before commencing the testing, in order to make the tests as efficient as possible.

A parent listing of all the equipment needed to conduct the tests specified in this document is defined in the following segment:

- Protractor
- High speed camera
- Solidworks CAD program
- Climate chamber
- Torque wrench
- Strain gauges
- Measuring tape
- Scale
- Microsoft Excel

V.7 System validation tests

Note that all validation tests should be ran with a "dummy" RWS, weighing as close to 250 kg as possible, mounted on top of the OMS system. This is to prevent loss of valuable equipment in case of failure of structures during validation testing.

Test ID	Description	Ranking	Req. ID
VAT001	The emergency stop system shall be an independent system	AACB	SRQ008
Acceptance Criteria	A mechanically induced emergency stop button shall be connected to the wiring interfaces into the system		
Testing Procedure	A mechanical emergency stop button is clearly visible and easily reachable from the test operating area.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT002	The system should be able to offset the RWS' center from the motion table center with at least 30 cm at 10 cm increments.	BACC	SRQ010
Acceptance Criteria	It is possible to position the RWS 10 cm, 20 cm and 30 cm respectively, away from motion table center.		
Testing Procedure	Demonstration on physical model. The offset mechanism is set to 10,20 and then 30 cm, it is then proven using measuring tape.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT003	~~The system shall have a solution that limits the friction coefficient to a maximum value of 0.010.~~	AABB	SRQ003
Acceptance Criteria	Friction coefficient does not exceed 0.010.		
Testing Procedure	Confirmation of this fact is given by the external supplier. Alternatively it will be measured using mathematical models		
Testing Equipment	Data sheet form external supplier.		
Note	Deleted		
Performed by			

Test ID	Description	Ranking	Req. ID
VAT004	The system should have a free 360 degree azimuth movement range.	BCAA	SRQ055
Acceptance Criteria	The system must be able to rotate 360 degrees around its own vertical center axis.		
Testing Procedure	Done through a demonstration, where the OMS rotates three complete turns along its own axis. This procedure is performed in both azimuth directions.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT005	The Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0.1 mrad.	ABCB	SRQ013
Acceptance Criteria	The acquired motion data on the lab computer holds an alignment accuracy of 0,1 mrad.		
Testing Procedure	The position sensor is mounted onto the OMS. Data collected and analysed through computational software confirms the given accuracy.		
Testing Equipment	Relevant software.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT006	The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.	AABC	SRQ016
Acceptance Criteria	No permanent deformation is created to either component of the interface.		
Testing Procedure	The RWS is mounted onto the OMS with a preload torque of 130 Nm in the bolts, applied with a torque wrench.		
Testing Equipment	Torque wrench with adjustable torque load.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT007	The system shall be able to withstand being mounted to the motion table using a preload torque of 200 Nm.	AABC	SRQ018
Acceptance Criteria	No permanent deformation is created to either component of the interface		
Testing Procedure	The OMS is mounted on to motion table with a preload of 200 Nm with a torque wrench.		
Testing Equipment	Torque wrench with adjustable torque load.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT008	The system shall have a solution for the guidance of the wiring to the RWS.	AABD	SRQ025
Acceptance Criteria	The system is fitted with a slip ring. The bending radius of any of the output and input wires is no less than 5 times the diameter of the wire.		
Testing Procedure	During demonstration the system rotates three complete turns along its own vertical axis, without obstructing the wires.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT009	The system shall be assembled in a maximum time of 15 minutes.	ABBC	SRQ034
Acceptance Criteria	Time used from start to finish of the assembly does not exceed 15 minutes.		
Testing Procedure	A lab technician performs the assembly according to the guidelines given in the provided OMS product manual.The time from start to finish is measured.		
Testing Equipment	Stopwatch.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT010	The motor shall be able to deliver a peak torque output of 120 Nm at speeds ranging from 1 mrad/sec up to 2.1 rad/sec (120 deg/sec)	AACC	SRQ002
Acceptance Criteria	The system is able to rotate the system during a motion table incline of 25 degrees at a speed of 1mrad/sec and a speed of 2.1 rad/sec.		
Testing Procedure	The system is set to rotate 3 turns at 1 mrad/sec and 2.1 rad/sec respectively at a motion table heave incline of 25 degrees.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT011	The system shall have an azimuth movement range from -90 to +90 degrees.	AAAB	SRQ001
Acceptance Criteria	The system can be rotated at least 90 degrees rotation in each azimuth direction.		
Testing Procedure	During demonstration the system can rotate 90 degree in one direction before stopping and rotation 180 degrees in the other direction.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT012	The system shall have a minimum azimuth speed of 1mrad/sec.	AAAB	SRQ004
Acceptance Criteria	The slowest operating speed of the system, with the RWS mounted onto the offset disc, is no more than 1mrad/sec.		
Testing Procedure	A point of origin is selected (Point A). An additional point B is selected and placed 180 degrees from the point of origin. The time used to rotate from the point of origin to point B with the motor set to the lowest possible operating speed is measured through the help of a video camera.The collected data is analysed on a computer, where the video is slowed down significantly, and the time taken to rotate from A to B is used to find the average speed.		
Testing Equipment	Video camera (preferably high resolution).		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT013	The system shall have a maximum azimuth speed of at least 60degrees/s	AAAB	SRQ005
Acceptance Criteria	The average speed of the system during a 180 degree test run is no less 60 degrees/s		
Testing Procedure	A point of origin is selected (Point A). An additional point B is selected and placed 180 degrees from the point of origin. The time used to rotate from the point of origin to point B is measured through the help of a video camera.The collected data is analysed on a computer, where the video is slowed down significantly, and the time taken to rotate from A to B is used to find the average speed.		
Testing Equipment	Video camera (preferably high-speed).		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
~~VAT014~~	~~The system shall be able to decelerate from the maximum azimuth speed to a full stop in 1 second.~~	AABB	SRQ007
Acceptance Criteria	~~The system uses no more than 1 second to go from full speed to full stop.~~		
Testing Procedure	~~High speed camera placed above and facing the turret simulator. The camera will record time and position. The turret moves to -90 degrees, and the test is initiated from there. The turret accelerates, and reaches the maximum speed. When max speed is achieved, the system will start to brake, and the time will be recorded.~~		
Testing Equipment			
Note	Changed to VAT021 (20.04.2016).		
Performed by			

Test ID	Description	Ranking	Req. ID
VAT015	The system should have an azimuth speed of at least 120 degrees/s	BBBB	SRQ009
Acceptance Criteria	The average speed of the system during a 180 degree test run is no less 120 degrees/s		
Testing Procedure	A point of origin is selected (Point A). An additional point B is selected and placed 180 degrees from the point of origin. The time used to rotate from the point of origin to point B is measured through the help of a video camera.The collected data is analysed on a computer, where the video is slowed down significantly, and the time taken to rotate from A to B is used to find the average speed.		
Testing Equipment	Video camera (preferably high-speed).		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT016	The system shall be operable in a temperature range from 0 to 40 degrees Celsius.	ABBC	SRQ014
Acceptance Criteria	The system is able to complete a specified test run at 0 degrees Celsius, 20 degrees Celsius and 40 degrees Celsius.		
Testing Procedure	The system is inserted into a climate chamber and runs test VAT011, VAT012, VAT013 first in 0 degrees Celsius, then 20 degrees Celsius and lastly 40 degrees Celsius.		
Testing Equipment	KPS climate chamber.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT017	The system shall put zero strain on the wires connected to the OMS.	AABB	SRQ032
Acceptance Criteria	The bending radius of the any wire shall not be less than 5 times the diameter of the wire		
Testing Procedure	Wires are connected onto their corresponding interfaces on the OMS. The bending radius of the wire are measured and compared to their measured diameter. Relevant wire interfaces to measure are the outlet of the slip ring, entry of cables into the inlet at the bottom of the OMS.		
Testing Equipment	Measuring tape.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT018	The system shall put zero strain on the wires connected to the RWS.	AABB	SRQ033
Acceptance Criteria	The bending radius of the any wire shall not be less than 5 times the diameter of the wire		
Testing Procedure	Wires are connected onto their corresponding interfaces on the OMS. The bending radius of the wire are measured and compared to their measured diameter. Relevant wire interfaces to measure are the outlet of the slip ring, entry of cables into the inlet at the bottom of the OMS.		
Testing Equipment	Measuring tape.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT019	The system shall be able to cut off the power from the motor	AABB	SRQ056
Acceptance Criteria	The power is cut off within one second		
Testing Procedure	A mechanical emergency stop button is connected to the system. Pressing the button shuts off the power supply to the motor. Demonstration shows that the time spent to cut off power to the system is shut down is less then or equal to one second.		
Testing Equipment	Stopwatch		
Note			
Performed by			

Test ID	Description		Ranking	Req. ID
VAT020	The system is shall be prepared for the wiring of a 3-axis gyroscope		AABC	SRQ028 SRQ029
Acceptance Criteria	A free space of 50x60x40 mm^3 and the slip ring has free ports available for the signal transmission.			
Testing Procedure	Through demonstration the power train disc is disassembled and the planned mounting area measuring 50x60x40 mm^3 is shown. Through demonstration it is shown that the slip ring has available free ports for the signal transmission for the gyroscope.			
Testing Equipment	Measuring tape, wrench, torx screwdriver.			
Note				
Performed by				

Test ID	Description		Ranking	Req. ID
VAT021	The physical dimensions of the OMS shall not exceed 470 mm in length and 400 mm in width.		AACC	SRQ026 SRQ027
Acceptance Criteria	Total height less than 400 mm. Total width less than 470 mm.			
Testing Procedure	Through demonstration the total outer physical dimensions of the OMS are measured.			
Testing Equipment	Measuring tape.			
Note				
Performed by				

Test ID	Description	Ranking	Req. ID
VAT022	The system shall have a maximum cost of 350000 NOK	BBBB	SRQ031
Acceptance Criteria	Total cost of components and manufacturing does not exceed 350 000 NOK.		
Testing Procedure	All e-mails, receipts and other documentation are copied and collected into a folder. The numbers are gathered in an Excel spreadsheet, which provides details of costs, as well as total cost.		
Testing Equipment	Excel.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT023	The system shall withstand the stresses caused by pitch combination motion of the motion table.	AACB	SRQ037 SRQ038 SRQ039
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the pitch motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +25 degrees, the system is exposed to the full pitch acceleration motion of the motion table within a movement range from +25 degrees to -23 degrees. Holding a -23 degree incline, the motion table is set to move the system; five consecutive turns; at maximum pitch velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT024	The system shall withstand the stresses caused by roll combination motion of the motion table.	AACB	SRQ040 SRQ041 SRQ042
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the roll motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +22 degrees, the system is exposed to the full pitch acceleration motion of the motion table within a movement range from +22 degrees to -22 degrees. Holding a -22 degree incline, the motion table is set to move the system; five consecutive turns; at maximum roll velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT025	The system shall withstand the stresses caused by yaw combination motion of the motion table.	AACB	SRQ043 SRQ044 SRQ045
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the yaw motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +23 degrees, the system is exposed to the full pitch acceleration motion of the motion table within a movement range from +23 degrees to -23 degrees. Holding a -23 degree incline, the motion table is set to move; 5 consecutive turns; the system at maximum yaw velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT026	The system shall withstand the stresses caused by heave combination motion of the motion table.	AACB	SRQ046 SRQ047 SRQ048
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the heave motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +0.18 m, the system is exposed to the full heave acceleration motion of the motion table within a movement range from +0.18 m to -0.18m. The motion table then is set to move the system at maximum heave velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT027	The system shall withstand the stresses caused by surge combination motion of the motion table.	AACB	SRQ049 SRQ050 SRQ051
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the surge motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +0.27 m, the system is exposed to the full surge acceleration motion of the motion table within a movement range from +0.27 m to -0.27m. The motion table then is set to move the system at maximum surge velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT028	The system shall withstand the stresses caused by sway combination motion of the motion table.	AACB	SRQ052 SRQ053 SRQ054
Acceptance Criteria	The bolts and materials can withstand, without permanent deformation, the stresses imposed by the sway motion of the motion table.		
Testing Procedure	The RWS is mounted onto the OMS and set to rotate at 120 degrees/second. With the motion table set to a starting point of +0.26 m, the system is exposed to the full sway acceleration motion of the motion table within a movement range from +0.26 m to -0.26m. The motion table then is set to move the system at maximum sway velocity within the motion table's full range of motion.		
Testing Equipment			
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT029	The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 120 degrees/second and suddenly stopping.	AABB	SRQ020
Acceptance Criteria	No visible permanent deformation occurs in bolts nor material.		
Testing Procedure	The RWS is mounted onto the offset plate, which is set to 40 cm offset. The system is set to rotate at 120 degrees/second. The system rotates 5 complete turns, before the entire system is stopped through cutting the power to the motor. The test is repeated with 30 cm offset.		
Testing Equipment			
Note			
Performed by			

Test ID	Description		Ranking	Req. ID
VAT030	The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 90 degrees/second and suddenly stopping.		AACB	SRQ019
Acceptance Criteria	No visible permanent deformation occurs in bolts nor material.			
Testing Procedure	The RWS is mounted onto the offset plate, which is set to 40 cm offset. The system is set to rotate at 90 degrees/second. The system rotates 5 complete turns, before the entire system is stopped through cutting the power to the motor. The test is repeated with 30 cm offset.			
Testing Equipment				
Note				
Performed by				

Test ID	Description		Ranking	Req. ID
VAT031	The system shall have a threadless mounting interface to the motion table according to highlighted holes and information in Appendix B.		AABC	SRQ017
Acceptance Criteria	The OMS system has a threadless mounting interface to the motion table, that corresponds to the hole pattern of the motion table.			
Testing Procedure	The system (without the RWS) is placed on top of the motion table and fixed with bolts according to the OMS manual			
Testing Equipment	M22 torque wrench.			
Note				
Performed by				

Test ID	Description	Ranking	Req. ID
VAT032	The system shall have a physical mounting interface to the RWS with the hole pattern according to Appendix A.	AACB	SRQ024
Acceptance Criteria	The OMS system has a threadless mounting interface to the motion table, that corresponds to the hole pattern of the RWS.		
Testing Procedure	The RWS is placed on top of the offset plate (set at 30 cm offset) and fixed with bolts according to the OMS manual.		
Testing Equipment	M12 and M10 torque wrench.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT033	Each single part of the system shall have a maximum weight of no more than 39,5 kg.	ABCB	SRQ022
Acceptance Criteria	Each individual part (base, power train disc, offset disc, motor, slew bearing, slip ring, angled gear) weighs less than 39.5 kg.		
Testing Procedure	Each component is weighed separately on a scale.		
Testing Equipment	Scale.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT034	The system shall provide an azimuth acceleration of 1 rad/s^2.	AAAB	SRQ006
Acceptance Criteria	The wireless accelerometer data shows an acceleration of at least 1 rad/s^2.		
Testing Procedure	The total system is assembled as according to the OMS manual. The RWS is mounted onto the offset disc, which is fixed to 40 cm offset. The motion table is set to maximum +25 degrees pitch displacement and the OMS adjusted to start with the offset disc pointing in the direction of max pitch displacement. A wireless accelerometer is mounted to the offset disc with tape or glue. The motor is then set to initiate rotation of system at max acceleration.		
Testing Equipment	Wireless accelerometer.		
Note			
Performed by			

Test ID	Description	Ranking	Req. ID
VAT035	The system should provide an azimuth acceleration of 6 rad/ s^2.	BCAA	SRQ012
Acceptance Criteria	The wireless accelerometer data shows an acceleration of at least 6 rad/s^2.		
Testing Procedure	The total system is assembled as according to the OMS manual. The RWS is mounted onto the offset disc, which is fixed to 40 cm offset. The motion table is set to maximum +25 degrees pitch displacement and the OMS adjusted to start with the offset disc pointing in the direction of max pitch displacement. A wireless accelerometer is mounted to the offset disc with tape or glue. The motor is then set to initiate rotation of system at max acceleration.		
Testing Equipment	Wireless accelerometer.		
Note			
Performed by			

V.8 System verification tests

Test ID	Description		Ranking	Req. ID
VT001	The system shall have a threadless mounting interface to the motion table according to the highlighted holes and information in Appendix L.		AABC	SRQ017
Acceptance Criteria	Inspection of the OMS CAD model proves that the mounting interface corresponds with the 2D drawing from Appendix L.			
Verification method	Measurements and generated 2D drawings are collected from the SolidWorks model.			
Result(s)/ Report(s)	Verified through appendix L.			
Status	Accepted per 13.05.16			
Performed by	Fredrik Thoresen			

Test ID	Description	Ranking	Req. ID
VT002	The system shall have a physical mounting interface to the RWS with a hole pattern according to appendix K.	AACB	SRQ024
Acceptance Criteria	Inspection of the OMS CAD model proves that the hole pattern corresponds with the 2D drawing in Appendix K.		
Verification method	Measurements are taken from the CAD model		
Result(s)/ Report(s)	Verified through appendix K (KPS confidential drawings can not be provided).		
Status	Accepted per 13.05.16		
Performed by	Fredrik Thoresen		

Test ID	Description	Ranking	Req. ID
VT003	The system shall provide an azimuth acceleration of 1 rad/s ^{2}.	AAAB	SRQ006
Acceptance Criteria	Azimuth acceleration of the OMS must be at least 1 rad/s^2 in either direction.		
Verification method	Analysis: Mathematical calculations, and Newton's second law by knowing moment of inertia and net external torque.		
Result(s)/ Report(s)	The required motor specifications and torque profile necessary was calculated, and a suitable motor was selected based on the results. Details of calculations are provided in section "Motor" in "Components" chapter in the Design document.		
Status	Accepted per 29.04.16		
Performed by	Martin Sandberg and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT004	The system should provide an azimuth acceleration of 6 rad/ s^2.	BCAA	SRQ012
Acceptance Criteria	Azimuth acceleration of the OMS must be at least 6 rad/s^2 in either direction.		
Verification method	Analysis: Mathematical evaluation. Newton's second law by knowing moment of inertia and net external torque.		
Result(s)/ Report(s)	The required motor specifications and torque profile necessary was calculated, and a suitable motor was selected based on the results. Details of calculations are provided in section "Motor" in "Components" chapter in the Design document.		
Status	Accepted per 29.04.16		
Performed by	Martin Sandberg and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT005	The system shall have a minimum life span of 5 years	ABCB	SRQ036
Acceptance Criteria	The material and structures of the OMS shall withstand, without reaching fatigue failure, 5 years of exposure to the approximate test scenario at KPS.		
Verification method	Handwritten calculations and FEA in Solidworks.		
Result(s)/ Report(s)	TR005: The OMS structure and material has "infinite" life span. The bolts should be changed on a yearly basis.		
Status	Accepted per 16.05.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT006	The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.	AABC	SRQ016
Acceptance Criteria	No permanent deformation is created to either component of the interface while subjected to a preload torque of 130 Nm. Stress limit 260N/mm^2.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic material properties.		
Result(s)/ Report(s)	TR001, TR003		
Status	Accepted per 19.04.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT007	The system shall be able to withstand being mounted on to the motion table using a preload torque 200 Nm.	AABC	SRQ018
Acceptance Criteria	No permanent deformation is created to either component of the interface while subjected to a preload torque of 200 Nm. Stress limit 260N/mm^2.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic material properties.		
Result(s)/ Report(s)	TR001, TR003		
Status	Accepted per 19.04.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT008	The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 90 degrees/second and suddenly stopping.	AACB	SRQ019
Acceptance Criteria	The bolts and materials are not exposed to stresses larger than half their respective yield strength; ensuring a safety factor of 2.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR001, TR003		
Status	Accepted per 14.05.16		
Performed by	Fredrik Thoresen and Kjetil Fjeld		

Test ID	Description	Ranking	Req. ID
VT009	The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 120 degrees/second and suddenly stopping.	AABB	SRQ020
Acceptance Criteria	The bolts and materials are not exposed to stresses larger than half their respective yield strength; ensuring a safety factor of 2.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR001, TR003		
Status	Accepted per 14.05.16		
Performed by	Fredrik Thoresen and Kjetil Fjeld		

Test ID	Description	Ranking	Req. ID
VT010	Each individual part of the system shall have a maximum weight of no more than 39,5 kg.	ABCB	SRQ022
Acceptance Criteria	Each individual part of the OMS weighs no more than 39.5 Kg.		
Verification method	The weight of each individual part is guaranteed through supplier technical catalogues and/or OMS modelling in Solidworks.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT011	The system should have a maximum weight of 50 Kg.	BBAB	SRQ023
Acceptance Criteria	The OMS system should not exceed 50 Kg.		
Verification method	The weight of the OMS system is measured in Solidworks.		
Result(s)/ Report(s)	TR002		
Status	Partially accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT012	The system shall have a maximum diameter of 470 mm.	AACC	SRQ026
Acceptance Criteria	Maximum external system diameter does not exceed 470 mm.		
Verification method	The diameter of the OMS is measured on the CAD model in Solidworks.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT013	The system shall have a maximum height of 400 mm.	AACC	SRQ027
Acceptance Criteria	Height does not exceed 400 mm.		
Verification method	The height of the OMS is measured on the CAD model in Solidworks.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT014	The system shall have a maximum cost of 350000 NOK.	BBBB	SRQ031
Acceptance Criteria	The total cost of the system does not exceed 350000 NOK.		
Verification method	A mathematical summation of the total cost is conducted.		
Result(s)/ Report(s)	Estimated total cost $\approx$ 200 000 NOK, as presented in detail in the Budget section in the Design chapter.		
Status	Accepted per 16.05.16		
Performed by	Heidi Kallerud and Anders Gunbjørnsen		

Test ID	Description	Ranking	Req. ID
VT015	The system shall have an entry opening for the wiring to the absolute position sensor.	ABCB	SRQ028
Acceptance Criteria	The system shall have a free space of 60*50*40 mm^3.		
Verification method	A free space is shown in a 2D drawing in referred test report.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT016	The system shall be prepared for the wiring of a 3-axis gyroscope.	AABC	SRQ029
Acceptance Criteria	An entry opening of minimum 10 mm for the wiring to the gyro is available.		
Verification method	The CAD model is inspected.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT017	The Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0,1 mrad.	ABCB	SRQ013
Acceptance Criteria	The system has an inbuilt absolute position sensor that has a resolution equal to or higher than 1 mrad.		
Verification method	2D drawings of CAD model shows incorporation of the sensor.		
Result(s)/ Report(s)	TR002		
Status	Accepted per 04.05.16		
Performed by	Fredrik Thoresen and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT018	The system shall be fitted with a solution that allows 360 degree free azimuth movement range.	AABB	SRQ001 SRQ011 SRQ055
Acceptance Criteria	A bearing that enables 360 degree free movement range is integrated into the system.		
Verification method	Calculations and/or data from supplier confirms that the dimensions and load capacity of the bearing is suitable for the system's load situation		
Result(s)/ Report(s)	Load scenario calculated in chapter "Components" (under Design Document) was verified by supplier (SKF). Dimensional verification in SolidWorks.		
Status	Accepted per 28.04.16		
Performed by	Fredrik Thoresen		

Test ID	Description	Ranking	Req. ID
VT019	The motor shall have a torque profile that provides peak torque output at speeds from 1 mrad/sec to 2.1 rad/sec.	AACB	SRQ002 SRQ004 SRQ005 SRQ009
Acceptance Criteria	Peak torque output is minimum 120 Nm.		
Verification method	Technical catalogue from supplier (Wittenstein) confirms the desired power output.		
Result(s)/ Report(s)	Mathematical calculations provided in chapter "Components" in Design Document.		
Status	Accepted per 23.04.16		
Performed by	Martin Sandberg and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT020	The system facilitates offsets of the RWS at 10 cm increments, up to a total of 30 cm, from the system center of rotation.	BACC	SRQ010
Acceptance Criteria	The designed system allows the RWS to be fixed at offsets of 10 cm, 20 cm and 30 cm from the system's center of rotation.		
Verification method	3D model in SolidWorks.		
Result(s)/ Report(s)	Measurements on 3D model in Solidworks, ref appendix M.		
Status	Accepted per 15.04.16		
Performed by	OMS team		

Test ID	Description	Ranking	Req. ID
VT021	The system shall withstand a pitch displacement motion of the motion table of +25/-23 with a velocity of $\pm$ 30deg/s and an acceleration of $\pm$ 500 deg/s^2 .	AACB	SRQ037 SRQ038 SRQ039
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR003		
Status	accepted per 12.04.16		
Performed by	Fredrik Thoresen		

Test ID	Description	Ranking	Req. ID
VT022	The system shall withstand a roll displacement motion of the motion table of ± 22 with a velocity of ± 30deg/s and an acceleration of ± 500 deg/s^2.	AACB	SRQ040 SRQ041 SRQ042
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR003		
Status	accepted per 12.04.16		
Performed by	Fredrik Thoresen		

Test ID	Description	Ranking	Req. ID
VT023	The system shall withstand a yaw displacement motion of the motion table of ± 23 with a velocity of ± 40deg/s and an acceleration of ± 400 deg/s^2.	AACB	SRQ043 SRQ044 SRQ045
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR003		
Status	accepted per 12.04.16		
Performed by	Fredrik Thoresen		

Test ID	Description	Ranking	Req. ID
VT024	The system shall withstand a heave displacement motion of the motion table of $\pm$ 0,18m with a velocity of $\pm$ 0.30m/s and an acceleration of $\pm$ 0,5g.	AACB	SRQ046 SRQ047 SRQ048
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR001		
Status	Accepted per 19.04.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT025	The system shall withstand a surge displacement motion of the motion table of $\pm$ 0,27m with a velocity of $\pm$ 0.50m/s and an acceleration of $\pm$ 0,6g.	AACB	SRQ049 SRQ050 SRQ051
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR001		
Status	Accepted per 19.04.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT026	The system shall withstand a sway displacement motion of the motion table of ± 0,26m with a velocity of ± 0.50m/s and an acceleration of ± 0,6g.	AACB	SRQ052 SRQ053 SRQ054
Acceptance Criteria	No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.		
Verification method	Analysis: A Finite Element Analysis (FEA) study is performed on a CAD model with realistic fixtures, material properties and forces.		
Result(s)/ Report(s)	TR001		
Status	Accepted per 19.04.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT027	The system shall consider a roof stiffness of 30 Hz	AAAB	SRQ015
Acceptance Criteria	The resonance frequency of the system assembly is above 30 Hz.		
Verification method	FEA frequency analysis in SolidWorks.		
Result(s)/ Report(s)	TR004		
Status	Accepted per 15.05.16		
Performed by	Kjetil Fjeld and Heidi Kallerud		

Test ID	**Description**	**Ranking**	**Req. ID**
VT028	The system shall put zero strain on the wires connected to the OMS.	AABB	SRQ032
Acceptance Criteria	The bending radius of the wires shall be no less than 5 times their diameter.		
Verification method	Measurements on 3D model in Solidworks		
Result(s)/ Report(s)	TR002.		
Status	Accepted per 20.05.16		
Performed by	Fredrik Thoresen and Heidi Kallerud		

Test ID	**Description**	**Ranking**	**Req. ID**
VT029	The system shall put zero strain on the wires connected to the RWS	AABB	SRQ033
Acceptance Criteria	The bending radius of the wires shall be no less than 5 times their diameter		
Verification method	Measurements on 3D model in Solidworks		
Result(s)/ Report(s)	TR002. Requires development of an adapter, by future students.		
Status	Accepted per 20.05.16		
Performed by	Fredrik Thoresen and Heidi Kallerud		

Test ID	Description	Ranking	Req. ID
VT030	The system shall have a solution for the guidance of the wiring to the RWS	AABB	SRQ025
Acceptance Criteria	The system contains a solution that allows free rotation without obstructing or twisting the wires to the RWS		
Verification method	3D modelling and evaluation of budget.		
Result(s)/ Report(s)	System is designed with an integrated slip ring that allows unrestricted rotation of the system, as described in chapter "Components" in the Design Document. Budget confirms feasibility of solution.		
Status	Accepted per 11.05.16		
Performed by	OMS team		

Test ID	Description	Ranking	Req. ID
VT031	Standard supply metric bolts shall be used on all applications.	BBCC	SRQ058
Acceptance Criteria	Only standard supply metric bolts as defined in the Tingstad technical catalogue are used.		
Verification method	M5, M6, M8, M10, M12, M16 and M20 bolts in 8.8 quality are used, which are standard supply by definition through Tingstad.		
Result(s)/ Report(s)	All bolts can be fastened using a wrench of corresponding size.		
Status	Accepted per 13.05.16		
Performed by	OMS team		

Test ID	Description	Ranking	Req. ID
VT032	The system shall be operable in a temperature range from 0-40 degrees Celsius.	ABBC	SRQ014
Acceptance Criteria	The motor, slew bearing, slip ring and gear box must be operable within an ambient temperature of 0-40 degrees Celsius.		
Verification method	Verification of operability within the given temperature range has been given by suppliers and through technical catalogues. The friction moment of the slew bearing within the operating temperature has been integrated into calculations of total system moment.		
Result(s)/ Report(s)			
Status	Accepted per 13.05.16		
Performed by	OMS team		

University College
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Mechanical Engineering
2016 - 07

Test Reports
Orbital Motion Simulator

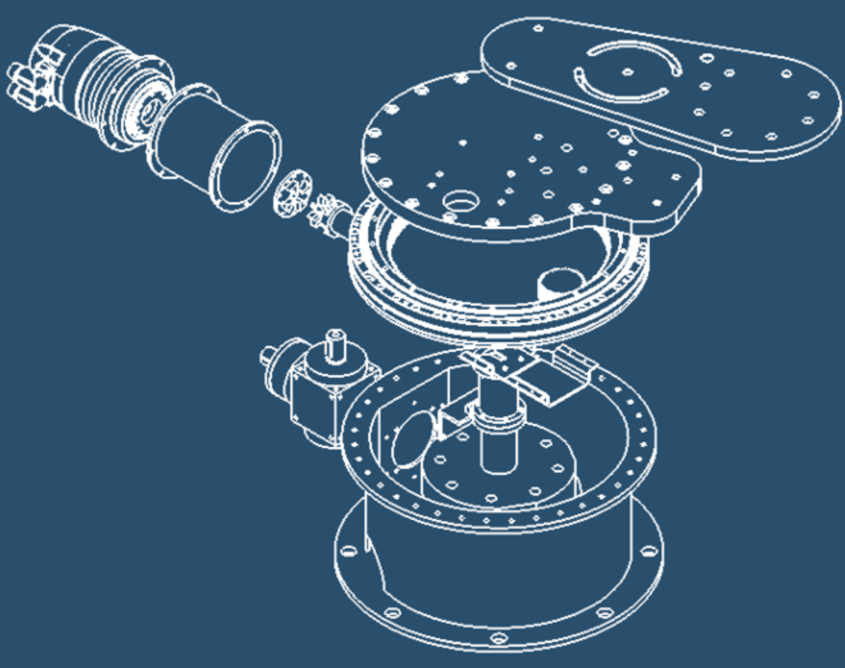


Table of Contents

VI.1 TR001

Date	19.04.16
Performed by	Kjetil Fjeld and Heidi Kallerud
Content	Stress analysis during combined rotation and motion table translational motion
Tests	VT006-007, VT024-026

Revision History

Date	Version Number	Comment	Approved by
19.04.16	1.0	Documentation of process and calculations	Heidi Kallerud

VI.1.1 Test Purpose

The purpose of the simulation is to assess if the system can withstand the forces imposed from translation of the motion table during heave, sway and surge movements.

VI.1.1.1 Verification Tests

The following verification tests are covered by TR001:

- **VT006**: *The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.*
- **VT007**: *The system shall be able to withstand being mounted to the motion table using a preload torque of 200 Nm.*
- **VT024**: *The system shall withstand a heave displacement motion of the motion table of* $\pm$ *0,18m with a velocity of* $\pm$ *0.30m/s and an acceleration of* $\pm$ *0,5g.*
- **VT025**: *The system shall withstand a surge displacement motion of the motion table of* $\pm$ *0,27m with a velocity of* $\pm$ *0.50m/s and an acceleration of* $\pm$ *0,6g.*
- **VT026**: *The system shall withstand a sway displacement motion of the motion table of* $\pm$ *0,26m with a velocity of* $\pm$ *0.50m/s and an acceleration of* $\pm$ *0,6g.*

VI.1.1.2 Description

The simulation of translation on the system was divided into two separate studies. One covering the offset disc, power-train disc and their bolted interface to each other and to the slew bearing. The other study will cover the base and its bolted interface to the slew bearing. This division was necessary as the slew bearing has some clearances between the rotating parts. Defining contact sets within the bearing assembly proved too complex. Computer power also put limitations on how many parts could be put in the same study. The simulation uses the the worst case load scenario described in the design document. The scenario in question simplifies the load condition to four external forces. These forces are listed in the table below.

External forces	
F_{gy}	2225N
F_{gx}	1050N
F_{OMS}	600N
F_{Trans}	1475N

Table VI.1.1: External forces

VI.1.2 Test Setup

VI.1.2.1 Study: Offset and Power-train discs

The parts included in this analysis were the offset-disc, the power train disc and the upper part of the slew bearing. To simplify the analysis, the RWS was replaced by a dummy part in order to reduce the amount of nodes in the mesh and load conditions. Component contacts were set to "no penetration". Assessing resulting forces on the bolt interfaces between parts is done with bolt connectors. The M12 bolts interface between RWS and offset disc has a preload torque of 130 Nm as specified by VT006.

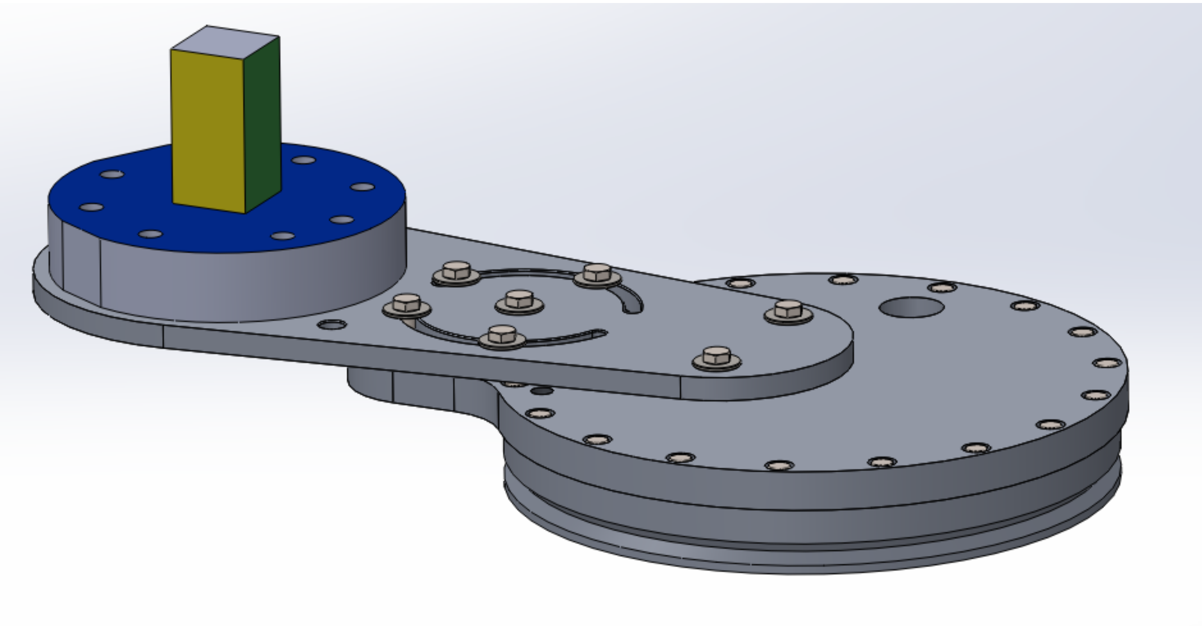
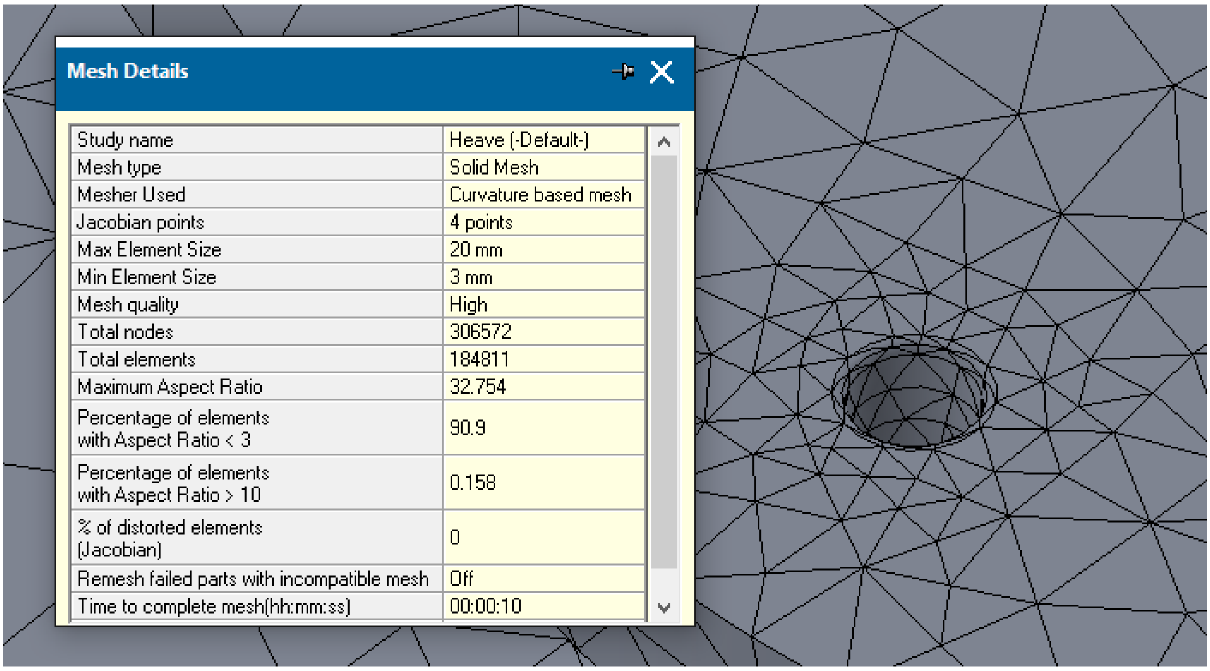


Figure VI.1.1: External load placement

The external forces listed in table VI.1.1 was placed on the RWS dummy part. Gravity was decomposed, because of the tilt of the motion table into two loads. The component working normal to the discs (F_{gy}) was placed as seen in figure VI.1.1 on the blue face. While the other component (F_{gx}) from gravity was placed on the yellow face. Resultant loads from the rotation of the OMS (F_{OMS}) was placed on the yellow face. Finally the resultant force of the translation (F_{Trans}) was placed on the green face. The geometry is fixed to the plane at the bottom of the slew bearing.



Mesh Details

Study name	Heave (-Default-)
Mesh type	Solid Mesh
Mesher Used	Curvature based mesh
Jacobian points	4 points
Max Element Size	20 mm
Min Element Size	3 mm
Mesh quality	High
Total nodes	306572
Total elements	184811
Maximum Aspect Ratio	32.754
Percentage of elements with Aspect Ratio < 3	90.9
Percentage of elements with Aspect Ratio > 10	0.158
% of distorted elements (Jacobian)	0
Remesh failed parts with incompatible mesh	Off
Time to complete mesh(hh:mm:ss)	00:00:10

A curvature based mesh were used to maximise accuracy of the analysis [61], while still keeping the amount of nodes below what a regular computer can handle. This will force Solidworks to use a finer mesh around difficult geometry and transitions.

VI.1.2.2 Study: Base

Parts included in this study is the base. Dummy parts was made to represents the motion table and bearing. External forces listed in table VI.1.1, was placed on the bearing. The sum of F_{gx} and F_{Trans} was placed on the green face as a bearing load. To simulate the power-train disc pulling on the bearing. F_{OMS} at 400mm offset will create a torque on the bearing of 240 Nm, this torque load was placed on the green face. F_{gy} was placed on the blue face.

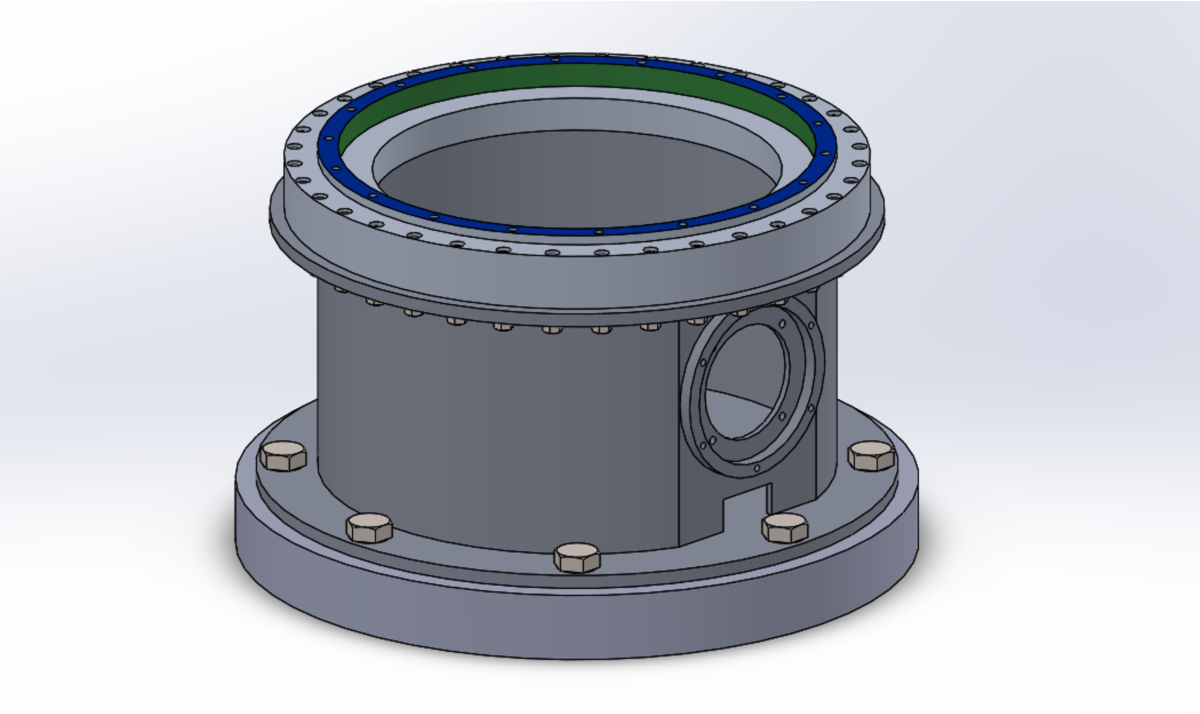


Figure VI.1.2: External load placement on base

Geometry is fixed to the plane at the bottom of the motion table dummy part. A curvature based mesh was also used for this study. Global contact was set to no-penetration, bolt connectors was used as fixtures between parts. Bolts connecting the base to the motion table was preloaded with 200 Nm.

VI.1.3 Test Results

VI.1.3.1 Study: Offset and Power-train discs

Figure VI.1.4 shows a color coded plot that visualises how the resultant stresses are distributed on various faces of the model. A maximum Von Mises stress of 274N/mm^2 was found at the edge of the middle bolt hole of the drive-train disc. Apart from these local high stress areas around some bolt holes, the highest stress was around 100N/mm^2.

Local high stress areas form around every bolt holes of the power-train disc. The stress levels at these points increased with mesh details. With lower mesh details the local high stress values was around 130N/mm^2. Within the acceptance criteria of the verification tests. An explanation for the stress levels rise do not converge when increasing the mesh details, could be whats referred to as a singularity. In a FEA stress singularity happens when a force in the analysis is placed on a sharp edge or on a point. Calculations have been done on thread engagement and bearing stress for the bolts, to ensure that the bolts fail before the threads of the fixture.

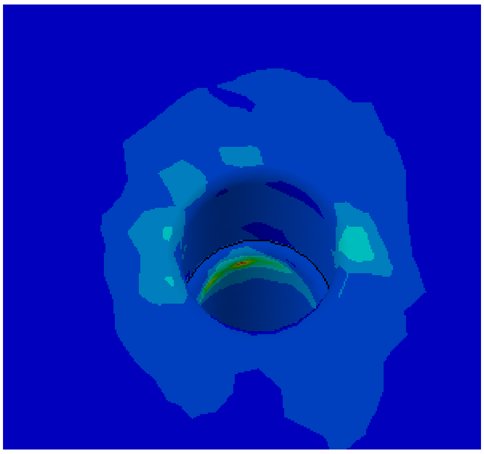


Figure VI.1.3: Stress Singularity

The lighter blue patches on the offset disc shows areas exposed to bending stresses imposed by placing the RWS at the maximum offset. The resulting stresses are well within the elastic deformation region of the materials.

The acceptance criteria for VT024, VT025 and VT026 are fulfilled, as the threshold for meeting the acceptance criteria were stated as "no fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength".

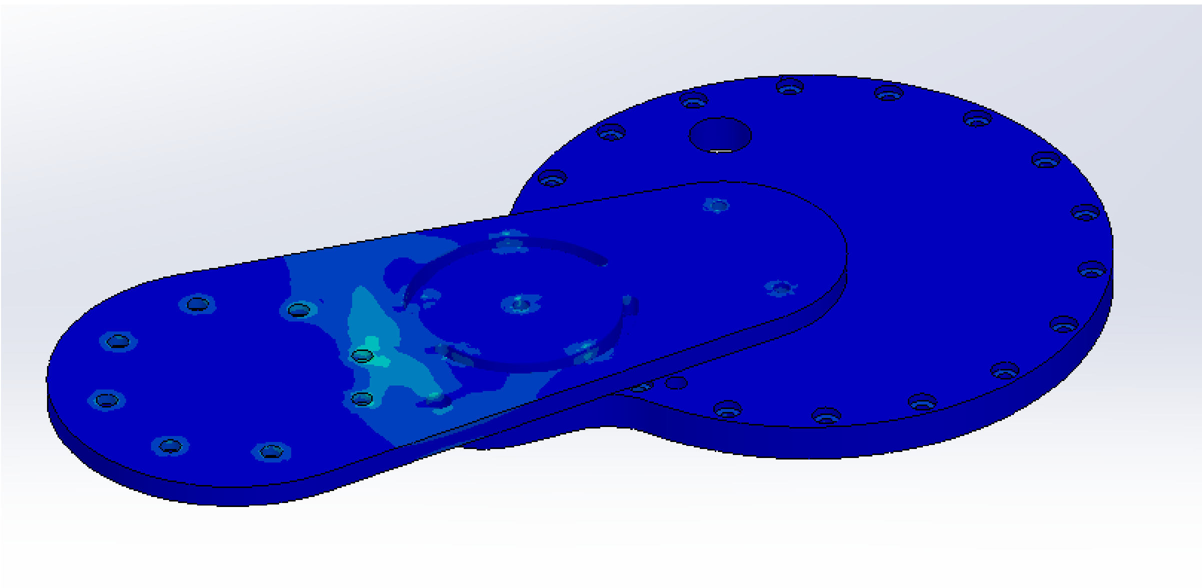


Figure VI.1.4: Plot of resulting stresses

Furthermore, the acceptance criteria of verification test VT006 is also met. The criteria states that *No permanent deformation is created to either component of the interface while subjected to a pre-load torque of 130 Nm.*. The deformation limit was in these acceptance criteria set to 260N/mm^2, which is the yield strength of Aluminum 6082-T6; and 640N/mm^2 for the bolts. The bolt check plot shows that the bolt subjected to the highest stress had a factor of safety of 2.65. Confirming that no plastic deformation of the bolts takes place.

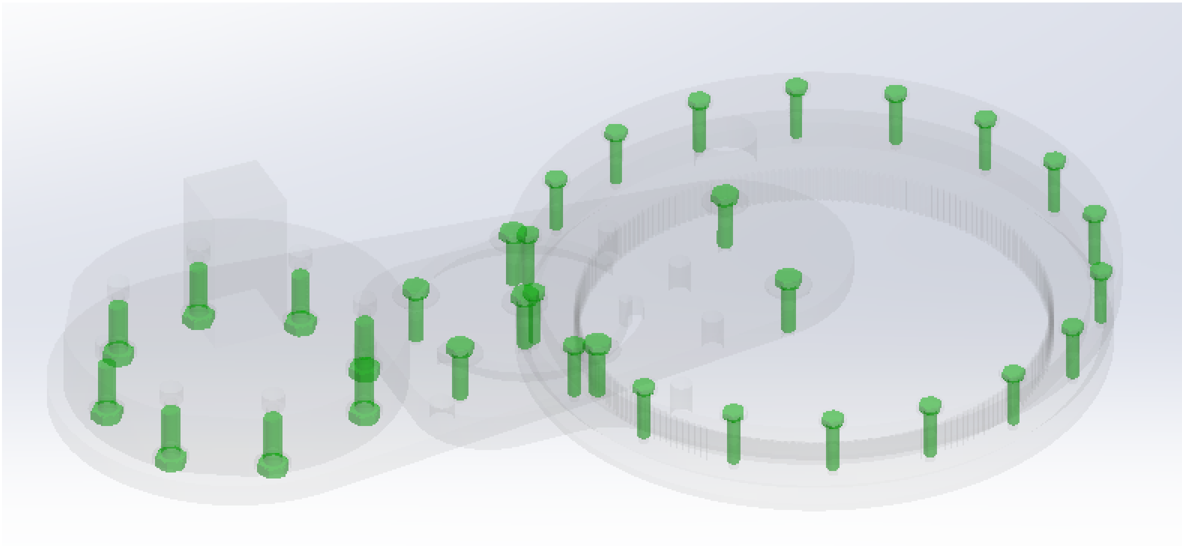


Figure VI.1.5: Factor of safety for bolt connectors

The loads applied in this analysis are higher than what they would have been in reality. With a load of over 250 kg the motion table will not be able to provide the acceleration specified in the data-sheet. The motion table will not be able to provide maximum acceleration in all directions at the same time.

VI.1.3.2 Study: Base

This study shows that the base is subjected to very little stress from the loading. Highest stress found in this study was 43 N/mm^2, on the inside of one of the bolt holes connecting the base to the motion table. The acceptance criteria for VT024, VT025 and VT026 are fulfilled, as the threshold for meeting the acceptance criteria were stated as *No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.*

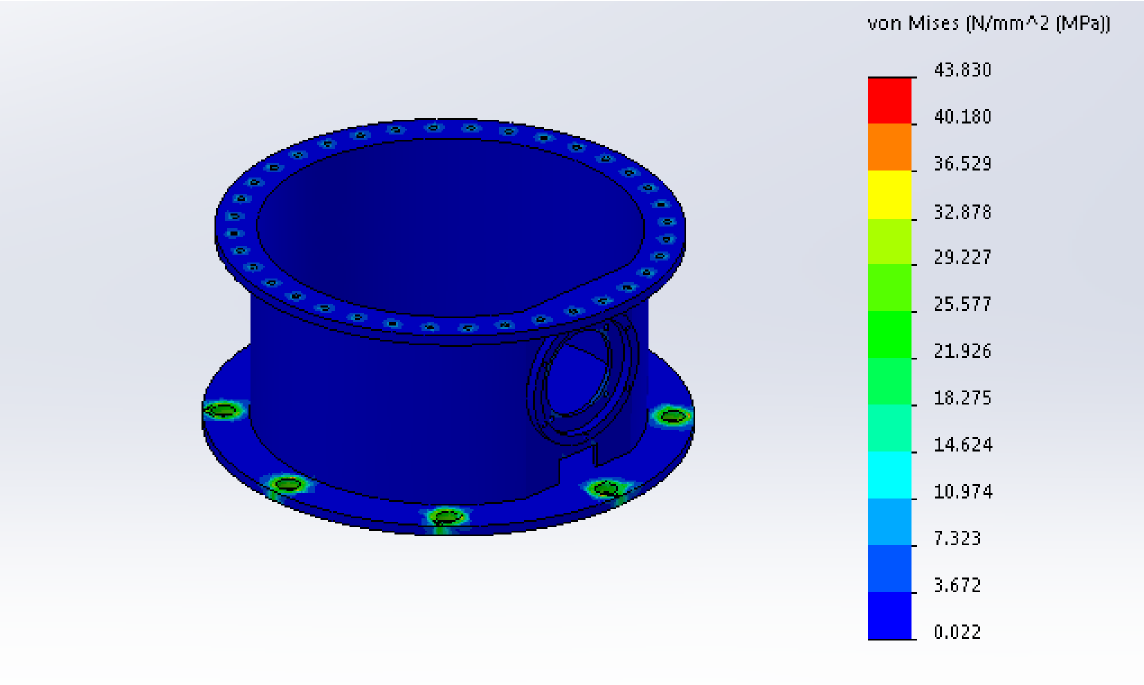


Figure VI.1.6: Plot of resulting stresses

All bolts connecting the base to either motion table or bearing have a factor of safety of more than 2, as shown in figure VI.1.7. Acceptance criteria for VT007 states that *No permanent deformation is created to either component of the interface while subjected to a preload torque of 200 Nm.* Meaning that VT007 is fulfilled as there are no stresses above the yield strength of aluminium.

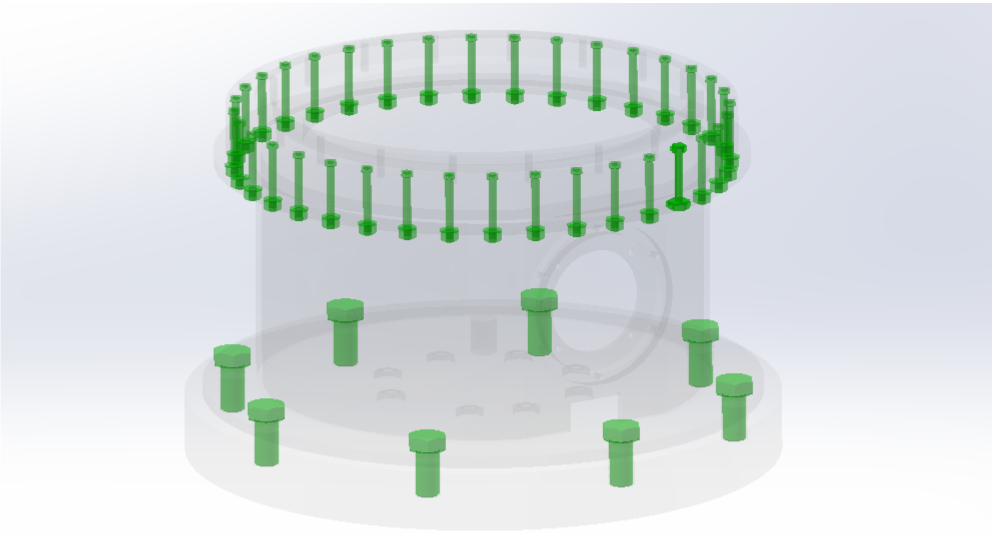


Figure VI.1.7: Factor of safety for bolt connectors

VI.1.4 Conclusion

The results of the current test report showed that the designed system, when exposed to maximum translational motion, meets the acceptance criteria set in test VT006, VT007, VT024, VT025 and VT026. This implies that the system requirements corresponding to these tests can be considered fully verified. The local high stress areas around bolt holes are viewed as a stress singularity.

VI.2 TR002

Date	04.05.2016
Performed by	Heidi Kallerud
Content	Geometry and mass properties
Tests	VT010 - VT013, VT015-VT017, VT028-029

Revision History

Date	Version Number	Comment	Approved by
04.05.16	1.0	Created	Heidi Kallerud

VI.2.1 Test purpose

The purpose of the test is to verify that the geometry and mass properties of the individual components, as well as the system in entirety, fulfills the requirements relating to mainly the moveability of the system.

VI.2.1.1 Verification Tests

The following verification tests are covered by Test Report 002:

- **VT010**: *Each individual part of the system shall have a maximum weight of no more than 39,5 kg*
- **VT011**: *The OMS system shall not exceed 50 kg*
- **VT012**: *Maximum system diameter does not exceed 470 mm*
- **VT013**: *Total system height does not exceed 400 mm*
- **VT015**: *The system contains a free space of* $60 \cdot 50 \cdot 40\ mm^3$ *on the internals of the power train disc.*
- **VT016**: *The system shall be prepared for the wiring of a 3-axis gyroscope*
- **VT017**: *The Turret Simulator shall incorporate an absolute position sensor with a resolution better than or equal to 0,1 mrad*
- **VT028**: *The system shall put zero strain on the wires connected to the OMS.*
- **VT029**: *The system shall put zero strain on the wires connected to the RWS.*

VI.2.1.2 Description

The acceptance criteria for the verification tests covered in this test report primarily originates from stakeholder requirement STRQ025, which states that *The system shall be movable by one person as specified in MIL-STD-1472G.* This dictates the maximum dimensions and weight an object can have in order to be movable by one person, in accordance to health and safety regulations. The measure and mass geometry tools in SolidWorks are used to verify that the modelled dimensions and weight of the parts meet the acceptance criteria stated above.

VI.2.2 Test Setup

The system was decomposed and the separate components were firstly evaluated separately. The relevant components under consideration were the mounting disc, the power train disc, the off-set disc, the slew bearing, the slip ring and the motor. The mass properties and geometrical dimensions of each component was measured by means of the tools provided in SolidWorks. Next, the system as an entity was evaluated. The total assembly consists of the mentioned parts with the addition of bolts for mounting to the motion table, the bearing, the RWS and the off-set disc. Again, mass properties and geometrical dimensions of the system as an entirety was measured by means of the tools provided in SolidWorks. One verification test pertained to the requirement that the system shall have an internal free space allowing the placement of a 3-axis gyroscope. As described in the Detailed Design chapter, a suitable gyroscope was identified and modelled according to acquired 2D drawings. The modelled gyroscope was then mounted inside the mounting disc in SolidWorks to verify that the there was in fact free space available.

VI.2.3 Test Results

Table VI.2.1 shows the weight of each single component in the OMS system. The weight of the base, power train disc and offset disc was found using SolidWorks, while the weight of the other components were found in supplier technical catalogues. The acceptance criteria was set to a total system weight of maximum 50 kg, which was exceeded slightly. This is mainly due to the combined weight of all the bolts and nuts that were needed for the system. The table shows that the acceptance criteria that no individual component should have a higher weight than 39.5 kg was met. The requirement about total weight of the system was a *should* requirement that was mainly meant as a general goal to keep the weight of the system as low as possible. The requirement stating that no component could weigh more than 39.5 kg was a *shall* requirement that must be fulfilled, and originates from a stakeholder requirement referring to a Health & Safety standard that KPS must comply with.

Component	Weight (kg)
Base	8.9
Power train disc	9.0
Offset disc	11.3
Motor (Wittenstein)	8.5
Bearing	9
Slip ring	3.9
Pinion	0.4
Bracket	0.8
Gear	8.5
Bolts, washers, nuts	≈ 4.5
Cables	≈ 2
Position sensor assembly	1
Total	**61.3**

Table VI.2.1: Component weight

The 2D drawings in figure VI.2.1 show that the internals of the mounting disc holds a free area of 60 x 50 x 40 mm; thus, verifying test number VT015. The surrounding free space together with free access from the designed wire entry opening shown in figure VI.2.2 the motor verifies that the system has an entry system and available space for cables for the gyro (VT016). The system has two such entries. Figure VI.2.3 also shows that the maximum diameter of the system meets the acceptance criteria of test VT012 of not exceeding 500 mm. The total system height from mounting interface to motion table up to the top of the off-set disc is 305.90 mm. This measure is well within the acceptance criteria of 400 mm; verifying VT013.

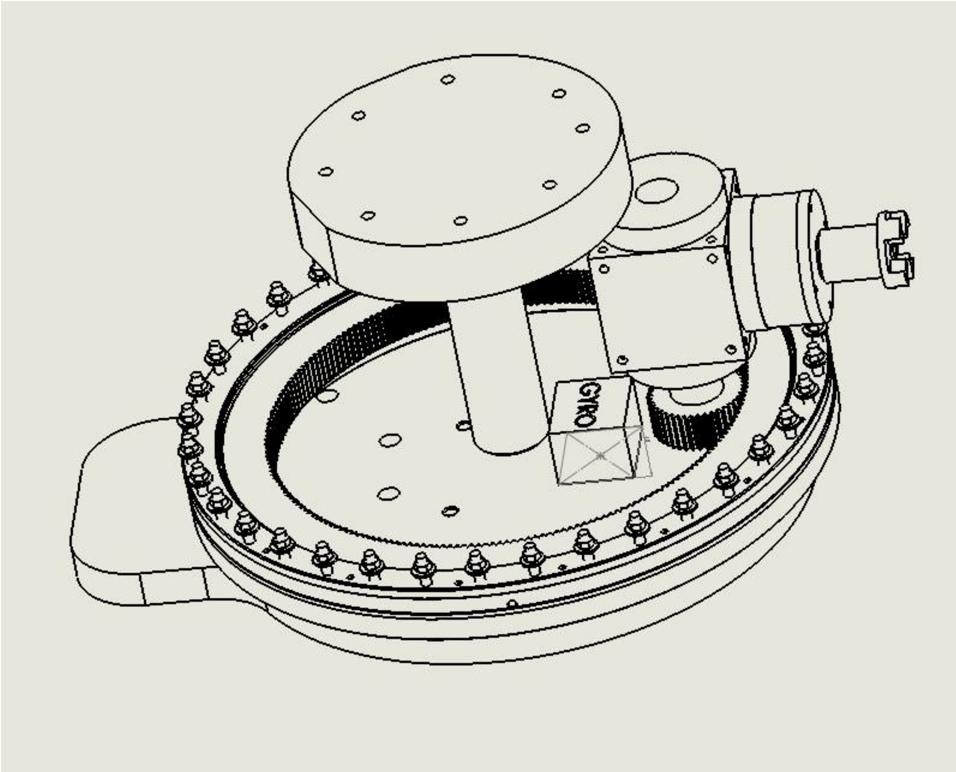


Figure VI.2.1: Internal free space for mounting of gyro

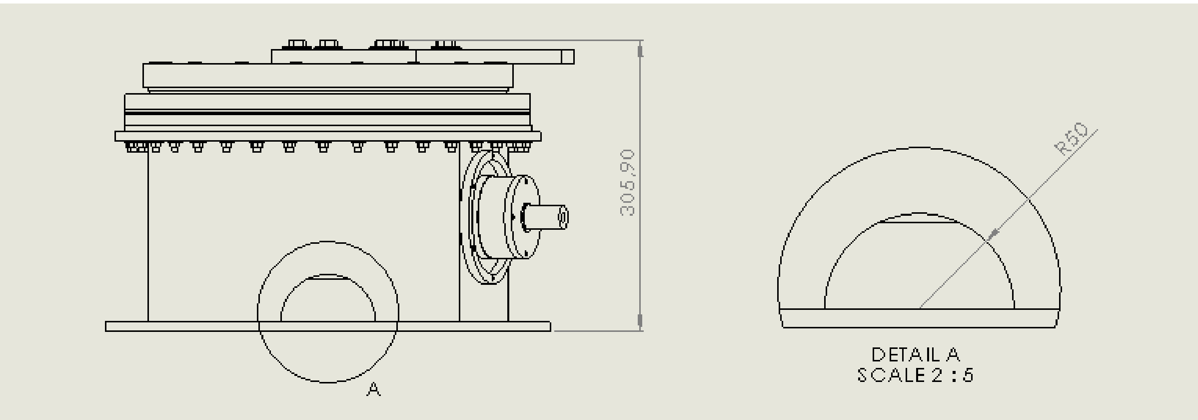


Figure VI.2.2: Total height of the system and details of entry opening

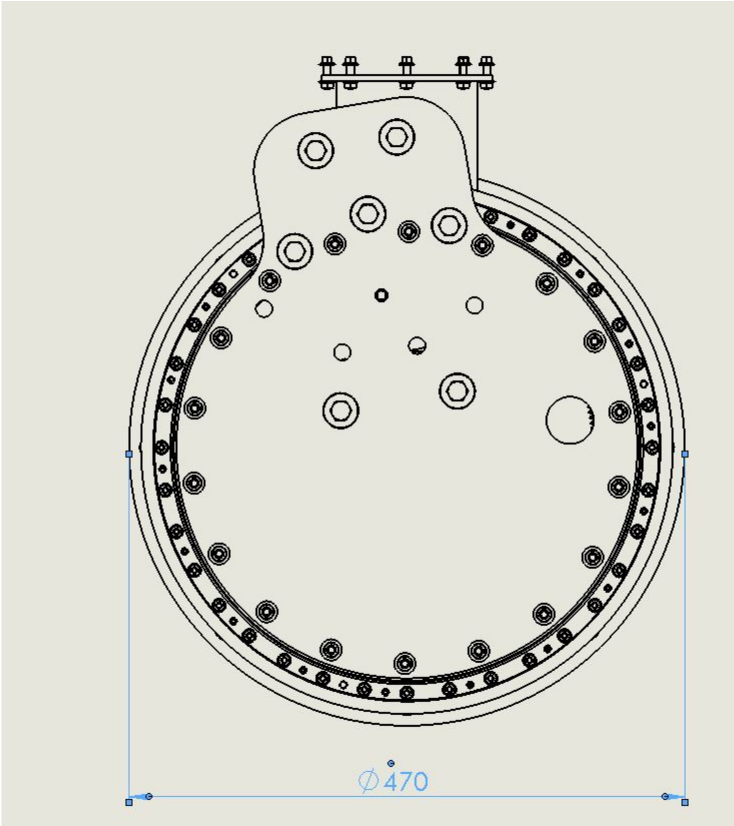


Figure VI.2.3: Total width of the system

An absolute position sensor with a resolution of 0.014 mrad has been integrated into the design of the system, as shown in figure VI.2.4.

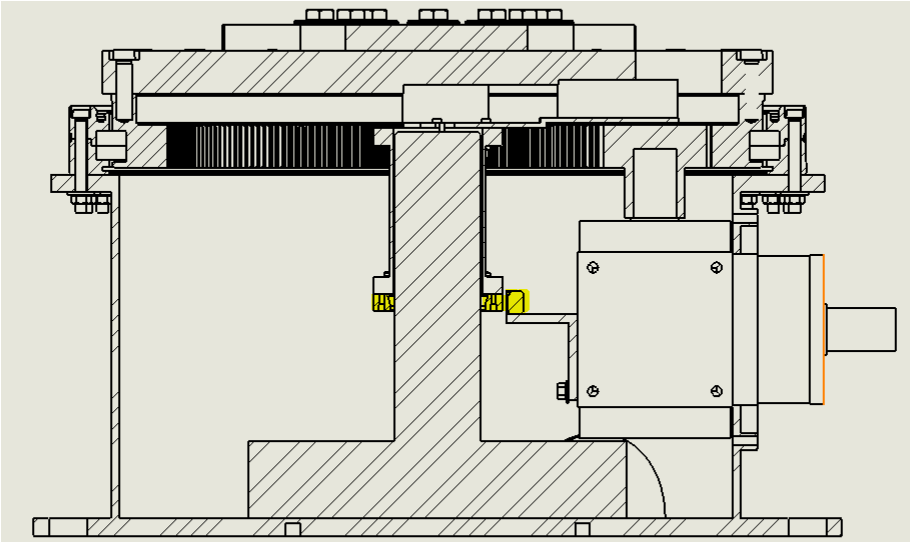


Figure VI.2.4: Integrated position sensor

VT028 and VT029 states that the wires to and from the system shall be exposed to zero strain. The acceptance criteria in both cases is the the bending radius of the cable shall be no less than 5 times the diameter of the wire. The 2D drawings in figure VI.2.5 shows the cable to the OMS as it enters through one of the entry openings. The cables will hang freely from the opening. A different solution has been chosen for the cables from the top of the slip ring to the RWS. It is intended (and agreed with KPS) that a 90 degree angled adapter will be made, which will output the cables from the slip ring sideways instead of straight upwards.

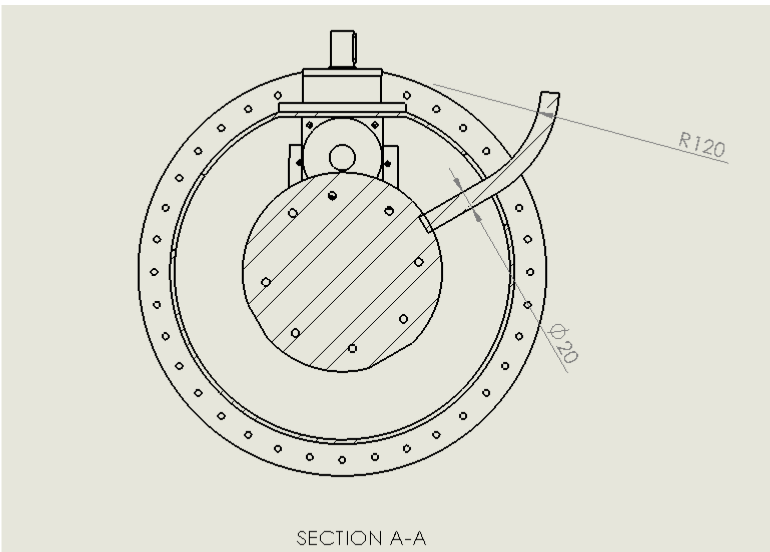


Figure VI.2.5: Zero strain on cables

VI.2.3.1 Conclusion

The results of the current test report showed that the geometry and mass properties of the designed system meets the acceptance criteria set in verification test VT010, VT011, VT012, VT013, VT015, VT016, VT017 and VT028. This implies that the system requirements corresponding to these tests can be considered fully verified. VT029 is verified, but requires follow-up by future project teams.

VI.3 TR003

Date	12.04.2016
Performed by	Kjetil Fjeld and Fredrik Thoresen
Content	Stress analysis during combined rotation and motion table translational motion
Tests	VT006-009, VT021-023

Revision History

Date	Version Number	Comment	Approved by
12.04.2016	1.0	Created	Fredrik Thoresen

VI.3.1 Test Purpose

The purpose of this test is to verify that the OMS will be able to withstand the pitch motion of the motion table. The ability of all bolt connections and material to withstand the pitch motion of the motion table, the weight of the RWS and the rotation of the OMS system is to be tested. The worst case scenario will always be the base of all calculations and tests.

VI.3.1.1 Verification Tests

The following verification tests are covered by TR003:

- **VT006**: *The system mounting interface to the RWS shall withstand a preload torque of 130 Nm.*
- **VT007**: *The system shall be able to withstand being mounted to the motion table using a preload torque of 200 Nm.*
- **VT021**: *The system shall withstand a pitch displacement motion of the motion table of +25/-23 with a velocity of* $\pm$ *30deg/s and an acceleration of* $\pm$ *500 deg/s*^{2} .
- **VT022**: *The system shall withstand a roll displacement motion of the motion table of* $\pm$ *22 with a velocity of* $\pm$ *30deg/s and an acceleration of* $\pm$ *500 deg/s*^{2}.
- **VT023**: *The system shall withstand a yaw displacement motion of the motion table of* $\pm$ *23 with a velocity of* $\pm$ *40deg/s and an acceleration of* $\pm$ *400 deg/s*^{2}.
- **VT008**: *The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 90 degrees/second and suddenly stopping.*
- **VT009**: *The system shall be able to withstand, without damage to itself or interfaced units, a 250 Kg RWS rotating at speeds exceeding 120 degrees/second and suddenly stopping.*

VI.3.1.2 Description

To carry out this test a CAD model will go through a Finite Element Method study using Solidworks Simulations. Also, to simplify the testing, the system will undergo a "worst case scenario", meaning forces from not only the motion table will be added. The desired load situation has its base in the motion table operating at the specified worst case conditions. All external forces and components will be added in order to portrait reality in a sufficient way. So the RWS will contribute to the most unfavorable load situation that could occur. To make the simulation results as accurate as possible the system will be broken down into two subsystems. The first subsystem will consist of the RWS being mounted on the offset disc, which will be mounted to the power train disc, and finally mounted to the bearing.

The second subsystem will be the base mounted to the motion table. In order to make the test more realistic and unfavorable for the components of the system, the forces from general operation will be added. Meaning that the OMS will be in normal operation in the two cases, and the forces emerging from this motion will be added to the different subsystems.

VI.3.2 Test setup

As this test is a FEM analysis test carried out through Solidworks the set up chapter will not only describe the parts of the system, but the mesh quality, the loads and the fixtures used.

As previously mentioned the system will undergo a worst case scenario, this case is based on the following:The system will have full acceleration from both the motion table and the OMS, then hit a sudden stop. Furthermore the weight from the RWS will be added. The different test setups will then distribute the loads differently giving a clear picture of the most vulnerable sections of the different components.

External forces	
F_{gy}	2225N
F_{gx}	1050N
F_{OMS}	600N
F_{roll}	875N

Table VI.3.1: External forces

Also the yield strength of the materials and bolt connection will determine if the tests are passed or not. Therefor the yield strength are listed in table VI.3.2.

		Yield Strengths
Offset disc	AISI 316	210 N/mm^2
Bearing	Al 7075	505 N/mm^2
Base and Power train disc	Al 6068	260 N/mm^2
8.8 Bolts		640 N/mm^2

Table VI.3.2: Yield strengths

VI.3.2.0.1 First subsystem

This system will test the bolt connections between the RWS to the offset disc, the bolt connections between the offset disc and the power train disc and the bolt connections between the power-train disc and the bearing.Furthermore the material of the off the power-train disc and offset disc will be tested.

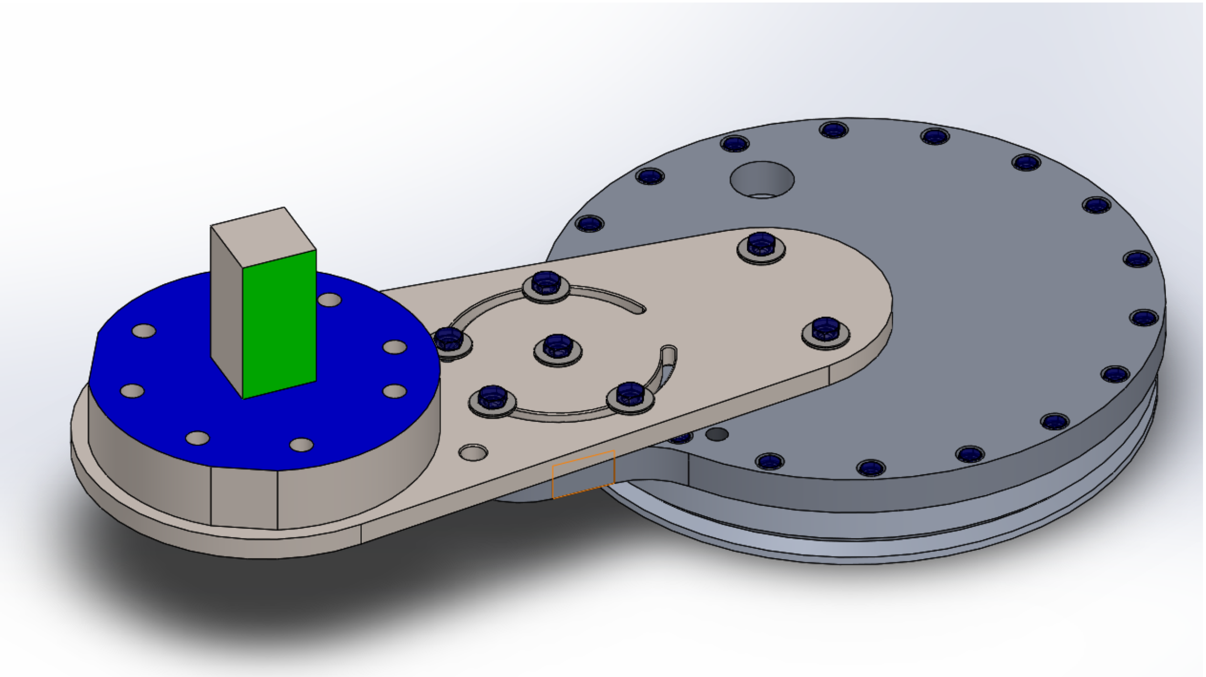


Figure VI.3.1: First subsystem

The forces listed in table VI.3.1 was applied to the system figure in VI.3.1. The rotation from the OMS (F_{OMS}) and the tilt of the motion table (F_{gx}) was applied at the green face. The resulting weight of the RWS from the decomposed tilt (F_{gy}) and the roll motion (F_{roll}) of the motion table was applied at the blue face. The yaw and roll motion will not be applied as forces as stated in the worst case scenario in the design document.

Except the bolt connections one fixture was used on the bottom of the bearing to lock the system in place. The simulated bolt connections in Solidworks were applied with a yield strength of 640MPa which matches the yield strength of an 8.8 bolt. The M12 bolts fastening the RWS was given a preload of 130Nm as specified from KPS, the M10 bolts connecting the offset disc was given a preload of 10000N and the M8 bolts connecting the power-train disc to the bearing was given a preload of approximately 3400N.

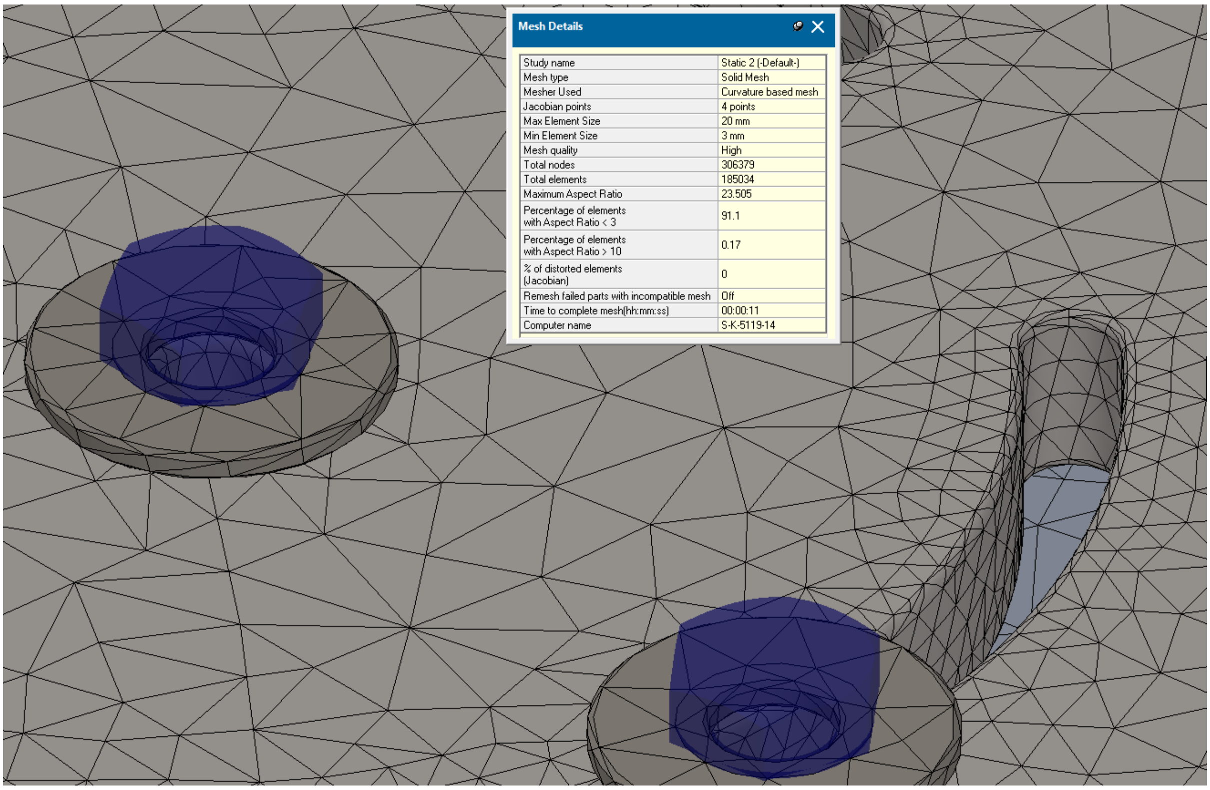


Figure VI.3.2: Mesh Quality

The mesh quality used can be seen in figure VI.3.2. A curvature mesh was applied to force Solidworks create a finer mesh around sharp edges. This is considered beneficial as stress concentrations usually appear around edges and crevasses.

VI.3.2.0.2 Second subsystem

This system will consist of a mockup bearing using the same material as the real bearing connected to the base, connected to the motion table as seen in figure VI.3.3. A mockup bearing is used to spare the analysis for the though calculation it would have to do when simulating a seizing bearing and by using the same material the mockup bearing will still transmit the stresses in a accurate way.

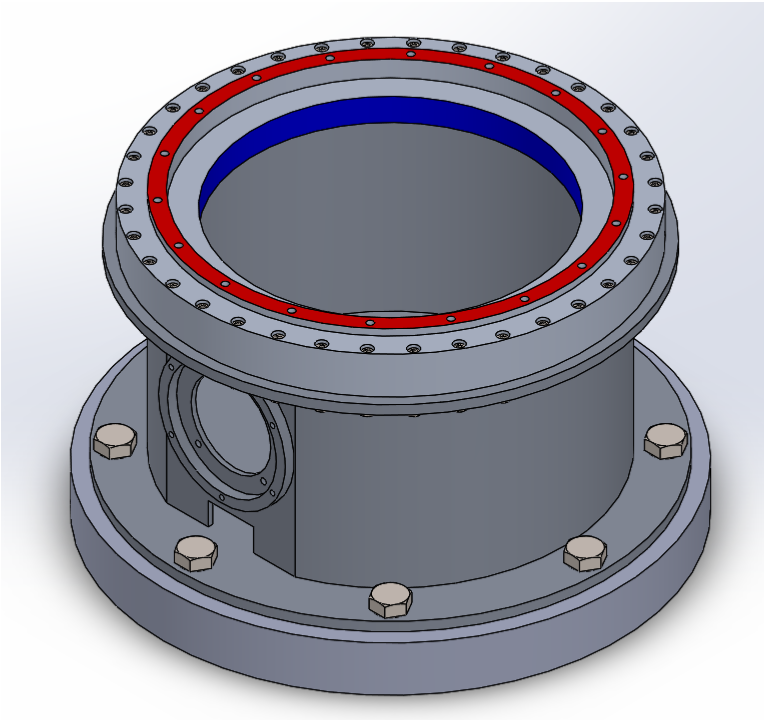


Figure VI.3.3: Second subsystem

In a operational environment the base will only bear the weight of the second subsystem, but as the systems are undergoing a worst case scenario where the motion table goes to a sudden stop after full acceleration and the bearing seizes and transfers all the torque from the rotation to the power-train disc the forces will be as following: the base will be under the stresses of the weight of the second subsystem and the RWS, the roll of the motion table, and the rotation of the OMS.

The rotation will be applied as a torque $T_{OMS} = 240Nm$ and the roll and weight will be applied as an axial force $F_{AxialTotal} = 3100N$. The torque (T_{OMS}) are be applied to the blue face and the axial forces ($F_{AxialTotal}$) are applied to the red face which you can see in figure VI.3.3. Besides the bolt connection connecting all the components together, a fixture is placed on the bottom of the motion table to lock the system in place. The M20 bolts connecting the base to the motion table were given a preload torque of 200Nm as specified by KPS and the M6 bolts connecting the bearing to the base was given a preload of 2511N.

VI.3.3 Test results

VI.3.3.0.1 Study: First subsystem

Figure VI.3.4 shows a color coded plot of the resulting stresses in the material. The maximum stress was identified as 160 N/mm^2 at the edge of the bolt hole shown in figure VI.3.5. Besides the local high stress at this edge the highest stress was below 100N/mm^2 which can be seen at the gap where the offset disc holds the weight of the RWS in figure VI.3.4.

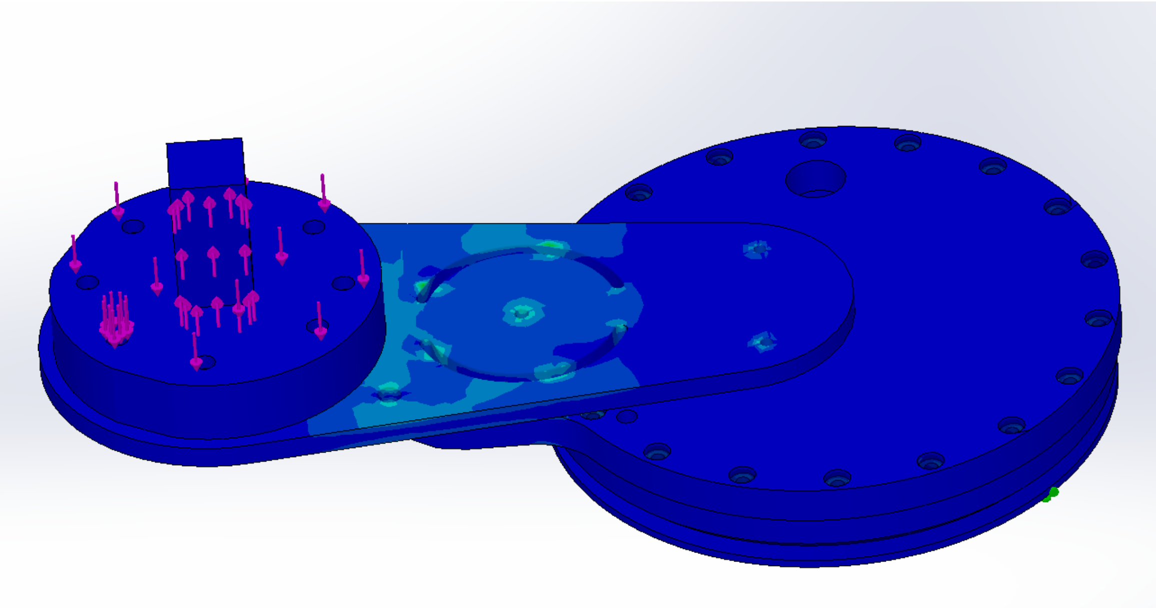


Figure VI.3.4: Stress plot first subsystem

The local high stress concentration around the bolt connecting of the power-train disc is explained in test report TR001 as singularities, ref. chapter VI.1.3.1. Since the maximum stress concentration was identified as a singularity the maximum value on the offsett disc is 82N/mm^2. Which is well below the required acceptance criteria of VT021, VT022 and VT023: *No fixtures nor interfaces are exposed to stresses above 70 percent of the materials respective yield strength.*

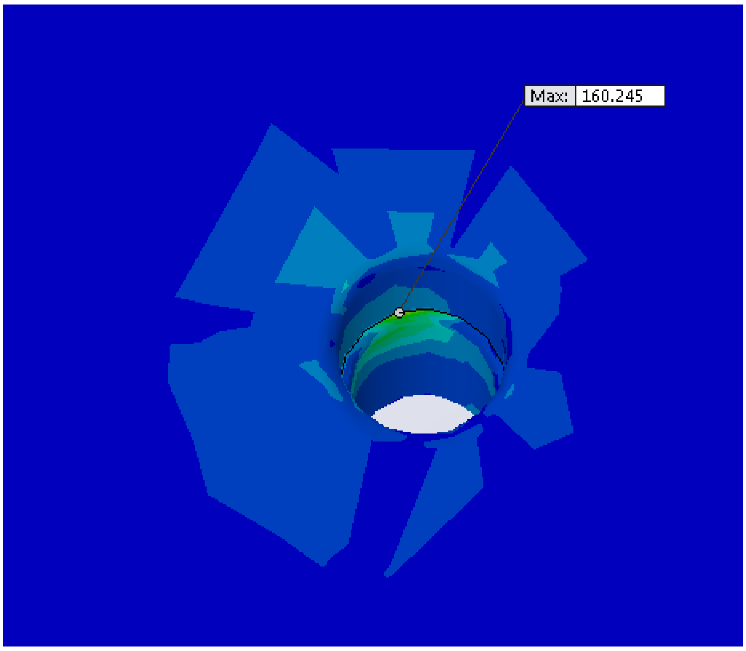


Figure VI.3.5: Stress concentration

Furthermore, as shown in figure VI.3.6 the acceptance criterion for VT006: *No permanent deformation is created to either component of the interface while subjected to a preload torque of 130 Nm. Stress limit 260N/mm^2.* was met. All the forces and preload resulted in a maximum stress in one of the bolt connections of 67 N/mm^2.

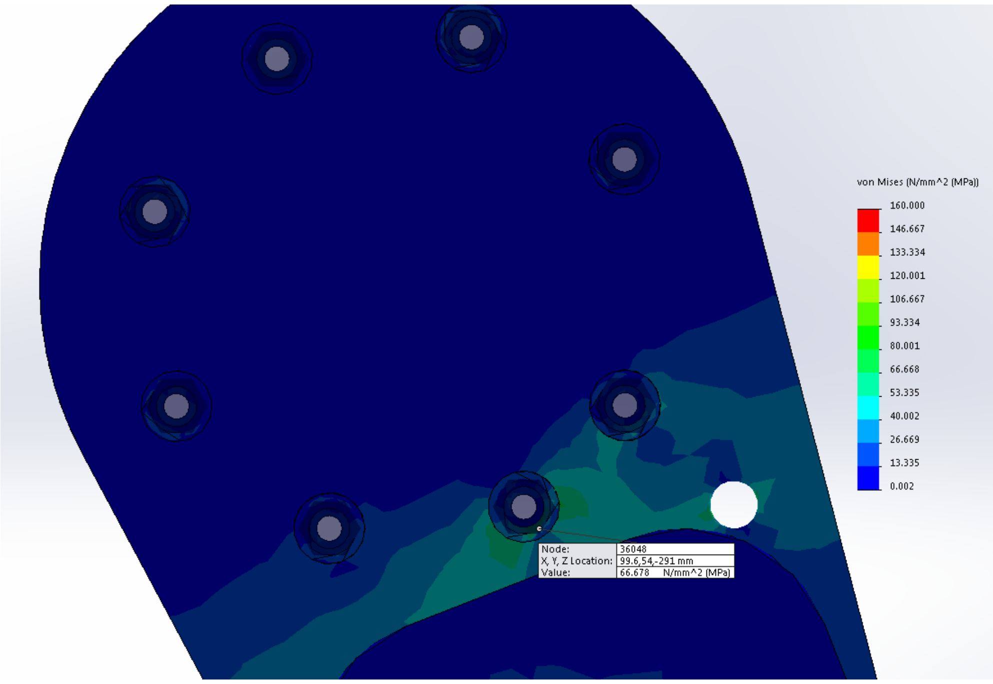


Figure VI.3.6: RWS bolt interface

The bolt connection plot shown in figure VI.3.7 shows that all the bolts passed the required safety factor of 2. The lowest safety factor for the bolts were 2,39 being the M10 bolt which endured the most bending stresses. The acceptance criteria for VT008 and VT009:*The bolts and materials are not exposed to stresses larger than half their respective yield strength; ensuring a safety factor of 2* is therefor also met.

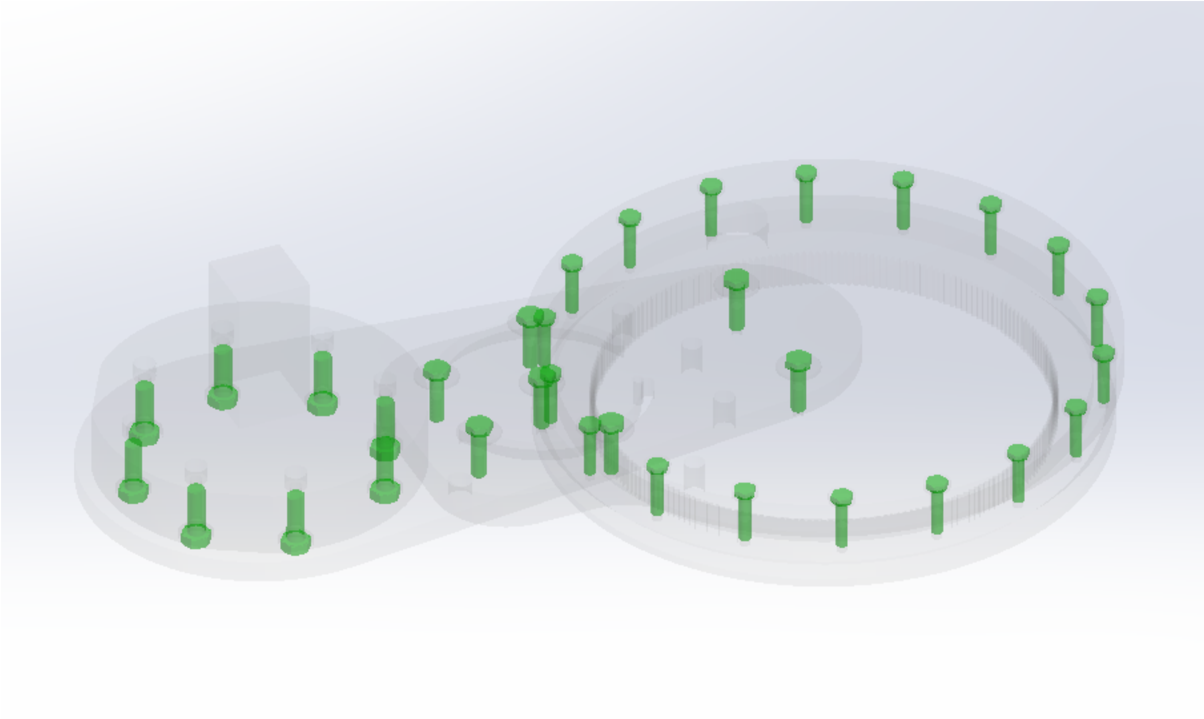


Figure VI.3.7: Bolt connections results

VI.3.3.1 Study: Second subsystem

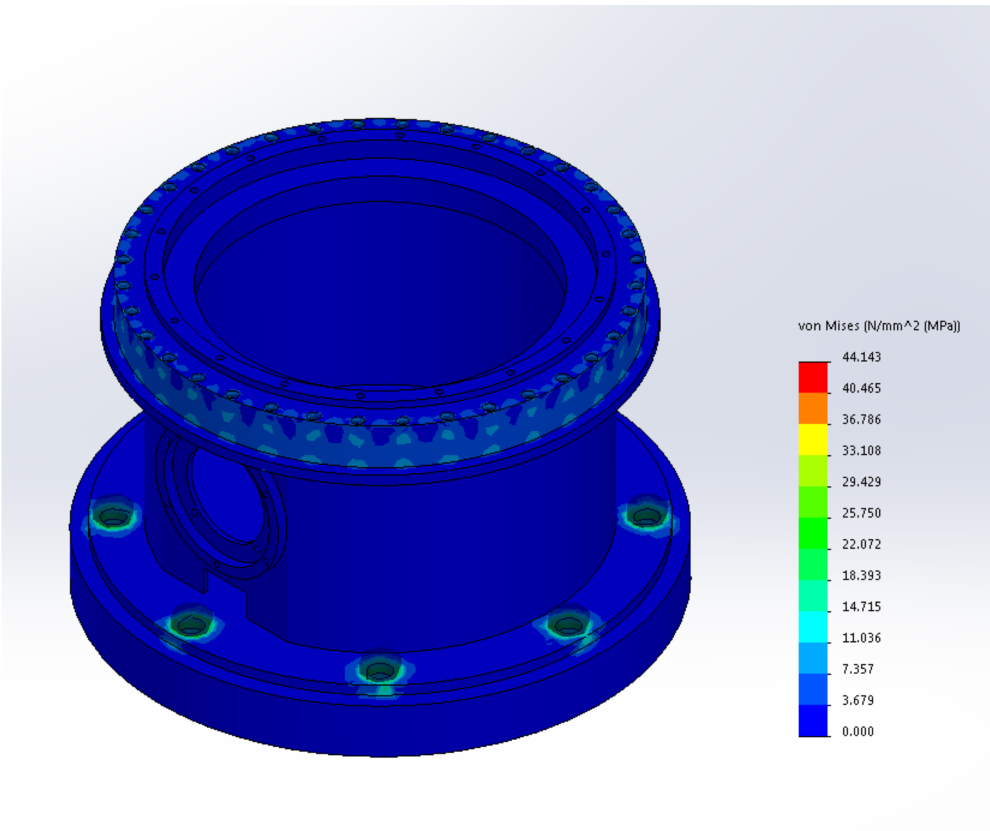


Figure VI.3.8: Stress plot second subsystem

Figure VI.3.8 shows the stress plot resulting from the forces described in chapter VI.3.2.0.2. As seen from the graph the maximum stress is 44 N/mm^2 which is well below all yield strengths listed in table VI.3.2. Therefor VT021, VT022, VT023, VT008, VT009 and VT007 have all passed. VT007's acceptance criterion being: *No permanent deformation is created to either component of the interface while subjected to a preload torque of 200 Nm. Stress limit 260N/mm^2.*

VI.3.3.2 Conclusion

The resulting studies of both subsystem generated stresses well below a safety factor of 2, on this bases all acceptance criteria was passed for both subsystem. The test first subsystem was also done with a 30cm offset which results in one less bolt applied to hold the system together. The resulting stress of this study was well within all yield strength and safety factors. The reasoning for not creating a own test report for this test was that all the resulting stresses was approximately half of the stresses resulting from the 40cm offset test.

VI.4 TR004

Date	15.05.2016
Performed by	Kjetil Fjeld and Heidi Kallerud
Content	Vibration analysis
Tests	VT027

Revision History

Date	Version Number	Comment	Approved by
15.05.16	1.0	Created	Heidi Kallerud

VI.4.1 Test purpose

The test aims to identify the resonance frequency of the system and assure that it does not coincide with a frequency of 30 Hz.

VI.4.1.1 Verification Tests

The following verification test IS covered by Test Report 004:

- **VT027**: *The resonance frequency of the system assembly is above 30 Hz.*

VI.4.1.2 Description

Requirement SRQ015 states that *the system shall consider a roof stiffness of 30 Hz*. This particular frequency should be avoided because the frequency that is imposed on the system when performing recoil tests in the test simulation lab at KPS is 12-15 Hz. A system's eigenfrequency is defined as it's natural tendency to vibrate when an external force is applied. Resonance can occur is the system's eigenfrequency coincides with the frequency of any external influence; such as the frequency of recoil in testing in this instance. Resonance can lead to structural failure at impacts much lower than what the construction is originally designed for, and must thus be avoided. The current verification test will be performed in SolidWorks as a frequency analysis.

VI.4.2 Test Setup

The simulation was done on a bonded assembly without bolts, as Solidworks simulation does not support the use of bolt connectors in frequency studies. The only load applied was gravity. A dummy part with a weight of 250 kg was placed on the offset disc, to represent the RWS. The study was set up to identify the first five eigenfrequencies of the assembly.

VI.4.3 Test Results

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)
1	222.69	35.443
2	303.1	48.239
3	485.69	77.299
4	826.59	131.56
5	1164.2	185.29

Table VI.4.1: First five resonance frequencies of assembly

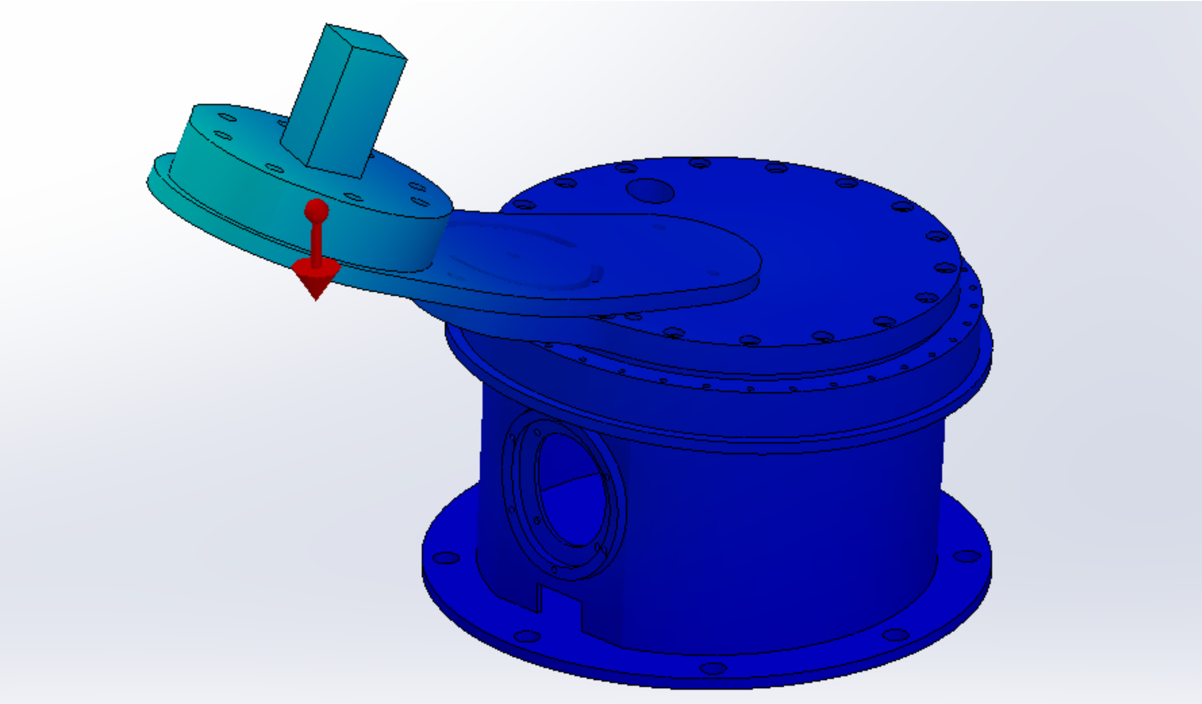


Figure VI.4.1: Resonance Frequency of Assembly

Operating at rotational speeds near the recoil frequency can also induce resonance. The required operating speeds defined in SRQ005 and SRQ009 is 90 degrees/second and 120 degrees; equalling 0.16 Hz and 0.33 Hz; respectively. This is approximately half the recoil frequency and is thus not an issue.

VI.4.3.1 Conclusion

The results of the current test report showed that the eigenfrequencies of the designed system does not coincide with the 30 Hz recoil frequency. Verification test VT027 is thus passed and corresponding system requirement SRQ015 is accepted.

VI.5 TR005

Date	04.05.2016
Performed by	Kjetil Fjeld and Heidi Kallerud
Parts Under Testing	Life span analysis
Tests	VT005

Revision History

Date	Version Number	Comment	Approved by
04.05.16	1.0	Created	Kjetil Fjeld

VI.5.1 Test purpose

To verify that the minimum life span of the system is 5 years.

VI.5.1.1 Verification Tests

The following verification test IS covered by Test Report 005:

- **VT005**: *The system shall have a minimum life span of 5 years*

VI.5.2 Description

To test the life span of the system a number of load cycles that the system is likely to be exposed to over the required 5 years must be estimated. Fatigue analysis of materials and structural geometry was performed in SolidWorks. The fatigue life of bolts can not be simulated in SolidWorks and had thus to be estimated through handwritten calculations, using the Miner's rule.

VI.5.3 Test Setup

From test report TR001 and TR003 it was discovered that maximum stress occurred in the offset disc. These stresses were on around 100 N/mm^2; far below the endurance limit of AISI 316 alloy steel at 260 N/mm^2 [62]. The endurance limit of a material is defined as the maximum amplitude of cyclic stress that can occur without causing fatigue failure of the material [62]. Thus, when running a fatigue analysis in SolidWorks with the worst case load scenarios it was not expected to show fatigue failure of the material. An S-N curve describes the number of cycles at a given stress level that a material can be exposed to before fatigue failure is likely to occur.

As the larges stresses occurred at the offset disc, as described in TR003 and TR001, the bolts used to fix the offset disc to the power train disc (dimension M10, quality 8.8) were subject for further analysis. The Miner's rule is used when there are several different stress magnitudes occurring during a load scenario, each of which contributing to n number of cycles [63]. The number of cycles at a certain stress magnitude (n) is divided by the total cycles (N) that can be withstood at this stress magnitude without failure. The constant C is the fraction of the life cycle consumed by the input load scenario. When C = 1 fatigue failure is reached. The Miner's rule states as follows:

$$\sum = \frac{n}{N} = C \tag{E.5.1}$$

For fatigue analysis of the bolts an estimation of the various stress magnitudes and corresponding number of cycles for each had to be defined. The number of cycles were estimated from demonstration of a test in the KPS test lab, while the stress levels were extrapolated from calculations and other FEA analysis. The details of the estimates of life cycle exposure to load in the bolts were as follows:

- Stress magnitude 1 (SM1): 182 N/mm^2
- Stress magnitude 2 (SM2): 135 N/mm^2
- Stress magnitude 3 (SM3): 91 N/mm^2
- Stress magnitude 4 (SM4): 45.5 N/mm^2
- SM1 and SM2 cycles per minute: 4
- SM3 and SM4 cycles per minute: 30
- Minutes per test: 5
- Tests per week: 10
- Weeks of testing per year: 51
- Total number of cycles oer SM1 and SM2: n = 10 200
- Total number of cycles oer SM3 and SM4: n = 76 500

The endurance limit of the bolts were found by applying the formula defined by Sakai ([64], 2008) which estimates the endurance limit of heat treated bolts after thread rolling:

$$\pm \sigma_e = 0.75(180/d + 52) \tag{E.5.2}$$

This gives an endurance limit of 55.6 N/mm^2 for M10 bolts.

VI.5.4 Test Results

Figure VI.5.2 shows a plot of the number of cycles with exposure to the worst case scenario load that the structure (excluding bolts) can withstand before reaching fatigue failure. As expected based on the average occurring stresses and the endurance limit of the material, the structure can be exposed to a nearly infinite number of cycles. This is also clearly visible through the S-N curve of AISI 316 (VI.5.1), which shows that the occurring stresses of around 100 N/mm^2 is well below the endurance limit, thus allowing an unlimited number of cycles before fatigue failure.

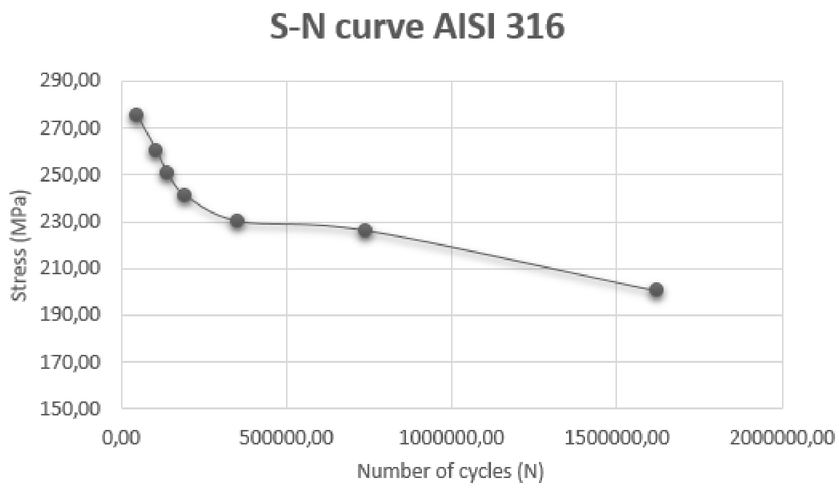


Figure VI.5.1: S-N curve of offset disc

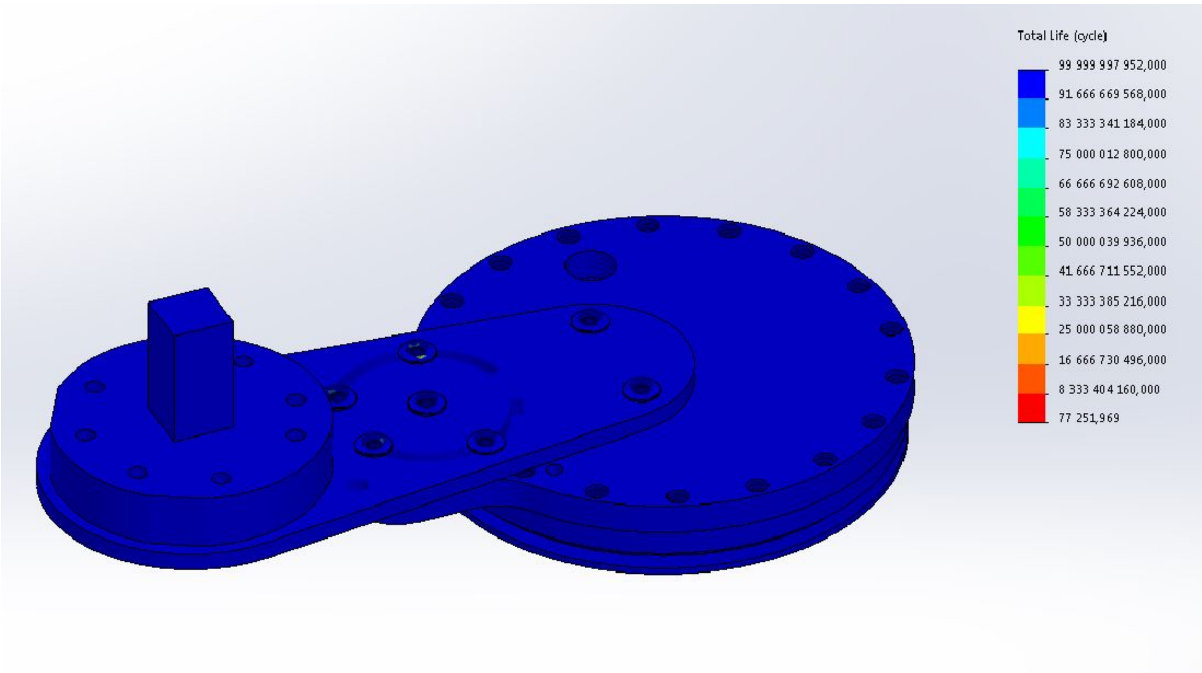


Figure VI.5.2: Total life cycle (n cycles to failure) of structure

Figure VI.5.3 shows details of the fatigue analysis performed in SolidWorks. The plot shows that the washers are exposed to higher stresses, thus reducing the number of cycles that can be withstood before failure to approximately 72 000 cycles. This finding further verified that calculation of the fatigue life of the bolts was necessary.

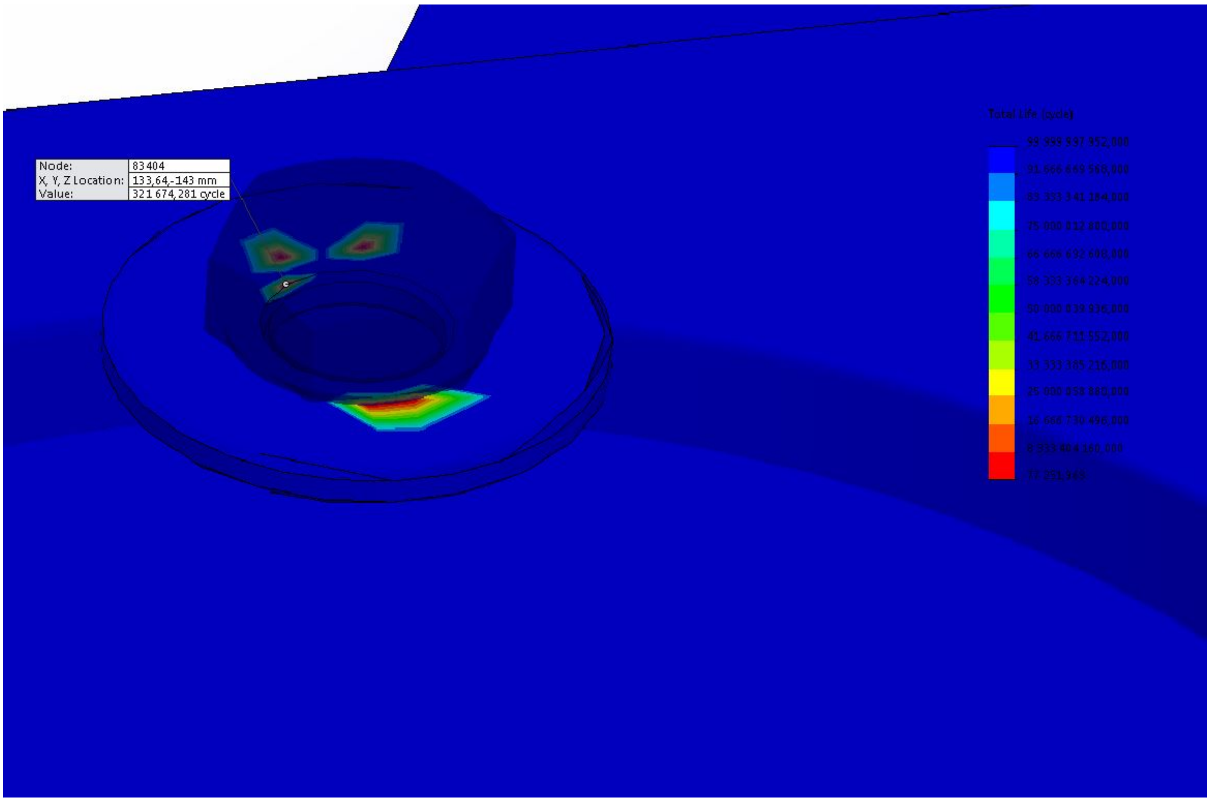


Figure VI.5.3: Details of fatigue analysis

The input load cycles for the Miner's calculation of the constant C was defined above. The total number of cycles that the bolt can withstand at any given stress magnitude was found through the S-N curve of a high strength steel bolt with a similar yield strength and preload as that used in the study by Thor ([65], 2013).

$$\sum = \frac{10200}{20000} + \frac{10200}{120000} + \frac{76500}{1000000} + \frac{76500}{\infty} = 0.51 + 0.085 + 0.0765 + 0 = 0.6715 \qquad \text{(E.5.3)}$$

The output constant C for the calculation of bolt life span shows that the bolts are likely to withstand the defined the described load scenario for **one** year of testing. This means that the bolts should be changed on a yearly basis to safeguard against the likelihood of fatigue failure.

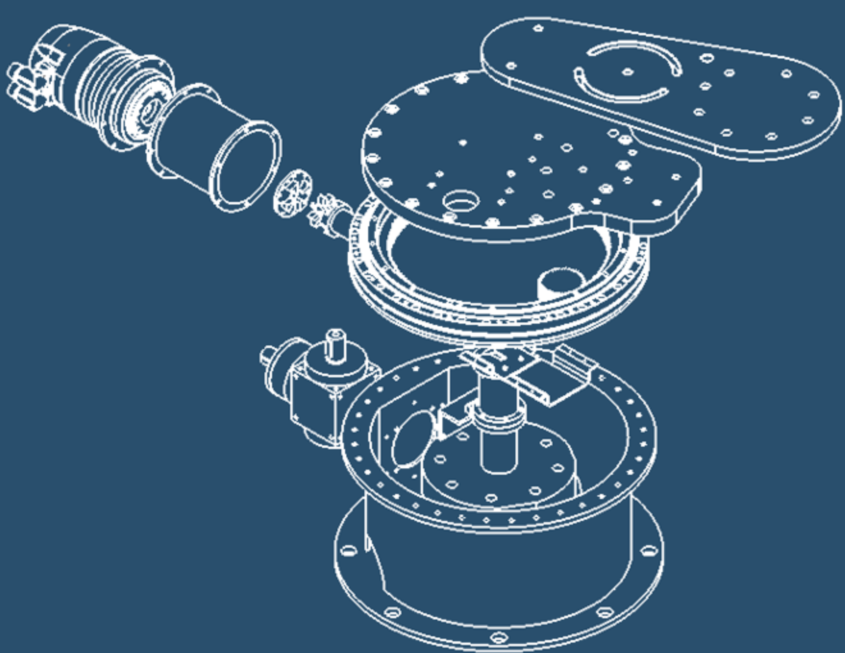
VI.5.4.1 Conclusion

The results of the life cycle analysis shows that the material in the structure that is exposed to the highest concentration of stresses (the offset disc) will have a nearly infinite life time under the defined load scenario. The bolts should be changed on a yearly basis to safeguard against fatigue failure of the bolts. This is an easy measure, with low additional cost. Verification test VT005 is thus considered as accepted.

University College of Southeast Norway

Mechanical Engineering
2016 - 07

Post-Project Review
Orbital Motion Simulator



Abbreviations

Abbreviation	Explanation
KPS	Kongsberg Protech Systems
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
MBT	Main Battle Tank
IFV	Infantry Fighting Vehicle
CAD	Computer-Aided Design
DDMM	Day, Month
HTML	Hyper Text Markup Language
LATEX	Lamport TeX
CSS	Cascading Style Sheets

Revision History

Date	Version Number	Comment	Approved by
03.05.16	1.0	Document created. Introduction, Changes to Project Plan	Heidi Kallerud
22.05.16	1.1	Document approved	Anders Gunbjørnsen

Table of Contents

Abstract

The aim of the project plan was to provide guidelines for execution and progress of the project. The milestones provided major feedback on whether or not the project was on the right track, while the activity list in particular was frequently revisited to ensure continuous daily and weekly progress. In the case of unexpected obstacles or a need to extend certain project phases, changes to the original time schedule needs to be made. This challenges the project team to quickly and efficiently rearrange tasks, change milestones and adjust the time schedule in order to still deliver a satisfactory product at the termination of the project. Several challenges were met in the current project; changes to milestones, challenges within other engineering sciences, requirement identification. The team proved to be adaptable and solution oriented in the face of these challenges, which will be discussed in detail in this chapter. This document reviews how the project went with special regards to the project plan. As this is the first major project undertaken in the team members upcoming career as mechanical engineers, numerous lessons have been learnt that will prove valuable in future projects. The chapter ends with a summary with these lessons, which are also hoped to prove useful to fellow students.

VII.1 Review of the Project Plan

VII.1.1 Milestones

The initial milestones of the project were set with the goal of making both a 3D printed prototype, as well as a fully functional prototype to be tested in the KPS lab. In retrospect we see that goal of making a fully functional prototype was rather ambitious, given the timescale of the project. Design development requires numerous iterations in order to assure that all options have been thought of, as well as ensuring a thorough evaluation of all suggested designs based on carefully chosen evaluation criteria. Furthermore, detailed analysis is time consuming as any mistakes in calculation of input variables to the simulations can have severe ripple effects. If an input variable is wrong, a satisfying result from the simulations will no longer be valid. Lastly, the project team consists of bachelor students who have little, or no, experience in project management and applied engineering sciences, which results in more time being spent on all tasks compared to engineers with work experience.

The milestone "Prototype Alpha" was changed to "Preliminary Design Decision", as much more time and emphasis was placed on design development and detailed evaluation of the design. This process was both emphasised and recommended by our employer, KPS. The milestone "Prototype Beta" was changed to "3D print prototype", effectively representing what would be made in the prototype alpha model. A result of these changes were in effect that validation of the system could not be undertaken, as this requires a fully functioning model to be tested in its intended operating environment. Hence, the last milestone "Test verification and validation finished" was changed to "Test verification finished".

VII.1.2 Iteration Planning

Seven iterations were planned at the initiation of the project. However, as the project evolved and new "knowns" and "unknowns" appeared, it was deemed necessary to add two more iterations; to duplicate iteration 5, and to add iteration 4 and 7. The CAFCR+ is a highly flexible model with regards to going back and revisiting all domains if needed, or adding in iterations when needed. This is a particularly important trait when choosing a model for a project team consisting of inexperienced members, or when developing a system that is completely new or contain a large amount of uncertainties and "unknowns" to the project team. Iteration 4 was added to gain a more detailed understanding of the dependencies between components and functions within the system, and to map what technical trade-offs we were likely to meet. Iteration 5 was added because a more detailed evaluation of the preliminary designs were needed, in order to be confident of our final design decision. Lastly, iteration 7 was added to initiate the analysis phase of the project. This iteration helped get a rough overview of the forces acting on the system and provided a path for how to move forth into detailed analysis in a more structured, step-wise manner. Choosing this flexible project model allowed the project team to take the time they needed to ensure that proper understanding was gained before moving forth into the next step. A more rigid model could in this instance have led to premature decisions being made and important aspects of understanding could have been lost.

VII.1.3 Activity List and Timeline

The changes made to the Milestones and the Iteration Plan were reflected in the Activity List and the Timeline. The final date for Presentation 3 was added, as well as a time box for performing verification tests and writing test reports.

VII.2 Risk Management

Numerous risks were identified at initiation of the project, each of which were rated according to their likelihood of occurrence, severity of consequence and detectability. A likelihood-severity chart (figure VII.2.1) was made in order to clearly visualise which risks were most critical. The chart showed a cluster of risks related to requirement identification (either lack of identification, misinterpretation or occurrence of new requirements) in the upper, middle area. This meant that these risks were both likely to occur and the consequences of occurrence could be extensive. As will be discussed in chapter VII.3, special attention was placed on requirement management. A risk management matrix was developed and all risks were assigned to a period in which they were most likely to occur. This helped the project team to easily get an overview of what risks they should pay most attention to in the current or upcoming period. The risk management matrix was frequently revisited through numerous iterations and the status and strategy for the most critical risks were discussed.

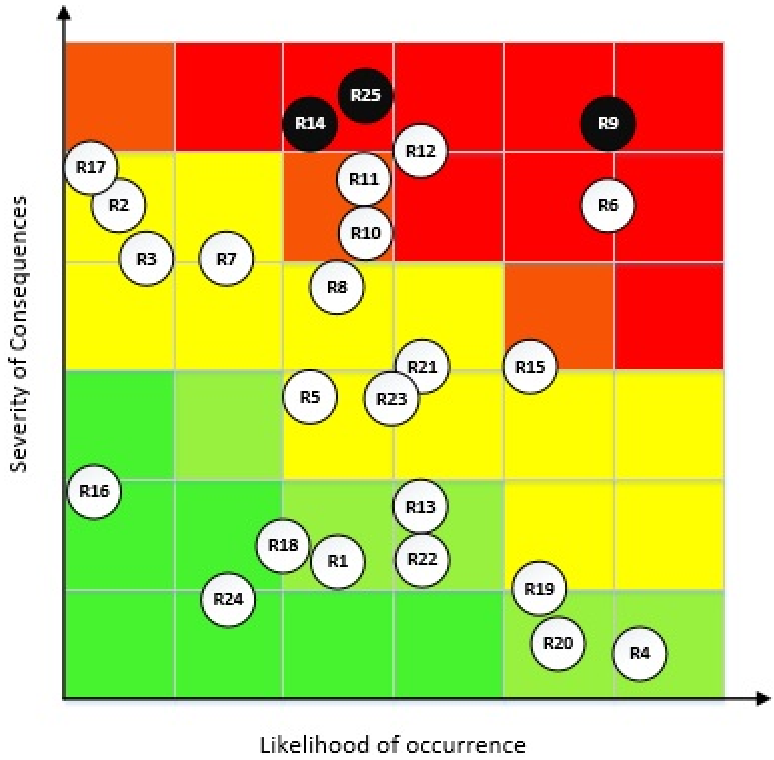


Figure VII.2.1: Likelihood-Severity Risk Chart

VII.2.1 Knowledge within Other Engineering Sciences

The project team consists of mechanical engineering students only, and risk number R6 and R9 relates to lack of electro and computer programming knowledge. These were risks of high rating and were relevant in the design development phases, the detailed design and analysis phase. The planned strategy was to clearly limit the scope of project in Project Plan; however, in order to design a system that would be possible to work with and further develop in future projects (as required by KPS), some attention to electrical and computational detail was imperative. Thus, our second strategy for mitigating this risk was to "cooperate closely with KPS engineers to verify suggested solutions for electronic and electrical interfaces". Advice and verification was sought from knowledgeable people at both KPS and HSN. However, at the end, the project team had to be responsible for making the final choices for electric components; most importantly the motor. After much reading and many smaller "iterations" to arrive at two options which were deemed; by our best assessment; a suitable solution for an electric motor. Although the project team believed to have performed the correct calculations needed for a well-informed decision, it was decided to safe-guard the design against any errors due to lack of knowledge. This was made by both providing two alternatives for motors, and to develop a design that could easily be adjusted to fit a motor and/or gear head of a different length by simply changing one dimension in the mounting disc design.

VII.2.2 Parts and Validation

Risk R22-R25 were no longer as applicable as initially thought, after realising that production of a fully functioning prototype could not be realised. These risks pertained to acquisition and delivery of parts, and mechanical failure of the system during validation tests or usage. Risk R5 was defined as "mechanical failure of the system during testing or usage". The system was designed with this risk in mind, as a safety factor of minimum 2 (DRQ025) was used in the design of all mechanical features. Risk R23; "Acquisition of parts is challenging"; was considered when choosing specific components for the detailed design. E.g. when possible, suppliers that already exist in the supplier database at KPS were chosen, as this would simplify the process of consulting, ordering and approving parts.

VII.2.3 Motivation and Illness

Risk R1 and R3 pertains to the risk of a group member losing motivation, getting sick or unexpected illness occurring sometime during the project period. Just about every group member experienced sickness or unexpected events during the project period. Necessarily, the "strategy of action" for this risk had to be to accept it, but to develop a mitigation strategies that reduced the consequences. The mitigation strategy firstly involved redistributing the work of the ascent group member. Secondly, the group aimed to work in pairs on most tasks in order to always have at least one person with an overview and knowledge of each working area. In this way, work on a task can rather uninterruptedly progress if one group member gets ill. The latter strategy in particular proved very useful when members of the group at various times were either away or got ill.

VII.3 Requirement Management

VII.3.1 Requirement Risks

The likelihood-severity chart that was developed for risk management purposes showed a cluster of risks related to requirement identification in the red zone; indicating both high severity of consequences and high likelihood of occurrence. The relevant risks are presented in figure VII.3.1 below.

RISK MANAGEMENT MATRIX			Rating	
Type	Risk ID	What	Strategy of action	Sum of rating
Technical	R10	Misinterpretation of stakeholder or system requirements	Avoid	BAB
Technical	R11	All requirements have not been captured	Protect	BAB
Technical	R12	System design fails to meet requirements	Protect	BAB
Environment	R14	Customer dissatisfied with process or project outcome	Protect	CAA
Environment	R15	New requirements appear during the project life-cycle	Accept	BBB

Figure VII.3.1: Requirement Risks

Based on this finding from the likelihood-severity chart it was decided to frequently revisit and re-validate the requirements during iterations throughout the project period. Primary identification and formulation of requirements was undertaken throughout iterations 1-3, where a progressively deeper understanding of the system led to further questions and perceptions. In iterations 5 and 6 a discussion of occurrence of any new requirements was provided. This proved very valuable, as our increasing knowledge with the system through development and frequent dialog with KPS, revealed both new requirements and misinterpretation of some initial requirements. For example, reviewing the manual for the motion table, as well as seeing the table in the lab, revealed numerous additional requirements with regards to the motion and forces the system would need to withstand in its operating environment.

Another successful method for uncovering "forgotten" or misinterpreted requirements was to hold a frequent dialog with KPS and provide presentations of initial and preliminary designs. Through these presentations the group got a better understanding of which requirement that weighed the most to KPS. E.g. the group had interpreted the requirement of having numerous offset increments (STRQ013) as highly desirable and thus aimed to find a design that would allow an almost indefinite number of offsets within the 30cm range. However, discussion with KPS during presentation of the preliminary designs revealed that other requirements; such as ease of mounting; weighed more to them. Furthermore, the requirement regarding *emergency stop* (STRQ005) was interpreted by the group as a requirement of integration of a mechanical stop function, which would significantly increase the complexity of the design. A discussion with the originator of this requirement; the KPS Test Division; clarified that a mechanism that simply cut the power supply to the motor would be sufficient.

The group believes to have mitigate risk R14; *customer dissatisfied with process or project outcome*, by ensuring frequent dialog with KPS, asking questions and presenting our thought and concepts along the way. Furthermore, the group also chose to alter our initial time schedule by a week to comply with KPS' wish to extend the design evaluation phase by including a more detailed preliminary design evaluation. This proved to be a very wise choice, as the result of this extended evaluation period revealed design aspects that changed our views of the candidate systems and ultimately led to final selection of a design that initially was not considered the best one.

VII.3.2 Breakdown of Requirements

As described in the Requirement Specification document, the stakeholder requirements were broken down into system requirements. These system requirements are further broken down into design requirements, and in a few selected cases the design requirements were broken further down into component requirements. The last step in the requirement breakdown pertained to complex components where great consideration of interfaces or features were needed, e.g. in the case of the slip ring. The level of breakdown greatly depended on the how complex the situation were with regards to the component or feature involved. The requirement breakdown also served the purpose of traceability and documentation of why a certain component was chosen ahead of another. All components or features had to be verified at both component requirement and design requirement level before being eligible to be integrated into the design. Due to this it was deemed appropriate to undertake testing at system requirement level. This

VII.3.3 Requirement Status and Fulfilment

The last requirement reassessment in iteration 9 served as an evaluation of the status of each and every requirement. This evaluation revealed which requirements that was already fulfilled, which ones that were ready to be verified, which ones that were in progress and which that were in need of urgent attention in order to be fulfilled. This helped the group identify what requirements that should be focused on in the nearest future. E.g. the requirements pertaining to strain on wires (SRQ032 and SRQ033) were identified as urgent. This was due to questions of how we could actually provide a measurable acceptance criteria for this requirement without the use of strain gauges. After some research it was found that there were standards for the minimum bending radius that should be applied to wires.

System requirement SRQ023; *The system should have a maximum weight of 50 kg*; was also marked as *urgent*, because it was uncertain if this requirement could be fulfilled. Concern about this requirement arose already at the development of the preliminary designs, when details of the emerging designs revealed that this requirement could present great challenges. To ensure that the consequences of potentially not fulfilling this requirement were not too severe, efforts were made throughout the detailed design period to design a system that constituted of sub-assemblies of 2-3 parts weighing less than 39.5 kg, which could very easily be assembled. The exact weight of 39.5 kg stems from stakeholder requirement STRQ025, which dictates the maximum dimensions and weight the system can have for health and safety reasons. This was a *shall* requirement and was thus highly prioritised. No single part weighs more than 39.5 kg, and the intended sub-assemblies for service does not weigh more than 39.5 kg separately. The 50 kg weight requirement was used more as a guideline to keep total weight down as much as possible during the design process. As shown in test report TR002 the total weight of the entire assembly weighs approximately 60 kg, thus rejecting the *should* requirement SRQ023. However, the *shall* requirement regarding weight is fulfilled and does not compromise greatly the mounting time of the system. Furthermore, a crane is easily available in the lab if it is needed to move the system in one single piece.

Stakeholder requirement STRQ005, with accompanying system requirements SRQ008 and DRQ011, pertained to the need of having an emergency stop function integrated into the system. It was initially believed that this involved a mechanical stop function. I was challenging to find the exact person at KPS whom this requirement originated from, but eventually a discussion with the relevant person revealed that the need for an emergency stop function meant a switch or button that shut down the power supply to the system. Due to the technical scope of the project electrical components were not part of the system development, but was kept in mind for consideration of future students. Thus, integration of a switch was not fulfilled in the current project. KPS was notified about this as soon as it was clarified that an electrical; and not a mechanical; emergency stop function was sought. It was agreed that this was a requirement that pertained to those who will develop the electrics and computational control of the system. The mentioned requirements are thus listed in chapter VII.8; *Guidance for Future Development of the Extended OMS System*; to ensure that they will be addressed when further development of the system commences.

At termination of the project 50 out of a total of 53 system requirements were fulfilled. The designed system fulfills (by verification) more than 94 percent of all the system requirements, including numerous requirements that were listed as *should* requirements. *Should* requirements are considered highly desirable, but plausibly unachievable, by the stakeholder. By providing functionality beyond the minimum specifications, the stakeholder consequently have more freedom to design their desired test simulation scenarios.

VII.4 Time Management

According to the Activity List it was estimated that the group as a whole would use around 3838 hours to complete the project. At termination of the project 3513 hours were used, including an approximation of the hours that would be spent to finish the prototype and make the final presentation. This equals an error of approximately 54 hours per person, which is not too bad considering that this is the first time the project team attempts to schedule and estimate time usage for a larger project. A comparison of the cumulative sum of planned versus used hours throughout the project period is provided in figure VII.4.1. There is a "jump" between the two lines at initiation of the project, which is due to the team not being structured enough yet to log hours daily, as well as we did not start to use TimeBank until approximately week 2-3.

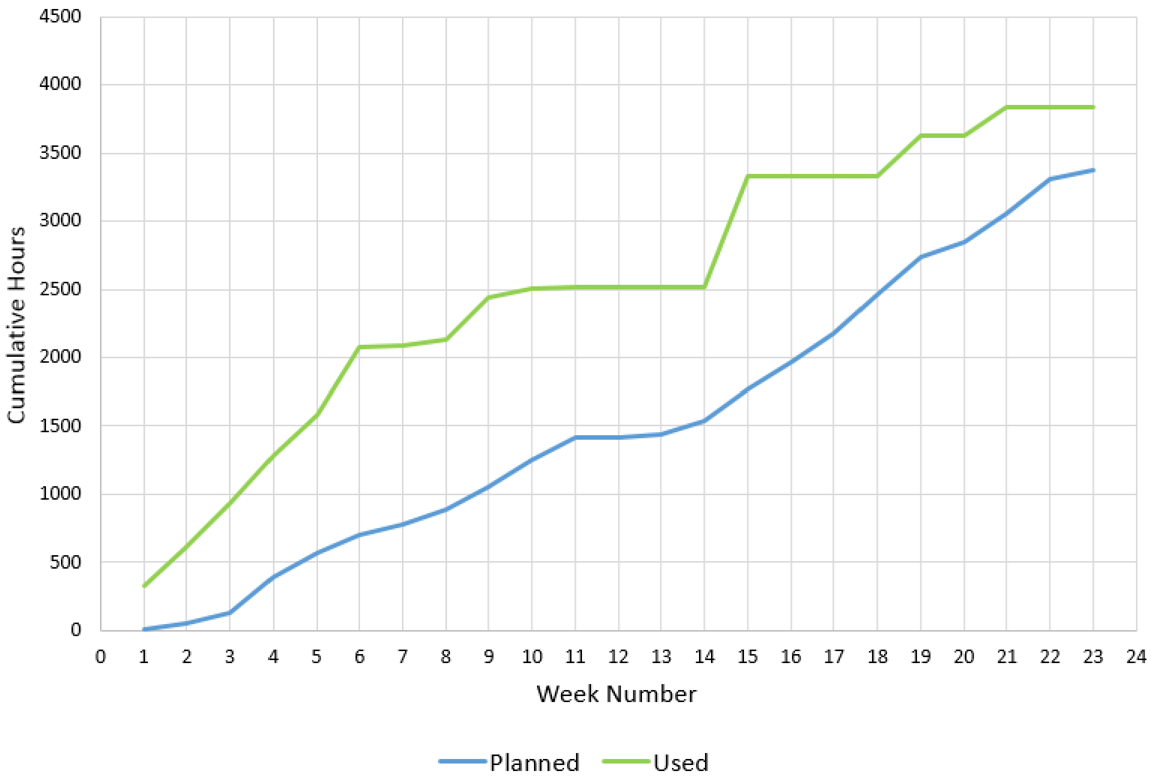


Figure VII.4.1: Planned hours compared to actual spent hours

Figure VII.4.2 shows an overview of the hours spent within the defined categories. As visible from the bars each person spent approximately the same total amount of hours; ranging from 566 to 599,5 hours.

Figure VII.4.3 shows the distribution of work within categories for each person in the project team.

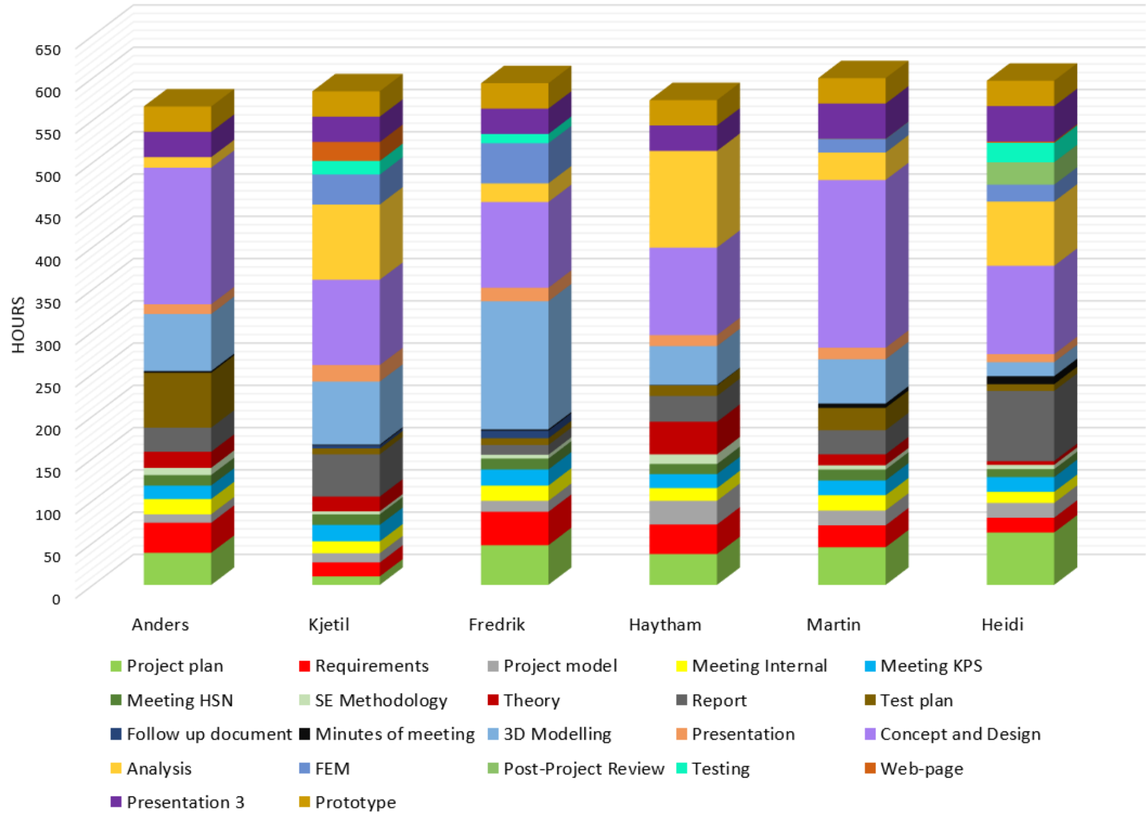


Figure VII.4.2: Hours spent per category

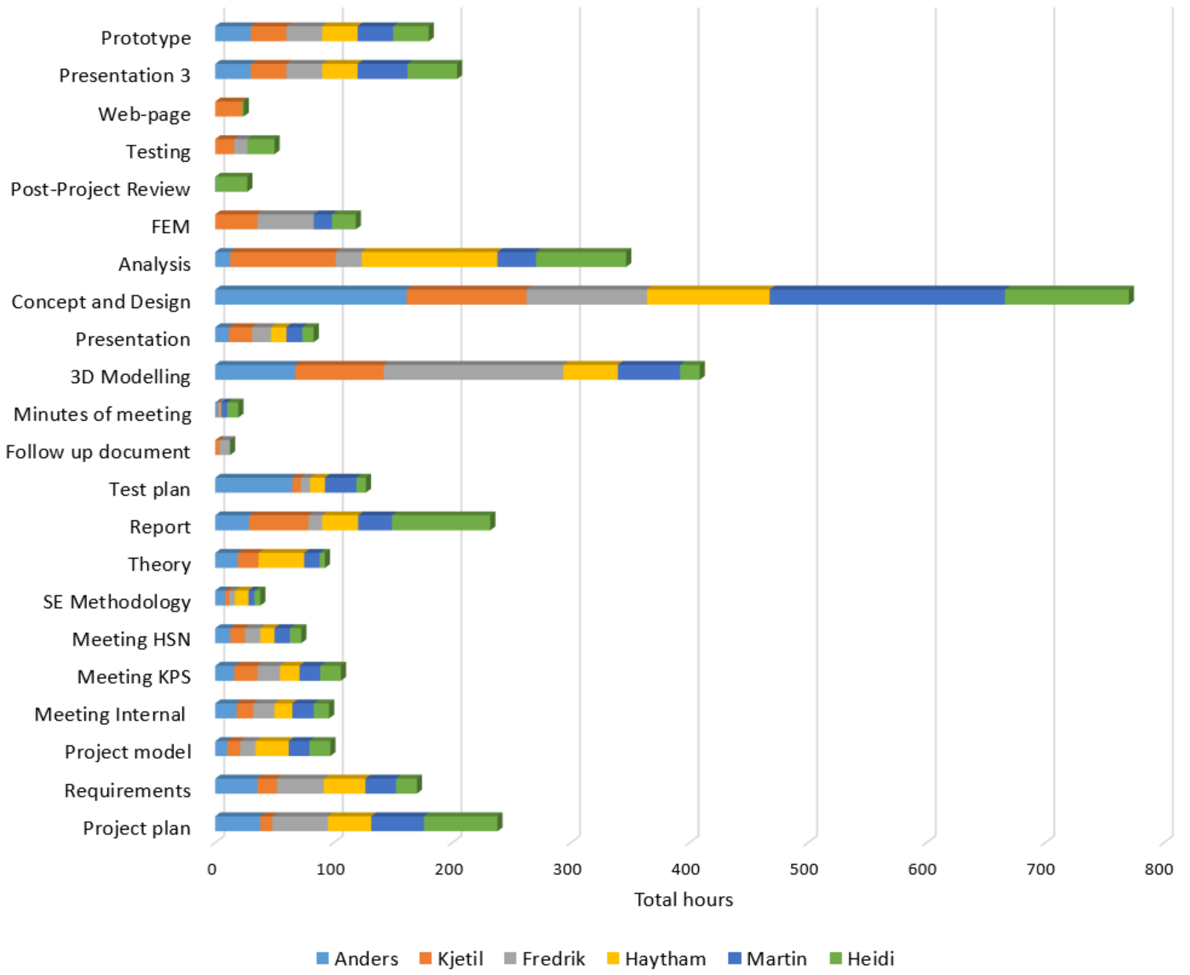


Figure VII.4.3: Distributed hours per person

In retrospect we see that it would have been very advantageous if the categories and tasks defined in TimeBank had coincided with the activities in the Activity List. This would have made it easier to compare the number of planned hours per activity to the actual spent hours per activity.

VII.5 Review of the Test Plan

Following the realisation that production of a fully functioning prototype was not feasible for the scope of the current project, the validation tests became obsolete. For a requirement to be fully validated it is necessary to test the functionalities of the system as an entirety in its intended operable environment. Thus, the requirements could only be verified in the current project. The validation tests were however kept in the Test Specifications document. The intention was to provide documentation of how the team had worked to ensure that fulfilment of each stated requirement shall be possible to demonstrate directly to the stakeholder. Furthermore, a description of how the team intended to test various mechanical and functional properties of the system might also prove helpful for future students who might be required to eventually realise the manufacture, assembly and full scale operation of the final system.

All components or features had to be verified at both component requirement and design requirement level before being eligible to be integrated into the design. Due to this it was deemed appropriate to undertake testing at system requirement level. This is because it was already verified at a lower requirement level that the features and characteristics we thought were needed to deliver a function were fulfilled. Whether the components and features actually worked together as thought to deliver a function is then assessed at systems level. As seen in the Test Specification document all tests pertain to a certain system requirement. Also, it was deemed more feasible to formally test at a systems level due to the time scope of the project, as testing and documentation at the lower levels would involve a much more substantial protocol. Developing the method and going through the process did however uncover why it is important in many cases to keep track of decisions and choices all the way down to a component level. This might be particularly important in large projects where the various project members do not work as closely with each other as we had the opportunity for in this project, as is provides clear guidelines and makes it easier to trace back errors if a tests at system level fail.

Hand-in of a Test Specification document was mandatory at the project's first presentation. This was found rather challenging as all requirements had not been identified and the stakeholder's true intention of each requirement had not yet been fully clarified. In retrospect it has become clear that development of a test plan at such an early stage introduces a considerable amount of corrections and additional work. However, a requirement shall not be stated without knowing for certain that it is actually possible to both verify and validate it. Also, the time span of the project did not allow for development of a test plan to be initiated that much later either. As a lesson learnt, in future projects of greater scope, the project team would emphasise to the greatest extent to clarify the true meaning of each stakeholder requirement before developing a test plan.

Choosing and following a test method that is appropriate for our project proved very helpful with regards to structuring the test phase. The Incremental Test Method was chosen (as described in the Test Plan) and two Incremental Testing Pathways were developed to help us structure the order in which components should be tested. These pathways were well thought through pathways that ensured that each component was verified in isolation before being incrementally added into the assembly, where the gradually more complex assembly was tested as an entirety. This approach made it a lot easier to allocate what components and interfaces that introduced errors or failures.

An extensive requirements matrix was developed for this project. Both verification and validation test IDs were added to the row of the corresponding requirements. This helped keep an overview of the status of each requirement at any given time; which requirements that could be tested, which ones that were accepted or which that did not meet the acceptance criteria and thus needed attention. For the scope of the current it was decided to test all requirements at a system level. Design requirements and sometimes even component requirements were stated for some components. However, these detailed requirements were considered when choosing or designing specific components, while whether or not they were capable of serving their intended functionality within the given context of the system was deemed more feasible to test at a high level; system requirements level. In more comprehensive projects with even more complex systems it is likely purposeful to write specific tests for design requirements, and maybe even component requirements. This is because larger projects might involve more team members that possibly do not see each other every day, which the OMS team did. Very close cooperation resulted in everyone having an overview of the components, progress and design at most times; such that we quickly could consult each other with regards to design and component requirements. In larger teams this might not be possible; resulting in a greater need for more detailed component requirements and accompanying tests to ensure that the system in entirety will function once assembled.

VII.6 Challenges

The following chapter presents in brief the most considerable challenges the group met throughout the project period. Along with a description of how these challenges were dealt with, a retrospective discussion of how successful this approach was is provided. The aim of the chapter is to highlight useful strategies or approaches that should be avoided in the future.

VII.6.1 Decision of Final Design

The development, evaluation and selection of design was a comprehensive process consisting of numerous phases:

1. Three brainstorming sessions for concept development
2. Coarse feasibility assessment and filtering of concepts
3. Detailed feasibility assessment and filtering of concepts
4. Preliminary design development
5. Final design decision

The concept filtering did not point out a clear best alternative. The project team identified the three best concepts and looked for a hybrid solution that could mix and match the best parts from each of the strongest concepts. In the detailed design evaluation the Hybrid solution received a slightly higher score than the Double Discus (later called OMS). As the two concepts received such similar scores it was challenging to try to decide which was actually better, as both at that stage were only draft designs. By advise from KPS it was thus decided to model both concepts in further detail to more realistically uncover the advantages and challenges with each design. This decision implied that the whole project schedule would be delayed by minimum one week and the chance of realising the goal of making a fully functional prototype would be greatly reduced. However, the system is intended for long-term use in an environment that puts high requirements to accuracy, safety and performance. It was thus decided that the most advantageous for the customer would be to put more emphasis in the design phase, to ensure that the most optimal solution was actually chosen and further developed into the final product. This decision appear to be a wise one, although it resulted in us not being able to make a functioning prototype. This is because the preliminary design development of the two options revealed more detailed design aspects that previously had been based on assumptions only. Presentation of the two to the customer also revealed that which requirements they rated as most important were different from what the project team had interpreted it to be. Thus, the final selection fell on a design that at the detailed design that initially did not appear as the most optimal one.

The whole design selection process taught us that flexibility and making sacrifices of personal interests are sometimes necessary in order to provide the customer with a solution that is likely to fulfil their needs to the greatest extent. The decision of extending the design phase led to logistic challenges, restructuring of work and changes to milestones. The positive outcome was that more time was distributed into going deeper into analysis and development, to ensure to a greater extend that all detailed design decisions were made on the basis of profound understanding, thorough calculations and a holistic system view.

VII.6.2 Technical Software

LaTeX is the document typesetting and preparation system used for all documents pertaining to the project. When writing with LaTeX the end user writes in plain text instead of in formatted text as with Microsoft Word. Markup tagging similar to HTML is used to define document structure, stylize text and citations. Documents are written as .tex files that will go trough a compiler to produce a .pdf output. An example of the Tex markup language can be found in Code VII.6.1, said markup will produce the table found in figure VII.6.1.

Code VII.6.1: Tex markup of a table

```
\begin{table}(ht)
    \centering
    \rowcolors{2}{TableOne}{TableTwo}
    \begin{tabular}{|l|l|l|}
        \rowcolor{cpiGray!60}
        \multicolumn{3}{c}{\textbf{Electric Motor Selection}} \\
        \textbf{Solution} & \textbf{Pros:} & \textbf{Cons:}  \\ \hline
        \rowcolor{TableOne}\textbf{Permanent Magnet} & $\bullet$ Smooth torque & $\bullet$ High cost \\
        \rowcolor{TableOne}\textbf{(PMSM)} & $\bullet$ High efficiency & $\bullet$ Risk of demagnetisation\\
        \rowcolor{TableOne}& $\bullet$ Good heat dissipation &  \\
        \rowcolor{TableOne}& $\bullet$ High current-to-torque ratio  & \\
        \rowcolor{TableOne}& $\bullet$ Compact &  \\ \hline
        \rowcolor{TableTwo}\textbf{Induction} & $\bullet$ High dynamic performance & $\bullet$ Lower current-to-torque ratio \\
        \rowcolor{TableTwo}\textbf{(asynchronous AC)} & $\bullet$ Low cost & $\bullet$ Low efficiency \\
        \rowcolor{TableTwo}& $\bullet$ Simple construction & $\bullet$ Large size \\
```

```
            \rowcolor{TableTwo}& & $\bullet$ Complicated control \\
            \hline
        \end{tabular}
        \caption{Electric motor selection}
        \label{tab:elmotor}
    \end{table}
    \FloatBarrier
```

LaTeX provides many advantages and some disadvantages over other typesetting software, in therms of communication and publication of scientific and technical documents. These advantages and disadvantages will be discussed in this document.

Electric Motor Selection		
Solution	**Pros:**	**Cons:**
Permanent Magnet	• Smooth torque	• High cost
(PMSM)	• High efficiency	• Risk of demagnetisation
	• Good heat dissipation	
	• High current-to-torque ratio	
	• Compact	
Induction	• High dynamic performance	• Lower current-to-torque ratio
(asynchronous AC)	• Low cost	• Low efficiency
	• Simple construction	• Large size
		• Complicated control

Figure VII.6.1: Tex output of Code VII.6.1

VII.6.2.1 Advantages

The main advantage of using LaTeX is its handling of citations and cross-references. Unique labels can be added to every element of the document i.e. chapters, sections, figures, references and many more. The LaTeX compiler will work out their order in the document, and number each element to generate table of contents and figure lists. As an example the 5th figure of chapter 3 will be refereed to as figure 3.5, LaTeX is also able to output which page said figure resides on.

Another advantage is that styling of the documents can be done by defining variables and environments. Formatting of the chapter headings exists in the preamble of the document. Changing the style of an element in the preamble will change the format of every element of that type in the document. Colors can be defined as variables, these variables can be used to define things like the color of the table headings throughout the documents.

The idea is that when LaTeX is applied and used correctly, the user will spend more time on content creation and less on content management. Changing the order of chapters in a document will never result in jumbled or incorrect table of contents or chapter numbering. The references will still be numbered chronologically as they appear in the document.

LaTeX also supports creation of macros, these macros can be used to define custom elements that appear multiple times in the document. Requirement boxes in the Requirement Specification was made using macros. The output of Code VII.6.2, is shown in figure VII.6.2

Code VII.6.2: Tex markup of a requirement box

```
%Requirement macro
\newcommand{\krav}[7] {
\begin{table}[ht]
\begin{tabularx}{\linewidth}{|X | p{2cm} p{2cm}|}
        \hline
        \rowcolor{cpiGray!60}
        \multicolumn{2}{|l}{} & \multicolumn{2}{r|}{ \LARGE\textbf{#1}} \\ \hline
        \multicolumn{2}{|l|}{\textbf{Description}} & \multicolumn{2}{|l|}{\textbf{Status}}  \\
        \multicolumn{2}{|p{10cm}}{#5} & \multicolumn{2}{|l|}{#2}  \\
        \multicolumn{2}{|l|}{\textbf{Test ID(s)}\cellcolor{gray!10}} & \textbf{Ranking} \cellcolor{TableOne}& \textbf{Origin}\cellcolor{TableOne} \\  \multicolumn{2}{|l|}{#6 \cellcolor{TableOne}} & #3\cellcolor{TableOne} & #4\cellcolor{TableOne} \\
        \multicolumn{2}{|l|}{\textbf{Note(s)}} & \multicolumn{2}{|l|}{}   \\
        #7 & & \multicolumn{2}{|l|}{} \\ [5pt] \hline
\end{tabularx}
\end{table}
\FloatBarrier}

%Calling the requirement macro
\krav{SRQ006}{Fulfilled}{AAAB}{STRQ004}{The system shall provide an azimuth acceleration of 1 rad/s\textsuperscript{2}.}{\shortstack{VT003\\VAT034}}{The motor was selected based on detailed calculations of required torque under "worst case scenario" load}
```

		SRQ006
Description	**Status**	
The system shall provide an azimuth acceleration of 1 rad/s^2.	Fulfilled	
Test ID(s)	**Ranking**	**Origin**
VT003 VAT034	AAAB	STRQ004
Note(s)		
The motor was selected based on detailed calculations of required torque under "worst case scenario" load		

Figure VII.6.2: Tex output of Code VII.6.2

VII.6.2.2 Disadvantages

The main disadvantage of using LaTeX as a typesetting system, is it's learning curve. If one is unfamiliar with LaTeX the production speed will be low. Another disadvantage of LaTeX is that its getting old, the last release was Latex2e which was released in 1994. To put it in perspective just think how much the markup language used when creating webpages has changed since the introduction off CSS in 1996.

VII.6.2.3 LaTeX Usage and Discussion

Sharelatex was used as the LaTeX editor. Sharelatex is an online service, that works much like Google Docs. It provides real-time collaboration, and a basic change-log with rollback functionality. An example of the change tracking is shown in figure VII.6.3. Sharelatex also provides backup functionality, as it saves the content in the cloud. It also provides backup to Dropbox every time a document is recompiled.

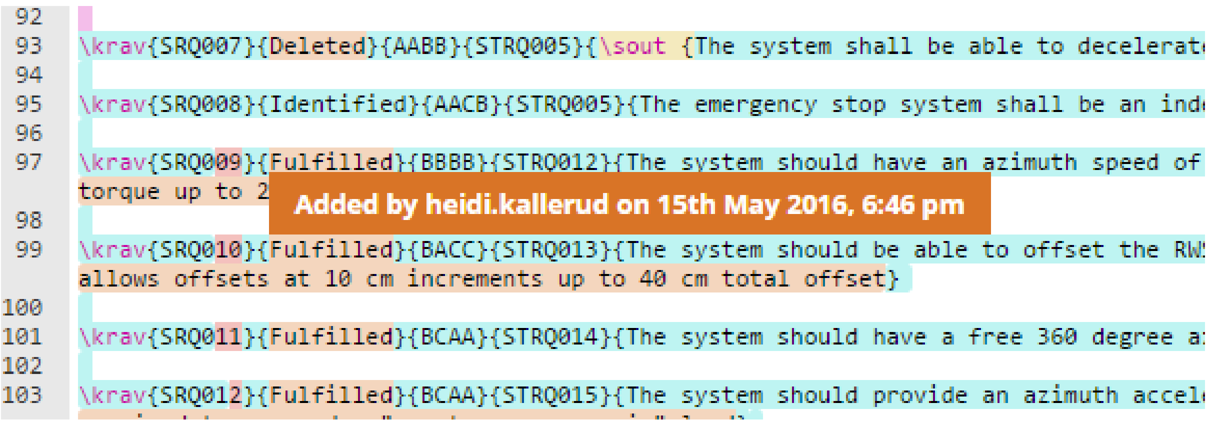


Figure VII.6.3: Change tracker in Sharelatex

Since most of the project group had never used LaTeX before. More time had to be invested at the start of the project, for project members to learn the markup language of LaTeX and how it works. As the project went on, production efficiency in LaTeX would soon compensate for the time invested in learning LaTeX. The time spent on finalizing each document at the end of the project was reduced greatly as a result of the way LaTeX handles formatting and cross referencing.

VII.6.3 Suppliers

Several suppliers were contacted in the process of selecting motor, bearing and gear head. Enquiries were made with regards to obtaining specific input values that were required for calculations, 2D drawings and step files for accurate modelling, and in some cases the general information about the products were highly limited. Acquiring desired information and getting a satisfactory respondance rate from suppliers sometimes proved to be very challenging. Parts of this is likely due to us being students and not a larger company, as well as the time span of this project was rather short and compact, which meant that we necessarily were very rather eager to get the data and progress we needed. However, most companies were very helpful and accommodating. Formulating polite, concise e-mails where sufficient explanation of the enquiry took us a long way.

VII.6.4 Motor Selection

Selecting an appropriate electric motor for the system turned out to be one of the greatest challenges in the project. None of the group members had any knowledge or experience in electric engineering; thus, we started at complete scratch. The process was started by acquiring basic knowledge of what an electric motor is and what factors are important when selecting or designing a motor for the intended system. Books, articles and university staff were consulted and some basic calculations were performed. Considerable confusion arose at the seemingly endless options of motors. After learning by mistake that there was no step-wise method of finding the optimal motor; rather that an iterative trial-and-error method had to be used; considerable time was spent looking for various models. The process was one of the more long spanning ones in the project, but we were persistent in our determination of not choosing the easiest way out and leaving this selection up to next year's project team who is planned to develop the electric and computational control of the system. The outcome of the process was that the members; from stepping out of their comfort zone; gained valuable knowledge and experience in another exciting engineering discipline.

VII.6.5 Group Dynamics

At initiation of the project a group contract was jointly formulated and signed by all group members. The contract affirm the group norms for attendance to meetings, codes of conduct, areas of responsibility, as well as a manual for how and where to organize and store files, and how to write and structure written work. Unanimously agreed consequences for non-compliance with the codes of conduct were also stated. All group members have during the project period had both an administrative and engineering specific area of responsibility. These areas of responsibility were based on both the individual wishes and academic strengths. Overall, throughout the project period, each individual rather naturally complied to their defined areas of responsibility. However, all group members were at some point involved in most of the different academic and administrative tasks. As this project is at bachelor level it was considered important that all members got the opportunity to attack various challenges. Furthermore, project management also involves more daunting tasks such as documenting meetings and ensuring that all matrices are up-to-date, which group members took turns in doing. As pointed out by Busmann (2014; [66]) small groups require flexibility and multi-tasking from the group members. All group members must be able to undertake additional structural work in the group, and not only feel responsible for specific tasks.

In all groups, conflicts of interest are likely to occur at some point during a project period [66]. This reasons can be differences in personality and expectations, conflicting interests with regards to the project outcome, or processes and decisions made along the way. The group accepted from early on that conflicting interests could appear and decided that an open dialog with constructive "storming" should be held. Constructive storming means that all members of the group get their chance to voice their opinion freely [66]. Throughout the project period all group members also complied with the decision that any dissatisfaction or concerns should be discussed with the group in its entirety, without excluding any members.

An identified risk pertaining to group dynamics was the potential loss of motivation. Some sporadic, temporary dips in motivation was experienced along the way. These events raised concern for potentially compromising the progress of the project. Thus, the group sat down to look for solutions that could have immediate effect and it was pointed out that our efforts in the early phase of keeping very clear, short-term goals seemed to promote motivation and progress. Thus, it was decided to be consistent in writing both weekly (short-term) and semi-weekly (medium-term) tasks with deadlines on the whiteboard, and distributing responsibility for these tasks. This promoted a more continuous feeling of achievement and gave more reasons for smaller celebrations of targets that were met.

VII.6.6 Interaction with Employers

As mentioned in chapter VII.3; Requirement Management; continuous dialog with the employers was held, in order to assure that all requirements were collected and interpreted correctly. The project team were also lucky to get an office space at KPS' buildings, which promoted interaction with other employers and access to the lab where the system is intended to be in use. A demonstration of a test scenario where the RWS was mounted onto the motion table was given by KPS in early April. This demonstration could desirably have occurred earlier in the project phase, as it gave deeper understanding of the test scenarios that the OMS will be subject to. In retrospect, the group realises that they could have taken even more initiative themselves to get this demonstration earlier. However, it was often found challenging to balance how much contact we should have with various employees at KPS and how "pushy" we as students should be; thus, we found it more appropriate to keep a lower profile.

VII.7 Key Lessons Learnt

- Frequently seek to identify new requirements. Revisit, reevaluate and clarify requirements throughout the project period.
- Continuously keep all documentation up to date as you go. This ensures that nothing is forgotten and it is much easier to provide well reasoned arguments with the ideas, processes and research fresh in mind. This saves you from a lot of work when the deadline is closing up.
- Keep frequent dialog with your employers and ask questions. To not overwhelm your employer with e-mail, phone calls and casual office drop-ins, write down all the questions and present them at your semi-weekly supervisor meetings. If this feels too long to wait, do your best to discuss and gather all questions into one e-mail.
- Invest time in the beginning of the project to thoroughly understand your chosen project model. Project models often provide a "toolbox" with helpful tools, figures and processes that will facilitate step-wise development of the system and help arrive at the "right" product for the customer.
- In case of illness or accidents involving any of the group members, quickly redistribute the work for this individual. Opt to work in pairs on all or most tasks in order to always have at least one person with an overview and knowledge of each working area. This ensures uninterrupted progress when facing unexpected events.
- Be consistent in writing short- and longer term goals, as this will promote a sense of achievement and continuous progress. Loss of motivation is much less likely to occur this way.
- Work on the larger engineering challenges as a team. More minds equals more ideas. When discussing an engineering problem various people often bring new viewpoints to the problem. Also, people remember different things from the curriculum, which jointly within a team results in broader knowledge. The aim of forming groups to solve complex tasks is that the problem solving ability of the team in entirety is larger than on an individual level.
- Choosing and following a test method; such as the Incremental Test method; can prove very helpful in allocating what components or interfaces that causes errors or failures when testing complex systems.

VII.8 Guidance for Future Development

Future development of the system is likely to involve aspects of electric engineering and computer engineering, in order to provide KPS with the desired dynamic control required for accurate simulation purposes and acquisition of relevant data. Although these aspects were beyond the scope of the current project, efforts were made to ensure that no unnecessary constraints were put on those who will further develop the extended system and its interfaces in the future. The following sections will present tips and guidance we believe can be of use for future developers, based on the insight and knowledge acquired through development of the OMS.

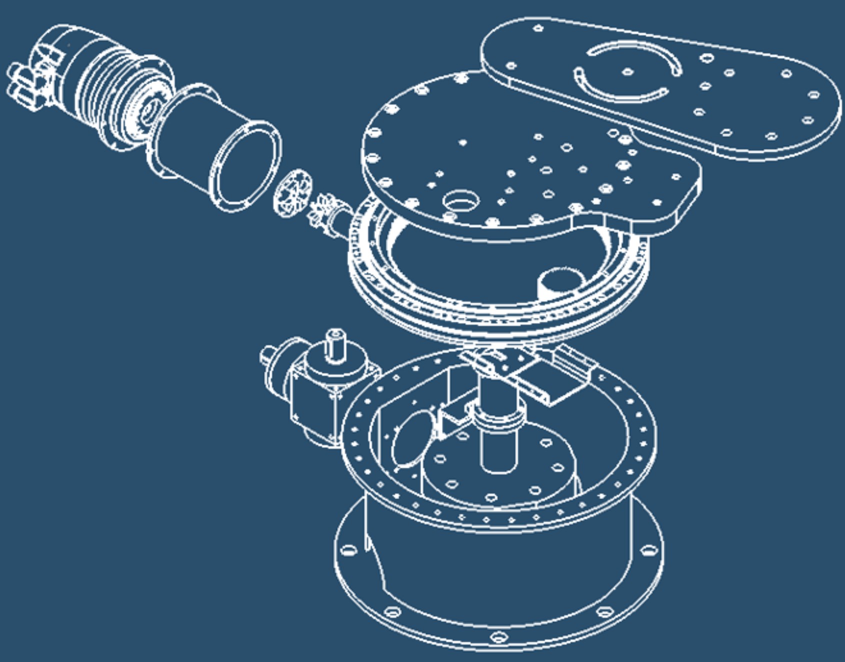
1. Some backlash is likely to be experienced with the currently designed system involving an angled gear box and pinion. Future projects could consider if integration of a "harmonic drive" solution could be feasible, as this would eliminate the problem with backlash and thus increase the accuracy of the system.
2. The validation tests in the Test Specification document can be consulted for guidance of how to validate the mechanically related requirements in this project.
3. A control system for the motor has to be chosen. The Wittenstein actuator comes with numerous different options for package solutions.
4. When designing a control system for the motor an emergency stop function that cuts the power to the motor must be integrated.
5. An adapter or similar to provide sideways output of cables from the slip ring must be made. A bracket has been designed, which will ease the guidance of wires out through the OMS to the RWS.

University College of Southeast Norway

Mechanical Engineering

2016 - 07

User Manual
Orbital Motion Simulator



Abbreviations

Abbreviation	Explanation
OMS	Orbital Motion Simulator
RWS	Remote Weapon Station
BOM	Bill of Material

Revision History

Date	Version Number	Comment	Approved by
09.05.16	0.1	Document created. Assembly and usage added.	Anders Gunbjørnsen
12.05.16	1.0	Maintenance, assembly- and offset adjustment step by step figures added.	Martin Sandberg
22.05.16	1.0	Document approved	Martin Sandberg

Table of Contents

Abstract

The manual is an essential document for the product's practical use. When designing a product the designer should always have usability fresh in mind. The product should have good usability, in order to satisfy the customer. This document aims to explain the usage and assembly of the product.

It is very common for complex products to be an assembly of parts or smaller components. Very rarely is a complex product composed of just one part. In the case of the OMS it consists of several parts that have to be put together. This document will help explain how to accomplish that in a way that safeguards the products functionality and make sure that the product is possible to put together in a time efficient manner. The manual will also contain a Bill of Materials (BOM), which is a detailed overview of all the parts needed in the assembly.

Important aspects such as safety and maintenance will be addressed. Safety is the most important aspect regarding both the usage and assembly of the product, making it a central part of the manual. Maintenance will obviously also play a prominent role. Without proper maintenance the product will start to deteriorate, which will create repercussions in both functionality and safety.

Conclusively, this manual will serve as a user guide. It is a technical communication document that includes assembly, usage and maintenance; the products operational life. It will make the user capable of assembling the product, and also put it in to use, with proper safety and maintenance as a base.

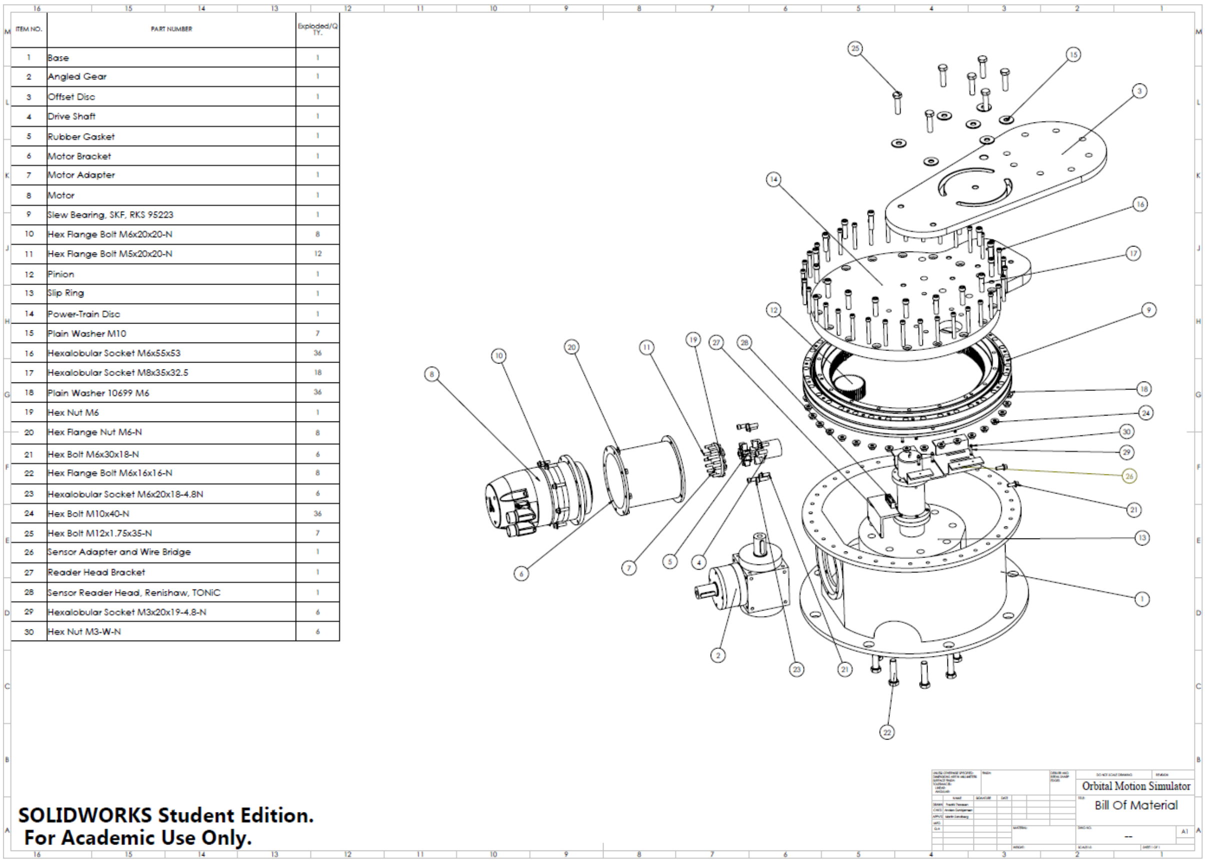
VIII.1 User Manual

VIII.1.1 Assembly

This section will address the assembly procedure of the OMS. This involves the bill of materials, the assembling sequence and the safety procedures. Since the system consists of several different parts, a thorough description of how to perform the assembling sequence is beneficial to the customer. The safety procedures for the assembling process is also described in this section.

VIII.1.1.1 Bill of Materials

The BOM contains of all the parts needed to assemble the OMS.



ITEM NO.	PART NUMBER	Exploded/QTY.
1	Base	1
2	Angled Gear	1
3	Offset Disc	1
4	Drive Shaft	1
5	Rubber Gasket	1
6	Motor Bracket	1
7	Motor Adapter	1
8	Motor	1
9	Slew Bearing, SKF, RKS 95223	1
10	Hex Flange Bolt M6x20x20-N	8
11	Hex Flange Bolt M5x20x20-N	12
12	Pinion	1
13	Slip Ring	1
14	Power-Train Disc	1
15	Plain Washer M10	7
16	Hexalobular Socket M6x55x53	36
17	Hexalobular Socket M8x35x32.5	18
18	Plain Washer 10699 M6	36
19	Hex Nut M6	1
20	Hex Flange Nut M6-N	8
21	Hex Bolt M6x30x18-N	6
22	Hex Flange Bolt M6x16x16-N	8
23	Hexalobular Socket M6x20x18-4.8N	6
24	Hex Bolt M10x40-N	36
25	Hex Bolt M12x1.75x35-N	7
26	Sensor Adapter and Wire Bridge	1
27	Reader Head Bracket	1
28	Sensor Reader Head, Renishaw, TONiC	1
29	Hexalobular Socket M3x20x19-4.8-N	6
30	Hex Nut M3-W-N	6

Figure VIII.1.1: Bill of Materials

VIII.1.1.2 Required Items

The following items are needed in order to assemble the OMS:

- Torque wrench
- Torx tools
- Socket wrench set
- Lubrication
- Crane

VIII.1.1.3 Assembling Sequence

The following assembly sequence is recommended:

1. **Mount the pinion and drive shaft to the angled gear, since they are press fits. Make sure to put lubrication to the parts that will be rotating and transfer power.**

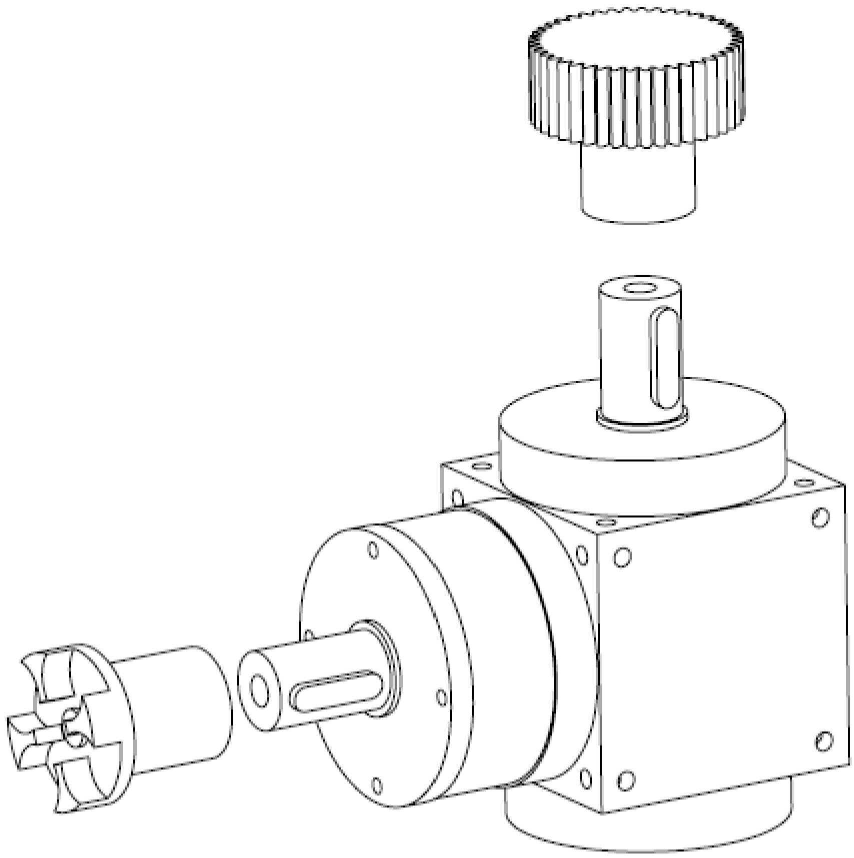


Figure VIII.1.2: Step 1.

2. Mount the angled gear assembly to the base.

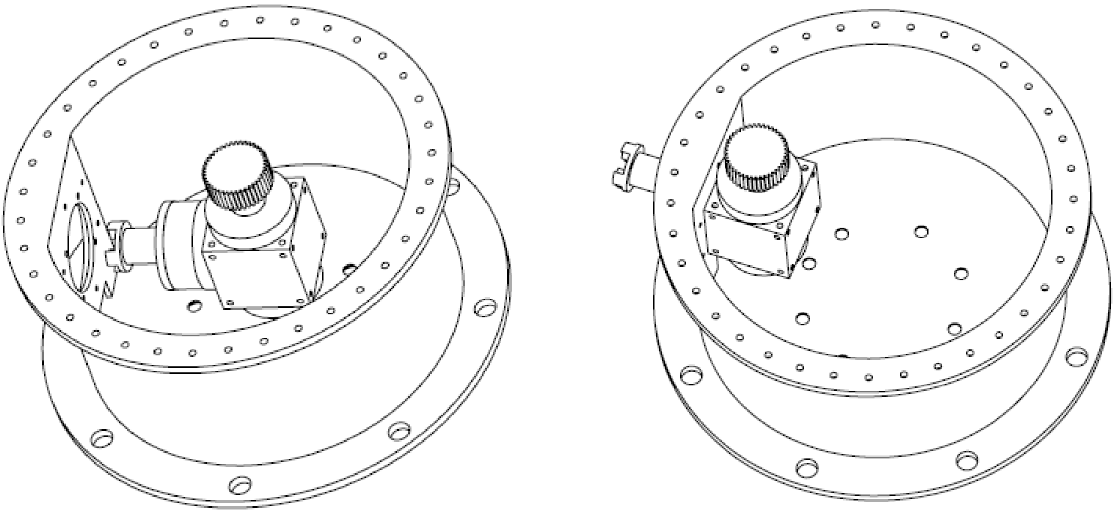


Figure VIII.1.3: Step 2.

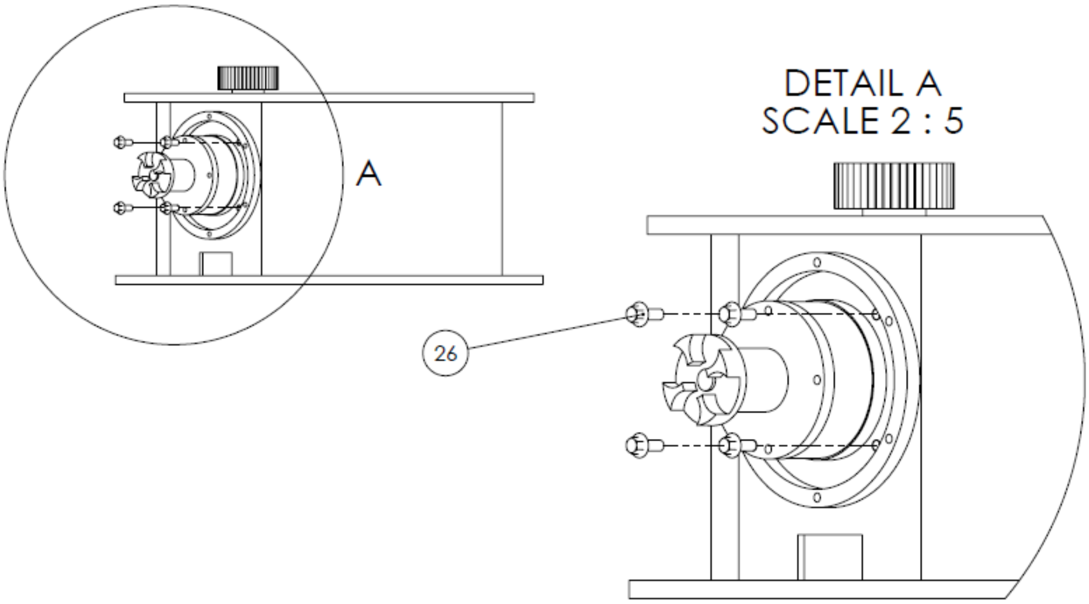


Figure VIII.1.4: Step 2.

3. Mount the slip ring to the base.

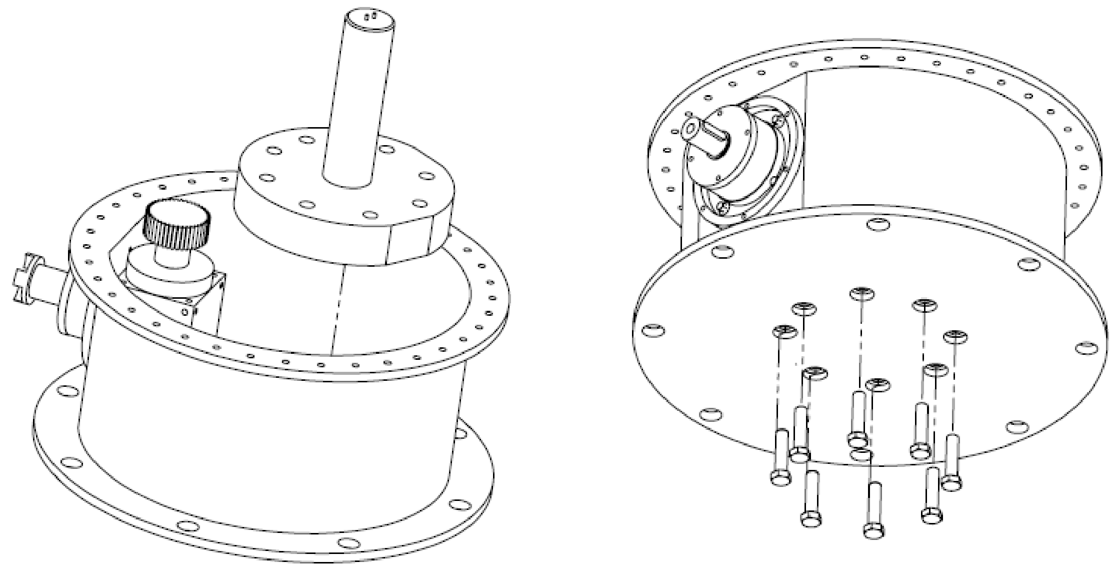


Figure VIII.1.5: Step 3

4. Mount the base to the motion table, using a preload torque of 200 Nm.

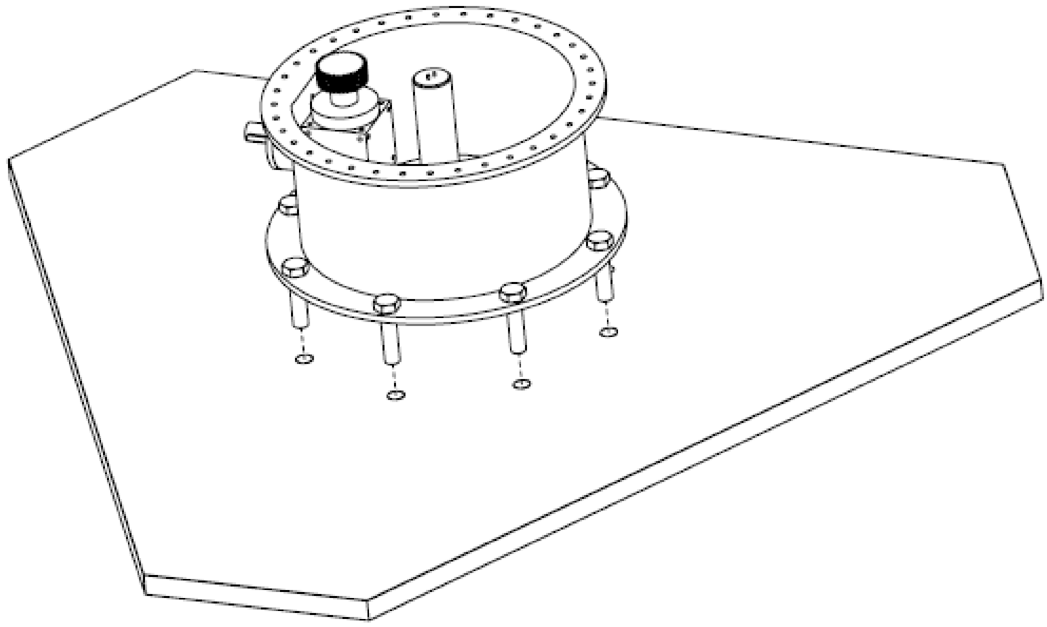


Figure VIII.1.6: Step 4.

5. **Connect the output wires to the slip ring and guide them to the openings in the bottom of the base.**
6. **Mount the reader head to the reader head bracket.**

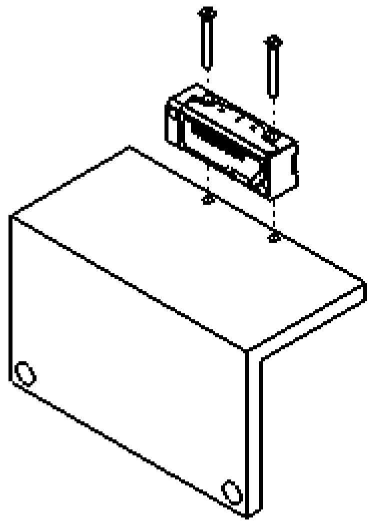


Figure VIII.1.7: Step 6.

7. **Mount the reader head bracket to the gearbox.**

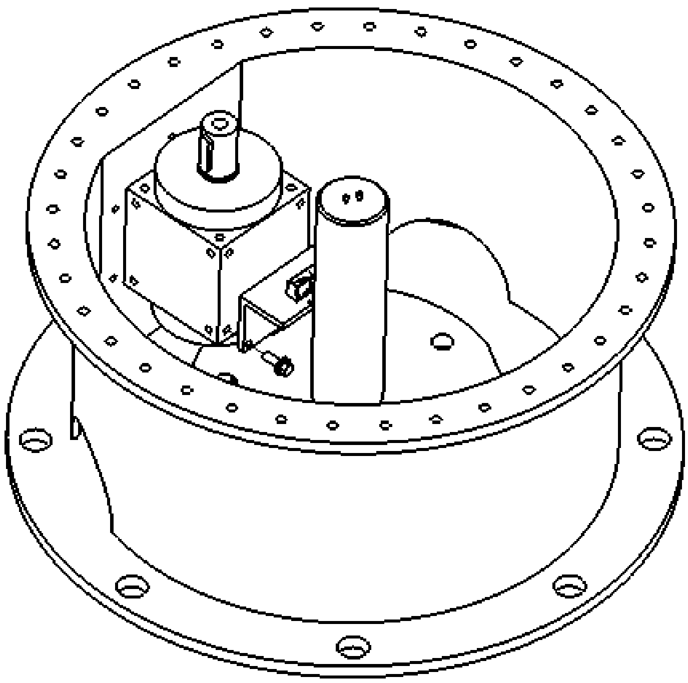


Figure VIII.1.8: Step 7.

8. Mount the encoder ring to the sensor mount

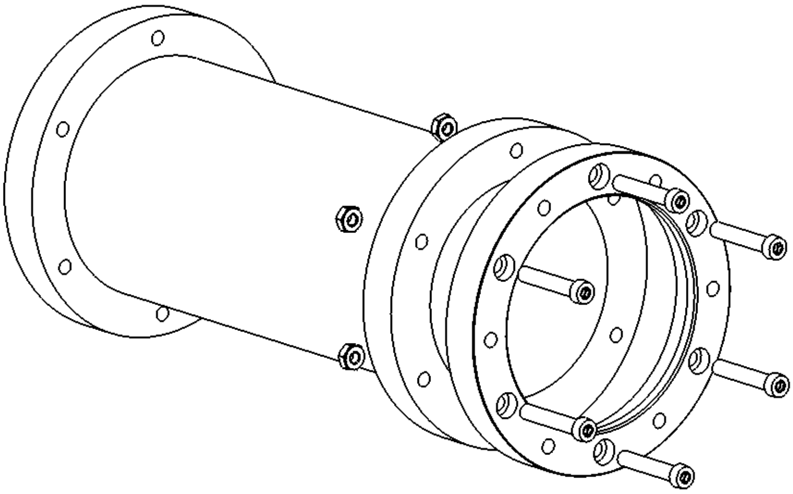


Figure VIII.1.9: Step 8.

9. Mount the cable bridge to the sensor mount and install the bolts that are used to fasten/position the cable bridge to the power-train disc. This concludes the sensor mount sub assembly.

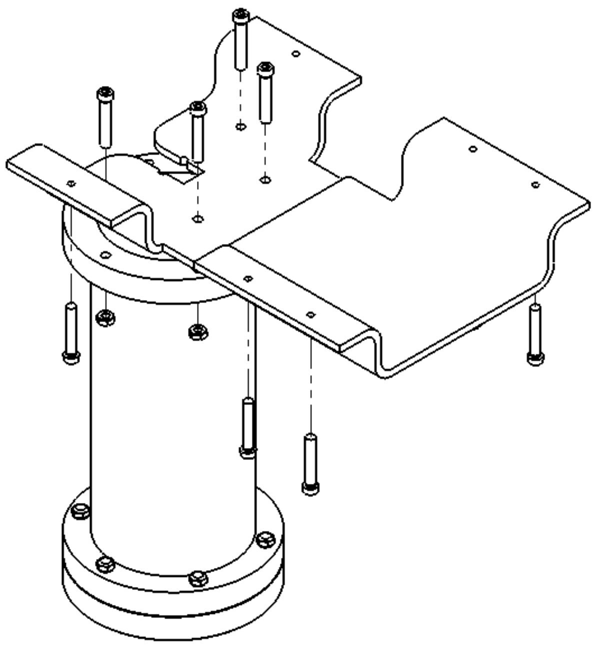


Figure VIII.1.10: Step 9.

10. Mount the sensor sub assembly to the slip ring using the guide pins on the slip ring, mind to guide the wires through it.

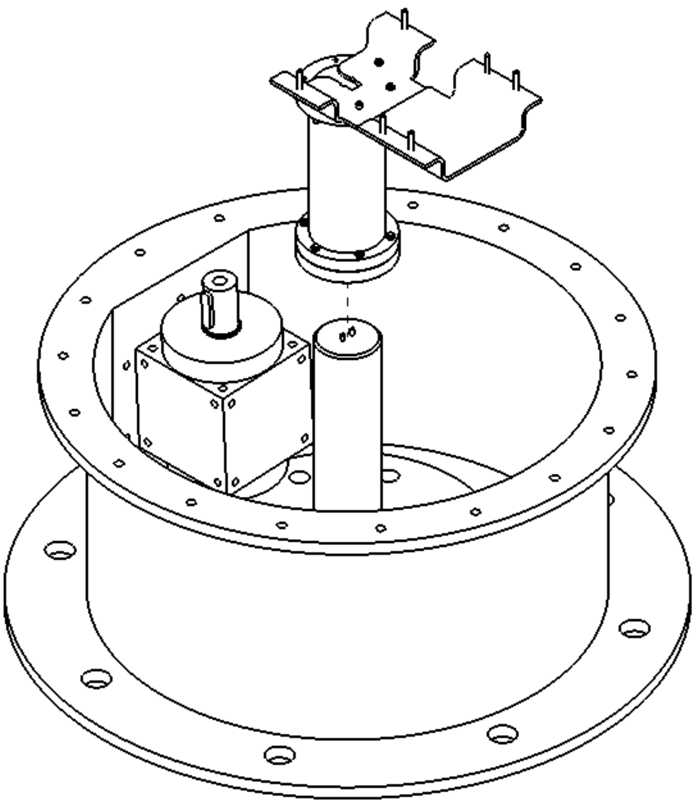


Figure VIII.1.11: Step 10.

11. Mount the slew bearing to the base, mind that it is positioned correct in regards to the pinion.

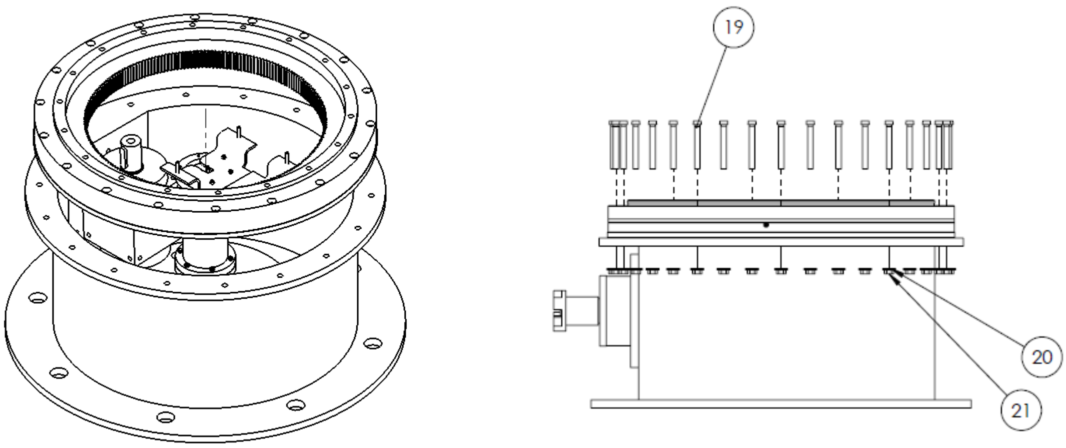


Figure VIII.1.12: Step 11

12. **Mount the power-train disc to the sensor sub assembly. Make sure to guide the wires from the slip ring through the designated wire hole on the power-train disc.**

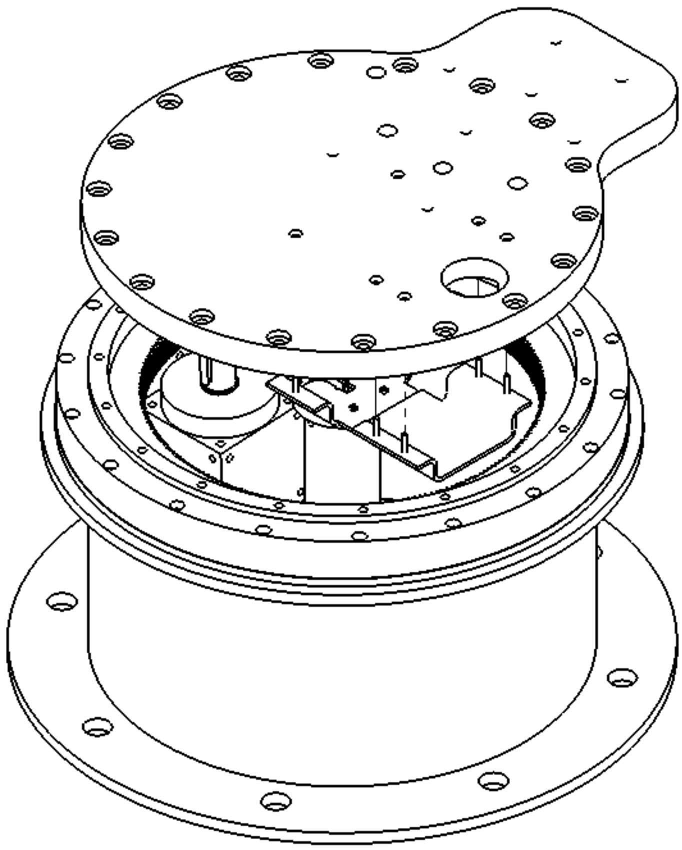


Figure VIII.1.13: Step 12.

13. Mount the power-train disc to the bearing.

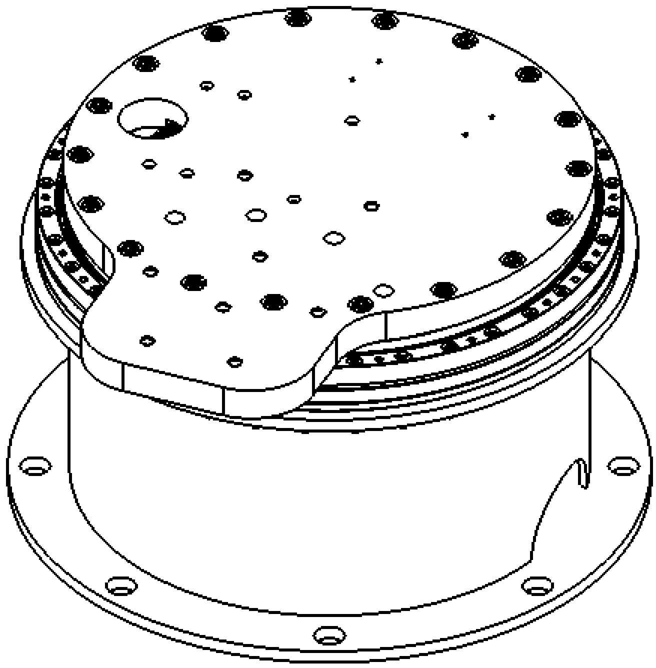


Figure VIII.1.14: Step 13.

14. Put the rubber gasket in place, at the end of the drive shaft.

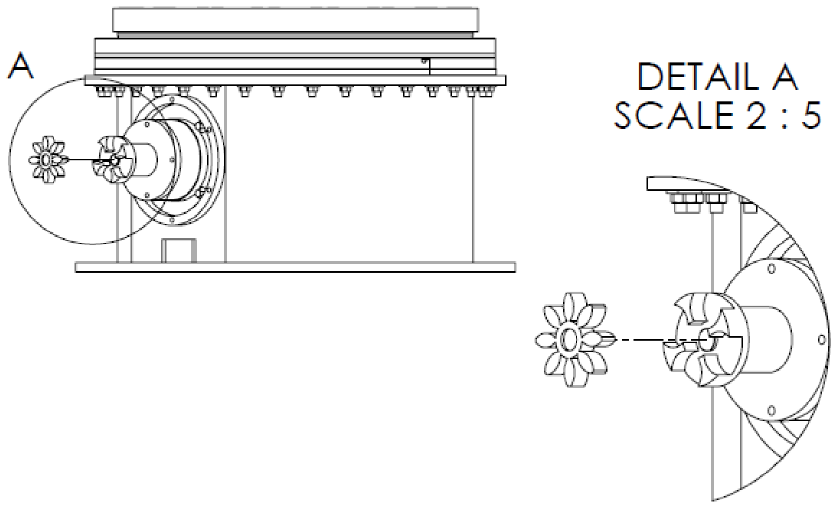


Figure VIII.1.15: Step 14.

15. Connect the Motor adapter to the motor.

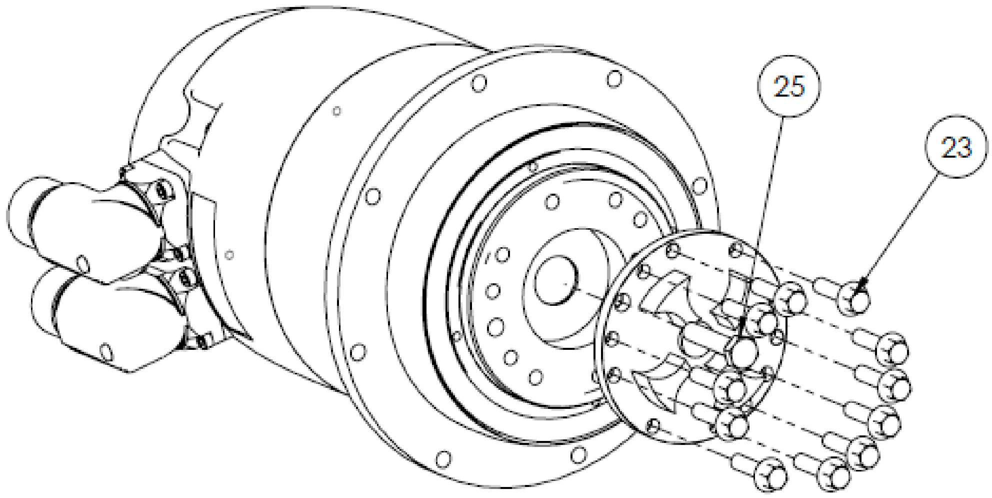


Figure VIII.1.16: Step 15.

16. Mount the motor bracket to the base.

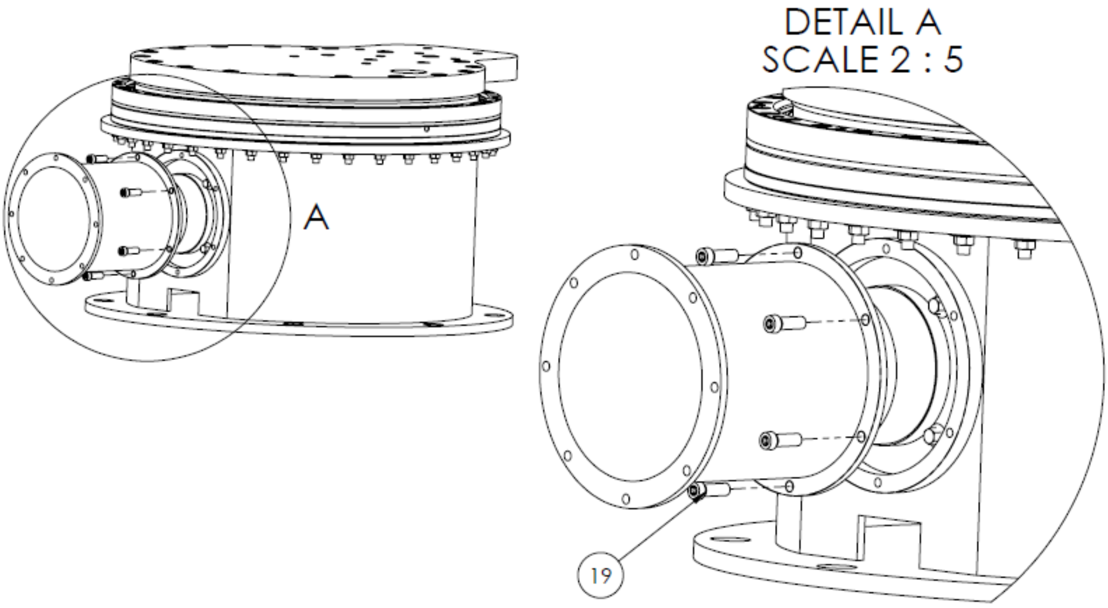


Figure VIII.1.17: Step 16.

17. Connect the motor to the motor bracket, mind that the rubber gasket is in its correct position.

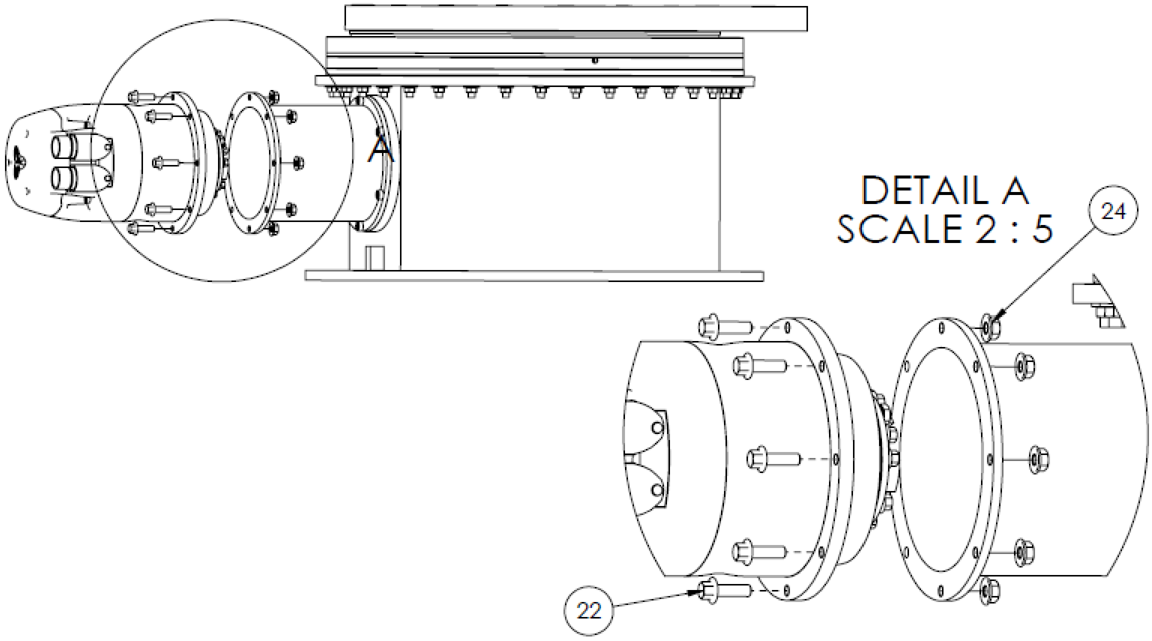


Figure VIII.1.18: Step 17.

18. Mount the offset disc to the power-train disc in its max offset position, in order to be able to mount the RWS to it.

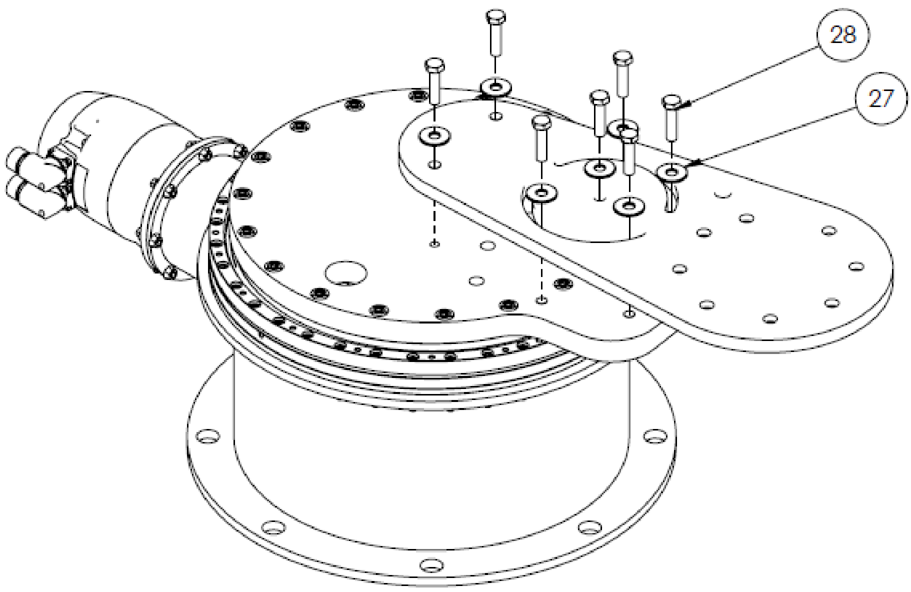


Figure VIII.1.19: Step 18.

VIII.1.1.4 Safety Procedure

The most logical starting point is what to do when the system is delivered, and put to use. The first thing that commences when the systems is delivered is the assembly. The assembling sequence is described in section VIII.1.1.3 and explains the order in which the system is put together. However this section will focus only on the safety aspect related to the assembly. It is expected that the assembling sequence is known before the safety section is read.

When assembling the system there are several aspects that relate to safety. Safety in this sense aims to prevent the risk of permanent damage to the system or interfaced units, at the same time the safety relates to human interaction. Human interaction is the most important safety aspect, this includes minimising the risk of human casualties.

There are two essential themes when describing the systems safety precautions regarding the assembling:

- **Bolt Fastening**
  The systems assembling is based on bolt fixtures. When fastening the different components it is important to fasten the bolts with proper preload, in order to prevent the stationary parts from moving and at the same time prevent permanent damage to interfaced components. Further information regarding bolts in general is provided in the design document under chapter IV.3.9.
  The recommended preload to the bolts are as follows:
  - Base to motion table: 200 Nm
  - Bearing to Base: 12 Nm
  - Power-train disc to bearing: 30 Nm
  - Offset disc to power-train disc: 90 Nm

  It is important to apply proper lubrication to the bolts before fastening since they are made of steel and the threaded holes in the interfaced components consists of an Aluminium alloy. Aluminium and steel have a tendency to get stuck together when in close contact as a result of corrosion, this phenomenon is called seizing. When Aluminium and steel are in close contact under a static load over longer periods of time, a layer of Aluminium oxide is created and as a result the bolts may be hard to loosen. PERMATEX® #133 Anti-Seize lubricant [67] is suggested. This lubricant may be a bit excessive for this application, but the project team do not want to take any chances when it comes to performance.

- **Lifting Operations**

  The assembly of the components requires the parts to be positioned together, this is done by lifting the components in to place. Certain components are to be lifted by hand, in accordance with MIL-STD-1472G, this standard is only valid for individual components in the assembly. All components are approved for lifting by hand.

  However, it is recommended to use a crane in any instance of lifting, in order to avoid damage to limbs as a result of lifting heavy objects, or wrong lifting technique. If the system as an entirety is to be moved the use of a crane is required, because the weight being to large.

  Under no circumstances shall any personal be positioned under the object being lifted by the crane.

VIII.1.2 Usage

This section will describe the general usage of the system. In order to get the system to perform as desired, a proper guide for usage is required. If the product is used in an incorrect manner it will have an effect on both the safety regarding the product, and also the general functionality. It is therefore crucial that proper usage is applied.

The usage of the product has three main categories related to each other. First an foremost there is the safety aspect, this will create the foundation for proper usage. Furthermore there is the maintenance, this is important to address both before and after the usage. Lastly there is the usage itself, how to maneuver the system in to performing the desired task.

VIII.1.2.1 General Disassembly

When a test is finished and the OMS shall be moved there are two ways to go about this. Either the base can be unbolted from the motion table and lifted off as a whole by a crane, or the OMS can be disassembled in three parts.

First, the offset disc must be unbolted from the power-train disc and lifted away. Then the bearing (with the power-train disc still attached) can be unbolted from the base and lifted away. Lastly, the base can be unbolted from the motion table and moved away by hand.

VIII.1.2.2 Safety Procedure

The most important aspect of any manual is the safety instructions. The aspect of safety will manifest itself in both usage and assembly. This section will address the safety related to the direct usage of the system. The following guidelines are presented in terms of safety for the active usage of the OMS.

Fixtures

Before putting the system to use it is crucial that every bolt is examined and confirmed that all bolts are properly fastened, in accordance with the recommendations in the assembling section VIII.1.1.4. This is examined using a torque wrench to measure preload.

Adjustments

When adjusting the offset on the device, the external load of the RWS shall never be active. Meaning that the RWS's weight has to be taken care of by a crane.

In order to adjust the offset all bolts have to be removed except the offset center bolt. This enables the offset disc to be adjusted into position, without the danger of the disc falling down and causing physical damage to personnel.

VIII.1.2.3 Adjusting Offset

The system has 5 different positions regarding the offset. The first one allows the RWS to be located at the center position, i.e. 0 cm offset. Positions two to five allows the RWS to be located at an offset of maximum 40 cm, with 10 cm increments between each position. The position that has to be used when mounting the RWS to the offset disc is the the fifth one, that allows an offset of 40 cm.

As mention in subsection VIII.1.2.2, **the RWS has to be carried by a crane when adjusting the offset**.

The following sequence is recommended when adjusting the offset:

1. **Remove the bolts connecting the offset disc to the power-train disc except for the center bolt that is just slightly loosened, this allows the offset disc to be rotated.**

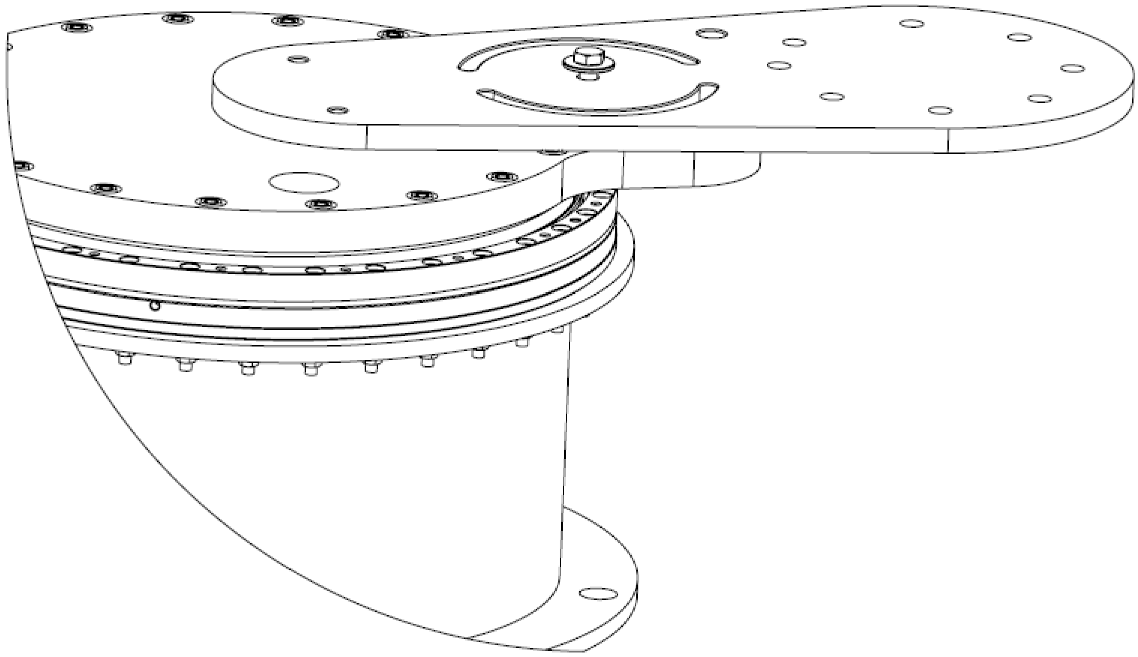


Figure VIII.1.20: Step 1.

2. **Rotate the offset disc into the desired position. Mind to rotate the offset disc cautiously and follow the movement with the crane. The position is found by matching the aligning bolt with the hole on the drive-train disc.**

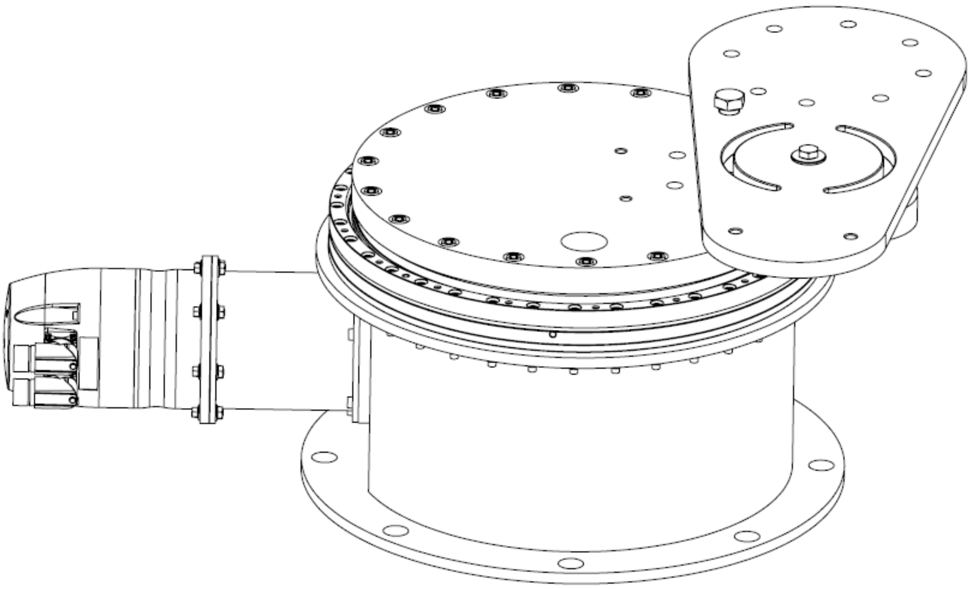


Figure VIII.1.21: Step 2.

3. **Tighten the bolts when the desired position has been reached.**

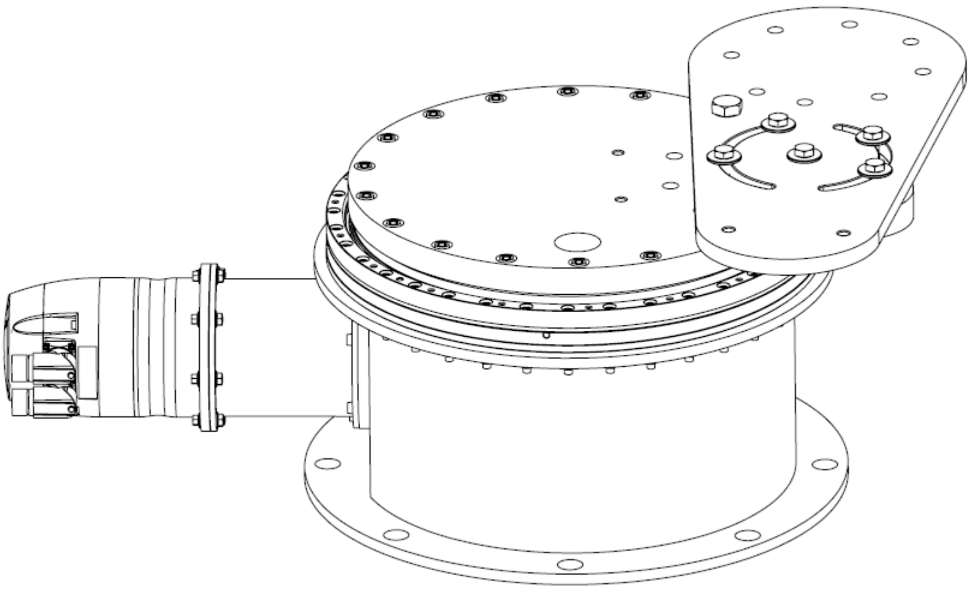


Figure VIII.1.22: Step 3.

4. **The system is now ready for use.**

VIII.1.3 Maintenance

This section will describe the general maintenance of the system. Since the OMS consists of several parts that rotates, lubrication plays a big role. Inspection of fixture points in regards of deformation is also brought up in this section.

VIII.1.3.1 Lubrication of Slew Bearing

Lubrication of the slew bearing shall be done as specified by SKF in their catalogue [26] using LGEP 2 [68] or an equivalent oil.

VIII.1.3.2 Lubrication of Pinion

To get access to the pinion the offset disc must be removed first, then the power-train disc can then be unbolted from the bearing.

The pinion interface must be regreased every 12th week. Before regreasing the gear, the teeth should be cleaned of any impurities. The lubricant can be brushed or sprayed onto the gear or by any other suitable method. The grease applied must have a base oil viscosity of at least 500 mm^2/s at 40°C, have good adhesive properties and a high resistance to water washout [26].

VIII.1.3.3 Lubrication of Bolts

All off the fixtures in the assembly comes in the form of bolts. Like described in safety under assembly VIII.1.1.4, the bolts may get stuck together as a result of corrosion. An appropriate countermeasure is lubrication. PERMATEX® #133 Anti-Seize lubricant [67] is suggested. This lubricant is applied to all bolt fixtures in the assembly, and is important in order to ensure easy assembly, and disassemble.

VIII.1.3.4 Inspection of Fixture Points

The most critical points of the product is the fixture points. Whenever the OMS is assembled or disassembled an inspection is performed on all fixture points. The inspection will involve detecting hazardous deformation in the material. This will prevent any unforeseen deformation in the member. This inspection is performed at any assembly or disassemble.

VIII.1.3.5 Replacement of Bolts

TR005 in the testing document indicated that the bolts can withstand the testing conditions during **one** year. This means that the bolts in the OMS assembly have to be replaced after this time period, in order to maintain safe test conditions.

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Production Manual
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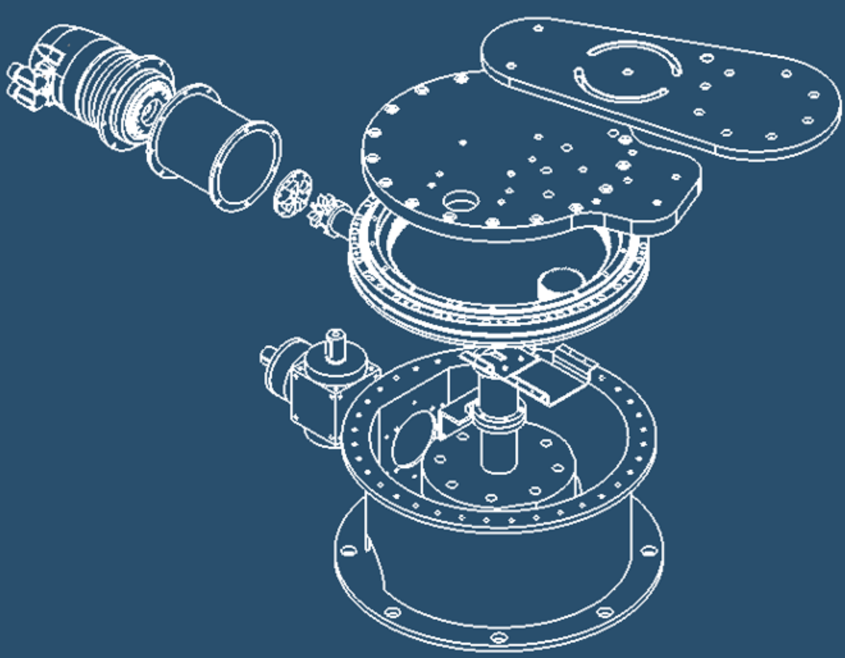


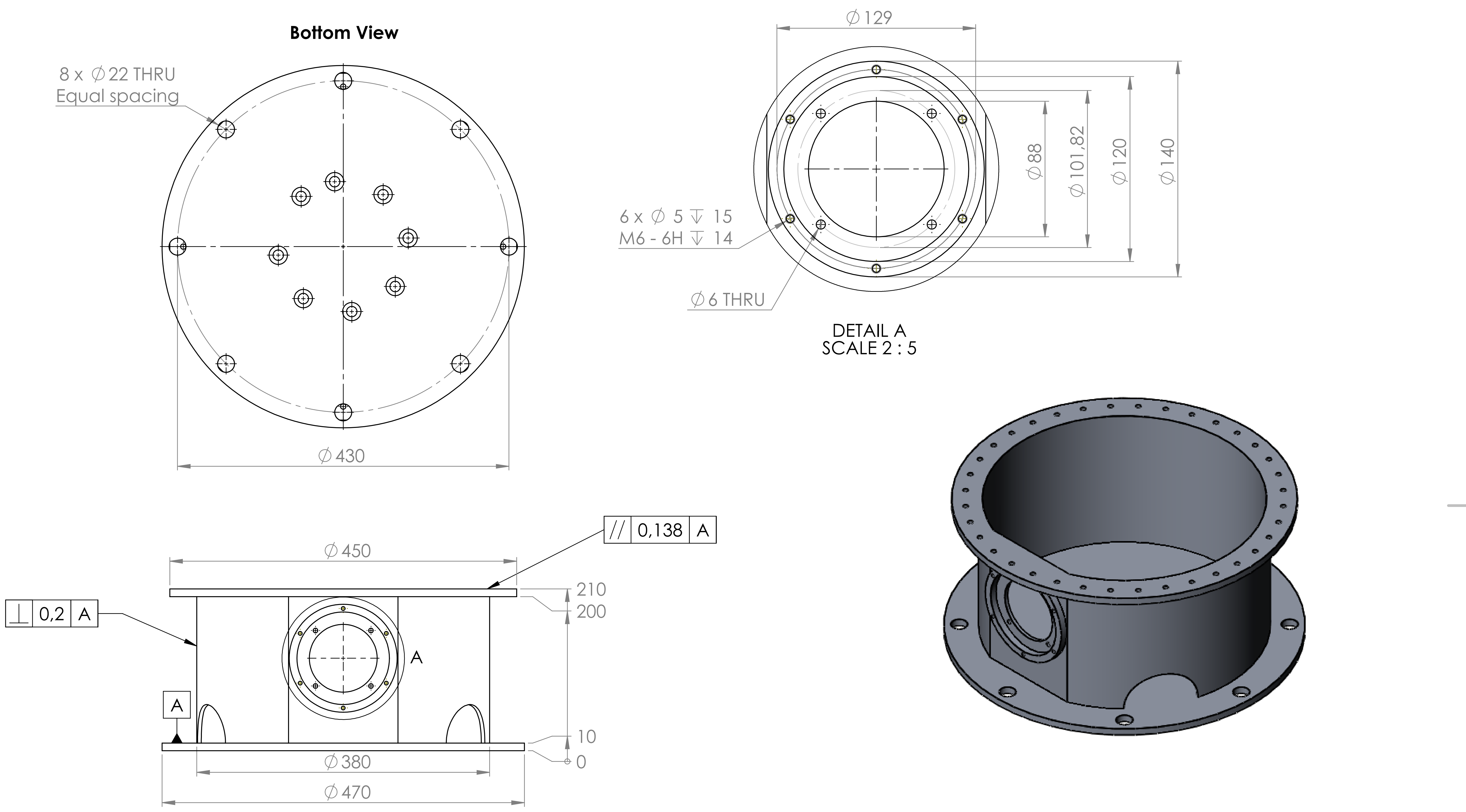
Abstract

The production manual is made for production purposes only. The intent of this document is to describe the parts of the system that need to be manufactured. This is a document directly aimed at the manufacturer. When designing parts it is vital to keep the manufacturing process in mind, as ignorance of this may lead to design of parts that are difficult, not to say impossible, to manufacture. An understanding of manufacturing methods can also significantly reduce cost.

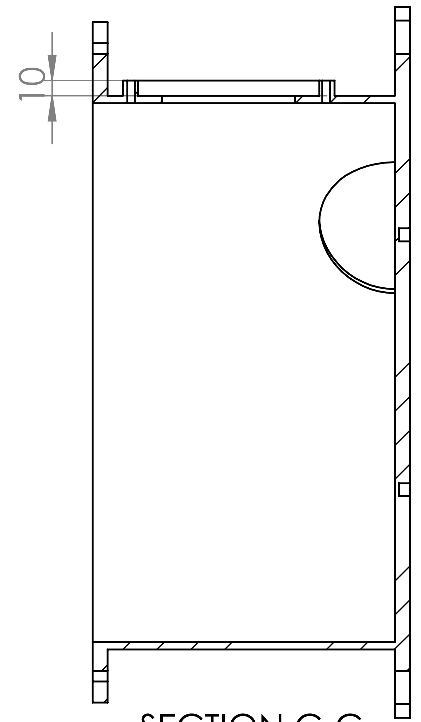
IX.1 2D drawings

The relevant parts are described using 2D drawings, with relevant measurements and tolerances. These documents are found in the subsection 2D drawings. The drawings basically describe to the manufacturing facility what shapes the parts have. Additionally the weight and material is also stated. The 2D drawings are often called a production underlay.

The drawings have boxes named "drawn" ,"checked" and " approved". These boxes are put into use and distributed in accordance with the roles and responsibilities, described in the project plan. Which again was distributed at the start of the project. The boxes are filled in with the proper names, printed and lastly signed by the appropriate personnel. This makes sure that the personnel responsible is held accountable and is easy to contact should there be complications in the production underlay.

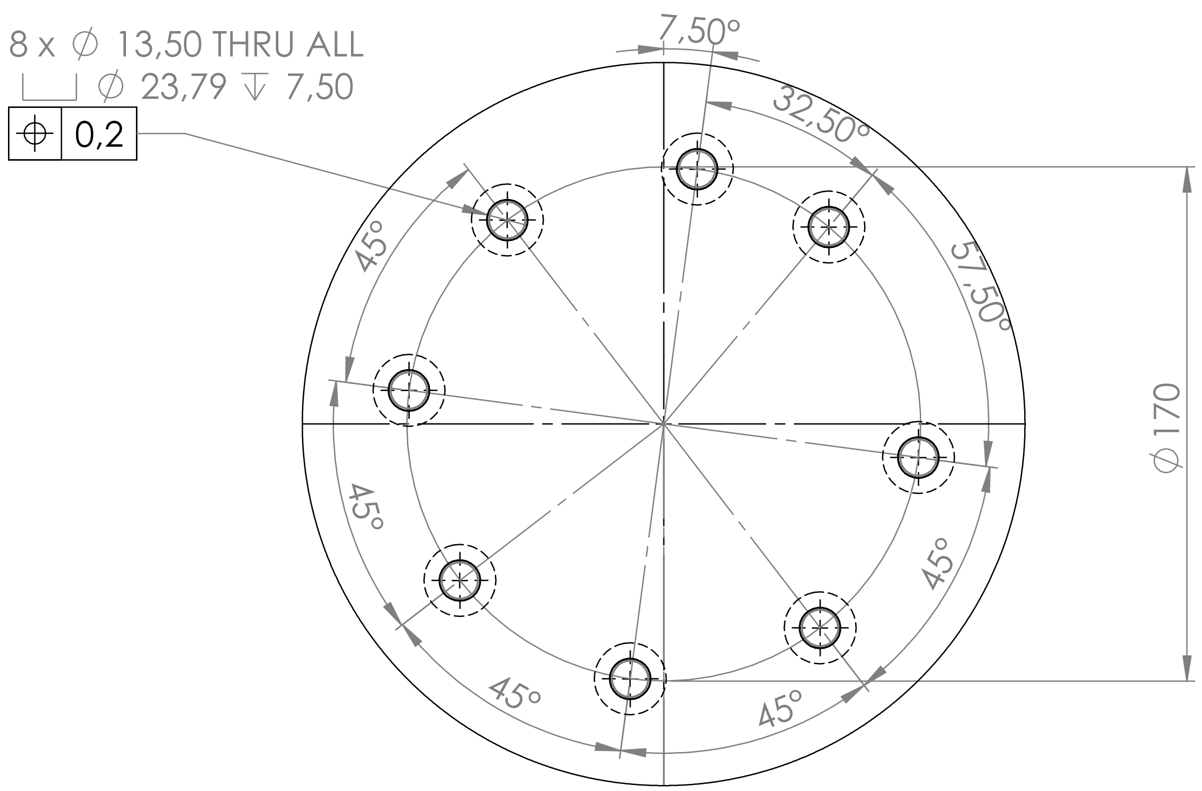


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 1mm ANGULAR: ± 1degree	FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
				Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Fredrik Thoresen	FRT	19.05.16	Base	
CHK'D	Anders Gunbjørnsen	ADG	20.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 1	A3
			WEIGHT: 8838.76 gram	SCALE:1:5	SHEET 1 OF 3

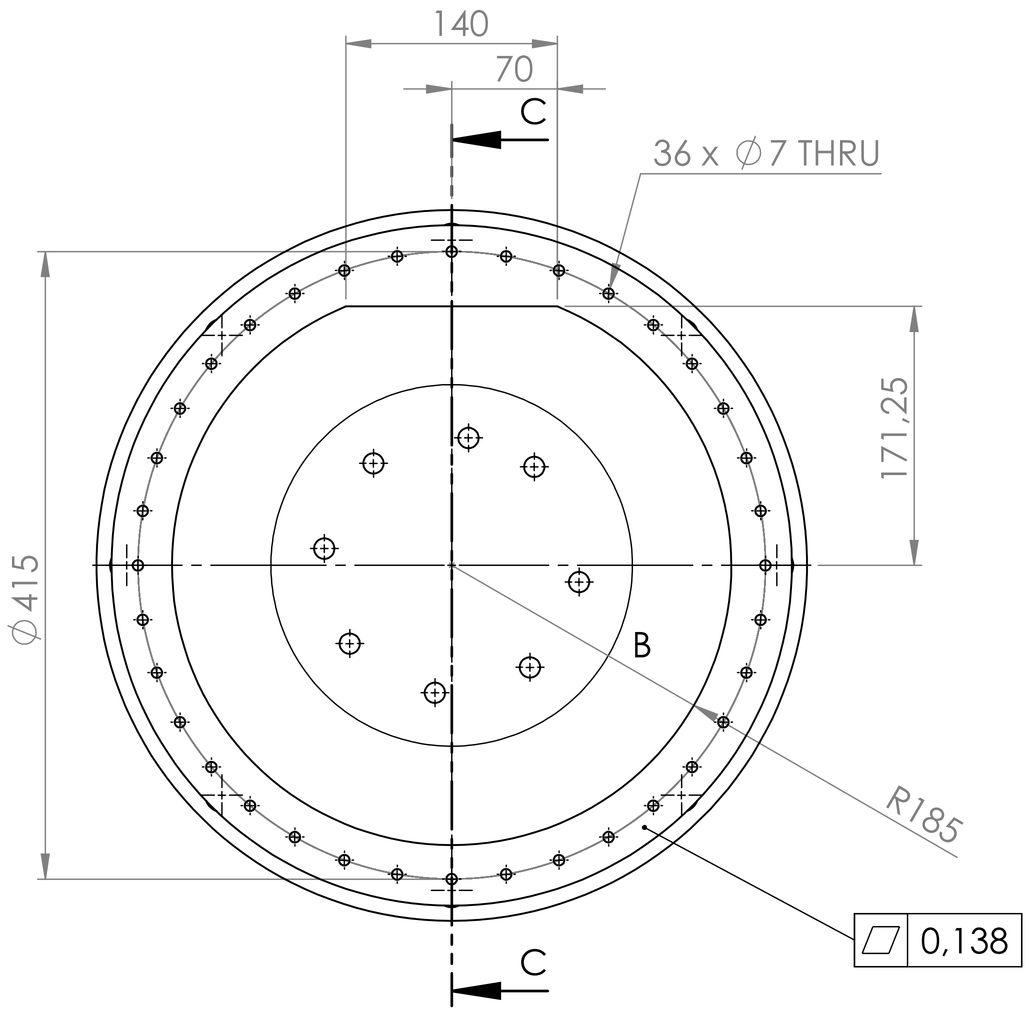


SECTION C-C

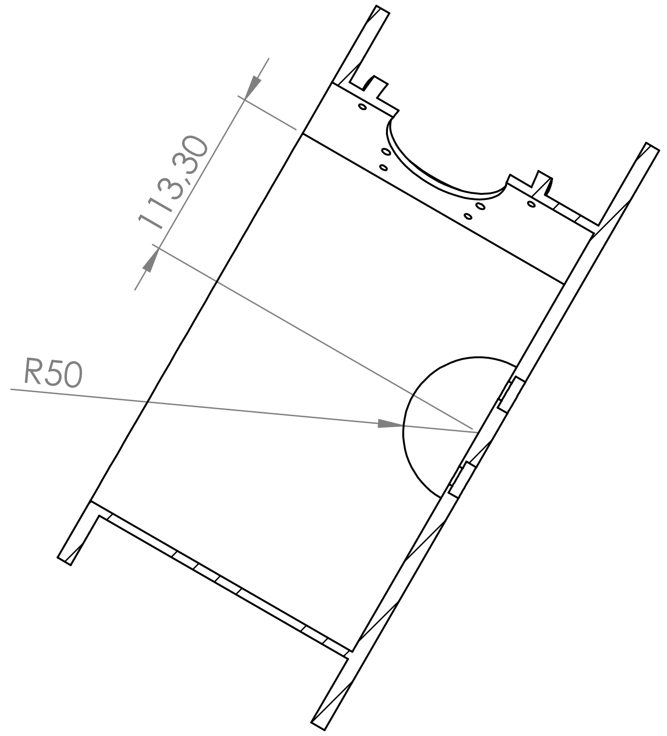
Top View



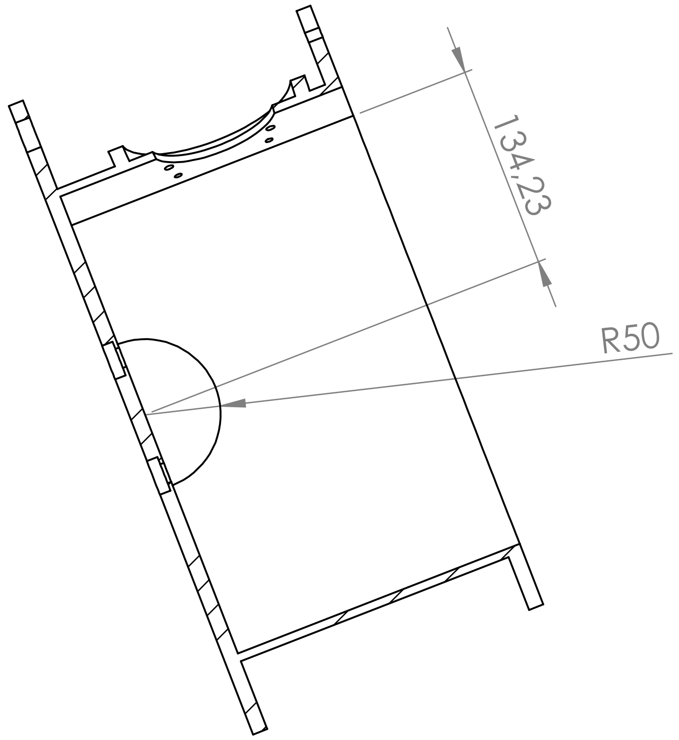
DETAIL B
SCALE 2 : 5



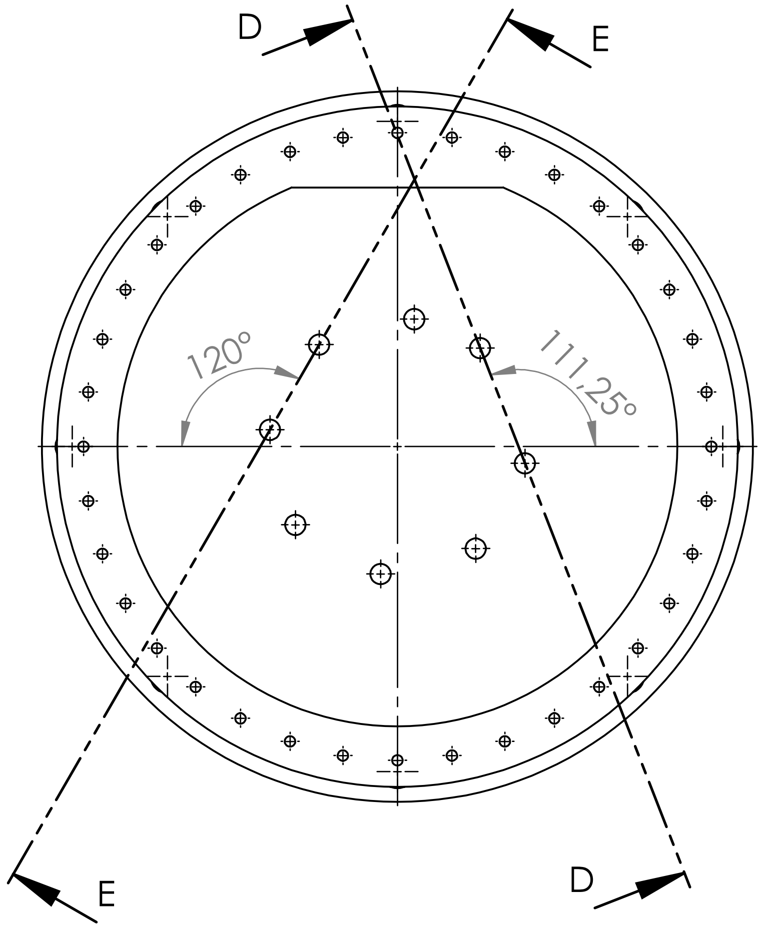
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 1mm ANGULAR: ± 1degree	FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
				Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Fredrik Thoresen	FRT	19.05.16	Base	
CHK'D	Anders Gunbjørnsen	ADG	20.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 1	A3
			WEIGHT: 8838.76 gram	SCALE:1:5	SHEET 2 OF 3



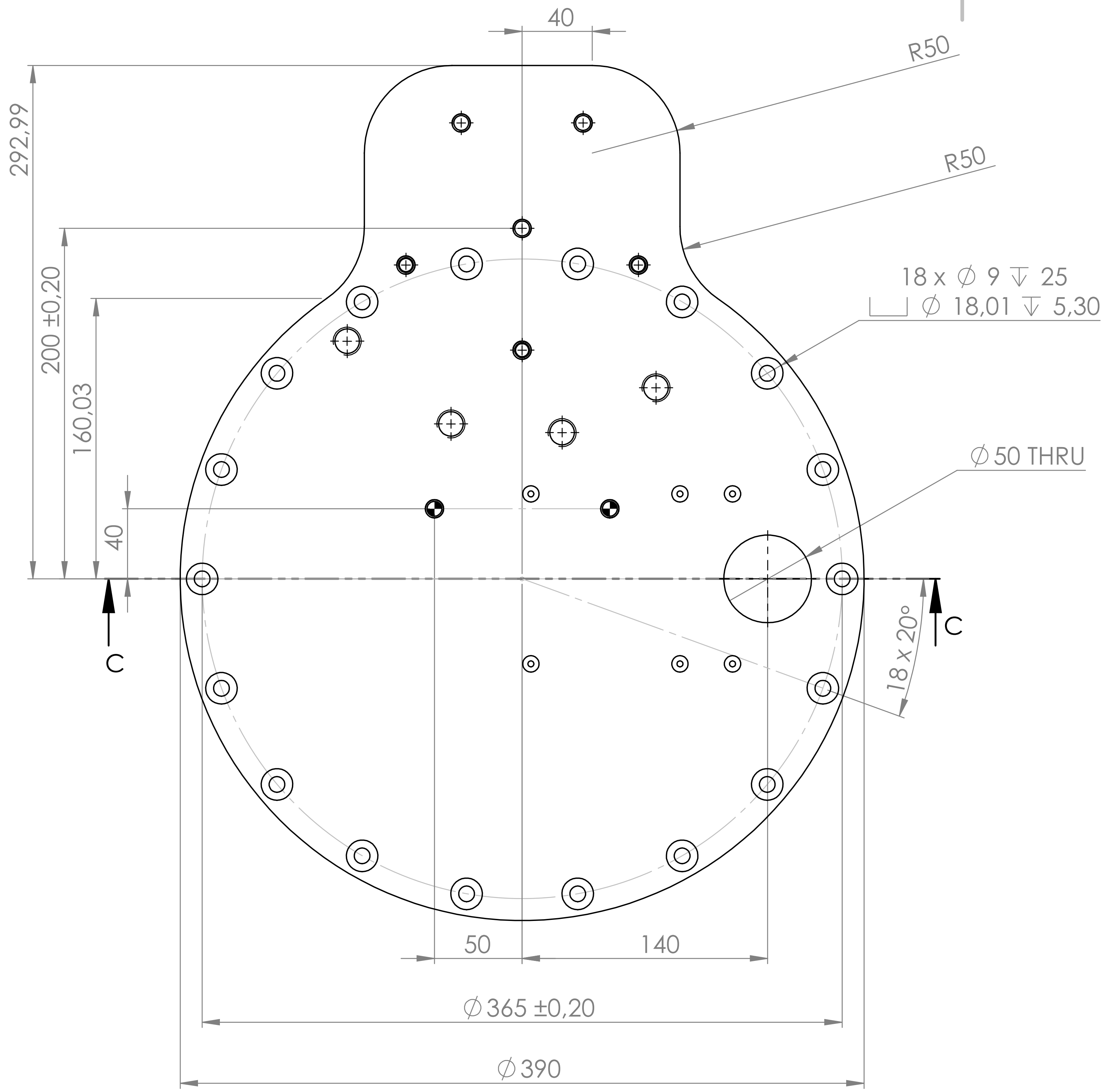
SECTION E-E

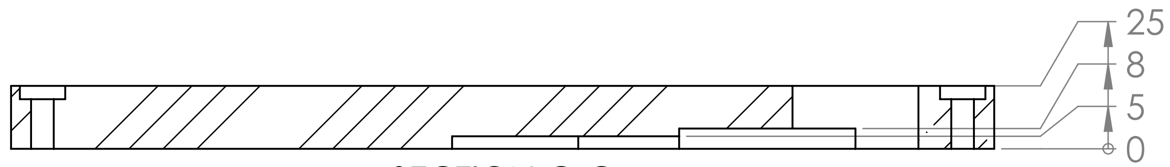


SECTION D-D

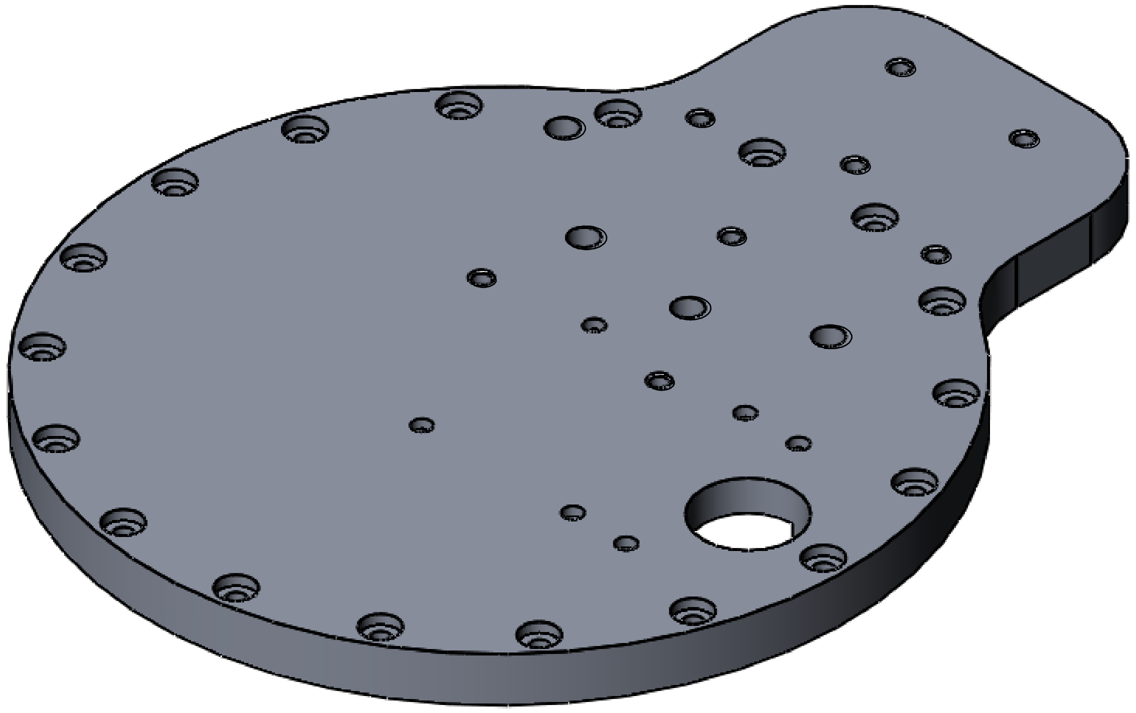


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 1mm ANGULAR: ± 1degree		FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION	
					Orbital Motion Simulator		
	NAME	SIGNATURE	DATE		TITLE: Base		
DRAWN	Fredrik Thoresen	FRT	19.05.16				
CHK'D	Anders Gunbjørnsen	ADG	20.05.16				
APPV'D	Martin Sandberg	MS	20.05.16				
MFG							
Q.A				MATERIAL: Al 6082-T6	DWG NO. 1		A3
				WEIGHT: 8838.76	SCALE:1:5	SHEET 3 OF 3	

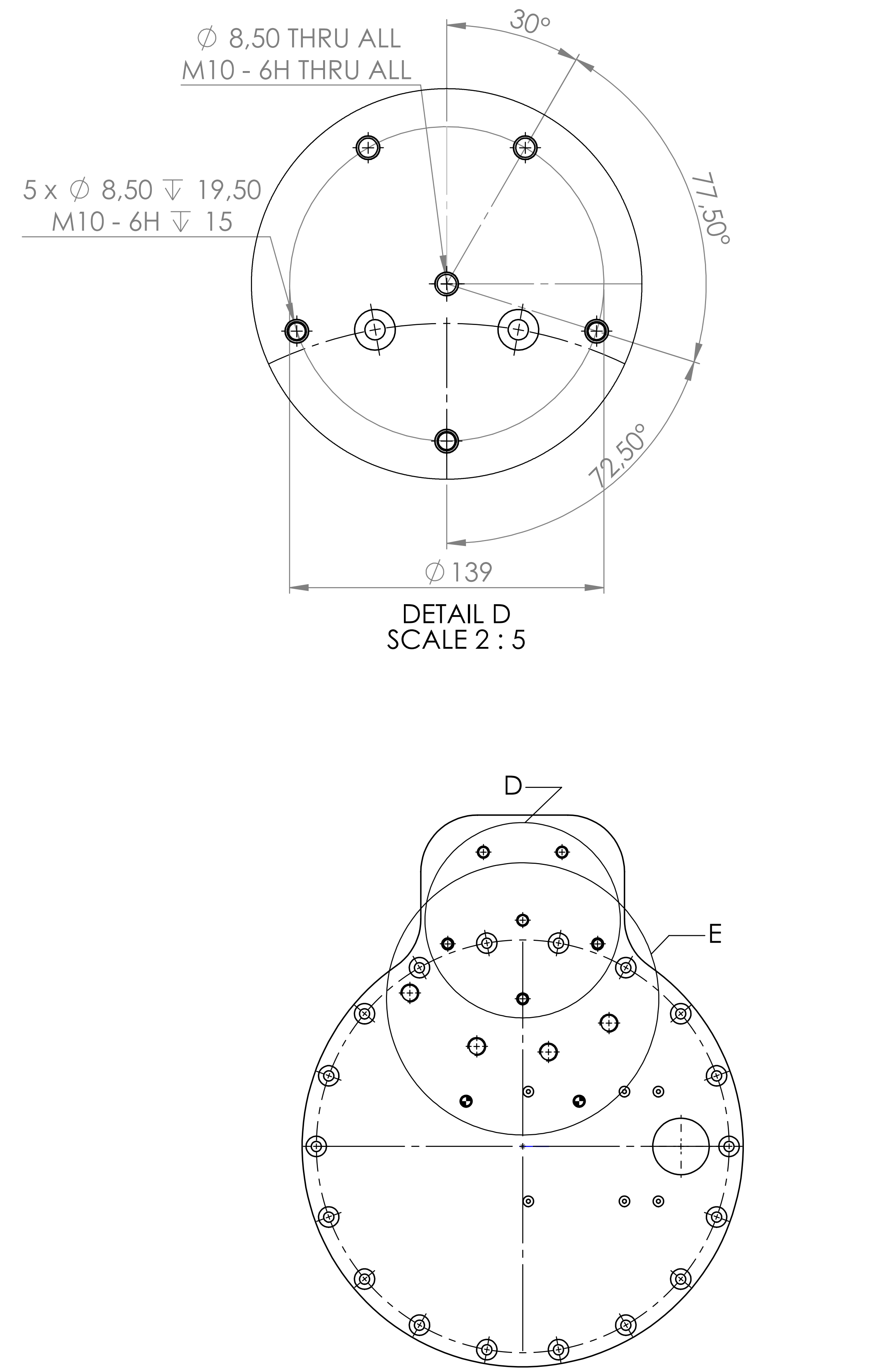


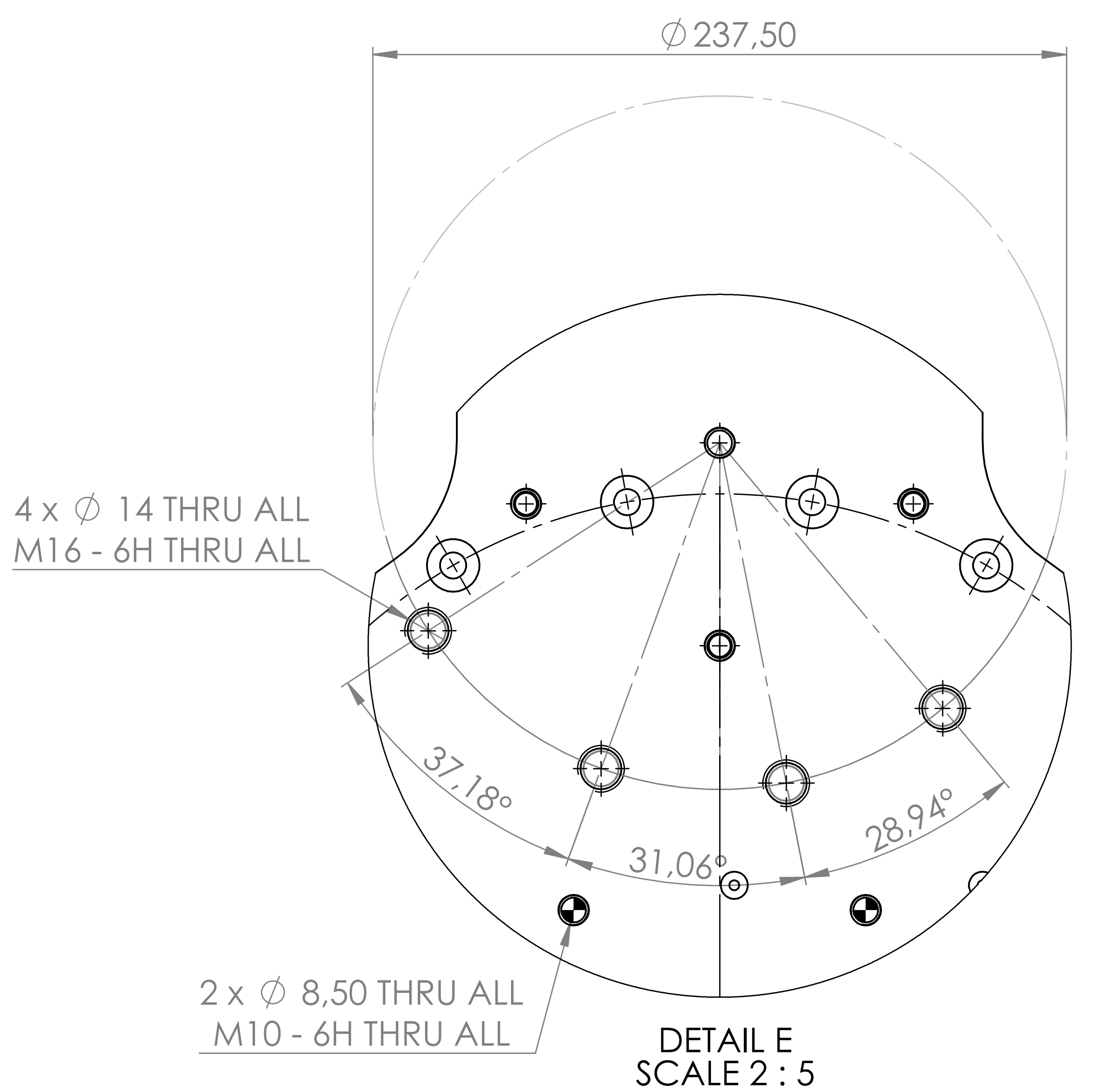


SECTION C-C



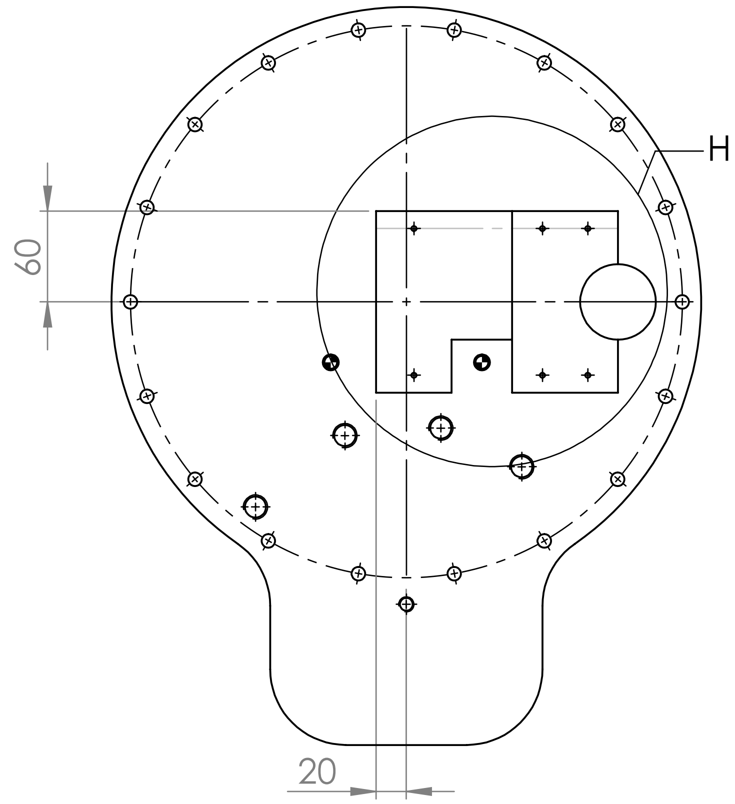
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 0,5mm ANGULAR: ± 0,1degree	FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
				Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE: Power-train Disc	
DRAWN	Fredrik Thoresen	FRT	08.05.16		
CHK'D	Anders Gunbjørnsen	ADG	19.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 14	A3
			WEIGHT: 8661.92 gram	SCALE:1:3	SHEET 1 OF 3

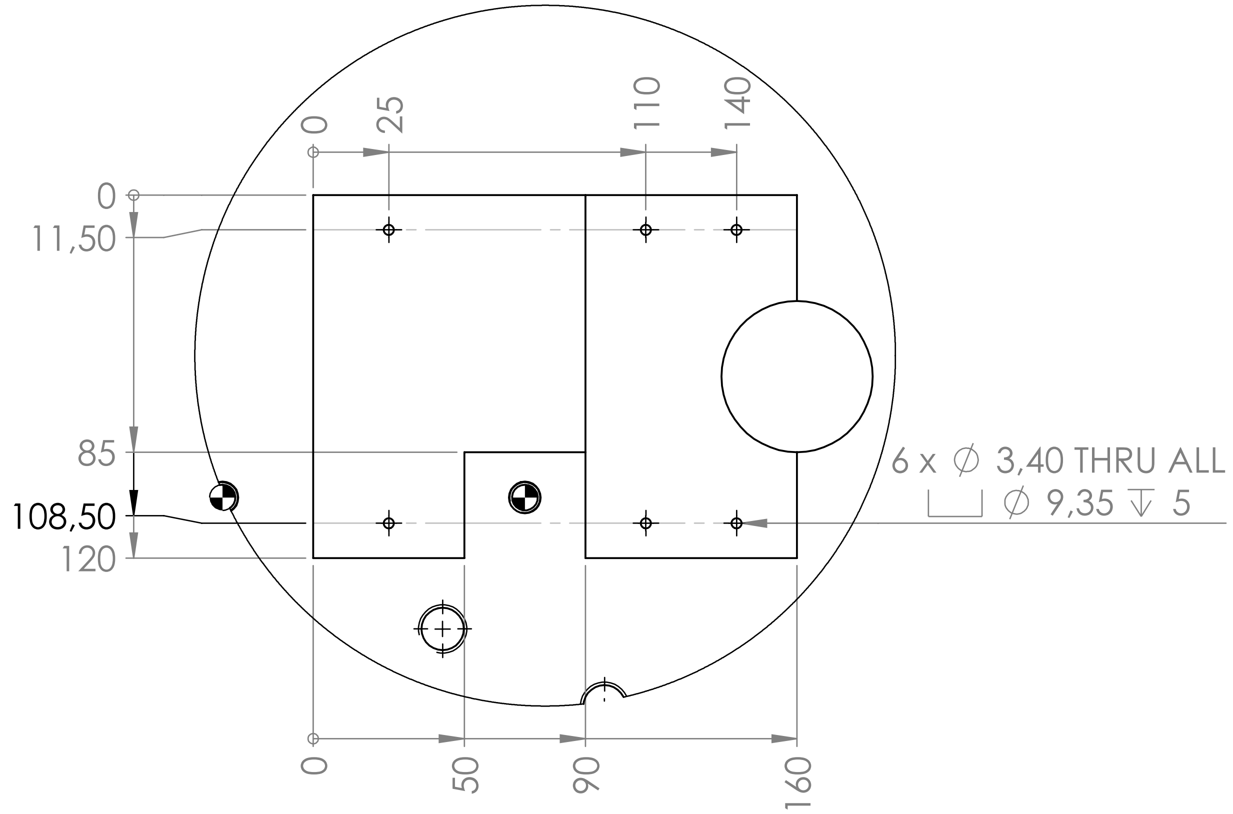




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 0,5mm ANGULAR: ± 0,1degree	FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	Orbital Motion Simulator	
DRAWN	Fredrik Thoresen	FRT	08.05.16	TITLE: Power-train Disc	
CHK'D	Anders Gunbjørnsen	ADG	19.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 14	A3
			WEIGHT: 8661.92 gram	SCALE:1:5	SHEET 2 OF 3

BOTTOM VIEW

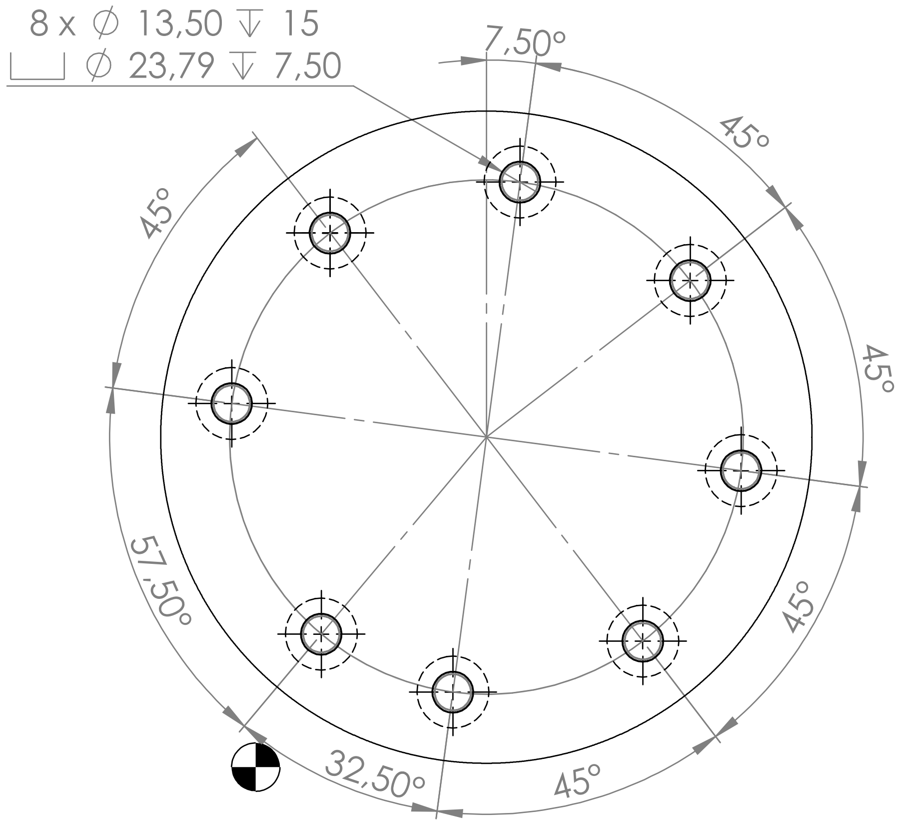




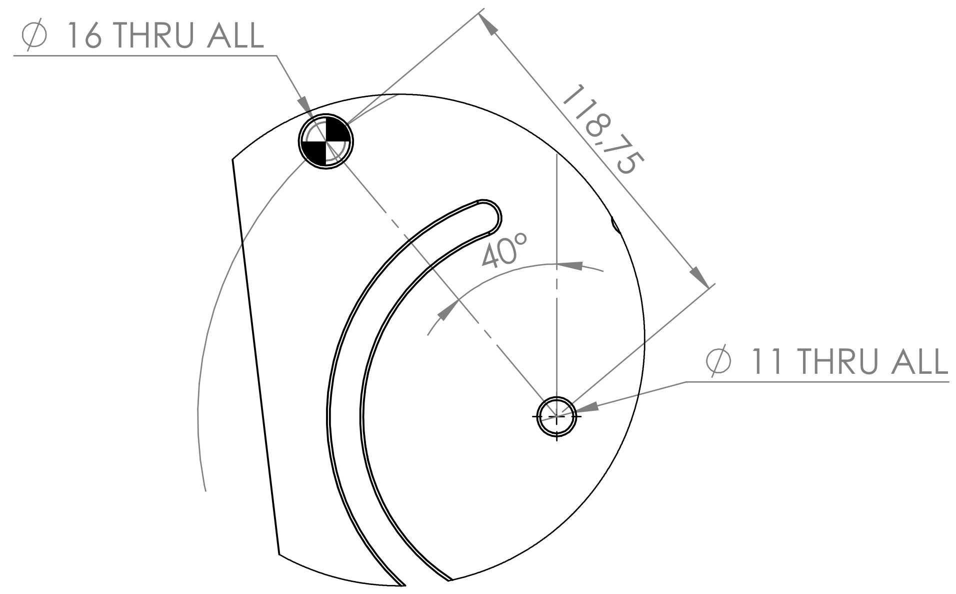
DETAIL H
SCALE 2 : 5

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 0,5mm ANGULAR: ± 0,1degree	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
			Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE: Power-train Disc
DRAWN	Fredrik Thoresen	FRT	08.05.16	
CHK'D	Anders Gunbjørnsen	ADG	19.05.16	
APPV'D	Martin Sandberg	MS	20.05.16	
MFG				
Q.A			MATERIAL: Al 6082-T6	DWG NO. 14 — A3
			WEIGHT: 8661.92	SCALE:1:5 — SHEET 3 OF 3

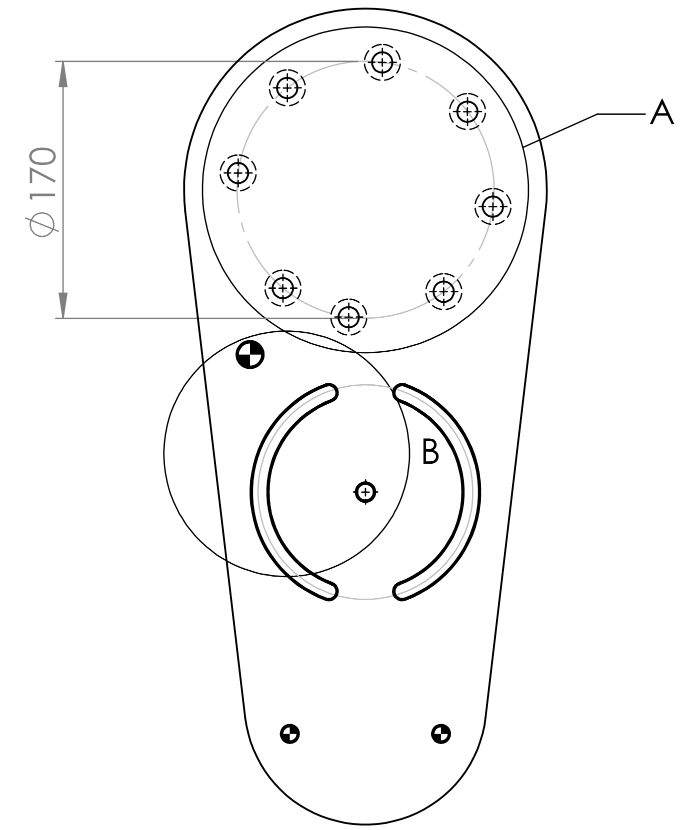
Top View

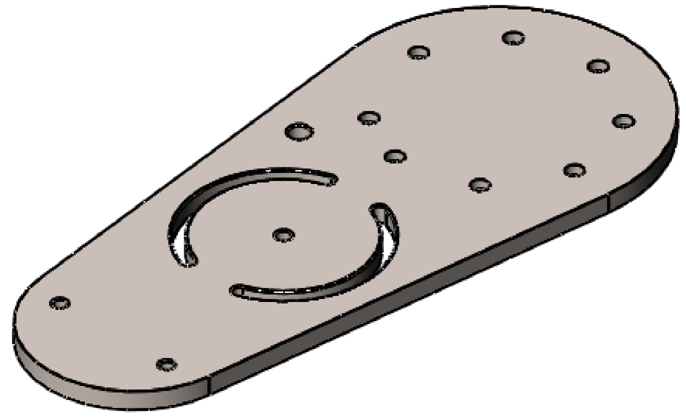


DETAIL A
SCALE 2 : 5



DETAIL B
SCALE 2 : 5





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ± 0,5mm
ANGULAR: ± 0,5degree

FINISH:

DEBURR AND BREAK SHARP EDGES: 1mm

DO NOT SCALE DRAWING

REVISION

Orbital Motion Simulator

	NAME	SIGNATURE	DATE
DRAWN	Fredrik Thoresen	FRT	08.05.16
CHK'D	Anders Gunbjørnsen	ADG	15.05.16
APPV'D	Martin Sandberg	MS	16.05.16
MFG			
Q.A			

TITLE: Offset Disc

MATERIAL: AISI 316 Stainless Steel Sheet (SS

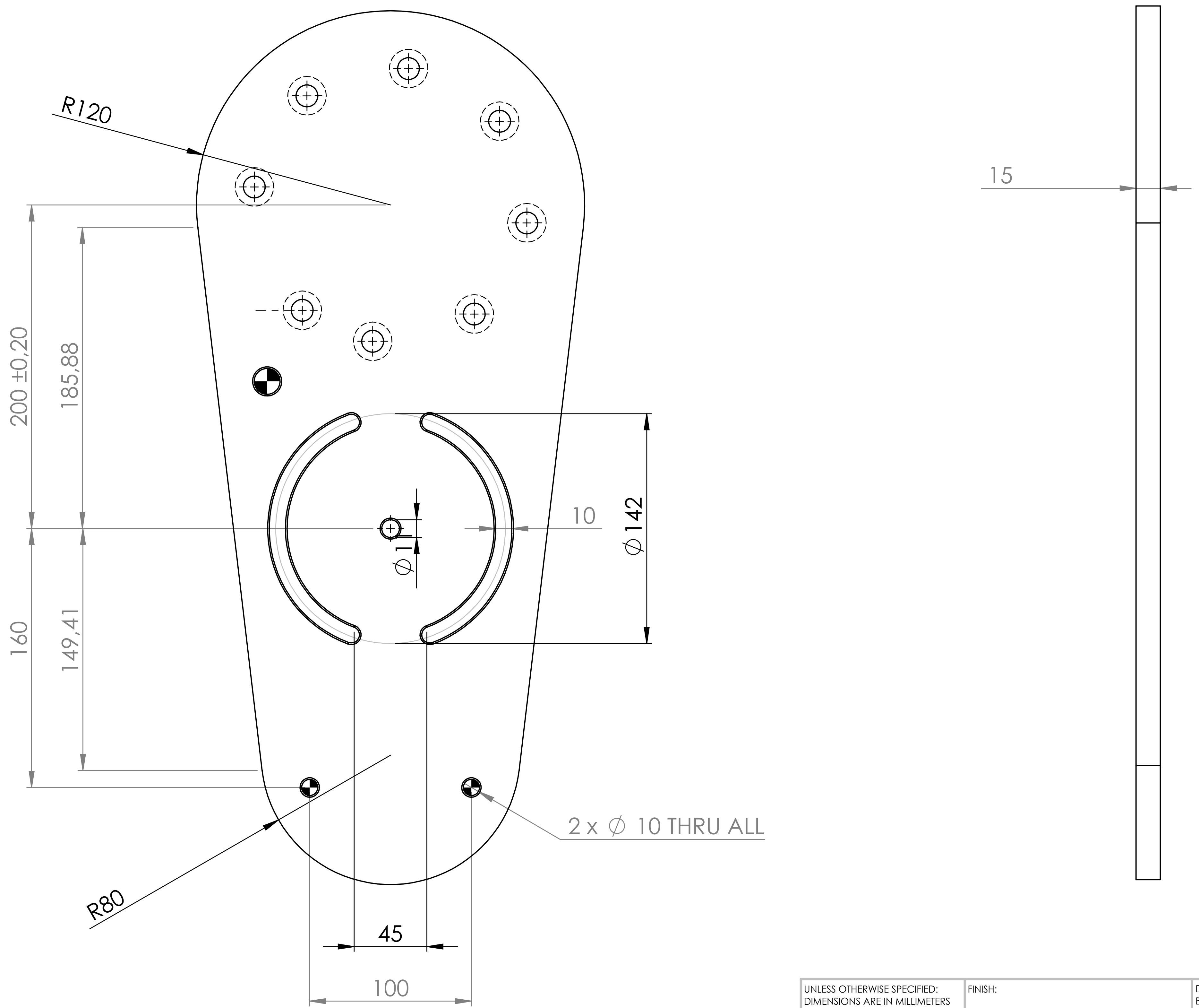
DWG NO. 3

A3

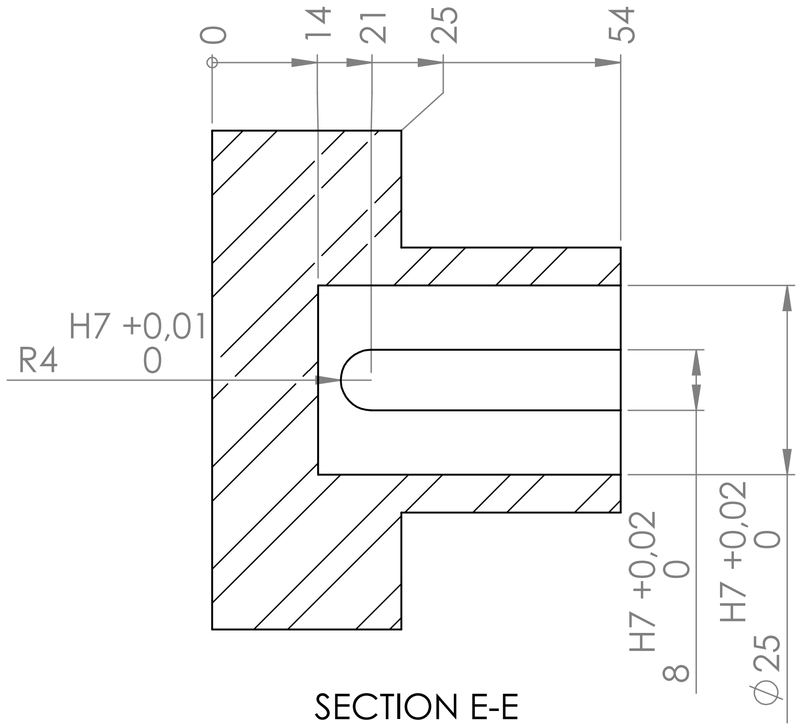
WEIGHT: 11370.04 gram

SCALE:1:5

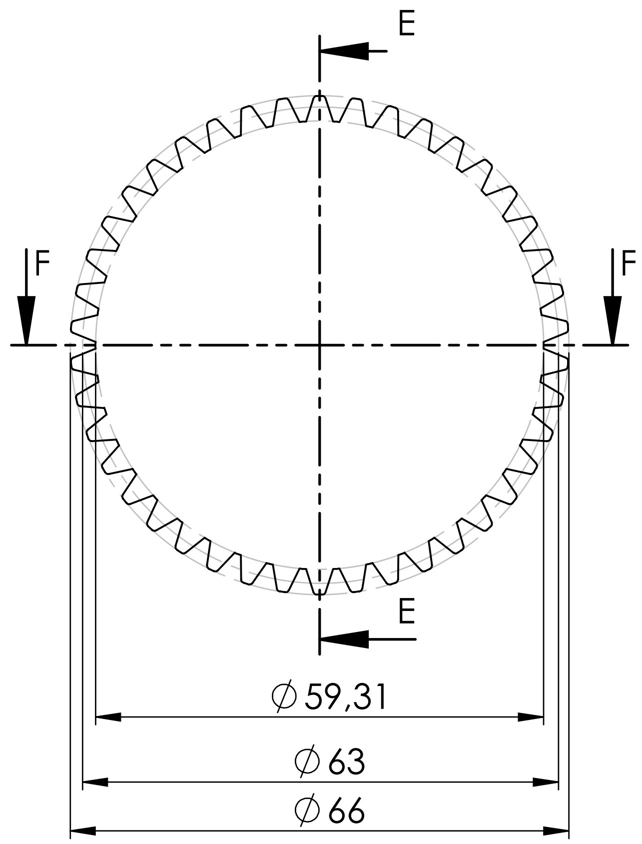
SHEET 1 OF 2

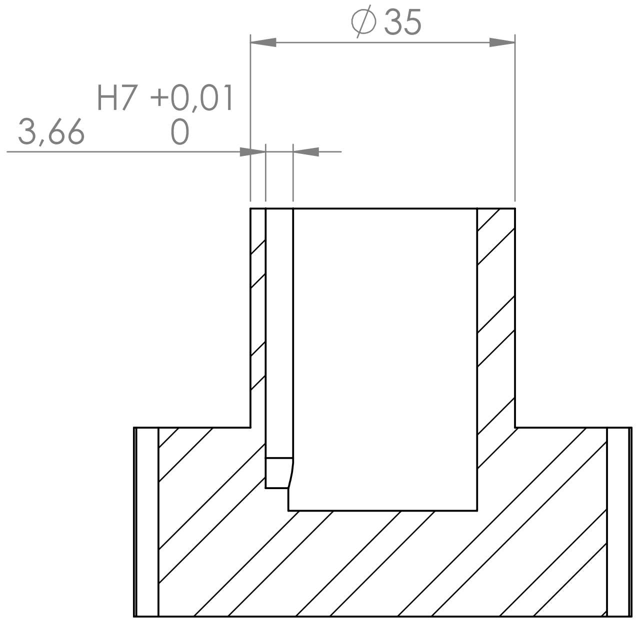


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ± 0,5mm ANGULAR: ± 0,1degree		FINISH:			DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
						Orbital Motion Simulator	
	NAME	SIGNATURE	DATE			TITLE: Offset Disc	
DRAWN	Fredrik Thoresen	FRT	08.05.16				
CHK'D	Anders Gunbjørnsen	ADG	15.05.16				
APPV'D	Martin Sandberg	MS	16.05.16				
MFG							
Q.A				MATERIAL: AISI 316 Stainless Steel Sheet (SS)		DWG NO. 3	A3
				WEIGHT: 11370.04 gram		SCALE:1:3	SHEET 2 OF 2

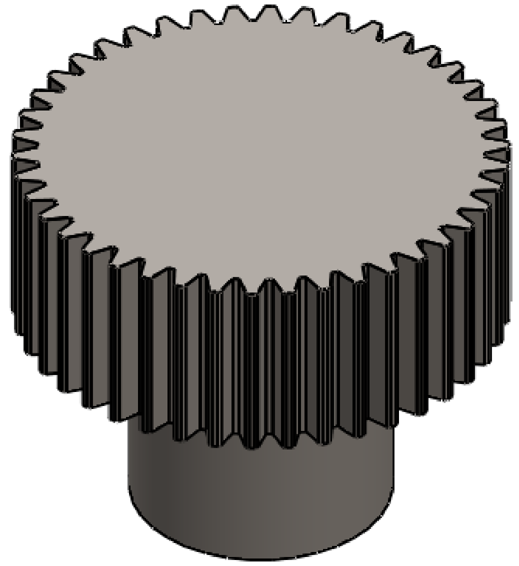


SECTION E-E



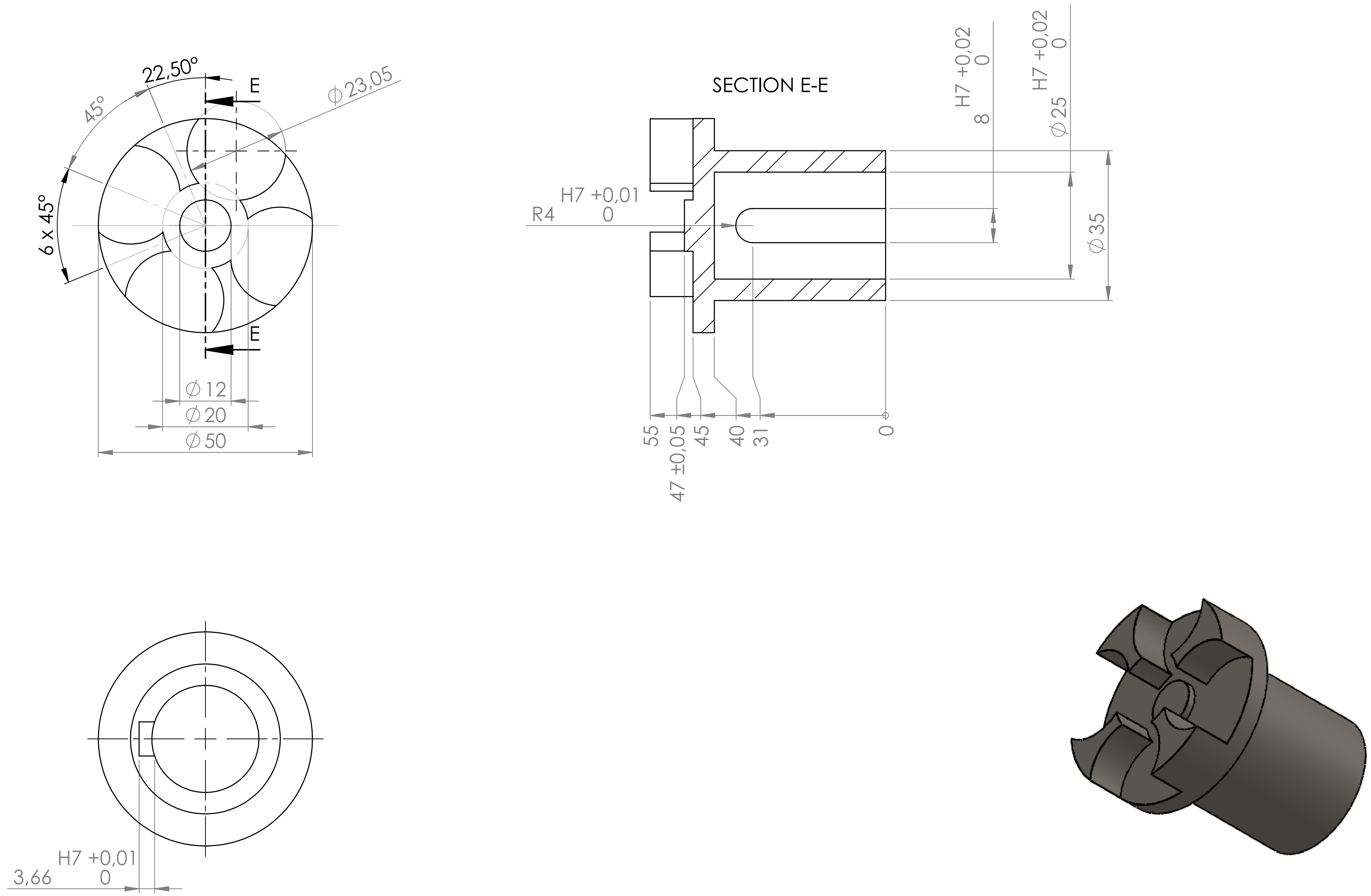


SECTION F-F

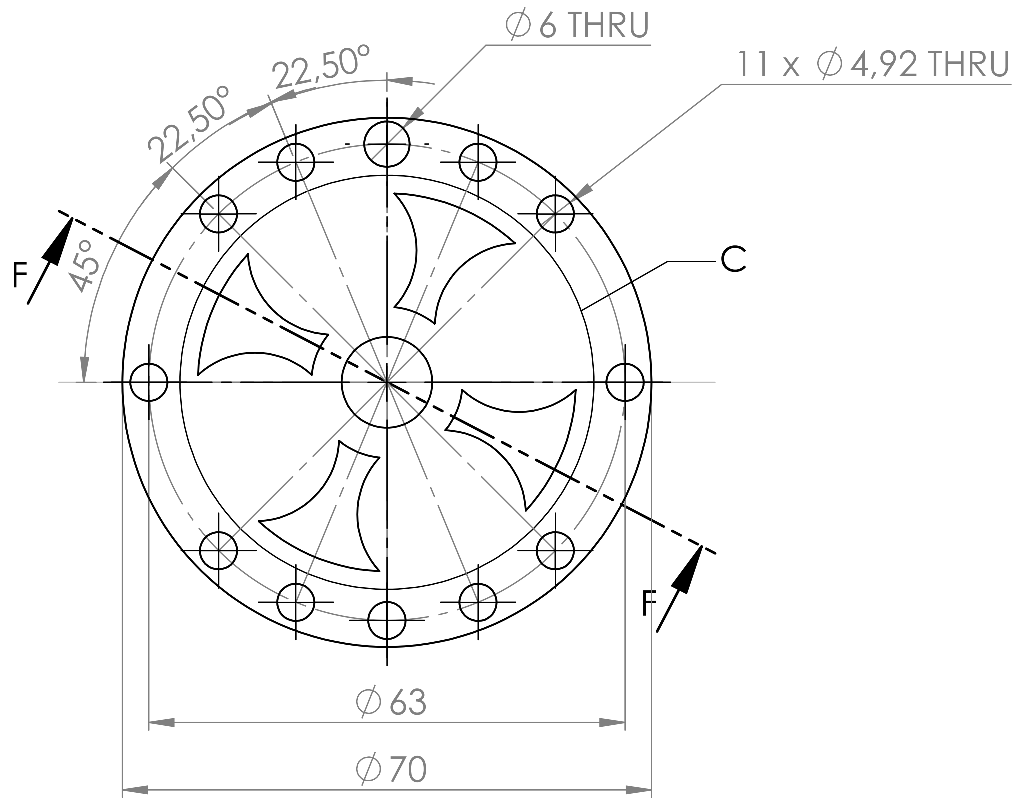


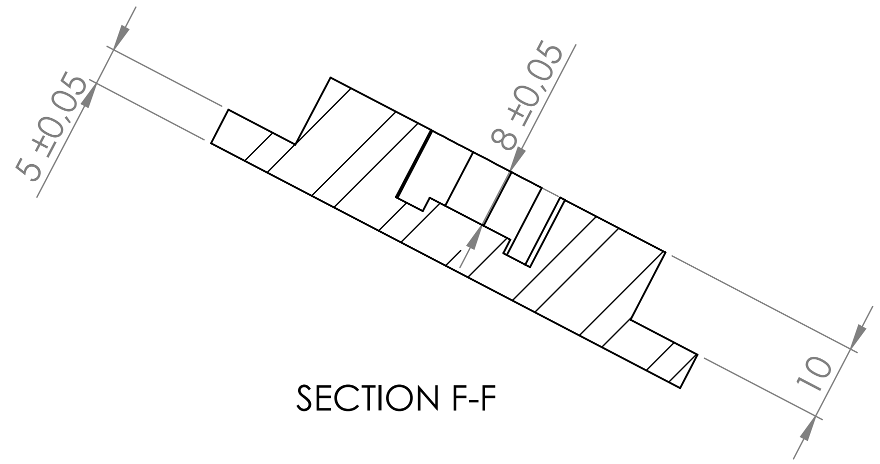
Notes:
Manufacturing data for pinion:
Number of teeth: 42
Reference diameter: 63mm
Module: 1.5
Pressure angle: 20°

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ±0,1 mm ANGULAR: ±0,1 degree		FINISH: Abrasive blasting - KVS 121		DEBURR AND BREAK SHARP EDGES 0,5mm	DO NOT SCALE DRAWING / REVISION
	NAME	SIGNATURE	DATE		Orbital Motion Simulator
DRAWN	Fredrik Thoresen	FRT	10.05.16		TITLE: Pinion
CHK'D	Anders Gunbjørnsen	ADG	16.05.16		
APPV'D	Martin Sandberg	MS	18.05.16		
MFG					
Q.A				MATERIAL: AISI 4340 Steel, normalized, EN 10083	DWG NO. 12 A3
				WEIGHT: 667.30 gram	SCALE:1:1 SHEET 1 OF 1



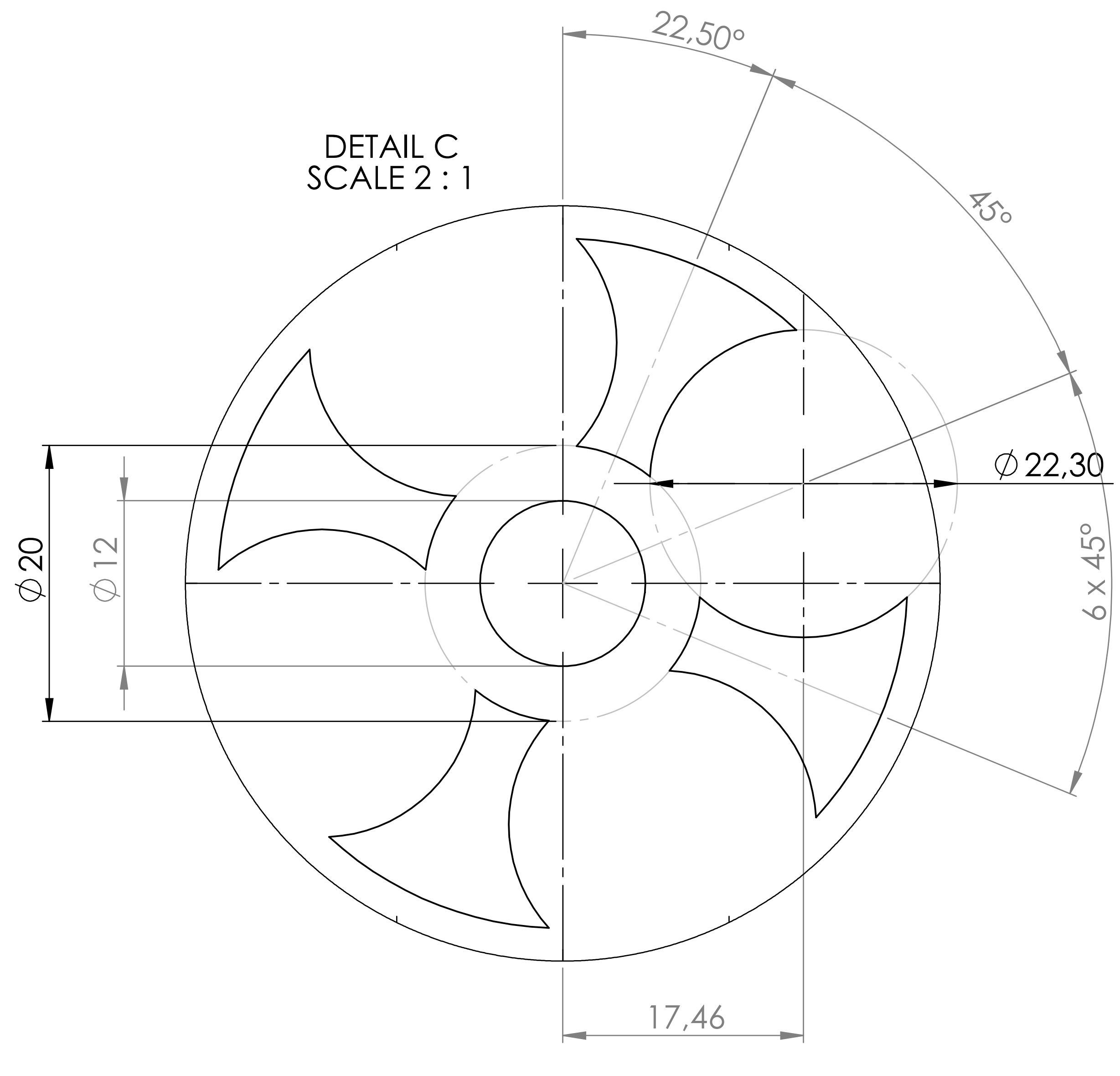
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ±0,1 mm ANGULAR: ±0,1 degree	FINISH:					DEBURR AND BREAK SHARP EDGES 0,5mm	DO NOT SCALE DRAWING	REVISION
							Orbital Motion Simulator	
	NAME	SIGNATURE	DATE				TITLE: Drive Shaft	
DRAWN	Fredrik Thoresen	FRT	08.05.16					
CHK'D	Anders Gunbjørnsen	ADG	18.05.16					
APPV'D	Martin Sandberg	MS	19.05.16					
MFG								
Q.A				MATERIAL: AISI 4340 Steel, normalized EN10083			DWG NO. 4	A3
				WEIGHT: 252.29 gram			SCALE:1:1	SHEET 1 OF 1

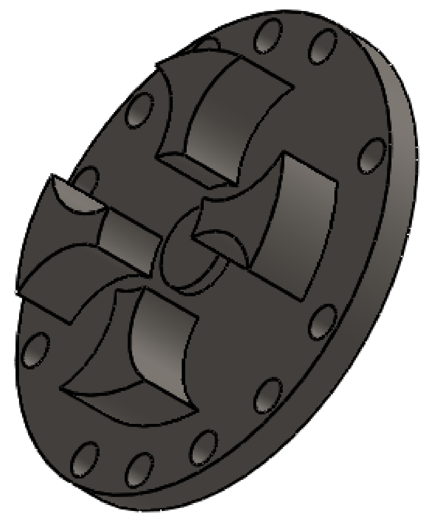




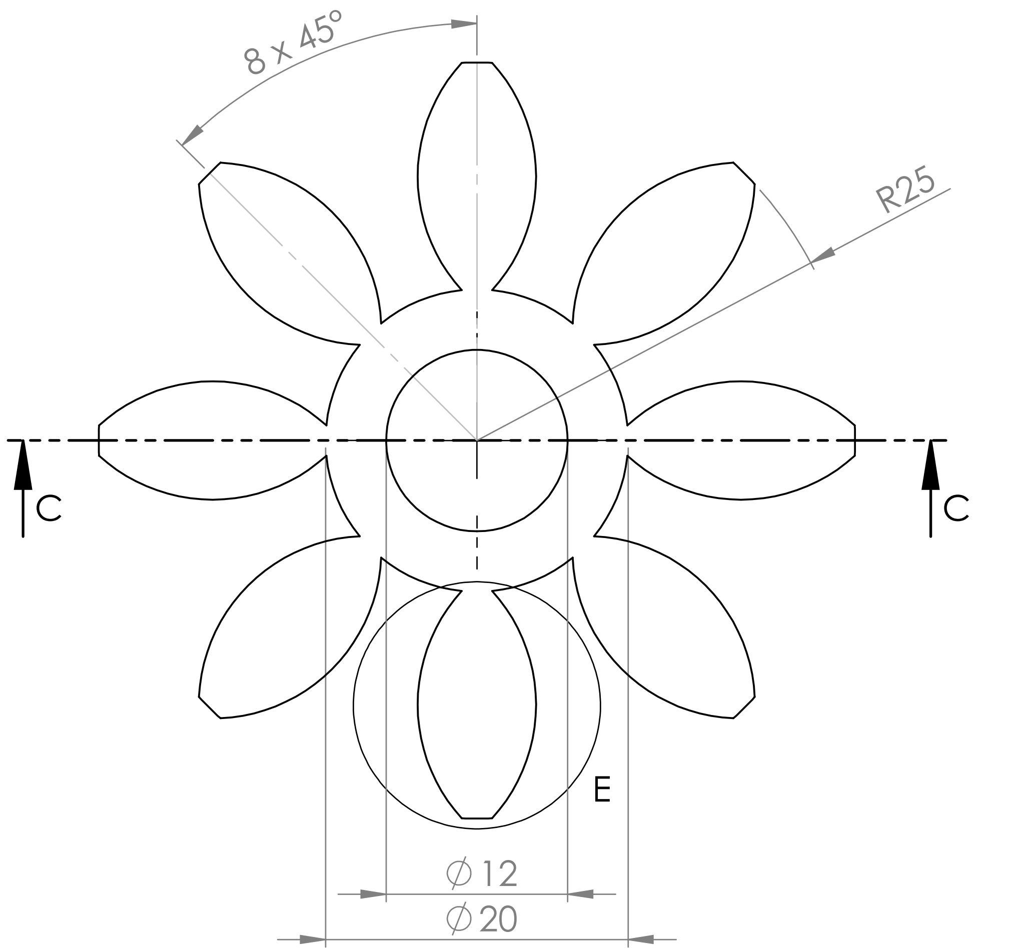
SECTION F-F

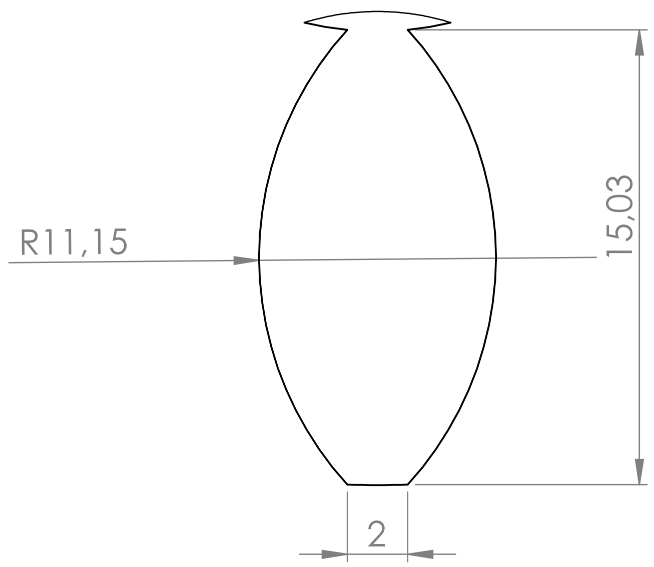
DETAIL C
SCALE 2 : 1



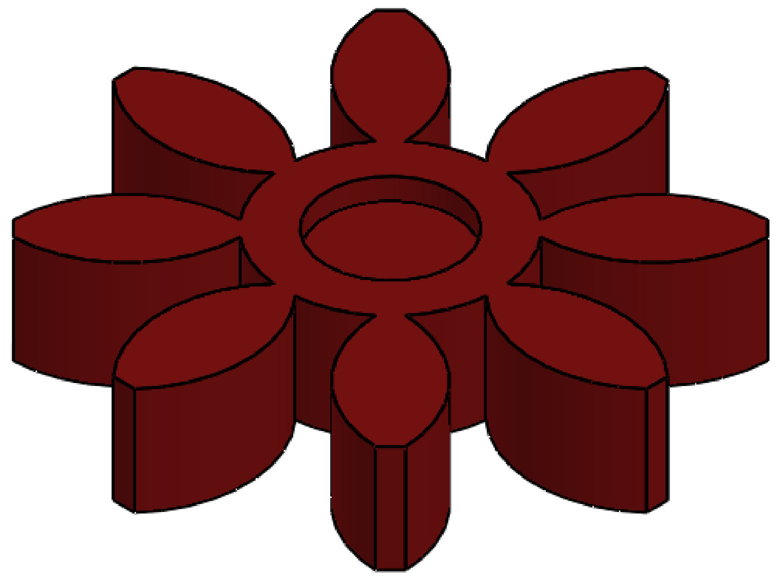


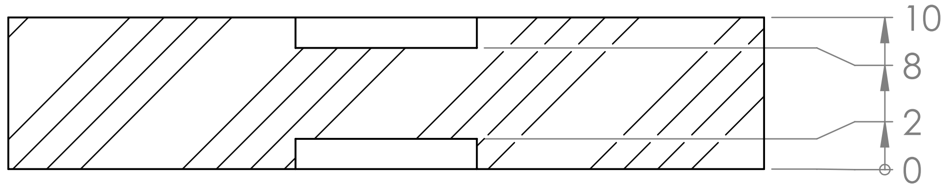
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ±0,1 mm ANGULAR: ±0,1 degree	FINISH:		DEBURR AND BREAK SHARP EDGES 0,5mm	DO NOT SCALE DRAWING	REVISION
				Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE: Motor adaptor	
DRAWN	Fredrik Thoresen	FRT	08.05.16		
CHK'D	Anders Gunbjørnsen	ADG	15.05.16		
APPV'D	Martin Sandberg	MS	16.05.16		
MFG					
Q.A			MATERIAL: AISI 4340 Steel, normalized EN10083	DWG NO. 7	A3
			WEIGHT: 179.95 gram	SCALE:1:1	SHEET 1 OF 1





DETAIL E
SCALE 4 : 1





SECTION C-C

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ±0,1 mm
ANGULAR: ±0,1 degree

FINISH:

DEBURR AND BREAK SHARP EDGES
0,5mm

DO NOT SCALE DRAWING

REVISION

Orbital Motion Simulator

	NAME	SIGNATURE	DATE
DRAWN	Fredrik Thoresen	FRT	12.05.16
CHK'D	Anders Gunbjørnsen	ADG	15.05.16
APPV'D	Martin Sandberg	MS	16.05.16
MFG			
Q.A			

TITLE:

Rubber Gasket

MATERIAL:
Natural Rubber

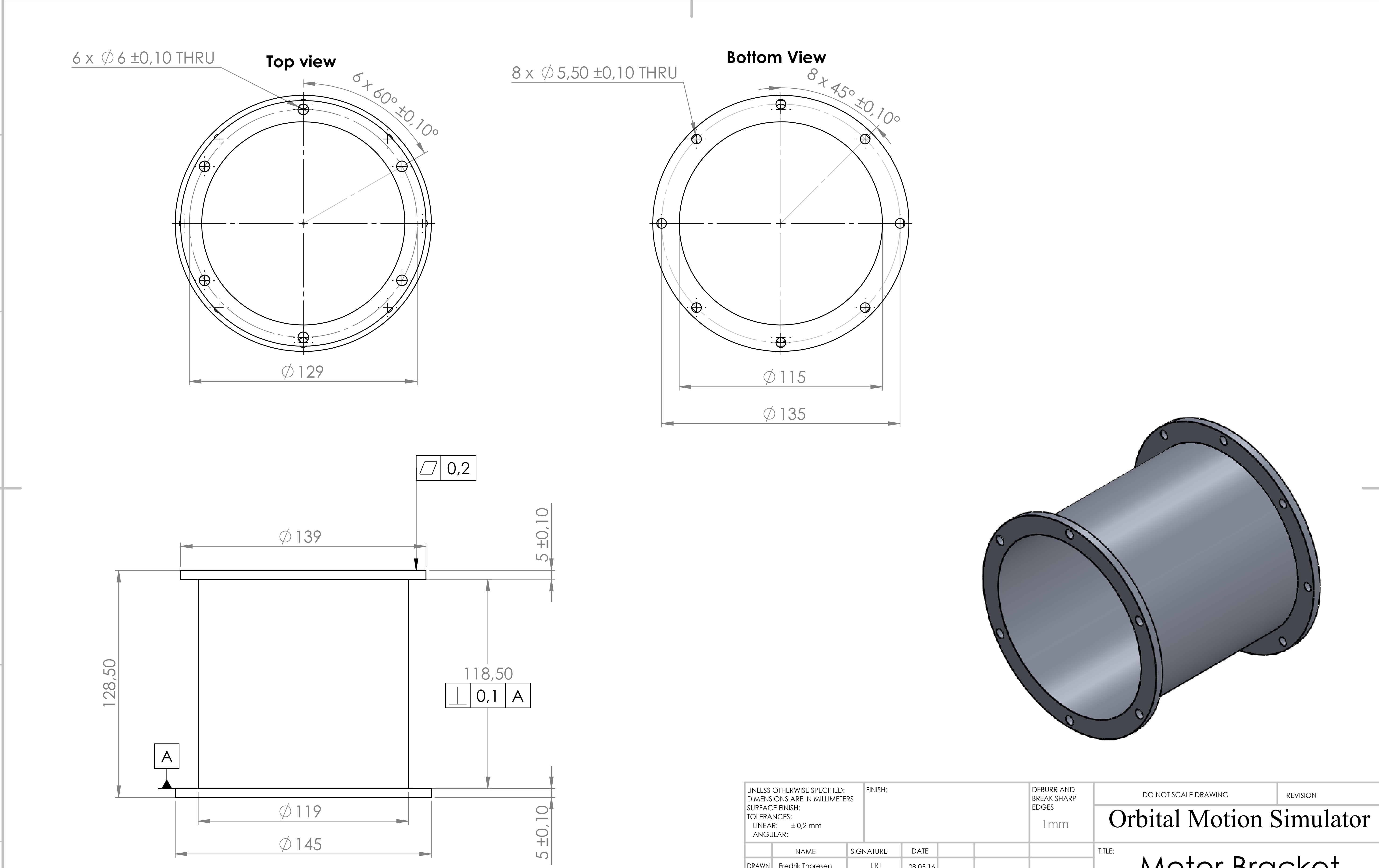
WEIGHT: 9.50 gram

DWG NO.
5

A3

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ± 0,2 mm
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES: 1mm

DO NOT SCALE DRAWING

REVISION

Orbital Motion Simulator

TITLE:

Motor Bracket

	NAME	SIGNATURE	DATE
DRAWN	Fredrik Thoresen	FRT	08.05.16
CHK'D	Anders Gunbjørnsen	ADG	15.05.16
APPV'D	Martin Sandberg	MS	16.05.16
MFG			
Q.A			

MATERIAL: Al 6082-T6

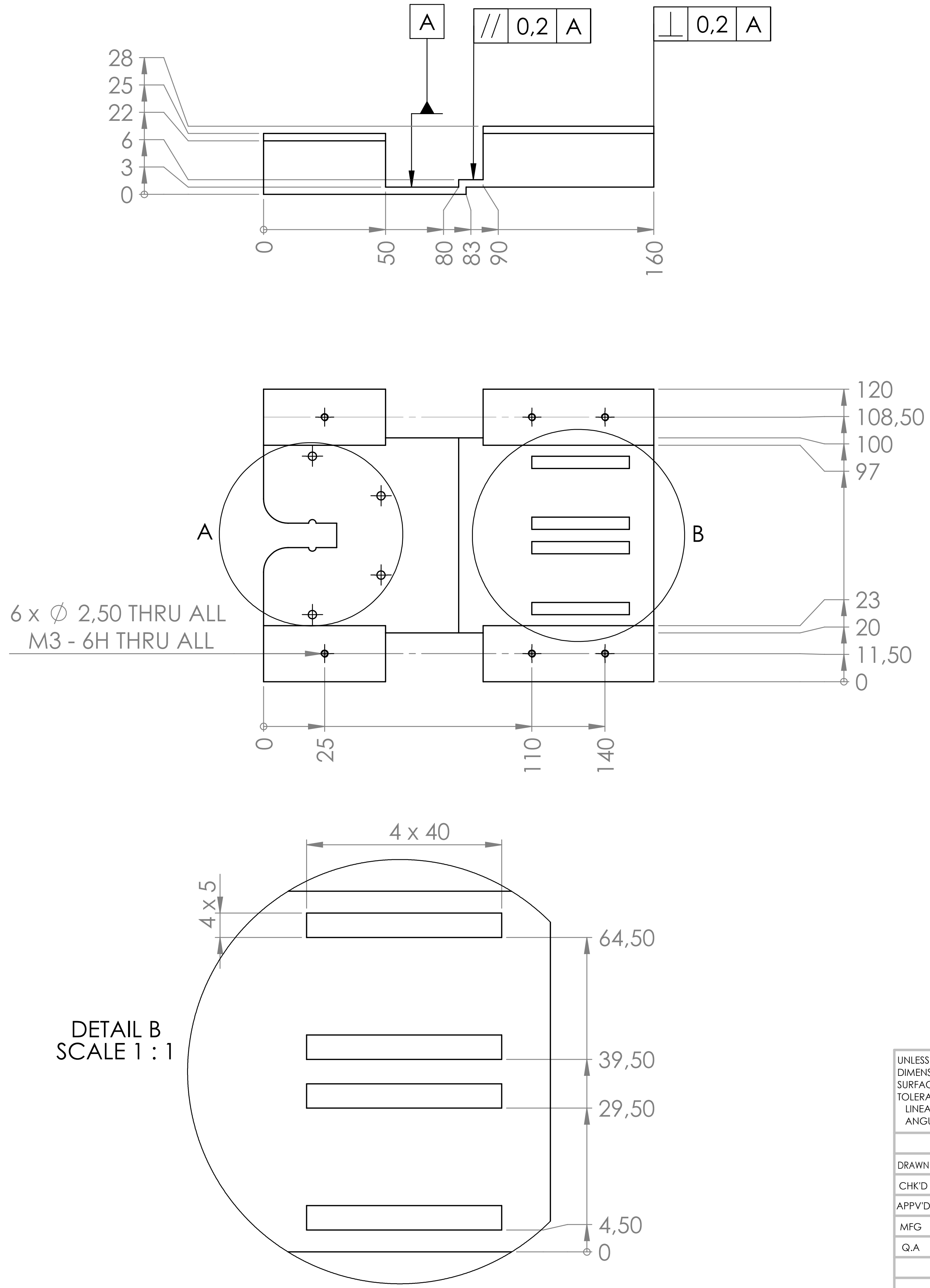
DWG NO. 6

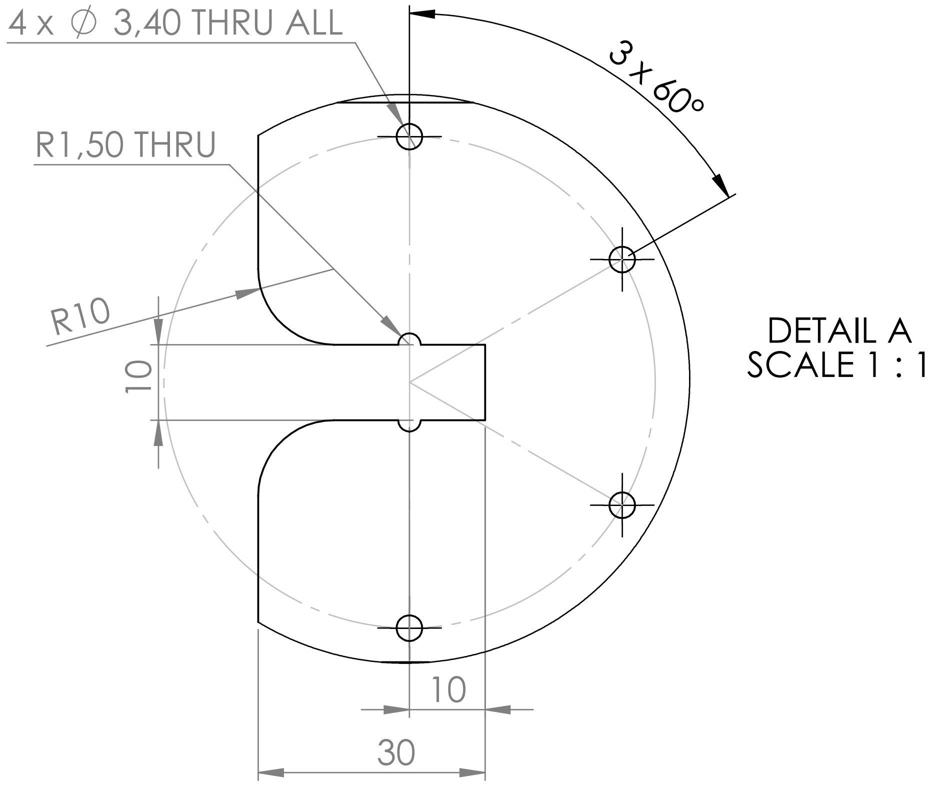
A3

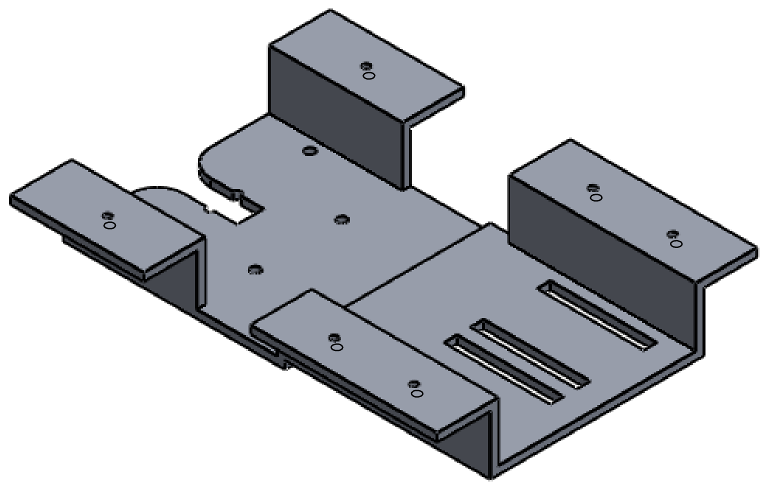
WEIGHT: 377.69 gram

SCALE:1:2

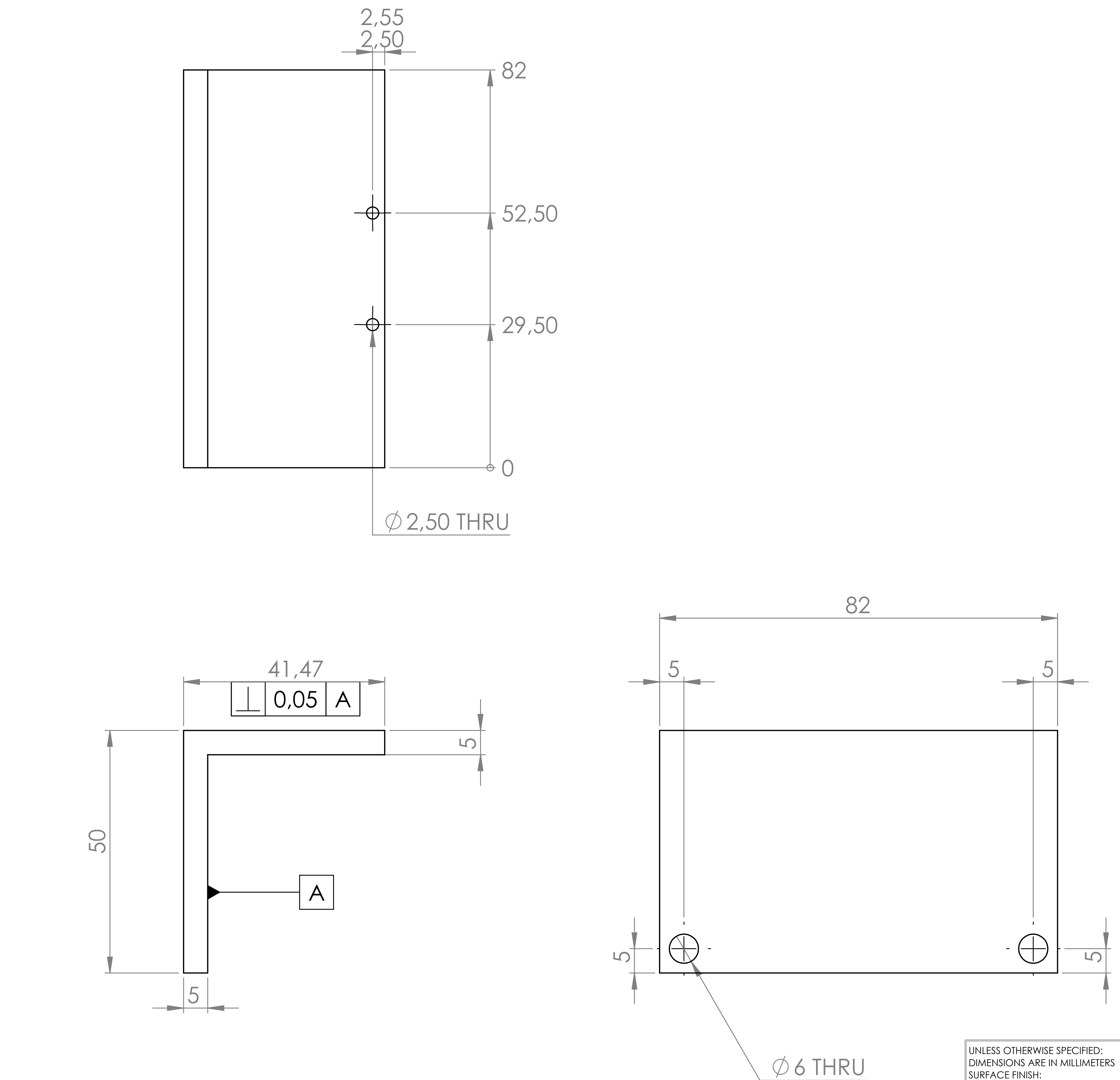
SHEET 1 OF 1

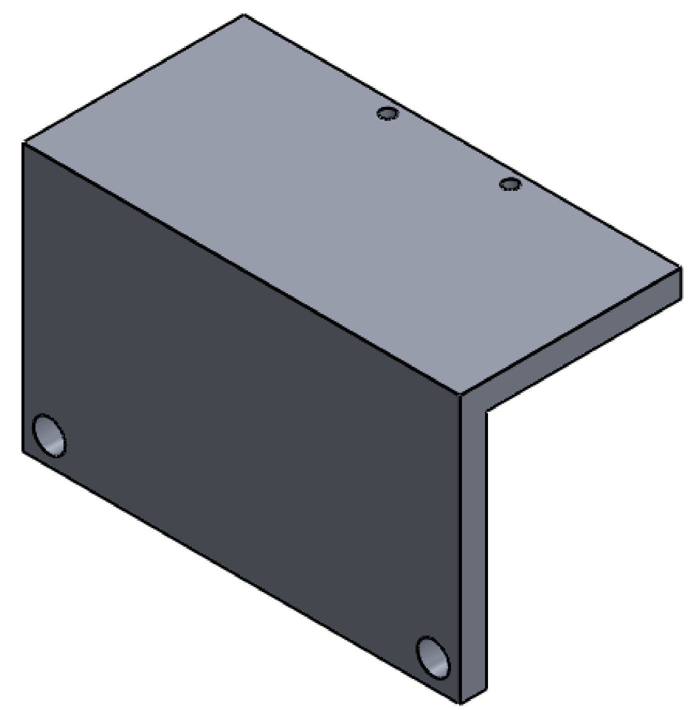






UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ±0,1 mm ANGULAR: ±0,1 degree	FINISH:		DEBURR AND BREAK SHARP EDGES 1mm	DO NOT SCALE DRAWING	REVISION
				Orbital Motion Simulator	
	NAME	SIGNATURE	DATE	TITLE: Cable Bridge	
DRAWN	Fredrik Thoresen	FRT	19.05.16		
CHK'D	Anders Gunbjørnsen	ADG	20.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 26	A3
			WEIGHT: 177.42	SCALE:1:2	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ±0,1 mm
ANGULAR: ±0,1 degree

FINISH:

DEBURR AND BREAK SHARP EDGES 0,5mm

DO NOT SCALE DRAWING

REVISION

Orbital Motion Simulator

	NAME	SIGNATURE	DATE
DRAWN	Fredrik Thoresen	FRT	19.05.16
CHK'D	Anders Gunbjørnsen	ADG	20.05.16
APPV'D	Martin Sandberg	MS	20.05.16
MFG			
Q.A			

TITLE:

Reader Head Bracket

MATERIAL: Al 6082-T6

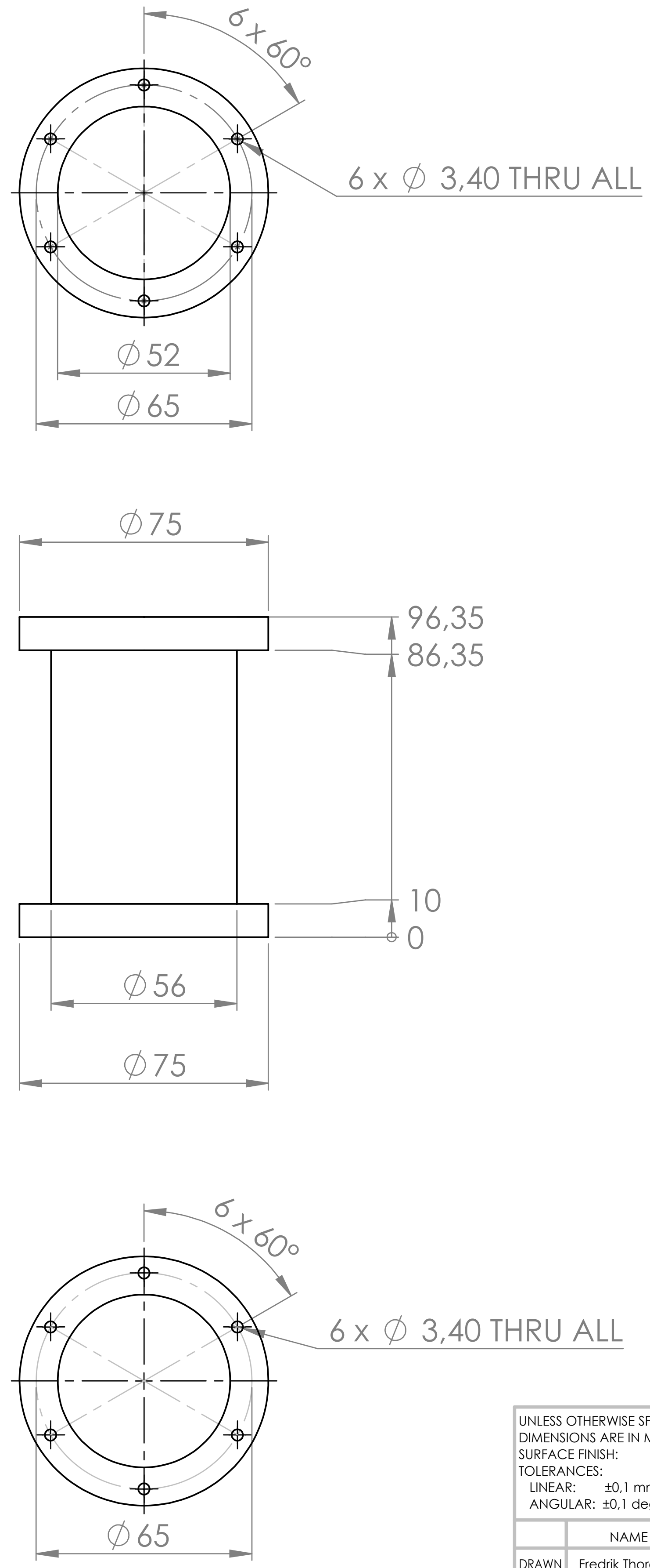
DWG NO. 27

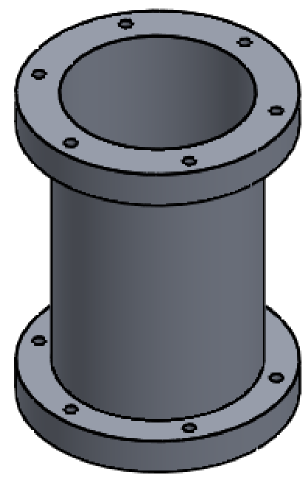
A3

WEIGHT: 94.83

SCALE:1:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ±0,1 mm ANGULAR: ±0,1 degree	FINISH:		DEBURR AND BREAK SHARP EDGES 0,5mm	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	Orbital Motion Simulator	
DRAWN	Fredrik Thoresen	FRT	19.05.16	TITLE: Sensor Adapter	
CHK'D	Anders Gunbjørnsen	ADG	20.05.16		
APPV'D	Martin Sandberg	MS	20.05.16		
MFG					
Q.A			MATERIAL: Al 6082-T6	DWG NO. 28	A3
			WEIGHT: 190.89	SCALE:1:2	SHEET 1 OF 1

Project Conclusion

The aim of the project was to design a system that will support rotation of a remote weapon station (RWS) in isolation, and in parallel axes off-set, to a rotating turret. Kongsberg Protech Systems (KPS) provided the project and they intend to implement the system in a test simulation laboratory. The project included numerous requirements pertaining to both project management and technical engineering. At termination of the project each of these two branches have corresponding conclusions.

The project was delimited to comprise mechanical and mechatronic aspects of the desired system. A mechanical system that supports parallel axis rotation of the RWS at offsets up to 40 cm was designed. Offset increments of 10 cm intervals is enabled and the assembled system can support rotational speed and acceleration beyond the minimum requirements of the stakeholder. At termination of the project period a system design is delivered that through verification fulfills more than 96 percent of all the system requirements. This includes numerous requirements that were listed as *should* requirements and thus introduce additional functional freedom to the stakeholders beyond the minimum specifications. The system was required to be operable while mounted onto a motion table with 6 degrees of freedom. This implied analysis of a very complex motion and load pattern, as the system was also required to rotate around its own center axis with an offset load of 250 kg. A comprehensive dynamic model of the system and the motion table was developed in SimuLink through the use of differential equations and vector analysis. This enabled development and analysis of a "worst case" load scenario, which formed the basis for evaluation and selection of components, as well as structural optimisation of the design. The system, including interfacing components such as the motor and bolts, are thus designed to withstand the worst case scenario with a safety factor of two. The system is verified to have a life span of minimum five years by taking measure to protect against corrosion and fatigue failure. A potential limitation with the design is the backlash introduced by the bevel gear and pinion. As the system is intended to be further developed by future students a suggestion for a mechanical solution has been proposed, in case this is found to be a limitation worth addressing.

The CAFCR+ model was used to structure the systems engineering and development process. The model proved particularly useful at quickly initiating the process of understanding the system, its environment and required functions. This was a very beneficial trait of this model for rather unexperienced students trying to develop a system that currently does not exist and thus involves a large number of "unknowns". The team proved to be adaptable and solution oriented in the face of larger changes to the planned milestones, which challenged the project team to quickly and efficiently rearrange tasks, change milestones and adjust the time schedule.

The project plan and iterations were developed to frequently revisit the major identified risks of the project; being requirements identification and interpretation. Throughout the project numerous important "hidden" requirements were identified, e.g. those pertaining to the motion table, which could have had large consequences for the structural safety of the design had they not been identified. The benefits of undertaking a careful risk assessment, developing risk strategies and integrating them into the project plan were largely evident. Likewise were the benefits of following a test strategy and putting effort into maintaining the team’s motivation. Advice for future students based on the lessons learnt have been provided.

University College of Southeast Norway
Mechanical Engineering
2016 - 07

Appendices

Orbital Motion Simulator

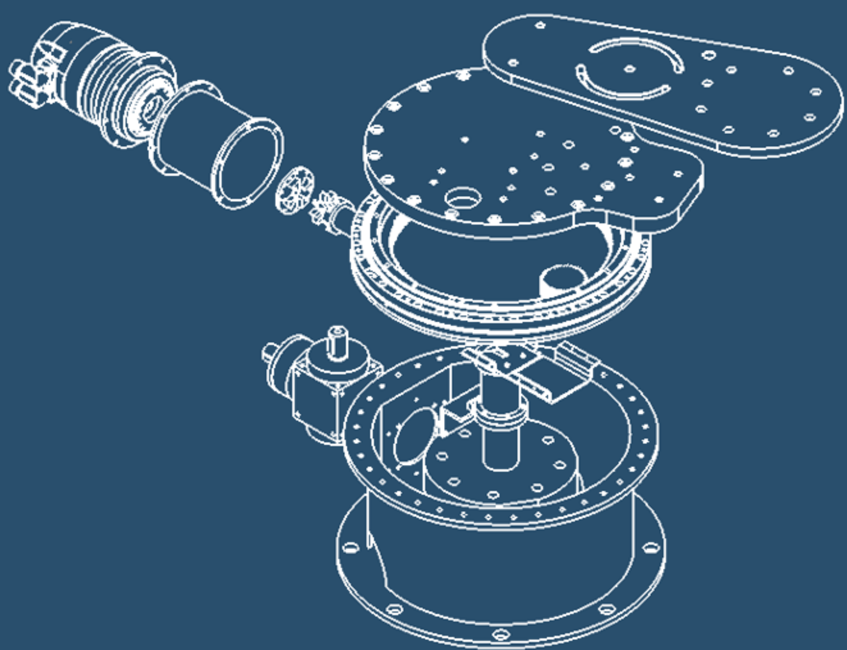


Table of Contents

A Hole Pattern

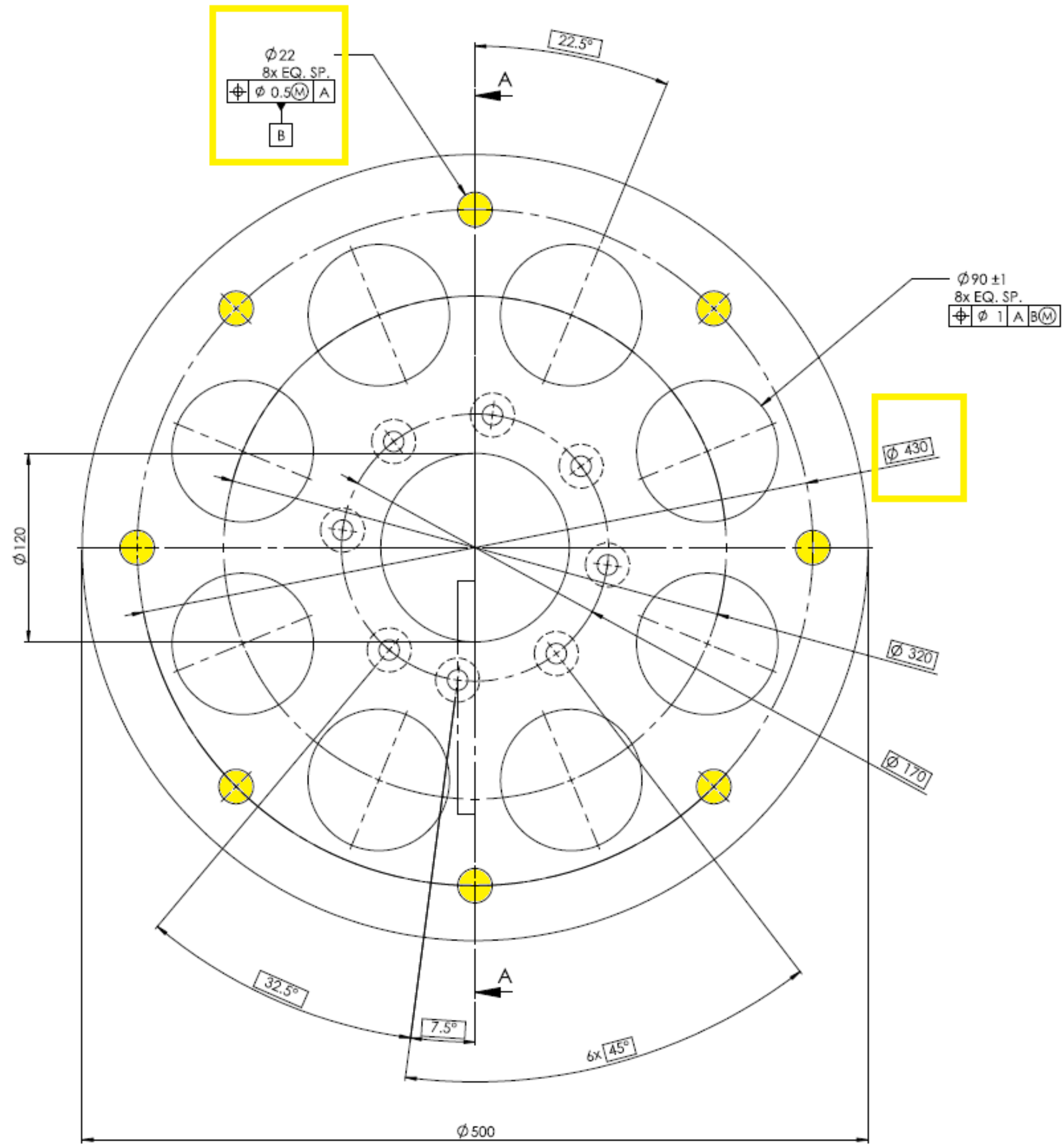


Figure A.1: Hole Pattern Motion Table

B Gantt

ID	Task Name	Duration	Start	Finish
1	**1.0 Start up**	**8 days**	**Wed 16-01-06**	**Fri 16-01-15**
2	1.1 Administrative plan	8 days	Wed 16-01-06	Fri 16-01-15
3	1.2 Project model	5 days	Mon 16-01-11	Fri 16-01-15
4	**2.0 Iteration 1**	**1 day**	**Mon 16-01-18**	**Mon 16-01-1**
5	2.1 System of interest	1 day	Mon 16-01-18	Mon 16-01-1
6	2.2 Initial design	1 day	Mon 16-01-18	Mon 16-01-1
7	2.3 Black box	1 day	Mon 16-01-18	Mon 16-01-1
8	2.4 Identify stakeholders	1 day	Mon 16-01-18	Mon 16-01-1
9	2.5 Identify Life cycle stakeholders	1 day	Mon 16-01-18	Mon 16-01-1
10	3.0 - Requirements identification	0 days	Mon 16-01-18	Mon 16-01-1
11	**4.0 Requirement specificaton V1.0**	**6 days**	**Mon 16-01-18**	**Mon 16-01-2**
12	4.1 Requirements arrangement	6 days	Mon 16-01-18	Mon 16-01-2
13	4.2 Templates	6 days	Mon 16-01-18	Mon 16-01-2
14	4.3 Identification	6 days	Mon 16-01-18	Mon 16-01-2
15	4.4 Ranking	6 days	Mon 16-01-18	Mon 16-01-2
16	**5.0 Project plan V1.0**	**7 days**	**Mon 16-01-18**	**Tue 16-01-26**
17	5.1 Scope and boundaries	7 days	Mon 16-01-18	Tue 16-01-26
18	5.2 Organisation	7 days	Mon 16-01-18	Tue 16-01-26
19	5.3 Roles and responsibilities	7 days	Mon 16-01-18	Tue 16-01-26
20	**6.0 Iteration 2**	**1 day**	**Wed 16-01-27**	**Wed 16-01-2**
21	6.1 System to subsystem	1 day	Wed 16-01-27	Wed 16-01-2
22	6.2 Functional model	1 day	Wed 16-01-27	Wed 16-01-2
23	6.3 Key performance parameters	1 day	Wed 16-01-27	Wed 16-01-2
24	6.4 Technical budget	1 day	Wed 16-01-27	Wed 16-01-2
25	6.5 Review and make plan	1 day	Wed 16-01-27	Wed 16-01-2
26	**7.0 Requirement specificaton V2.0**	**5 days**	**Wed 16-01-27**	**Tue 16-02-02**
27	7.1 Breaking down requirements	5 days	Wed 16-01-27	Tue 16-02-02
28	7.2 Methode	5 days	Wed 16-01-27	Tue 16-02-02
29	**8.0 Project plan V2.0**	**5 days**	**Wed 16-01-27**	**Tue 16-02-02**
30	8.1 Background	5 days	Wed 16-01-27	Tue 16-02-02
31	8.2 Introduction	5 days	Wed 16-01-27	Tue 16-02-02
32	8.3 Schedules	5 days	Wed 16-01-27	Tue 16-02-02
33	8.4 Deviation and risk management	5 days	Wed 16-01-27	Tue 16-02-02
34	8.5 Scope and boundaries	5 days	Wed 16-01-27	Tue 16-02-02
35	8.6 Stakeholder analysis	5 days	Wed 16-01-27	Tue 16-02-02
36	8.7 Organisation	5 days	Wed 16-01-27	Tue 16-02-02
37	9.0 - Project plan finished	0 days	Tue 16-02-02	Tue 16-02-02
38	**10.0 Test specification V1.0**	**5 days**	**Wed 16-01-27**	**Tue 16-02-02**
39	10.1 Strategy	5 days	Wed 16-01-27	Tue 16-02-02
40	10.2 Methode	5 days	Wed 16-01-27	Tue 16-02-02
41	10.3 Classification	5 days	Wed 16-01-27	Tue 16-02-02

Figure B.1: Gantt part 1

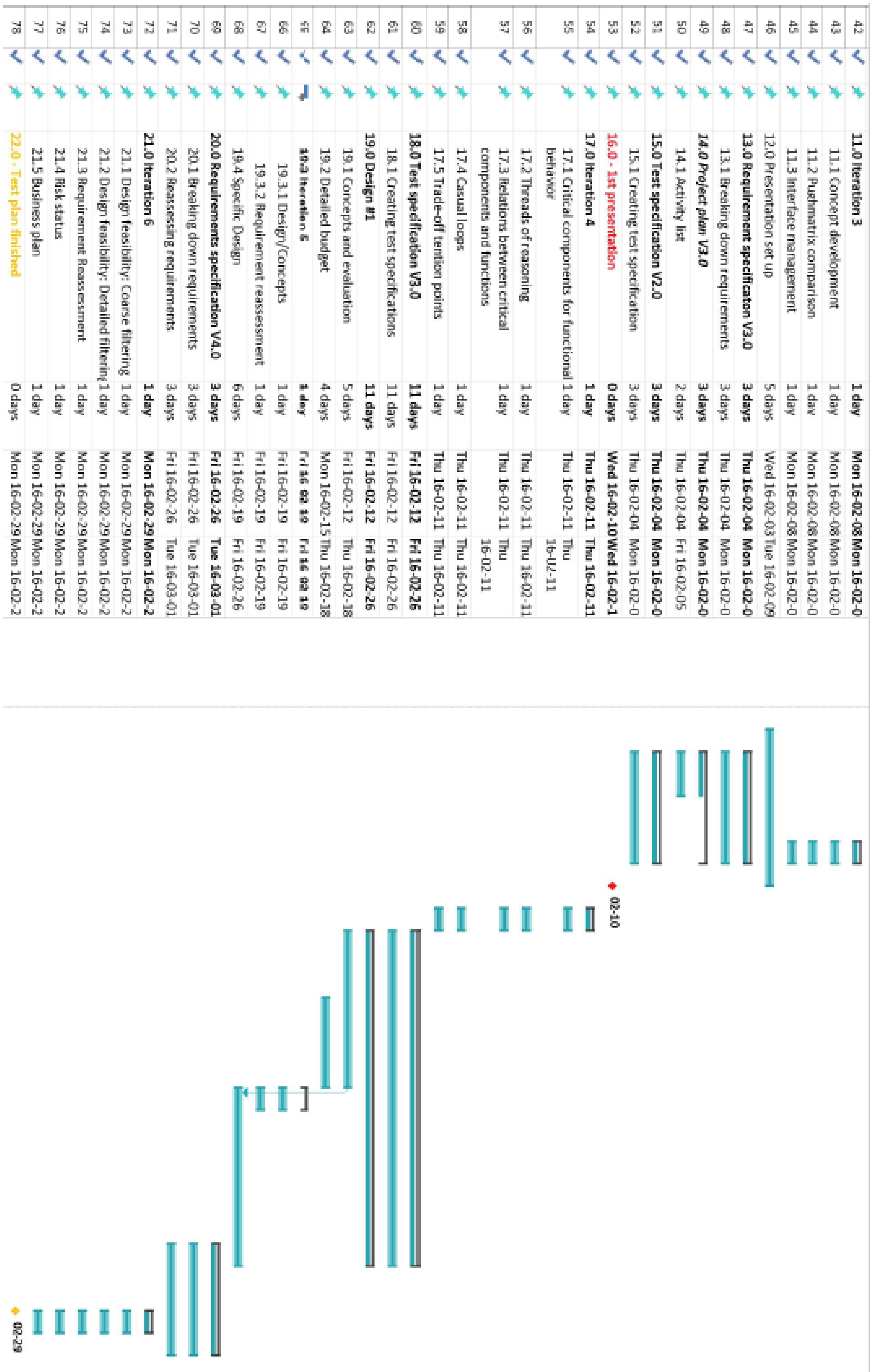


Figure B.2: Gantt part 2

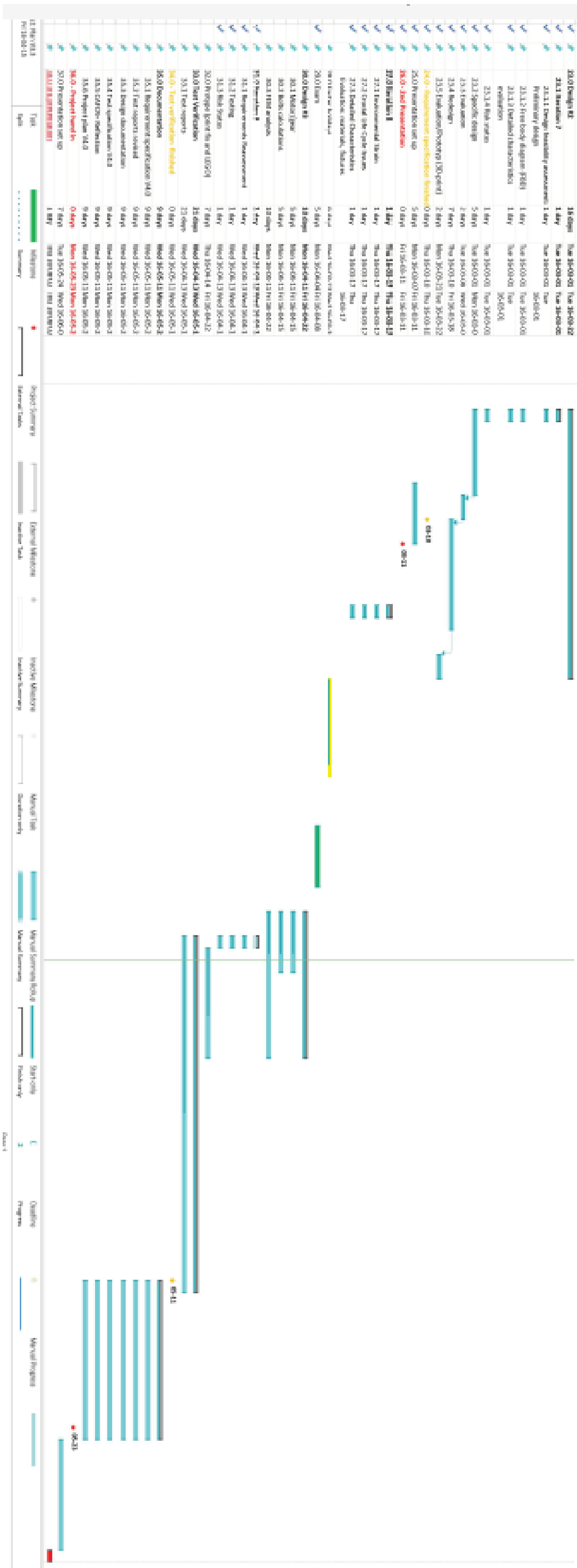


Figure B.3: Gantt part 3

C Requirement Traceability Matrix

	A	B	C	D	E	F	G	H	I	J	
1									REQUIREMENTS TRACEABILI		
2				Requirement							
3	SH ID	STRQ	SRQ	SRQ Description	Type	RPCE Ranking	Allocation	Use Case	Primary interface	DRQ	DRQ
4		STRQ001	SRQ001	The system shall have an azimuth mo	Functional	AAAB					
5		STRQ001,	SRQ002	The system shall have a motor.	Functional	AACB					
6		STRQ001,	SRQ003	The system shall have a solution that	Functional	AABB					
7		STRQ002	SRQ004	The system shall have a minimum azir	Functional	AAAB					
8		STRQ003	SRQ005	The system shall have a maximum azi	Functional	AAAB					
9		STRQ004	SRQ006	The system shall provide an azimuth a	Functional	AAAB					
10		STRQ005	SRQ007	The system shall be able to decelerat	Functional	AABB					
11		STRQ005	SRQ008	The emergency stop system shall be a	Functional	AACB					
12		STRQ012	SRQ009	The system should have an azimuth s	Functional	BBBB					
13		STRQ013	SRQ010	The system should be able to offset tl	Functional	BACC					
14		STRQ014	SRQ011	The system should have a free 360 de	Functional	BCAA					
15		STRQ015	SRQ012	The system should provide an azimutl	Functional	BCAA					
16		STRQ016	SRQ013	The Turret Simulator shall incorporate	Functional	ABCB					
17		STRQ006	SRQ014	The system shall be operable in a tem	Physical	ABBC					
18		STRQ018	SRQ015	The system shall consider a roof stiffr	Physical	AAAB					
19		STRQ020	SRQ016	The system mounting interface to 1	Physical	AABC					
20		STRQ021,	SRQ017	The system shall have a thread less m	Physical	AABC					
21		STRQ022	SRQ018	The system shall be able to withstand	Physical	AABC					
22		STRQ023	SRQ019	The system shall be able to withstand	Physical	AACB					
23		STRQ024	SRQ020	The system shall be able to withstand	Physical	AABB					
24		STRQ025	SRQ021	The system shall be movable by one p	Physical	AACB					
25		STRQ025	SRQ022	One single part of the system shall ha	Physical	ABCB					
26		STRQ026	SRQ023	The system shall have a maximum we	Physical	AACB					
27		STRQ027	SRQ024	The system shall have a physical mou	Physical	AACB					
28		STRQ027,	SRQ025	The system shall have a solution for tl	Physical	AABB					
29		STRQ028	SRQ026	The system shall have a maximum dia	Physical	AACC					
30		STRQ029	SRQ027	The system shall have a maximum hei	Physical	AACC					

Figure C.1: Requirement Traceability Matrix part 1

H	I	J	K	L	M	N	O	P	Q
	REQUIREMENTS TRACEABILITY MATRIX								
					Testing				
Jse Case	Primary interface	DRQ	DRQ Description	Verification	Validation	ID	Acceptance Criteria	Result	Comment
				Solidworks	High speed camera test		180 degree movement range		
				Calculation	High speed camera test		Speed sensitivity of 1 mrad/s		
				Calculation	High speed camera test		Speed of 60 degrees/s		
				Calculation	High speed camera test		Acceleration of 1 rad/s^2		
				Solidworks FEM					
							Pass / Fail		
				Cross referencing with manual			Pass / Fail		
				Solidworks FEM	Bolt test		130 Nm preload torque without permanent defor		
							Hole pattern complies with appendix XX		
				Solidworks FEM	Bolt test		200 Nm preload torque without permanent defor		
				Solidworks FEM			FEM analyses confirmes tolerance with safety fac		
				Calculation					
				Cross referencing with MIL-STD-1472G			Complies with MIL-STD-1472G		
				Solidworks mass p	Weight test		Total weight of 50kg		
				2D drawing cross	Physical mounting test		Hole pattern complies with appendix XX		
				2D drawing	Physical measurement		Diameter of XXmm		
				2D drawing	Physical measurement		Height of XXmm		
				3D model confirm	Physical measurement		Internal free space 50 x 50 x 50mm		
				Cross referencing with appendix XX			Pass / Fail		
				Cross referencing	Physical mounting test		Pass / Fail		
				Cross referencing with tool list			Pass / Fail		
				Cross referencing with tool list			Pass / Fail		
				Cross referencing	Physical mounting test		Pass / Fail		
				Cross referencing with budget					
				Calculation	High speed camera test		Speed of 120 degrees/s		

Figure C.2: Requirement Traceability Matrix part 2

D Stakeholder Matrix

STAKEHOLDER MATRIX							
Stakeholder ID	Categor	Concern	Origin	STRQ ID	Stakeholder Requirement	System requirement/ action for adressing concern	Status
HSN	Non-functional	Time	OMS	na	Documentation and presentation of results shall be presented by end of May 2016	Gantt diagram, running documentation	Fulfilled
KPS A	Non-functional	Confidenciality	KPS A	na	All group members must sign Consent of Confidentiality	Consent of Confidentiality signed by all group members per 18.01.2016	Fulfilled
KPS A	Non-functional	Confidenciality	KPS A	na	All group members must attend safety briefing at KPS	Safety briefing attended by all group members per 29.01.2016	Fulfilled
KPS A	Non-functional	Supply Chain	KPS A	STRQ007	The system components shall comply with the KPS supply chain requirements	SRQ058	Fulfilled
KPS HSE	Secondary	Safety	OMS	na	Handling of system must be safe for all users	SRQ021, SRQ022, SRQ008	Verified
KPS S	Functional	Performance	KPS S	STRQ001	The system shall have an azimuth movement range from -90 to +90 degrees	SRQ001, SRQ002, SRQ055, SRQ025	Verified
KPS S	Functional	Performance	KPS S	STRQ002	The system shall have a minimum azimuth speed of 1 mrad/sec	SRQ002, SRQ004	Verified
KPS S	Functional	Performance	KPS S	STRQ003	The system shall have a maximum azimuth speed at least 60 degrees/sec	SRQ002 SRQ005	Verified
KPS S	Functional	Performance	KPS S	STRQ004	The system shall provide an azimuth acceleration of 1 rad/sec^2	SRQ002, SRQ006	Verified
KPS T	Functional	User-friendly	KPS T	STRQ005	The system shall have an emergency stop function	SRQ056, SRQ008	Open
KPS T	Functional	Performance	KPS T	STRQ006	The system shall be operable in the lab used by KPS	SRQ014	Verified
KPS T	Functional	Complexity	KPS T	STRQ008	The system shall be mountable onto the Moog Motion Table without any permanent change to motion table	SRQ017	Verified
KPS T	Functional	Complexity	KPS T	STRQ009	The system shall be mountable onto the Moog Motion Table with the equipment available in the current lab	SRQ017	Verified
KPS T	Functional	Performance	KPS T	STRQ010	The system shall be possible to mount onto a pedestal with the equipment available in the current lab	SRQ017	Verified
KPS T	Functional	Performance	KPS T	STRQ011	The system shall be possible to mount onto the existing pedestal without any permanent change to the pedestal	SRQ017	Verified

Figure D.1: Stakeholder Matrix

E Risk Matrix

	Type	Risk ID	What	Origin	Strategy of acti	Likelihood	Severity	Detectability	Sum of rating	Likely phase of occu	Mitigation strategy
1	RISK MANAGEMENT MATRIX				Rating						
16	Environment	R14	Customer dissatisfied with process or project outcome	KPS, HSN	Protect	C	A	B	CAA	Phases 2-10	validation of requirements with stakeholders throughout the project life-cycle.
17	Environmer	R15	New requirements appear during the project life-cycle	Group members	Accept	B	B	B	BBB	Phases 3-8	validation of requirements with stakeholders throughout the project life-cycle.
18	Environmer	R16	Loss of KPS access card	KPS	Protect	C	B	C	CBC	All phases	Precautiously always keep access card hidden underneath clothing when outside KPS area. Never lend an access card to people external to the project. No public talking about holding a KPS acess card.
19	Environmer	R17	Violation of KPS' Consent of Confidentiality	KPS	Protect	C	A	B	CAB	All phases	Never use uncertified storage devices on KPS computers. Use wireless network when using private computer at KPS; never connect cables to KPS ports.
20	Financial	R18	Budget does not support suggested concepts	KPS	Avoid	C	B	B	CBB	Phases 5-6	Meeting arranged to present various concepts to KPS and to get feedback on each concept with regards to their budget.
21	Financial	R19	KPS budget not given	Group members	Accept	A	B	C	ABC	Phases 3-4	Meeting arranged to present various concepts to KPS and to get feedback on each concept with regards to their budget.
22	Financial	R20	Lack of knowledge about budgeting and prices	Group members	Accept	A	C	C	ACC	Phases 5-6	Check prices on main constituents of designed system for an overall estimate of price.
23	Life-cycle	R21	Incongurency in technical trade-offs	Group members	Protect	B	B	B	BBB	Phases 5-8	Meeting arranged to present various concepts to KPS and discuss concepts with regards to requirements.
24	Life-cycle	R22	Long delivery time of system parts	KPS	Protect	C	B	B	CBB	Phases 5-8	System requirements for following KPS supply chain
25	Life-cycle	R23	Acquisition of parts is challenging	KPS	Protect	C	A	B	CAB	Phases 5-8	System requirements for following KPS supply chain
26	Life-cycle	R24	Delivery of wrong system parts	KPS	Accept	C	C	C	CCC	Phases 6-8	Provide clear specifications of wanted parts in orders. Clearly check shipping documents from suppliers.
27	Life-cycle	R25	Mechanical failure of system during testing or	Group members	Protect	B	A	B	BAA	Phases 6-8	Design with safety factors.

Figure E.1: Risk Matrix

F SWOT

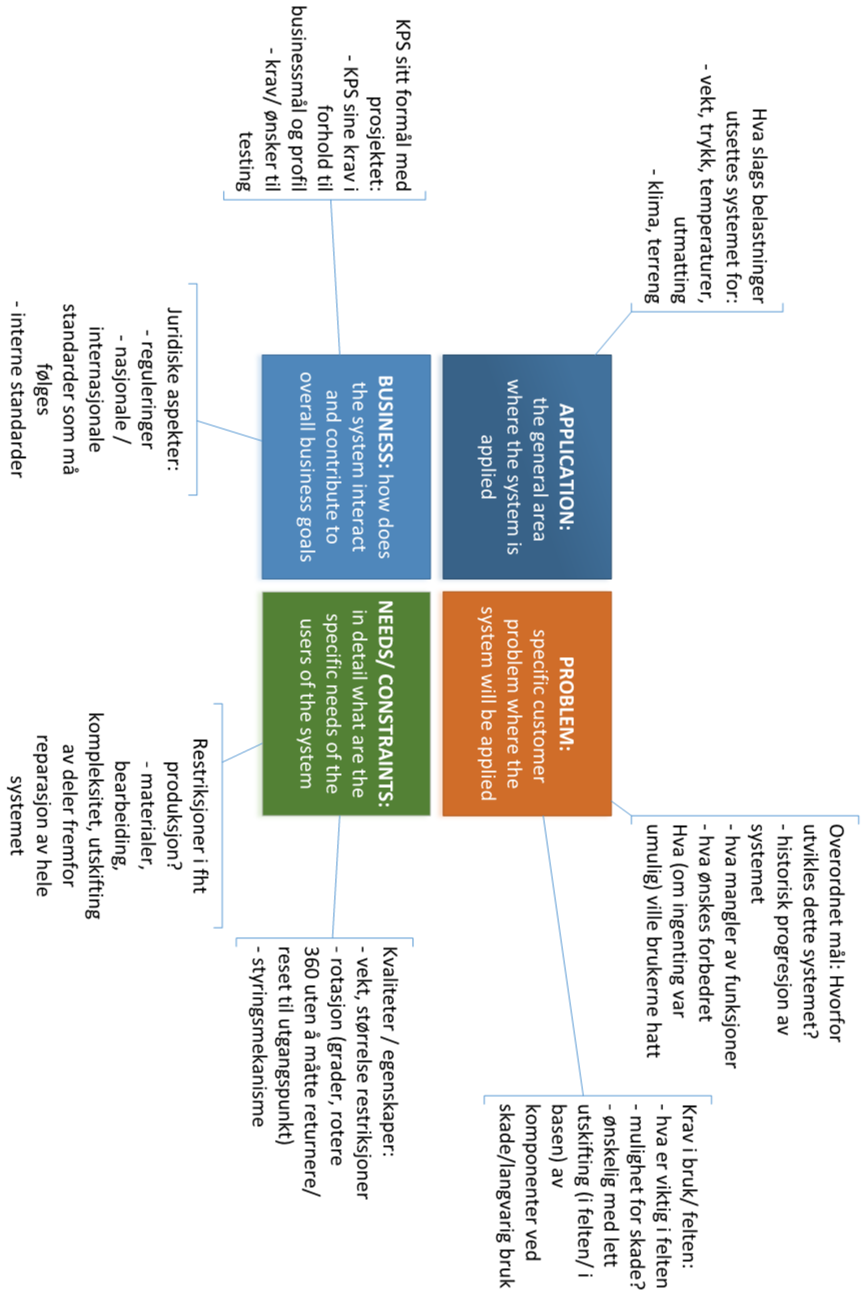


Figure F.1: SWOT Diagram for development of initial questions for requirements

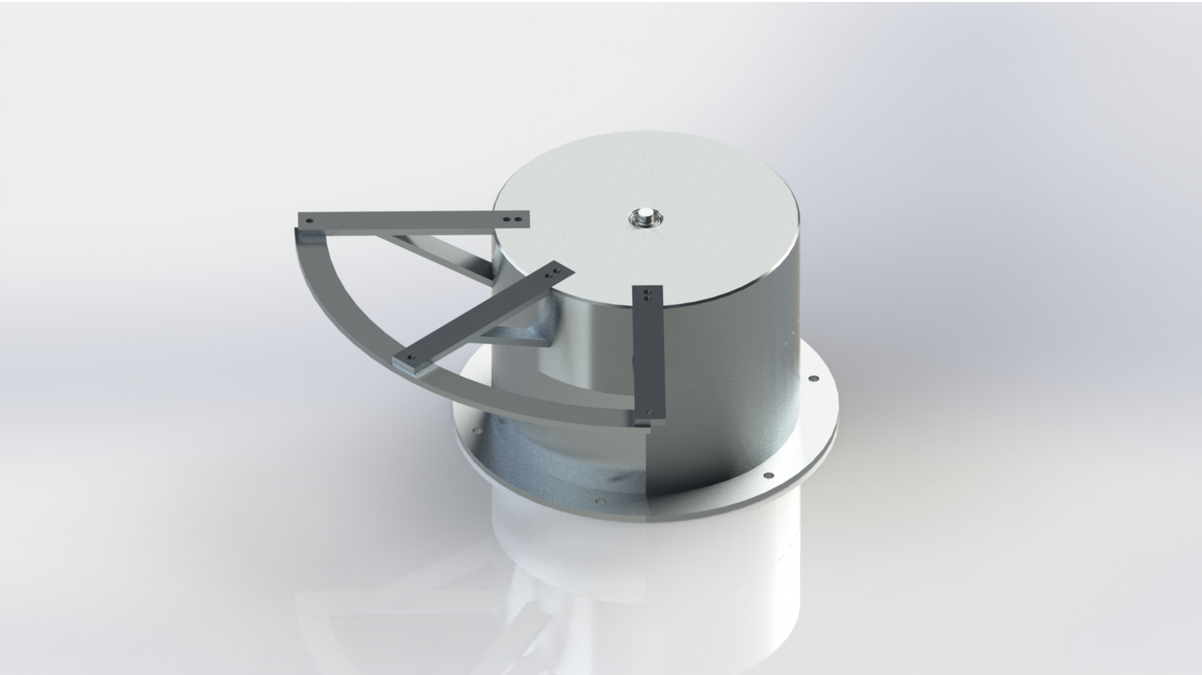
G Initial Offset Concepts

Assembly of RWS on turret

The RWS has threaded holes used to fasten it to vehicles. In order to fasten the RWS to the simulator, screws will go trough the OMS and into the RWS's threaded holes from underneath, effectively locking the RWS on to the simulator.

As a consequence of the interface between the turret simulator and the RWS it is expedient to consider how to fasten the RWS from underneath. The design has to make room for the RWS to be fastened with the bolt heads being protruding through the offset disc towards the surface of the power train disc.

G.1 Understøttet Arm



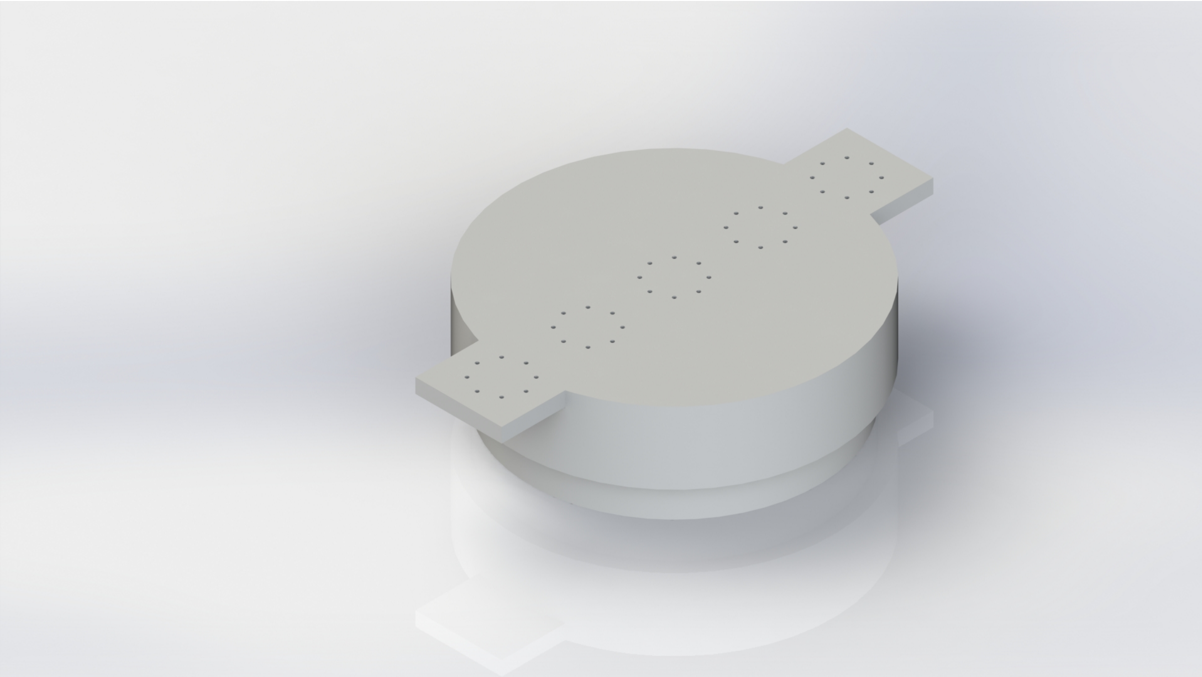
Description

The main functionality for this concept was to give sufficient support to a offset system. The idea was to use three support beams connected to an arched beam. This would then give support to the offset plate which would hold the RWS. The three beams was intended to be welded to the rotating top of the system and the offset plate would be bolted in place to the arched beam and the top part of the rotating system.

The pros of this system is its ease of manufacturing as the geometry and design of the concept is simple.

The offset-system would be threaded holes in the plate mounted on top of the bearing beams. A con with this system is it would work perfectly when the RWS is offset, but when you put the RWS at the center of rotation fixing it to the plate would not be possible without disassembling the OMS.

G.2 Hamburger 1



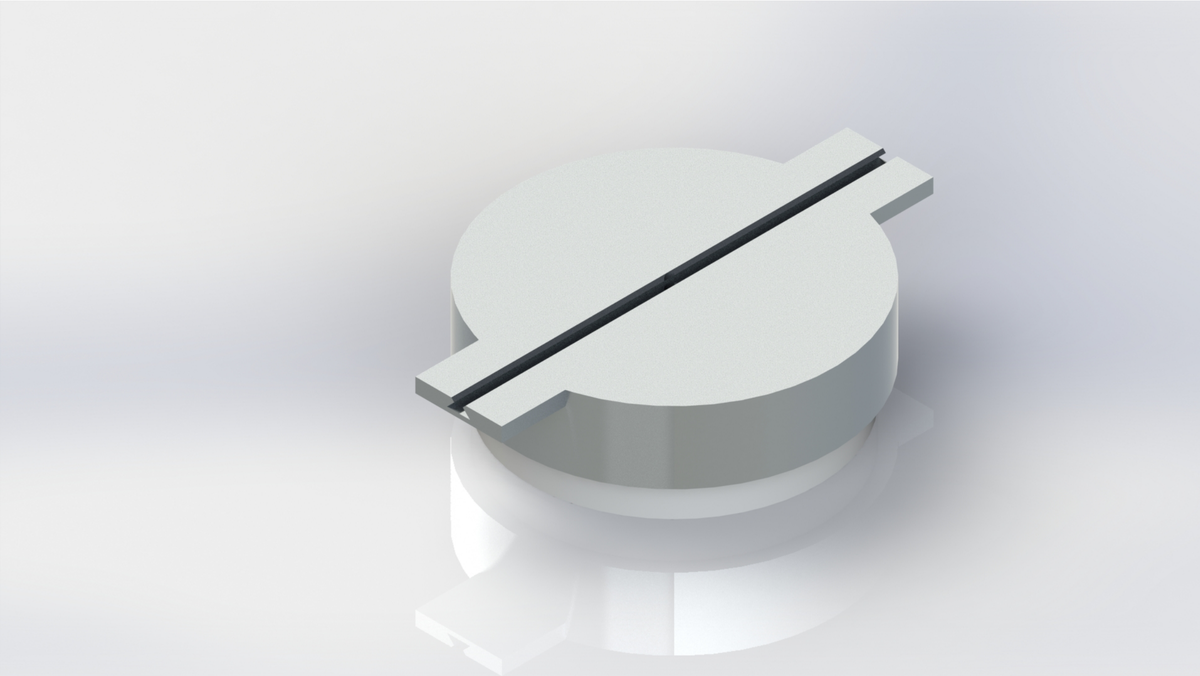
Description

This concept consists of two discs in a concentric assembly, where the top disc can rotate freely. The geometry of this system is very simple, making it easy to manufacture. The top disk will have multiple hole-patterns aligned across the center of rotation.

This setup has multiple fixed offsets. A consequence is the need to manually remove each bolt between the RWS and OMS, to change the offset and then fasten the bolts again. This operation will most likely require a crane to move the RWS as it weighs more than 50 kg.

One obvious drawback of this concept is that the assembly is more time consuming. First you will need to separate the top and bottom of the OMS. Then the top has to be fitted to the RWS with screws. Then the top fitted to the RWS will be mounted on the OMS again. Another weakness of this setup is when the RWS is mounted without offset. As the RWS will then block the center of rotation making it harder to to fit a cable slip-ring as this have to be placed at the center of rotation.

G.3 Hamburger 2

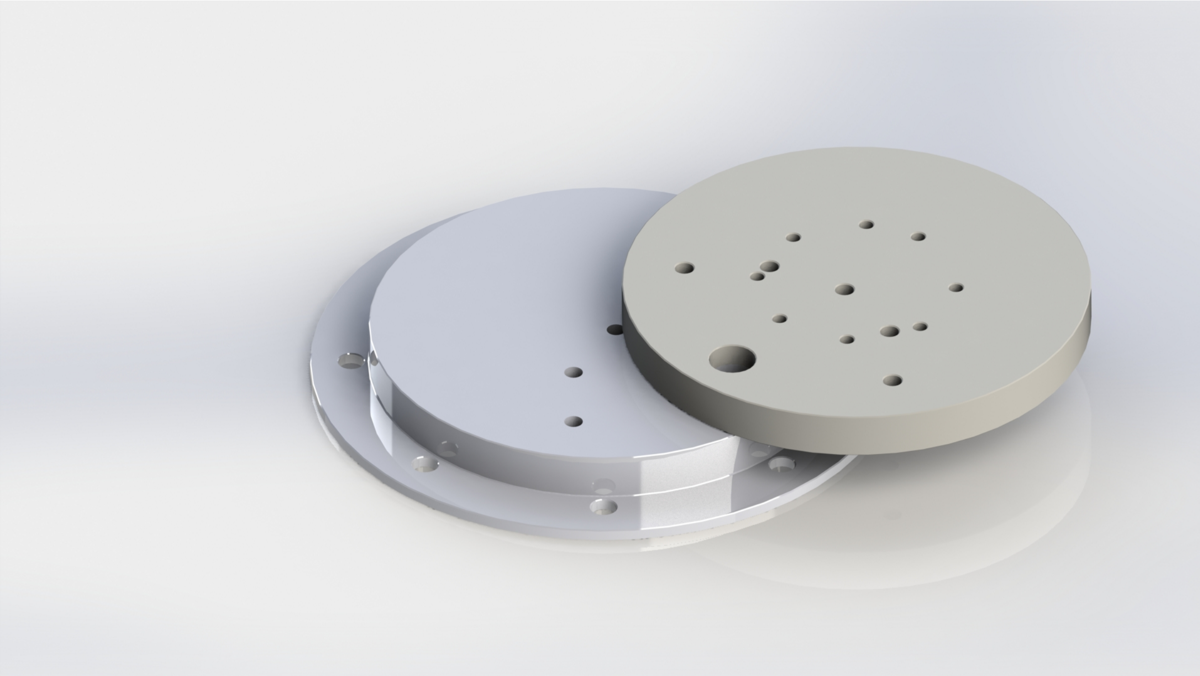


Description

This concept is based on G.2, but instead of having the top fitted with multiple hole-patterns to mount the RWS on, we have a rail-system that can support free offset. This setup makes it possible to change the offset without removing the RWS from the OMS.

As with concept G.2, the geometry is still very simple and easy to manufacture, but it requires a solution on how to fix the RWS to the groove. This solution should also adress the problems identified with concept G.2 in terms of interface between OMS and RWS. There is also a need for a mechanism to lock the RWS in place before simulation.

G.4 Double Discus



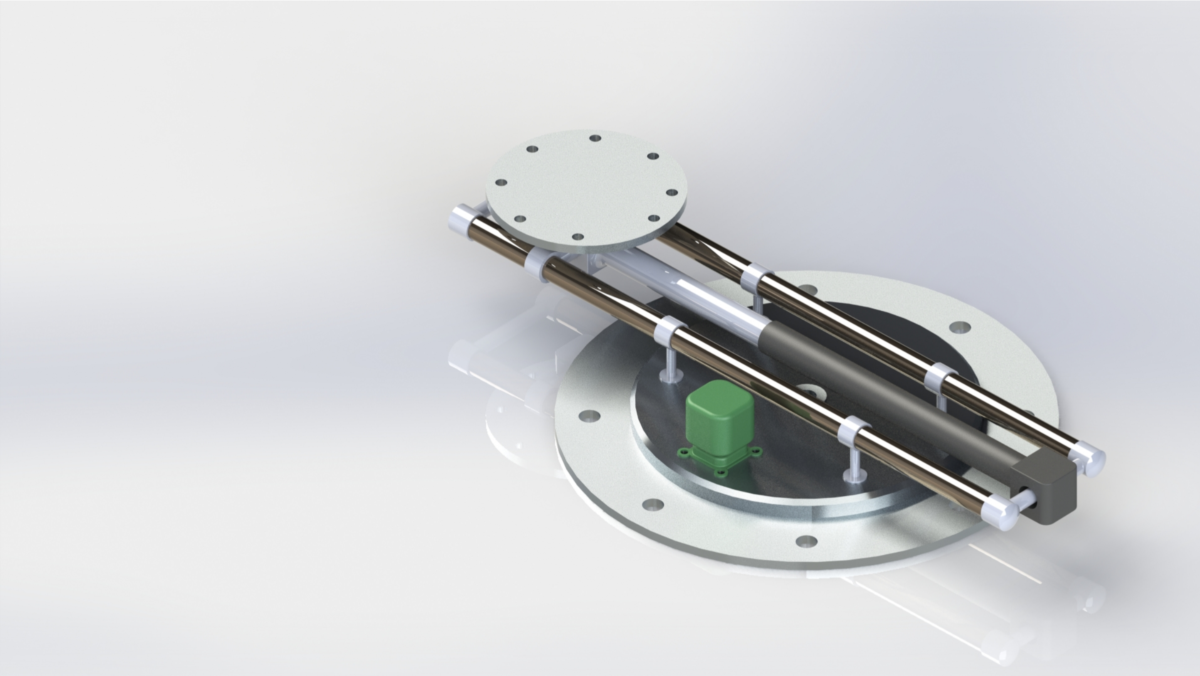
Description

Similar to concepts G.2 and G.3, however the top that is freely rotating consists of two discs connected at an axis that is not at the center of turret-rotation. Hence the name double discus. These two discs can be rotated creating a variable offset from the OMS' center. There will be multiple holes in the top discus with matching threaded holes in the bottom discus, in order to lock the offset.

The beauty of this concept is that it is reducing the actual moment arm of the offset. The discus' can slide on each other using a low friction surface material. Or alternatively be placed on bearings and adding a gap between the discuses. The bearing option will make wiring easier.

The double discus also solves some of the problems of G.2 and G.3 in terms of assembly. If you turn the discs to get maximum offset, the underside of the holes used to fasten the RWS is exposed. Making assembly a lot less complicated.

G.5 Hydraulic slider

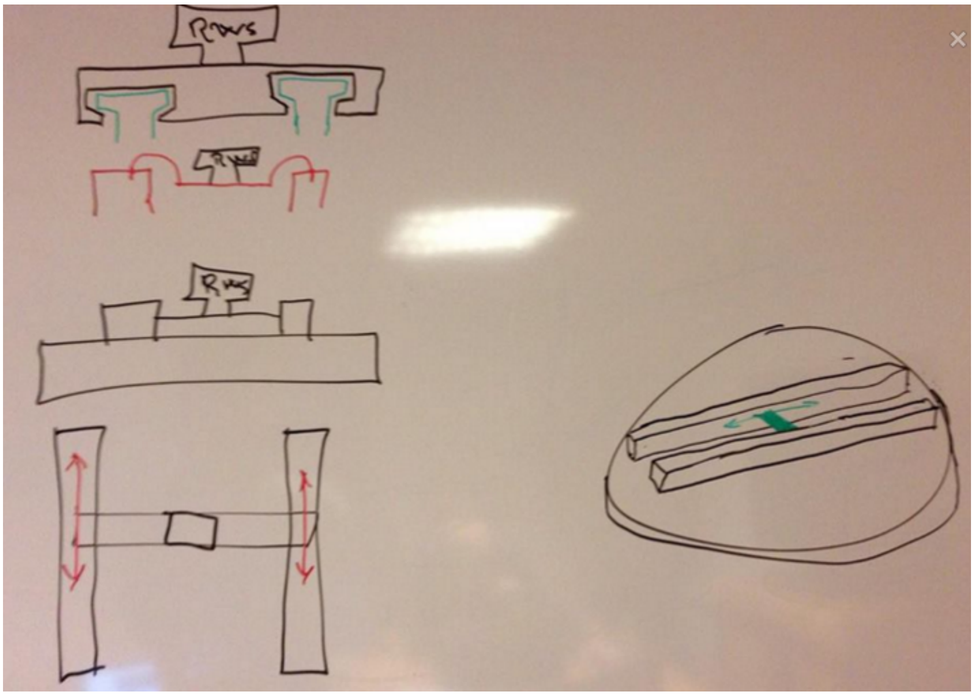


Description

The mounting interface's offset will be controlled by a hydraulic cylinder. The Mounting interface will be connected to the hydraulic cylinder and slide on two sliders. This concept has free offset and the hydraulics will take care of locking the mounting interface to a certain offset.

Adding a hydraulic adds to the complexity of the system. As you will need a pump and container for the fluid. There is also the added maintenance that comes with hydraulics.

G.6 Havnekran



Description

This concept is inspired by a rail mounted stacking crane, used at ports all around the world. The RWS mounting interface will travel along two rails, giving the system free offset.

The RWS can be moved along the rails either using a motor or some manual interface.

By placing the RWS on rails, there will be enough room under the mounting interface to fasten the RWS from below.

G.7 Telescope arm

Figure G.1: An example of a simple telescopic arm [22]

Description

A concept based on the functions of a Telescopic loader. The RWS interface is connected to an arm, which can move in a linear path. This will change the RWS' offset and it can be adjusted as desired. This movement can come from either hydraulic/ electric pistons or in a more conventional way such as manual operation. The hydraulic/ electric solution requires more components which cause the complexity to increase.

Since the RWS interface plate is located at the end of the telescope arm, the RWS can easily be mounted in the same way as concept G.4.

G.8 Design Evaluation Matrix

Design Evaluation Matrix																				
	Coarse Filtering						Detailed Filtering													
Concept Name	Cost	Function	Complexity	User Friendliness	Maturity of Technology	GO / NO GO	Manufacturing Cost		Weight		Complexity		Off-set increments		Ease of assembly		Expertise		Sum	Weighted Sum
Criteria weight	1	1	1	1	1			10		15		15		15		25		20		
Understøttet arm	☺	😐	☺	😐	☺		4	40	3	45	4	60	2	30	2	50	4	80	19	305
Hamburger 2	😐	☺	☺	☺	☺		4	40	3	45	3	45	4	60	3	75	5	100	22	365
Hamburger 1	☺	😐	☺	😐	☺		3	30	3	45	5	75	2	30	1	25	5	100	19	305
Roterende arm 2	😐	😐	☺	😐	☺		-		-	-	-	-	-	-	-	-	-	-	-	-
Roterende arm 1	☺	😐	☺	😐	☺		5	50	5	75	4	60	2	30	2	50	4	80	22	345
Dobbel Discus	😐	☺	😐	☺	☺		4	40	2	30	4	60	3	45	5	125	4	80	22	**380**
Hydrauliske armer	☹	☺	😐	☺	☺		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Robotarm	☹	☺	☹	☺	☺		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hydraulisk/elektrisk glider	☺	☺	☺	☺	☺		2	20	4	60	2	30	5	75	4	100	3	60	20	345
Tiltet tårn	😐	☺	☹	☺	☺		-		-	-	-	-	-	-	-	-	-	-	-	-
Havnekran	☺	☺	😐	☺	☺		3	30	4	60	3	45	5	75	4	100	4	80	23	**390**
Teleskoparm	😐	☺	😐	☺	☺		1	10	4	60	3	45	5	75	4	100	3	60	20	350
Radiostyrt, induksjonsdrevet RWS	☹	☺	☹	☺	☹		-	-	-	-	-	-	-	-	-	-		-	-	-
Maglev-drevet RWS	☹	😐	☹	☺	😐		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hybridløsning	na	na	na	na	na		3	30	3	45	3	45	5	75	5	125	4	80	23	**400**

Figure G.2: The Design Evaluation Matrix

H Matlab code

Moment of Inertia

Code H.1: Moment of Inertia Script

```
g = 9.81;               %m/s^2
rho = 2700;             %kg/m^3

Hb = 0.040;           %height bearing, m
Dbo = 0.500;        %bearing outer diameter, m
Dbi = 0.360;          %bearing inner diameter, m
Ib = (pi/32)*rho*Hb*((Dbo^4)-(Dbi^4))%inertia of bearing

Db = 0.500;             %oms bottom (lower) diameter, m
Dt = 0.420;             %oms, top/outer diameter, m
Ht = 0.020;             %oms, height top, m
It = (pi/32)*rho*Ht*(Dt^4)

Hr = 0.04;              %ring for feste av lager
Ir=(pi/32)*rho*Hr*((Db^4)-(Dt^4))

Iofs = 0.018976;        %inertia of offset disc from SW, kg*m^2
Mofs = 1.998;           %kg
Rofs = 0.3;             %offset between oms COM and ofs COM, m
Mrws = 250;             %kg
Ipa = Iofs+((Mofs+Mrws)*(Rofs^2)) %paralell axis inertia
Itotal=It+Ib+Ipa+Ir     %kg*m^2
Itot=Itotal*(10^6)      %kg*mm^2

alpha = 1;                          %angular acceleration rad/s^2
omega = 2.095;                      %120 deg/sec (should req, (rad/sec)
torque = Itotal*alpha               %#ok<*NOPTS> %sum torque for rotating parts of oms
torquef = 40;                       %torque caused by friction in bearing
torquetillegg = 400                 %caused by tilt

torquemotor = torque+torquef+torquetillegg      %motor torque
power = torquemotor*omega           %required power of motor, kg*m^2/^2
```

Optimised Inertia

Code H.2: Optimised Moment of Inertia Script

```
g = 9.81;                %m/s^2
rho = 2700;              %kg/m^3

Hb = 0.040;            %height bearing, m
Dbo = 0.500;%          %bearing outer diameter, m
Dbi = 0.360;           %bearing inner diameter, m
Ib = (pi/32)*rho*Hb*((Dbo^4)-(Dbi^4));%inertia of bearing

Db = 0.500;              %oms bottom (lower) diameter, m
Dt = 0.420;              %oms, top/outer diameter, m
Ht = 0.020;              %oms, height top, m
It = (pi/32)*rho*Ht*(Dt^4);

%ring for feste av lager
Hr = 0.04;
Ir=(pi/32)*rho*Hr*((Db^4)-(Dt^4));

Iofs = 0.018976;         %inertia of offset disc from SW, kg*m^2
Mofs = 11.3;             %kg
Rofs = 0.4;              %offset between oms COM and ofs COM, m
Mrws = 250;              %kg
Ipa = Iofs+((Mofs+Mrws)*(Rofs^2)); %paralell axis inertia
Itotal=It+Ib+Ipa+Ir      %kg*m^2
Itot=Itotal*(10^6);       %kg*mm^2


alpha = 6;                       %angular acceleration rad/s^2
omega = 2.095;                   %120 deg/sec (should req, (rad/sec)
torque = Itotal*alpha;             %sum torque for rotating parts of oms
torquef = 50;                     %torque caused by friction in bearing
torquetillegg = 520;                     %caused by tilt
torquemotor = torque+torquef+torquetillegg     %required motor torque
power = torquemotor*omega         %required power of motor, kg*m^2/^2
```

Bolt calculations

Code H.3: Axial Force on Bolts

```
%%%% M12 %%%%

T = 130000;         %pre−torque , (Nmm)
dm = 11.063;        %middel diameter (mm)
mu = 0.6;           %coefficient of friction
a = pi/6;           %thread angle (rad)
P = 1.75;           %thread raise
s = 19;             %nominal width
dh = 12;

rm = dm/2;          %(mm)
etta = 180*(atan(mu/cos(a)))/pi  %input required in degrees
theta = 180*(atan(P/(pi*dm)))/pi %input required in degrees
rmm = (s+dh)/4;                  %r 'm (mm)
et = tan(pi*(etta+theta)/180)

F = T/((rm*et)+(rmm*mu)); %bolt axial force, (N)
FkN= F/1000             %bolt axial force, (kN)
```

I Simulink

Code I.1: Motion table function

```
function t = GT(theta, phi, psi, mass, offset)

%phi    −   Rotation about Y−axis
%theta  − Rotation about X−axis
%psi   −   Rotation about Z−axis
%offset −   m
%mass    −   kg

%Rotation matrices
R_x = [1 0 0; 0 cos(theta) −sin(theta); 0 sin(theta) cos(theta)];
R_y = [cos(phi) 0 sin(phi); 0 1 0; −sin(phi) 0 cos(phi)];
R_z = [cos(psi) −sin(psi) 0; sin(psi) cos(psi) 0; 0 0 1];

A = R_x*R_y*R_z;

```

```
%Vectors
RWS = A(:,1);    %X-Axis can be viewed as the position of RWS in R3
Y_NEW = A(:,2); %Y-Axis
N_OMS = A(:,3); %Z-Axis is the Normal vector to OMS / Motion Table /RWS

G = [0 0 -1]*mass*9.81; %Gravity of RWS as a vector
CENTER_RWS = RWS*offset; %Vector from origo to RWS

C = cross(CENTER_RWS,N_OMS);
F_g = -(dot(C,G)/norm(C))*C; %Contribution form gravity

%Deciding if F_g works with or against the rotation
Dir = dot((F_g/norm(F_g)),(C/norm(C)));
if (Dir >= 0)
  t = norm(F_g);
else
  t = -norm(F_g);
end
```

Code I.2: Velocity comparator

```
function [T_m, Alpha]= initial(A,I,sumtorque,vref,v,t)
%T_m          -    Output: Motor torque
%Alpha        -    Output: Angular acceleration
%A            -    Input: Acceleration goal
%I            -    Input: Inertia of the system
%sumtorque    -    Input: Torques working on the system
%Vref         -    Input: Reference velocity
%v            -    Input: System velocity
%t            -    Input: Simulation time
T_m = (A * I) - sumtorque;
if (t < 5)
    if (v <= vref)
        Alpha = 0;
    else
        Alpha = (T_m + sumtorque)/I;
    end
else
    Alpha = (sumtorque)/I;
    T_m = 0;
end
```

J Bearing

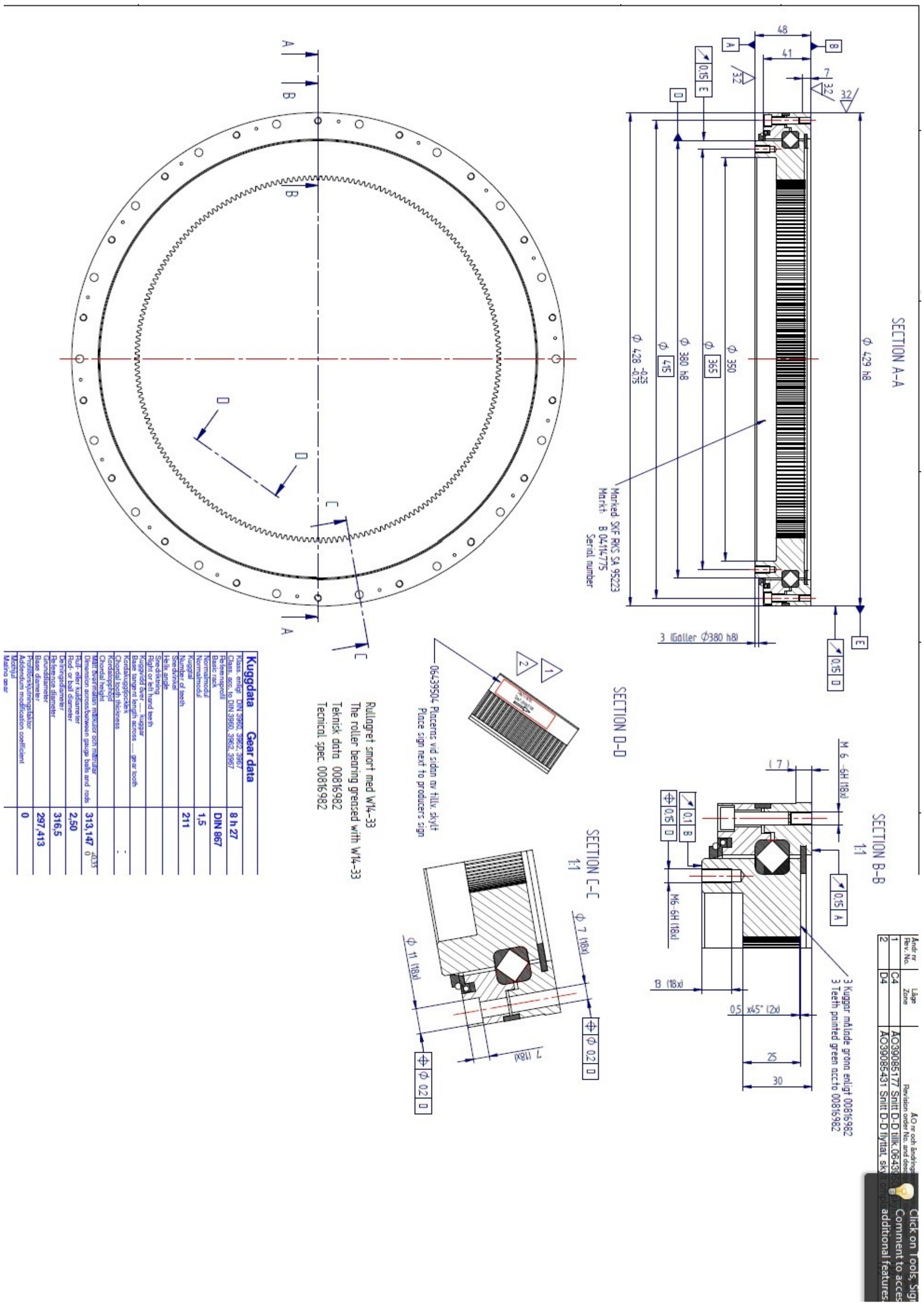


Figure J.1: SKF bearing

K 2D Offset Disc to RWS

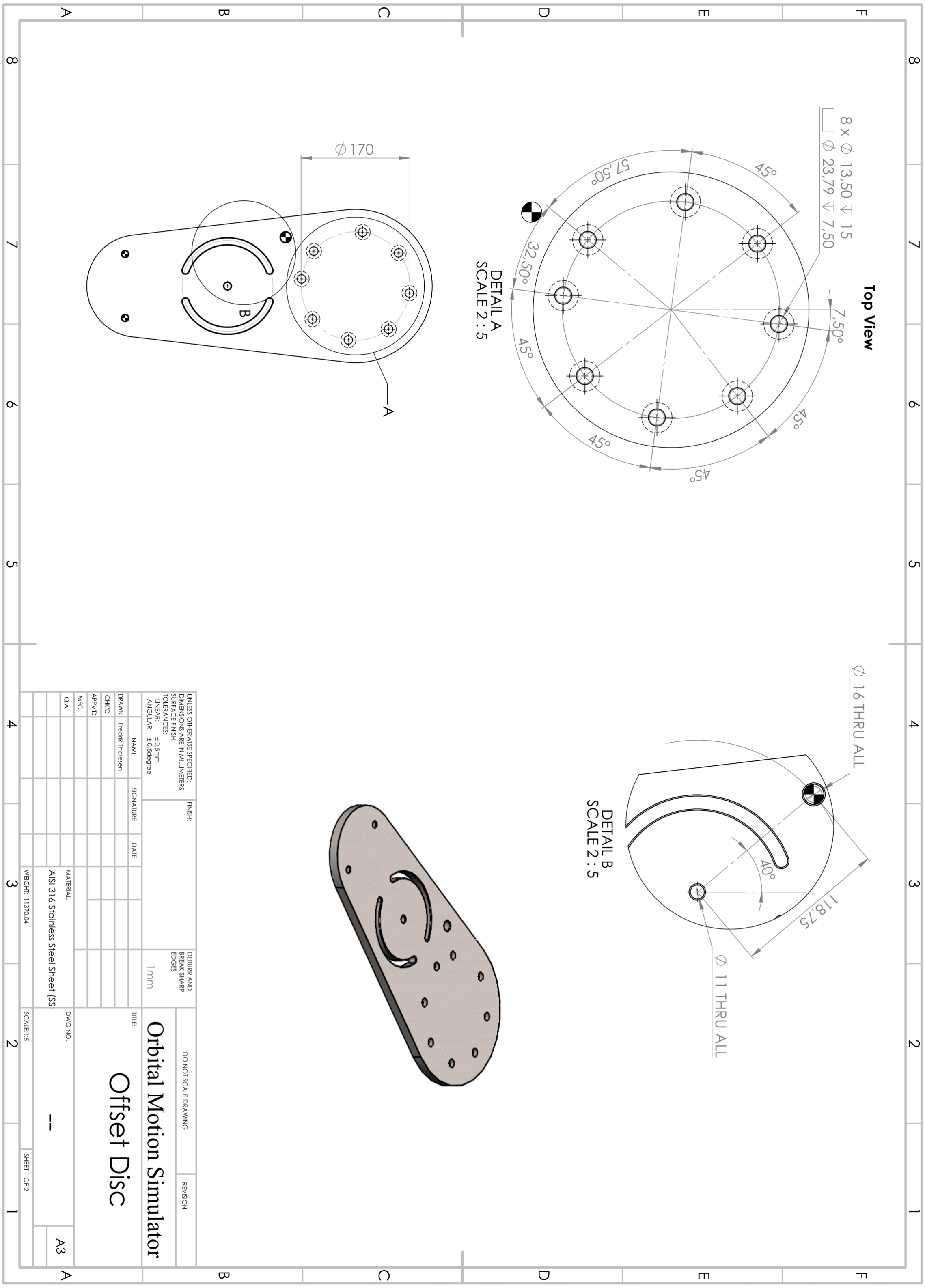


Figure K.1: Offset Disc interface

L 2D Base to motion table

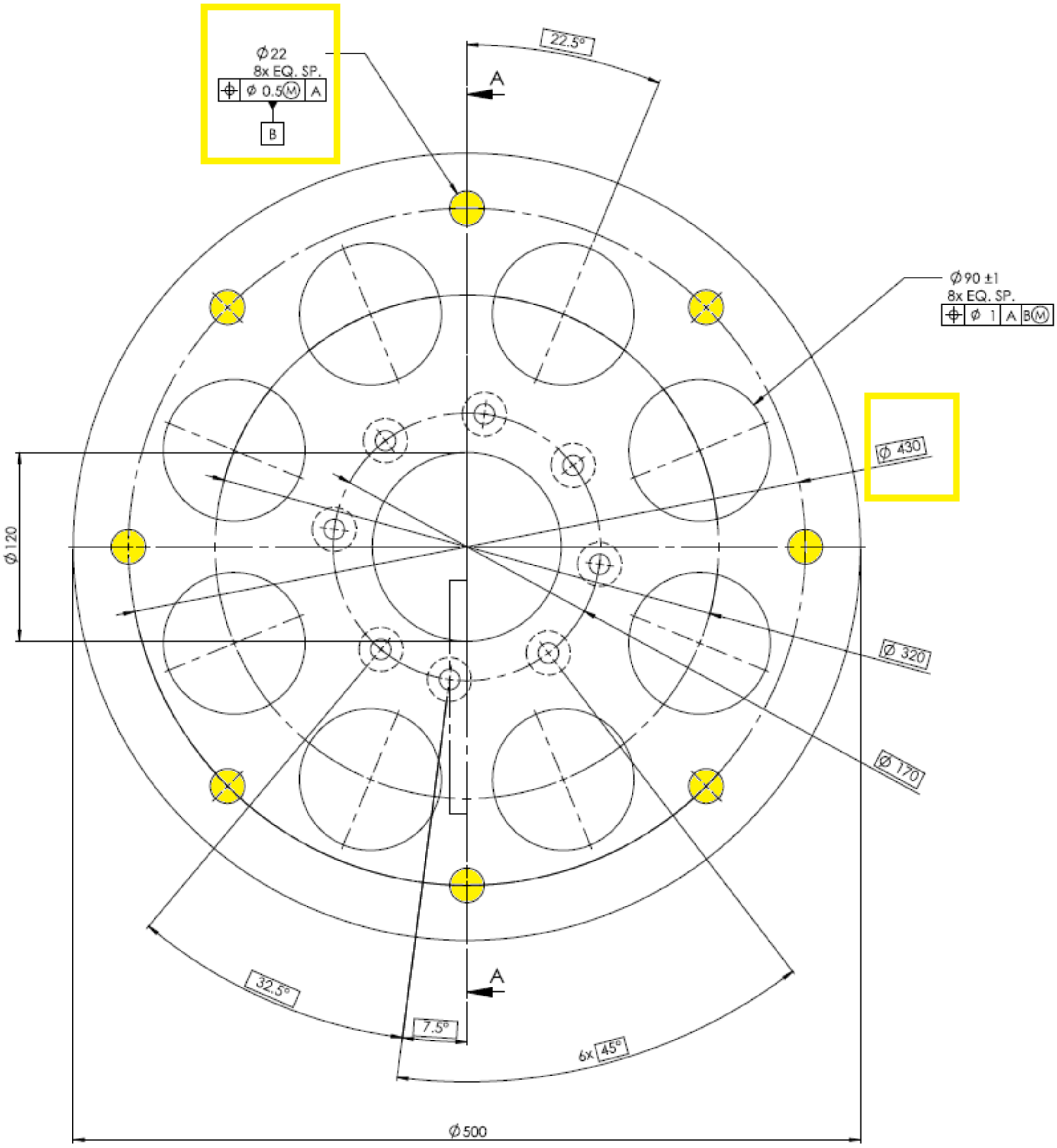


Figure L.1: Motion table interface

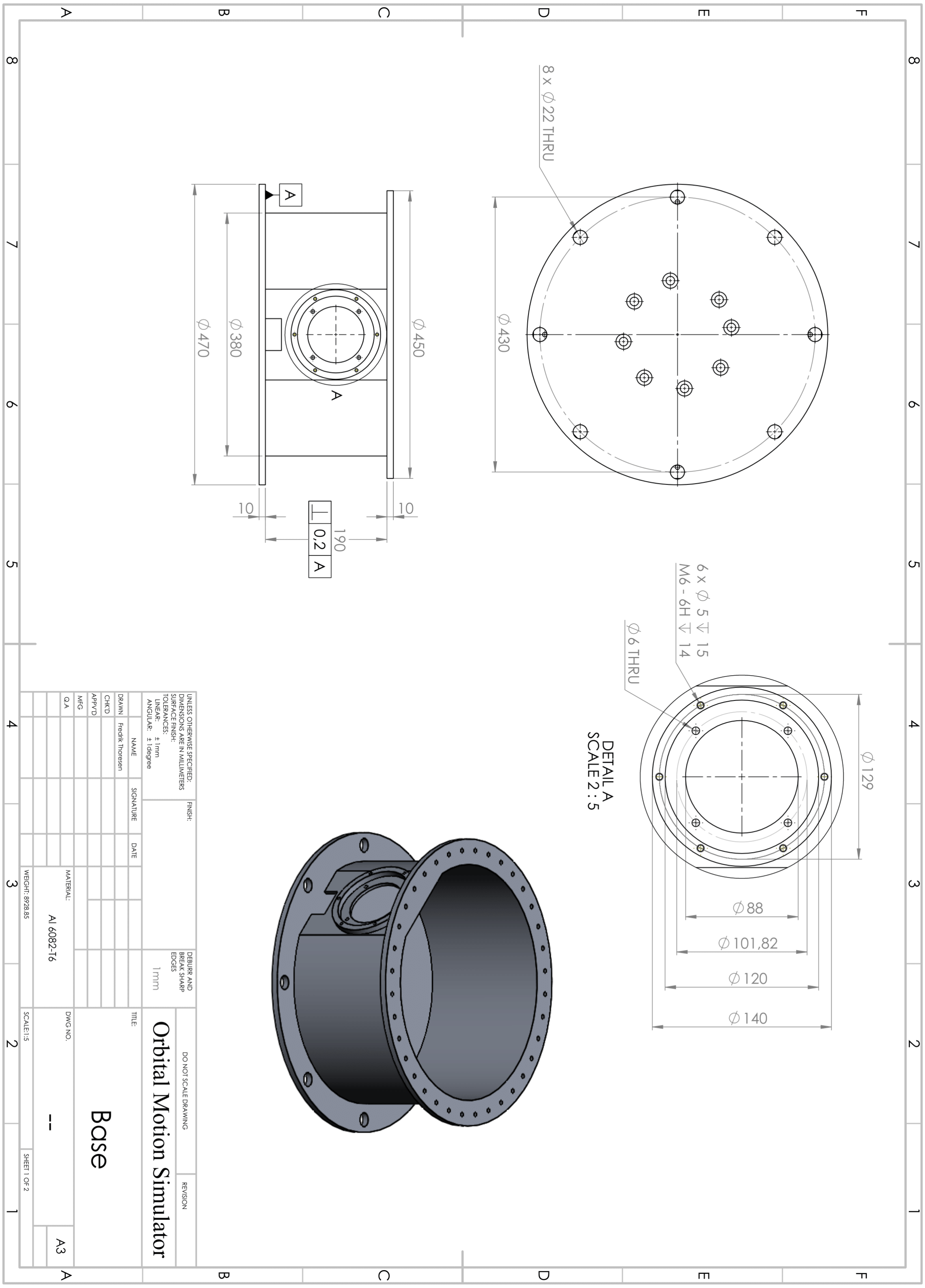


Figure L.2: Base interface to motion table

M Offset Positions

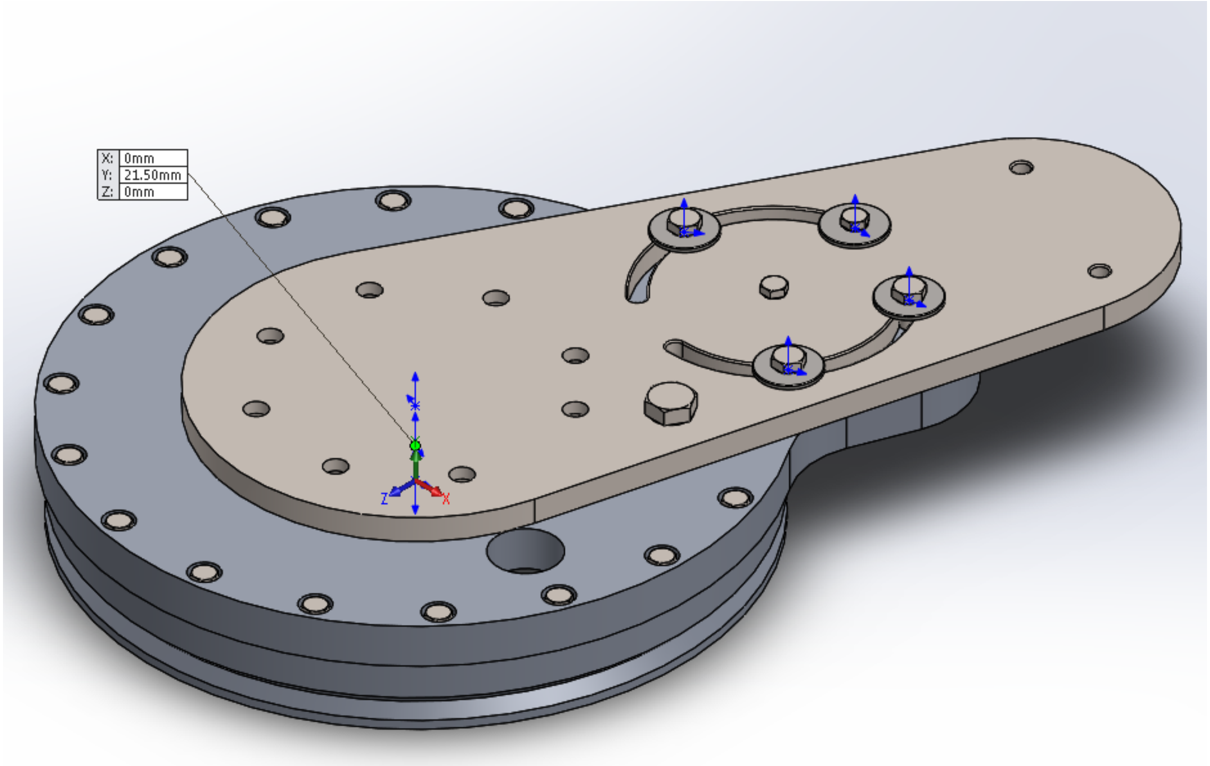


Figure M.1: Center position

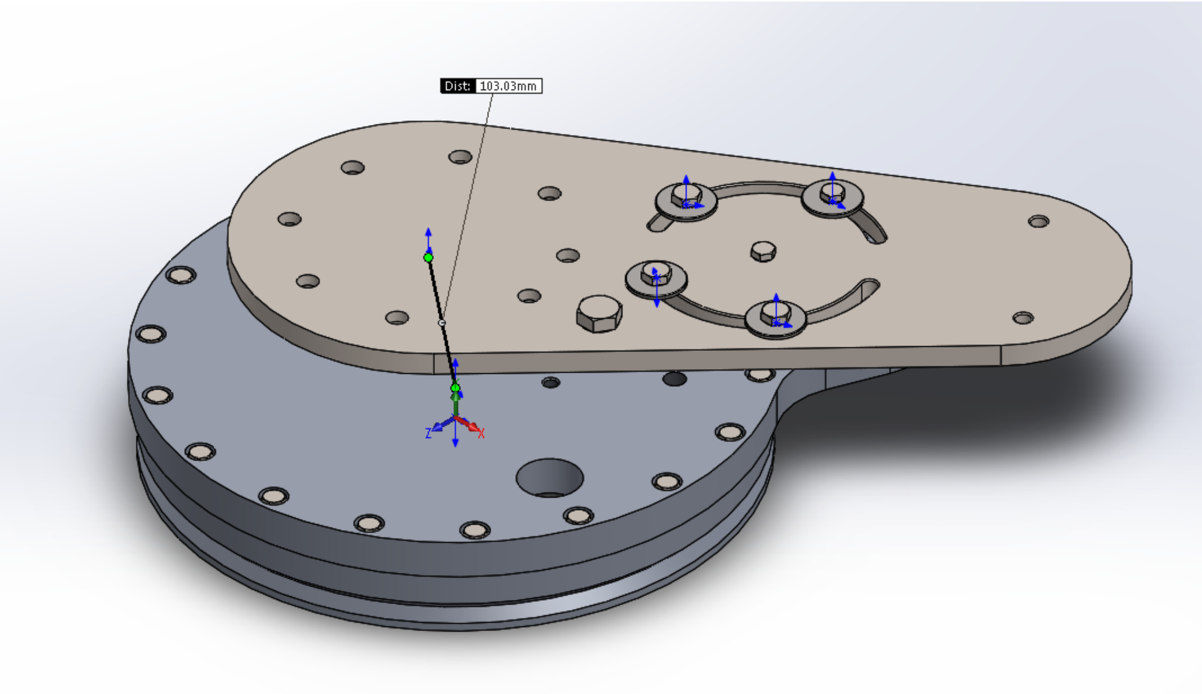


Figure M.2: 10cm offset from center

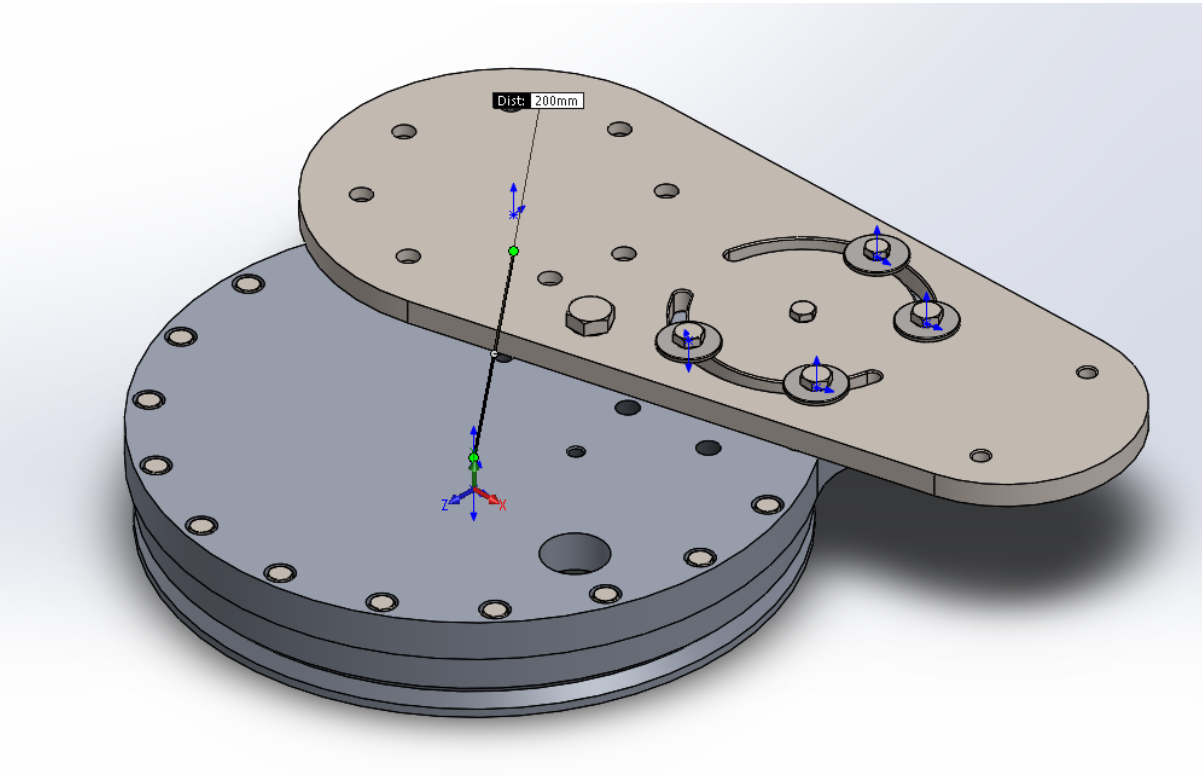


Figure M.3: 20cm offset from center

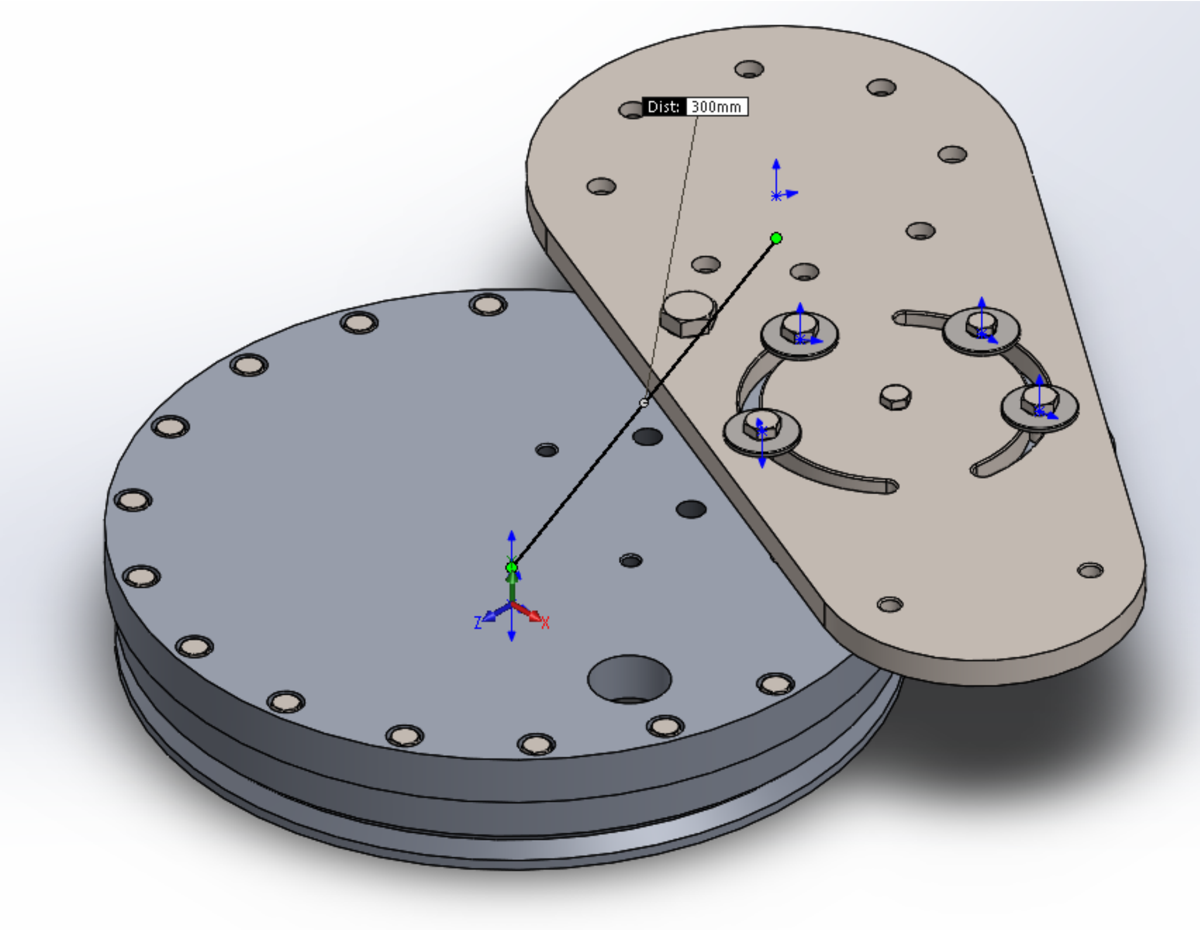


Figure M.4: 30cm offset from center

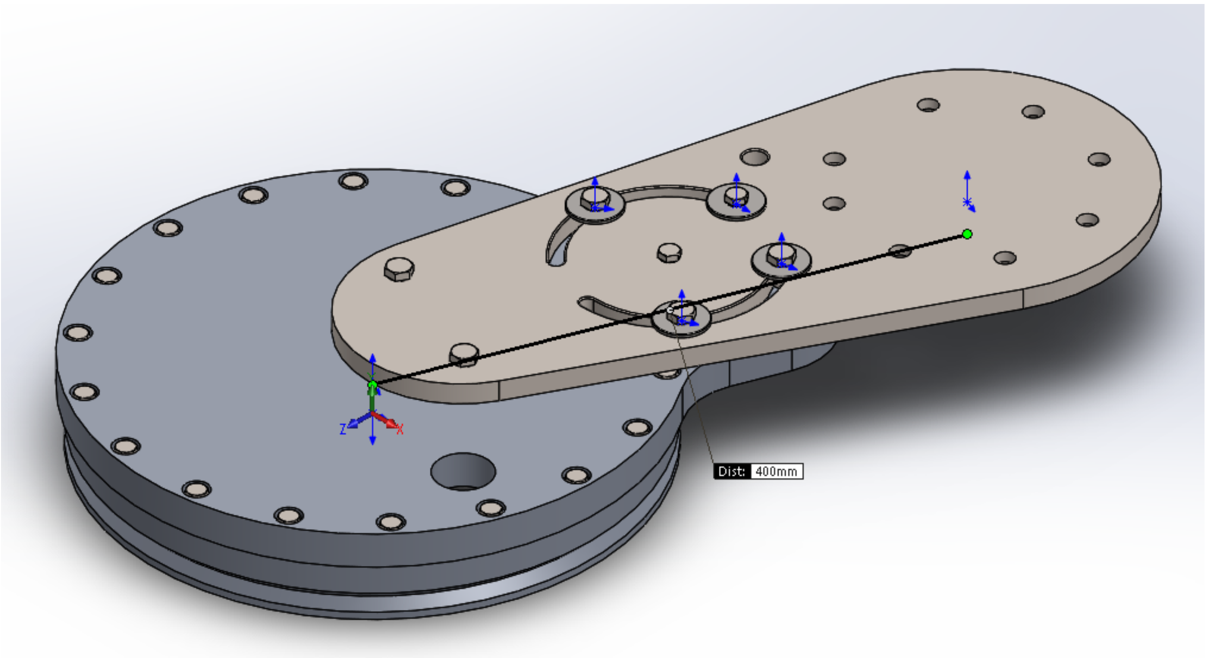


Figure M.5: Full offset position

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