Sensur av hovedoppgaver

Høgskolen i Sørøst-Norge
Fakultet for teknologi og maritime fag

Prosjektnummer: **2017-09**
For studieåret: **2016/2017**
Emnekode: **SFHO3201**

Prosjektnavn
Drone med sentral driftsenhet
Unified Collective Pitch Quadcopter

Utført i samarbeid med: Høgskolen i Sørøst-Norge. Fakultet for Teknologi, naturvitenskap og Maritime fag. Institutt for realfag og industrisystemer

Ekstern veileder: Ivar Ursin Nikolaisen

Sammendrag: Vi har bygget en drone med fire reimdrevne rotorer som drives av én motor, med utskiftbar motormodul. Dronen er designet for å kunne bruke både elektrisk motor og forbrenningsmotor for modellfly. Dronen styres ved å justere angrepsvinkel på rotorbladene og flyr svært stabilt.

Stikkord:
- Quadcopter
- Single engine
- Collective pitch

Tilgjengelig: JA

Prosjekt deltagere og karakter:

Navn	Karakter
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Severin Myhre	
Ann-Mari Snekkerhaugen	
Joakim Thorvaldsen	
Anastasia Timofeeva	
Daniel Christian Torsvik	

Dato: 9. Juni 2017

________________	________________	________________
Joakim Bjørk	Karoline Moholth	Ivar Ursin Nikolaisen
Intern Veileder	Intern Sensor	Ekstern Sensor

Unified Collective Pitch Quadcopter

PROJECT DOCUMENTATION OVERVIEW	
Project Name	Unified Collective Pitch Quadcopter
Version	3
Number of Documents	8
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik

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Unified Collective Pitch Quadcopter

PROJECT PLAN

Project Name	Unified Collective Pitch Quadcopter
Version	3.0
Number of Pages	27
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Author	Anastasia Timofeeva, Daniel Christian Torsvik

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1 ABSTRACT

The purpose of the project plan is to describe the project planning approach that is used to deliver the intended product. This document includes description of the bachelor group and project, as well as a model to develop the project, risk management connected to risks in the planning stage, activities to be done and time schedule.

2 Document Structure

2.1 Document History

Version	Date	Description	Author
2.0	23.03.2017	Project Schedule figure updated: Gantt charts and Activity List updated, Project Phases moved to the Systems Engineering Document.	Anastasia, Daniel Christian
2.1	18.04.2017	Formatting and figure setting	Severin, Ann-Mari
2.2	19.04.2017	Technical Risk Events figure added, Updated figure 5 (Matrix), Risk Assessment text added, added reference, formatting.	Daniel Christian, Severin
2.3	03.05.2017	Improved 4.4.2, 4.6, 5, 6, 7, figure names updated	Anastasia
2.4	09.05.2017	5.1 Figure updated	Daniel Christian, Anastasia
2.5	15.05.2017	6, 7 sections improved	Anastasia
2.6	18.05.2017	Overall formatting	Anastasia
3.0	23.05.2017	Final version	Anastasia, Ann-Mari

2.2 Abbreviations & Acronyms

A&A	Explanation
HSN	University College of Southeast Norway
UAV	Unmanned Aerial Vehicle
R&D	Research and Development
VTOL	Vertical Take off and Landing
RO1	Remotely Operated 1, classification in accordance with the Norwegian Civil Aviation Authority
CPP	Controllable Pitch Propeller
RPM	Revolutions Per Minute - a measure of frequency of rotation
EL	Electrical Engine
ICE	Internal Combustion Engine
CAFCR+	Project Model Abbreviation: Customer, Application, Functional, Conceptual, Realization, + means Lifecycle

Term	Definition
Project Group	Students who are working under the project
Customer	Employer, University College of Southeast Norway
Project	Task that students received from the customer
System	An unmanned aerial vehicle the project group members are designing
Multicopter	A mechanically simple aerial vehicle whose motion is controlled by speeding or slowing multiple downward thrusting motor/propeller units
Quadcopter	A drone or other aircraft that derives its lift from four vertically oriented rotors
Timebox	A time-box is a fixed amount of time allocated to perform one activity
Iteration	An iteration is an act of repeating a process
Follow-up Document	A document where the project group presents a project overview with the time required/used for the current week and time estimation for the next week
Meeting Minutes	A protocol or, informally, notes. The instant written record of a meeting or hearing

3 INTRODUCTION

The objective of the project given by the University College of Southeast Norway (HSN) is to design an unmanned aerial vehicle (UAV) with a single power source that distributes power out to rotors. Power to the rotors must be transferred mechanically. As there is a restriction to have only one source of power, the system must have a pitch mechanism to manoeuvre the UAV. Pitch mechanism of the rotor blades must also be a mechanical challenge. There are other ongoing project teams at HSN who work under variable pitch, they all focus on different aspects of UAV design.

All our team members are studying Mechanical Engineering at HSN, hence the focus of our project is to perform power transmission and pitch mechanisms mechanically. We are the only project team who deal with collective pitch together with a unified source of power.

There are some other restrictions to the system under the Research and Development (R&D) phase. These requirements come from our customer. The quadcopter must fall into the category RO1, which has general requirements and limitations for a UAV such as it must be of vertical take-off and landing (VTOL) type, its weight must not to exceed 2.5 kg and it must be operated without certificate. More details are described in the System Requirements Document.

4 BACKGROUND FOR THE PROJECT & OBJECTIVES

4.1 MULTIROTOR COLLECTIVE PITCH

One of the overlying challenges of the project besides a unified power source lies in designing a functional controllable-pitch propeller or variable-pitch propeller, which is a type of a propeller with blades that can be rotated around their longitudinal axis to change the pitch angle of the rotor blades [1]. There are many configurations of multirotor UAVs, quadrotors are the most popular, this is because of relatively low cost, simplicity, readily availability and inherent robustness.

The two utilized mechanisms to control a drone movement are by varying the revolutions per minute (rpm) of every single motor with a fixed pitch or by varying angle of attack of a collective pitch mechanism [2].

With a fixed pitch, the blades are held at a fixed or constant angle of attack. You control the amount of lift to your helicopter by simply varying the speed of the engine. If you increase the speed of the motor, the rotor blades turn faster and produce more lift. The reverse happens if you lower the speed of the motor. the drawback is that you have to overcome the rotational inertia of the motors and the rotors. For a fixed pitch rotor to reverse its thrust, the motors must stop and change its rotational direction. This procedure takes more time than a variable pitch rotor would take to reverse its pitch angle, and could results in poor response to changing wind conditions, and more sluggish performance.

With a collective pitch, the pitch or angle of attack of the main rotor blades changes to control lift while the engine speed and rotor speed stays more or less constant. This time when you want to gain altitude, you increase the collective pitch of the rotor blades, and your UAV starts lifting almost instantaneously with no lag time. To stop the rate of climb, you decrease the pitch of the rotor blades and again, the response of the drone is almost immediate. It takes only very small movements of the rotor blade pitch angle to achieve these instantaneous corrections and gives you very precise & immediate control [3].

4.2 POWERTRAIN DESIGN

Multirotor UAVs operate by having several motors (one per rotor). With us going for a collective pitch mechanism, we unite all the motors into one drive unit that distributes power to all rotors synchronously, i.e. they're all running at the same rpm. While hovering, the UAV will be able to quickly adjust blade pitch regardless of wind conditions without almost any increase in motor rpm. Furthermore, by using a single drive unit less power is needed to make directional changes to UAV.

Traditional multirotor UAV's biggest drawbacks is the rapid acceleration of the rotors which puts a significant increase on current drawn by the motors from the battery. Unifying the power source makes it a thing of the past.

There will always be pros & cons on different designs, and we're torn between either high electrical versus high mechanical complexity. We're a project group consisting entirely of mechanical engineering students, we see the mechanical complexity as a challenge to ourselves. Versatility is a huge factor, one of the benefits unifying the power source is that we have a much more adaptable platform which will accept both internal combustion engines and electric motors.

5 PROJECT MANAGEMENT

5.1 PROJECT TEAM

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Responsibility:
Documentation

5.2 Project Roles & Responsibilities

5.2.1 Project Management

Project Manager is responsible for activity planning and sequencing, resource planning and developing schedules. Besides, Project Manager should monitor and report progress, as well as serve as the main contact person for the project group.

5.2.2 Documentation

Documentation Responsible's main tasks include coordination of all documentation within the project, ensure that documents and templates are updated, as well as all documents have a consistent look.

5.2.3 Systems Design and Engineering

System Engineer is responsible for coordination of design, implementation, and integration of a project system, as well as developing and completing actions according to chosen project model.

5.2.4 Risk Management

Risk Manager is responsible for identifying risks within the project, make assessments for risk impacts, analyse risks according to the ranking.

5.2.5 Design & Mechanical Interface

Design Engineer is responsible for research of new developments and innovations, as well as turning those research ideas into technical plans. Besides, Design Engineer should consider effectiveness and safety of new designs and modify design according to project needs.

5.2.6 Testing

Test Engineer is responsible for the test work connected to the project, guiding the work of testing and preparing the necessary test plans.

5.3 Supervisors & Examiners

Internal Supervisor	**Joakim Bjørk** e-mail: Joakim.Bjork@usn.no phone: 31009406/95154961
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5.4 Project Planning

5.4.1 Project Schedule

The project group have developed a Project Schedule, according to which we are organizing our work.

Based on the task at hand, it is important to use an iterative project model to follow. Our group have decided to use CAFCR+ project model in the working process. The model is iterative, and when talking about short-term projects, an iterative model is the best way to achieve the best possible solutions.

From the very beginning we decided to work structured and effective. To accomplish that, it is very important to follow the chosen model. Since we have chosen CAFCR +, we are free to go back to change the iteration tasks, if necessary. Early in the planning it was calculated 8 different iterations as we go through in this bachelor thesis. Each of iterations is carefully planned, both containing tasks, and how long each of the iterations will take.

Detailed information and description of all iterations is provided in the supplementary document called Systems Engineering. This document gives a full overview over the iteration plan, as well as iteration protocol. Documentation is essential in recording all activities undertaken in making decisions during iteration processes.

The estimated project schedule covers everything that the project group will go through this semester. This includes Mechatronics, which is a subject that runs parallel with the

Bachelor's thesis. Under the subject’s exam period, there has been no work on the project paper. Easter holiday is also considered.

You can see a figure 5.1 showing the overview of the project with its main milestones in the second part of the project.

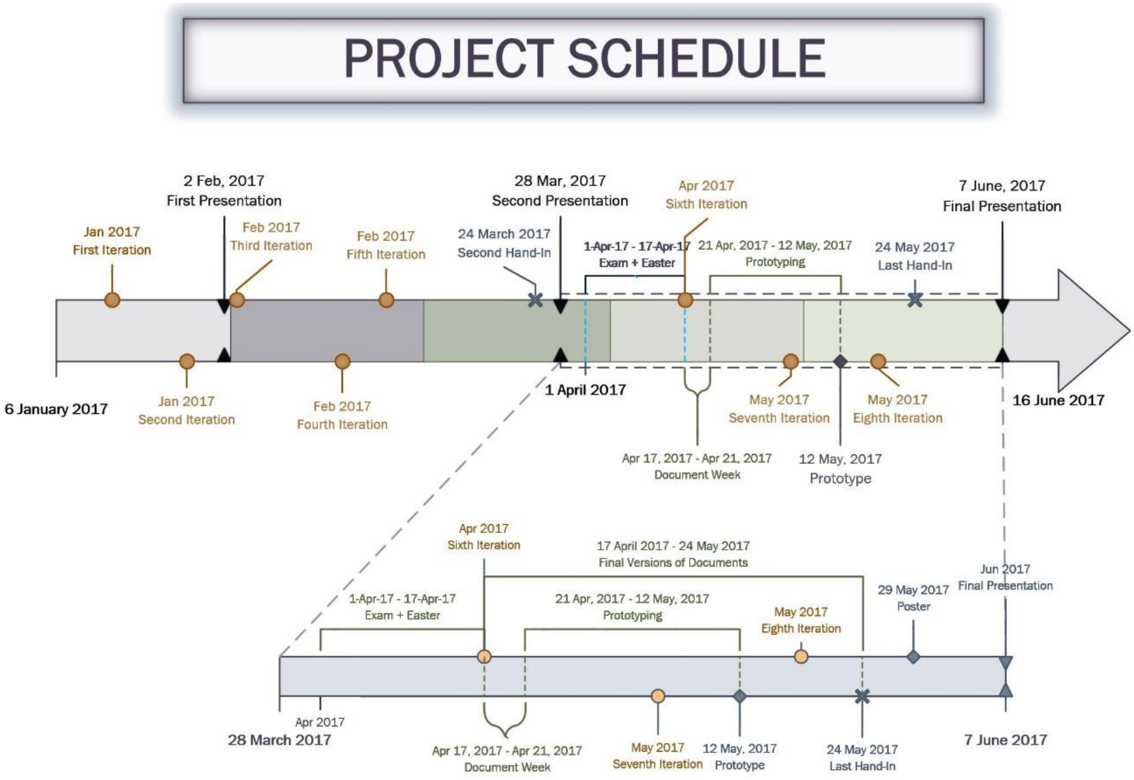

Figure 5.1: Project Schedule

5.4.2 Project Milestones

In the process of project development, we are facing certain milestones, main meaning of those is to serve as is a reference point that marks a major event in a project and is used to monitor the project's progress.

Date	Milestone
06.01.2017	First Group Meeting
16.02.2017	First Customer Meeting
31.02.2017	First Document Hand In
02.02.2017	First Presentation: Project Plan
03.02-23.03.2017	Technical & Design Research
14.03.2017	Requirements Approval
24.03.2017	Second Document Hand In
28.03.2017	Second Presentation: Prototype Design
01.04-17.04.2017	Mechatronics Examination and Easter Holidays
April 2017	Document Week & Design Re-evaluation
12.05.2017	First Prototype
May 2017	Verification & Validation
24.05.2017	Final Hand In
07.06.2017	Final Third Presentation

According to the Project Schedule provided to the first presentation, we were planning to build a partial prototype right before the second presentation as a part of the R&D process in the 5th iteration.

The project group had to revise the plan. As mentioned before, we have received a bachelor project from HSN, but due to some arrangement difficulties the customer was determined in week 6. We received a request from the customer to present several design concepts of the system before we could order parts. Design and calculations are time consuming activities. When it was done, we met our customer for discussion of more details in week 11. We presented different design concepts for both power transmission system and pitch mechanism. The most optimal design was discussed with the customer and then we could proceed with ordering. The first ordering session took place in week 13. After that, we found out that some of the items ordered were sold out right after ordering, so we had to cancel the order and find new items. For more details, see Conclusions & Recommendations Document, section 5.

Re-evaluation of the project plan was made and we agreed with the customer that building of the first and final prototype is planned for May 2017.

5.4.3 Activity Specification

The project includes a list of activities. The project group have decided to divide activities into different categories, putting the same type of work into the same category.

At the beginning of the project, we estimated time for the whole project and per team member. Totally, as it was stated in the Project Manual at HSN, 600 hours of workload per student per semester was a recommended value.

The project group have decided to fill in only effective hours of work. It means that although we were at school the whole working day, some time was used to social activities, breaks and lunchtime. This time was not taken into account.

Please see Appendix A for Activity Specification List.

5.4.4 Project Schedule, Gantt Chart & Timesheets

A Gantt chart, commonly used in project management, is one of the most popular and useful ways of showing activities, tasks and events displayed against time. The project group have created a Gantt chart to have an overview over project tasks, milestones and time for different activities within the scope of the project. In addition to this we have timesheet statistics which allows us to check estimated time with actual time used.

Please see Appendix B, C and D:

- Appendix B - Timesheet Statistics
- Appendix C - Gantt Chart for the whole Project
- Appendix D - Gantt Chart for the Project from the Second Presentation to the Third Presentation.

5.4.5 Communication

Communication is an essential part of implementing a successful project, thus the project group have set some rules for how the communication should take place.

Internal communication

The following internal communication channels are used:

- Facebook group
- Facebook chat
- Google Drive & Docs

- Group Briefing & Meeting

5.4.5.1 *COMMUNICATION WITH INTERNAL SUPERVISOR*

For contact with internal supervisor we are having meetings every week, as well as we can take contact per e-mail and in the office. The weekly meetings are arranged with the main purpose of updating regarding project progress, as well as getting feedback and help.

Google Drive is used for storing agenda for the meetings, Meeting Minutes and Follow-up Document with internal supervisor.

5.4.5.2 *COMMUNICATION WITH THE CUSTOMER*

For contact with the customer we are arranging meeting upon demand. The meetings take place at HSN in Krona. Communication per e-mail is also possible when needed. Google Drive is used for storing agenda for the meetings, Meeting Minutes with the customer.

5.4.5.3 *COMMUNICATION WITH EXTERNAL AND INTERNAL SENSORS*

Communication with external and internal sensors is mainly happening through presentations and mailing.

For convenience of all interested in the project, the project group have developed a web-site that provides information regarding the project development.

Project web-site: https://home.hbv.no/web-gr9-2017/

5.5 PROJECT SCHEDULE RISK MANAGEMENT

5.5.1 PURPOSE

The purpose of having and performing “Project Risk Management” is to identify possible risks that may occur during the project life and by doing this, mitigating the impact possible risks cause for the work process and to the product. If we early and correctly can identify these risks, it will be easier assess different risk and know how to handle them if and when they occur, and preferably preventing them from ever happening. Even though things are going smooth in a project, it is important to recognize that at some stage during the project, the group and its members, will run into big or small problems. Therefore, it is very important to identify these potential risks relatively early in the process, to help the group cope with such challenges as soon as they occur and in the best possible manner. The “Project Risk Management” also tells us something about the magnitude of the possible impacts, and prepare the group of what to expect and how to handle it, if a risk actually do occur [4]. It will also help us pinpointing out the risks that are very possible we will run into, and which ones that’s not that likely. If a risk is probable, we are well prepared, and we desirable already got the solution to the problem, even before it happens.

By using a “Project Risk Management” correctly we will [5]:

- Get better understand different risks and their impacts
- Get better decision making
- More control in what otherwise could have become chaotic situations
- Few negative surprises
- Control over the biggest risks

5.5.2 Risk Matrix

The Risk Matrix [fig 5.2] is a tool that tells us which events we need to be extra careful with regarding to probability of the event happening and the consequence if it happens. This will further help us with placing all the events in different bulks, where we need to take further steps. We place the events by multiplying an events chance of happening with the possible impact [6]. If an event lands on green for instance, let's say we multiplied 4 x 1, we will only monitor it, because even though some of these events are likely to happen, they won't be any major risk for the project.

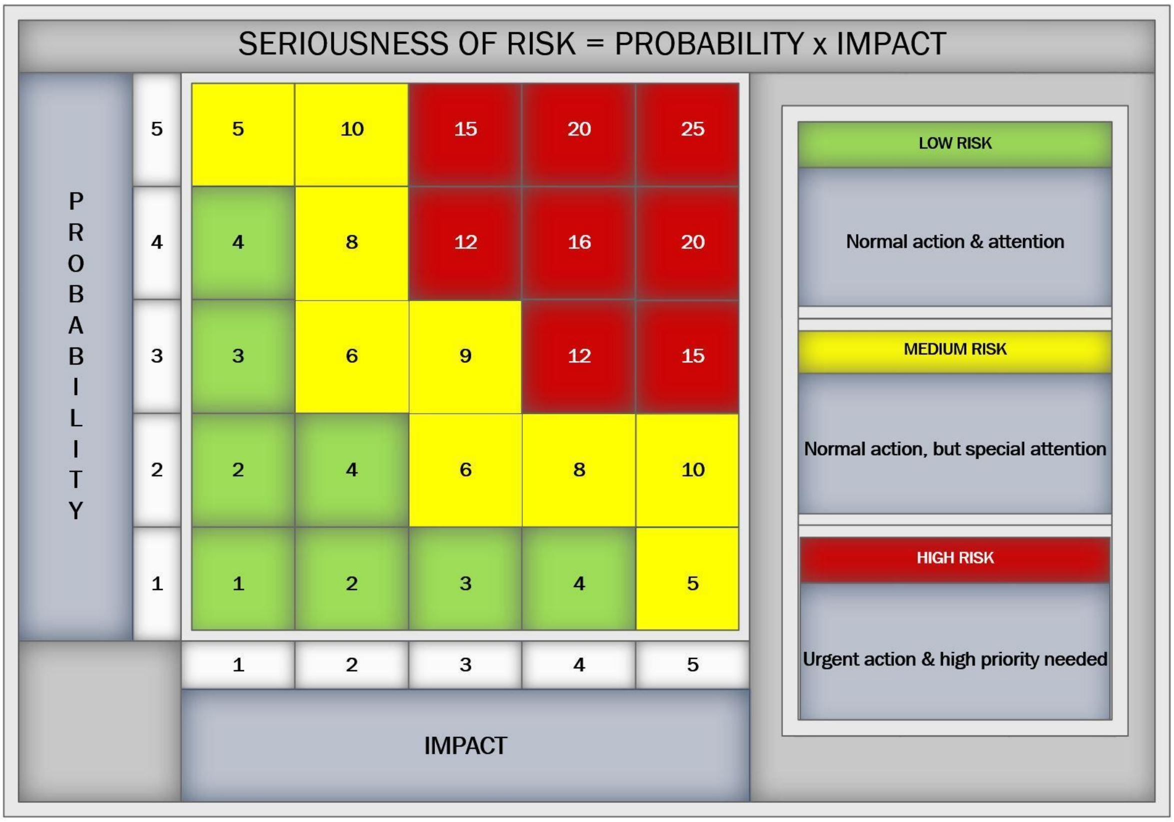

Figure 5.2: Risk matrix

5.5.3 Definitions

The different numbers in the Risk Matrix represents the probability and the impact to the project if the event occur on a scale from one to five [fig 5.3].

When talking about probability, the number one represents that the probability of it to happen is very low, and the chance of happening rises the higher number we got.

When talking about impact, the number one means that the impact is negligible, which means it won't have any negative effect on the project, and basically can be ignored. But the higher the number, the more "painful" an event can become to the project, and if an event of impact level five occurs, we got a big problem.

DEFINITION OF PROBABILITY

PROBABILITY	FREQUENCY TROUGHOUT THE ENTIRE PROJECT	PERCENTAGE
1	Very Infrequently	0%-20%
2	Infrequently	20%-40%
3	A Few Times	40%-60%
4	Several Times	60%-80%
5	Frequently	80%-100%

DEFINITION OF IMPACT

IMPACT	CONCEQUENCE	OUTCOME
1	Negligible	Insignificant impact to schedule
2	Minor	Internal schedule slips
3	Moderate	Schedule slips where minor deadlines are at risk
4	Severe	Deadlines will be exceeded. Project at risk
5	Critical	High chance of ruining the entire project

Figure 5.3: Probability & impact sefinitions

5.5.4 Administrative Risk Assessment

In figure 5.4 we have listed administrative events, that could occur during the project lifetime, and written which potential impacts these events got. Then we have multiplied the probability score and impact score, and have gotten a risk score. This risk score determines how many resources and how much time we need to delegate to deal with the evens. Then we have listed up how we can avoid it, and how to mitigate the damages if the event occurs.

#	Event	Potential Impact	Probability Score	Impact Score	Risk Score	How To Avoid It	Mitigate
1	Short-term illness	More work for co-workers	4	1	4	Wash hands/ Normal Hygiene	Notify if ill & ask for help to finish tasks
2	Long-term illness	Project lose a memeber	2	3	6	-	Groupleader delegates tasks
3	Lack of motivation	Little progress	3	4	12	Regular «Team buildings» to raise the team spirit	Plan the project as a stair. (Subgoals)
4	Intern disagreements	Bad moral/ Drop-outs	4	2	8	Always end discussions in a friendly manner	Count to ten, or take five
5	Avoidance	Angry co-workers/ missing intern deadlines	2	3	6	Mandatory meetings / Talk openly to eachother	Regular contact with eachother
6	Group member drop-out	More work shared among the others	1	5	5	Regualar team meetings	Version control & up-to-date documentation
7	General delays	Missing intern deadlines	5	3	15	Follow Project Plan	Work more efficiently to make up for lost time
8	Minor data loss	Redo work	4	1	4	Save documents on a regular basis	Redo the work immediately
9	Major data loss	Redo work/ Deadlines at risk	1	5	5	Backups	-
10	Disturbance in shared workspace	Slow progress/ annoyed co-workers	4	1	4	Use Library rooms	Use common decency
11	Damaged Workplace	Demotivating/ missing dealdines	1	4	4	Follow the HMS rules of Krona	Work at home

Figure 5.4: Description of administrative events

5.5.5 Technical Risk Assessment

In figure 5.5 you can see the technical events, that could occur during the project lifetime. These events represent technical challenges to the project, and has been plotted using the same parameters used in the administrative risk assessment in the paragraph above.

“Technical risk assessments are neither entirely objective nor necessarily very precise” -John Adams [7]. We as project members couldn’t give an entirely objective risk assessment of the project, and our models will not allow us to precisely predict future technical problems we may encounter. Still, a holistic view allows us to foresee the technical risks most likely to arise in the future, thus such an assessment is still valuable. The technical risk assessment concerns both the most likely events and the events with the highest consequence to the project. The technical risk assessment helps us understand the most pertinent technical risks and how to mitigate them. Should one of the risks occur, they will be dealt with and the improvements documented in the relevant technical document.

5.5.5.1 Potential Instance of Technical Risk

One of the important constraints of the system is weight. A technical risk is that some of the components exceeds their weight budget. This could result in the system exceeding its weight constraint, require other components to compensate or alter capabilities such as payload capacity. The risk of this happening can in part be avoided by thoroughly investigating alternative varieties of the component and using parts with high strength to weight ratios. In the unlikely event that this event occurs, it can be handled by cutting away excess mass wherever possible, as long as this does not affect the structural integrity of the system. Another solution might be to use components of lighter materials, while making sure reliability is not affected to an unacceptable degree. A third way around the issue may be to discuss the possibility of altering some of the requirements. One of these ways of handling the event may be sufficient to resolve the issue, or a combination of them might be used.

#	Event	Potential Impact	Probability Score	Impact Score	Risk Score	How To Avoid It	Mitigate
12	Exceeds weight budget	Redo design, order new parts, neglect R01	4	4	16	Follow Weight Budget	Alert the customer as early as possible if this happens
13	Exceeds budget	Can't afford all parts needed	3	5	15	Follow Budget	Alert the customer as early as possible if this happens
14	Failing different tests	Improve the system,then retest	4	2	8	Make sure parts etc, is ready for testing	Don't wait until the entire system is built to run tests
15	Parts doesn't arrive in time	Order new parts from Norway.	3	3	9	Order parts from Norway, or by fast shipping	Have a plan B in case this happens
16	The Quadcopter won't fly	Redo design, make improvements	2	5	10	Make sure the quadcopter is built properly	Test lift, do calculations
17	Defect/ruined parts	Have to order new parts	1	3	3	Use acknowledged suppliers	Handle the different parts with care
18	Issues with producing composite sheets	Make chassis in different material	1	3	3	Follow instructions carefully	Get assistance from faculty
19	Flight Controller isn't compatible with our system	Can't control the system	4	3	12	Hire a computer engineer	Get assistance from a computer engineer/ facutly
20	System design fails to meet requirements	Redo design	2	4	8	Build the design according to requirements	Check the system against requirements regulary

Figure 5.5: Description of technical events

5.5.6 Risk Matrix with Events

In the Risk Matrix [fig 5.6] we got all the possible events that we have listed up, and based on the score they got in the risk matrix, we have placed them inside the matrix for a better overview. This makes it easier for us to compare the different events, and by being extra careful with the events that "landed" in the yellow and red areas, and be extra well prepared to handle them if they occur, but preferably completely avoiding them.

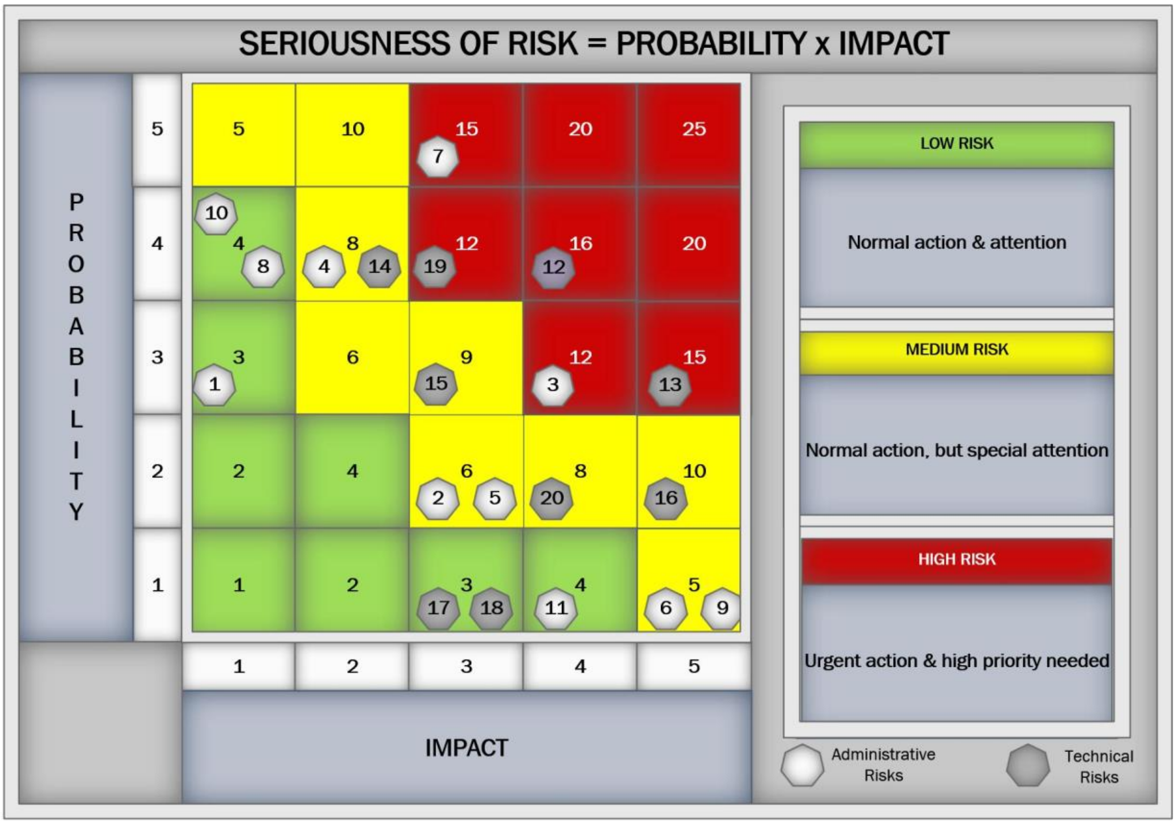

Figure 5.6: Risk matrix with events

5.6 COST BUDGET

During the system, R&D and prototyping, some financial expenses have taken place. The financial budget for the project includes all expenses required to run the project, particularly purchasing parts and materials. Some of materials and parts are available at HSN laboratories (carbon fiber, epoxy, plexiglass, medium-density fibreboard, flight controller). 3D printing is available for all bachelor projects.

We have a confirmed the budget of 10.000 NOK, with the possibility of additional funds if the need can be justified.

In Design Document, we specify the system in more details and describe what parts are needed to produce the final chosen design. We found most suitable suppliers. It is not just the price and quality what define the supplier, but also ware shipping time.

Project Group meet the approved Cost Plan very well.

See Appendix E, where a detailed Cost Budget is presented.

6 Document Overview

ID	Document Name	Date	Responsible
1	Project Plan	23.05.2017	Anastasia
2	Systems Engineering Document	23.05.2017	Severin
3	System Requirements	20.04.2017	Daniel Christian
4	Technical Document	23.05.2017	Ann-Mari
5	Design Decisions Document	23.05.2017	Ann-Mari
6	Test Plan & Specification	23.05.2017	Joakim
7	User Manual	23.05.2017	Daniel Christian
8	Conclusions and Recommendations	23.05.2017	Anastasia

7 RECOMMENDATIONS ON FURTHER WORK

Project Plan and other documents have been changed continuously as the project work developed. As challenges and opportunities arise through the system R&D, we have revised all documents to make sure they are up to date. This was done through stringent document discipline, where changes are archived in the document history, and revised documents are stored.

As the iterative work has progressed, changes to the project plan as well as all other documentation have occurred. This has been accounted for by the last two iterations of the project, where there is a margin to handle revisions of all documentation.

More information regarding recommendations on further work for technical part of the project is provided in Conclusions and Recommendations Document.

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2.0 Activity Specification List

Activity Category	Activity ID	Activity Name	Description	Est. Time per Activity, h	Est. Time per Category, h	Actual Time Used
Administrative	1001	Templates	Develop and design templates	20	525	331
Administrative	1002	Webpage	Set up, design and update the webpage	50		
Administrative	1003	Vision Document	Short introduction of task, challenges and group members	30		
Administrative	1004	Follow-up Document	Weekly schedule and an update to supervisor	50		
Administrative	1005	Time-Sheets	Document what activities have been done, and hours spent	60		
Administrative	1006	Project Leader Tasks	Work delegation, preparation to briefings, information collection, updating, book rooms, contacts with supervisor, mailing etc.	80		
Administrative	1007	Poster	Developing and designing poster	30		
Administrative	1008	Logo	Developing and designing logo	25		
Administrative	1009	Document Control	Proofreading, formatting, editing, referencing	100		
Administrative	1010	Graphic Design	Graphical interface using Visio, Excel etc.	60		

Administrative	1011	Procurement	Ordering and pick up parts	20		
Project Plan	2001	Gantt Diagram Project Schedule	Plan ahead, and get things in the right order	50	170	107
Project Plan	2002	Activity List	Find and describe different activities	30		
Project Plan	2003	Risk Management	Identify risks, and determine probability for them to happen and possible impact	30		
Project Plan	2004	Develop/Update Project Plan Document	Develop Project Plan documentation and update due to schedule changes	50		
Project Plan	2005	Estimates	Estimate time-consuming on each activity	10		
Systems Engineering	3001	CAFCR	Work and research	30	530	303
Systems Engineering	3002	Iterations	Follow the model and all its steps	300		
Systems Engineering	3003	Develop/Update Systems Engineering Document	Develop iteration, planning, sketching documents etc. Update documentation according to changes	100		
Systems Engineering	3004	Validation and Verification	Check if we are building right system and if we build it correct	50		
Systems Engineering	3005	Comparison analysis	Pugh Matrixes, House of Quality and other comparison methods	50		
System Requirement	4001	Identify Requirements	Find and translate customer needs into system requirements	30	150	92
System Requirement	4002	Develop/Update Req. Document	Define, specify and approve requirements. Alter documentation according to changes	120		

System Test Plan/ Specification	5001	Develop Test Plan/Test Spec Document	Describe scope, approach, resources and schedule; develop test procedures. What, How and When	80	210	126
System Test Plan/ Specification	5002	Update Test Plan/Spec	Alter documentation according to changes	50		
System Test Plan/ Specification	5003	Execute Tests	Study and write down results. Testing machine, drop tests etc.	80		
Design & Development	6001	Solidworks	2D and 3D modeling. Altering according to changes	250	800	670
Design & Development	6002	Calculations/Sketching	Math calculations and sketch drawing on paper	50		
Design & Development	6003	Simulation	Physical, mathematical, logical representation of a system using Simulink, Matlab, SW FEM/FEA. Altering according to changes	200		
Design & Development	6004	Prototyping	Develop and study prototype	100		
Design & Development	6005	Develop/Update Design Document	Describe design decisions. Update design document according to changes. Analysis and choosing of parts to order	100		
Design & Development	6006	Develop/Update Technical Document	Describe different alternatives. Update technical document according to changes.	100		
Research	7001	Choice of Material	Materials, manufacturing techniques	50	650	487
Research	7002	General Research	Solutions, general research, mapping and documentation	100		

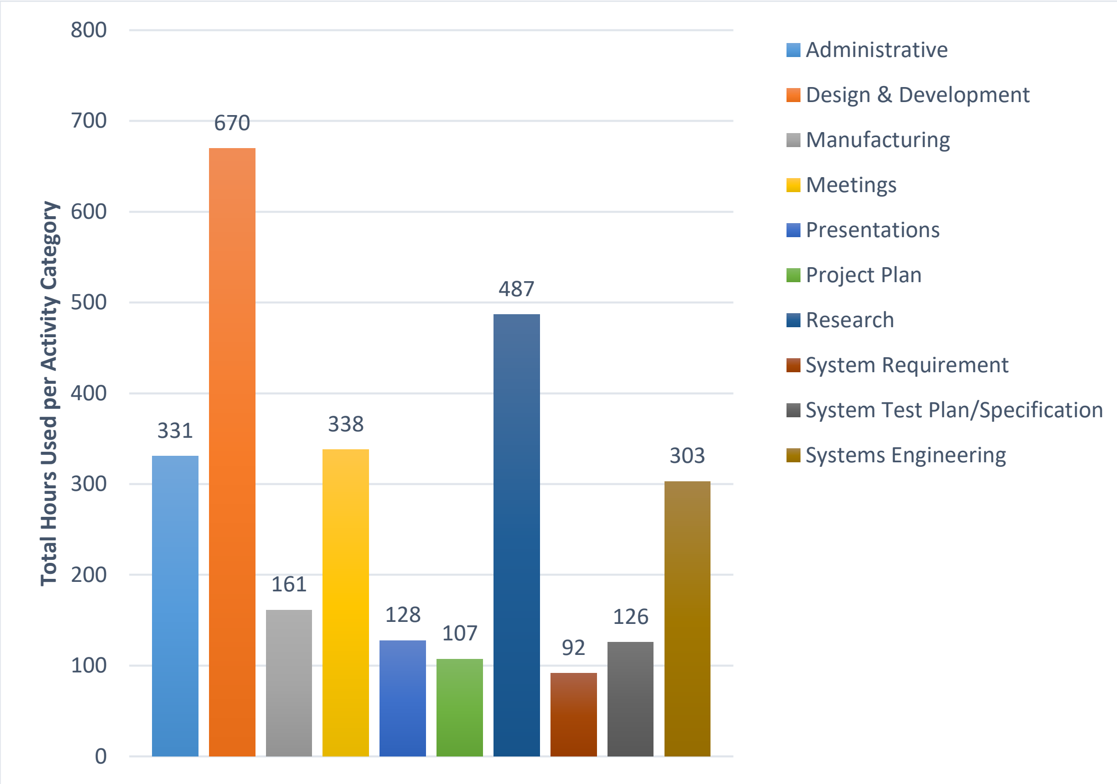
Research	7003	Attend Other Bachelor Presentations	Learn from their mistakes and success	20		
Research	7004	Tutorials	Solidworks, Matlab, EndNote, Simulink, Visio, Microsoft Projects etc.	100		
Research	7005	Pitch Solutions	Find possible/optimal solutions	150		
Research	7006	Powertrain Solutions	Find possible/optimal solutions	150		
Research	7007	Mechatronics	System control solutions, coding, electronic solutions	80		
Meetings	8001	Internal Group Meetings	Work, Discussion, Meetings	200	350	338
Meetings	8002	External Supervisor Examiner Meetings	Discussion, Q&A	40		
Meetings	8003	Internal Supervisor Meetings	Discussion, Q&A	80		
Meetings	8004	Meeting Minutes Report	Record taking and pre-planning	30		
Presentations	9001	Planning Presentations	Develop script and find out what to include in presentation, planning itineraries and dress code	100	270	128
Presentations	9002	Developing PowerPoints	Design slides and text	90		
Presentations	9003	Rehearsing	Listen to one another and dress rehearsal	60		
Presentations	9004	Presentations	Actual presentation and various meetings regarding this	20		

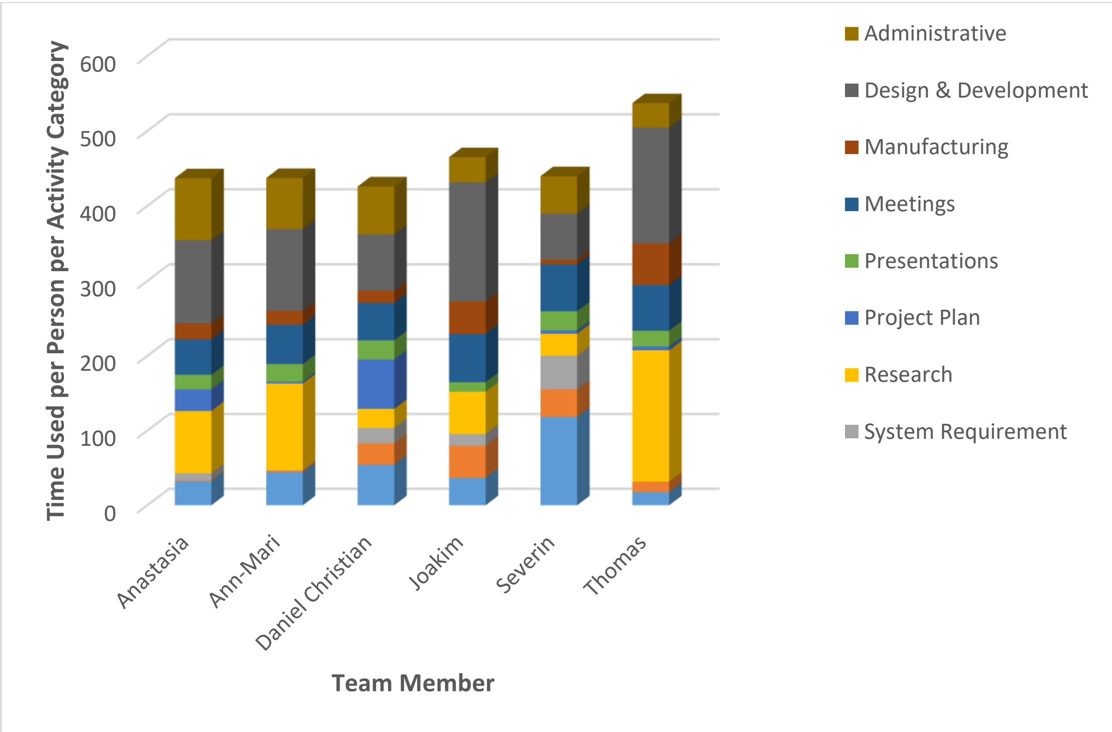
Manufacturing	1101	Manufacturing	Actual manufacturing & producing parts, using Autoklave, CNC, laser cutter, 3D-Printing (getting your hands dirty)	100	180	161
Manufacturing	1102	Making Assembly	Assemble sub-systems, making the whole system together	80		
Sum Accumulating Hours				3835	3835	2742

Appendix B – Timesheet Statistics

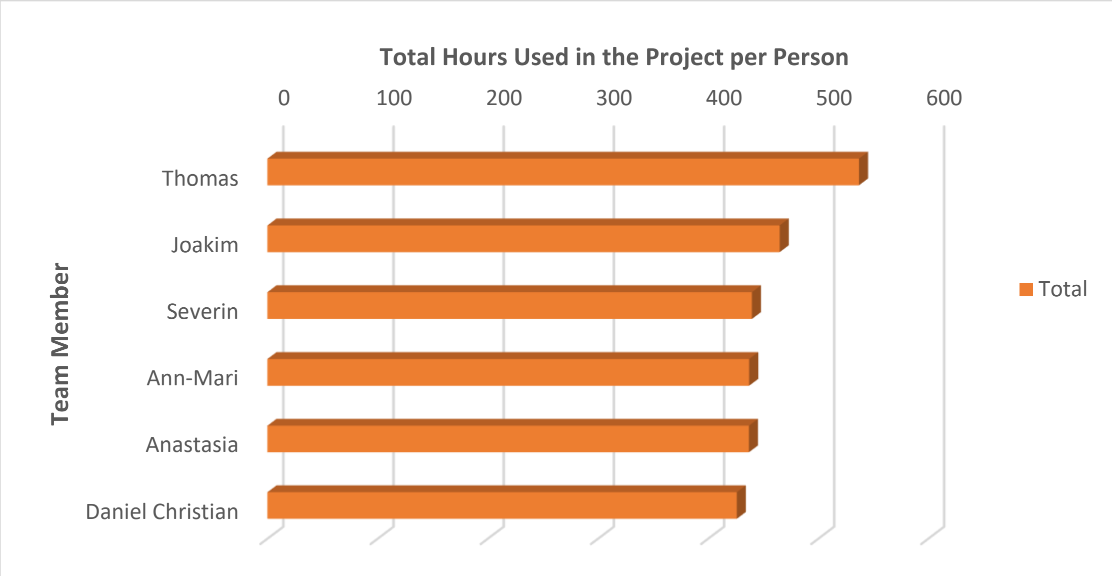
Information is updated up to and including week 20

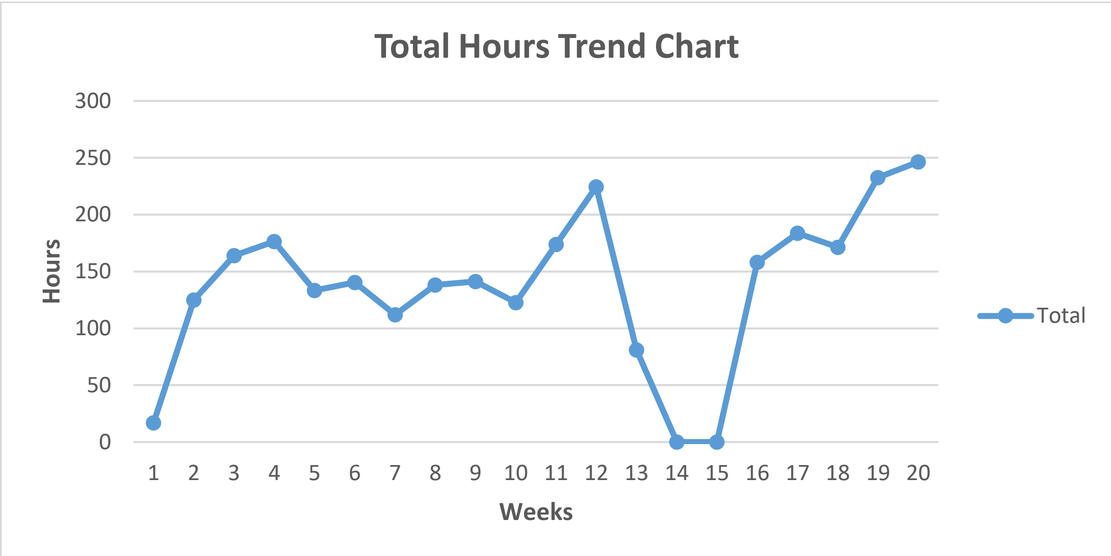
Grand total project hours: 2742



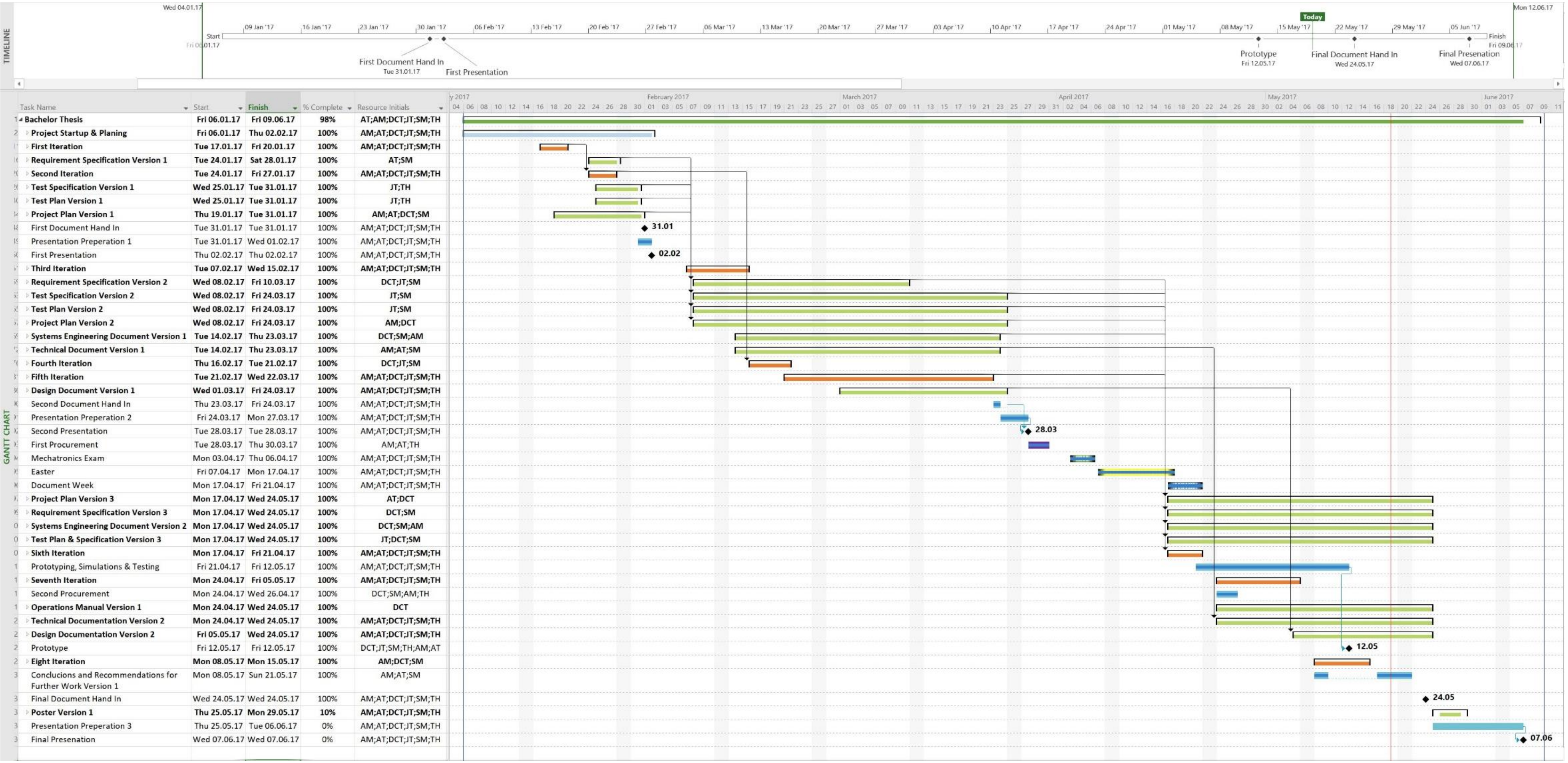


Appendix B – Timesheet Statistics





Appendix C –Gantt Chart: Project Overview

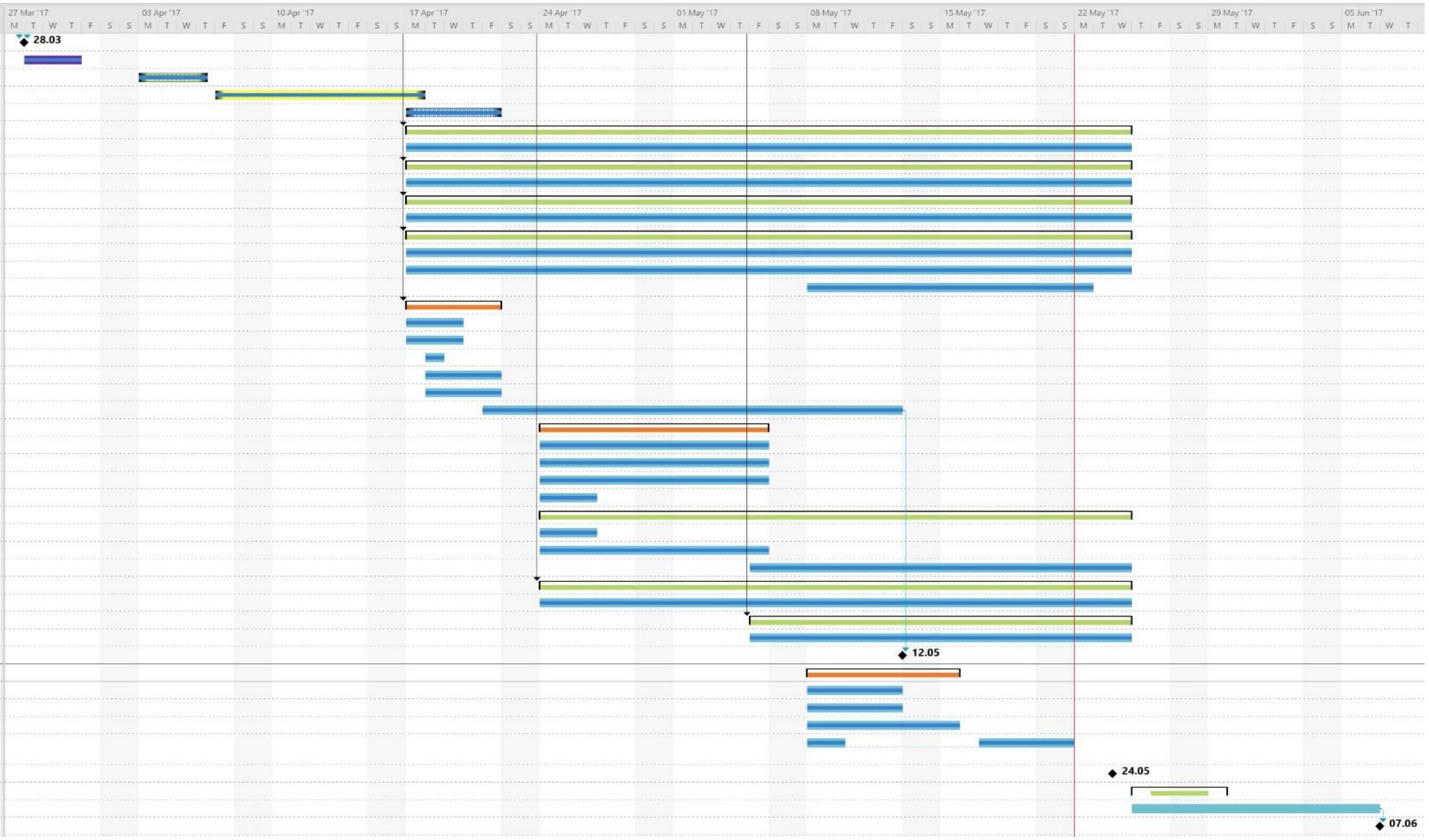


Task Name	Start	Finish	% Complete	Resource Initials
Bachelor Thesis	**Fri 06.01.17**	**Fri 09.06.17**	**98%**	**AT;AM;DCT;JT;SM;TH**
Project Startup & Planing	**Fri 06.01.17**	**Thu 02.02.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
First Iteration	**Tue 17.01.17**	**Fri 20.01.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Requirement Specification Version 1	**Tue 24.01.17**	**Sat 28.01.17**	**100%**	**AT;SM**
Second Iteration	**Tue 24.01.17**	**Fri 27.01.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Test Specification Version 1	**Wed 25.01.17**	**Tue 31.01.17**	**100%**	**JT;TH**
Test Plan Version 1	**Wed 25.01.17**	**Tue 31.01.17**	**100%**	**JT;TH**
Project Plan Version 1	**Thu 19.01.17**	**Tue 31.01.17**	**100%**	**AM;AT;DCT;SM**
First Document Hand In	Tue 31.01.17	Tue 31.01.17	100%	AM;AT;DCT;JT;SM;TH
Presentation Preperation 1	Tue 31.01.17	Wed 01.02.17	100%	AM;AT;DCT;JT;SM;TH
First Presentation	Thu 02.02.17	Thu 02.02.17	100%	AM;AT;DCT;JT;SM;TH
Third Iteration	**Tue 07.02.17**	**Wed 15.02.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Requirement Specification Version 2	**Wed 08.02.17**	**Fri 10.03.17**	**100%**	**DCT;JT;SM**
Test Specification Version 2	**Wed 08.02.17**	**Fri 24.03.17**	**100%**	**JT;SM**
Test Plan Version 2	**Wed 08.02.17**	**Fri 24.03.17**	**100%**	**JT;SM**
Project Plan Version 2	**Wed 08.02.17**	**Fri 24.03.17**	**100%**	**AM;DCT**
Systems Engineering Document Version 1	**Tue 14.02.17**	**Thu 23.03.17**	**100%**	**DCT;SM;AM**
Technical Document Version 1	**Tue 14.02.17**	**Thu 23.03.17**	**100%**	**AM;AT;SM**
Fourth Iteration	**Thu 16.02.17**	**Tue 21.02.17**	**100%**	**DCT;JT;SM**
Fifth Iteration	**Tue 21.02.17**	**Wed 22.03.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Design Document Version 1	**Wed 01.03.17**	**Fri 24.03.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Second Document Hand In	Thu 23.03.17	Fri 24.03.17	100%	AM;AT;DCT;JT;SM;TH
Presentation Preperation 2	Fri 24.03.17	Mon 27.03.17	100%	AM;AT;DCT;JT;SM;TH
Second Presentation	Tue 28.03.17	Tue 28.03.17	100%	AM;AT;DCT;JT;SM;TH
First Procurement	Tue 28.03.17	Thu 30.03.17	100%	AM;AT;TH
Mechatronics Exam	Mon 03.04.17	Thu 06.04.17	100%	AM;AT;DCT;JT;SM;TH
Easter	Fri 07.04.17	Mon 17.04.17	100%	AM;AT;DCT;JT;SM;TH
Document Week	Mon 17.04.17	Fri 21.04.17	100%	AM;AT;DCT;JT;SM;TH
Project Plan Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**AT;DCT**
Requirement Specification Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**DCT;SM**
Systems Engineering Document Version 2	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**DCT;SM;AM**
Test Plan & Specification Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**JT;DCT;SM**
Sixth Iteration	**Mon 17.04.17**	**Fri 21.04.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Prototyping, Simulations & Testing	Fri 21.04.17	Fri 12.05.17	100%	AM;AT;DCT;JT;SM;TH
Seventh Iteration	**Mon 24.04.17**	**Fri 05.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Second Procurement	Mon 24.04.17	Wed 26.04.17	100%	DCT;SM;AM;TH
Operations Manual Version 1	**Mon 24.04.17**	**Wed 24.05.17**	**100%**	**DCT**
Technical Documentation Version 2	**Mon 24.04.17**	**Wed 24.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Design Documentation Version 2	**Fri 05.05.17**	**Wed 24.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Prototype	Fri 12.05.17	Fri 12.05.17	100%	DCT;JT;SM;TH;AM;AT
Eight Iteration	**Mon 08.05.17**	**Mon 15.05.17**	**100%**	**AM;DCT;SM**
Conclucions and Recommendations for Further Work Version 1	Mon 08.05.17	Sun 21.05.17	100%	AM;AT;SM
Final Document Hand In	Wed 24.05.17	Wed 24.05.17	100%	AM;AT;DCT;JT;SM;TH
Poster Version 1	**Thu 25.05.17**	**Mon 29.05.17**	**10%**	**AM;AT;DCT;JT;SM;TH**
Presentation Preperation 3	Thu 25.05.17	Tue 06.06.17	0%	AM;AT;DCT;JT;SM;TH
Final Presenation	Wed 07.06.17	Wed 07.06.17	0%	AM;AT;DCT;JT;SM;TH

Appendix D – Gantt Chart: From 2nd Presentation to 3rd Presentation in Details

GANTT CHART

Task Name	Start	Finish	% Complete	Resource Initials
Second Presentation	Tue 28.03.17	Tue 28.03.17	100%	AM;AT;DCT;JT;SM;TH
First Procurement	Tue 28.03.17	Thu 30.03.17	100%	AM;AT;TH
Mechatronics Exam	Mon 03.04.17	Thu 06.04.17	100%	AM;AT;DCT;JT;SM;TH
Easter	Fri 07.04.17	Mon 17.04.17	100%	AM;AT;DCT;JT;SM;TH
Document Week	Mon 17.04.17	Fri 21.04.17	100%	AM;AT;DCT;JT;SM;TH
Project Plan Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**AT;DCT**
Update Project Plan	Mon 17.04.17	Wed 24.05.17	100%	AT;DCT
Requirement Specification Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**DCT;SM**
Update Requirement Document	Mon 17.04.17	Wed 24.05.17	100%	DCT;SM
Systems Engineering Document Version 2	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**DCT;SM;AM**
Update System Engineering Document	Mon 17.04.17	Wed 24.05.17	100%	DCT;SM;AM
Test Plan & Specification Version 3	**Mon 17.04.17**	**Wed 24.05.17**	**100%**	**JT;DCT;SM**
Update Test Specification	Mon 17.04.17	Wed 24.05.17	100%	JT;DCT
Update Test Plan	Mon 17.04.17	Wed 24.05.17	100%	JT;DCT
Testing	Mon 08.05.17	Mon 22.05.17	100%	AM;AT;DCT;JT;SM;TH
Sixth Iteration	**Mon 17.04.17**	**Fri 21.04.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
External Interfaces	Mon 17.04.17	Wed 19.04.17	100%	DCT;SM
System Verification	Mon 17.04.17	Wed 19.04.17	100%	AM;AT;DCT;JT;SM;TH
Benchmarking	Tue 18.04.17	Wed 19.04.17	100%	DCT;SM
Requirement Reassessment	Tue 18.04.17	Fri 21.04.17	100%	DCT;SM
Risk Assessment	Tue 18.04.17	Fri 21.04.17	100%	DCT;SM
Prototyping, Simulations & Testing	Fri 21.04.17	Fri 12.05.17	100%	AM;AT;DCT;JT;SM;TH
Seventh Iteration	**Mon 24.04.17**	**Fri 05.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Design Reassessment	Mon 24.04.17	Fri 05.05.17	100%	AM;AT;DCT;JT;SM;TH
Testing & V&V	Mon 24.04.17	Fri 05.05.17	100%	AM;AT;DCT;JT;SM;TH
Operations Manual (Develop)	Mon 24.04.17	Fri 05.05.17	100%	DCT
Second Procurement	Mon 24.04.17	Wed 26.04.17	100%	DCT;SM;AM;TH
Operations Manual Version 1	**Mon 24.04.17**	**Wed 24.05.17**	**100%**	**DCT**
Research	Mon 24.04.17	Wed 26.04.17	100%	DCT
Develop Operations Manual	Mon 24.04.17	Fri 05.05.17	100%	DCT
Update Operations Manual	Fri 05.05.17	Wed 24.05.17	100%	DCT
Technical Documentation Version 2	**Mon 24.04.17**	**Wed 24.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Update Technical Document	Mon 24.04.17	Wed 24.05.17	100%	AM;AT
Design Documentation Version 2	**Fri 05.05.17**	**Wed 24.05.17**	**100%**	**AM;AT;DCT;JT;SM;TH**
Update Design Document	Fri 05.05.17	Wed 24.05.17	100%	AM;AT
Prototype	Fri 12.05.17	Fri 12.05.17	100%	DCT;JT;SM;TH;AM;AT
Eight Iteration	**Mon 08.05.17**	**Mon 15.05.17**	**100%**	**AM;DCT;SM**
Characteristics Evaluation	Mon 08.05.17	Fri 12.05.17	100%	AM;DCT;SM
Value Proposition	Mon 08.05.17	Fri 12.05.17	100%	AM;DCT;SM
Life Cycle Evaluation	Mon 08.05.17	Mon 15.05.17	100%	AM;DCT;SM
Conclucions and Recommendations for Further Work Version 1	Mon 08.05.17	Sun 21.05.17	100%	AM;AT;SM
Final Document Hand In	Wed 24.05.17	Wed 24.05.17	100%	AM;AT;DCT;JT;SM;TH
Poster Version 1	**Thu 25.05.17**	**Mon 29.05.17**	**10%**	**AM;AT;DCT;JT;SM;TH**
Presentation Preperation 3	Thu 25.05.17	Tue 06.06.17	0%	AM;AT;DCT;JT;SM;TH
Final Presenation	Wed 07.06.17	Wed 07.06.17	0%	AM;AT;DCT;JT;SM;TH



Appendix E – Cost Budget

Items ordered for the project																		
Item	PCS	Supplier	Link	Cost p/item, $	Cost p/item, NOK	Cost p/item, £	Shipping, $	Shipping, NOK	Shipping, £	Shipping+Cost, $	VAT, $ 0.25	Admin Cost, $	Admin Cost, NOK	Total Cost, NOK	Total Cost, $	Order date	Received	Ordered by
Gear A	1	SDP	http://shop.sd	7,99			23,52			31,51	7,88				39,39	06.04.2017	22.04.2017	Anastasia
Gear B	1	RARGEARS	https://www.ra	18,05		14,21	68,59		54	86,64	30,76				117,40	07.04.2017	13.04.2017	Ann-Mari
Gear C	1	RARGEARS	https://www.ra	14,10		11,10				14,10	3,53				17,63	07.04.2017	13.04.2017	Ann-Mari
Gear D	2	RARGEARS	https://www.ra	17,39		13,69				34,78	8,70	16,43	140,00		59,91	07.04.2017	13.04.2017	Ann-Mari
Shaft 5mm	2	Ali	https://www.al	2,66			4,21			9,53					9,53	03.04.2017	27.04.2017	Anastasia
Shaft 6mm	2	Ali	https://www.al	1,92			1,26			5,10					5,10	03.04.2017	10.05.2017	Anastasia
Bearing 6x10x3, pack 5	1	Ali	https://www.al	1,71			2,02			3,73					3,73	02.04.2017	26.04.2017	Anastasia
Pulley 6 bore	4	SDP	https://shop.sd	7,93						31,72	7,93				39,65	06.04.2017	22.04.2017	Anastasia
Pulley 5 bore, pack 5	1	Ali	https://www.al	19,99			3,15			23,14					23,14	02.04.2017	13.04.2017	Anastasia
Belts	2	SDP	https://shop.sd	8,72						17,44	4,36				21,80	06.04.2017	22.04.2017	Anastasia
Belts	2	SDP	https://shop.sd	8,59						17,18	4,30				21,48	06.04.2017	22.04.2017	Anastasia
Motor	1	RotorStar	https://hobbyk	34,12			20,89			55,01					55,01	30.03.2017	04.04.2017	Joakim Bjørk
ESC	1	Rotorstar	https://hobbyk	44,91						44,91					44,91	30.03.2017	04.04.2017	Joakim Bjørk
Servo	4	Rotorstar	https://hobbyk	18,90						75,60					75,60	30.03.2017	04.04.2017	Joakim Bjørk
Flightcontroller	1	OpenPilot	https://hobbyk	46,99						46,99					46,99	30.03.2017	04.04.2017	Joakim Bjørk
Pitch Mech.	4	HobbyKing	https://hobbyk	20,60						82,40					82,40	30.03.2017	04.04.2017	Joakim Bjørk
Propellers	2	HobbyKing	https://hobbyk	14,00						28,00					28,00	30.03.2017	04.04.2017	Joakim Bjørk
RX	1	Turnigy	https://hobbyk	19,04						19,04					19,04	30.03.2017	04.04.2017	Joakim Bjørk
Bearing 5mm	1	VXB	https://www.vx	47,37			17,38			64,75	16,19				80,94	30.03.2017	19.04.2017	Joakim Bjørk
Bearing 6mm	4	VXB	https://www.vx	5,77						23,08					23,08	30.03.2017	19.04.2017	Joakim Bjørk
Bearing 6x15x5	8	Kulelager24	https://www.kulelager24.no/ind		115			55						975,00		24.04.2017	27.04.2017	Severin
Threaded rod, M3, 1m	2	Hobbymann			75									150,00			05.05.2017	Ann-Mari
Shaft, 6 mm, 1m	1	Hobbymann			55									55,00			05.05.2017	Ann-Mari
Glue for plastic	1	Biltema			79,90									79,90			11.05.2017	Daniel Christian
Diverse, screws, bolts, nuts	1	Hobbymann			457,13									457,13			11.05.2017	Daniel Christian
Servo battery	1	Hobbymann			130,00									130,00			11.05.2017	Daniel Christian
Reserve blades	1	HobbyKing			376,92									376,92			12.05.2017	Severin
													Total Sum, NOK	2223,95				
Notes:																		
1. Currency Color Coding													Total Sum, $	7022,15	814,71			
NOK													Total Sum, NOK (*8.62)	kr 9 246,10				
$																		
£																		
2. VAT																		
Shipments with a value of less than NOK 350 (=40.58 $) including freight and insurance, are exempt from VAT. This applies to all items with the exception of alcohol and tobacco.																		

Unified Collective Pitch Quadcopter

Systems Engineering	
Project Name	Unified Collective Pitch Quadcopter
Number of Pages	26
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Severin Myhre, Daniel Christian Torsvik, Ann-Mari Snekkerhaugen

Table of Contents

1 ABSTRACT

This document describes the development model the project team has been following during the Bachelor Thesis. The document describes the reasoning behind the choice of development model, and outlines the iterations and phases in the project. The main activities performed in each iteration are shown, so is an iteration overview. The document concludes with a life cycle view of both the project and the product, and finally an evaluation of the system development model.

2 Document Structure

2.1 Document History

Version	Date	Description	Author
1.1	28.04.2017	Abbreviations & acronyms added	Ann-Mari
1.2	02.05.2017	Added iteration log 6	Severin
1.3	15.05.2017	Added iteration log 7 & 8	Severin, Daniel Christian, Ann-Mari
1.4	21.05.2017	Added life cycle and evaluation of the system development model	Severin
2.0	23.05.2017	Document finalised	Severin

2.2 ABBREVIATIONS & ACRONYMS

A&A	Explanation
R&D	Research and Development
RO1	Remotely Operated 1, classification in accordance with the Norwegian Civil Aviation Authority
HSE	Health, Safety and Environment
FPV	First Person View
CAD	Computer Aided Design

Term	Definition
Project Group	Students who are working under the project
Customer	Employer, University College in Southeast Norway
Project	Task that students received from customer
System	Unmanned aerial vehicle that students are designing

3 Project Model

3.1 Our Reasoning and Requirements to the Development Model

Our project is to design and develop a single engine drone with variable pitch. All group members are mechanical engineering students, giving us a great potential to create elegant mechanical systems. As the group members have minimal experience with aeronautical engineering and coding, the main focus for this project will be the transmission of power from the engine to the rotors, and the mechanics of the pitch mechanism.

Several critical constraints apply to our project, and we will have to view the system from different perspectives to fully understand the system. As any changes to a part, assembly or component will affect other aspects of the system, we need to have a holistic view about the system throughout the project. Performing multiple iterations of the design will be essential to the completion of the project.

Beyond employing iterations and perceiving the system from multiple views, we will be looking at the system from both the top-down and bottom-up perspectives. Only by understanding what system we are to design based on intention (top-down), whilst also carefully considering the constraints and identifying the opportunities in the particular solution (bottom-up), can we meet the project objectives.

Based upon this, we deem the CAFCR+ systems engineering project model to be the most suitable for our project.

3.2 CAFCR+, AN AGILE ARCHITECTING APPROACH

The CAFCR+ model is used as a framework for system architecting and design. The core of the CAFCR+ model is the use of multiple viewpoints and multiple visualizations. The CAFCR+ model is similar to the standard CAFCR model, but with the addition of the life-cycle view. The views are customer objectives, application, functional, conceptual, realization and the life-cycle view [1].

- The Customers objective view (what does the customer want to achieve)
- The Application view (how does the customer realize his goals) captures the needs of the customer
- The what and how customers view provide the justification (why) for the specification and the design
- The Functional view describes the what of the product, which includes (despite its name) the non-functional requirements
- The how of the product is described in the Conceptual and Realization views

These views will be applied in a consistent and balanced way using viewpoint hopping, actively hopping between the viewpoints. As a function of this, we will be able to sample both the problem and solution space concurrently, which again allows for simultaneous top-down and bottom-up perspectives [2].

The order in which the viewpoints are alternated is chaotic. Problems or opportunities in one viewpoint trigger the switch to a related viewpoint. Although the five views are described as sharp disjunctive views, many subsequent models and methods do not fit entirely into one single view. This in itself is not a problem, as the model is a means to build understanding, not a goal in itself.

The general tools and methods we will be using throughout the project are shown in the Project Plan document, and more detailed in the Appendix A: Activities Specification list, in the same document. However, some of the key tools in the CAFCR+ development model are time boxing and iterations.

The time boxing and iterations instigates viewpoint hopping, encouraging us to have an overall holistic mindset.

Systems can be tremendously complex and difficult to fully understand. In order to comprehend a system, the operational, behavioural and physical views are employed. These views offer different perspectives for understanding the objectives and needs of the customer, and will be used concurrently with the CAFCR+ model.

The operational view focus on how the system will serve the user in operation. The operational view can help in understanding the life cycle needs and overall constraints attached to the system. This view is intuitive for investigating for example use case scenarios, performance requirements, operational sequences and operational interfaces [3].

The behavioural view focus on how the system must behave in order to create the required operational behaviour. This view includes looking especially at inputs and outputs in order to determine the behavioural characteristics of the system, as well as the internal interfaces. This view is adept at investigating system functions, the relationships between subsystems and what actions to perform.

The physical view focuses on how the system is constructed, viewing the actual physical design. This view is used to establish the physical interfaces, focusing especially on the interfaces between the user and the system. Physical limitations, limitations in technology, controls and interaction between user and system is discovered using this view.

These three views provide different ways of perceiving the system, and the combination of them allow us to get a complete picture of the system and its requirements. The views - How the system should serve the user, how the system should behave and how the system should be constructed - focus on different aspects of the system. Combining these views with the CAFCR+ model lets us perceive a complete picture of the system.

3.3 Project Phases

3.3.1 Feasibility

This first phase of the project consists of start-up and planning. We arrange the first meeting with the employer and define the main needs of the customer. We then start the project with preparation, gathering information about bachelor projects, making templates and deciding on a project model.

3.3.2 Definition

Working further using the project model, iterating concept design and possible/optimal design solutions for our system. Research and preliminary design is an integral part of the Definition phase, as we need to understand the challenges ahead in order to properly define the project. The Project Plan, System Requirements and System Test Plan documents are under constant development and update.

3.3.3 System Design

By performing simulations and 3D prototyping we are developing data as a basis for technical decision making. Design and simulation is the focus of this phase, evaluating and analysing decisions against preliminary requirements.

3.3.4 Engineering

Verifying system design, and testing performance to demonstrate and prove technical design decisions made earlier, checking whether they still meet customer needs and system performance. Prototyping and testing is an integral part of this phase.

3.3.5 Integration & Testing

In this phase, the main landmark is checking whether the system meets requirements and specifications and whether it fulfils its intended purpose. Different methods and approaches are used here. The system is being evaluated whether it meets the stakeholders' requirements and whether it meets a set of design specifications. Particularly the emerging synthesis from the interfaces of the subsystems is of interest in this phase.

3.3.6 Field Monitoring

After the developed product has been handed over to the customer, we will be evaluating how the product functions in service. Feedback will be used for potential future endeavours, to learn how the next version can be improved and assess whether the project can serve any commercial applications.

3.4 Model Views and Phases

Figure 3.1 explains the relationship between iterations, phases and activities. It shows how all of the CAFCR+ views are used in all iterations, and how the iterations alternate between top-down and bottom-up perspectives. The time allocated for each iteration is also displayed. The phases of the project are listed linearly, with boxes showing in what phase the different activities are expected to be completed.

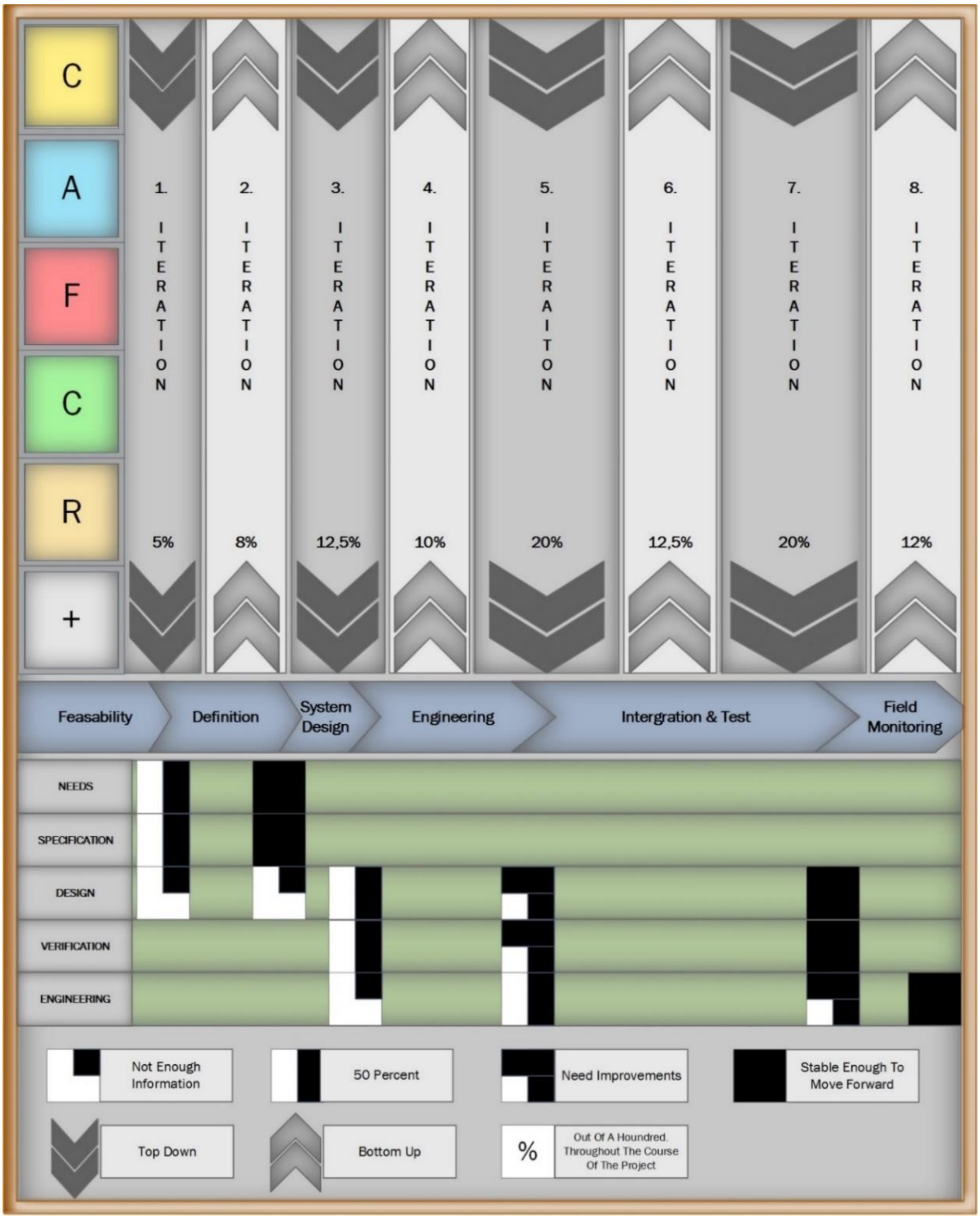


Figure 3.1: Model Views & Phases

3.5 Iteration Plan, Table

Figure 3.2 visually displaying each iteration is listed below. The main tasks in each iteration are displayed with letters representing the views needed to fully understand the problems. Please note that each iteration contains all views of the CAFCR model, except for the Life Cycle view (+). The Life Cycle view is not needed for the first iteration.

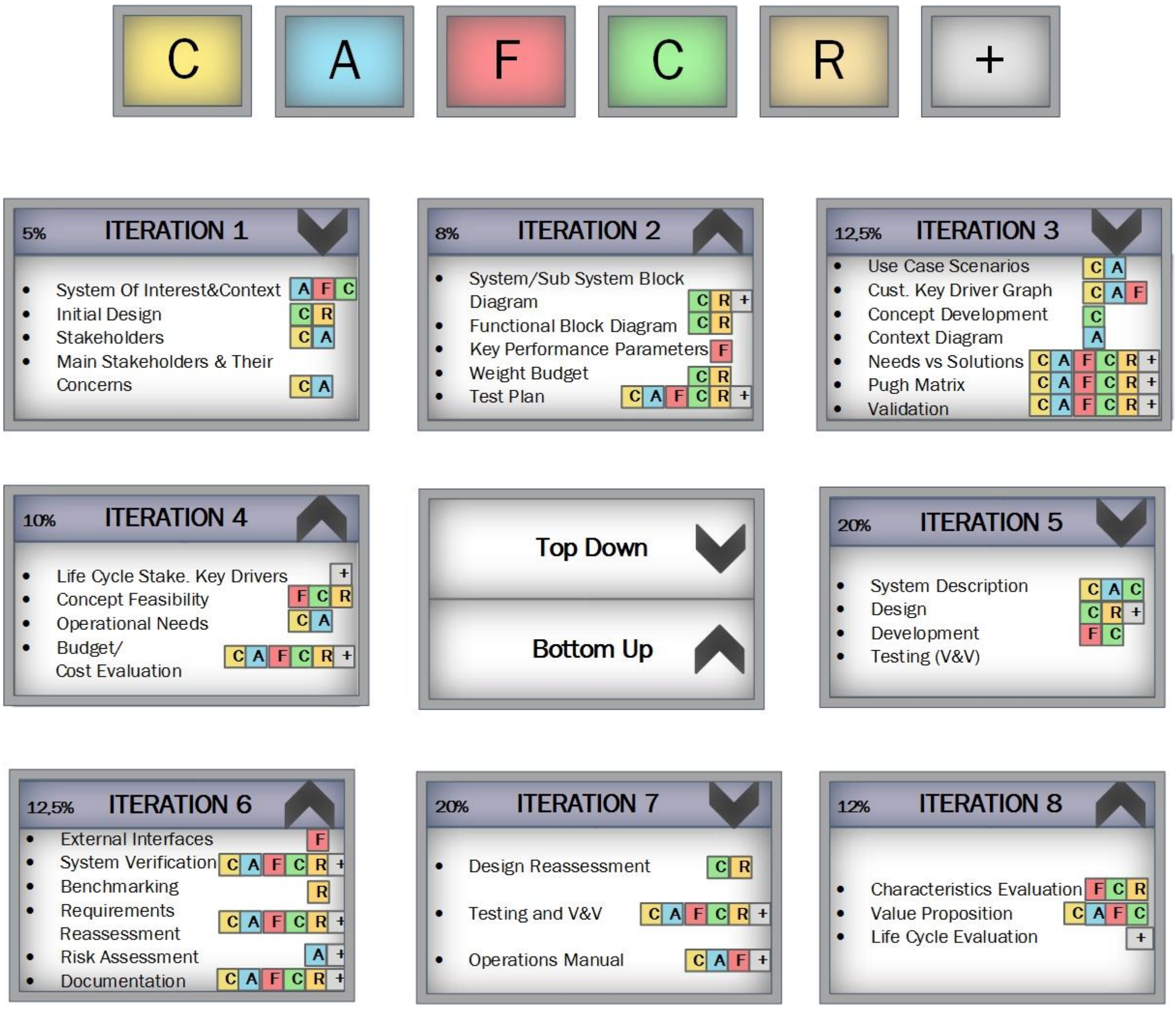


Figure 3.2: Iteration Plan

3.6 System Boundary & Scope

The main focus of this project will be the mechanical aspects of the system. In accordance with needs from our customer, the system shall meet the requirements of the Norwegian Civil Aviation Authority's regulation RO1. Therein follows certain requirements that can only be met through computer engineering, such as programming of the flight controller. This is outside of the project's scope. As we design and create a flightworthy system, the complete programming of a regulation-approved flight controller will not be covered by the system boundary.

Particularly the RO1 requirements about safe landing will be out of scope for this project. The final system shall be within RO1 and have a properly programmed flight controller, but that will not be the focus of this project. As prototyping and testing progress, Health & Safety will be maintained by the proper use of physical barriers between the system and personnel. An HSE assessment will be attached to test specifications where needed to ensure safety, until the system is proven to pose an acceptable safety risk to personnel and property.

Within Scope	Out of Scope
Single Engine	Inverted Flight
Power Transmission System	GPS Waypoint Navigation
Variable Pitch Mechanism	Fixed Wing System
FPV Camera System	

As seen from the table, all significant mechanical aspects are within scope, while advanced computing/flight controller related aspects are out of scope.

For navigational purposes a First Person View (FPV) camera system will be desirable. FPV navigation is partially within scope, and will be pursued given that all 'fully within scope' objectives have been accomplished.

4 ITERATION OVERVIEW

4.1 ITERATION 1

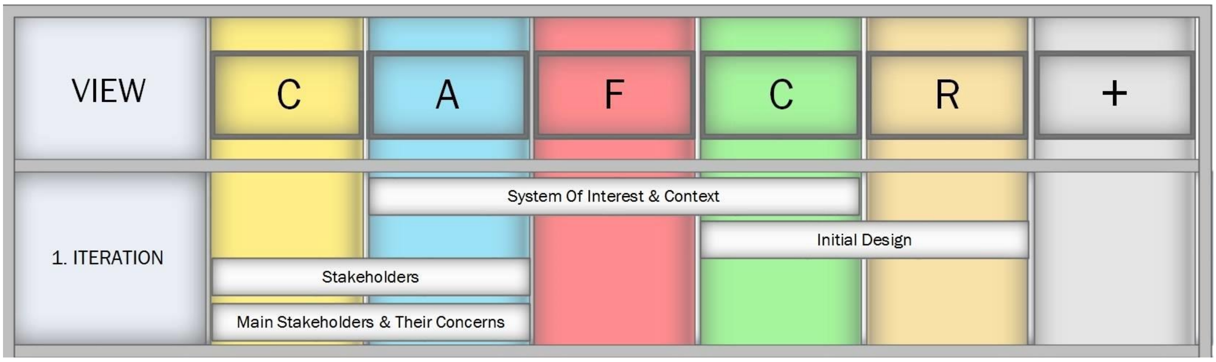


Figure 4.1: Iteration 1

In the first iteration, the main focus was on creating an overview of the project. The key focuses of systems engineering are to define the customer needs and required functionality early in the development cycle. The first iteration was therefore focused on identifying the stakeholders and the initial design. Block diagrams were used for the system of interest and identifying the stakeholders. The stakeholders were also categorised in the phases Pre-acquisition, Acquisition, Utilisation and Retirement. The concerns of the life cycle stakeholders were then identified. Time boxes of 15 minutes were used throughout the iteration to provoke out-of-the-box thinking amongst the team members.

4.2 ITERATION 2

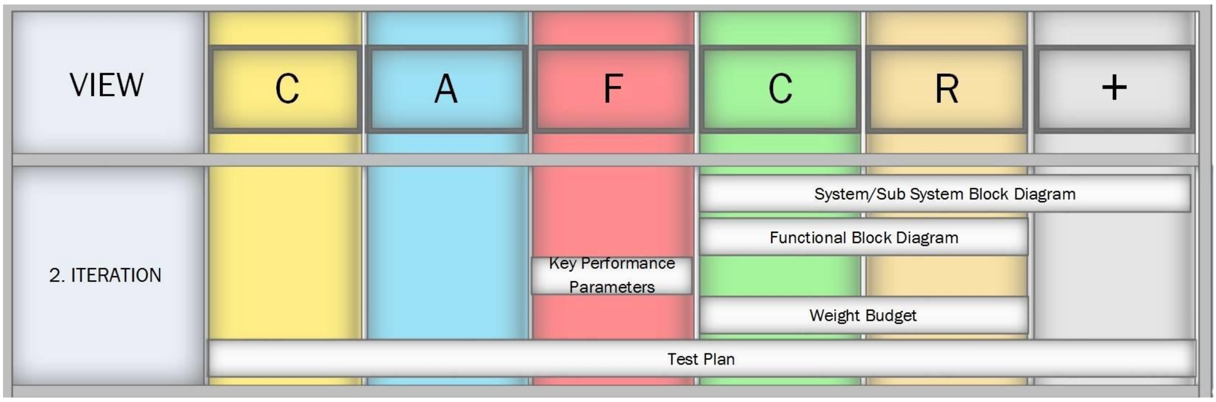


Figure 4.2: Iteration 2

In this iteration, a bottom-up perspective was used, to help understand the emergent system from the parts it consists of. The system and sub-systems were broken down into their components in a block diagram. Based on this a functional diagram was made, showing the internal interfaces in the system. Six key performance parameters were identified and displayed in a table. A preliminary mass budget was made, given that weight is one of the key parameters. The mass budget gave an indication of where later design challenges might arise. Finally, a simple table was made showing how some tests to verify the system could be carried out. The project plan was agreed upon and made into a Gantt diagram.

4.3 ITERATION 3

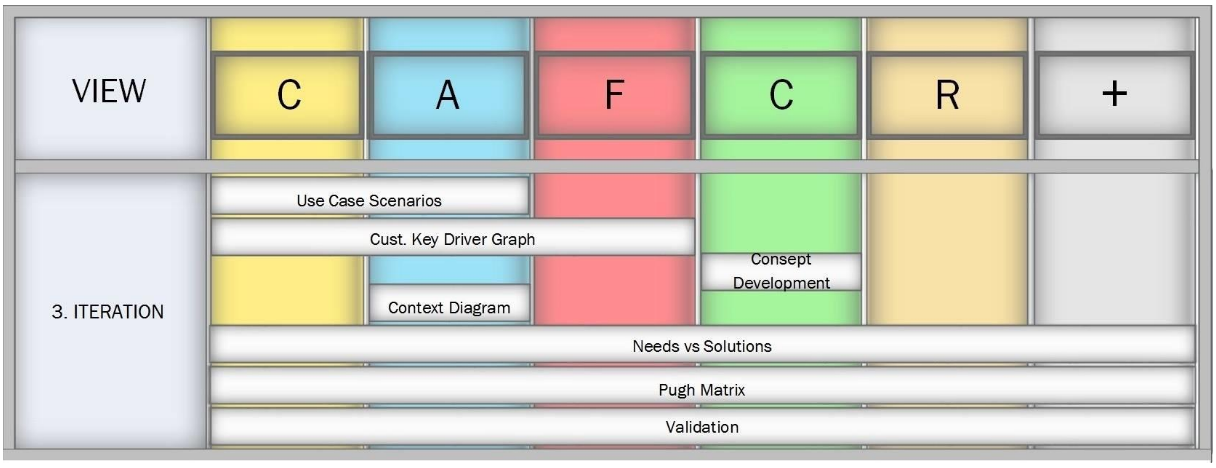


Figure 4.3: Iteration 3

Iteration three focused primarily on concept development and identifying possible solutions for the drone. Use case scenarios were made, where we challenged ourselves to think creatively and have an open mind about what applications the drone possibly could be used for. A key driver graph was made, connecting the key drivers with the derived applications. This helped in identifying the true objectives of the customer and what was needed to need them. Even though the general concept for the drone has been predetermined by the customer, there are still multiple concepts for how the project can be solved. Due to this we made a concept development text, explaining the importance of a sound concept. Pugh matrixes and other comparison methods were used to evaluate different solutions in airframe, motor, propellers, pitch mechanisms and power transmission. These comparisons helped us understand the design direction for the project and how we could best meet the project objectives. Time boxes of 20 minutes were used throughout the iteration.

4.4 ITERATION 4

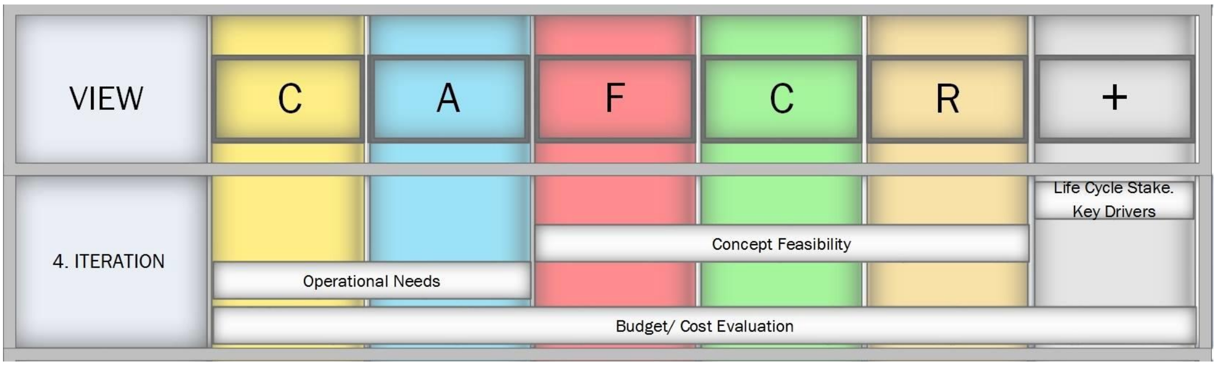


Figure 4.4: Iteration 4

In the fourth iteration, we focused on evaluating the concept and the surrounding factors, such as feasibility, needs and budget. A feasibility assessment was made discussing the technical and schedule feasibility of the project. Diagrams to show the methods we will use in order to make the technical aspects and schedule feasible were added as visual explanations. A document showing the operational needs was made. The operational needs regarding robustness, stamina, navigation, safety and ease of use were included, providing an easy-to-access overview of what to consider when making design decisions. Using excel, a budget for the project was made. It became apparent that all the customer's wishes could only be met with a budget of 15000 NOK. The expenses were divided into the categories "Prototype" and "Final Design". The prototype category primarily consisted of the costs regarding electric propulsion, while the final design category included the costs associated with combustion engine propulsion. After discussing the budget with the customer, the budget was approved, pending that a detailed purchase list is approved before ordering.

4.5 ITERATION 5

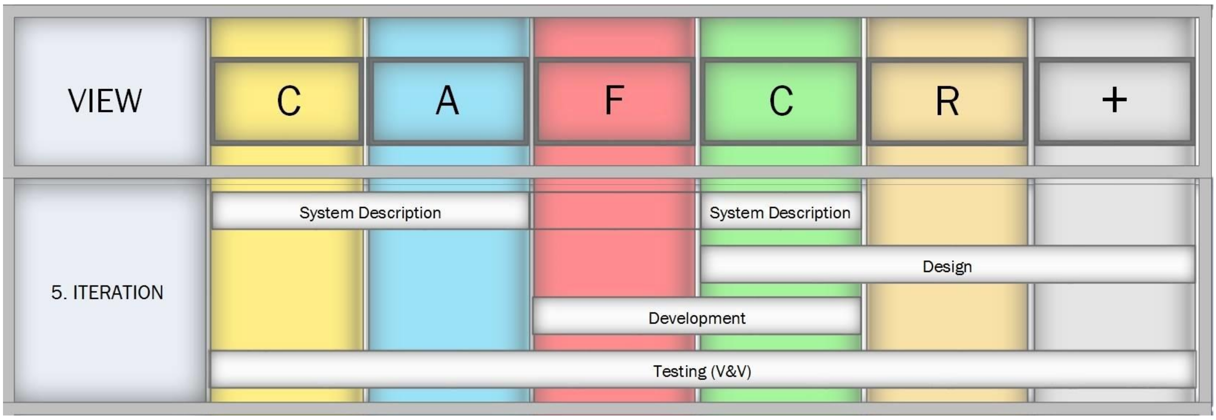


Figure 4.5: Iteration 5

The major focus of this iteration was the design of the system. Design, development and testing were the main tasks. Technical Document and Design Decisions Document were made. The exact components needed in the system were identified and listed, ready for purchase. Numerical calculations, modelling, simulation and Pugh matrixes were the main tools used for analysing the design and technical solutions. The reasoning behind the design solutions was described in detail in the technical documents. This way the design document itself could focus on the solutions and include only the fundamental reasoning, making the design document easy to read and providing an overview of the design. Solidworks was used extensively to make models and verify design concepts. Geometric and conceptual designs were constructed in SolidWorks and inserted in CAD-assemblies to check for interfaces and compatibility between the mechanical components. Drive train and airframe solutions were particularly in focus of CAD-modelling.

4.6 ITERATION 6

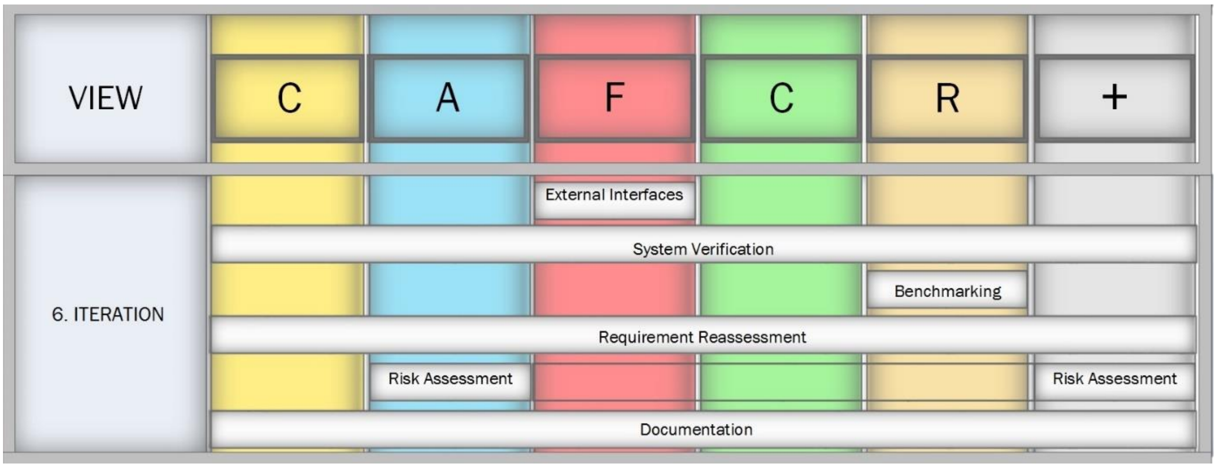


Figure 4.6: Iteration 6

Iteration six included defining the status of the system and relating it to the real world. The requirements were reassessed. Only minor clarifications to some of the requirement priorities were made. The system was compared to a similar existing system, benchmarking it against the competition. Both the similarities and differences between the systems was included in the benchmarking. A technical risk assessment was made, discussing both events, risks, impact and mitigation in the same format as for administrative risks. An example of a risk event was described, where the scenario was described with the consequences and the risk of the event occurring. How to reduce the probability of the event occurring was described, as well as several ways of mitigating the effects of the event should it occur. Most of the parts needed for constructing the system arrived by mail. System verification and evaluating the external interfaces was done, particularly in consideration of the arrived parts. Based on this, we iterated the design of the fuselage, making sure the interfaces between the sub-systems were still valid. We started manufacturing of the fuselage and programming of the flight-controller. Initial construction of the drone commenced, while verifying the design. All documents were updated.

4.7 ITERATION 7

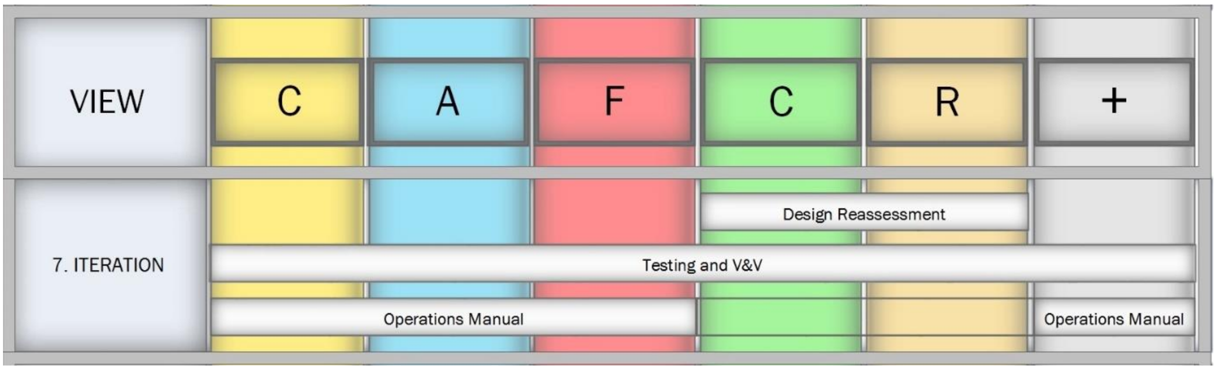


Figure 4.7: Iteration 7

The main focus of iteration 7 was design reassessment and prototype building. Since we ordered the parts before Easter, most of them arrived right after our documentation week, ready to be put together in our system. We had to align our design concepts in accordance with parts, subsystems and interfaces. In addition to these constrains, there were some design restrictions coming from manufacturing methods, which made us reassess our design and production. With a start up in manufacturing, we got more complete understanding of how the system should be put together. There were some design choices which had to be redesigned.

During manufacturing, we started testing the system according to what could be done in the distinct stages of development. The system was tested partly, verified and validated in accordance with requirements.

The operation manual was under production in this iteration, which describes how to operate the system and how to perform its maintenance.

4.8 ITERATION 8

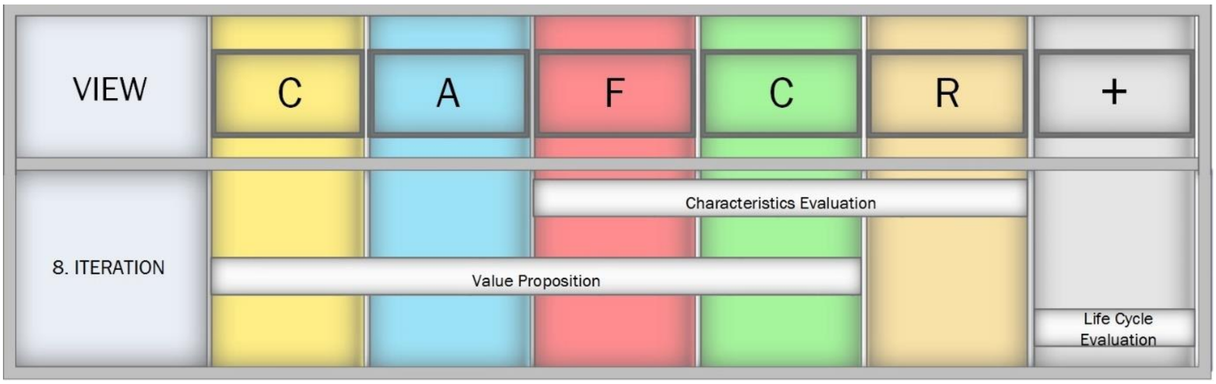


Figure 4.8: Iteration 8

Iteration 8 was the final iteration, marking the conclusion of the bachelor thesis. The main focus in this iteration was defining the system and its place in the real world, as well as making the final alterations to the prototype.

In this last iteration, all the remaining tests, validations and verifications were completed, on the final prototype. The system was evaluated by the project team, and possible improvements and future design reassessments were discussed.

5 LIFE CYCLE

A key part of the CAFCR+ development model address the life cycle view. Many of the activities we did during the first stages of the project - such as defining customer objectives, stakeholder concerns and key drivers – has helped in giving us a holistic view of the project. This holistic view has expressed itself particularly in regards to the life cycle of both the project and the product.

Any project has a defined start, but how the project ends and the project's path from cradle-to-grave is not. We quickly realised that this project had two different potential life cycles.

The first life cycle is through a commercial path. In this scenario, the project will be continued after the Bachelor Thesis has been concluded. We would register a company and continue the project in a commercial setting. Optimising the design for simpler product manufacturing, reducing component cost by negotiating trade deals with suppliers and improving functionality in accordance with the Conclusions & Recommendations document would drastically improve the value proposition of the system. Given the uniqueness of the product and the utility it can provide, there is a legitimate potential that it can meet a market need. Please see the Conclusions & Recommendations document for further future improvements.

The second project life cycle revolves around the College University of Southeast Norway. From the offset of the project we realised that we had the potential to create a system that could be used for further development by upcoming Bachelor projects or for educational purposes. Other Bachelor projects could consist of building on the system we have created, focusing for instance on autonomous flight or attempting to break the record for flight duration by using an internal combustion engine. The high payload capacity and the design of the airframe with room for mounting a large payload, allows for mounting several different instruments or a large fuel tank to the drone.

Through system engineering we have been able to account for both project life cycles. Getting a holistic view of the system at an early stage of the project was encouraged by the CAFCR+ development model, and we are left with a system that can be led down both paths.

The life cycle of the system itself has also been accounted for, especially in regards to recycling when the drone is disposed of. Please see the User Manual for further details about proper disposal of the system. The system-to-user interface and maintenance needs has also been a natural life cycle focus. The flight controller and the computer interface has been selected for its possibilities for adjustment and to satisfy both novice and professional pilots.

In order to maintain full functionality of the drone throughout its life time, service parts such as propellers and belts are commercially available. The open design of the airframe makes for good access to the internal components. Components are fastened with screws, bolts and Velcro, so that only a basic tool kit is needed to work on the drone. This has been done to ensure that a layman can maintain and repair the drone if needed.

Upgradeability is another aspect of the system life cycle. The drone is configurable, and is inherently susceptible to upgrades. The open airframe makes the interfaces between components visible, so the architecture can to a large extent be understood from inspection. Propeller blades can be changed as the operator sees fit, another flight controller can be used, another radio controller with a matching transmitter can be used [ref. User Manual] and the MMS allows for new engines and gear ratios. The combination of this allows the system to be upgraded and to keep pace with future technological advancements.

6 Evaluation of the System Development Model

The CAFCR+ development model was chosen for this project due to its viewpoint hopping encouraging a holistic view, stakeholder focus and active altering between top-down and bottom-up perspectives. The different views used throughout the iterations encouraged us to keep many different perspectives in mind simultaneously, looking at the problems from different angles. The iterations altering between top-down and bottom-up perspectives allowed us to balance between general and specific thinking about the challenges at hand.

Some specific examples of situations where the development model has aided in realizing the project are described below.

6.1 Weight Constraint and Requirement Issues

We ordered most of the parts needed to build the prototype before the Easter holiday. This way we could make use of the holidays to have most of the parts needed for construction ready after Easter. When the parts arrived however, we realised that some of the parts were different – heavier - than what we had expected. Particularly the gears were much too heavy. The effect of this added mass was amplified by the fact that we designed the system for robustness and for an internal combustion engine to be integrated.

At this point we realised that the actual product we would produce would not be in accordance with the RO1 weight requirement of 2.5 kg. This was a critical moment in the project, and the CAFCR development model allowed us to see the problem and act accordingly.

The CAFCR model stresses stakeholder communication and making sure the key stakeholders are kept in the loop. We immediately organised a meeting with our customer and informed him of the recent developments, allowing him to make an assessment of the situation and being part of the decision making. The scientific nature of the project and the fact that the combustion engine version of the drone is not constrained by RO1, meant that we could continue with the project as is.

Through the CAFCR model we spent most of the early iterations documenting and structuring the project. A function of this is that a Boundary & Scope document was made already in the second iteration. This document states that RO1 requirements are not the focus of the project.

Still, Requirement C05.2 dictates we should have a version of the drone weighing under 2.5 kg. Although the product we physically make – as discussed with the customer – will not be under 2.5 kg, the system we design will be. The iterative nature of the development model allows us to alter the design and document what the final product will be like. This way we can document the final design, beyond the physical drone we deliver for the Bachelor thesis itself. This is the system that will be built in a commercial setting, or if we choose to continue the project after the Bachelor project has been officially concluded.

This critical moment in the project could have been catastrophic. Through the development model and its focus on continuously documenting, keeping key stakeholders in the loop, iterating the design and designing beyond the next prototype, we managed to mitigate the effects of the issue and still prove that we have designed a product that meets the requirements.

6.2 Specificity versus Genericity

Regardless of the type of project, most development teams struggle with balancing genericity and specificity in the development model [4]. Finding the right balance between generic and specific architecting of the project is an integral part of the CAFCR development model.

In general, the generic aspects can be validated, while specific aspects can be verified. The job of the system engineer is to find the balance between genericity and specificity. The balance between being carried away by general thinking and being overwhelmed by details must be found. The risk of being too generic is that definitions and solutions can become too abstract, while being too specific can result in spending too much time defining details that add little value to the project.

Generic definitions that are difficult to validate or are poorly linked to reality is not only a problem in itself, it can also lead to the team overcompensating with the specific definitions. The risk of poor generic definitions is the team struggling to understand the large picture and as a result make incorrect specific solutions.

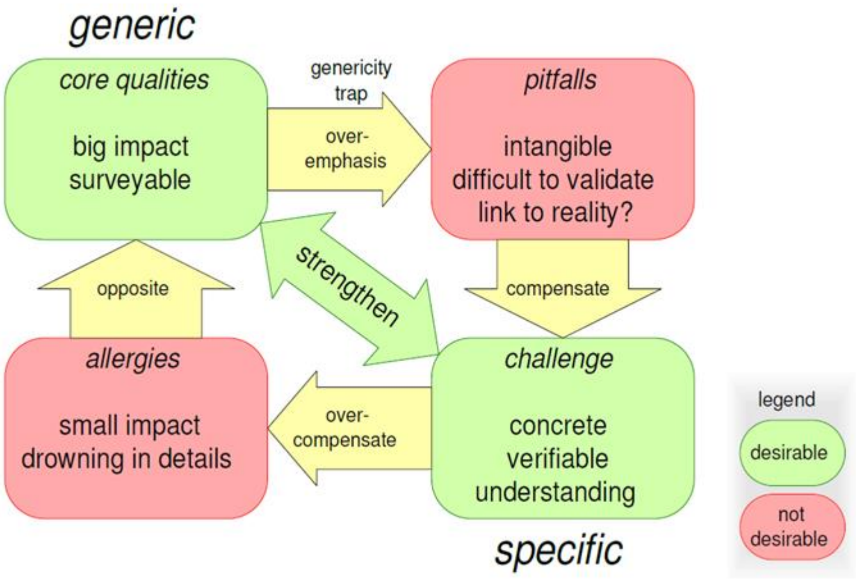


Figure 6.1: Genericity Vs Specificity model

The CAFCR development model contains models for managing this balance, as shown in figure 6.1. Good generic solutions that are surveyable and validatable will often strengthen good specific solutions that are verifiable. This model has helped us in understanding the context of the system, which can be validated, and then link this to the individual components and details, which can be verified.

An example of this balancing is in the architecture around the single engine powering the system. Due to the need of using several different engines, we had several requirements regarding the time needed to switch between propulsion systems. The generic solution to this was to fasten the propulsion system in an inherently simple fastening manner. By fastening the engine and some of its sub-components on one bracket, the entire assembly could be fastened and unfastened quickly and easily. This solution was both surveyable and validatable. The specific solution was to design the bracket and its interfaces with the rest of the airframe, fastened with screws and with positions for the specific sub-components of the assembly. Making a validatable generic concept made us better able to create a concrete specific solution.

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Appendix A: Iteration Protocol

TABLE OF CONTENTS

1 Iteration 1

1.1 Customer Stakeholders

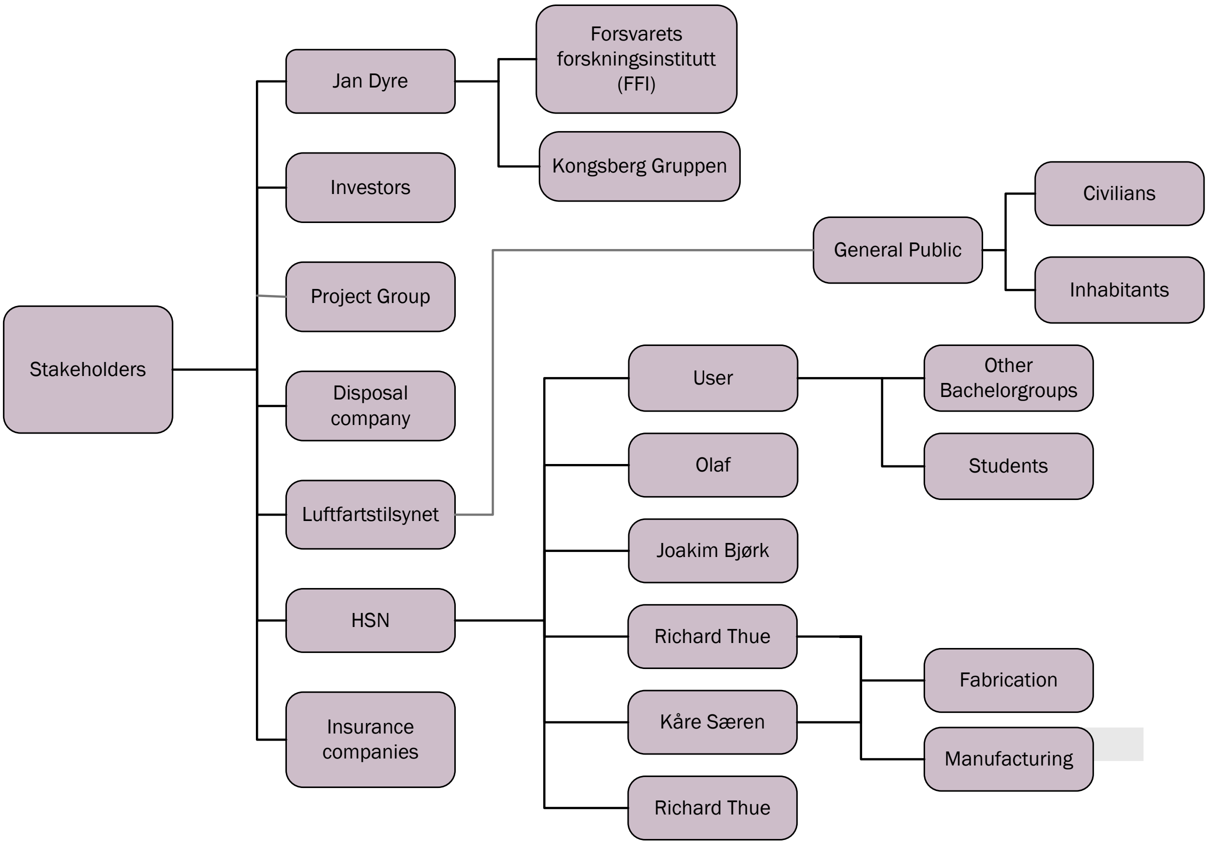


Figure 1.1: Customer stakeholders

1.2 Customer Objectives

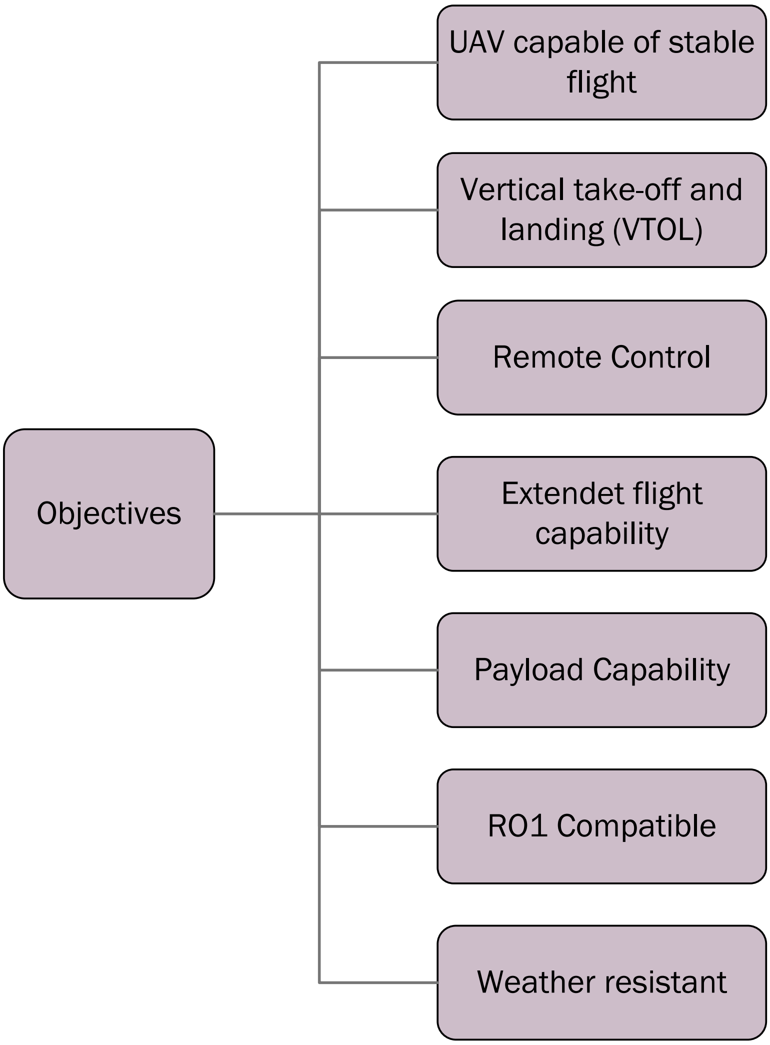


Figure 1.2: Customer Objectives

1.3 Life Cycle Stakeholders

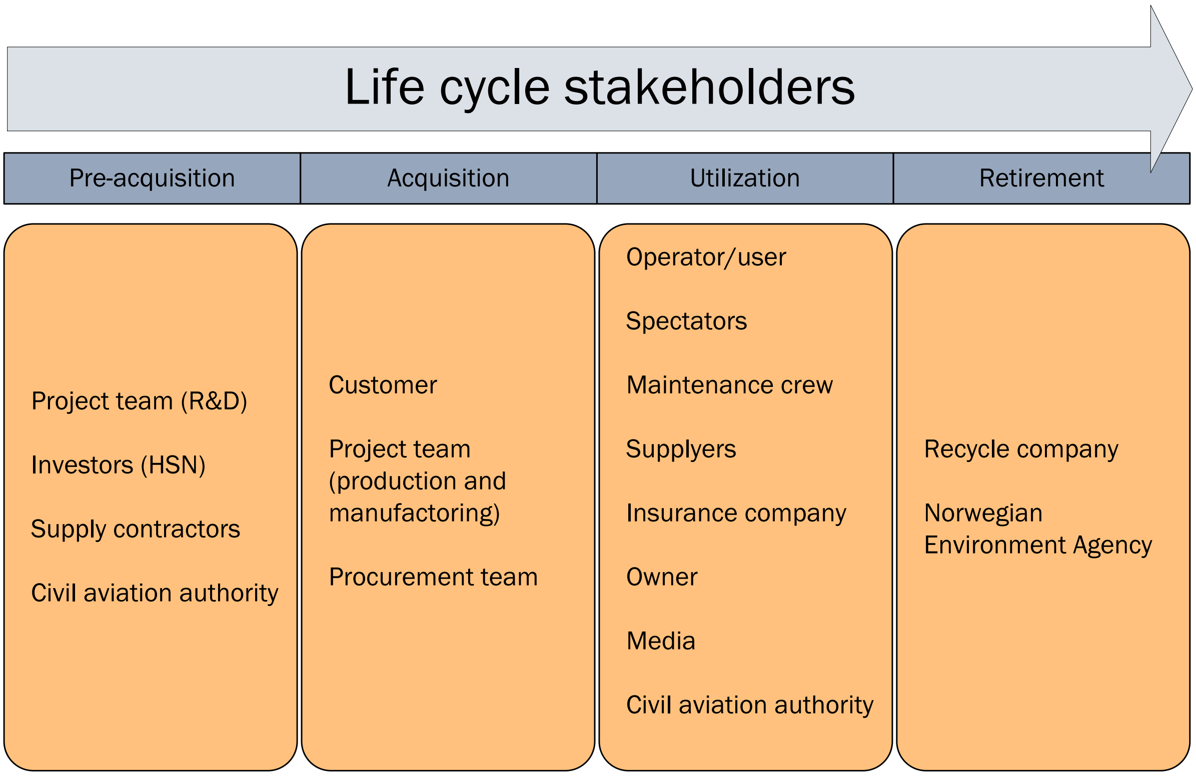


Figure 1.1.3: Life Cycle Stakeholders

1.4 Life Cycle Stakeholder and their Concerns

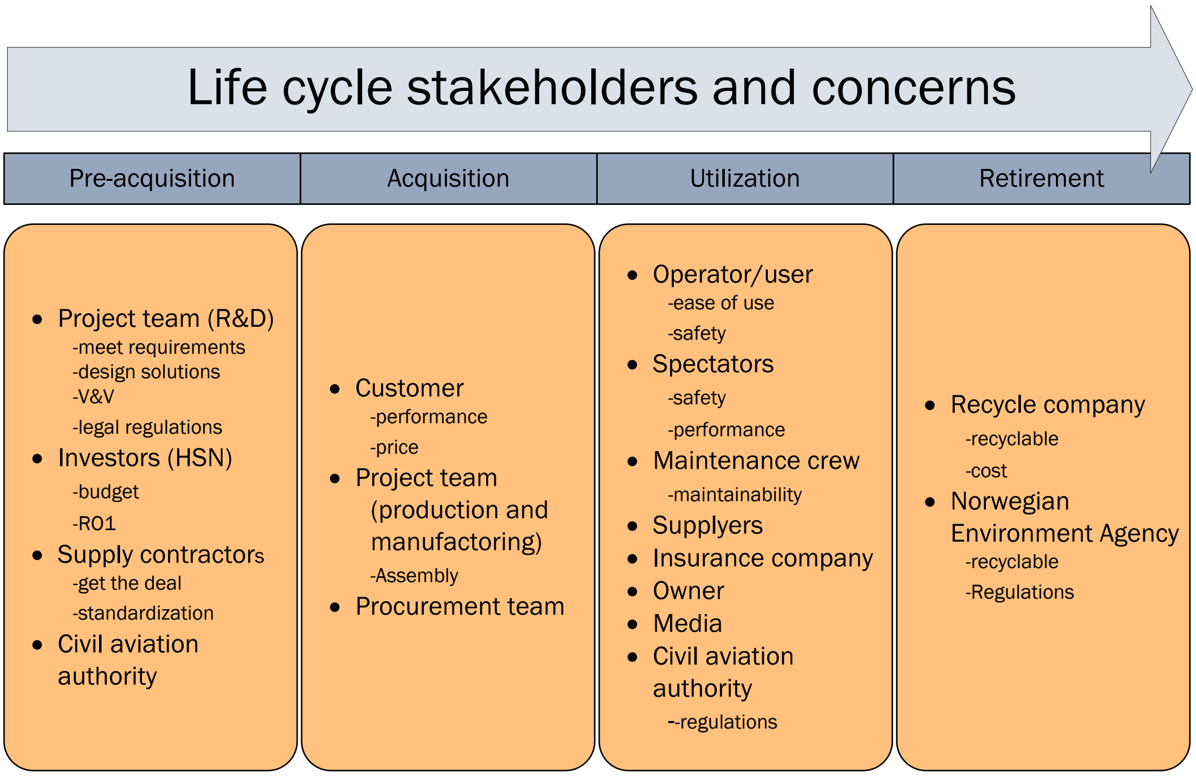


Figure 1.4: Life Cycle Stakeholders and concerns

1.5 Stakeholders & Concerns

Stakeholders and concerns	
Høgskolen i Sørøst-Norge	RO1, budget (investment)
Civil aviation authority	RO1, safety
Users	Students, teachers, all kind of people
Operators	Ease of use, safe
Customer	Payload, ease of use, price, quality, operational time
Project group	Deadlines, good result, cooperation within group/from customer (feedback)
Spectators	Safety
Insurance company	Safety, risk assessment
Competitors	Patent
Maintenance team	Ease of repair
Recycling plant	Recyclable

Lifecycle stakeholders: Maintenance team, Recycling plant

Figure 1.5: Stakeholders and concerns

1.6 System Applications

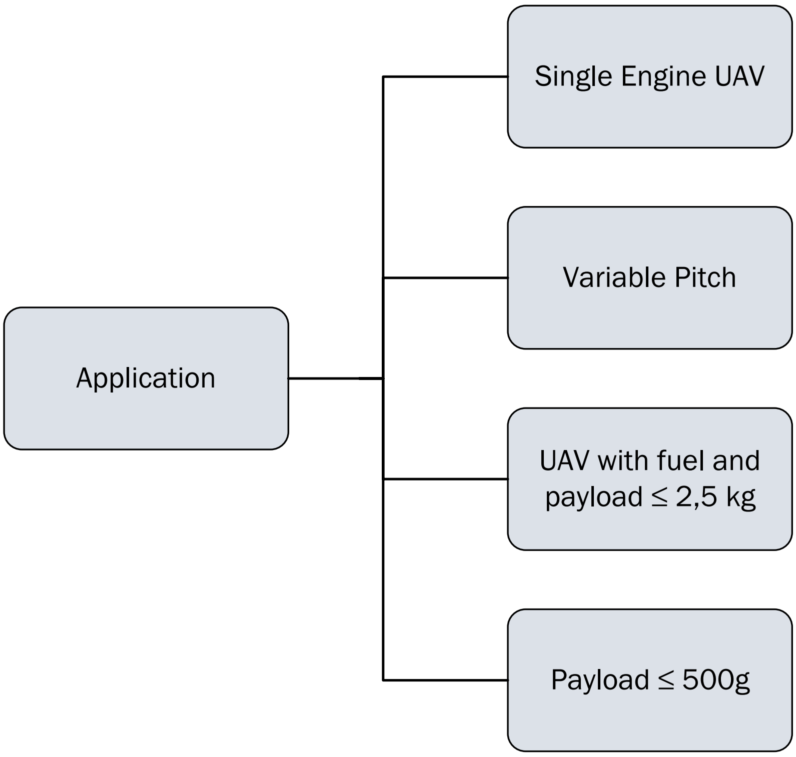


Figure 1.6:System Application

1.7 Initial Design

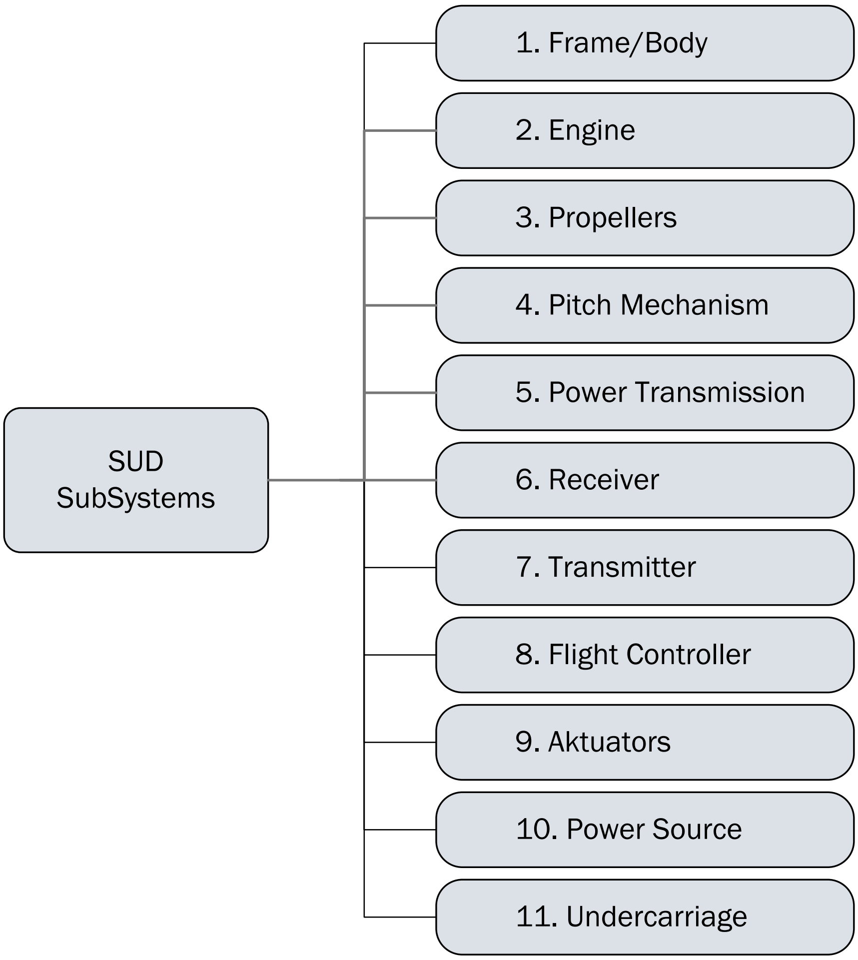


Figure 1.7: System Under Development Sub-Systems

1.7.1 Structure Alternatives

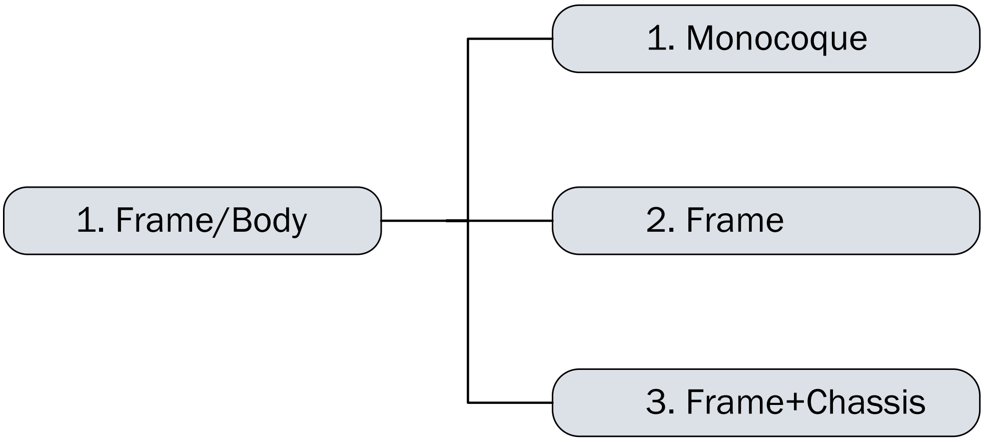


Figure 1.1.8: Structure Alternatives

1.7.2 Engine Alternatives

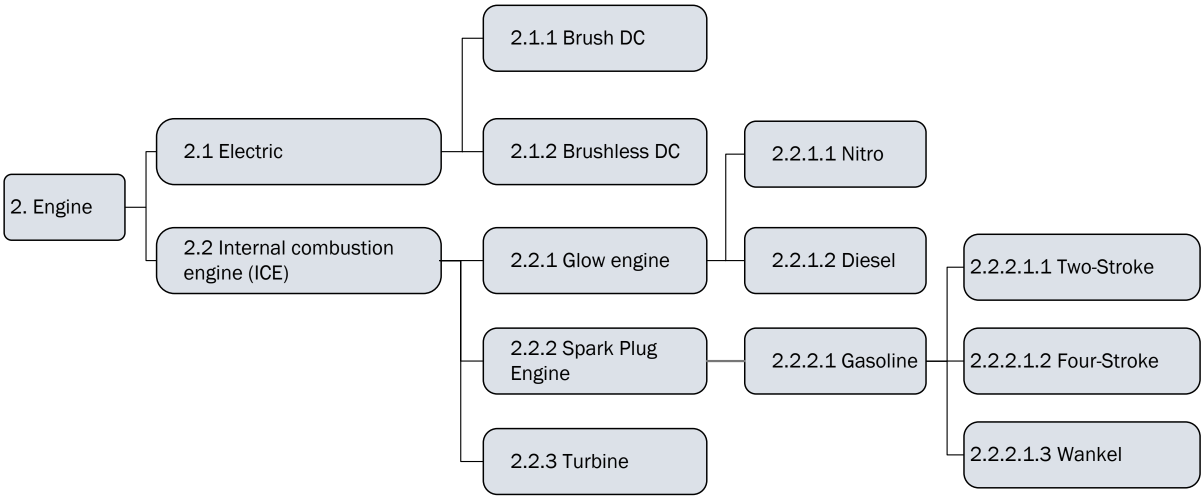


Figure 1.9:Engine Alternatives

1.7.3 Propeller Alternatives

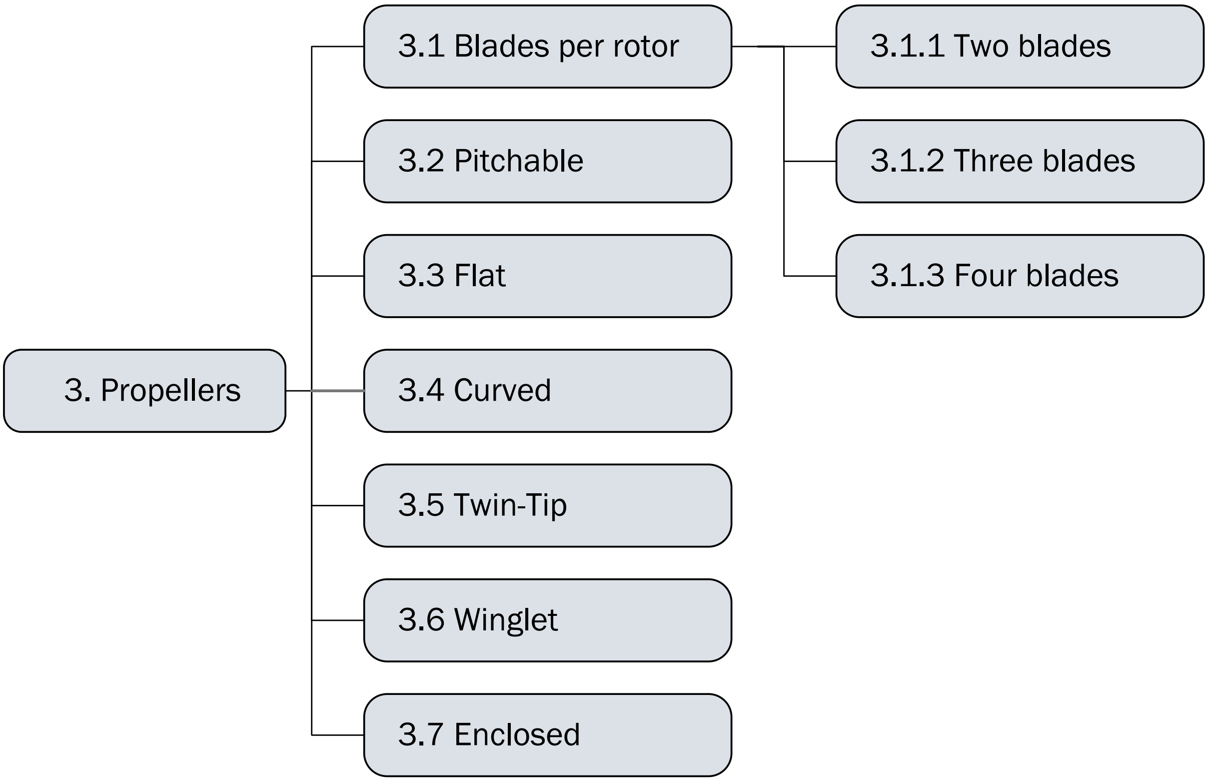


Figure 1.1.10: Propelles Alternatives

1.7.4 Pitch Mechanism Alternatives

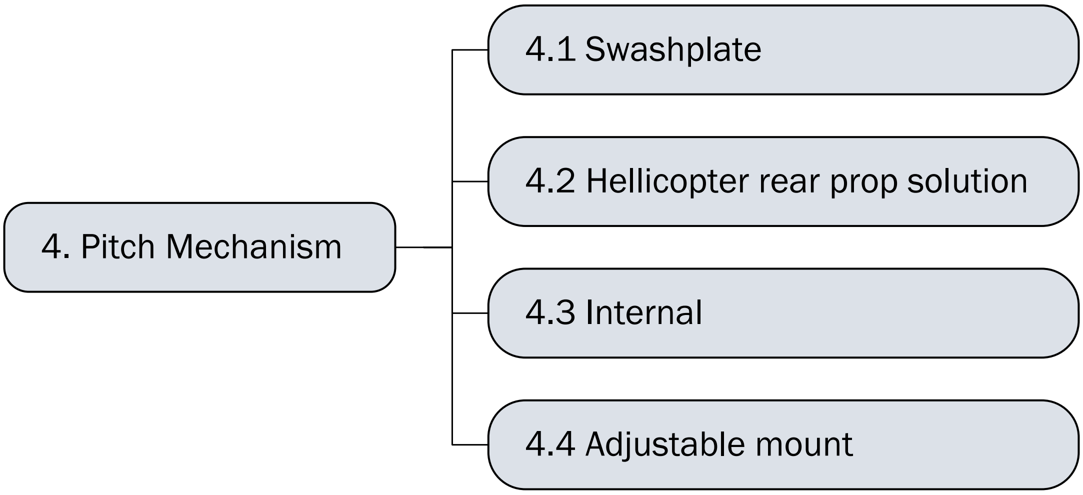


Figure 1. 1.11: Pitch Mechanism Alternatives

1.7.5 Transmission Alternatives

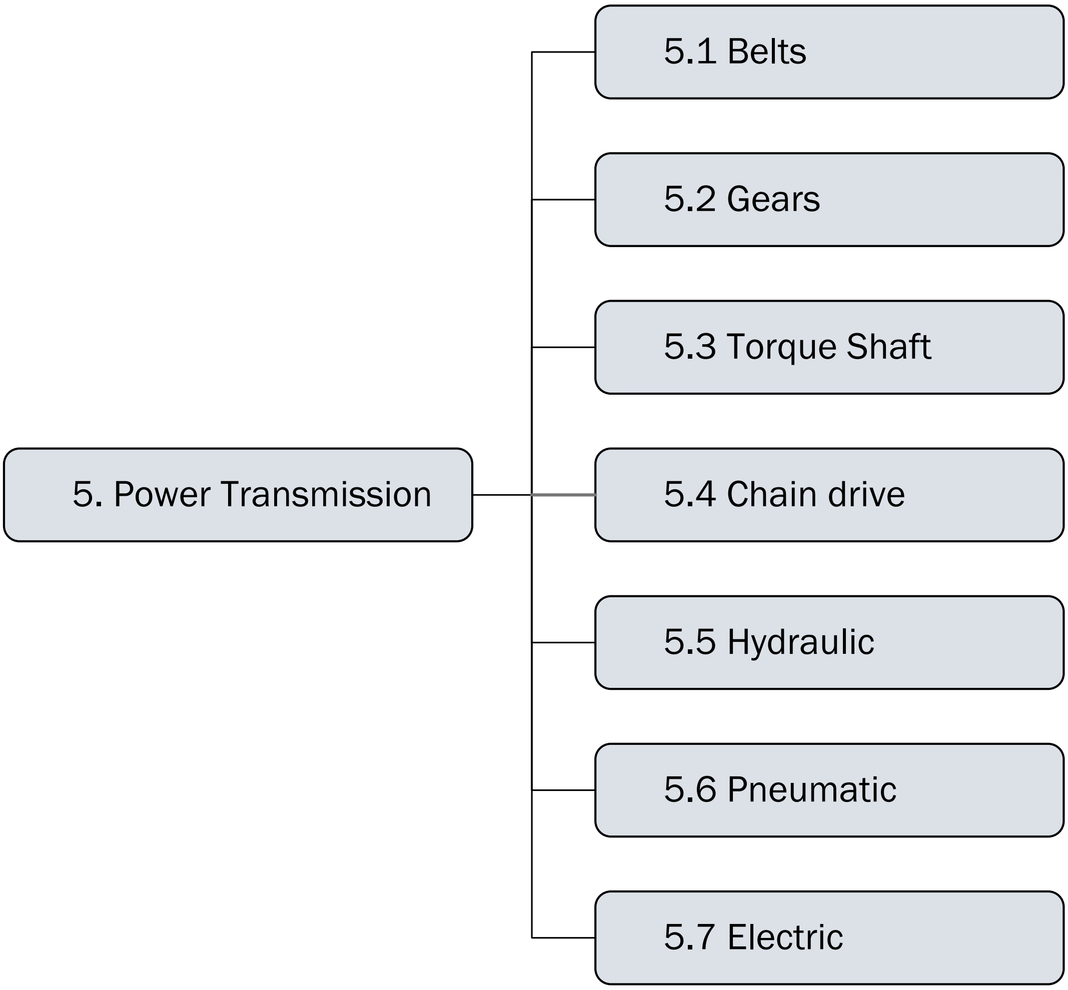


Figure 1.1.12: Transmission Alternatives

1.7.6 Receiver Alternatives

Figure 1.1.13: Receiver is receiver

1.7.7 Transmitter Alternatives

Figure 1.14: Radio Transmitter

1.7.8 Flight Controller

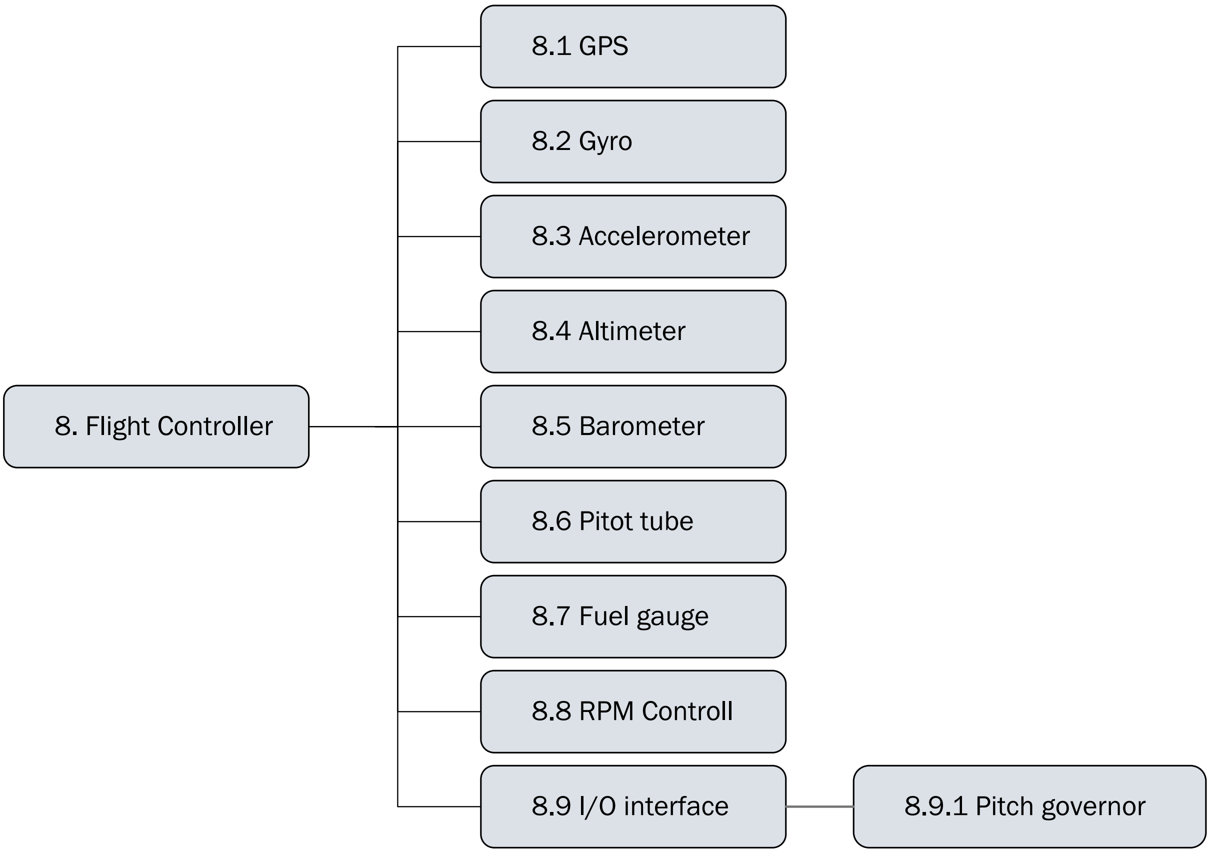


Figure 1.15: Flight Controller Functions

1.7.9 Actuator Alternatives

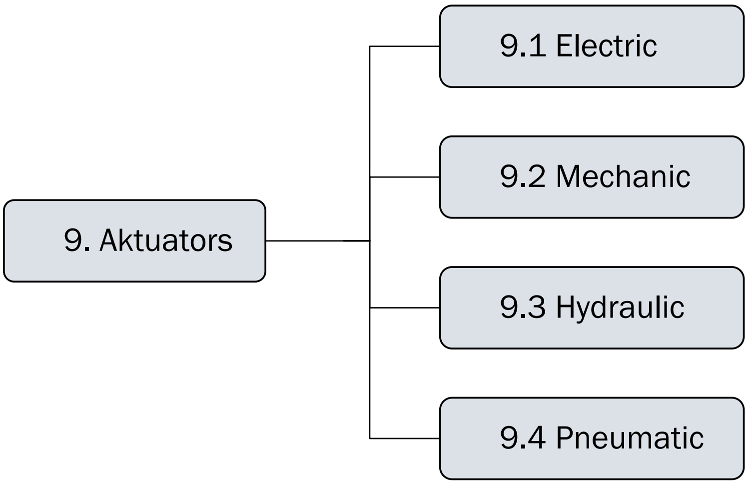


Figure 1.16: Actuator Alternatives

1.7.10 Power Source Alternatives

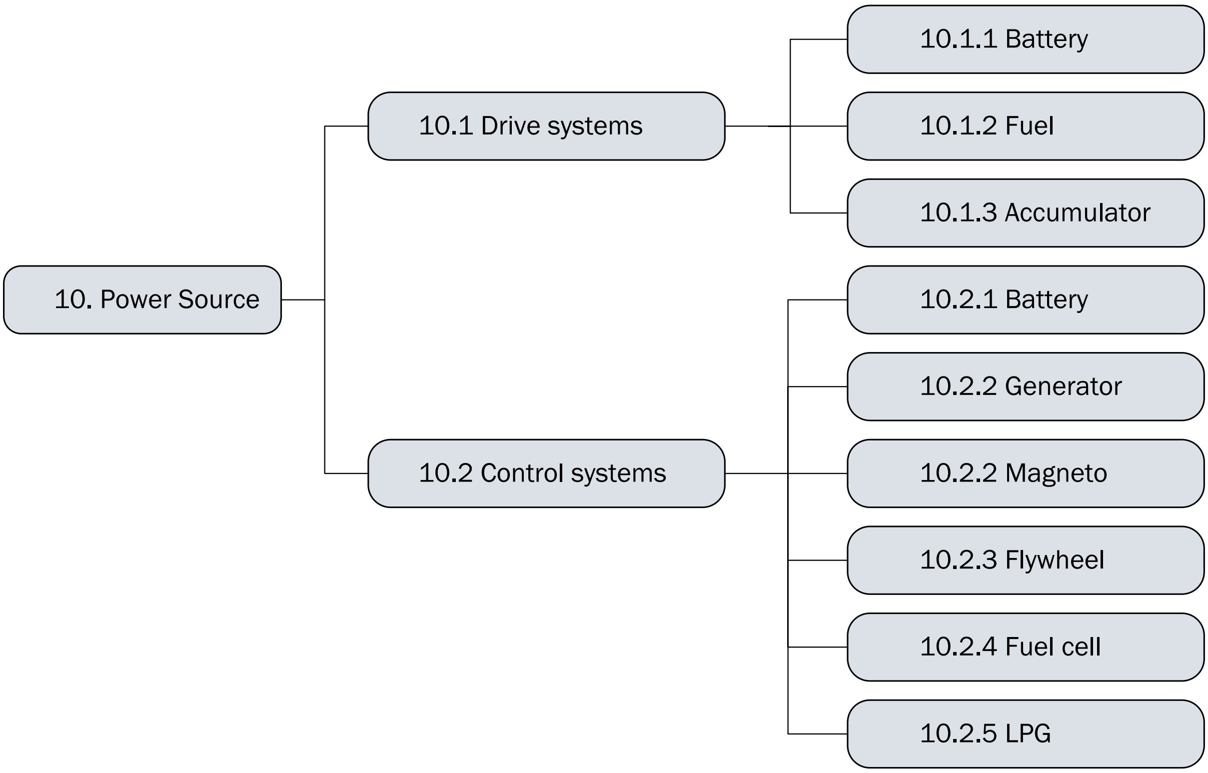


Figure 1.17: Power Source Alternatives

1.7.11 Undercarriage Alternatives

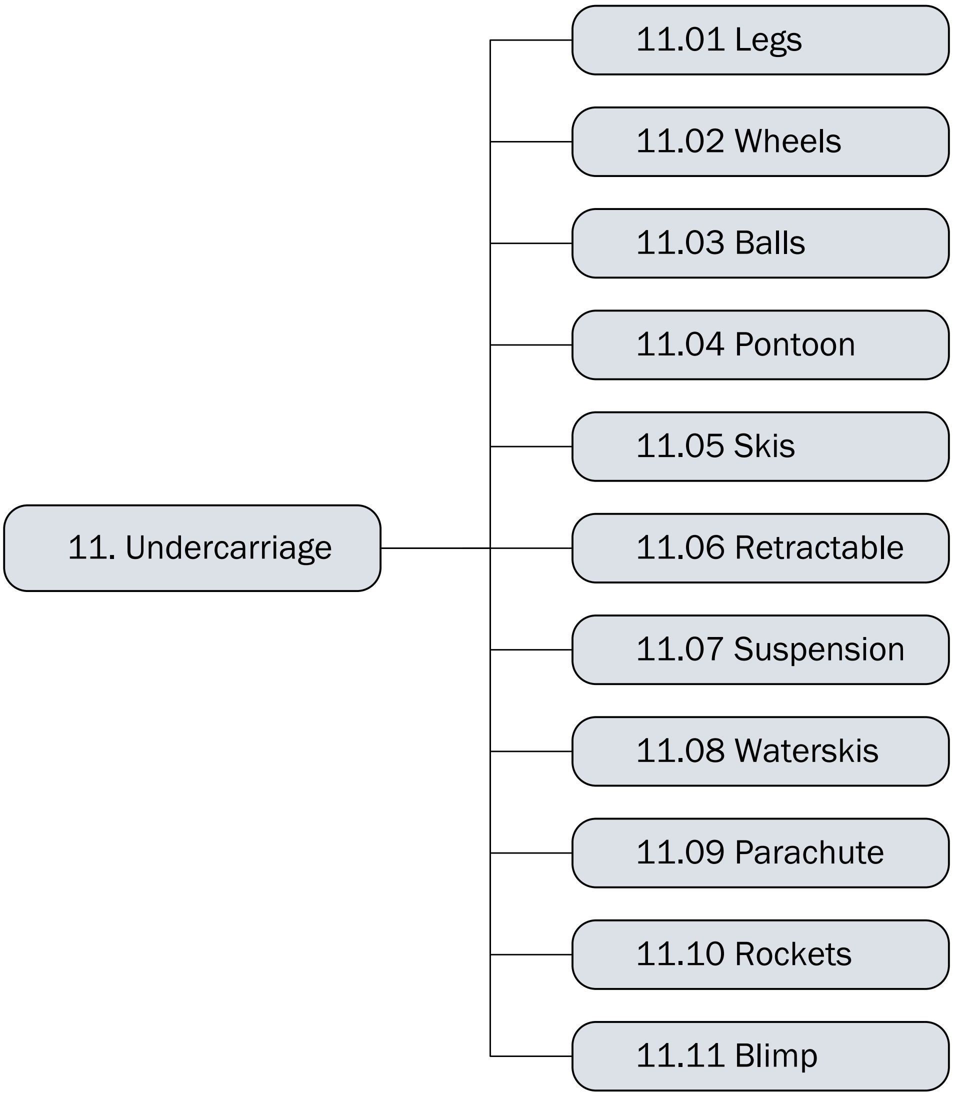


Figure 1.18: Undercarriage Alternatives

2 Iteration 2

2.1 System Block Diagram

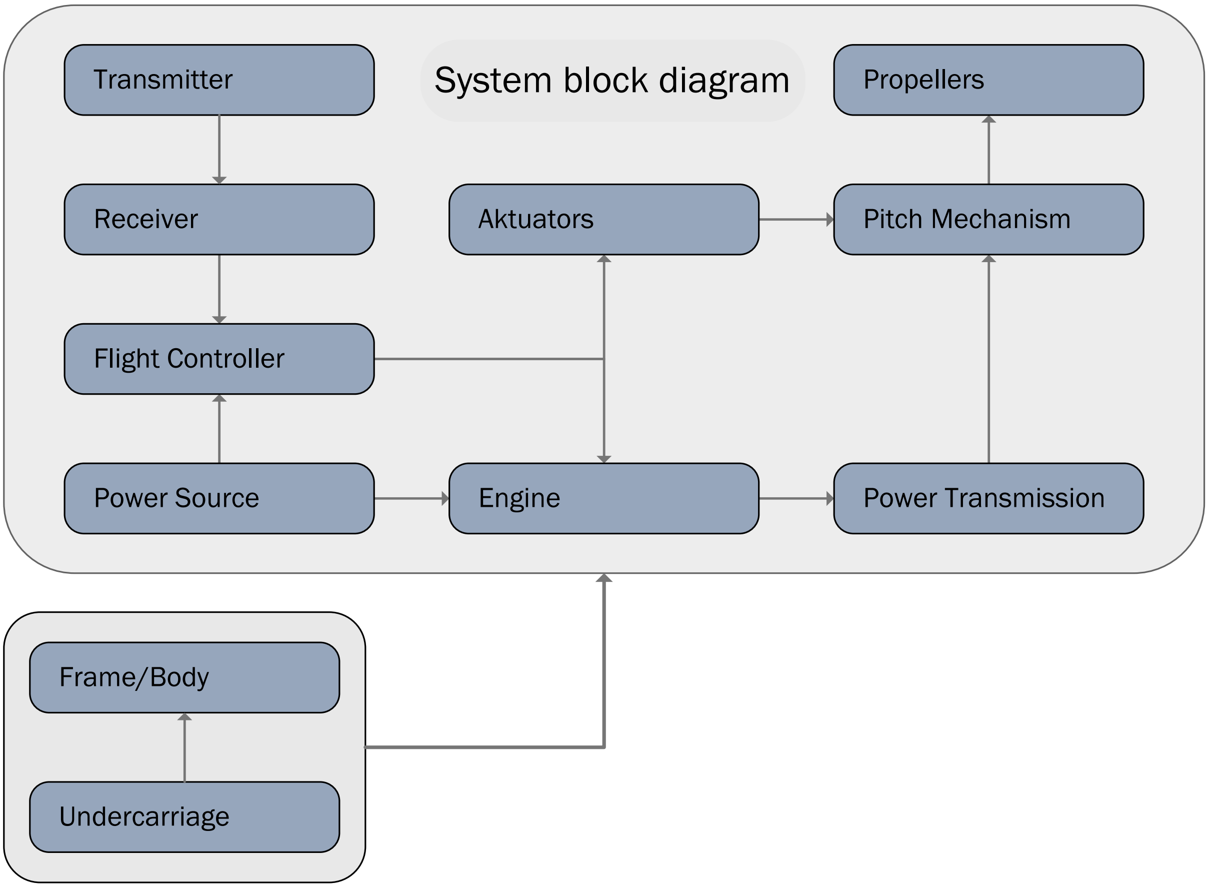


Figure 2.1: System block diagram

2.2 Functional Block Diagram

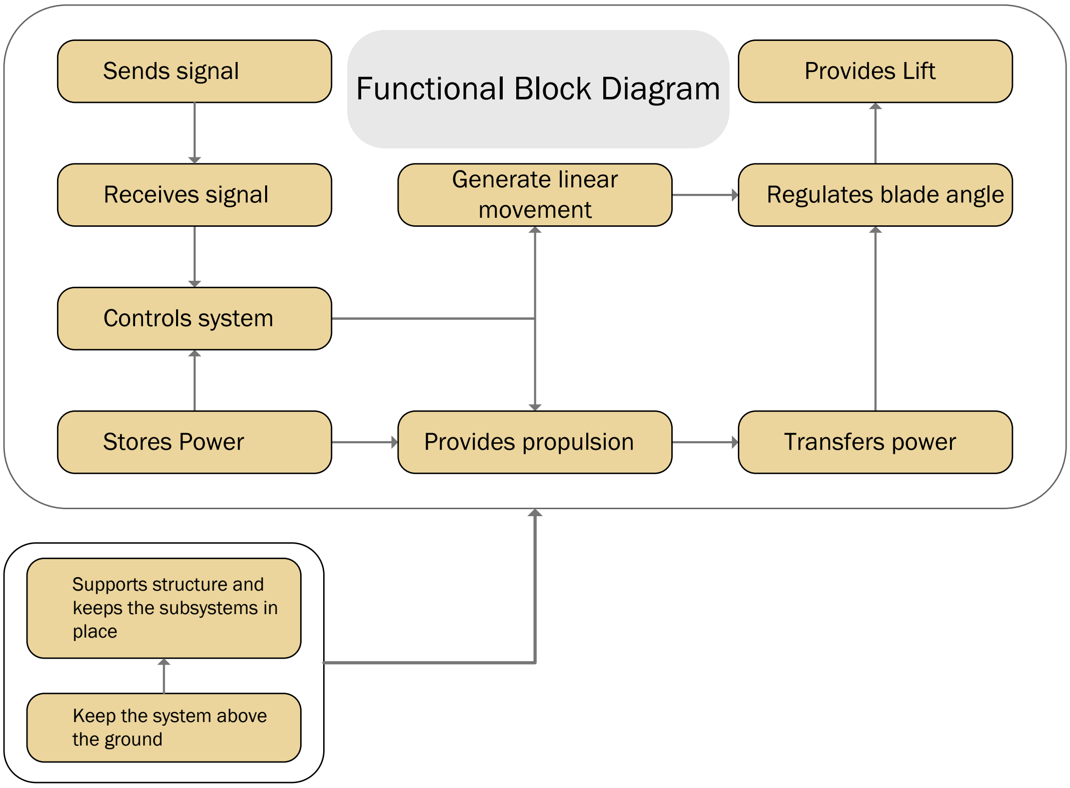


Figure 2.2: Functional Block Diagram

2.3 Key Performance Parameters

Key Performance Parameters	
Weight:	≤ 2,5 kg
Wind tolerance:	≤ 20 m/s (stiv kuling)
Flight time:	≤ 30 min
Range:	≤ 2,5 km (line of sight)
Speed:	≤ 60 kn
Payload capability:	≤ 500 g

Figure 2.3: Key Performance Parameters

2.4 Technical Budget (Mass)

Technical Budget (Weight)	
Frame/Body	350 g
Engine	470 g
Propellers x4	80 g
Pitch mechanism x4	180 g
Power transmission	200 g
Flight controller w/sensors	100 g
Actuators x4	80 g
Power source	500 g
Undercarrige	40 g
Grand total:	2000 g

Figure 2.4: Technical Mass Budget

2.5 Test Plan

Test Plan	
What	**How**
Altitude	Altimeter, barometer, radar
Speed/Velocity	GPS, Airspeed sensor, pitot tube
Weight	Place on scale
Power/weight	Bagage/fish scale
Variable Pitch mechanism	Visual inspection
Safe landing system	Engine cut-out test
Controllable by operator	Visual inspection
Engine swap	Physical inspection

Figure 2.5: Test Plan What and How

3 Iteration 3

3.1 Use Case Scenarios

Scenario 1:

Ola owns land along the river in Lærdal, an excellent and popular fishing area for fly fishers all over the world. Ola runs his own business providing services for the fishermen who comes to his place. He offers include fishing, hut rental, food and drinks service. There is a long waiting list and the business is going well. For an extra innovative service, Ola wants to offer private drone filming to capture each fly fishers experience and their moments with nature. To monitor the fish and get the entire fishing sequence on tape, he needs a drone who is capable of changing directions quickly and have an operational time of 15-45 minutes.

Scenario 2:

The universities in Norway has started a RO1 drone race and HSN has asked us to develop a drone for the race. To have the winning chance, the drone should have as low weight as possible, good manoeuvrability and operational time. The race takes place in open terrain where the drone must come through an obstacle course. The race consists of 3 laps. The first drone who has completed the race wins.

3.2 Key Driver Graph

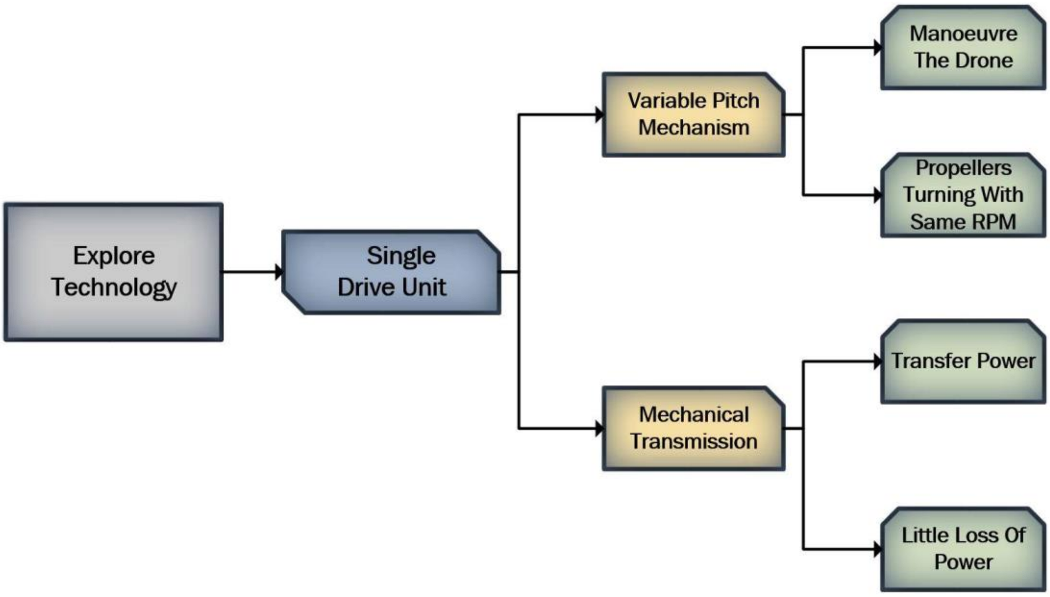


Figure 3.1: Key Driver Graph

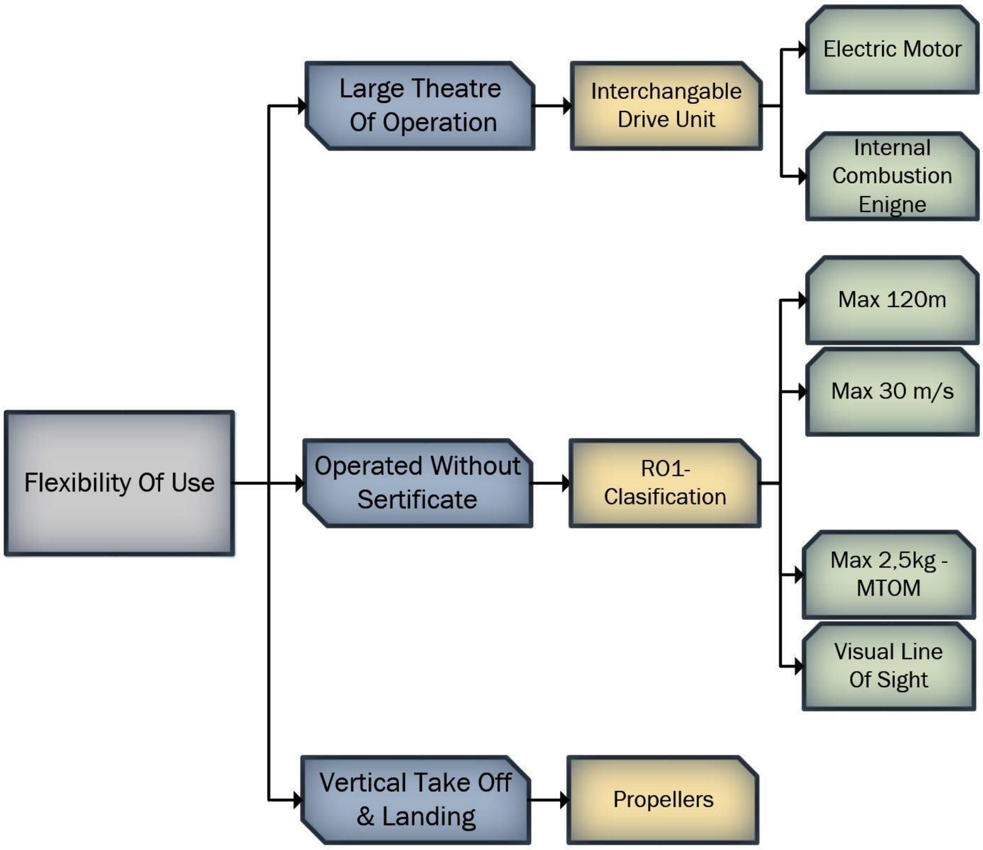


Figure 3.2: Key Driver Graph

3.3 Concept Development

As the system concept will dictate what the end outcome will look like, it is paramount to investigate multiple concepts. If the system concept is not optimal, then neither will the result be.

The systems concept will be the way or the method of which the objective will be reached. For example, if the objective is to steer a drone, one concept can be to vary each propeller’s speed while another concept can be to vary the pitch angle of each propeller.

For a given systems engineering problem, there will be many alternative system concepts. There are often multiple ways or reaching an objective, or multiple alternative design concepts.

In other to understand what can be achieved, you must first understand how it can be achieved.

I order to create a competitive system design; the system concepts must be investigated prior to defining a set of system performance requirements. Failing to examine a sufficient range of concepts, will lead to suboptimal solutions or solutions that do not adequately meet the performance requirements.

3.4 Context Diagram

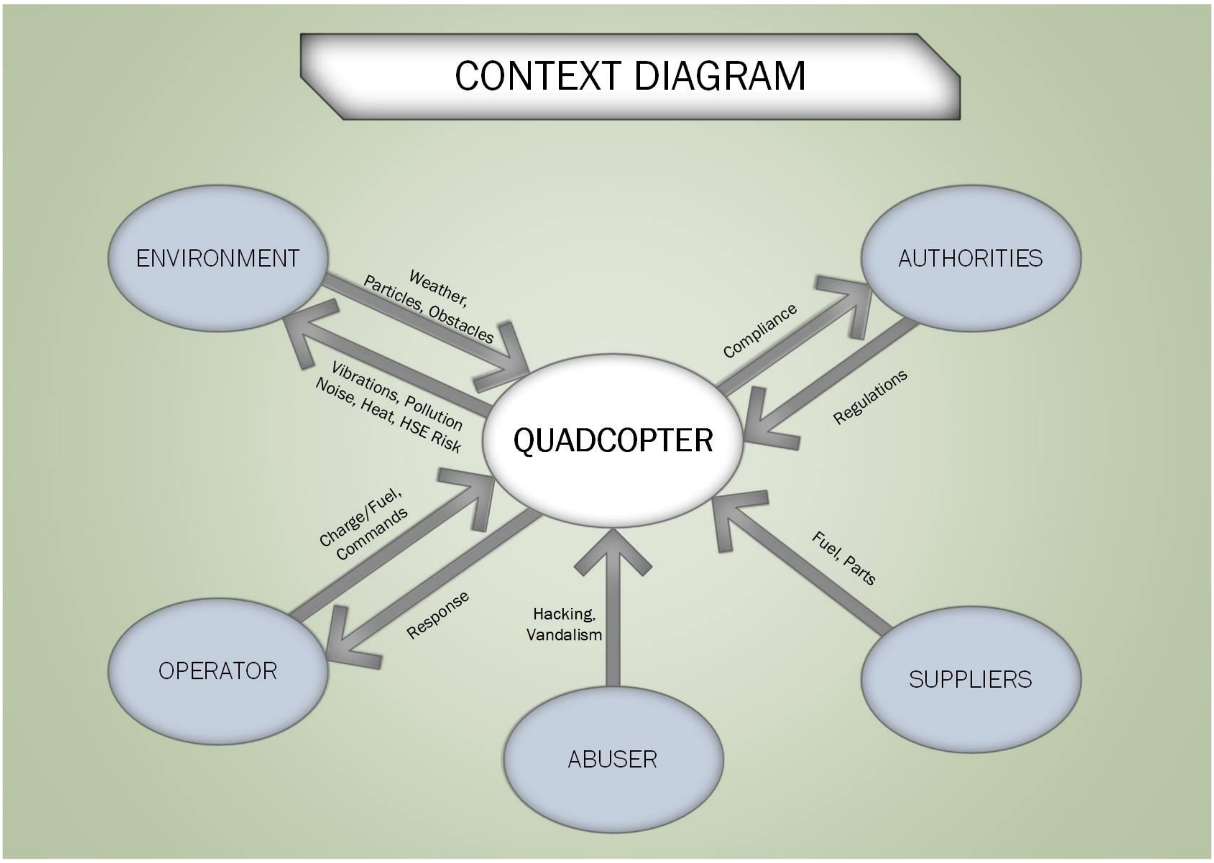


Figure 3.3: Context Diagram

3.5 Needs vs Solutions

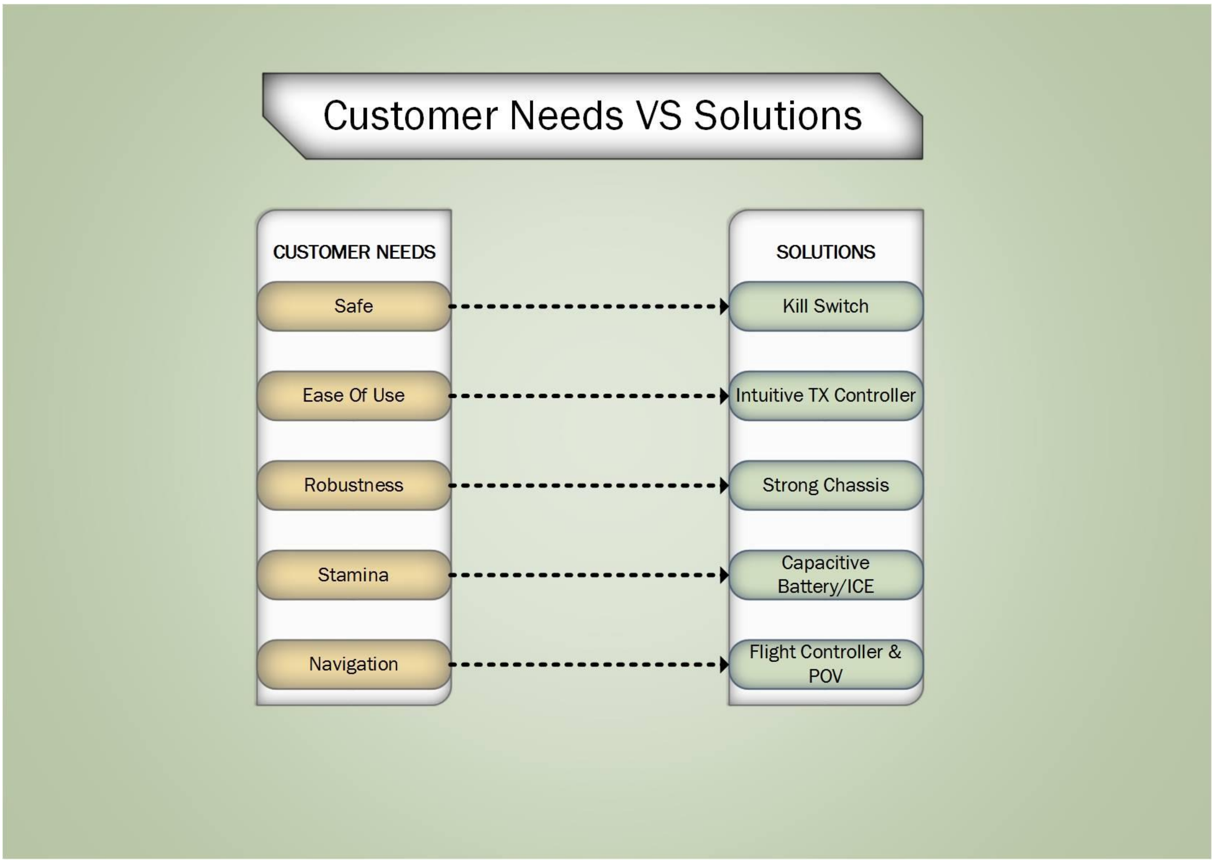
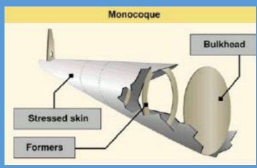
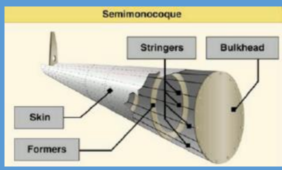


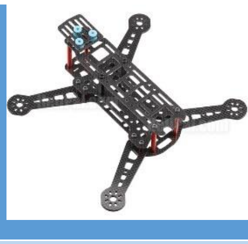
Figure 3.4: Customer Needs VS. Solutions

3.6 Pugh Matrix Validation

3.6.1 Frame







		Monocoque		**Semi-Monocoque**		**Frame**	
Criteria	Criteria Weight	Score	Weight %	Score	Weight %	Score	Weight %
Weight	0.3	5	1.5	4	1.2	3	0.9
Cost	0.2	3	0.6	2	0.4	4	0.8
Reliability	0.2	3	0.6	5	1	3	0.6
Maintenance	0.1	1	0.1	2	0.2	5	0.5
Complexity	0.2	3	0.6	2	0.4	5	1
SUM	1	15	3.4	15	3.2	20	3.8
Winner	**Frame**						

3.6.2 Motor

Motor Comparison Matrix							
Criteria		Weight	Cost	Reliability	Efficiency	Complexity	Sum
Criteria weight		0,35	0,15	0,15	0,25	0,10	1,00
Brush DC	Score	4	5	4	4	5	22
	Weighted	1,40	0,75	0,60	1,00	0,50	4,25
Brushless AC	Score	4	4	5	5	4	22
	Weighted	1,40	0,60	0,75	1,25	0,40	4,40
Nitro 2-stroke	Score	4	4	2	2	4	16
	Weighted	1,4	0,6	0,3	0,5	0,4	3,2
Nitro 4-stroke	Score	3	3	3	3	3	15
	Weighted	1,05	0,45	0,45	0,75	0,3	3
Petrol 2-stroke Glow	Score	4	3	2	3	4	16
	Weighted	1,4	0,45	0,3	0,75	0,4	3,3

Motor Comparison Matrix							
Criteria		Weight	Cost	Reliability	Efficiency	Complexity	Sum
Criteria weight		0,35	0,15	0,15	0,25	0,10	1,00
Petrol 4-stroke Glow	Score	3	2	3	4	3	15
	Weighted	1,05	0,3	0,45	1	0,3	3,1
Diesel 2-stroke	Score	4	4	2	2	4	16
	Weighted	1,4	0,6	0,3	0,5	0,4	3,2
Petrol 2-stroke spark	Score	3	3	3	3	3	15
	Weighted	1,05	0,45	0,45	0,75	0,3	3
Petrol 4-stroke spark	Score	2	2	4	4	2	14
	Weighted	0,7	0,3	0,6	1	0,2	2,8
2 Stage Turbine	Score	1	1	5	4	1	12
	Weighted	0,35	0,15	0,75	1	0,1	2,35
Score: 1 = min, 5 = max							

3.6.3 Pitch Mechanism

Pugh Matrix: Pitch Mechanism					
Criteria	Criteria weight %	External Actuated		Internal Actuated	
Weight	0,1	2,5	0,25	5	0,5
Cost	0,1	3	0,3	3	0,3
Reliability	0,3	2	0,6	4	0,8
Efficiency	0,2	4	0,8	4	0,8
Complexity	0,3	3	0,9	3	0,9
	1	12	2,85	19	3,2
Score 1=poor, 5=very good					

3.6.4 Propeller Design and Decision Making

Generally speaking, larger propellers will be more efficient than smaller diameter propellers. A large diameter propeller will provide more thrust per watt. Motor efficiency tend to drop with higher rpm, and a larger-diameter propeller would require lower rpm, making the system more efficient.

From the low-rpm concern, a large-diameter single bladed propeller would be optimal. But this design is undesirable due to the vibrations and instability such a propeller creates. Thus, a two-bladed propeller is the best solution, given that it can provide enough thrust for its diameter.

Large-diameter blades will create a larger inertia, so rpm changes will happen more slowly. This is not a concern for us, as the propellers will be driven at constant rpm.

Generally speaking, a lower pitch will generate more torque (and less turbulence) for lifting, and the motors don't have to work as hard to carry heavier loads. As a result, a motor that doesn't have to work as hard will draw less current/power, increasing flight time. This, using a lower pitch propeller is a simple way to increase flight time. A propeller with higher pitch angle can move a greater amount of air, but creates more turbulence and less torque.

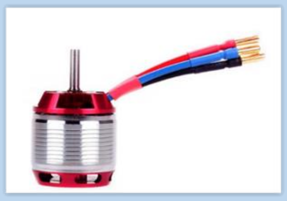
Two of the four propellers will be rotating in the opposite direction from the others. This will balance out torque effects that would occur if all propellers rotated in the same direction. Two propellers will rotate clockwise, two will rotate counter-clockwise.

"Helicopter blades need to be long and thin. The diameter of the rotor disc determines the efficiency of the rotor at low speeds and can be compared to the wing span in fixed-wing airplanes. The rotation creates strong centrifugal loads at the blade roots which grow with the square of the tip radius at a given rotation speed, so they cannot be tapered much. Adding chord to the middle of the blade would increase its area and add more friction drag, increasing the torque needed to keep the rotor spinning. If the helicopter is only designed for hover, the blade tips could be tapered, but the added complications of forward flight make a rectangular blade the better choice."

Twisted propeller vs non-twisted propeller:

All well-designed blades are twisted, such that the angle of attack is constant along the blade. Some drone propellers have no twist, in order to simplify production and reduce cost. Our blades will be able to pitch, to ensure good angle of attack throughout its air speed regimes. For the actual blade we end up using, price will be an important factor initially. The specific propellers for the final design might be altered from the propellers used in the testing stage of development.

3.6.5 Transmission

Pugh Matrix Transmission							
							
		Shaft drive		**Belt drive**		**Direct drive**	
Criteria	Criteria Weight	Score (1-5)	Weighted score	Score (1-5)	Weighted score	Score (1-5)	Weighted score
Weight	0,30	3	0,9	4	1,2	2	0,6
Cost	0,20	1	0,2	3	0,6	2	0,4
Reliability	0,15	4	0,6	4	0,6	3	0,45
Efficiency	0,20	4	0,8	4	0,8	1	0,2
Complexity	0,15	2	0,3	4	0,6	3	0,45
Sum			2,8		3,8		2,1

4 Iteration 4

4.1 Life Cycle Stakeholder Key Drivers

Life cycle stakeholder key drivers are not significantly different from the standard key drivers. The Key drivers for the project are listed in figure 3.1 in section 3. The life cycle stakeholder key drivers have therefore already been considered. For further clarification, please see figure 1.5 in section 1 diagram from the first iteration.

4.2 Feasibility Assessment

4.2.1 Technical Feasibility

Drones with a single drive unit and variable pitch mechanisms have been made before, relieving some of the technical concerns. However, no drone with an interchangeable drive unit has been produced before.

The interface between the drive unit and the power transmission will be of utmost importance for the successful completion of this project. A primary concern is that the weight limitations will limit the solutions space in regards of support structure around the engine and where the engine meets the power transmission. CAD techniques allow us to verify the solution geometrically, while prototyping will verify the functionality. CAD software, prototyping and numerical analysis will be our primary tools in solving the design. The project will be technically feasible given an active use of these engineering methods.

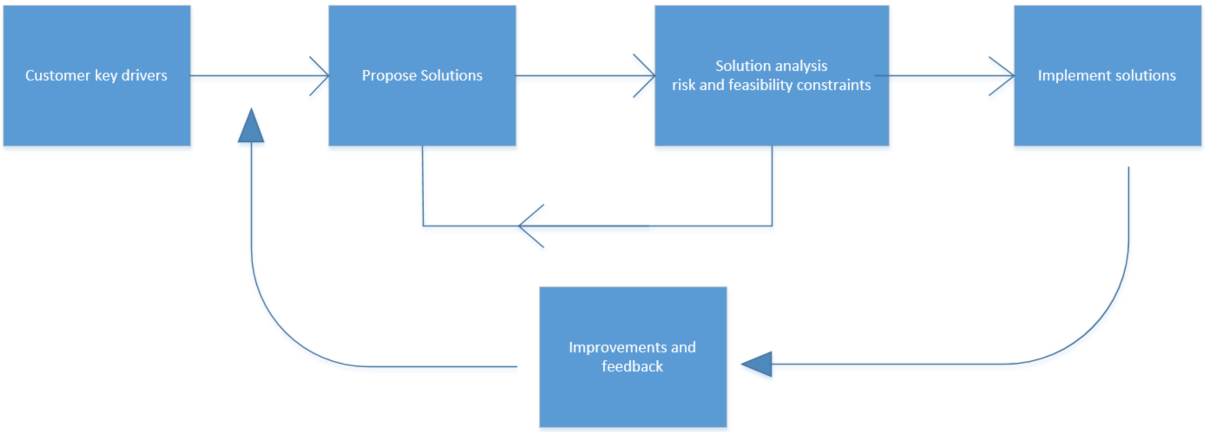


Figure 4.1: Possibility to improve solutions

4.2.2 Schedule Feasibility

The end objective for the project is to build a working pitch-controlled drone with a changeable single drive unit, at the end of May. As the prototyping progress, challenges in the mechanical design might arise. A heavy focus on systems architecting initially has given us a wide understanding of the problem and the primary challenges. Although challenges are expected to arise, we have developed a thorough understanding of the system and its context. The system scope is such that programming aspects, for instance FPV navigation, are not entirely within the bounds of the project. Prototyping ensures progressive completion of the project, as opposed to a single final build. The project schedule is deemed to be feasible.

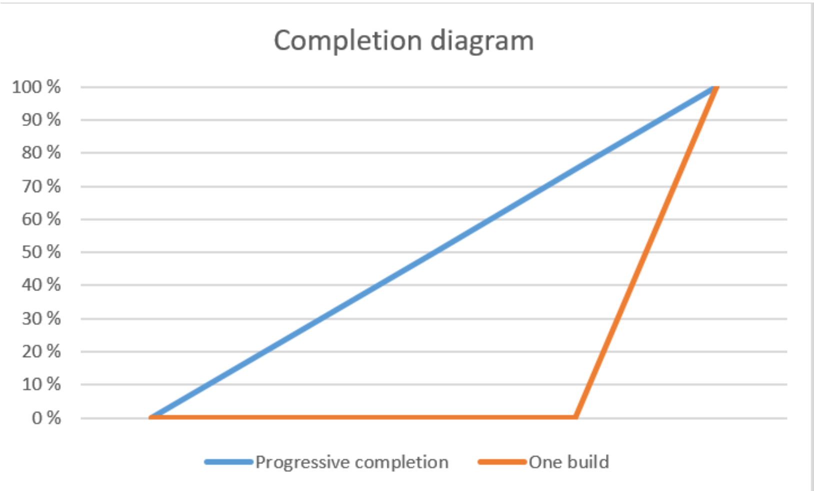


Figure 4.2: Completion Diagram of project schedule

4.3 Operational needs:

4.3.1 Robustness

The customer needs the drone to fly multiple times for extended periods of time without failure. This ad several requirements to the system regarding maintainability, stability and structural integrity. The drone must be robust enough so that it can handle landing and take-off by a novice operator. Particles in the air or sand should not hinder the operation.

4.3.2 Stamina

Most drones can fly for about 10 to 30 minutes before the battery is exhausted. The drone we are building should fly for a considerable longer timespan before needing refuelling. A flight time of one hour would allow the drone to film a sports event, with refuelling in the halftime – given that a camera system is installed. It would also allow the drone to transport light goods over relatively long distances.

4.3.3 Navigation

Per the Norwegian CAA RO1 classification, the drone we are building must be within visual line of sight at all times. Yet, me must consider the possibility of the drone being used by a certified operator who is not subject to the visual line of sight requirement. GPS waypoint navigation and FPV navigation open for a whole new range of applications. It is also conceivable that another group of students would want to implement this for their Bachelors Thesis, and we need to take this into consideration while designing the drone.

4.3.4 Safety

Fast rotating machinery pose a risk to safety, and a flying device even more so. The operator should be comfortable using the drone, feeling confident with the structural integrity and the stability of the aircraft. This poses great challenges for the engineering team when designing. In situ safety measures need to be taken, described by the CAA and by the user manual.

4.3.5 Ease of Use

The customer wants a drone that can be readied and flown without further ado. In situ assembly should not be required, unless for switching propulsion systems. The drone must respond appropriately to commands from the radio controller.

4.4 Budget/Cost evaluation

Budget Proposal, Unified Collective Pitch Quadcopter

Abstract: The basis for these budgets is that the Institute funds this project to the tune of 10'000 NOK, with the posibility of an aditional 5'000 NOK funding if justified. These budgets are preliminary and are subject for change.

Prototype

Item	Cost	
Motor	kr	600
Frame	kr	100
Powertrain	kr	800
Propellers	kr	200
Flight controller	kr	250
Electronic Speed Controller	kr	800
Radio controller	kr	1 000
Miscellaneous	kr	300
Actuators	kr	800
Power storage	kr	1 000
Pitch mechanism	kr	1 000
Freight	kr	800
VAT + customs	kr	1 750
	kr	9 400

Final Design

Item	Cost	
Motor	kr	3 000
Frame	kr	200
Powertrain	kr	200
Propellers	kr	200
Flight controller	kr	250
Electronic Speed Controller	kr	-
Radio controller	kr	-
Miscellaneous	kr	300
Actuators	kr	-
Power storage	kr	300
Pitch mechanism	kr	-
Freight	kr	350
VAT + customs	kr	800
	kr	5 600

Project total

Item	Cost	
Motor	kr	3 600
Frame	kr	300
Powertrain	kr	1 000
Propellers	kr	400
Flight controller	kr	500
Electronic Speed Controller	kr	800
Radio controller	kr	1 000
Miscellaneous	kr	600
Actuators	kr	800
Power storage	kr	1 300
Pitch mechanism	kr	1 000
Freight	kr	1 150
VAT + customs	kr	2 550
	kr	15 000

Balance

Primary budget:	kr	10 000
Difference:	kr	5 000
Secondary budget:	kr	15 000
Difference:	kr	-

Figure 4.3: Budget/Cost evaluation of Prototype, Final Design and grand total of the project

5 Iteration 5

The documentation for the second hand-in constitutes to a great extent the work done in iteration 5. Please see documents 4 and 5 for the Technical Document and Design Document respectively.

6 Iteration 6

6.1 Benchmarking

"Benchmarking is simply the process of measuring the performance of one's company against the best in the same or another industry" [1]

The reason Benchmarking is a good idea, and our project group has chosen this step in sixth iteration, is because it can be hugely benefiting for our system. We can get a better awareness of ourselves as a group, and a better awareness of how we measure up to the best comparable system out there. We also hope this can be an efficient way to make improvements to our system.

The system we have chosen to compare our quadcopter to, is the StingRay 500, which is of the more capable systems out there available for the public. This has made the Benchmarking challenging, because we don’t have any true insight in how this small business have worked during development, and all we can do is compare the two systems as is.

UCPQ vs StingRay 500

Differences

Lift:	UCPQ, better lift capacity
Robustness:	UCPQ, more robust design
Weight:	StingRay 500, lighter design
Design:	StingRay 500 – H-shape
	UCPQ – X-shape
Motor changing:	UCPQ, easy to change between propulsion systems
3D flight:	StingRay 500, sport/competition drone
Utility system:	UCPQ, payload carrier
Flight Time:	UCPQ, possible to carry higher capacity battery, and bigger fuel tank

Similarities

Both quadcopters:	Use one motor and pitching of blades to control the system
	Are more manoeuvrable than multi engine quadcopters
	Can use both ICE and EL-motors for propulsion
	Use belts, pulleys and axles for power transmission
	Air frames are mostly made from carbon fibres and metal, 85%
	Are in similar size

Cost about 1000$ including VAT

[1] Stevenson, William J. Production Operations Management. New York: Irwin/McGraw-Hill, 1999

7 Iteration 7

Please see the Operation Manual document for the Operation Manual

8 Iteration 8

8.1 Value Proposition

Headline

What is the end-benefit you're offering? in one short sentence. Can mention the product and/or the customer. Attention grabber.

Single Engine X-Shaped Quadcopter

Carbon Fiber Single Engine Quadcopter

Single Engine variable pitch quadcopter

3D- flight variable pitch quadcopter

Sub-headline or a 2-3 sentence paragraph

A specific explanation of what you do/offer, for whom and why is it useful.

The Unified Collective Pitch Quadcopter with its 3D-flight and great maneuverability, opens a whole new world of flying and gives the user a truly great flying experience. This together with its seamless mechanical power transmission and variable pitch system, allows for a single engine propulsion and makes this a quadcopter extraordinaire and have set a new standard for RPAS. (Remotely Piloted Aircraft System)

Bullet points

List the key benefits or features.

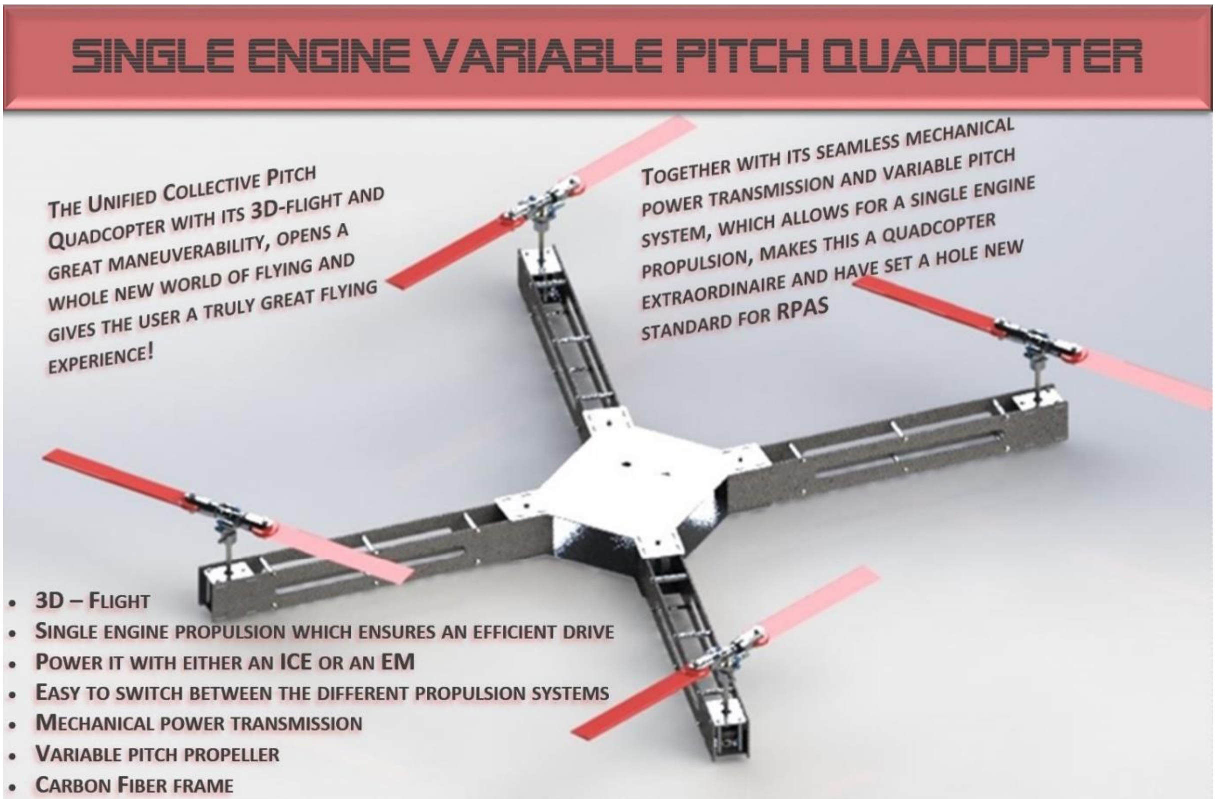
- 3D – Flight
- Single engine propulsion which ensures an efficient drive system
- Power it with either an Internal Combustion Engine or an Electrical Motor
- Easy to switch between the different propulsion systems

- Mechanical power transmission
- Variable Pitch Propeller
- Carbon Fiber frame

Visual

Images communicate much faster than words. Show the product, the hero shot or an image reinforcing your main message. [1]

[1] https://conversionxl.com/value-proposition-examples-how-to-create/



Unified Collective Pitch Quadcopter

SYSTEM REQUIREMENTS

Project Name	Unified Collective Pitch Quadcopter
Version	3.0
Number of Pages	13
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Daniel Christian Torsvik, Joakim Thorvaldsen, Severin Myhre

TABLE OF CONTENTS

1 ABSTRACT

The purpose of this document is to put the system in context and to describe how the finished system should function. This document contains all the requirements specified for the project. The requirements are divided into sub groups according to type and characteristics. Each requirement has its own unique ID, description, priority, origin and reviewed date. The Project Group has appointed a responsible for this document who approves it before final publication.

2 Document Structure

2.1 Document History

Version	Date	Description	Author
2.0	14.03.17	F01.1 changed to 2 minutes. TBR abbreviation added. Changed ID of NF11, NF12, NF09 and NF10. F01.1 moved to non-functional. Priority of F09, NF15 and NF17 changed. Frequency added to FC01. FC03 and FC04 deleted. FC05 changed to CR05. F10 added.	Daniel Christian, Severin
2.1	20.04.17	Proof-reading, added a paragraph about gradients of priority in section 4.3, Added gradients of priority to derived requirements, improved Abstract, formatting.	Daniel Christian, Severin
3.0	23.05.17	Final release	Joakim, Daniel Christian, Severin

2.2 Abbreviations & Acronyms

A&A	Explanation
ID	Identification
CAA	Norwegian Civil Aviation Authority
RO1	Remotely Operated 1, classification in accordance with the Norwegian Civil Aviation Authority
VTOL	Vertical take-off and landing
MTOM	Maximum take-off mass
EL	Electrical
ICE	Internal combustion engine
ISO	International Organization for Standardization
RC	Radio control
TBR	To be resolved

Term	Definition
Project Group	Students who are working under the project
Customer	Employer, University College in Southeast Norway
Project	Task that students received from customer
System	Unmanned aerial vehicle that students are designing

3 System Boundary and Scope

3.1 Customer Needs

The customer wants a single engine drone with variable pitch. The fundamental needs of the customer are stated in the Customer Requirements, defining the overarching objectives of the project. These requirements are as follows:

- The system shall have a single motor for propulsion
- The system shall be able to use an electric motor for propulsion
- The system shall be able to use an internal combustion engine for propulsion
- The system shall take-off and land vertically

These requirements define the critical constraints applying to the project. The solution space is limited by these requirements, for example in stating that a fixed wing design cannot be a solution. However, these requirements are instrumental in defining the design, as they define the fundamental design direction.

3.2 Exemptions from Regulation

The Norwegian CAA impose several regulatory constraints through the RO1 classification. These regulations affect not only the final design but also testing and operation. Particularly the use of an Internal Combustion Engine is affected. Fortunately, the scientific nature of this project exempt us from several of the RO1 restrictions, simplifying testing and development.

Still, there is a stated need from our customer that the final system should meet the requirements of the Norwegian Civil Aviation Authority’s regulation RO1. Therein follows certain requirements that can only be met through computer engineering, such as safe landing procedures. This is outside of the project’s scope, but will be considered in systems engineering through future-proofing.

4 REQUIREMENTS STRUCTURE

4.1 TYPES OF SYSTEM REQUIREMENTS

Type of system requirements	Description
Customer	Requirements specifically requested by the customer, reflecting their intentions.
Functional	Specify what the system should do; describe qualitatively the system functions or tasks to be performed in operation, specific behaviour.
Non-functional	Specify how the system works; describe criteria that can be used to judge the operation of a system, rather than specific behaviours.
Flight Controller	Requirements related to the Flight Controller
Certification	Requirements related to CAA RO1

4.2 REQUIREMENT ID

Each requirement is given a unique identification code to ensure that each requirement is identifiable and so that references to the requirements can be made across different documents. The requirements are divided into Customer, Functional, Non-Functional, Flight Controller and Certification sub groups. Requirements occurring as derivative requirements from other more top-level requirements will be identified with a punctuation mark. As an example, the F02.1 requirement is a derivative requirement from the F02 requirement.

4.3 REQUIREMENT PRIORITY RANKING

Each requirement possesses its own priority ranking. We divide requirements into the priorities critical, important and desirable.

Ranking ID	Description
A	Critical: requirements that must be met for the project to be completed, or that are important for safety
B	Important: important requirements that should be in place, but are not necessary for the project to be completed
C	Desirable: requirements that will enhance the overall quality of the system, but that should only be met if time permits

Furthermore, derived requirements also have derived priorities. For instance, C05.1 is a derived requirement from C05. C05.1 is itself a requirement with priority A, but also keeps its ties with C05, which has priority C. Thus, the final priority for requirement C05.1 is C-A. In other words, the primary requirement has a low priority, but C05.1 has higher priority compared to other requirements with priority C. The purpose of this priority method is to keep the connection between related requirements unambiguous. This way we allow for gradients of priority, making the priorities of the requirements more precise.

5 Requirements

5.1 Customer Requirements

	Customer Requirements			
I.D.	**Requirement**	**Priority**	**Origin**	**Reviewed**
C01	The system shall have a single motor for propulsion	A	Customer	20.04.17
C02	The system shall be able to use an electric motor for propulsion	A	Customer	20.04.17
C03	The system shall be able to use an internal combustion engine for propulsion	C	Customer	20.04.17
C04	The system shall take-off and land vertically	A	Customer	20.04.17
C05	The system shall be compliant to CAA classification RO1	C	Customer	20.04.17

5.2 Functional Requirements

Functional Requirements				
I.D.	**Requirement**	**Priority**	**Origin**	**Reviewed**
F01	The propeller blades shall be replaceable	A	Project Group	20.04.17
F02	The drive unit shall be changeable by a layman	A	Customer	20.04.17
F02.1	A layman shall be able to change between propulsion systems ≤ 30 minutes	A-A	Project Group	20.04.17
F02.2	A layman shall be able to change between propulsion systems ≤ 15 minutes	A-C	Project Group	20.04.17
F03	The system shall have a variable pitch mechanism	A	Customer	20.04.17
F04	Screws shall comply with ISO standard	A	Project Group	20.04.17
F05	Bolts shall comply with ISO standard	A	Project Group	20.04.17
F06	The system shall be operable by one person	B	Project Group	20.04.17
F07	The outdoor flight time with electric motor shall be ≥ 10 min	C	Project Group	20.04.17
F08	The outdoor flight time with internal combustion engine shall be ≥ 30 min	C	Project Group	20.04.17
F09	The system shall withstand a vertical free fall to a flat concrete surface on a parallel horizontal plane, from the height of 0,25 meters	B	Project Group	20.04.17
F10	The system shall have a payload capacity of at least 250 grams	C	Project Group	20.04.17

5.3 Non-Functional Requirements

Non-Functional Requirements				
I.D.	**Requirement**	**Priority**	**Origin**	**Reviewed**
F01.1	A layman shall be able to replace a propeller blade within 2 minutes using only basic tools	A-A	Project Group	20.04.17
NF01	The system shall have a mechanical transfer of power to rotate propeller blades	A	Project Group	20.04.17
NF02	A mechanical power transmission shall transfer power from motor to rotors with no less than 70% efficiency	A	Project Group	20.04.17
NF03	A mechanical power transmission shall transfer power from motor to rotors with no less than 80% efficiency	B	Project Group	20.04.17
NF04	A mechanical power transmission shall transfer power from motor to rotors with no less than 90% efficiency	C	Project Group	20.04.17
NF08	The system's thrust to weight ratio shall be ≥ 2:1	A	Project Group	20.04.17
F02.3	The drive units shall be fastened with non-permanent fastening mechanisms	A-A	Project Group	20.04.17
F02.4	A layman shall be able to change between propulsion systems by using basic tools only	A-A	Project Group	20.04.17
F04.1	Screws shall have either Phillips, Pozidriv or Hexagonal type sockets	A-A	Project Group	20.04.17
F05.1	Bolts shall have either Phillips, Pozidriv or Hexagonal type sockets	A-A	Project Group	20.04.17
NF13	Screws shall withstand 10 hours of flight induced vibrations without unscrewing	A	Project Group	20.04.17
NF14	Bolts shall withstand 10 hours of flight induced vibrations without unscrewing	A	Project Group	20.04.17
NF15	The support structure shall have a factor of safety ≥ 1,5	B	Project Group	20.04.17
NF16	The support structure shall have a factor of safety ≥ 2	A	Project Group	20.04.17

	Non-Functional Requirements			
I.D.	**Requirement**	**Priority**	**Origin**	**Reviewed**
NF17	The support structure shall be able to hold both power system assemblies	C	Project Group	20.04.17
F02.1.1	A layman shall be able to attach the power system assembly to the support structure within 15 min	A-A-A	Project Group	20.04.17
F02.1.2	A layman shall be able to detach the power system assembly from the support structure within 15 min	A-C-A	Project Group	20.04.17
NF20	The power storage shall be fastened to the power system assembly without the use of tools	A	Project Group	20.04.17

5.4 Flight Controller Requirements

Flight Controller Requirements				
I.D.	**Requirement**	**Priority**	**Origin**	**Reviewed**
FC01	Flight controller shall receive and interpret 2,4 MHz signals from radio control transmitter	A	Project Group	20.04.17
FC02	The flight controller shall regulate pitch angles to the extent that a skilled operator can hold the system within 1 m^3 for 5 consecutive seconds	C	Project Group	20.04.17

5.5 Certification Requirements

Certification Requirements (C05 derived)				
I.D.	**Requirement**	**Priority**	**Origin**	**Date reviewed**
C05.1	The system shall be clearly marked with the operator's name and telephone number	C-A	Norwegian CAA	20.04.17
C05.2	The system's take-off mass shall be ≤ 2.5 kg	C-A	Norwegian CAA	20.04.17
C05.3	The system should be equipped with an instrument for measuring altitude	C-C	Norwegian CAA	20.04.17
C05.4	Maximum speed shall not exceed 60 knots	C-C	Norwegian CAA	20.04.17
C05.5	The system shall be equipped with a kill switch	C-C	Project Group	20.04.17

6 BIBLIOGRAPHY

[1] Civil Aviation Authority - Norway (2015). "Regulations concerning aircraft without a pilot on board etc." from http://luftfartstilsynet.no/caa_no/Regulations_concerning_aircraft_without_a_pilot_on_board_etc

[2] Jamal Safi, University College of South-East Norway, Module 8 Completing the System Requirements, 2016

[3] Gerrit Muller, Module Requirements, University College of South-East Norway, July 2016

Unified Collective Pitch Quadcopter

DESIGN DECISIONS

Project Name	Unified Collective Pitch Quadcopter
Version	2.0
Number of Pages	21
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik

TABLE OF CONTENTS

1 ABSTRACT

This document contains the design decisions made after evaluating alternative design solutions. The content of this document is based on the research described in the Technical Document, and the references are to be found there. The purpose of this document is to provide a straightforward overview of the system design.

2 Document Structure

2.1 Document History

Version	Date	Description	Author
1.0	22.03.2017	Transmission system, design, propellers, pitch mechanism, servo and flight controller sections added	All group members
1.1	03.05.2017	Formatting, fixed automatic figure numbering, proof-reading, added chapter about Camera Mount and some pictures	Daniel Christian
1.2	12.05.2017	Section 3 is updated	Anastasia
1.3	15.05.2017	3 and 6 sections are updated	Anastasia
1.4	21.05.2017	All sections updated. Section 10 was removed. Formatting.	Ann-Mari, Severin
2.0	23.05.2017	Section 5 added, Document Finalised	Thomas, Ann-Mari, Joakim, Severin

2.3 ABBREVIATIONS & ACRONYMS

A & A	Explanation
ICE	Internal Combustion Engine
MMS	Modular Motor System
SW	SolidWorks
FOS	Factor of Safety
FPV	First Person View
UAV	Unmanned Aerial Vehicle
HSE	Health, Safety and Environment

3 TRANSMISSION SYSTEM

Based on Pugh Matrix evaluation, we have reached the conclusion that a belt drive is the optimal solution for the quadcopter. Please see more details in section 4.4 Transmission evaluation of the Technical Document. We made a 3D model of the transmission system in SolidWorks (SW).

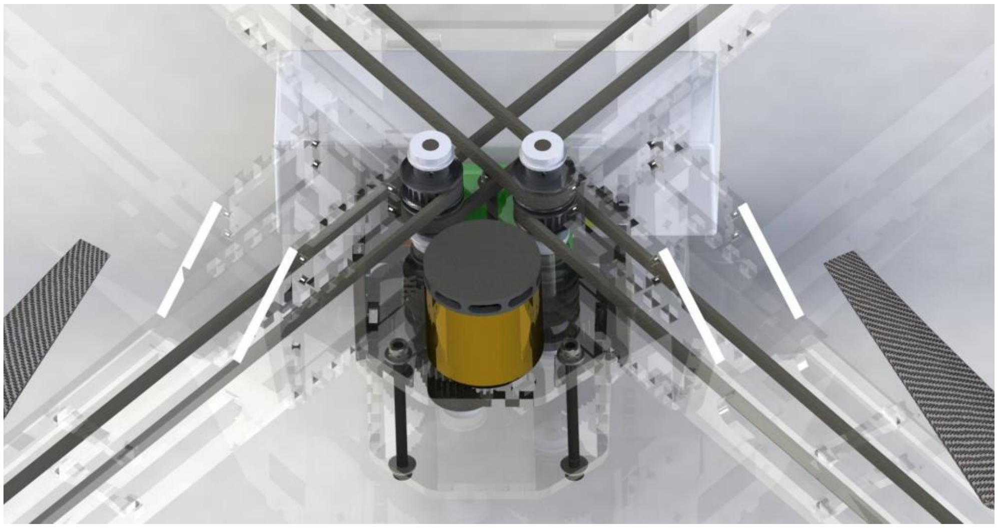


Figure 3.1: Belt & Pulley Transmission System: SW Model

Based on the transmission system, we assembled the prototype in plexiglass [fig. 3.2] and verified that the parts fit together and perform intended functions. The mechanical transmission system works as intended. For more details, please see the System Test Plan, Test Reports 01, 02.

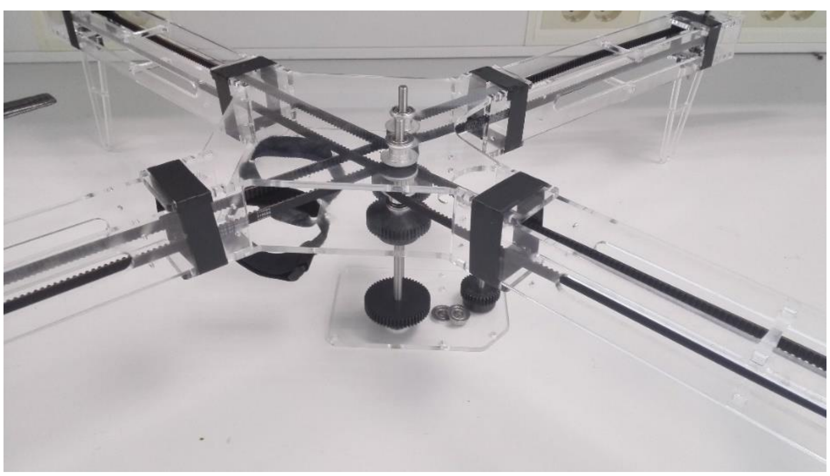


Figure 3.2: Belt & Pulley Transmission System; Our Prototype

3.1 Gears & Shafts

Shafts are needed for the motor, gears and propellers. Figure 3.3 displays the central transmission assembly for our electrical motor attachment.

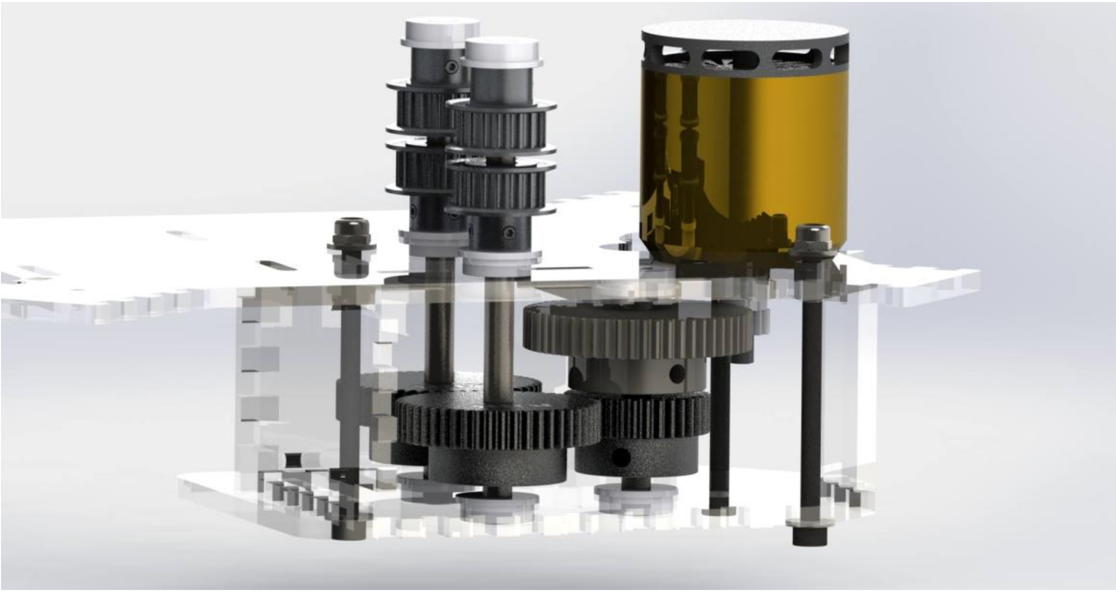


Figure 3.3: Transmission Assembly, SW Model

The material for both shafts and gears should be steel, as the stress applied to these parts will be in the range of 300-400 MPa, and steel has its yield strength ranging within 400-600 MPa.

The chosen gears and shafts are listed in table 3.2 and 3.3. An illustration of the gears A-E and shafts A-E, are shown in figure 3.4, page 6.

Gear	No. of teeth	Face width, mm	Pitch diameter, mm	Material
A	12.00	5.00	9.60	303 Stainless Steel
B	56.00	8.00	44.80	Carbon Steel S45C
C	35.00	8.00	28.00	Carbon Steel S45C
D	50.00	8.00	40.00	Carbon Steel S45C
E	50.00	8.00	40.00	Carbon Steel S45C

Table 3.1: Gear values

Shaft	Diameter, mm	Recommended values, mm	Final values, mm
A	5.00	5	5
B	5.02	5	5
C	5.63	6	6
D	5.58	6	6
E	5.50	6	5

Table 3.2: Shaft values

For all shafts, except shaft E, we choose the recommended diameters shown in table 3.3. Due to the pitch mechanism, the E shaft has to be smaller than the calculated diameter [section 4.8 in Technical Document]. Shaft E has a final diameter of 5 mm. Our calculations include a factor of safety (FOS) of 2, but in aircraft components, the FOS can vary between 1.5-2.5. With a FOS of 1.5, a 5mm diameter shaft will be sufficient.

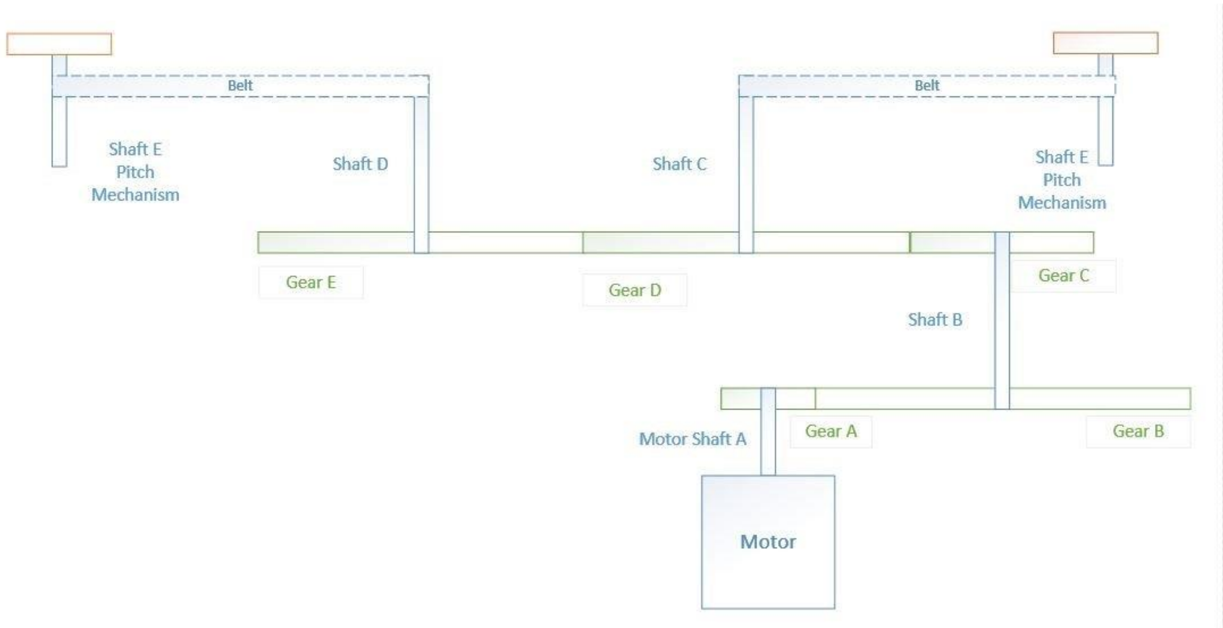


Figure 3.4: Overview of shafts and gears

3.2 BELTS & PULLEYS

To be able to transfer power to the propellers, we are using timing belts. Among the reasons for this are price, good grip, strength and flexibility. All these factors are extremely important in small applications and machinery where a small deviation have big consequences, and a definite motion sequence is involved.

According to the specifications of the motor, the maximum output is 1660 W, or 2.225 hp, and the rotors operates in the range of 4000-6000 rpm. From these parameters, we select 3mm GT2/GT3 belt. We are using 6mm wide single sided neoprene belts reinforced with fiberglass cords. The belts are in two pairs of 840.00 mm and 735 mm length. Please see section 4.5 of the Technical Document.

Figure 3.5: 3mm GT2/GT3 belt

The pulleys we have chosen are made of anodized aluminium alloy, which gives good resistance against wear. The diameter for the shaft is equal to the bore diameter of the pulley. The pulleys should have the same parameters as the belts with both pitch and pressure angle. Please see table 3.1 for the pulley dimensions.

Pulley, no. of items	Pitch, mm	No. of teeth	Bore, mm	Pitch diameter, mm	No. of teeth	Belt width, mm	Pressure angle, deg
4	3	20	6	19.10	12.00	6	20
4	3	20	5	19.10	56.00	6	20

Table 3.3: Pulley values

Figure 3.6 on the next page shows the shaft/pulley/belt assembly on our prototype.

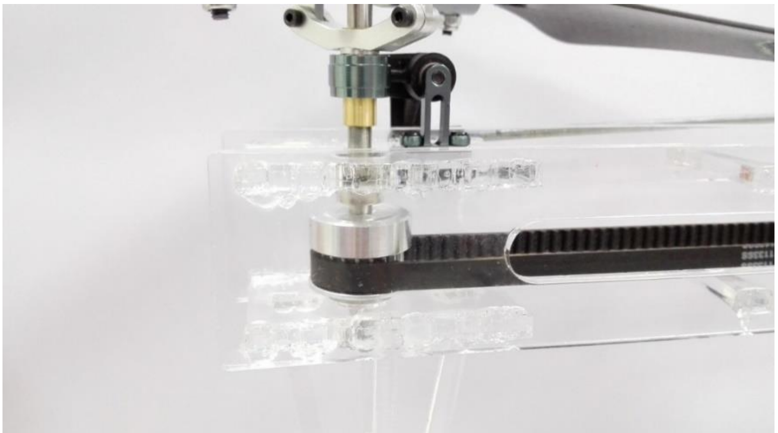


Figure 3.6: Shaft/Pulley/Belt Assembly

4 Design

4.1 Airframe, X-Shaped Belt Driven Quadcopter

The frame shown in figure 4.1 is a developed and optimized design solution for our intended X-Shaped quadcopter with belt propulsion. In this design, the quadcopter frame won't consist of only two plates lying parallel and horizontal to each other which constitutes both arms and body. The quadcopter will rather consist of a smaller midsection, and the propeller arms will be fastened to it. This will make the quadcopter easier to manufacture, simply because it can be manufactured in smaller parts. The design of the propeller arms consists of two vertical plates which are tightened together with standoffs, and the arms are fastened to the midsection in grooves. Vertical orientation of the arm plates ensures good rigidity in the vertical axis, providing great resistance against potential bending stresses.

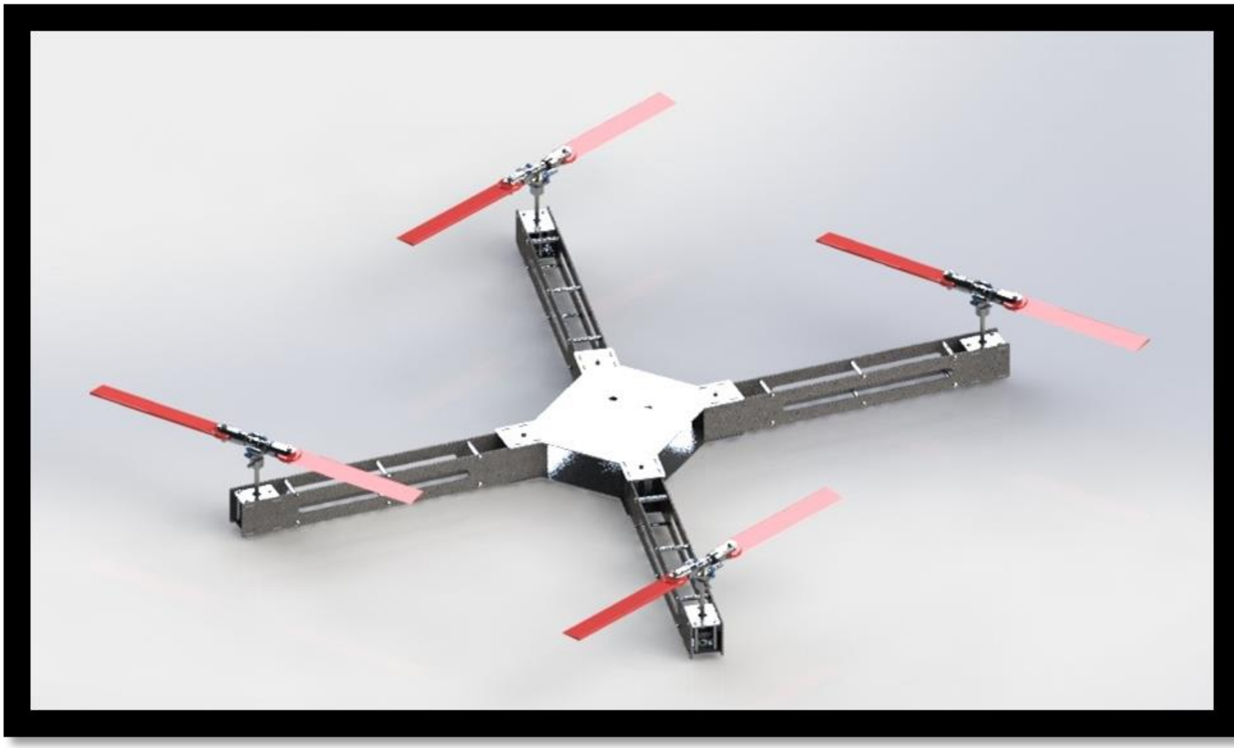


Figure 4.1: X-Shaped belt driven Quadcopter

4.2 Modular Motor System

A key requirement for the drone is that the operator shall be able to switch between electric and combustion engine. The obvious solution to this would be to fasten the engine, power source and flight controller with screws, so that they can be switched fairly easily. This solution has some major drawbacks, particularly that making the switch would take considerable time with many components involved. Health, safety and environment (HSE) would also be affected; When removing the combustion propulsion system, the fuel line between the tank and engine would have to be disconnected, and spilling of fuel onto the drone or environment would be likely.

We solve this problem by placing the electric motor and all gears onto a bracket. A similar bracket will be made for the combustion engine. This way, the motor assembly can be easily attached and reattached to the airframe.

By placing the power assemblies onto a bracket, only the bracket must be switched to change between electric and combustion power trains. This will allow for quick and simple switching between propulsion systems, and the probability of fuel spill is drastically reduced.

By using this method, the propulsion system and the drone airframe itself will be separate sub-assemblies, with the bracket providing the interface between them. This will provide great flexibility when configuring the propulsion system, as well as allow for future changes or upgrades without having to make changes to the drone's airframe.

We named this system the "Modular Motor System", or MMS.

The prototype is equpped with an electric motor attached the the MMS. A variant of the MMS for the internal combustion engine (ICE) configuration has also been designed in SW [fig. 4.2].

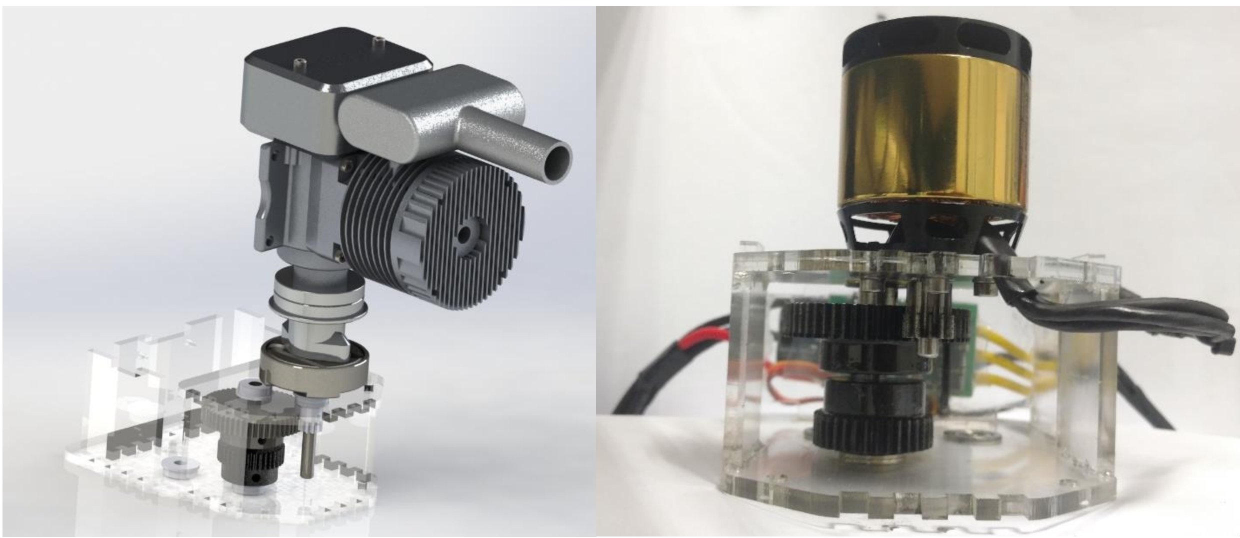


Figure 4.2: ICE MMS vs. El MMS

5 ICE ADAPTION

There are two major concerns about fitting ICE to the quadcopter. There is the weight aspect. In addition, for internal combustion engines to run at idle speed without the propellers spinning, we need to have a clutch.

The clutch will need to have a different configuration for the various internal combustion engines. This is because different engines have different power bands and idle speeds. E.g. A nitro glow engine has a much higher power band and idle speed than a spark two-stroke gasoline engine has.

We have decided to mount the ICE on the top with the output shaft pointing down; this is because we wanted a design with the lowest stack height possible. The model aircraft engines use oil in the fuel for lubrication, which will give oil particles in the exhaust. This will often leave a sticky oil residue on the aircraft; therefore, we have mounted the exhaust facing away from the quadcopter towards the rear rotors.

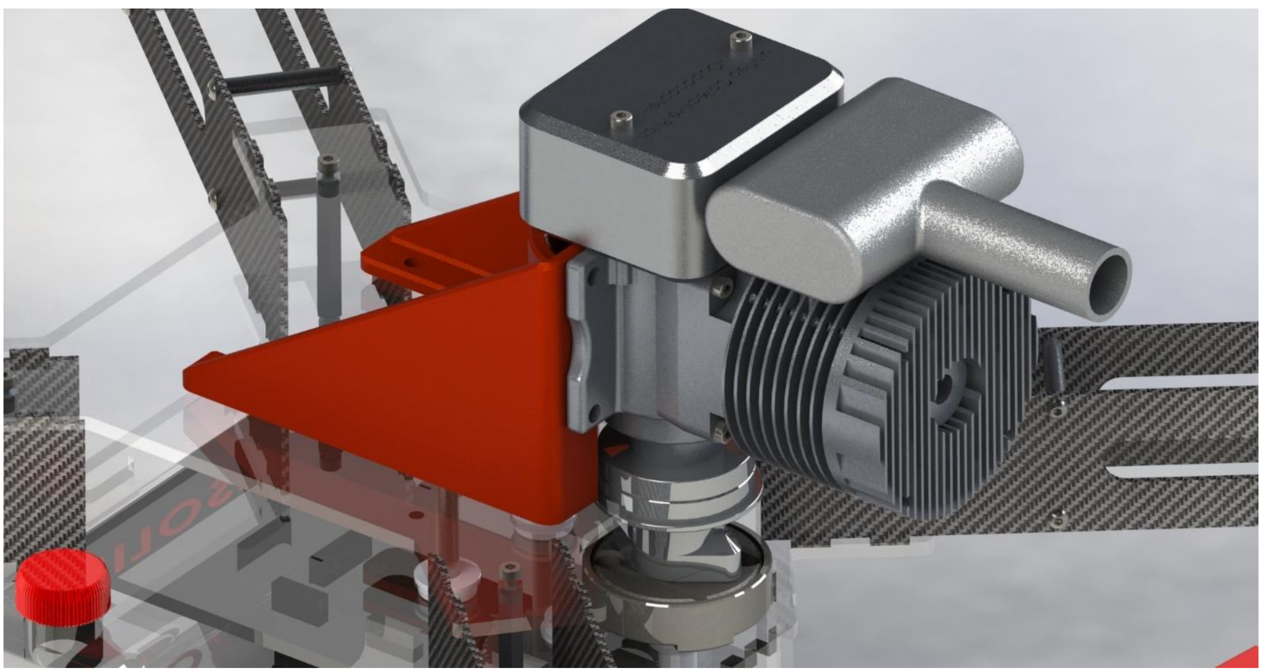


Figure 5.1: ICE motor attached to the frame; output shaft pointing down into the clutch assembly and exhaust pointing rearwards

With our powertrain design, we have a system that easily accepts changes and configuration. The MMS is easily removed. It has a low stack height and is designed to be adapted to different motor/engine configurations with their different gearing. The MMS for the ICE engine consist of spur gears, bearings, gear shaft, clutch bell and the MMS frame [fig.5.2]. Once the MMS is secured to the quadcopter using three M4 Allen head bolts, the ICE engine slides in vertically to mate with the clutch bell. The engine is then secured to the top of the motor using four M4 Allen head bolts.

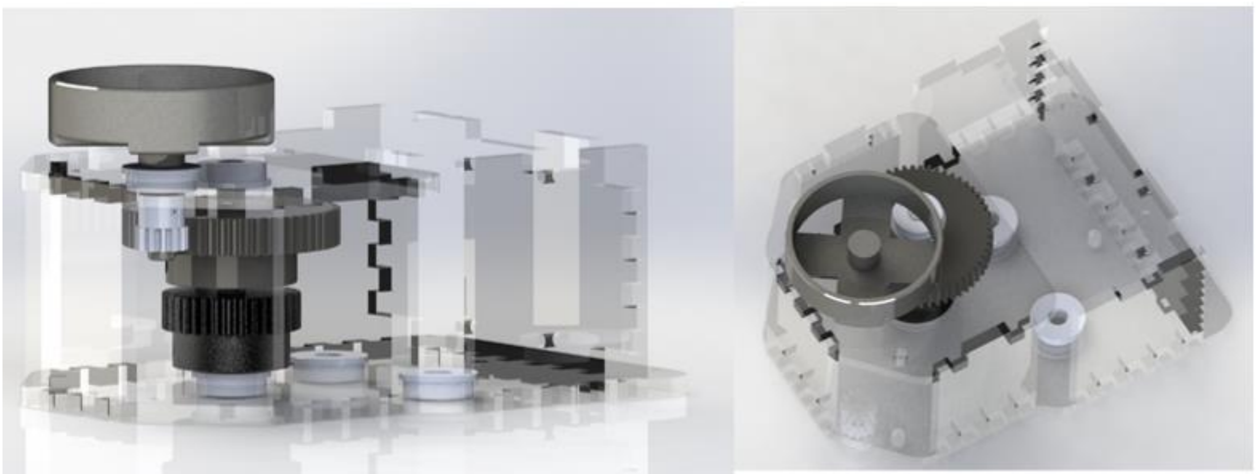


Figure 5.2: Two different angles of the ICE MMS; the clutch bell is seen on top of the MMS

Figure 5.3: MMS mounted to the frame with the ICE installed

The Gasoline engine is modelled after the “RCGF 10cc RE” model airplane two-stroke spark engine.

Weighing in at a total of 623g (engine, muffler and ignition) and with a maximum power output of 1.9hp/1.4KW it fulfils our power requirement while still being fairly light for a spark gasoline engine. A model of the RCGF 10cc RE engine can be seen in figure 5.4.

Figure 5.4: Illustration of ICE without clutch assembly

The clutch is a metal disc with cut-outs [fig.5.5]. The clutch is mated to the prongs on the clutch receiver [fig.5 5]. The clutch receiver is attached with a nut on the crankshaft of the engine [fig. 5.6]. The clutch spins freely in the clutch bell at idle. When the revolutions per minute (RPM) is further increased, the clutch disc expands and engages the inside walls of the clutch bell [fig.5.6] When the clutch/clutch bell is engaged, the gears starts turning and the rotors will spin. The clutch disc is different on different engines because they will have to engage at different RPM’s

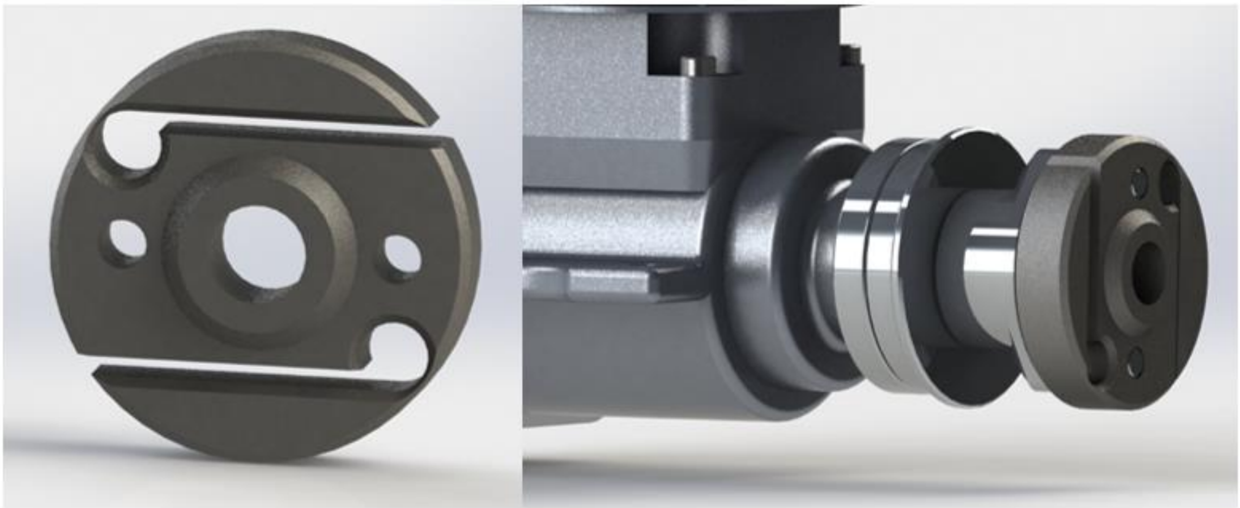


Figure 5.5: Left-clutch disk. Right-clutch disk attached to the clutch receiver on the ICE

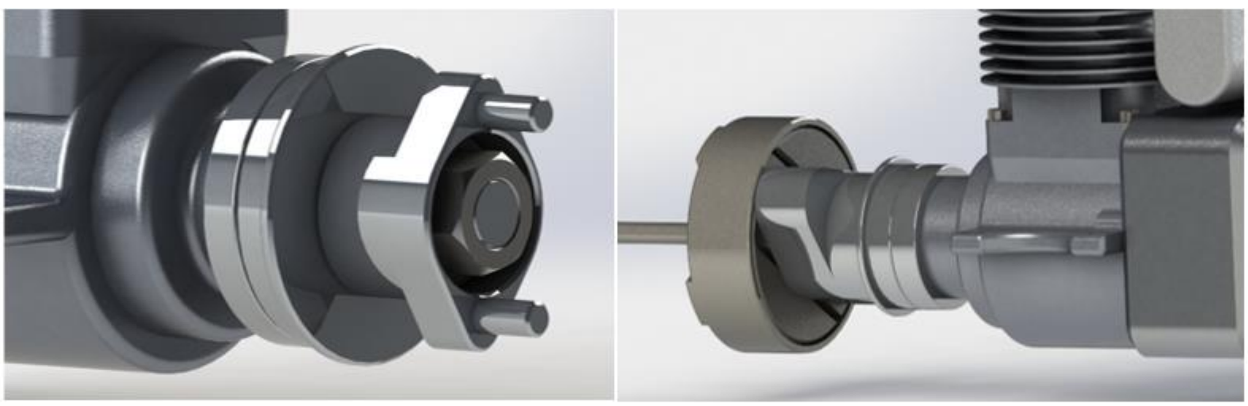
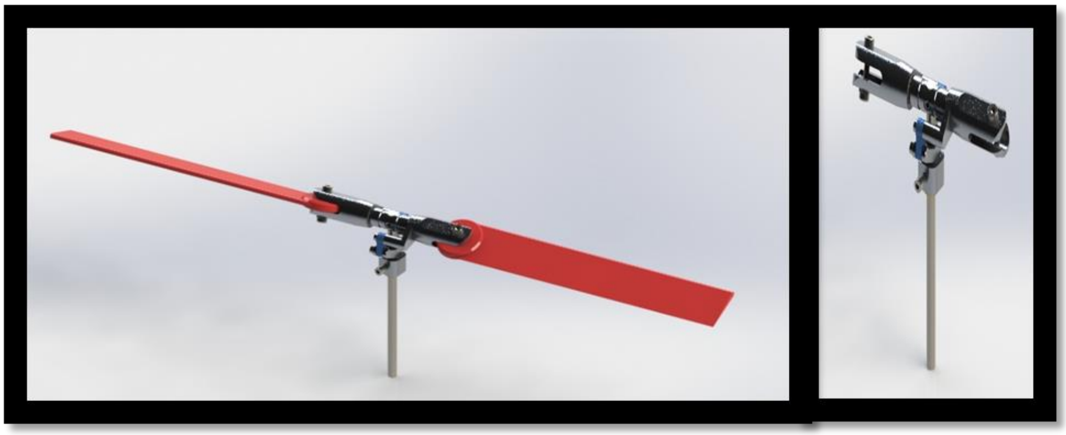


Figure 5.6: Left-clutch receiver/mount. Right-complete clutch assembly mounted to the engine

6 PITCH MECHANISM

Based on the results from the Pugh matrix evaluation (section 8.3 in Technical Document) of the concepts, we have chosen to go for alternative number 3, which is to use a RC helicopter tail pitch assembly from the HK600/T-rex 600 line. Figure 6.1 shows more pictures of the selected design, including an exploded view.



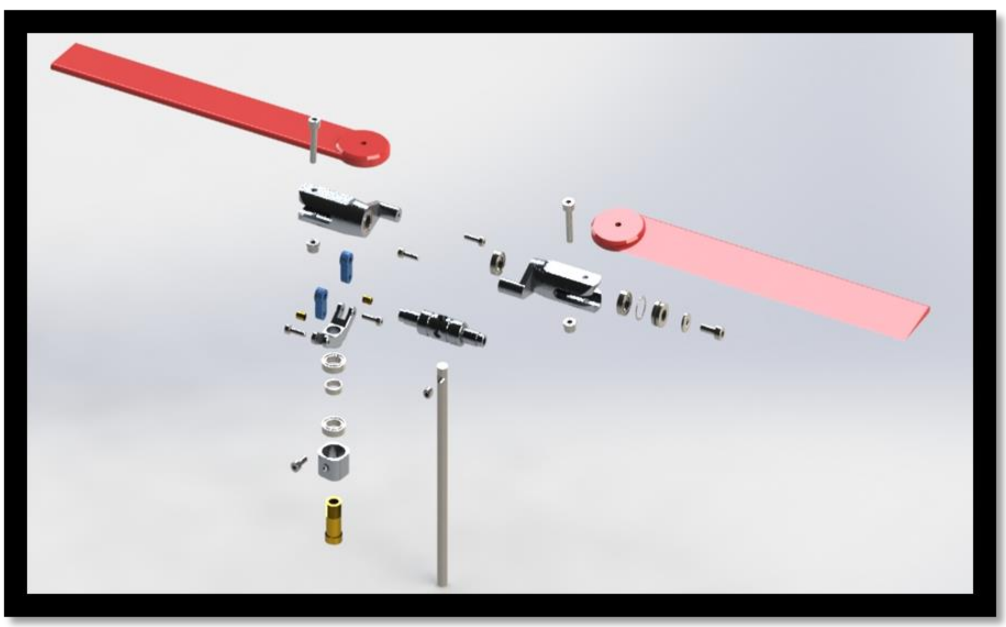


Figure 6.1: HK600/T-Rex 600 line

7 Propellers

The propellers used must be either RC helicopter propellers or foldable drone propellers, due to the pitch mechanism. The pitch mechanism at each rotor constitutes the mounting points for the propeller blades. Thus, one propeller will be made up of two separate blades. Refering to the “Pitch Mechanism” section 5, two blades with a 3mm mounting hole and no more than 5mm width are needed per rotor.

An inherent quality of the pitch mechanism is that it has hub room, allowing for travel of the propeller blades around the fastening bolt’s axis. The fastening points for the propeller blades will have hub room, allowing the blades to travel. Thus, the blades will be foldable.

Since inverted flight is out of scope, a blade with uniform profile along its length - typically for 3D-flight - can be avoided. This allows for using a foldable drone blades, keeping the angle of attack constant. We will be using the commercial blades “Multirotor Carbon Fiber Propeller 15x5.2 Black”.

Figure 7.1: Multirotor Carbon Fibre Propeller 15x5.2 Black

8 SERVO

We are using four “RotorStar 550/600” servos, shown in figure 8.1.

Figure 8.1: Actuator/Servo

The servo is both reliable and fast enough for our use, and it has gotten excellent reviews. It has a metal gear train, coreless motor and weighs 59.3 grams. We are using a 2 cell Lipo battery with 7.4V for our servos.

9 FLIGHT CONTROLLER

We are using the OpenPilot Revolution flight controller [fig.9.1]. This is based on price, availability, performance and because it is a proven platform with consistent quality that is widely used by enthusiasts. Most of the smaller flight controllers are stripped down to the essentials and aim more towards the First Person View (FPV) racer. We need a flight controller with a good gyro that has a fast loop time and fast loop time aids in canceling out noise because of vibrations. A mechanically complex Unmanned Aerial Vehicle (UAV) such as ours is subjected to more vibrations than the average UAV with one motor per propeller and fixed pitch. It also supports telemetry, and other peripherals such as GPS and Sonar.

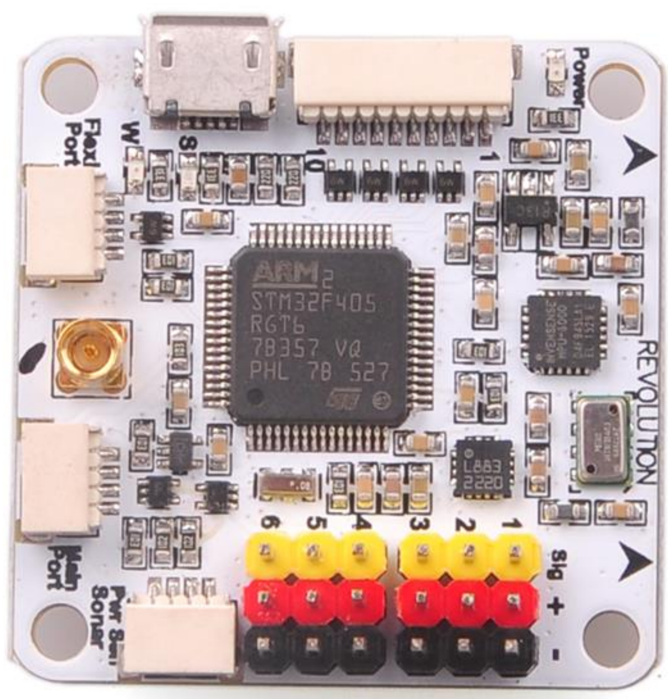


Figure 9.1: Open pilot revolution FC

10 CAMERA MOUNT

One of the features the quadcopter will have, is the ability to carry a camera while flying. This can be solved in many ways, but our team have chosen a Carbon Fibre FPV Gimbal PTZ [fig.10.1] as a camera platform. The reason behind this is that it can carry many different cameras, it cost only $8 and it weighs only 53 grams. The most common camera to fasten to this kind of gimbal mount, is a GoPro Hero, which is a camera suitable for outdoors filming, because of its water resistance, ease of use and video stabilization. Together with the gimbals on the camera mount, it will give the user a satisfying quality of the pictures/videos, at least for amateur usage.

Figure 10.1: Carbon Fiber FPV Gimbal PTZ Parts

The project group won't buy this camera mount or a GoPro Hero, simply because it is out of scope. There are far more important features to our drone, and because it is a prototype, this won't be prioritised at this stage. With that being said, the project group have made all the parts in SolidWorks to show how the camera mount would look and work, thus giving a good indication of how this could look on our system, visually and conceptually.

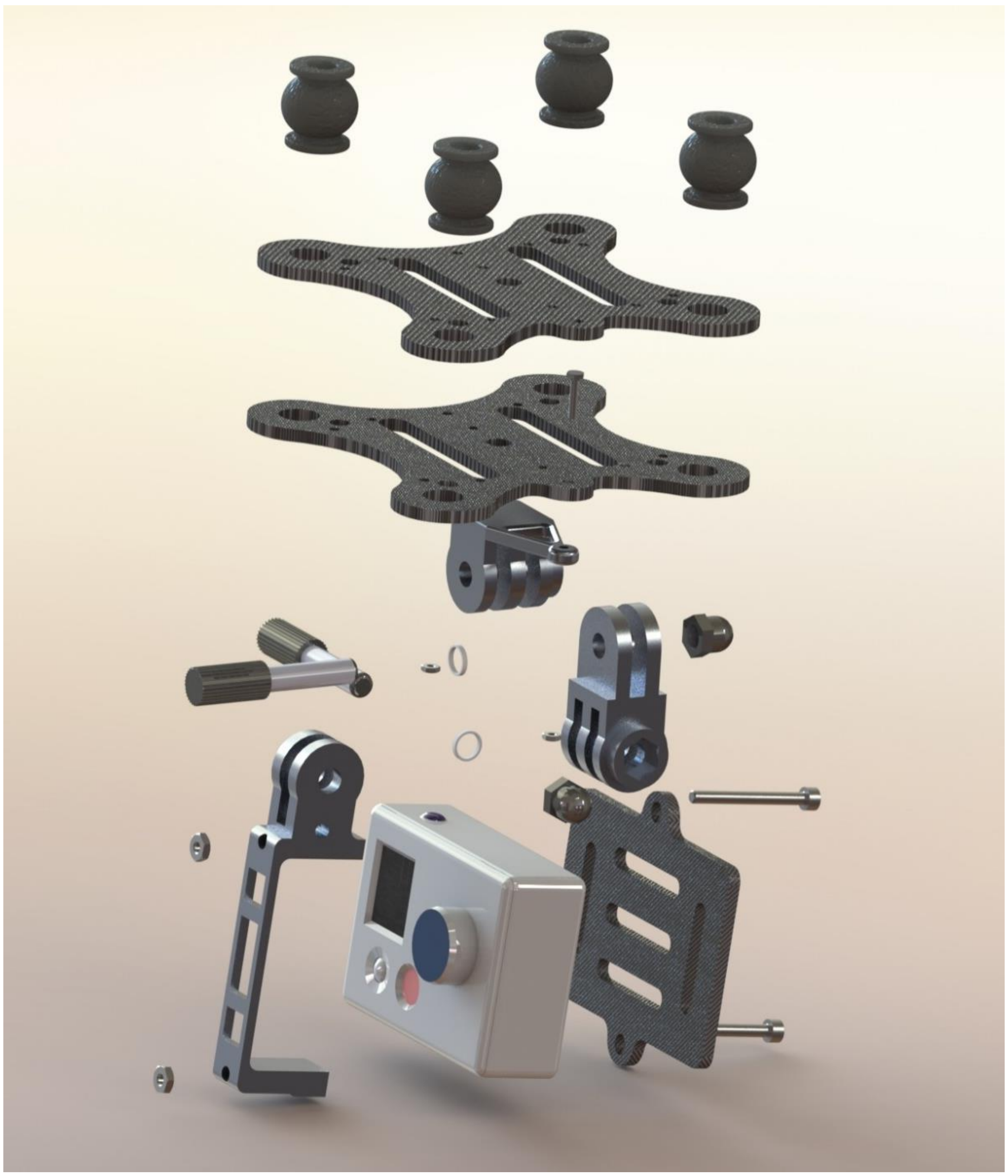


Figure 10.2: Exploded View of SW model of the Carbon Fibre FPV Gimbal PTZ

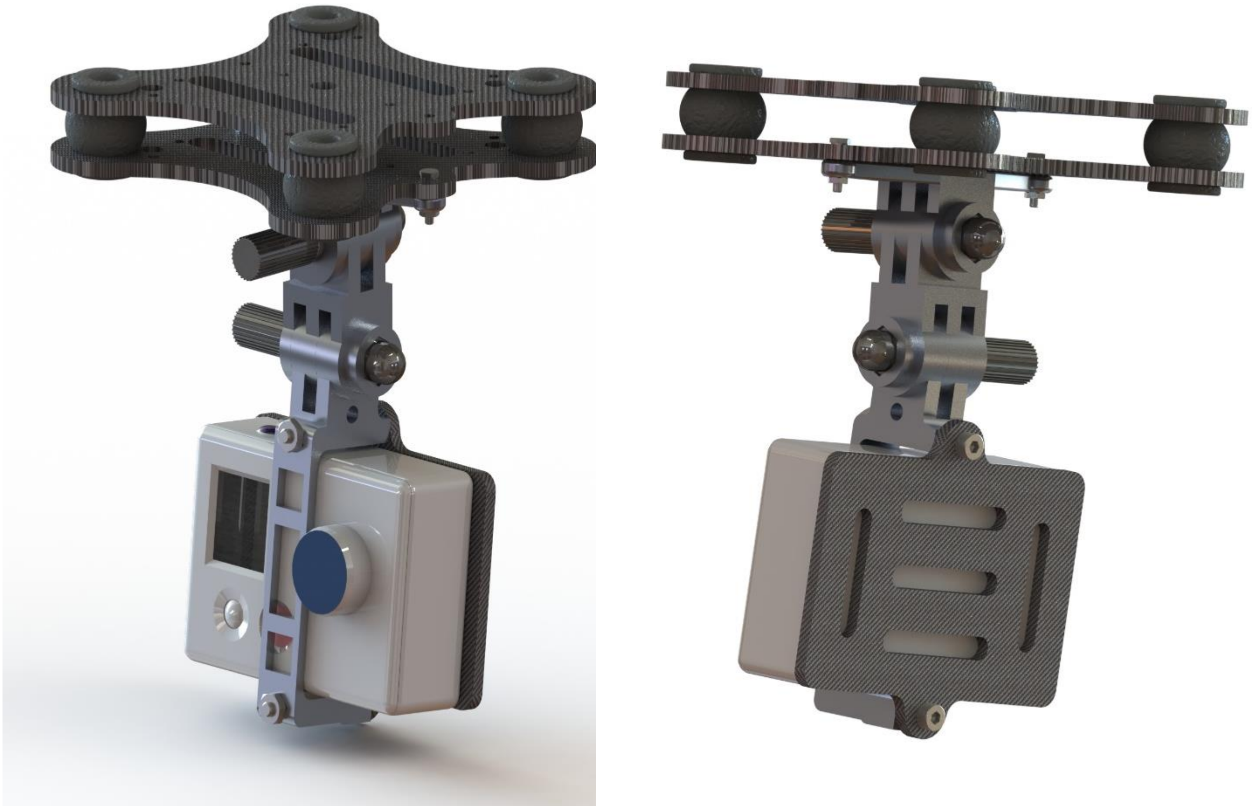


Figure 10.3: SW model of the final assembly of the Carbon Fiber FPV Gimbal PTZ

Unified Collective Pitch Quadcopter

TECHNICAL DOCUMENT	
Project Name	Unified Collective Pitch Quadcopter
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Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik

Table of Contents

1 ABSTRACT

This document describes the research we have done when developing the system design. The major technical components and challenges have been investigated. The purpose of this document is to account for the factors influencing the system and its sub components, as well as to evaluate design decisions. This document provides a more detailed explanation and reasoning behind the system design & development process. The final solutions are collected in the Design Decisions document.

2 Document structure

2.1 Document history

Version	Date	Description	Author
1.0	22.03.2017	First release	Thomas, Severin, Ann-Mari, Joakim, Anastasia, Daniel Christian
1.1	17.04.2017	Formatting and figure setting	Ann-Mari, Severin, Daniel Christian
1.2	21.04.2017	Added optimal material in transmission system	Ann-Mari
1.3	24.04.2017	Added section 7 Camera Mount. Formatting	Daniel Christian
1.4	27.04.2017	Improved section 4.3, 4.4, 4.5 and 4.6	Anastasia, Ann-Mari
1.5	02.05.2017	Improved chapter 2, 4.3-4.5. Camera Mount section moved to “Design Decisions” document. Figures and tables fixed.	Anastasia
1.6	02.05.2017	Added sections 6.6 and 6.7	Ann-Mari
1.7	05.05.2017	Improved all of section 6.7, and section 6.8 added.	Anastasia
1.8	09.05.2017	Changed order of sub-sections 6.7 and 6.8. Added section 6.10	Ann-Mari
1.9	09.05.2017	Added section 4.9 Bearings	Severin
1.10	10.05.2017	Formatting, pictures	Anastasia
1.11	11.05.2017	3.4 added, 3.5 updated, 6.7.1 formatting	Anastasia
1.12	12.05.2017	8.5 added, overall editing	Anastasia
1.13	15.05.2017	Abbreviations updated	Anastasia
1.14	16.05.2017	Added section 11	Ann-Mari
1.15	17.05.2017	Added section 6.6.2, updated 6.10	Anastasia
1.16	21.05.2017	General editing	Severin, Joakim, Anastasia
1.17	23.05.2017	9.3 added, 11.1 &11.2 updated, composite section moved to a separate appendix A, general editing and formatting	Anastasia, Ann-Mari, Thomas
2.0	23.05.2017	Final release	Ann-Mari

2.2 Abbreviations & acronyms

A&A	Explanation
UAV	Unmanned aerial vehicle
VTOL	Vertical take-off and landing
RPM	Revolutions per minute
RC	Radio control
EL	Electrical
ICE	Internal combustion engine
CW	Clockwise
CCW	Counter clockwise
UTS	Ultimate tensile strength
MDF	Medium density fibreboard
MMS	Modular motor system
CFRC	Carbon fibre reinforced composite
MMC	Metal matrix composite
CMC	Ceram matrix composite
PMC	Polymer matrix composite
CNC	Cutting machine with computer numerical control
KDA	Kongsberg Defence & Aerospace AS
PLA	Polylactic acid
PVA	Polyvinyl alcohol
MIPS	Million instructions per second
GUI	Graphical user interface
GCS	Ground control station
ESC	Electronic speed control

Term	Definition
Project Group	Students who are working under the project
Customer	Employer, University College in Southeast Norway
Project	Task that students received from customer
System	Unmanned aerial vehicle that students are designing

3 Physics of quadcopter

Any object has a set of forces acting on it, at any time. To determine whether the object is standing still or moving, and if so, in which direction, one simply have to determine every force acting on the object and add them all together. To represent a force, we use a *vector*, which means “carrier” on Latin. A vector carries the point A to point B [1]. A vector contains both direction and size.

3.1 Aerodynamic equilibrium

The conservation of angular momentum states that if something on a body is spinning, there has to be a spinning force in the opposite direction of the body, in response [2]. To be able to fly, the quadcopter must overcome the gravity. When propellers spin, they push downward on the air around them, causes the quadcopter to lift. The air applies an equal and opposite reaction force to the propeller as described in Newton’s third law.

The quadcopter is in horizontal equilibrium when drag force and flow rate of the air are equal. Then the quadcopter fulfils Newton’s first law of motion. The quadcopter will move with constant speed. If either the drag force or the flow rate gets greater than the counteracting force, the aircraft will come out of equilibrium and start accelerating or deaccelerating.

When thrust and gravity are equal and in opposite direction, the quadcopter is in a vertical equilibrium. If the thrust force gets greater than the gravity, the quadcopter will rise above ground, and if the force is less than gravity, the quadcopter will lose altitude [3]. Hover equilibrium is achieved when all of the propellers are spinning in the same velocity and when they are producing equal amount of torque and thrust [4], [5].

3.2 LIFT AND THRUST

There are four forces that have an impact on every flying object [fig. 3.1] [6]:

1. The force of gravity. It acts downward to the centre of Earth (weight)
2. Lift, the counterforce of weight
3. Thrust, the propeller force (total thrust of propellers equals to the systems lift)
4. Drag, the force that acts opposite to the direction of motion. Air resistance, or drag is caused by friction and differences in air pressure.

Lift, the upwards force in aircraft, must equal the weight to make it hover. But this is not enough to make it fly. More lift is needed to get the quadcopter up in the air [7]. When hovering, the amount of thrust must be equal to the weight of the quadcopter, like in the illustration below.

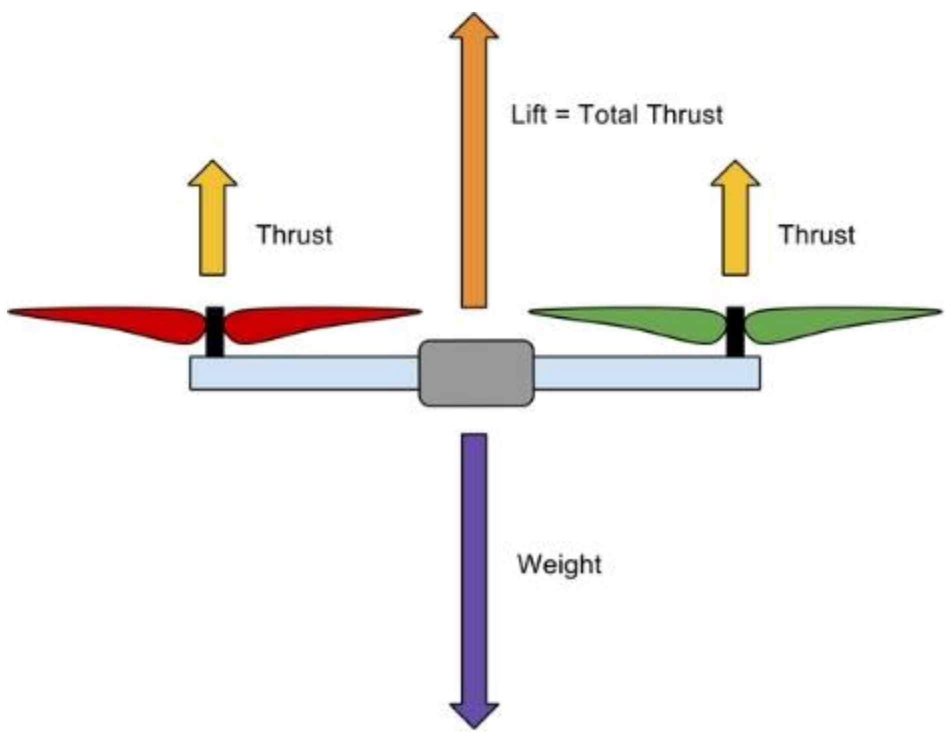

Figure 3.1: When hovering level, weight=lift=total thrust

If the quadcopter gets tilted, either by the wind or because of the control inputs, only a portion of the total thrust gets converted to lift [fig 3.2]. The rest becomes horizontal thrust and accelerates the drone forward, backward, or sideways. This missing lifting force needs to be compensated for to prevent the quadcopter to lose altitude [7].

The total thrust must be even larger. Necessary thrust, to provide the same vertical lift while moving, can easily be calculated by Pythagoras's theorem [7].

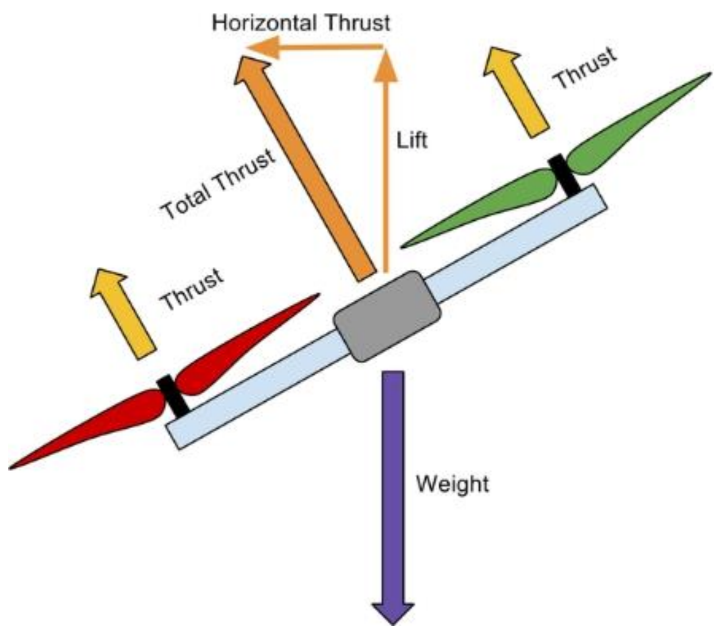

Figure 3.2: Only part of the total thrust becomes lift when the drone is tilted

3.3 PITCH, YAW & ROLL

There are three different ways to control an Unmanned Aerial Vehicle (UAV). It moves in the three-dimensional x, y and z axis.

In figure 3.3, planes of Vertical Take Off and Landing (VTOL) are depicted:

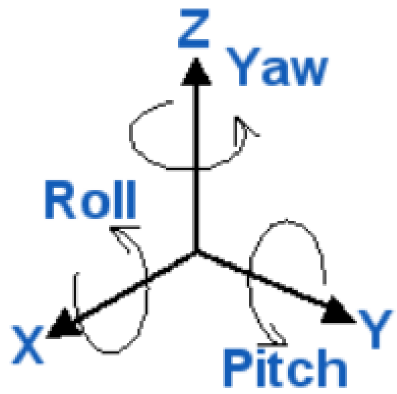

Figure 3.3: VTOL planes, Pitch, Yaw & Roll

A quadcopter is moving by tilting the whole body in either roll, pitch or yaw direction [fig. 3.4]. Pitch means tilting forward or backwards, roll means tilting side to side, and yaw means rotation around the vertical axis [fig. 3.3] [7]. A normal quadcopter is steering by adjusting the speed of the propeller on every motor, but since our quadcopter doesn't have a motor attached to every propeller, we use variable pitch to be able to steer in different directions.

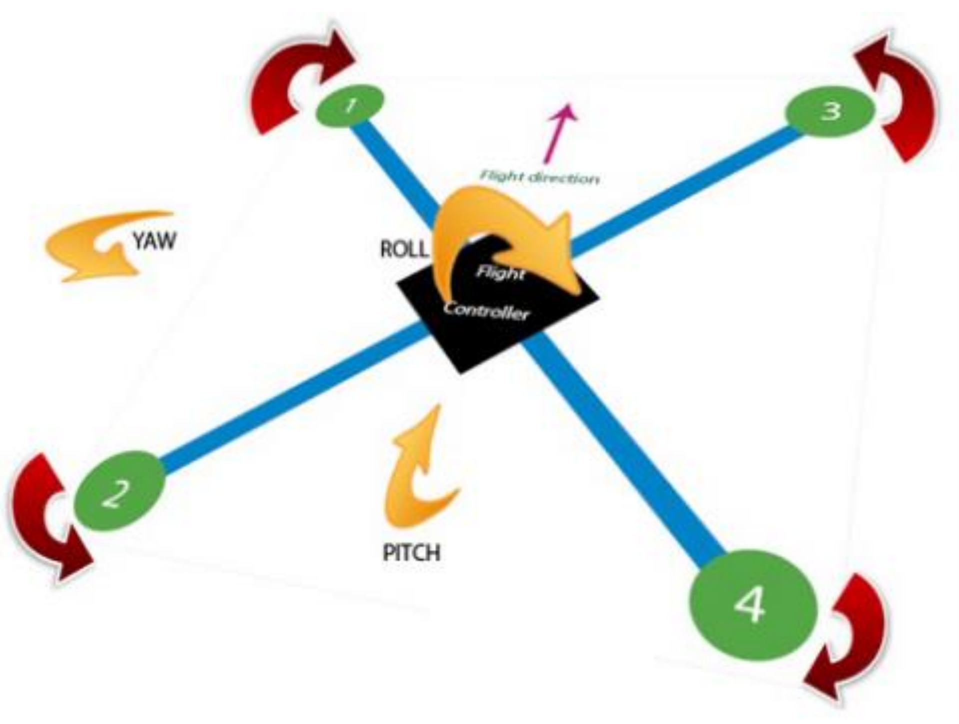

Figure 3.4: Pitch, Yaw & Roll

When steering the quadcopter, we are using different pitch angles to accomplish the command from operator. To move upwards from the ground, we can use a larger amount of rpm to lift, but this will require more energy than we need to, and it will only make the quadcopter moving upwards and downwards.

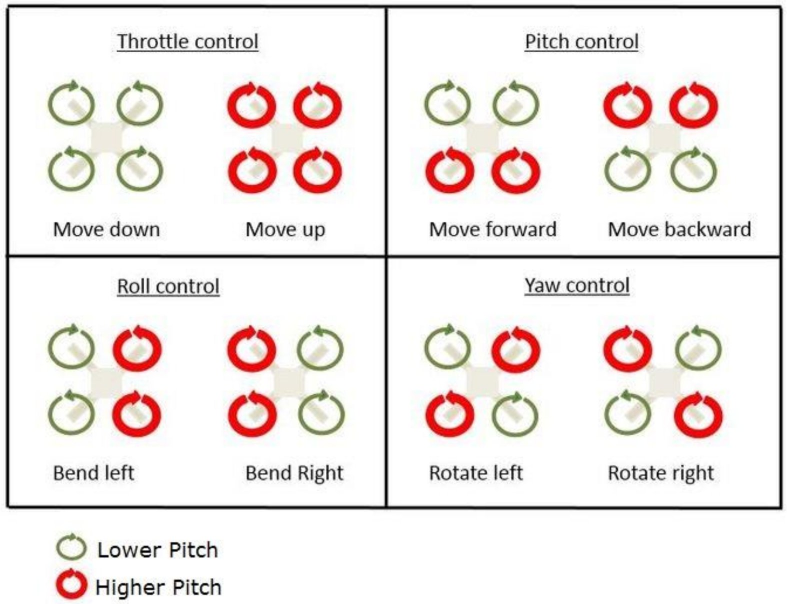

Figure 3.5: Illustrates how to steer the quadcopter with only variable pitch of blade

With variable pitch propellers, the quadcopter can steer in all directions by adjusting the propellers pitch. For instance, with variable pitch, the quadcopter can hover (*throttle control*) with either low pitch and high RPM, or using high blade pitch and low RPM.

For moving forward and backward (p*itch control*), the quadcopter uses either the two propeller pairs in the front, or in the rear, with higher pitching angle.

Higher pitch in the rear causes the quadcopter to move forward, and vice versa. For tilting the quadcopter from side to side, around its horizontal axis, it is either the propellers on the right side, or left side which has more pitch angle. Higher pitch angle on the left side will cause the quadcopter to tilt to the right, and vice versa. This is called the *roll control*.

Then there is *yaw control*. When yawing, the quadcopter is rotating from side to side, around its vertical axis. There are either clockwise (CW) propellers, or counter clockwise (CCW) propellers which have the highest pitch angle [8].

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4 TRANSMISSION SYSTEM

In the design of power transmission, one must consider the following factors:

1. Nature of the driven machine
2. Level of power to be transmitted
3. Rotational speed of the drive motor/engine unit
4. Desired output speed of the transmission

When designing the transmission system, it is important to do preliminary calculations and evaluation analysis.

Shaft, chain and belt drives are most known and commonly used. Some power transmission systems use two or more types in series to optimize the performance of each. We have been evaluating three types of transmission systems: shaft, belt and chain. All of them have certain advantages and disadvantages such as weight, cost, reliability, efficiency and complexity.

4.1 Shaft Transmission

Shafts can be used to transmit power from the motor to the propellers. With shafts, differentials would be needed to divert the direction of rotation. One alternative would be diverting the axis of rotation from the z-axis of the engine to the y-axis, then to the x-axis, and finally to the z-axis of the propellers. Such a design is illustrated in figure 4.1:

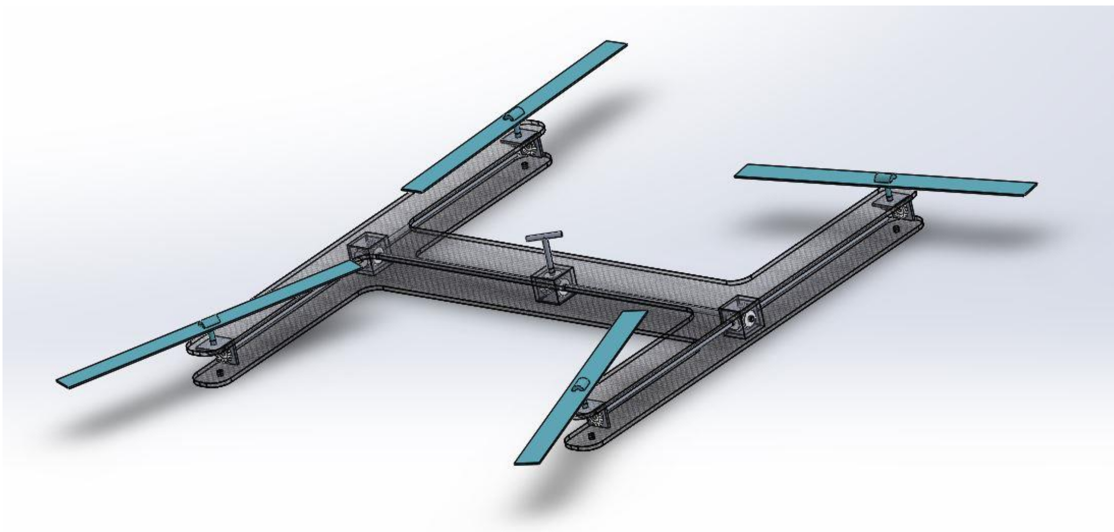

Figure 4.1: Conceptual Assembly, Shaft Transmission SolidWorks model

In a shaft transmission system, the motor is directly connected to the propellers through gears and shafts. This construction significantly reduces the severity of backlash or play between the motor and the propellers when compared to belt drives. Backlash occurs when there is a clearance or lost motion in a mechanism because of gaps between the components.

Complete machined steel differentials with associated components such as bearings can be purchased. However, the cost is around 200-300 $ per differential [1], and therefore outside of this project's budget. Even purchasing machined steel bevel gears and manufacturing the housing ourselves would not be financially viable.

Alternatively, we could purchase moulded nylon bevel gears and pinions, and assembled the differentials with 3D-printed parts. Specifically, we would then use mitre gears. A more detailed sketch is provided in figure 4.2:

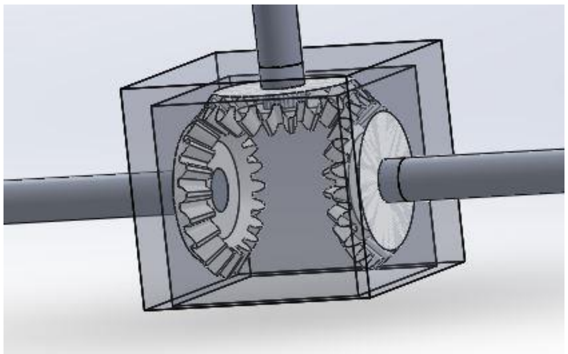

Figure 4.2: Bevel Gears in Housing SolidWorks model

Mitre Gears are a type of bevel gears made specifically to transmit rotational motion at a 90-degree angle with a 1:1 ratio. For this drone application, mitre gears would be most suitable.

In order to evaluate how suitable any gear is for a given application, we need to know the capacity of the gears and the conditions they will operate in. The most challenging conditions the gears will be subjected to is during maximum acceleration, where the motor power output will be 1500 W and the propellers will be running at 4000-6000 rpm [table 4.5 section 4.8]. A torque calculation is provided:

$$\tau = \frac{P}{\omega} \qquad \text{I}$$

$$P_{\max} = 1500W \,@\, 6000rpm$$

$$\tau_{\max} = \frac{1500W}{\frac{2\pi \cdot 6000[rpm]}{60}}$$

$$\tau_{\max} = 2.4Nm$$

At 1500W power and 6000 rpm, the engine produces 2.4 Nm torque. From data sheets [2], we find the suitable polymer mitre gear “PM2.5-20”, with 3.34 Nm allowable torque. This is one of the lightest mitre gears that meets the torque requirements.

The mass of this gear is 46 g [2]. With 17 gears needed, the total weight of the gears would be 782 grams, with shafts and gear houses not included.

Although using mitre gears has several advantages over belt drive, such as reduced backlash and ability to transmit a wider range of torque, the mass of the gears exclude them as a design solution.

4.2 CHAIN TRANSMISSION

Chain drives are used to transmit power from one component to another. They transfer power and torque through a linked chain and sprockets. Chain drives are widely used in industrial applications, due to their capacity to transmit large amounts of torque [3]. The most typical examples where chain transmission systems are used, include:

1. Rigging and moving heavy materials
2. Hydraulic lift truck fork operation
3. Increasing or decreasing a driver's output speed by altering gear ratios between the driver and the sprocket being driven

Figure 4.3 represents a typical chain drive. This type of drive is not applicable for our purpose because of its weight and high cost. Please see Transmission Pugh Matrix table 4.1 in section 4.4 for further details.

Figure 4.3: Chain Drive

4.3 BELT TRANSMISSION

Belt drives represent the major type of flexible power transmission elements. A typical example can be seen in figure 4.4. Belt drives are particularly useful in applications where layout flexibility is important. They enable the designer to place components in more advantageous locations at larger distances without paying a price penalty. In our system, this type of drive is of special interest, as it gives certain advantages which are crucial for our system, including a big flexibility in belt and pulley variety. Many types of belts are available: flat belts, timing or synchronous belts, grooved or cogged belts, standard V-belts, double-angle V-belts, and others. Evaluation of these types will be made later in the document, section 4.5.

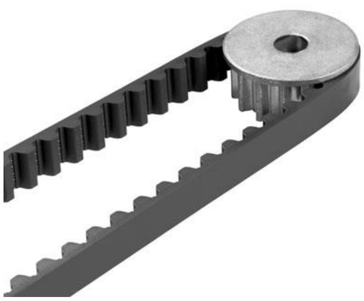

Figure 4.4: Belt Drive

4.4 Drive Evaluation

Based on Pugh Matrix evaluation, we have made a decision that belt drive is the most suitable solution for our project.

Transmission Pugh Matrix							
							
		Shaft transmission		Belt transmission		Chain transmission	
Criteria	Criteria Weight	Score (1-5)	Weighted score	Score (1-5)	Weighted score	Score (1-5)	Weighted score
Weight	0.30	3	0.9	4	1.2	1	0.3
Cost	0.20	1	0.2	3	0.6	2	0.4
Reliability	0.15	4	0.6	4	0.6	3	0.45
Efficiency	0.20	4	0.8	4	0.8	1	0.2
Complexity	0.15	2	0.3	4	0.6	4	0.6
Sum			2.8		3.8		1.95

Table 4.1: Transmission Pugh Matrix

4.5 BELT TYPES

There are many belt types: flat belts, timing or synchronous belts, grooved or cogged belts, standard V-belts, double-angle V-belts, and others. For our system of interest – where weight and price play crucial roles, a timing belt seems to be the best alternative.

Reasons for this choice are many:

1. Timing belts are basically flat belts with a series of evenly spaced teeth on the inside circumference, thereby combining the advantages of the flat belt like 98-99% efficiency with the positive grip features of chains and gears
2. Timing belt drives employ positive engagement of meshing teeth. Hence, they do not slip and there is no relative motion between the two elements in mesh
3. Different parts of the drive maintain a constant speed ratio or even a permanent relative position
4. These drives can transmit large torques and withstanding rapid accelerations
5. They are particularly useful in applications where layout flexibility is important
6. They enable the design engineer to place components in more advantageous locations at larger distances without paying a price penalty

All these factors are extremely important in small applications and automatic machinery where a small deviation have big consequences, and a definite motion sequence is involved [4].
Other belt types are not applicable, as they are used for bigger constructions and greater torque. Summarizing the analysis, to be able to transfer power from our single motor to all the four propellers, we will use a timing belt.

One of the suppliers we were considering was SDP-SI. They provide belt drive systems "Power Grip GT2/GT3". It is an advance in product design over the older standard HTD system, providing higher torque carrying capability and improved load carrying strength. The Power Grip GT3 Belt Drive System is the newest design and offers additional benefits over GT2. The improved construction and material compound provides superior load bearing capacity. The GT2 belts are being phased out and replaced by the new GT3 belts. Deep tooth design increases the contact area which provides improved resistance to ratcheting. The modified curvilinear teeth enter and exit the pulley grooves cleanly, resulting in reduced vibration [5].

These belts and pulleys are available in 2, 3, 5, 8 and 15mm pitches and provide the following advantages:

1. Longer belt life
2. Precision registration
3. Increased load-carrying capacity
4. Quieter operation
5. Precise positioning

Application examples for the Power Grip GT2/GT3 drive systems are machine tools, hand power tools, 3D-printers, medical diagnostic equipment, automated teller machines, robotics equipment, and vending equipment.

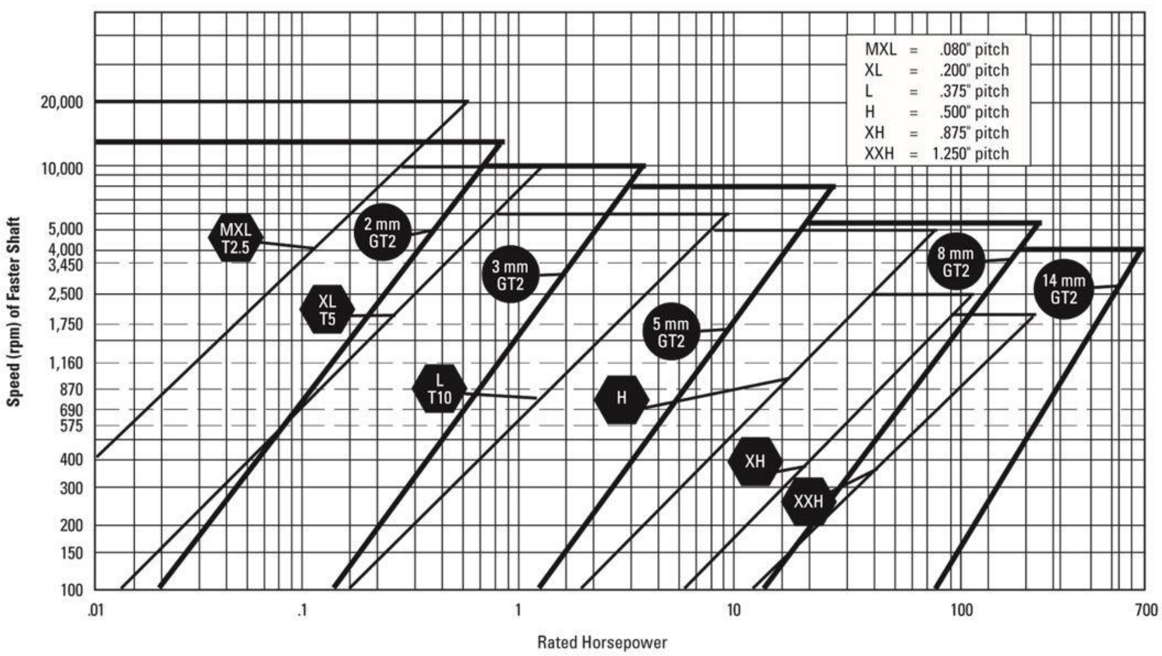

Figure 4.5: Timing Belt Choice

The efficiency and integrity of a belt drive is closely attributed to the quality of pulleys involved. The pulleys therefore, should be supplied by qualified and licensed suppliers. The GT2/GT3 pulleys manufactured by Stock Drive Products are made using licensed hobs, achieving the precise fit for the drive system. The belts we are using are Power Grip GT2/GT3. Calculating belt profile, using SDP-SI table [fig. 4.5], we use motor power and rpm values: 1660 W (2.225 HP), and the rpm area is 4000-6000 rpm for the fastest shaft on the best transmission system. The final selection is 3mm GT2/GT3 belt.

4.6 TIMING BELT DESIGN AND INSTALLATION

There have been evaluated several different suppliers. We use some technical data from SDP-SI supplier, as they have reasonable prices, broad variety and advanced technical approach.

Some general guidelines which are applicable to all timing belts per the aforementioned supplier [4]:

1. Drives should be designed with large reserve horsepower capacity
2. Check min pulley diameter: pitch, rpm → suggested minimum number of grooves & pitch diameter
3. The pulley diameter should never be smaller than the width of the belt
4. Because of a slight side thrust of synchronous belts in motion, at least one pulley in the drive must be flanged. When the centre distance between the shafts is 8 or more times the diameter of the smaller pulley, or when the drive is operating on vertical shafts, both pulleys should be flanged
5. Belts are, in general, rated to yield a minimum of 3000 hours of useful life if all instructions are properly followed
6. Belt drives are inherently efficient. It can be assumed that the efficiency of a synchronous belt drive is greater than 95%
7. Belt drives are usually a source of noise. The frequency of the noise level increases proportionally with the belt speed. The higher the initial belt tension, the greater the noise level. The belt teeth entering the pulleys at high speed act as a compressor and this creates noise. Some noise is the result of a belt rubbing against the flange, which in turn may be the result of the shafts not being parallel
8. The choice of the pulley material (metal vs. plastic) is a matter of price, desired precision, inertia, colour, magnetic properties and, above all, personal preference based on experiences. Plastic pulleys with metal inserts or metal hubs represent a good compromise

The professional specification of power transmission belts comprises the following steps:

1. Gathering the drive data
2. Selection of the optimal belt type
3. Calculation of the required belt dimensions

To select the optimal belt type and to calculate the required belt dimensions it is crucial to have exact information on the application, the drive data and the operating conditions.

For the calculation of a belt length L, the following data are required [6]:

d_1 -diameter of driving pulley, mm

d_2 - diameter of driven pulley, mm

c - centre distance, mm

In our design, we are not increasing/decreasing rpm or torque through pulleys, they only transmit these values without changes, thus both pulleys should be of equal size. Diameters can be chosen based on rpm levels we have 4000-6000. Using the tables, we choose 20mm [7].

$$L = 2C + \frac{\pi(d_1+d_2)}{2} \quad \text{II}$$

$$L = 2 \cdot 340mm + \frac{\pi(20+20)mm}{2} = 743mm$$

Belts are only made in certain lengths, so we need to slightly adjust shaft spacing to find one that suits best.

4.7 GEARS

Gears are a part of our belt transmission drive, as they transfer power directly from the motor. Gears are round mechanical components which have its purpose of transferring mechanical energy from one place to another, either by directly contact with another gear or power transfer with belts.

Gears can increase torque while reducing speed, and the other way around, but they cannot increase (or decrease) both at the same time.

4.7.1 TYPES OF GEARS

Spur gears [fig. 4.6] have straight teeth, and they are the simplest, and most common types of gears, and is used for rotary transmission of motion between parallel shafts. Many spur gears can be used together to create a very large reduction or increase in speed and torque. Spur gears are mostly wanted within a ratio range between 1:1 and 1:6 to get the best efficiency of the gears. The spur gears are very efficient gears with an operating efficiency of 98-99%. Because the entire face of the spur gear teeth is being engaged at once, they generally produce more noise when compared to most other gears such as helical gears with twisted teeth [8].

Figure 4.6: Spur Gear

Helical gears [fig. 4.7] run much quieter than spur gears, because the teeth have more gradual impact on each other. The impact contact starts at one end of the tooth and spreads further as the gear rotates. How fast they will impact on each other, depends of the tooth angle.

Figure 4.7: Helical Gear

Normal gear ratio is from 3:2 to 10:1, so they can reduce more torque and speed than the spur gears [9]. The disadvantage of helical gears is that they are more expensive to produce, and they are less efficient than spur gears. A parallel pair of helical gears have an efficiency of 96-98%, which is lower than the efficiency of spur gears. The energy loss results in more heat generated. Because of this, helical gears have more power loss and less efficiency, and some of the efficiency is also lost in axial thrust of the gear when spinning.

There is another gear type like the helical gears [fig. 4.8], only there is two identical pair of them joined together as one gear, mirrored – herringbone gears. This is a slight advantage over the helical gears because the axial thrust load will be cancelled. These gears are expensive to produce and they are normally used for high power applications [9].

Figure 4.8: Herringbone Gear

4.7.2 GEAR MESHING

When a gear is engaged with another gear, the gears are meshing. The pitch of a gear is the arc distance from a point on a tooth at the pitch circle [red arc at fig. 4.9] to the corresponding point on the next adjacent tooth, measured along the pitch circle.

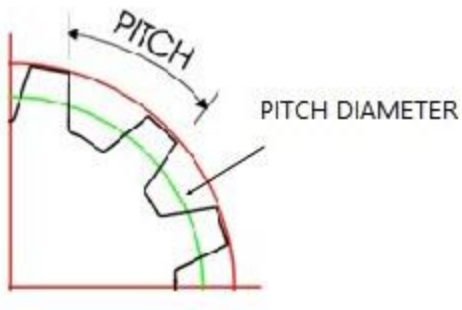

Figure 4.9: Pitch of a gear

Pitch diameter is used as the characteristic size of the gear for calculations of speeds. Pitch diameter for a gear is a theoretical concept and depends on a standard for pitch system. Module is the unit of size that indicates how big or small a gear is. It is the ratio of the pitch diameter of the gear divided by the number of teeth. Metric module, m, is given for both pinion and gear and they must be identical. The smaller values of m denote smaller teeth and vice versa:

$$m = \frac{pitch\ diameter}{number\ of\ teeth} \qquad \text{III}$$

The essential features of a gear mesh are stated below and are shown in figure 4.10:

1. Centre distance – C, mm
2. The pitch circle diameters (or pitch diameters) – D, mm
3. Number of teeth - Z
4. Size of teeth (or module) – m, mm
5. Pressure angle of the contacting involutes

Most gear teeth have the standard whole depth and a standard pressure angle 20°.

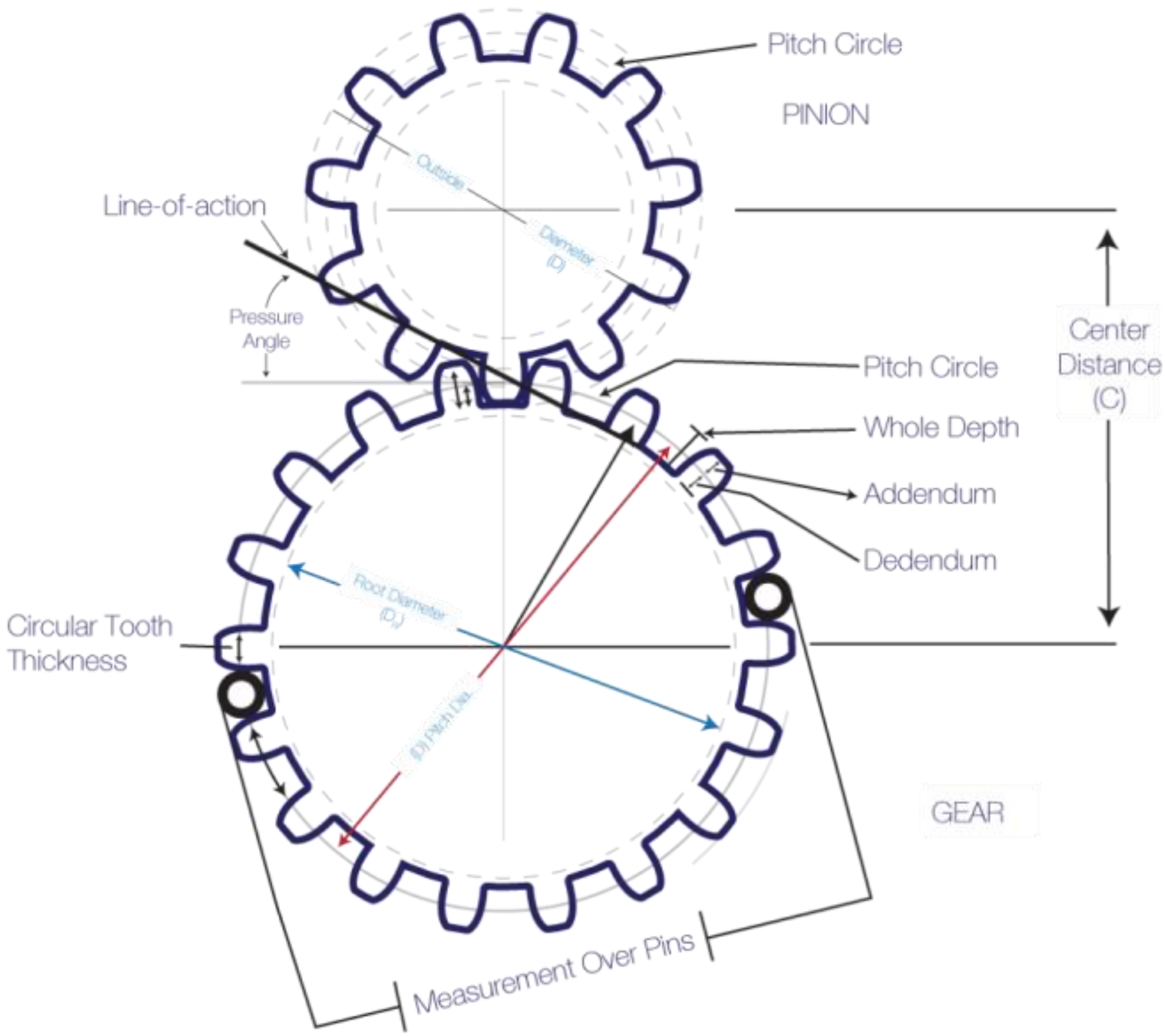

Figure 4.10: Basic Gear Geometry

1. A main factor a tooth profile must meet is that the angular speed of the driven wheel should be constant if the angular velocity of the driving wheel is constant (ω_1/ω_2 is constant)
2. The relative movement between the teeth should be a rolling movement, so that the friction and wear can be minimised
3. There is a demand that every gear with the same pitch diameter must work together no matter the tooth number. This will be possible if the angle of attack to the different teeth is congruent [10].

4.7.3 Calculation of stresses in gears

The choice of material for gears is determined by forces the gear is being exposed to. The weakest point on a gear is its teeth; they are subjected to excessive amounts of force while rotating. The strength of gears is generally expressed in terms of bending strength and surface durability. These are independent criteria which can have differing criticalness, although usually both are important.

When designing gears, we need to design it for the greatest stresses the system is subjected to. In our system, the gear subjected to the greatest stresses is the pinion gear connected to the motor shaft. This gear should be able to rotate at 27000 rpm whilst transmitting all motor power to the rest of the system.

In our system, we have 5 gears [fig. 4.11], where we have called them A, B, C, D and E.

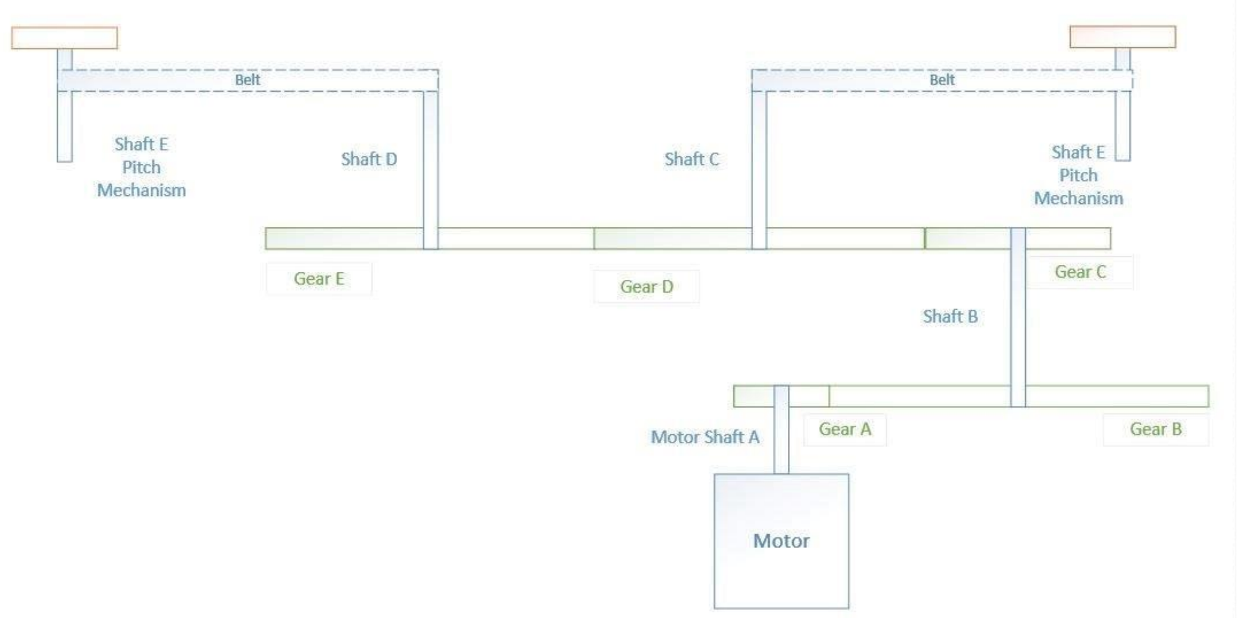

Figure 4.11: Sketch of Transmission System

Gear A, pinion gear, is directly attached to the motor. Gear A and B has a ratio of 1:4.7

Gear ratio E-D-C has a ratio of 1.43:1.43:1

All gears are spur gears, thus have an efficiency of 98%, $\eta=0.98$

η = (output power) / (input power)

We have calculated torque for each gear [eq. I, section 4.1], based on power, efficiency and angular velocity values.

Torque is the input shaft transmits the power from the coupling to the point where the pinion is mounted. The teeth of the pinion drive the teeth of the gear and thus transmit the power to the gear.

Torque calculations give the following results [table 4.2]:

Gear	Number of items	Power, W	RPM	Torque, Nmm
A	1.00	1500.00	27000.00	530.00
B	1.00	1470.00	5745.00	2440.00
C	1.00	1470.00	5745.00	2440.00
D	1.00	1440.60	4017.00	3420.00
E	1.00	1411.80	4017.00	3360.00

Table 4.2: Power and Torque Values

If the gears are rotating at a constant speed and are transmitting a uniform level of power, the system is in equilibrium. Therefore, there must be an equal and opposite tangential force exerted by the gear teeth back on the pinion teeth. This is an application of the principle of action and reaction.

This tangential force causes bending stress in a tooth. The classic method of estimating bending stresses in gear teeth is the Lewis equation [eq. IV]. It models a gear tooth taking the full load at its tip [9, 10].

First, we calculate stresses at the pinion – the driving gear from the motor. The calculations are done by treating the tooth as a simple short beam and tooth contact is occurring at the tip as shown in figure 4.12.

Assumptions for simplicity reasons:

1. The full load is applied to the tip of a single tooth in static condition
2. The radial component is negligible
3. The load is distributed uniformly across the full-face width
4. Forces due to tooth sliding friction are negligible
5. Stress concentration in the tooth fillet is negligible

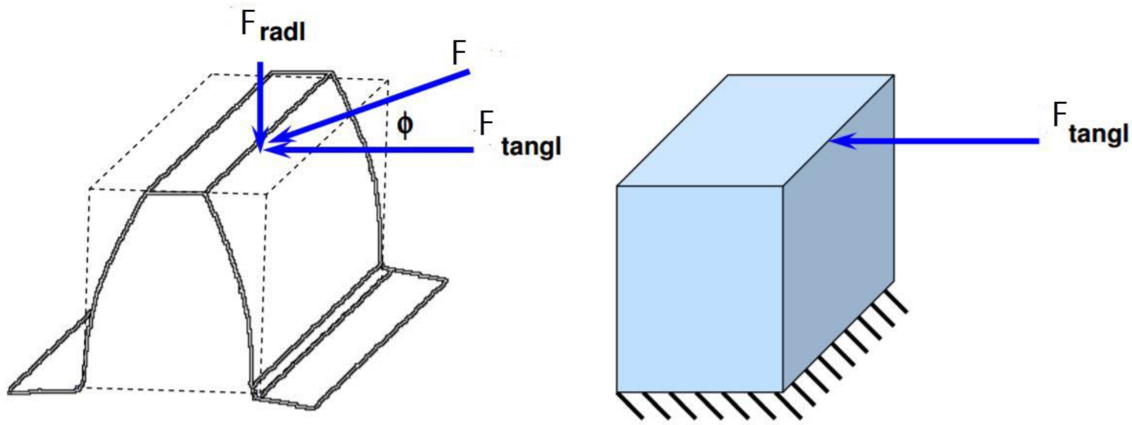

Figure 4.12: Bending Load on a Gear Tooth

$F_{tooth} = \frac{2 \cdot M_{torque}}{Z \cdot m \cdot \cos(\theta)}, where$ IV

$M_{torque} - \ motor\ torque, Nmm$

$m - modul, mm$

$Z - number\ of\ teeth$

$\theta - pressure\ angle$

$$F_{tooth} = \frac{2 \cdot 530.5Nmm}{12 \cdot 0.8mm \cdot \cos(20°)} = 117.61\ N$$

The bending tangential load on one tooth is found and we can calculate the bending stress. Bending stress is serving as a reference point of minimal yield strength of the pinion material.

$\sigma_{bending} = \frac{F_{tooth}}{b \cdot m \cdot Y}, where$ V

$Y - Lewis\ form\ factor, see\ figure\ 4.13$

$b - face\ width, mm$

$m - modul, mm$

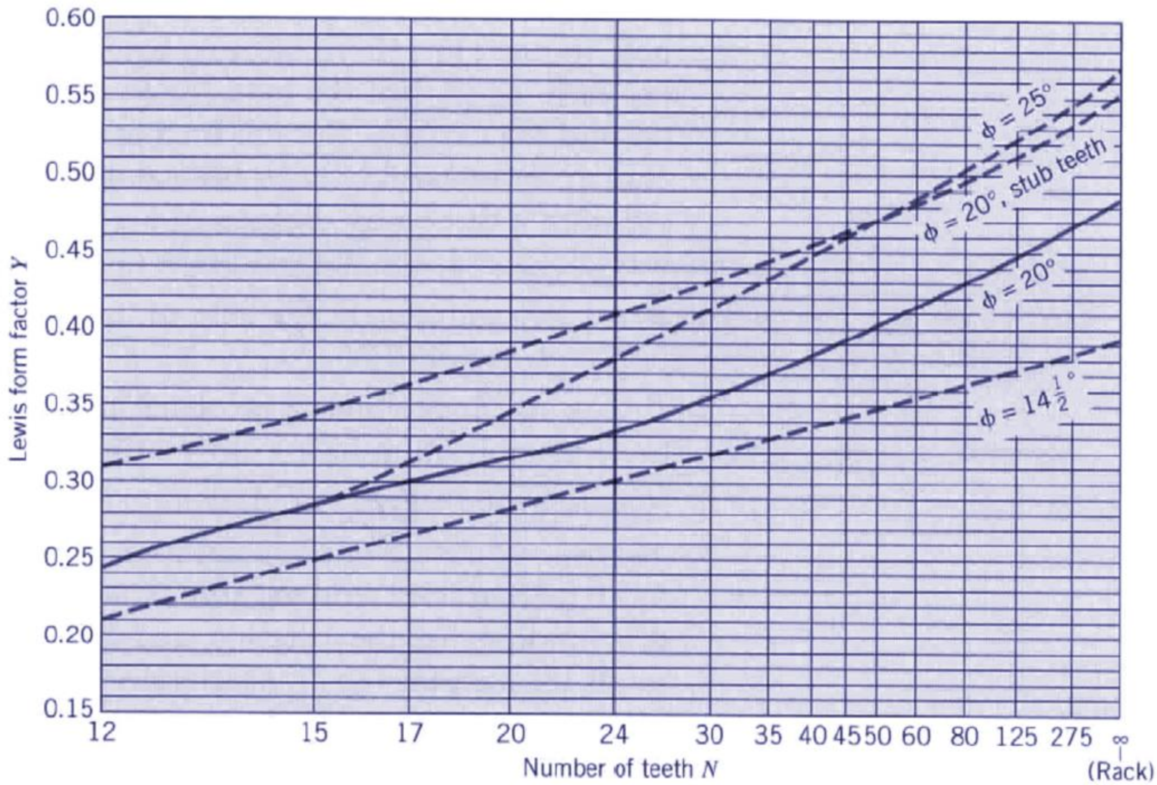

Figure 4.13: Lewis Form Factor Y

Drawbacks of the Lewis equation are [11]:

1. The tooth load in practice is not static
2. It is dynamic and is influenced by pitch line velocity.
3. It is assumed that the whole load is carried by single tooth. But it is not correct. Normally load is shared by teeth since contact ratio is near to 1.5.
4. The greatest force exerted at the tip of the tooth is not true as the load is shared by teeth. It is exerted much below the tip when single pair contact occurs.
5. The stress concentration effect at the fillet is not considered.

As in our system we have very high rotational speed (27000 rpm), we must consider velocity factor. Velocity factor is given by Barth's equation [VI]:

$K_v = \frac{6+v}{6}$, where: VI

$K_v - velocity\ factor$

$v - pitch\ line\ velocity, m/s$

We calculate pitch line velocity using angular velocity:

$\omega = \frac{2\pi \cdot n}{60} \frac{rad}{s}, where$ VII

$n - number\ of\ revolutions, rpm$

$v = \frac{d}{2} \cdot \omega, where$ VIII

$d - pitch\ diameter, m$

$$v = \frac{0.0096\ m}{2} \cdot \frac{2\pi \cdot 27\ 000}{60} \frac{rad}{s} = 13.57\ m/s$$

$$K_v = \frac{6 + 13.57}{6} = 3.22$$

Modified Lewis equation for bending stress:

$\sigma_{bending} = \frac{F_{tooth}}{b \cdot m \cdot Y} \cdot K_v$ IX

$$\sigma_{bending} = \frac{117.61\ N}{5\ mm \cdot 0.8\ mm \cdot 0.25} \cdot 3.22 = 378.7\ N/mm^2$$

The same calculations have been made for all gears [fig. 4.11]. The results for bending stresses on the gear teeth are given in the tables below [tables 4.3 and 4.4]:

Gear	Number of Items	Power, W	RPM	Torque, Nmm	Force, N	Bending stress, MPa
A	1.00	1500.00	27000.00	530.00	117.50	383.29
B	1.00	1470.00	5745.00	2440.00	115.92	370.26
C	1.00	1470.00	5745.00	2440.00	185.47	395.90
D	1.00	1440.60	4017.00	3420.00	181.97	419.65
E	1.00	1411.80	4017.00	3360.00	178.78	412.29

Table 4.3: Gear Calculations 1

Gear	Angular velocity, rad/s	Pitch line velocity, m/s	Velocity factor	Lewis form factor	No. of teeth	Face width, mm	Pitch diameter, mm
A	2827.43	13.57	3.26	0.25	12.00	5.00	9.60
B	601.61	13.48	3.25	0.41	56.00	3.00	44.80
C	601.61	8.42	2.40	0.37	35.00	3.00	28.00
D	420.66	8.41	2.40	0.40	50.00	3.00	40.00
E	420.66	8.41	2.40	0.40	50.00	3.00	40.00

Table 4.4: Gear Calculations 2

A reference point for choosing an optimal material is bending stress the gear is subjected to. Based on this information, it is now possible to choose the optimal material.

4.7.4 GEAR MATERIAL

Gear teeth must withstand a high amount of bending stress, and therefore it is needed to choose a material with enough tensile strength. In bending stress calculations, we have found out that with safety factor 3.22, bending stresses range between 300-400 MPa [section 4.7.3].

After evaluation of properties of different materials, we have found out that steel and titanium can be an option for our system. From the table 4.5 you can see that tensile strength is highest for titanium, but it is the most expensive material as well.

We have checked availability of products and their price at different suppliers (SDP, KHK, Powge). We have been in contact with "Eie Maskin AS" and "Tandhjulsfabrikken AS" in Norway to check whether they supply the necessary parts. They do not have gears of our type in titanium, but it could be made at a special order. That is out of cost budget of our project.

Material	Density, g/cm^3	Specific Gravity, -	Tensile Strength, MPa	Young Modulus, GPa	Bending Strength, MPa	Cost, USD/pinion gear, 12 teeth
Acetal	1.57	1.40	75.80	3.10	89.6	50
Nylon	1.64	1.14	82.70	2.93	103	50
Aluminium	2.70	8.00	310	68.9	310	10
Stainless steel	7.81	7.70	505	200	505	30
Titanium	4.51	4.5	800-1200	115	600-1200	200

Table 4.5: Comparison table; material properties

So, steel at a reasonable price and with enough strength has become the most optimal solution. As a result, the weight budget has increased with steel parts.

4.8 SHAFTS

A shaft is a mechanical component that transmits rotational motion and power. It is integral to any mechanical system in which power is transmitted from a prime mover, such as an electrical motor or an engine, to other rotating parts of the system. In our case shafts are incorporated into the belt drive system.

In the process of transmitting power at a given rotational speed, the shaft is inherently subjected to a torsional moment, or torque. Thus, torsional shear stress is developed in the shaft. Also, a shaft usually carries power transmitting components, such as for our system, gears and belt pulleys, which exert forces on the shaft in the transverse direction (perpendicular to its axis) [10]. These transverse forces cause bending moments to be developed in the shaft, requiring analysis of the stress due to bending. Shafts must be analysed for combined stress. Typically, bearings are used to support the shaft while permitting rotation relative to the housing of the machine.

Shaft geometry is greatly affected by the mating elements such as bearings, couplings, gears and other kinds of power-transmitting elements.

To design a shaft correctly we must follow the following procedure [13]:

1. Determine the rotational speed of the shaft
2. Determine the power or the torque to be transmitted by the shaft
3. Determine the design of the power-transmitting components or other devices that will be mounted on the shaft, and specify the location of each device
4. Specify the location of bearing to support the shaft. Normally two and only two bearings are used to support the shaft.

The shaft is being exposed to both bending and shear stresses.

We use the Von Mises formula to find out optimal diameters for shafts A-E [13]:

$$\sigma_{eq} = \frac{\sqrt{M_b^2 + 0.75 \cdot M_v^2}}{\frac{\pi \cdot d^3}{32}} \qquad X$$

Where:

σ_{eq} - equivalent stress acting on a shaft

M_b - bending moment

M_v - torsion moment

d - diameter of shaft

We have made calculations on the shafts to find an optimal diameter for each one [fig. 4.11, table 4.6]:

Gear	Shaft	Power, W	RPM	Torque, Nmm
A	A	1500	27000	530
B	B	1470	5745	2440
C	B	1470	5745	2440
D	C	1441	4017	3420
E	D	1412	4017	3360
Belt & Pulley	E	1384	4017	3260

Table 4.6: Shaft Calculations

Assumptions [13]:

- Equivalent stress for a cylindrical solid shaft is equal to maximum allowable stress of a chosen material
- As there is no danger of fatigue, and all shafts are thick and smooth, we use a factor of safety n=2, so the yield strength of a chosen material $\sigma_{max} = \frac{\sigma_y}{2}$

- As we have high torque and rpm values, we decided to assume that it will we optimal to use stainless steel and we take it as a starting point
- 416 Stainless steel have yield strength at $\sigma_y = 340\ MPa$
- No bending moment occurs, $M_b = 0$

Thus,

$$d = \sqrt[3]{\frac{\sqrt{M_b^2 + 0.75 \cdot M_v^2}}{\sigma_{eq} \cdot \frac{\pi}{32}}} \quad \text{X}$$

$$M_v = 9.55 \cdot 10^6 \cdot \frac{P}{n}\ , where \quad \text{XI}$$

P – power, kW

n – revolutions per minute

The table below shows the resulting diameters for all shafts for our system [fig 4.11], having taken into account stresses and properties of steel [table 4.7]:

Shaft	Number of items	Diameter, mm	Resulting values, mm
A	1	5.00	5
B	1	5.02	5
B	1	5.02	5
C	1	5.63	6
D	1	5.58	6
E	2	5.50	6

Table 4.7: Shaft Diameters

When considering a factor of safety, it is important to notice that for some applications its value is 1.3-1.5 [14]. This can be a case for use with reliable materials, such as steel, where loading and environmental conditions are not severe. Besides, factor of safety of 1.5-2.5 is used in aircraft components due to high weight restrictions.

4.9 Bearings

Rotary bearings hold rotating components such as shafts or axles within mechanical systems, and transfer axial and radial loads from the source of the load to the structure supporting it. In a ball bearing, to prevent sliding friction, rolling element balls are located between the races of the bearing assembly. The races are the grooves of the inner and outer ring, making the surface the balls are resting on. A wide variety of bearing designs exists to allow the demands of the application to be correctly met for maximum efficiency, reliability, durability and performance. The most common ball bearing is the single-row, deep-groove ball bearing [fig. 4.14].

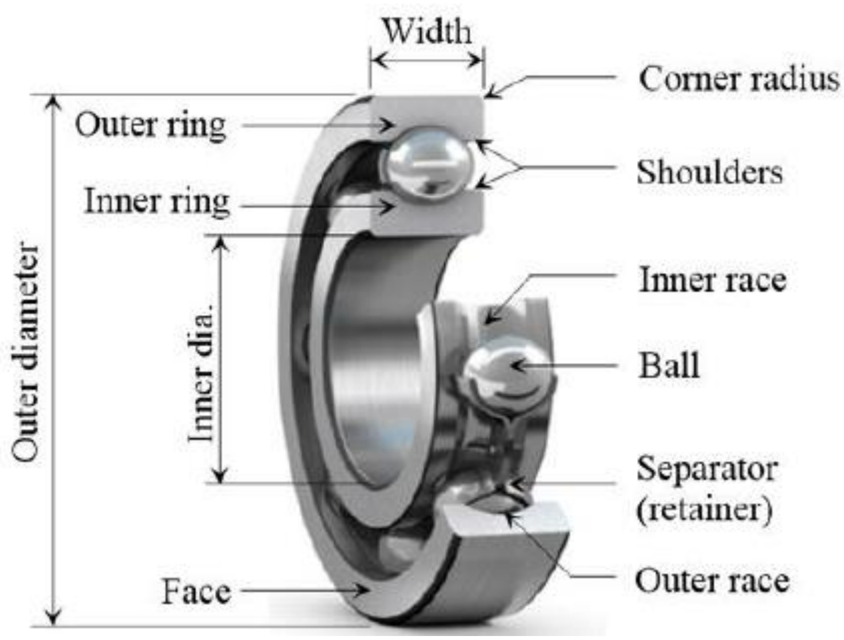

Figure 4.14: Ball bearing schematics [15]

4.9.1 Materials

The load applied to a ball bearing results in forces exerted on very small areas of contact. Contact stresses of 2000 MPa are not uncommon [16]. Because of the high contact stress, both the balls, rollers and races are typically made of hard high-strength steel alloys or ceramics.

4.9.1.1 Stainless steel bearings:

Generally comprised of all steel parts, stainless steel is one of the most trusted and common materials for ball bearings. Steel ball bearings are generally able to handle extremely high loads and high RPMs. A few drawbacks can be their heavy weight, noise, and low chemical resistance [17].

4.9.1.2 Ceramic Bearings:

In ceramic ball bearings, the balls are made of silicon nitride, providing a very hard surface. Ceramic ball bearing therefore rotate with less friction, resulting in reduced heat and noise production. The ceramic ball bearings are often used in applications that need high speeds, accuracy and reduced friction, such as aircraft instruments and medical hand-pieces like dental drills. Ceramic bearings are however more expensive and not as common as steel bearings [18].

4.9.2 Loads

In a single-row, deep-groove ball bearing the balls roll inside the groves of the inner and outer races. The radius of the ball is slightly smaller than the radius of the groove to allow free rolling of the balls. This ball bearing is primarily designed for carrying radial loads, but the deep groove allows it to carry a sizable axial load [13]. The inner race is pressed on to the shaft to make sure the bearing rotates with the shaft.

4.9.3 Calculations

In the drone, the bearings exposed to the most complex loads are the bearings on the propeller shafts [fig. 4.15]. These bearings will like the other bearings in the system be subjected to radial loads, but they will also be subjected to a fair amount of axial load. The propeller shaft is shaft E [fig. 4.11]. This shaft is upheld with two bearings, one on each end of the frame. The entire weight of the drone will pass through these bearings, with increased loads during acceleration. We are therefore verifying these bearings numerically by analysing the loads. We are especially interested in the Basic Dynamic Load Rating, as it indicates what dynamic stress the bearing can tolerate throughout its life time. In order to calculate the Basic Dynamic Load Rating, the design life and the equivalent load of the axial and radial loads must be found.

Figure 4.15: The propeller shaft bearing

4.9.3.1 RADIAL LOAD

The radial load consists of two load components, the preload by the belt and the centripetal load.

Preload:

The propeller shaft bearings will be subjected to a preload from the belt. This load is induced by tightening the belt so that there is little play. According to the belts manufacturer, the recommended preload is 1 kg [19]. The preload will be distributed over both propeller shaft bearings, making the load on each bearing 0.5 kg.

$$F_{preload} = 0.5kg$$

$$F_{preload} = 0.5kg \cdot 9.81\frac{m}{s^2}$$

$$F_{preload} = 4.9N$$

Centripetal load:

The centre of gravity of any rotating machine element will deviate slightly from the axis of rotation. This is known as eccentricity. When the shaft is rotating, a centripetal force acts in the centre of gravity:

$$F_C = m \cdot \omega^2 \cdot e_0 \qquad \text{XII}$$

Where F_c = centripetal force

m = mass of the shaft

w = angular velocity

e_0 = eccentricity

As the upper bearing is mounted on the middle of the propeller shaft, the centripetal force will be exerted by the shaft onto the upper bearing. The mass of the propeller assembly is 110 grams.

We cannot determine the eccentricity of the propeller assembly, but the accuracy of the machining and the small dimensions, leads us to assume an eccentricity of 0.1 mm. To factor inn tolerances in assembly and to leave margins for misalignment in the airframe, we generously set the eccentricity to 1 mm.

$$m = 110g$$
$$\omega = 628\frac{rad}{s} \text{ at 6000 rpm}$$
$$e_0 = 1mm$$

Thus,

$$F_c = 0.11kg \cdot 628\frac{rad}{s} \cdot 0.001m$$
$$F_c = 0.069N$$

The vector of this centrifugal force will move with the rotation of the shaft, alternating between positive and negative. The maximum radial force on the upper bearing becomes;

$$F_{radial} = F_{preload} + F_c$$
$$F_{radial} = 4.9N + 0.069N$$
$$F_{radial} = 4.97N$$

4.9.3.2 AXIAL LOAD (THRUST LOAD)

The entire weight of the system, except for the propeller assembly, will be held by the propeller shaft bearings. If we assume a generous final weight of the system of 3 kg, and a thrust-to-weight ratio of 3:1, the highest load during acceleration will be equivalent to 9 kg. Allowing for different system configurations, we assume a max load of 10 kg, 2.5 kg per arm.

$$F = ma$$
$$F = 2.5kg \cdot 9.81m/s^2$$
$$F = 24,5N$$

This load is distributed over both bearings, making the axial load on each propeller bearing;

$$\mathrm{F}_{\mathrm{axial}} = 12,25N$$

4.9.3.3 EQUIVALENT LOAD WITH RADIAL AND THRUST LOADS:

As the bearings are subjected to both radial and axial loads, the equivalent load is found:

$$P = VXR + YT \qquad \text{XIII}$$

Where P = equivalent load

V = rotation factor

R = applied radial load

T = applied thrust (axial) load

X = radial factor

Y = thrust factor

The radial and thrust factors X and Y are assumed to be X=0.56 and Y=1.50 [16] As the inner race of the bearing is the one rotating, the rotation factor V is 1.0, as per standard convention. Thus,

$$P = VXR + YT$$
$$P = 1 \cdot 0.56 \cdot 4.97N + 1.5 \cdot 12,25N$$
$$P = 21.16N$$

4.9.3.4 DESIGN LIFE:

In order to find the Basic Dynamic Load Rating, we must first find the design life of the bearing in revolutions. The bearing will carry an equivalent load of 21.16 N, running at 4500 rpm [table 4.5 section 4.8]. The recommended design life for bearings in aircraft applications, Design life L_{10} ranges from 1000 to 4000 hours [16]. The L_{10} life indicates a 90 % probability that the bearing will carry its rated dynamic load for he specified number of hours. The bearings will be subjected to vibrations and highly varying loads. To leave room for margins, we define the L_{10} to be 1000 hours. The Design life (L_d) is found:

$$L_d = (h)\cdot(rpm)\cdot\left(60\frac{\min}{h}\right) \quad \text{XIV}$$

$$L_d = 1000\cdot 4500\cdot\left(60\frac{\min}{h}\right)$$

$$L_d = 2.7\cdot 10^8 \text{ revolutions}$$

4.9.3.5 BASIC DYNAMIC LOAD RATING:

The basic dynamic load rating indicates the tolerances for the bearing in operating conditions.

$$C = P_d(L_d/10^6)^{1/k} \quad \text{XV}$$

Where C = Basic dynamic load rating

P_d = Design load

L_d = Design life

k=3.00 for ball bearings [16]. Thus,

$$C = P_d(L_d/10^6)^{1/k}$$

$$C = 21.16N\cdot\left(\frac{2.7\cdot 10^8}{10^6}\right)^{\frac{1}{3}}$$

$$C = 136.8N$$

4.9.4 BEARING VALIDATION

The upper propeller bearing, the one subjected to the largest loads, is subjected to a Basic Dynamic Load Rating of 136.8 N. Obtaining a data sheet for the bearing in question turned out to be challenging. The manufacturers seem reluctant to provide a full data sheet of their bearings, but through contact with the supplier we managed to get some data for comparison [fig. 4.16].

m	3,65 g	Mass
C_r	1020 N	Basic dynamic load rating, radial
C_{0r}	415 N	Basic static load rating, radial
n_G	57000 1/min	Limiting speed
C_{ur}	13,7 N	Fatigue limit load, radial

Figure 4.16: Manufacturer's data sheet [20]

The data sheet only list the radial Basic Dynamic Load Rating, which does not account for axial loads. Yet, it is interesting to note that the bearing is specified for a 1020 N radial Basic Dynamic Load Rating, while the Basic Dynamic Load Rating the bearing will be subjected to is only 136.8 N per the calculations. Considering that single-row deep-groove ball bearings can handle substantial axial loads [13], we can conclude by analogy that the bearings are well within their mechanical tolerances during operation. Also note that the bearings are rated for 57000 rpm, while they will normally operate at 4500 rpm. Comparing the calculations to the manufacturer's data sheet adequately validates the use of the bearings.

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5 Frame concepts

The frame and layout of our quadcopter drone has been extensively considered during design and development in iteration 5. We have modelled a total of eight different solutions in SolidWorks to identify solutions and options for our project. Below is a brief presentation of the frame and layout solutions we have modelled.

5.1 Concept 1

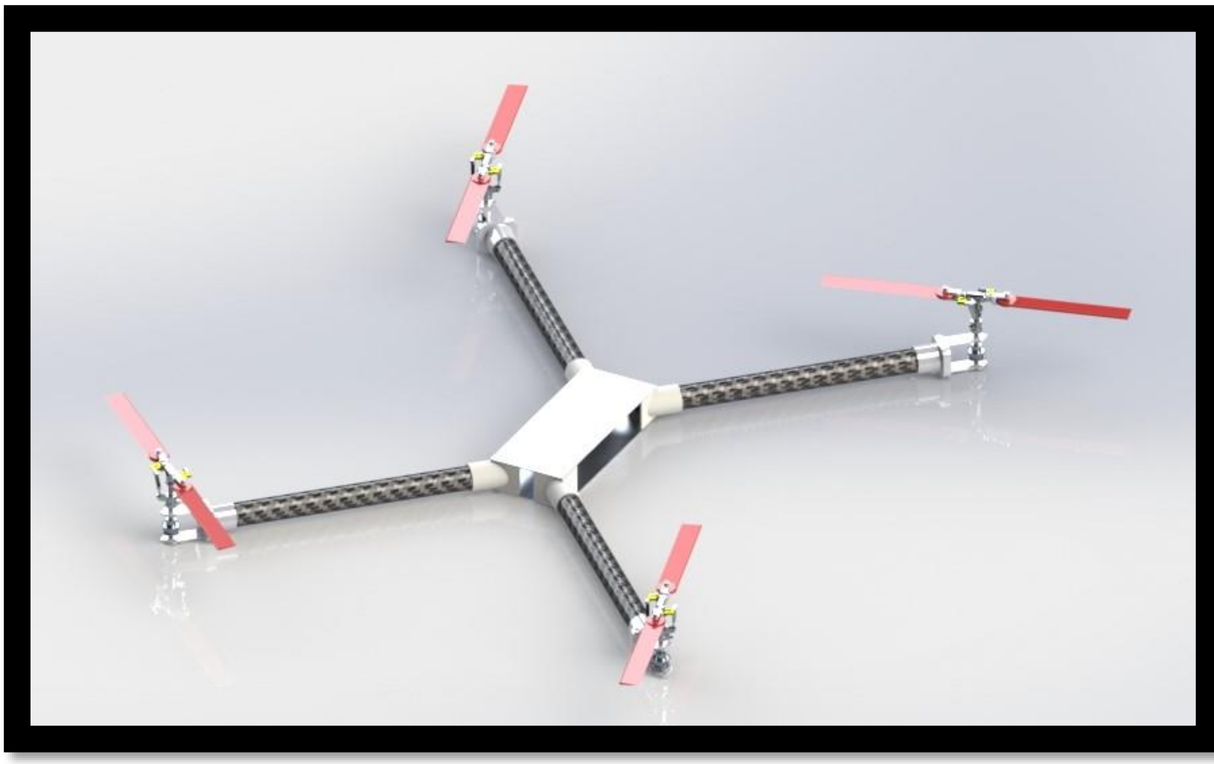

Figure 5.1: Conceptual X-Shaped Carbon Tube Quadcopter

Concept one [fig. 5.1] is a X-shape drone with carbon tubes connected to the quadcopters main body, made of simple aluminium plates. The intention for this design was to use belts and pulleys to drive the propellers with the belts running internally in the tube for robustness. A big issue we discovered with this design is that the diagonal arms are not on the same axis, making the location of shafts or belts unnecessarily complicated, in the main body part of the quadcopter. On the positive side this frame would be quite easy to manufacture and offer good protection of internally moving parts.

5.2 CONCEPT 2

Figure 5.2: Conceptual H-Shaped Quadcopter

The design of this frame layout [fig. 5.2] is inspired by a quadcopter called StingRay 500. The power propulsion is done by belts and a drive shaft going through the middle of the quadcopter. The motor pulley which is connected to the motor, transfer power to the main drive pulley with the use of a belt. This main drive pulley is then again connected to the drive shaft, who delivers power to all the quadcopter arms. This is done by smaller pulleys which is fastened to the drive shaft, which uses belts to rotate the propellers. The design is a typical H-Shape, where two plates made of composite are placed parallel to each other, only separated by several standoffs. The reason we didn't choose this design in the end, is because it doesn’t work with the kind of power propulsion that the project group landed on. Another drawback with this design, is that to get every other propeller to turn counter clockwise while the others turn clockwise, the belts on each side will need to be twisted 90 degrees, which is not preferable due to wear.

5.3 CONCEPT 3

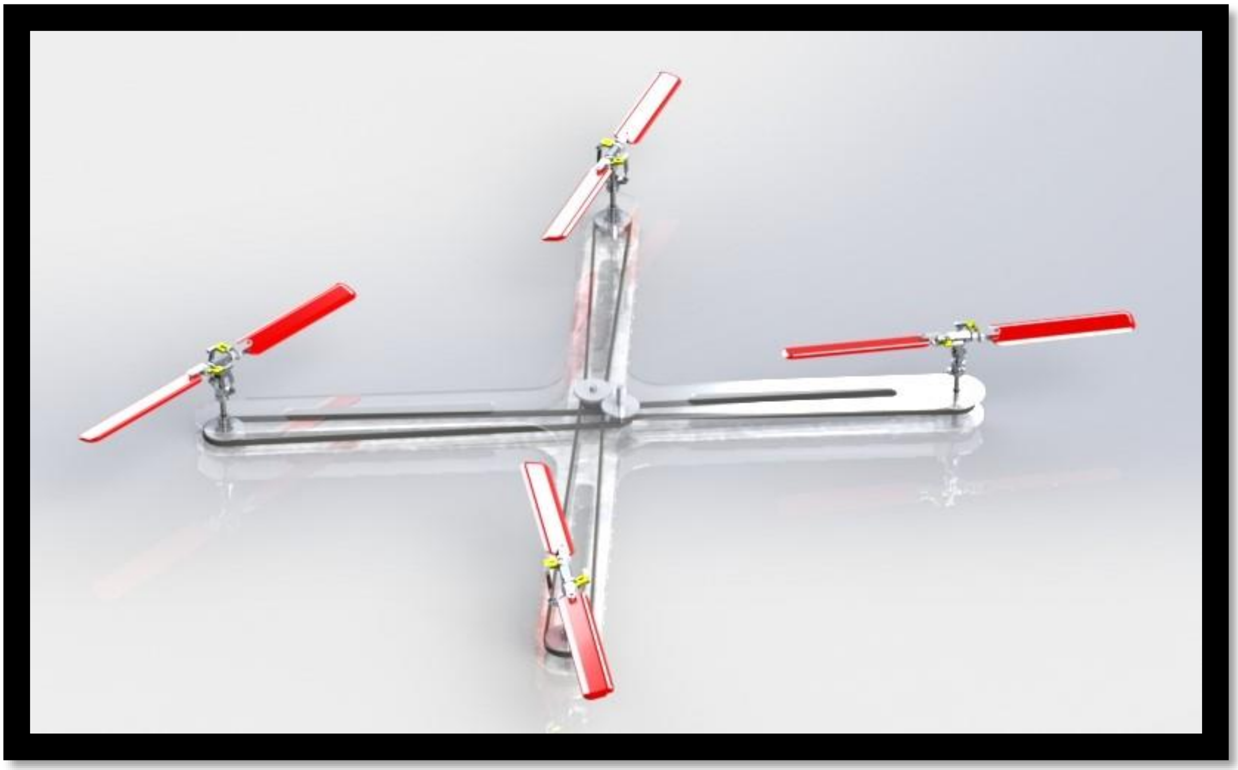

Figure 5.3: Conceptual X-Shaped Plexiglas Quadcopter

The frame/layout concept shown in figure 5.3 is a simple x-shape drone. The frame consists of two Plexiglas plates where most of the moving parts on the drone would be placed between them. The main purpose of this design concept was to investigate the optimal solution and placement of timing wheel pulleys, belts and gears. The arms are diagonally on the same axis which makes the placement of pulleys and gears relatively easy. It would be easy to manufacture and the frame material is cheap. A disadvantage of the solution is that standard Plexiglas plates are quite heavy and the design would be unsuitable for taking up bending stress, compared to a frame design with vertically aligned plates.

5.4 CONCEPT 4

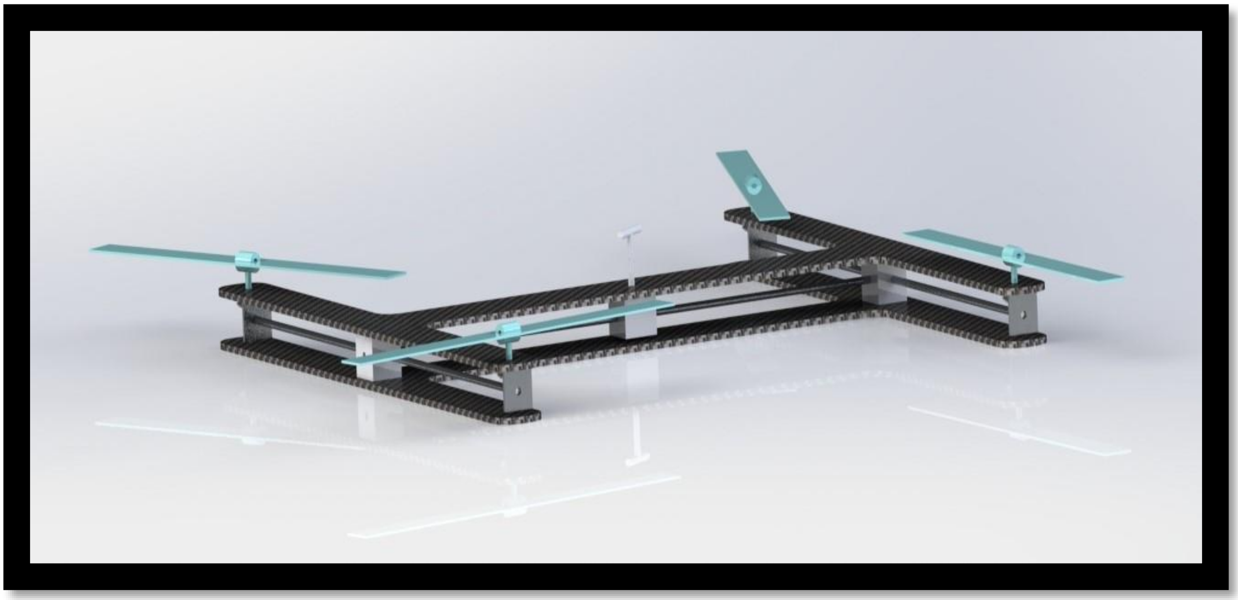

Figure 5.4: Conceptual H-Shaped Differential Quadcopter

Figure 5.4 depicts a conceptual H-shape quadcopter. It was designed with one goal in mind - to design a quadcopter which only uses shafts and differential gears for power propulsion. Because all the other concepts rely on belts for propulsion, the design team wanted to make something different to challenge the collective idea of how the quadcopter should work. The design itself is not completely different from some of the others we made, but it is a conceptual design that makes this type of power propulsion possible. We didn't spend much time developing this design further, because it became clear relatively early in the process, that it would get too expensive and too heavy to realize it [section 4.1].

5.5 CONCEPT 5

Figure 5.5: Conceptual X-Shaped Belt Driven Quadcopter 0.1

Concept five shown in figure 5.5 is an X-shaped drone, where the frame consists of two composite plates, which will protect the mechanisms running through it. In this design, we thought of a belt driven power propulsion system. The holes in the frame serves solely the purpose of weight reduction. As this drone was made early in the design process, it didn't have enough space for vital components to be placed in the middle. But it was designed with the purpose of giving the design team information about the belt propulsion system.

5.6 CONCEPT 6

Figure 5.6: Conceptual X-Shaped Belt Driven Quadcopter 0.2

Frame design in figure 5.6 is an improved version of the previous [fig. 5.5]. At this point in the process the project group decided that we would build an X-shaped drone with belts, timing wheel pulleys and gears. As seen in figure 5.6, this conceptual design has some different solutions than the others. The drone is still to be made of composite, but instead of two parallel plates, this drone has arms where composite plates stand vertically. This is to give the frame more stiffness, and thus making it stronger. This type of frame makes belt system available. It allows to tighten the belts if/when it is needed. This design has enough space in the middle for all necessary components. Although this design brings a lot of advantages, it has some drawbacks as well. Firstly, the arms of the quadcopter have angular shape, which would have given the project group problems when assembling it. Thus, it would be difficult to manufacture it ourselves. Secondly, the construction is quite tall at its highest, which can cause unnecessary problems in the future and make it unnecessary big.

5.7 CONCEPT 7

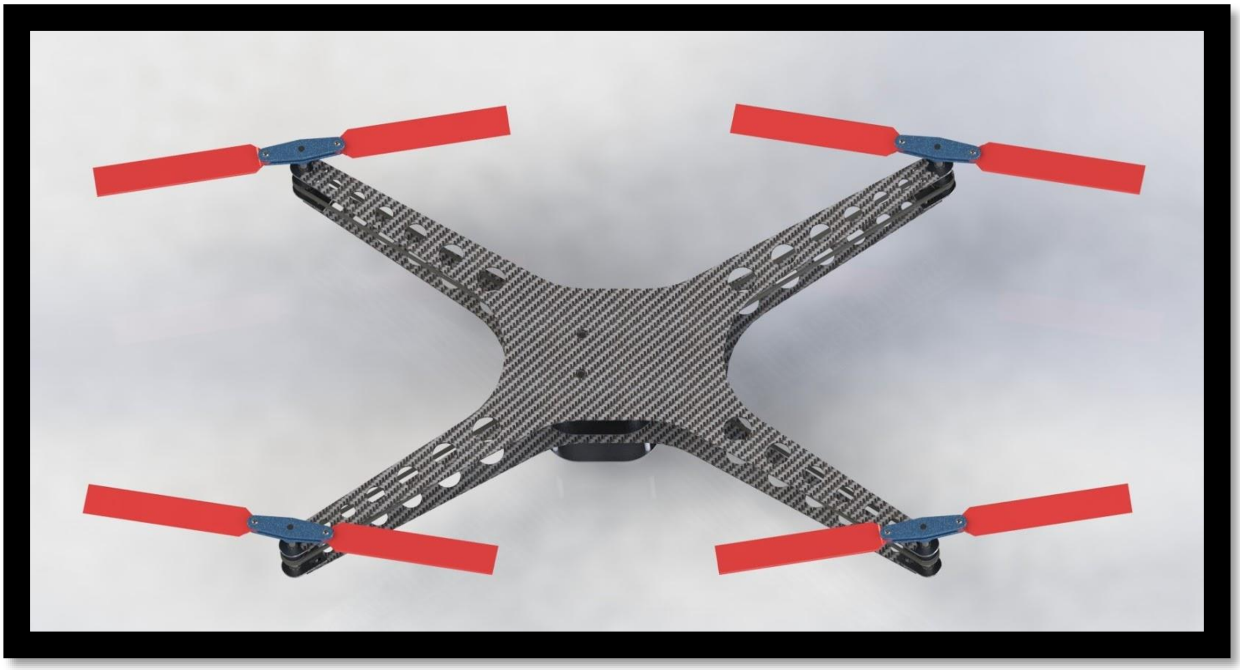

Figure 5.7: Conceptual X-Shaped Belt Driven Quadcopter 0.3

Design of this conceptual quadcopter [fig. 5.7] has taken the X-shape design from the previous two concepts into consideration, trying to find a better solution. It has the same composite frame as concept 5 [fig. 5.5], and the same space in the middle section as concept 6 [fig. 5.6]. The frame is slimmer and lighter, while it still should be stiff and strong enough that it would cope with bending stresses. The power propulsion still consists of belts, pulleys and gears. As a result, the design process has gone more in the direction of optimizing the frame design, rather than reinventing the wheel. The design will also make the mechanisms inside quite visible and relatively easy to reach, thus making it easy to repair.

5.8 CONCEPT 8

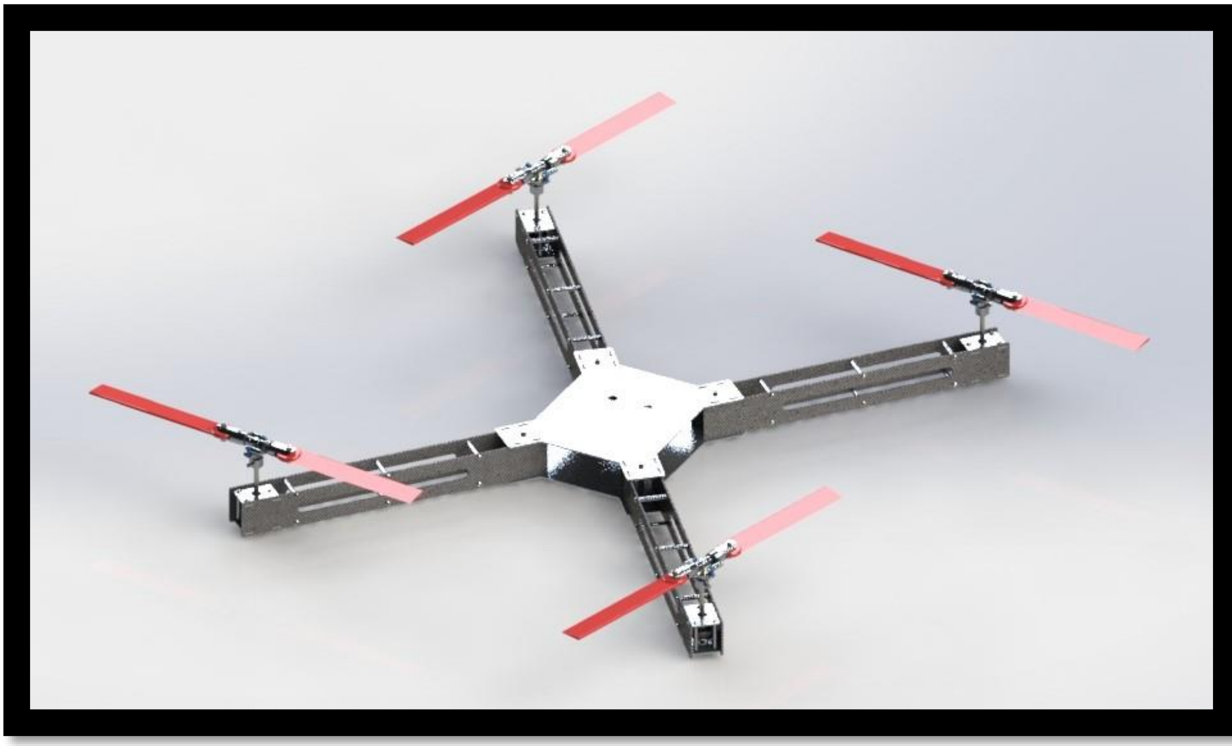

Figure 5.8: Conceptual X-Shaped Belt Driven Quadcopter 1.0

Concept 8 [fig. 5.8] is an even further developed and optimized solution for our intended X-shaped quadcopter with belt propulsion. In this design, the quadcopter frame won't consist of only two plates lying parallel and horizontal to each other constituting both arms and body. The quadcopter will rather consist of a smaller midsection, and the propeller arms will be fastened to it. This will make the quadcopter much easier to manufacture. Simply because it can be manufactured in smaller parts, instead of one big piece, which requires manufacturing in larger machines. The design of the propeller arms consists of two plates standing vertically to each other, and is tightened to one another with the help of standoffs and bolts. This mechanism will also fasten the arms to the midsection. As the arms are standing vertically to one another, they will also make the structure very stiff and durable to bending stresses occurring during acceleration. The design is a bit more complex than many of its predecessors, but the design team is convinced that it got far more advantages than drawbacks.

6 FRAME MATERIAL

As mentioned earlier in the documents, one of the main requirements from the customer is a weight restriction. Thus, during R&D we have had a challenge in choice of correct material which has good strength and low weight at the same time.

Engineers are always looking for a material with a high specific strength. Table 6.1 compares the specific strength of different industrial materials [1]:

Material	Mass density, g/cm^3	Tensile Strength, MPa	Specific Strength, kNm/kg
Aluminium 7075-T6	2.8	600	214
Magnesium alloy AZ91D	1.7	230	135
Titanium	4.4	950	216
Carbon Steel (0.45 % C)	7.8	850	108
Maraging Steel	8.1	2500	300
Carbon composite	1.6	1240	785

Table 6.1: Comparison of material properties to different materials

The materials with a high strength and low mass density provide a high specific strength and are ideal for engineers. Steel has become the optimal material for most of power transmission elements such as shafts, gears, bolts, screws, washers, bearings. It can be seen [table 6.1] that carbon-fiber-reinforced composites (CFRC) possess the highest specific strength. The specific strength of carbon composites are at least two times more than maraging steel, which is characterized with the highest strength among all types of steels. This means that for a certain required strength, the weight of a component is reduced to half if CFRC is used instead of maraging steel. For automobile applications, this means a lighter vehicle that consumes less fuel. Low crack growth due to impact or fatigue, the ability to produce in directional mechanical properties, and being cost-effective in mass production are the other highlighted properties of carbon-reinforced composites. As a result, this material is considered to be an advanced structural material. The bonding between fibers and matrices is created during the manufacturing phase of the composite material. This has fundamental influence on the mechanical properties of the composite material [1].

The reason that composites are used increasingly is the strength-to-weight advantages they offer. The key to obtain these advantages is maximizing the fiber-to-resin ratio. The reinforcement (fiberglass, aramid Kevlar®, carbon, etc.) is not particularly strong in the textile state. Also, thermosetting resins such as polyester and epoxy are quite brittle if cured without reinforcement. But when combined, composites become an advanced material with excellent characteristics: weight reduction and as a result fuel saving and increase in payload, good fatigue resistance, enhanced life, saving in long-term cost of the product, good corrosion resistance.

6.1 Plan A: Composite

When it comes to frame and its elements, the project group have decided to make arms and middle plates [fig. 6.1] in composite. That's due to high strength and low weight ratio of this advanced material.

Figure 6.1: SW model of frame in composite

Frame in composite has been plan A for our project from the very beginning. At our composite laboratory "Krag" at HSN, we can manufacture products in composite using vacuum to produce a laminate of high quality. All members in our project group have had a subject in Composites &

Polymers, and we were eager to apply our knowledge in our bachelor project. Especially because composites are widely used in drone industry due to its high strength and light weight.

6.1.1 Composite production

We have made a scientific research and tried to make frame for our drone in composite. A detailed report is provided in the Appendix A – “Composite Production Report”.

We have experienced that production and manufacturing of parts is more time-consuming than first assumed. There are some factors that must be in place to have our frame ready in due time. We had to take precautions and have in mind that our frame in composite might not be ready in time, because of limited access to our laboratories and external assistance on the machines.

At earlier stages of the project, we planned to make carbon fiber plates and cut them in necessary parts using CNC machine. We got confirmed that using of CNC for cutting carbon fiber is possible, and we have a machine available at school, but the CNC machine has size restrictions of 40x30x25cm. Therefore, we adjusted our frame design according to production restrictions and cut ready composite plates cut into smaller pieces [see Appendix A: Composite Production Report].

Another restriction is that no one in the project group has experience in operating CNC machine. We had to come in contact with our CNC operator at school to fulfil the operation. Time schedule for the operator is quite dense, and the cutting operation could get time-consuming.

Composite laminates of high quality were produced in the laboratory. After that, the idea was to cut laminates into arms and plates to construct the frame. We tried CNC machine and manual cutting, but both methods didn’t give us sufficient quality. That’s why we had to evaluate other materials for the frame and switch to plan B.

6.2 Available materials

There are some available materials for us to use as a plan B for our project.

- MDF (Medium density fibreboard) are manufactured from pressure cooked wood, and are composed of small fibers of compressed wood and resin
- Plywood is a material manufactured by several thin layers of wood glued together, like sheet layers of composites. The wood sheets are orientated 90 degrees to one another [2]

- Plexiglas are rigid acrylic sheets which is commonly used as unbreakable glass. It weighs half as much, but is up to 17 times more impact resistant than glass.
- Aluminium is a light and durable metal [3]

When comparing the properties of these materials, there is no doubt that aluminium is the strongest material of the ones we have available at our university [table 6.2]. But aluminium takes a lot of time to adapt and cut into the desirable design. The plates available are also very flexible because of their lack of thickness. So, aluminium was not recommended for our usage.

Properties	MDF	Plywood	Plexiglass	Aluminium 6061
Tensile strength, MPa	18	31	70	310
Compressive strength, MPa	10	31.0 - 41.4	103	--
Shear strength, MPa	N/A	6.2	62	207
Bending strength, MPa	44	--	98	386
Elongation, %	0.5	--	4.5	12
E-modul, MPa	4000	--	3300	3100
Density, g/cm^3	0.75	0.615	1.19	2.70

Table 6.2: Mechanical properties of MDF, Plywood and Plexiglass

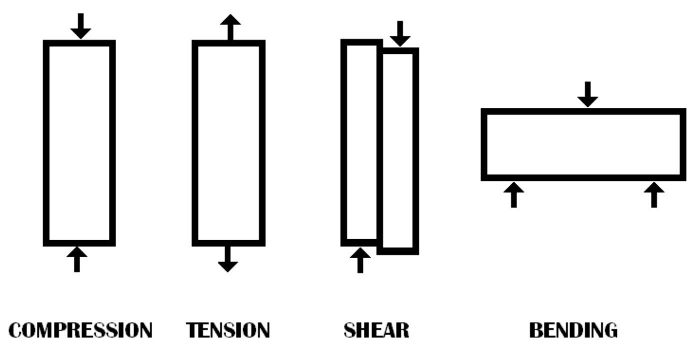

Figure 6.2: Illustration of the different stresses from property table 6.2

Another factor is water resistance of materials, as our quadcopter can be used outside.

The MDF plates don’t handle moisture very well, so it is not recommended for outside use [4]. When comparing strength, plywood is stronger than MDF [5]. Plywood is more water resistant than the MDF plates, and will not soak up water so quickly.

Plexiglass protects against rain, hail and stormy weather. Then we can conclude that plexiglass is the most suitable of them. One disadvantage is its density. Again, plexiglass is the best option between the three available materials.

6.3 PLAN B: PLEXIGLASS

As discussed in the Project Plan, the weight restriction coming from RO1 is no longer crucial for us to follow. As long as the quadcopter has the necessary lifting capacity to hover, we can choose a material which is heavier [6].

Summarizing the results of 3 trials with composite plates, project group have decided not to proceed with carbon fiber composite. Although we had belief in this material both due to its strength to weight ratio and appearance, manufacturing and cutting of composite materials demand special tools and experience.

When it was clarified, we switched to our plan B at once. Plan B was to made frame in Plexiglass.

After thorough evaluation of the result in composite, the project group have made a decision to stop production of frame in composite. The main reasons for that are:

- Quality not accurate enough to meet the tolerances for bolts, screws etc. [fig. 6.3, 6.4]
- Lack of necessary cutting tools/machines at school to increase the quality of manufacturing
- Too tight cost and time budget to be able to use external help (companies, sponsors etc.)
- More focus on functionality of the drone than appearance due to tight schedules
- Plexiglass prototype is functional and satisfy our goals

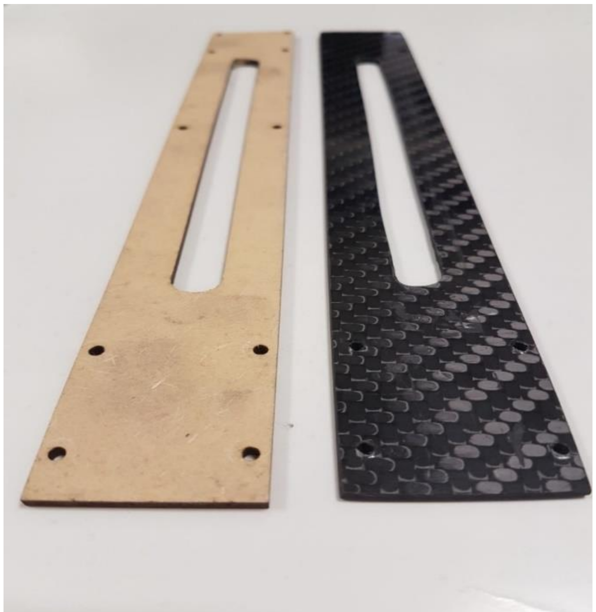

Figure 6.3: MDF and carbon fiber arms

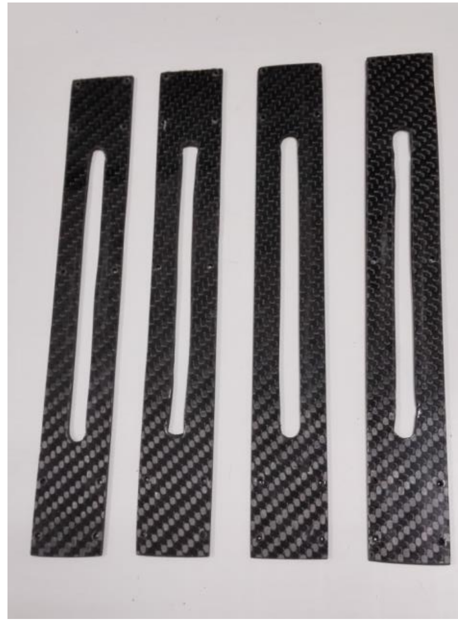

Figure 6.4: Carbon fiber arms

Having taken into assumption all the factors described above, we are building our drone in plexiglass as a final design.

6.4 LASER CUTTING

Since machining of carbon fibre composites failed, we jumped to plan B, made some design changes to the frame, and optimized it for cutting in a laser cutting machine. The material chosen was 4mm Plexiglas. For more information on material choice and backup plan, please see section 6.2.

6.4.1 HARDWARE

The measurement technology lab at HSN, campus Kongsberg, is equipped with an Epilog Laser Fusion M2 Engraving & Cutting System (fig. 6.5). This is a 75W CO2 laser cutting machine that can easily cut, engrave and etch many materials, like plywood, MDF and Plexiglass. It is run in conjunction with an air extraction device, which provides extraction of hazardous gases during operation.

Figure 6.5: Epilog Laser Fusion M2 Engraving & Cutting System

6.4.2 SOFTWARE

To cut the desired frame parts with the laser cutter, we first had to produce a 2D drawing in Solidworks. Solidworks .DWG file ("Binary file format used for storing two- and three-dimensional design data" [7]) was then saved as a .DXF file ("Drawing Interchange Format, or Drawing Exchange Format is a CAD data file format for enabling data interoperability between CAD software and other programs" [8]) and imported to the FlexiDESIGNER software for further processing.

In the GUI of FlexiDESIGNER, copies of the parts which had to be cut several times where made. So, the parts were arranged in a way that minimized the use of raw material (80x50 cm Plexiglass sheet). Figure 6.6 shows the layout of the frame to be cut in the FlexiDESIGNER software after processing.

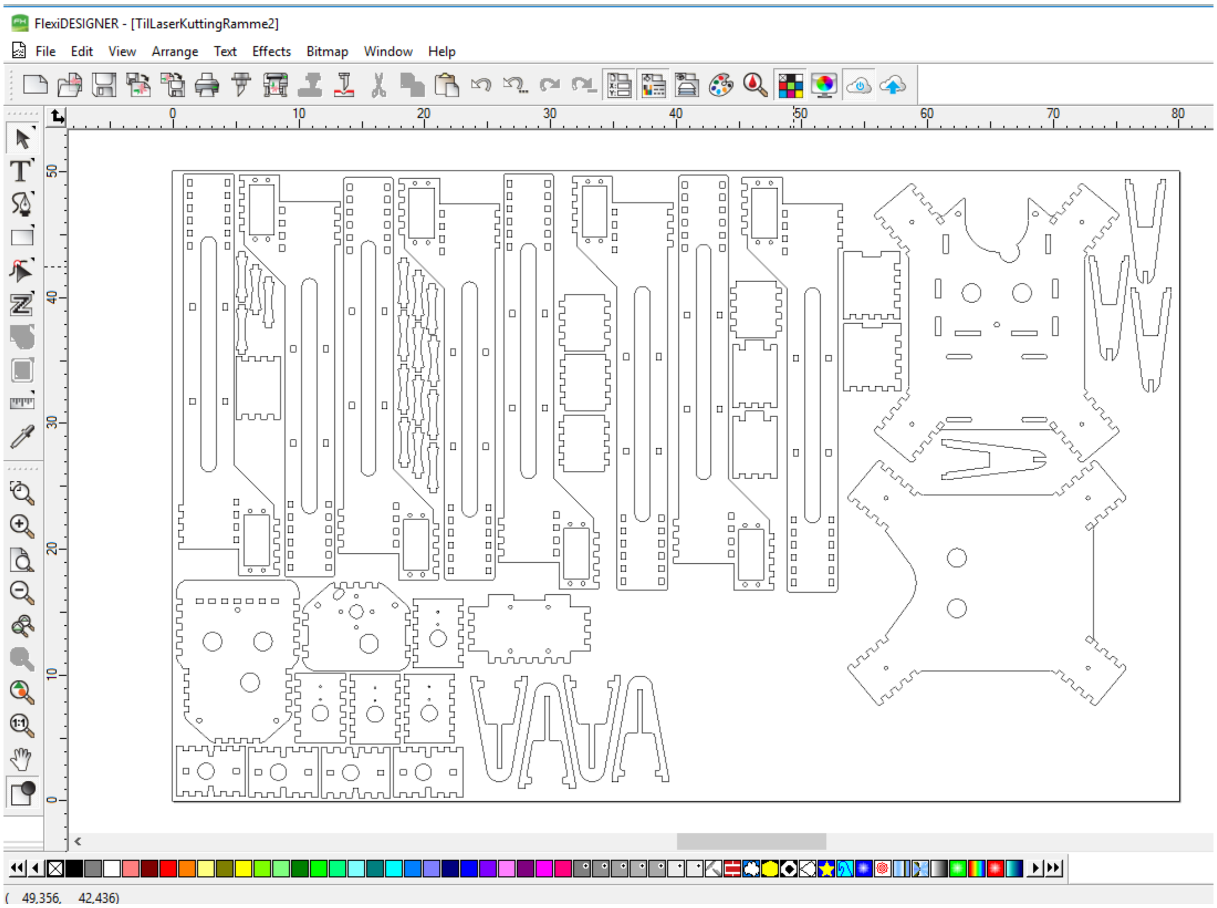

Figure 6.6: Frame layout in FlexiDESIGNER

Epilog laser cutting settings ready for print were tuned according to results from a previous test cut. Test cuts were performed to ensure proper cutting with just one pass of the laser. Figure 6.7 below shows the Epilog settings for the given cutting operation. A short summary of the settings used for cutting our frame follows:

- Material thickness was set to 4mm
- Autofocus and Vector Grid was checked
- Job Type: Vector (used for cutting)
- The stock Plexiglas sheet size (80x50cm) was set (mm)
- Cutting speed was set to 7%
- Power to 100%

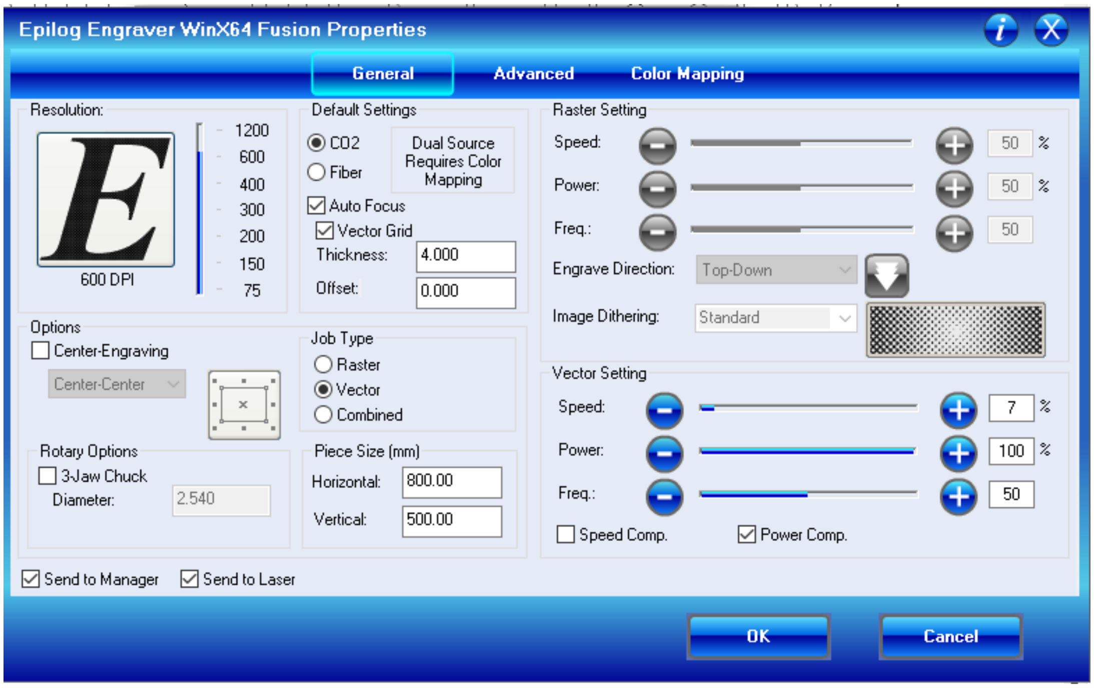

Figure 6.7: Epilog settings for the cutting operation

The laser was jogged to the upper left corner of the sheet to be cut, the air extraction device started, and the process initiated. Cutting the entire frame took approximately 40 minutes. Upon completion, the parts were pressed out of the stock material, and debris from the cutting job was cleared, so the machine would be ready for the next user.

6.4.3 Results

The Epilog laser cutter made very accurate and fine cuts, allowing the frame parts to fit together with tight tolerances. After assembling our first frame, we did a partial assembly of the entire structure to make sure everything fitted like intended. As suspected, the world of 3D CAD models is not perfect, and we had to make some minor adjustments to the frame, before we cut another and final one for our project. The adjustments consisted of:

- Making the bearing holes 0.1mm smaller for a tighter bearing fit
- Increasing the distance to the rotor shaft bearing holes with 1.5mm to provide adequate tightening of the belts
- Modifying the arms to provide space and a place to mount the servos
- Added a support structure to the legs, to make it more rigid

6.4.4 Additional cutting and engraving

After the prototype was built, we also cut out an additional top cover plate [fig. 6.8]. This was done to add some protection to the electronics mounted on top of the drone. The part was engraved with our logo and the project group name, to give it an aesthetically pleasing appearance. The engraving job was done by checking the centre-engraving checkbox and using the raster settings with speed 50% and power 35%. Since engraving took place on the backside of the transparent part, the logo and group name was mirrored before the job was evoked, so that it would come out right when viewed from the opposite side.

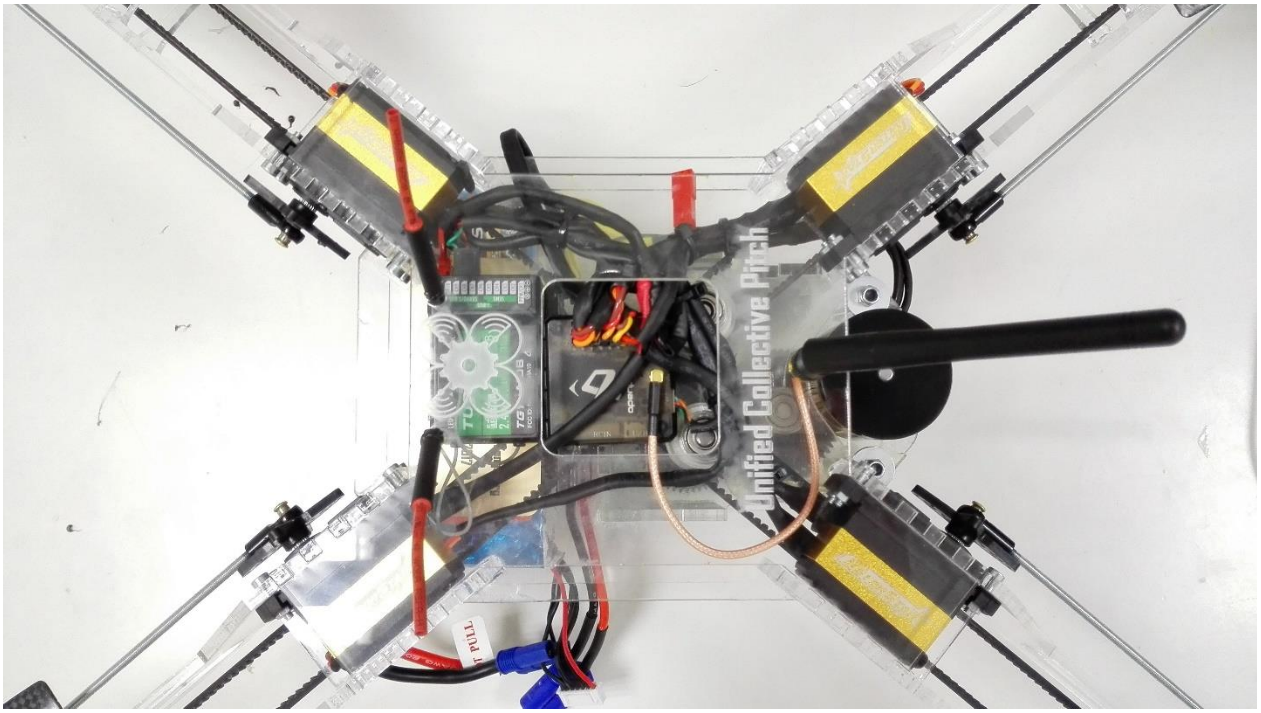

Figure 6.8: Cover top plate with logo and project name

Plexiglass provides a clear view into our quadcopter, which will let us see what is going on "inside" the drone. Plexiglass is being cut in the laser cutter, and will get a nicely shaped cut.

Having assembled the drone in plexiglass [fig. 6.9], we have checked our design, as well as power transmission concept. We are very satisfied with the result.

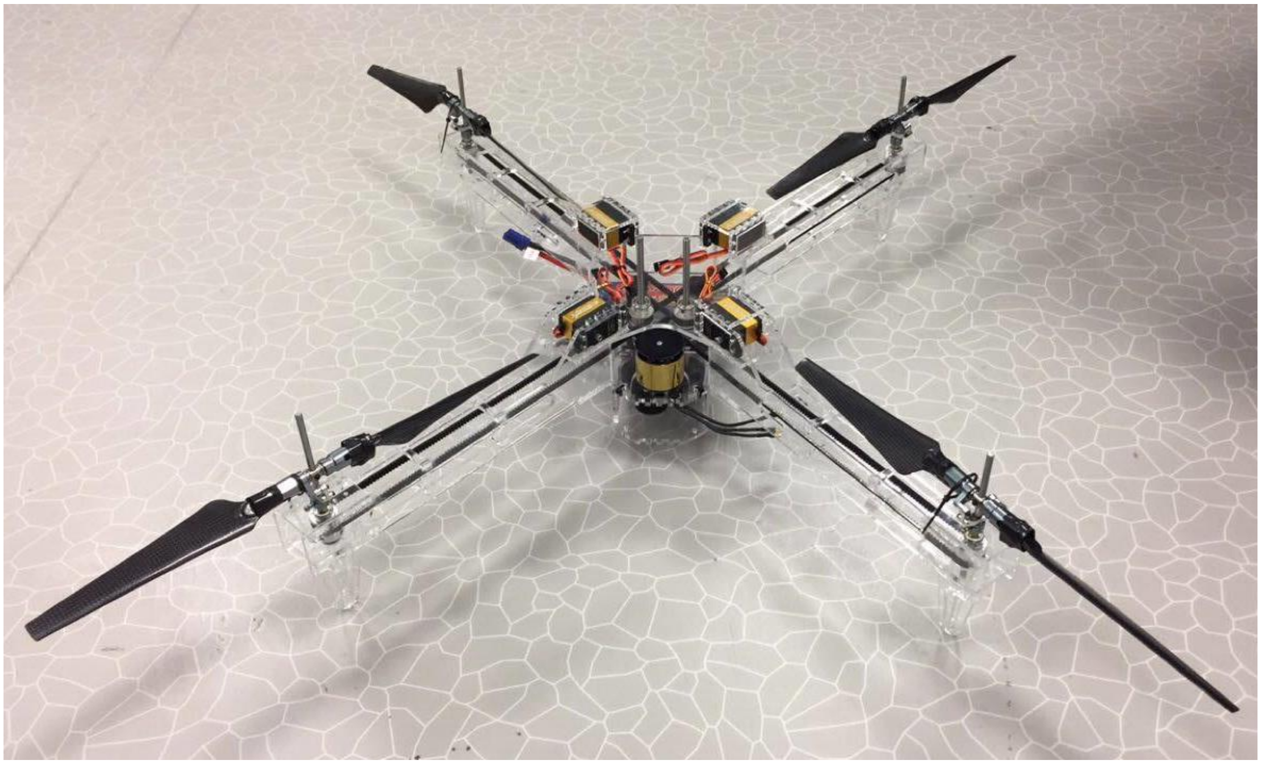

Figure 6.9: Functional prototype in plexiglass

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7 PROPELLERS

7.1 DIAMETER AND PITCH ANGLE

A propeller blade is a rotating airfoil which produces lift and drag, and because of a trailing vortex system has an induced-up wash and an induced downwash [fig. 7.1] [1, 2].

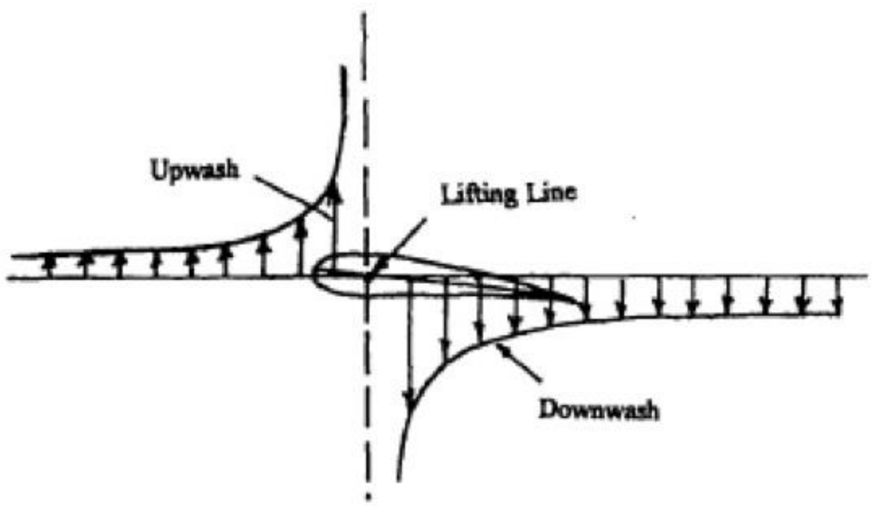
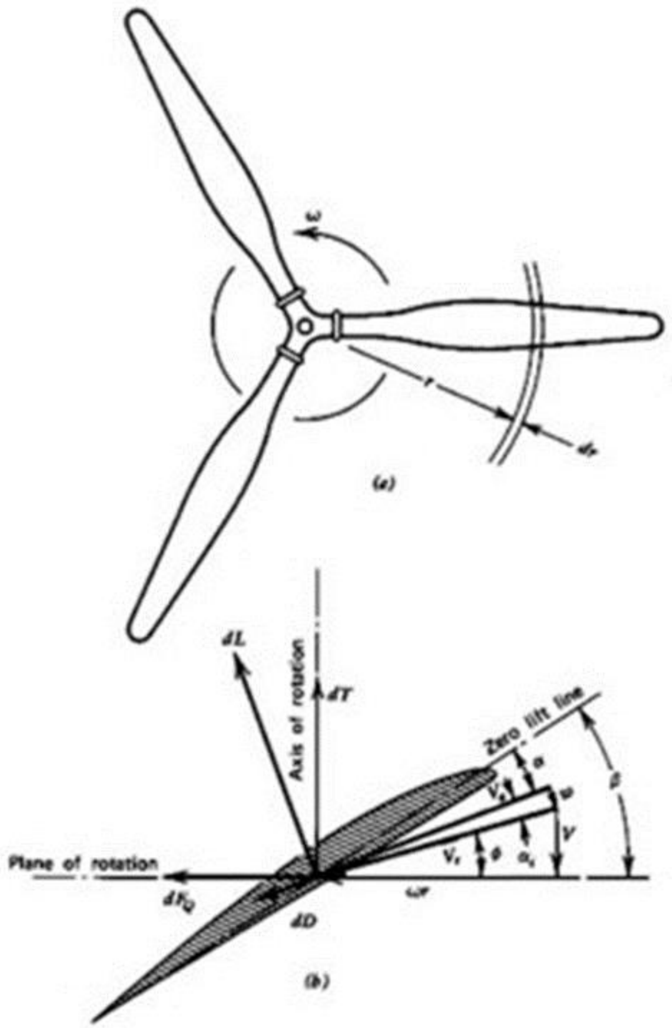


Figure 7.1: Induced downwash and upwash

In general, larger propellers produce more thrust per unit power compared to smaller diameter propellers. Motor efficiency tend to drop with higher rpm, and a larger-diameter propeller would require lower rpm and lower pitch angle, making the system more efficient.

The Pitch angle of a propeller is the angle at which a propeller is set with respect to the plane of rotation. Pitch is normally measured in distance, showing how far the propeller would travel in one revolution [fig. 7.3].



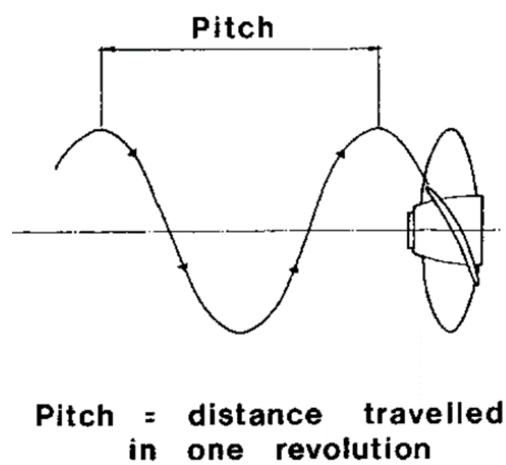


Figure 7.2: Schematic of a tree bladed propeller (McCormick, 1979) [1]

Figure 7.3: Schematics of propeller pitch [9]

For any two propellers of the same type and diameter, but different pitches, the propellers with lower pitch will have lower angle of attack than the prop of higher pitch. Lower angle of attack means better flow attachment, less separation, less induced drag, and therefore less profile drag / pressure drag [3].

The more blades there are on a propeller, the higher torque will be needed to keep the same rpm. Of two propellers with a different number of blades in the same operating conditions, the propeller with fewer blades will rotate faster. More blades cause increased drag from air resistance, and a blade may disturb the air and create turbulence for the next blade. Depending on the combination of the different parameters, a two-blade propeller may be the most efficient, but as power increases additional blades are generally required to efficiently utilize the increased power [4]. Theoretically, a large-diameter single bladed propeller would be the most efficient. However, propellers with only one blade is undesirable due to vibrations and instability. Thus, a two-bladed propeller is considered optimal, given that it can provide enough thrust for its diameter.

A larger diameter propeller would produce more lift compared to a smaller diameter propeller running at the same rpm. By increasing the diameter of the propeller, the rotational speed can be reduced while maintaining thrust.

Inertia increase with increased radius of the mass, and rpm changes will happen more slowly with greater propeller diameters. Since the propellers on the drone will be driven at constant rpm, this is not a concern for us.

7.2 DIRECTION OF ROTATION

If all propellers rotate in the same direction, an equal torque in the opposite direction will be induced, fulfilling Newton's third law and causing the drone to spin around its centre axis. To balance out this torque effect, two of the four propellers will be rotating in the opposite direction from the others. Two propellers will rotate clockwise, two will rotate counter-clockwise [5].

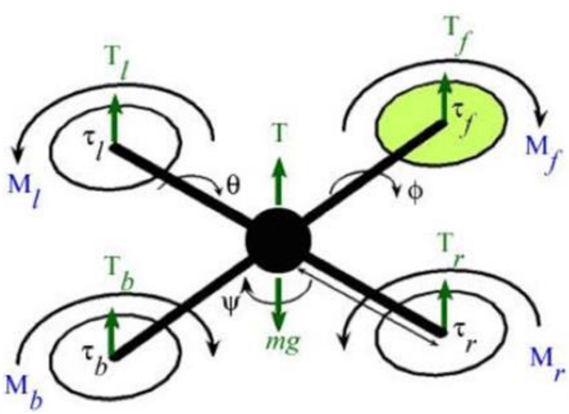


Figure 7.4: Quadcopter schematics [10]

Regulating the propellers' thrust allows for pitch and roll, movement in the direction of flight and the transverse direction. But the effective way of yawing a quadcopter is to have the propellers spinning in the same direction increase thrust, and thereby inducing torque about the drone's centre axis, making the drone rotate. The propellers going the opposite direction will reduce thrust accordingly to maintain altitude. Coincidently, in order to yaw a quadcopter, the propellers rotating in the same direction have to be placed across each other. The result of this is that every other rotor will have different direction of rotation.

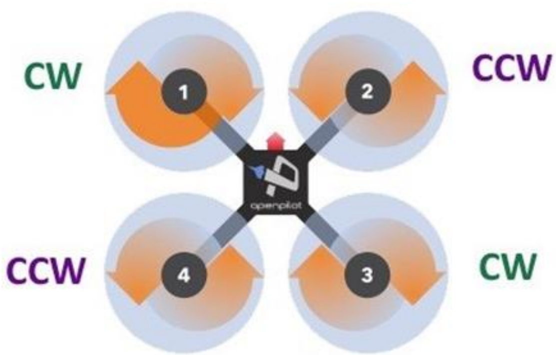


Figure 7.5: Rotational direction

7.3 Twisted and non-twisted blades

Most blades are twisted, such that the angle of attack is constant along the blade. The tangential velocity of the blade increases with radius; $v = r\omega_{rad}$ where v is tangential velocity, r is radius and ω is angular velocity.

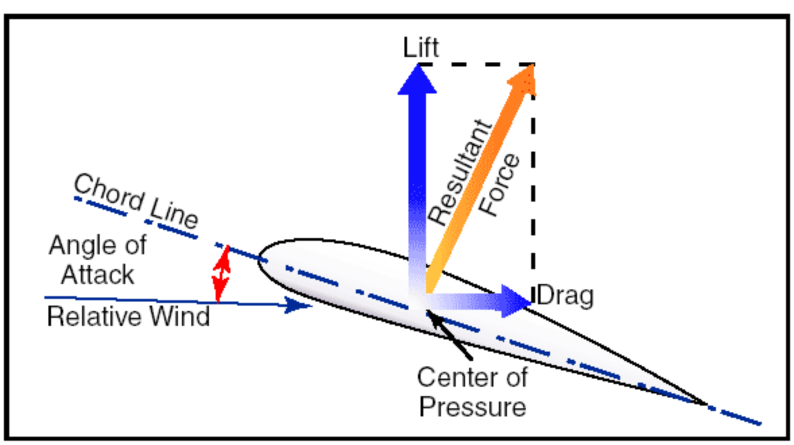


Figure 7.6: Force vectors on an airfoil [11]

The two forces acting upon the blade are drag and lift. As the tangential blade velocity increase with the radius, the blade must be twisted in order to keep the resultant force vector constant along the blade. By twisting the blade such that the pitch angle is reduced as the radius increase, the resultant force vector is kept constant along the blade [6].

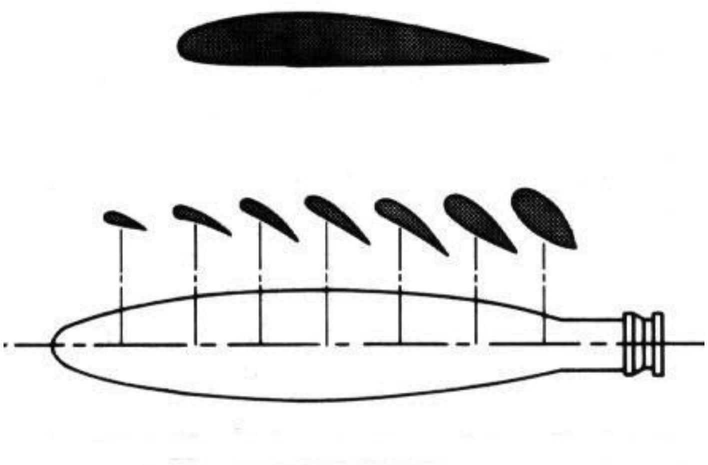


Figure 7.7: Schematics of profiles along the blade length

All blades used in aircraft propellers, helicopters or wind turbines are designed such that the resultant force vector is kept constant. However, blades that have a uniform cross section along the entire length of the blade – blades that are "flat" - exist for RC applications. These blades are typically used for 3D-flight applications to allow for inverted flight. During inverted flight an aircraft is flying upside-down.

Figure 7.8: Uniform blades

These blades use their uniform surfaces to physically push the air up or down, applying the same principles as traditional wind mills. Airfoils or standard blades however use Bernoulli's theory and airfoil theory to make lift more efficiently [7].

7.4 CALCULATION OF THRUST

To investigate what propeller dimensions are needed, we need to know how much thrust each propeller produce. Particularly the thrust they produce to hover the drone is interesting, as hover time is a key property of drones and is also a requirement for this project. However, calculating the propeller thrust at hover – when the aircraft velocity is zero – proves to be complicated. A theoretical propeller thrust equation is given [3]:

$$F = \rho \frac{\pi d^2}{4}\left(V_e^2 - V_e V_{ac}\right) \qquad \text{I}$$

Where d is the propeller diameter, V_e is the induced velocity of the air by the propeller and V_{ac} is the velocity of the aircraft. We do not know V_e, but we can assume V_e is equal to the pitch speed of the propeller. The following equation can be used to express the pitch speed:

$$V_{pitch}(mph) = RPM_{prop} \cdot Pitch_{prop(in)} \cdot \frac{1ft}{12in} \cdot \frac{1mile}{5280\,ft} \cdot \frac{60\min}{hr} \qquad \text{II}$$

By setting V_{ac} to zero – aircraft velocity will be zero when hovering -, inserting equation II for V_{pitch} and converting to metric gives the following equation:

$$F = \rho \frac{\pi \cdot (0.0254 \cdot d)^2}{4} \left(RPM_{prop} \cdot 0.0254 \cdot pitch \cdot \frac{1\min}{60s} \right)^2 \qquad \text{III}$$

This equation for static thrust only contains the variables propeller pitch angle, the propeller RPM and the propeller diameter. The advantage of this equation is that it combines rotational speed and diameter, showing the relation between them. However, this equation is theoretical. In practice V_e does not equal the propeller pitch speed, it is affected by the number of propeller blades, and the air inflow velocity is not constant over the cross-section of the propeller. Comparing the results from equation III with empirical data reveals a correcting factor. Based on empirical data by G. Stables, correcting the equation for practical measurements gives the following equation [4]:

$$F = \rho \frac{\pi \cdot (0,0254 \cdot d)^2}{4} \left(RPM_{prop} \cdot 0.0254 \cdot pitch \cdot \frac{1\min}{60s} \right)^2 \left(\frac{d}{3.29546 \cdot pitch} \right)^{1,5} \qquad \text{IV}$$

7.5 Validity of formula IV

G. Staples had been researching drone propellers, particularly how propellers produce thrust, and how the quadcopters velocity affects the thrust. G. Staples has a B.S. in Aeronautical Engineering from the US Air Force Academy and a M.S. in Mechanical Engineering from the University of Colorado [8].

To establish the correction factor of equation IV, G. Staples measured 149 data points by testing different propeller diameters and RPM. The results are displayed in the next graph [fig. 7.9]:

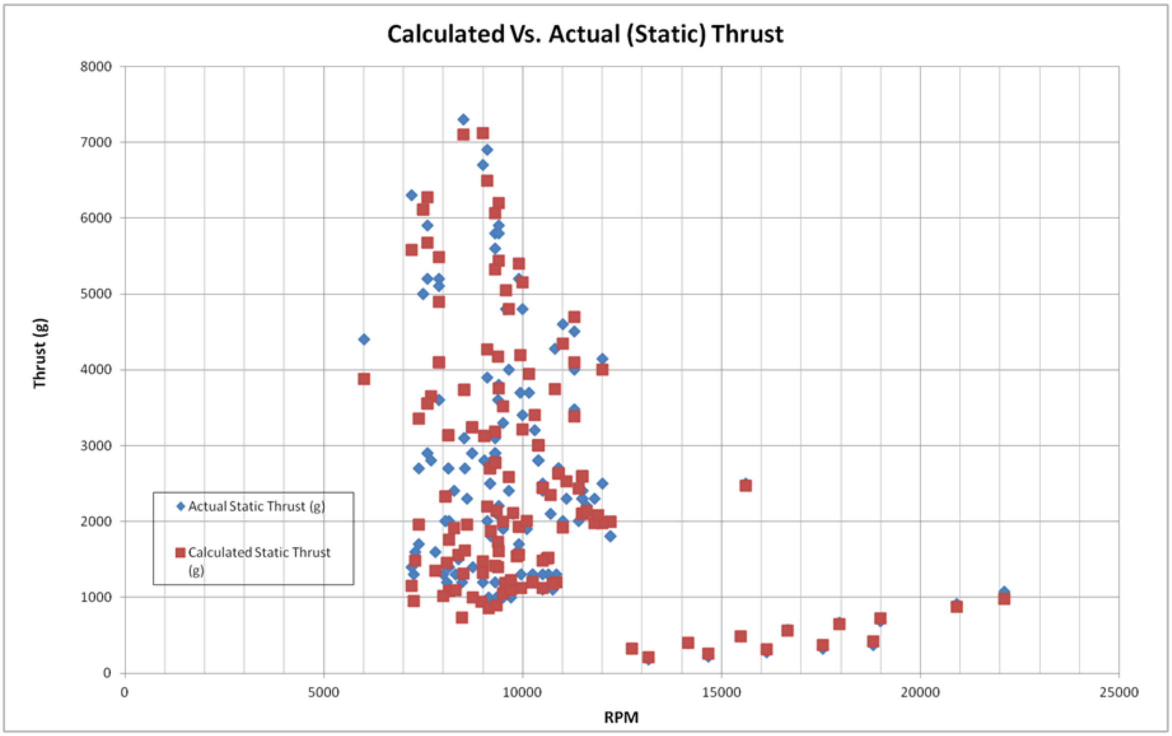


Figure 7.9: Data points of actual vs. calculated static thrust, for propellers ranging from 5x5 ~ 17x8 [3]

For all the compared data, the calculated thrust was at the most 30% higher than the actual thrust, and at the least 40% lower than the actual thrust. For 68% of the cases, Staples thrust calculations was +/- 13% of the actual thrust, and for 95% of the cases, the thrust calculations were +/- 26%. For 58% of the 149 cases, the calculation was a slight overestimate, and for the remaining 42% of the cases, the calculation was a slight underestimate. From these measurements, Staples found the empirical correction factor for the final static thrust equation.

7.6 THRUST AT HOVER

Per the Motor section of this document, operating the propellers at 4500 rpm and 4inch pitch is at the lower end of the drone's operating regime. Inserting these values into equation IV gives:

$$F = 1.225 \cdot \frac{\pi \cdot (0.0254 \cdot 15)^2}{4} \left(4500 \cdot 0.0254 \cdot 4 \cdot \frac{1\min}{60s} \right)^2 \left(\frac{15}{3.29546 \cdot 4} \right)^{1,5}$$

$$F = 9.84N$$
$$F = 1.0kg$$
$$F_{total} = 4kg$$

These calculations show that a 15-inch diameter propeller running at 4500 rpm and at a 4-inch pitch will be more than sufficient to hover the drone. This is well within the operating range of the system, verifying the dimensions of the propellers.

7.7 Propeller efficiency

The efficiency of the propellers is paramount to the overall performance of the drone. Comparing the efficiencies of propellers proves to be difficult, as the manufacturers seem reluctant to provide the relevant data needed. In addition, the drone itself will impact the propellers' effective lift, as passing air will be obstructed by the airframe.

Calculating the propeller efficiency: [1]

The power supplied to the propeller is;

$P_{in} = 2\pi nQ$, where n is the propeller speed in RPM, and Q is torque. V

The useful power output is;

$P_{out} = Tv_0$, where T is thrust and v_o is flight velocity VI

Therefore, the efficiency is given by;

$$\eta_{prop} = \frac{P_{out}}{P_{in}} = \frac{Tv_0}{2\pi nQ} \qquad \text{VII}$$

As seen from equation VII the flight velocity and torque produced must be known in order to calculate the efficiency of the propellers. In addition, the airframe itself will affect the usable thrust. This can only be measured by flying the aircraft, we cannot predetermine the propeller efficiency before purchasing and testing them. Because of this, we will be selecting the propellers based on analogy; a blade with constant pitch angle will be more efficient than a geometrically uniform blade.

7.8 Selected propeller

The propellers used must be either RC helicopter propellers or foldable drone propellers, due to the pitch mechanism. The pitch mechanism at each rotor constitutes the mounting points for the propeller blades. Thus, one propeller will be made up of two separate blades. According to the

Pitch Mechanism section (section 8), two blades with a 3mm diameter mounting hole and no more than 5mm width are needed per rotor.

Since inverted flight is outside of the scope, a blade with uniform profile along its length - typically for 3D-flight - can be avoided. This allows for using a foldable drone blades, keeping the angle of attack constant. We will be using the commercial blades “Multirotor Carbon Fiber Propeller 15x5.2 Black”.

Specifications of the blades:

- Diameter:	15 in
- Pitch:	5.2 in
- Mounting hole:	3 mm
- Mounting hub thickness:	4.15 mm
- Weight:	7.5g per blade
- Material:	3K plain weave carbon fibre

The 4.5mm mounting hub thickness will be corrected by using shims/spacer discs in the pitch mechanism mounting hub. The diameter is measured from blade tip to blade tip, with an adapter for the folding propellers at the rotor.

Figure 7.10: Multirotor Carbon Fibre Propeller 15x5.2 Black

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8 Pitch mechanisms

8.1 Introduction

The project group has been doing its best with regards to find an optimal pitch solution for our quadcopter. This has been a time consuming and at times difficult task, since available concepts and designs are poorly documented in academia and online. Thus, we have modelled several possible solutions based on pictures/drawings of already existing solutions or solutions we think might work.

A variable pitch mechanism is a mechanism by which all the blades on a propeller hub can be rotated about the blade center axis, while the propeller is spinning. All propellers are actuated by the same mechanical linkage.

8.2 Possible solutions

8.2.1 Differential gear pitch solution

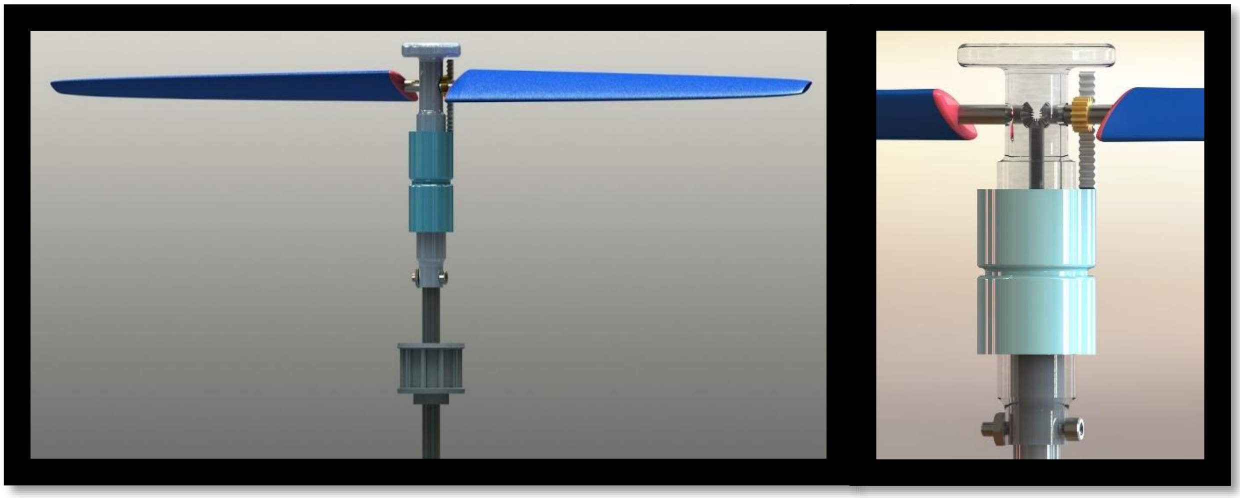


Figure 8.1: Conceptual Differential Gear Pitch

A variable pitch mechanism concept shown in figure 8.1 is a direct result of the lack of information and different solutions in academia and on the internet as stated above, and it made the design team think outside the box. The designer got inspiration from a fellow team member. He designed a quadcopter with a power transmission made of differential gears and axles. [fig. 5.2, section 5.2] It also uses a spur gear and a rack to control the mechanism on one of the sides of the propeller.

The differential reverses this movement to the other propeller. The model works as intended, but it's an unproven technology and the design has it drawbacks and weaknesses. It wouldn't be a smart move in our opinion to choose this concept over some of the others that are more proven and already exist on the marked. It would also have been hard to find the correct parts, and would be difficult to assemble. The price would also be hard to determine, but since it's a concept model, it would be one of a kind, which almost exclusively means expensive to manufacture. The weight of the model is in the right ballpark. With its 49 grams, it's one of the lightest, but in the end, it could be altered as well, and end up heavier.

8.2.2 MODIFIED HELICOPTER MAIN SHAFT PITCH SOLUTION

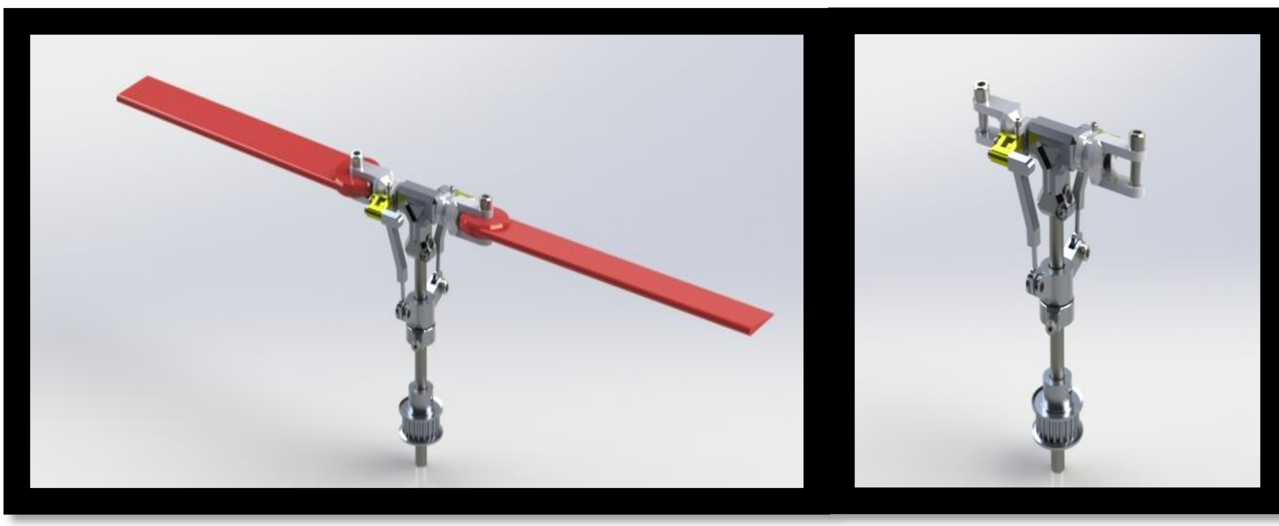


Figure 8.2: Conceptual Main Shaft Pitch

This SolidWorks model is based on a modified main rotor pitch mechanism from the Tarot 450 line [1] series of RC helicopters. The model uses a slider to actuate and pitch the blade holder, instead of the swash plate that would normally be used on a helicopter.

It is a proven design, and parts are easily accessible, even though they are quite expensive compared to other solutions we have considered.

A disadvantage with this design is the relative long range of motion needed to pitch the blades as the parts was originally designed to be attached to a swashplate.

8.2.3 HELICOPTER TAIL PITCH SOLUTION

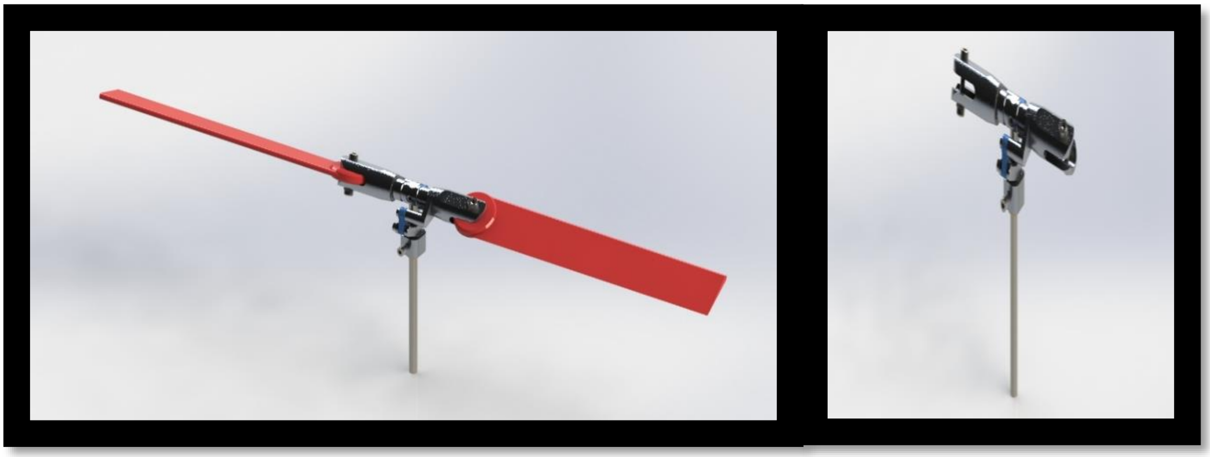


Figure 8.3: Conceptual Helicopter Tail Pitch

A Solidworks model in figure 8.3 is based on the tail pitch mechanism for the HK600/T-rex 600-line series [2] of RC helicopters, produced by several suppliers. The appearance and functionality of the conceptual pitch mechanism is similar to the modified helicopter main shaft pitch mechanism [fig. 8.2]. But this conceptual design [fig. 8.3] has fewer parts and simpler geometry, thus less machining is needed to produce the mechanism. The rotor hub is smaller allowing a shorter range of motion for the slider while still allowing a considerable positive and negative blade pitch.

As mentioned the RC helicopters this was designed for are produced by several suppliers and the tail pitch mechanism can therefore be purchased inexpensively as a spare part for as little as $20 [3]. This is a great advantage since the project has a limited budget.

8.2.4 MODIFIED HELICOPTER TAIL PITCH WITH STEERING SLOT SOLUTION

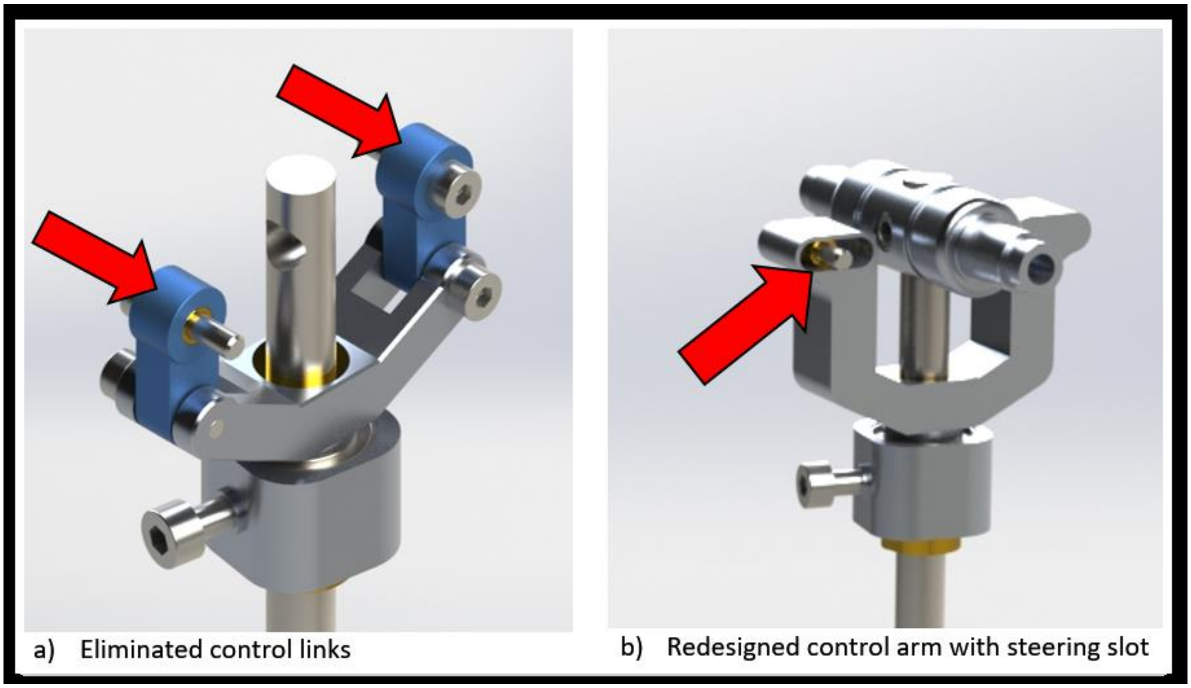


Figure 8.4: Conceptual Helicopter Tail Pitch with Slot

To reduce the number of parts and trying to make the mechanism as simple as possible we modelled a second variant shown in figure 8.4 of the modified RC helicopter tail pitch solution in section 8.2.3. By eliminating the control links and redesigning the control arm with steering slots, we could make a similarly functioning assembly with fewer parts. We have not been able to find a similar actuator arm design available for sale, so this part would have to be machined by the project group. This again allows us to assume that this will be an expensive solution.

8.2.5 SPUR GEAR RACK SOLUTION

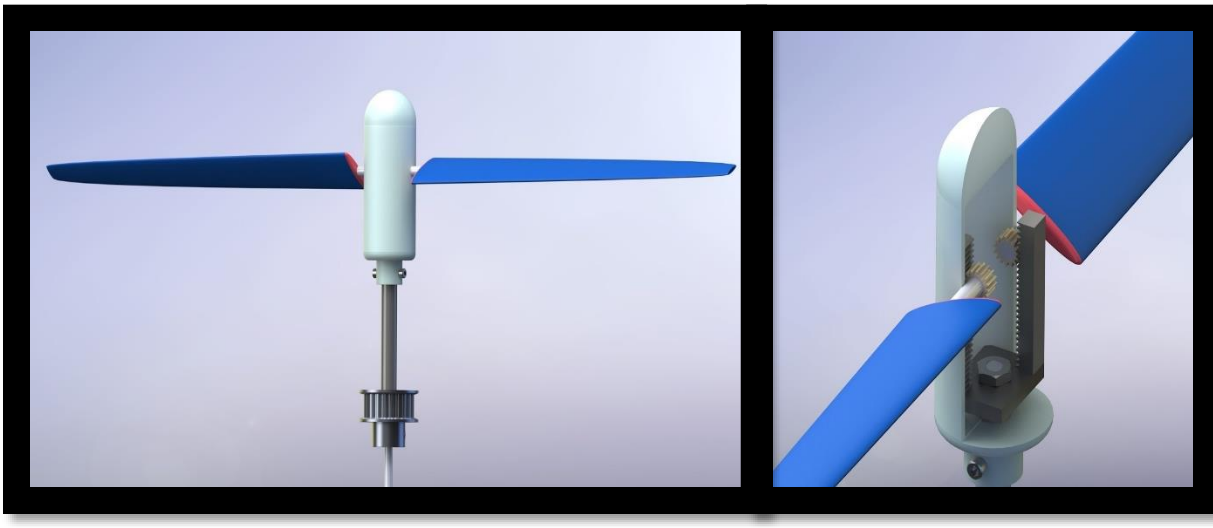


Figure 8.5: Conceptual Spur Gear & Rack Pitch

Model presented in figure 8.5 is a very concept stage kind of variable pitch mechanism. This design solves pitching challenge without help of differentials. It uses instead two sets of spur gears and racks. The racks are set up in opposite directions and placed on each side of the propeller setup, which enables them to move the blades in the opposite direction of each other. This design is more robust than some of the others, because the mechanism is protected by a plastic cover, which keeps particles away and hinder direct contact with its surroundings. Another advantage of this design is that it is actuated internally in the shaft. Albeit this often makes the mechanism more complex, it protects the mechanism better than when it is placed externally. But even though it is very safe, it is a concept model, and is not proven by any means. This will make it expensive to manufacture, and we have to order parts separately and assemble it ourselves. This is a very time consuming process, that also will require a lot of testing, which we basically don't have time or manpower to fulfil. And we can't risk the project due to one solution that would be more expensive, complex and time consuming than one of the other solutions.

8.2.6 Internal pitch solution

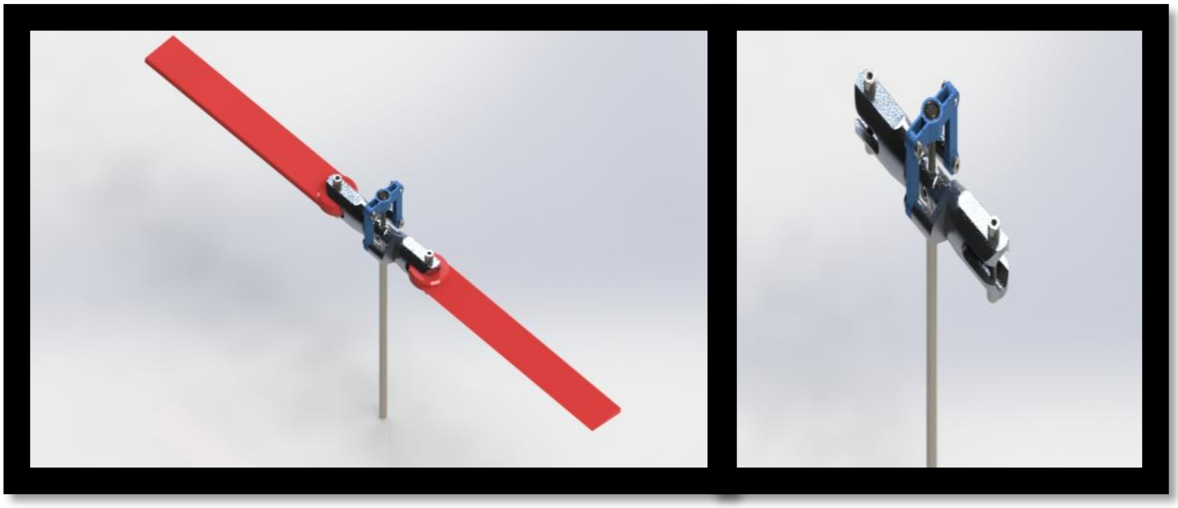
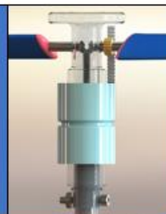


Figure 8.6: Conceptual Internal Pitch

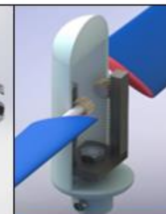
Pitch mechanism depicted in figure 8.6 is an internally actuated design where the slider is replaced with an axle through the drive shaft. The control arm and links are now placed over the rotor hub and blade holders, opposite to concept 1-5. Blade pitch angle is adjusted when the axle is moved up and down through the shaft by an actuator. Variants of this design is available on the marked, meaning that all necessary parts could be bought, and that it is a proven design. Hollow driveshaft is considered to be a disadvantage due to bending stresses from the belt pulleys we are using.

8.3 PUGH MATRIX PITCH MECHANISM

To help us differentiate between different pitch concepts and designs, we have created a Pugh matrix, where we have scored the concepts based on different criteria.








Criteria	Weight	Differential		Heli Main		Heli Tail		Tail Slot		Spur Gear		Internal	
Complexity	25 %	2	0,5	4	1,0	4	1,0	5	1,3	2	0,5	4	1,0
Price	25 %	1	0,3	4	1,0	5	1,3	1	0,3	1	0,3	4	1,0
Ease of Production	10 %	1	0,1	1	0,1	1	0,1	1	0,1	1	0,1	1	0,1
Weight (g)	5 %	49	2,5	59	3,0	53	2,7	56	2,8	50	2,5	51	2,6
Feasibility	35 %	2	0,7	4	1,4	5	1,8	2	0,7	1	0,4	4	1,4
Score	100 %		4,0		6,5		6,8		5,1		3,7		6,1

Table 8.1: Pugh Matrix Pitch Mechanisms

Except for mechanism weight, the criteria have been scored from 1 to 5, where one is worst, and five is best. The weight criteria are scored with mass data from the Solidworks model, because these are our best estimations on how heavy different mechanisms would be. The scores were then multiplied with a weighted percentage based on what we considered to be most important, then added to give a final score. Highlighted with green in the Pugh matrix is the concept that scored most points, namely the Helicopter Tail Pitch Solution [section 8.2.3].

8.4 OUR SOLUTION

Based on the results from the Pugh matrix evaluation of the concepts we have chosen to go for alternative 3 [section 8.2.3], which is to use a RC helicopter tail pitch assembly from the HK600/T-rex 600 line. Figures 8.7 shows chosen design, including an exploded view [fig. 8.8].

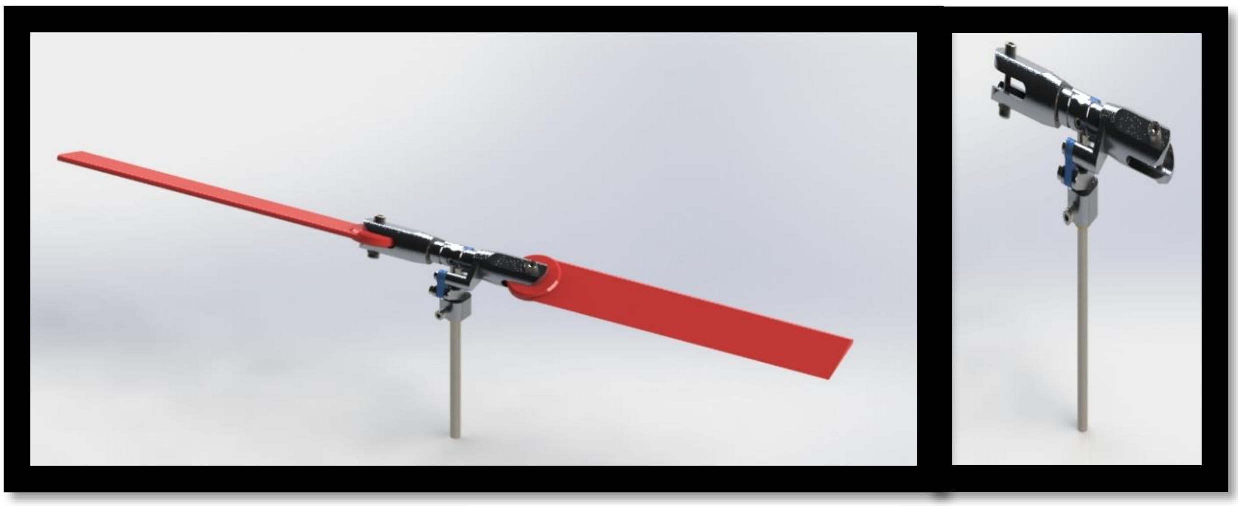


Figure 8.7: Conceptual Helicopter Tail Pitch

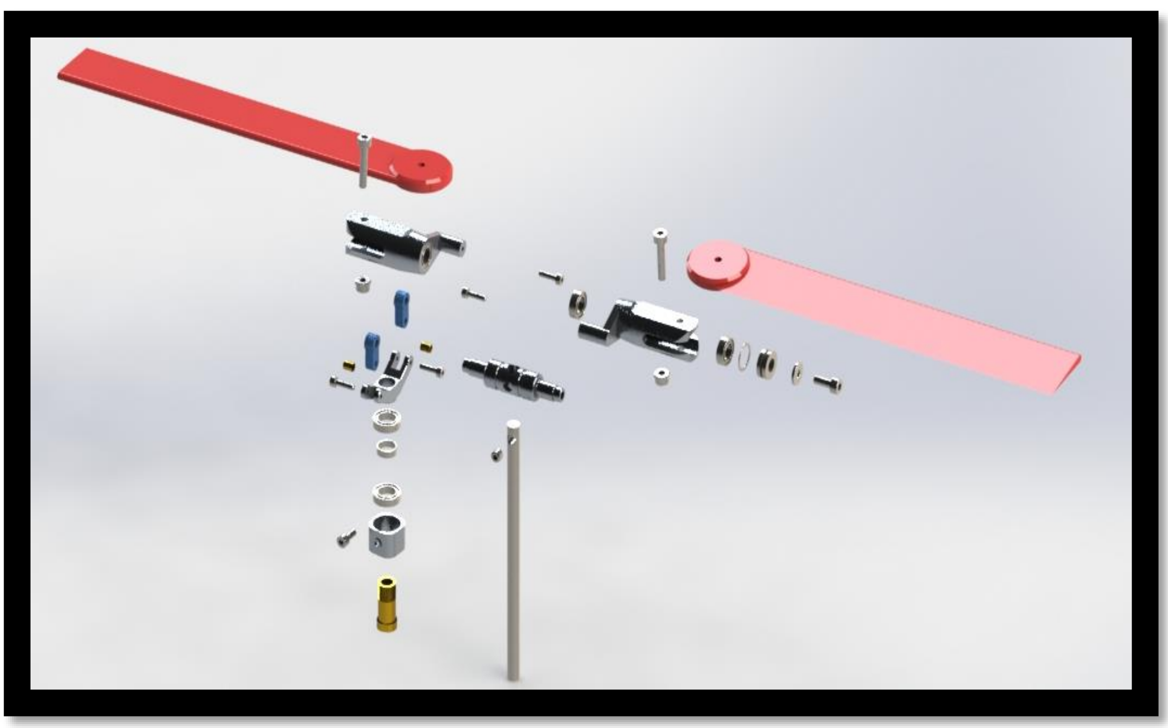


Figure 8.8: Exploded View of Conceptual Helicopter Tail Pitch

8.5 ADJUSTMENT OF PITCH MECHANISM AND 3D PRINTING

When designing our pitch mechanism, we had to make some adjustments, as not all parts from the pitch assembly we ordered could suit our frame design. The pitch lever arm was too short and interfered with the frame, so a redesign was necessary.

The easiest way to produce small parts with no special requirements to strength is 3D printing.

At HSN we have an Ultimaker 3 with dual extrusion meaning that two filaments are being fed simultaneously what gives better opportunities when printing complex geometry. PLA (polylactic acid) is used as a building material, and it is one of the most widely used materials in 3D printing. PVA (polyvinyl alcohol) is a support material used to create water soluble support structures to achieve complex geometries.

Figure 8.9 shows the modified pitch lever arm for our project which had to be 3D printed.

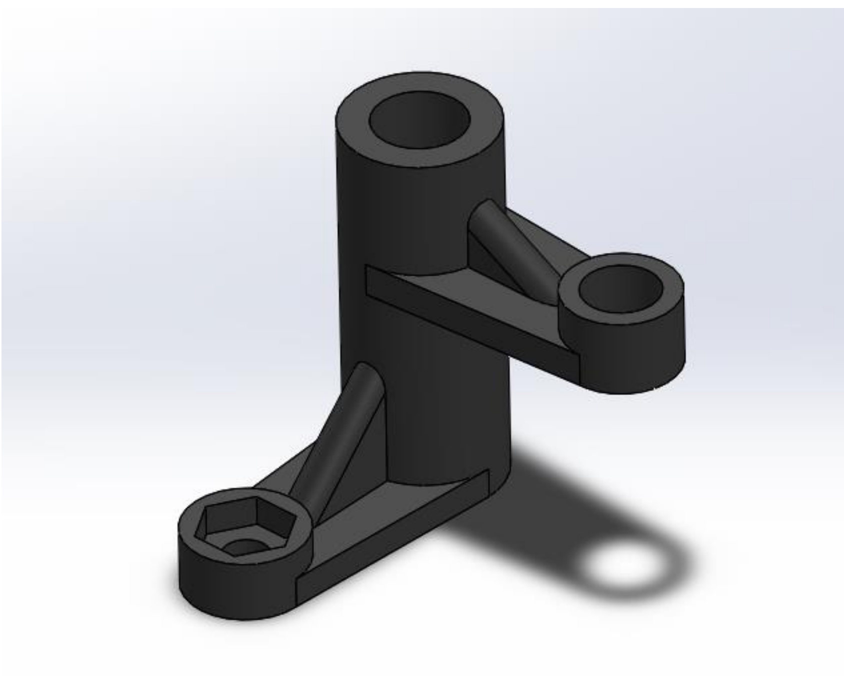


Figure 8.9: 3D part in Solidworks

After the part was modelled in Solidworks, we export it in the necessary format (stl, 3mf, obj) and use a special program named Cura for slicing the model [fig. 8.10-11].

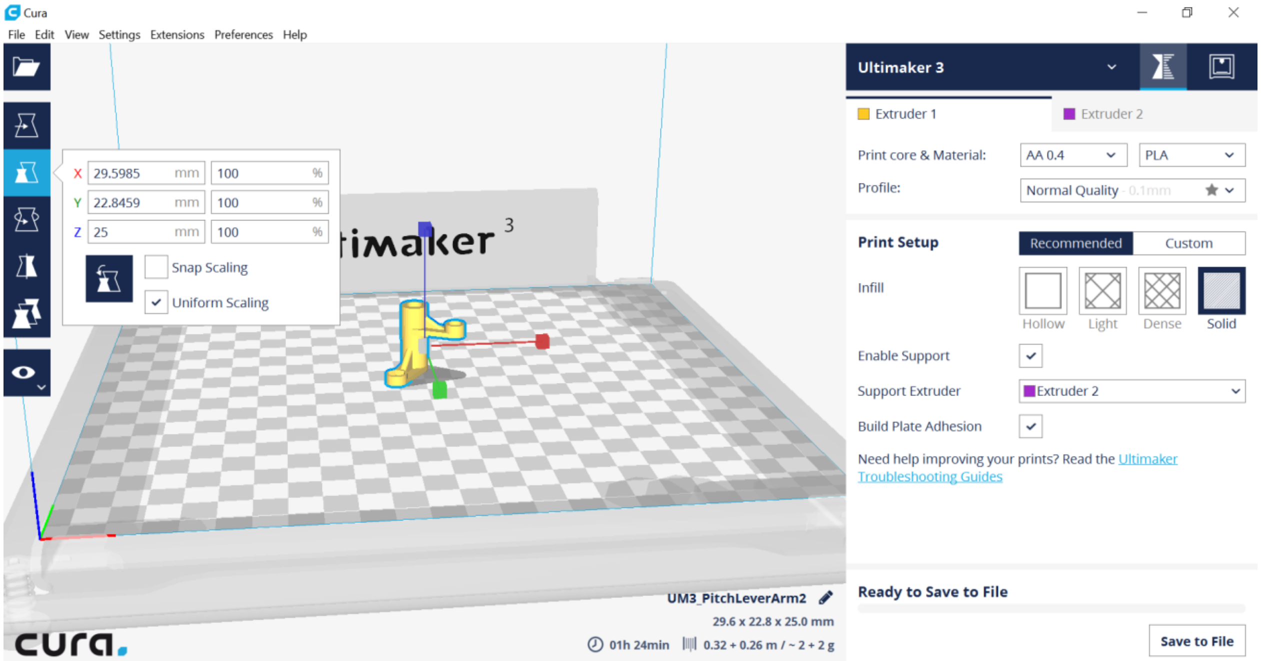


Figure 8.10: Part positioning in the printer

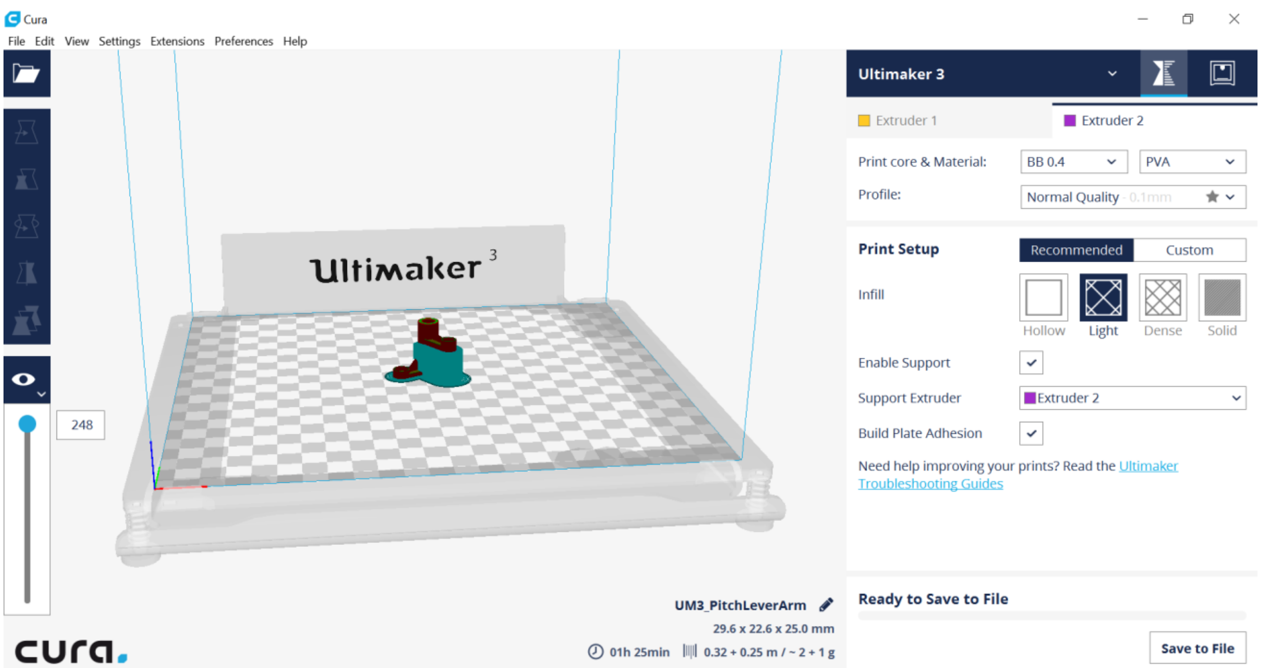


Figure 8.11: Part before printing with both building and support material shown

We can see both number of slices – 248, estimated time and weight of the part what is quite useful [fig. 8.12].

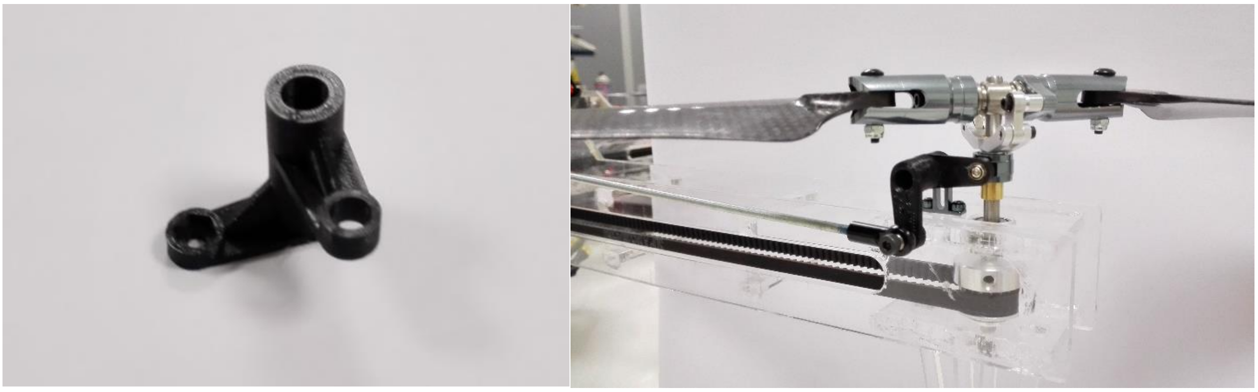


Figure 8.12: Printed part in the assembly

PLA offers quite good surface quality, and it's made from organic, renewable sources. PVA can be dissolved in water without leaving the trace [4].

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9 ACTUATOR/SERVO

Servos convert electrical commands from receiver, into physical movement. To be able to steer our quadcopter we need a servomotor that reacts fast.
A servo's characteristics are defined by torque, speed, dimensions and weight. The larger and more powerful motor it has, the more torque it can produce for a given speed. Servos comes in varied sizes.

9.1 TORQUE

Torque is the load force the servo can exert [eq. 1]. The higher the torque, the larger load it can manage to move. It is a measurement of the servo's strength.

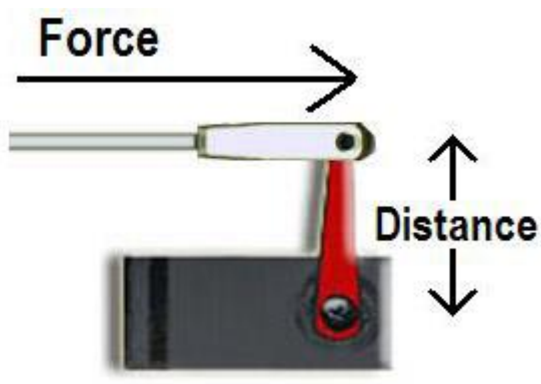

Figure 9.1: Torque equals to Force multiplied Distance

$$T = F \cdot r \qquad \text{I}$$

where, T is the torque in [Ncm], F is the force in [N], and r is the distance (radius) in [cm].
In servos specification, torque is often referred in kg.cm.

It is a wrong, but common way of specifying a servos torque. Meaning, the torque is divided by the gravity.

Newton's second law [eq. II]:

$$F = m \cdot a \qquad \text{II}$$

where, F is the force in newton [N], m is the mass in kilogram [kg], a is the gravity in $[\frac{m}{s^2}]$.

$$T = m \cdot a \cdot r \qquad \text{III}$$

$$\frac{T}{a} = m \cdot r\ [kg.cm]$$

Even though this is theoretically incorrect, servos specifications are given in kg.cm.

The higher the torque, the faster the motor will spin. Reducing the torque, the motor slows down. In other words, if the motor doesn't have large enough torque, the load may be too demanding for the motor. It is important to choose a servo which has enough torque to lift/push the weight it is supposed to. In our case, it is the propellers thrust because the servo is pushing on the pitch mechanism to rotate the blades [fig. 9.2]. The servo should overcome the wind resistance acting on the propellers [1].

The first step is to determine the required torque, then decide the most suitable weight and dimension for the specific purpose.
When talking about the servos torque, we are interested in the thrust of the propellers at max rpm and pitch. We have decided that max rpm on the propellers is in the range 4000-6000 rpm [table 4.5 section 4.8].

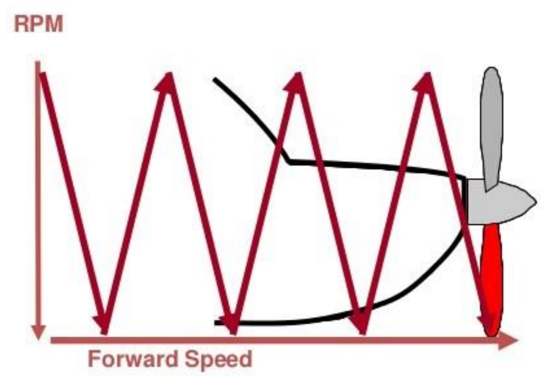

Figure 9.2: Pitch is a function of both forward speed and RPM

Max speed within the RO1 requirement, is 30 m/s. This restriction is the same no matter what the direction the quadcopter is going. If we assume the quadcopter goes straight up, we can determine maximum pitch of the propellers [eq. IV]:

$$Pitch = \frac{Forward\ speed}{RPM} = \frac{30\frac{m}{s}}{6000\frac{r}{min}\cdot\frac{1min}{60s}} = 0.3m \qquad \text{IV}$$

Converting meters to inches:

$$\frac{1\ inch}{0.0254\ m} = \frac{x}{0.3\ m}$$

$$X = \frac{1\ inch \cdot 0.3\ m}{0.0254\ m} = 11.81\ inch$$

Max pitch on a RO1 drone running on 6000 RPM, is 11.81 inches.

Dynamic thrust equation:

$$F = 4.392399\times10^{-8} \cdot RPM \times \frac{d^{3.5}}{\sqrt{pitch}} \cdot (4.2333\times10^{-4} \cdot RPM \cdot pitch - V_o) \qquad \text{V}$$

These calculations were put in excel from 0 m/s – 40 m/s to see how the thrust and velocity are working together.

As shown in figure 9.3, at 6000 RPM and maximum pitch the quadcopter cannot move faster than 30 m/s because the air velocity towards the propellers gets greater than the thrust, and the quadcopter will lose altitude.

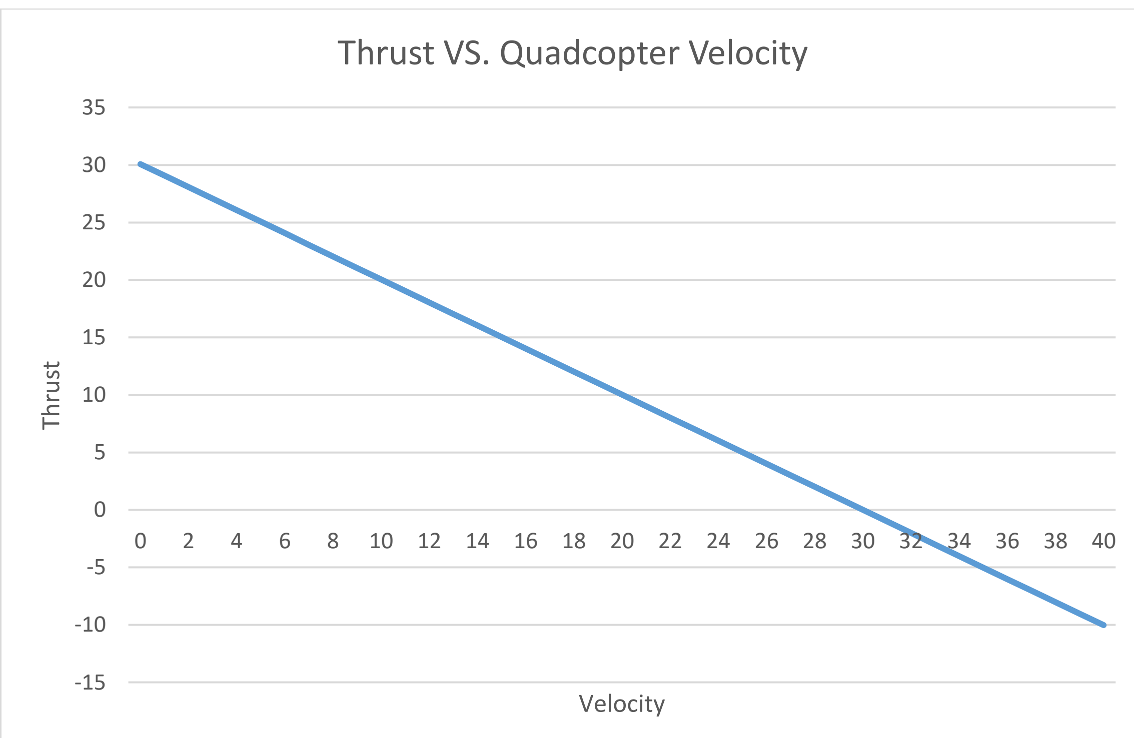

Figure 9.3: Plots of dynamic thrust

From the diagram [fig. 9.3], we see that maximum thrust 30.07 N is achieved at V_0= 0. At the same time, it can be seen that at velocity more than 30 m/s, air resistance is too high to produce thrust.

Converting from N to kg:

$$m = \frac{F}{a} = \frac{30.07\ N}{9.81 \frac{m}{s^2}} = 3.065\ kg \approx 3.07\ kg$$

This means that the force acting on each propeller is at the highest 3.07 kg if we assume no external forces, like wind etc.

We can conclude that the servo at least needs to handle a weight of 3.07 kg, assuming the arm to be 1 cm.

Total thrust should be at least 5 kg, considering the quadcopter to be 2.5kg and lift/weight ratio 2:1. We have four propellers with 3.07 kg each. Which means 12.28 kg all together.

9.2 Speed

Speed ratings are listed as a measurement of the time it takes the servo to rotate a certain number of degrees. The most common, is 60 degrees. That means, the time it takes the servo arm to turn 60 degrees unloaded [2].

9.3 Determination of the servos torque and speed

We are using interpolation [eq. VI] to figure out the servos torque and speed when running on a 7.4V battery.

$$Y = Y_1 + (Y_2 - Y_1) \cdot \left(\frac{X - X_1}{X_2 - X_1}\right) \qquad \text{VI}$$

The servos speed goes from 0.095sec/60deg at 6V to 0.072sec/60deg

Using the interpolation formula [VI]:

Y: unknown speed	Y_1: 0.095 sec	Y_2: 0.072 sec
X: 7.4V	X_1: 6.0	X_2: 8.4V

$$Y = 0.095 + (0.072 - 0.095) \cdot \left(\frac{7.4 - 6}{8.4 - 6}\right) \approx 0.082$$

The servo will have a speed at 0.082sec/60deg, when operating on a voltage of 7.4V

The servos torque runs from 8.75kg.cm at 6V to 11.25kg.cm at 8.4V

Using the interpolation formula [VI]:

Y: unknown torque	Y_1: 8.75 kg.cm	Y_2: 11.25 kg.cm
X: 7.4V	X_1: 6.0V	X_2: 8.4V

$$Y = 8.75 + (11.25 - 8.75) \cdot \left(\frac{7.4 - 6}{8.4 - 6}\right) \approx 10.21$$

The servo will have a torque as much as 10.21 kg.cm

9.4 Analog vs. Digital

An analog servo operates with on and off voltage signals, or pulses, on the motor. This is the way it controls the speed of the motor, but in most cases, they won't react fast enough for our usage. Neither for production of torque in small operation commands or when external forces, such as wind, are pushing on the quadcopter.

The solution to this problem, is using a digital servo. Digital servos are sending the signals in a different way to the motor. The signals are shorter, but they are sent at a high speed simultaneously what speeds up the motor and provides constant torque.

The conclusion is that digital servos have faster response, quicker and smoother acceleration, increase in speed and torque. One disadvantage is usage of battery power, caused by all the power signals. Although the power consumption is greater, this is not an issue because it has better holding power as well [3, 4].

9.5 Servo motor types

With coreless motor armatures, there is no wire core like in conventional motors, which result in quicker acceleration and deacceleration, more torque and faster response time. Simply because it doesn't have to overcome the momentum of a metal core when changing directions.

Brushless motor is more efficient than brushed motors. This is simply because more of the total power used by the brushless motors is being converted into rotational power and less is being lost in heat, caused by friction. They provide more torque and power, and there are no worries in wear of the brushes [3, 4].

9.6 Deadband

Deadband is how much movement the servo can move, back and forth, without responding or having a command sent to maintain its position. Servo will not try to interact with the system to correct errors until the error is above the servos deadband. The lower the deadband, the better it will be to hold a steady position. Without the deadband, the servo would use much power continuously to balance between back and forth to hold the right position all the time [1].

9.7 Decisions

Several factors need to be considered when choosing servos. The servo should be strong and quick and weight as little as possible. Lighter servos would keep the mass of the drone low, and less energy would be required to fly the drone. Cost is also an essential factor.
Different servos have been compared [table 9.1]:

Type	Dimensions, mm	Weight, g	Speed, sec/60º	Torque, kg.cm	Price, $
Goteck HB1621S	40x20x37	53	0.07	19	34.80
HXT12K	40.7x19.7x42.9	55	0.16	10	10.09
Corona DS-319HV	32.5x17x34.5	34	0.05	4.2	10.49
Turnigy™ TGY-S4505B	--	40	0.10	4.8	05.85
RotorStar™ RS-550MGC-HV	40.5x20.5x36.5	59.3	0.072	11.25	20.25

Table 9.1: Five types of servos compared

When comparing the servos, we have concluded that RotorStar RS-550MGC-HV is both strong and fast enough for our use.

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10 FLIGHT CONTROLLER

There's an array of different flight controllers (FC) on the market [fig. 10.1], some of them are better than others and there is a variety of similar specifications to choose from.

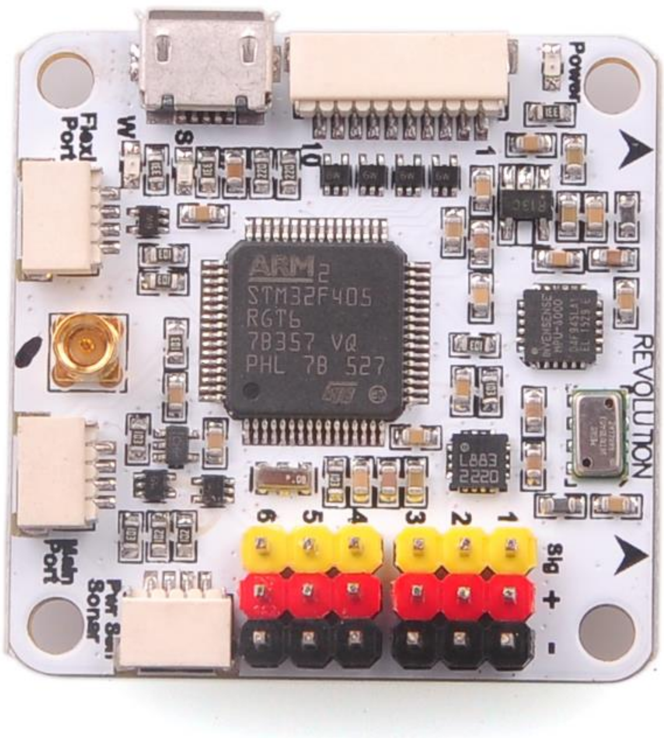

Figure 10.1: Open pilot revolution FC

10.1 PROCESSOR CHIP

Processor chip collects and processes signals from all the sensors and signal inputs in real time and turns them into output signals.

There are some essential characteristics important when choosing a processor chip. One of them is processing speed. Arduino platform is based on 8bit processor that's so widely used because of its simplicity and availability of code and support. Although, advancements in technology and the increasing demand for more processing power have shifted the market towards 32bit chipsets. This is due to the addition of more sensors, increasing demand for higher loop times and added functionality that requires more processing power and external add-ons such as GPS for waypoint navigation/mission planning. When flying, it is important to have a responsive aircraft, which means the flight controller must process inputs and outputs fast. There are several processor chipsets currently in use. Although ATMEGA2650 chip is still used, the most widely used is STM cortex chipsets, F1, F3 and F4 [1 - 5].

The F4 chipsets utilizes an integrated Floating Points Unit (FPU). FPU is a math coprocessor that manipulates numbers faster than a fixed-point unit micro coprocessor. It makes heavier arithmetic operation process faster. The performance of the FC comes down to latency, loop time, clock rate and MIPS (million instructions per second). MIPS is a measurement of task performance speed if comparing the performance of different chipsets with the same system architecture [7]. Underneath some typical characteristics of chips follow:

ATMEL2650

- 16 MHz
  16 MIPS

STM32

- F105 72 MHz
  61 MIPS
- F305 72 MHz
  90 MIPS
- F405 168MHz
  210 MIPS
- F427 180MHz
  210 MIPS

10.2 GYROSCOPE

The gyroscope (gyro) is a sensor package that senses changes in attitude. A gyro senses movement in three axes. A 6 axes gyro is a gyro with an accelerometer on it. The accelerometer senses acceleration. There are several other configurations: gyros with 10 degrees of freedom have an array of sensors, and it makes more sense to call it a sensor package. It consists of a 3-axis gyro, 3-axis accelerometer, magnetometer (compass) and a barometer to sense measure altitude. The altitude sensor together with the magnetometer can be used to position-hold the UAV in the air. The most used gyros are those made by Invensense, namely MPU-6000, MPU-6050 and MPU-9250. MPU-6000 has faster loop times and lower latency than MPU-6050 and MPU-9250 and is therefore considered to be more responsive and generate less noise [6].

10.3 Clones and copies

Good products tend to be copied by the Chinese. While you can get, what looks like the same flight controller but at a lower price, it's usually a clone. Some clones can be decent some not. There's often sub-par soldering and the quality of the components can be somehow questionable. Therefore, is always advisable to get the original, or at least make sure the one you purchase is of decent quality.

10.4 GUI vs GCS

The most widespread way to set up and calibrate flight controllers is by either using a Graphical User Interface (GUI) or by using a Ground Control Station (GCS) they are initially the same but the GCS has extended functionality, the GCS can set up GPS navigation, and it also communicates with the UAV while in flight, meaning it can display real-time data of the UAV's performance and position. The GCS can also monitor live video, upload commands and set parameters while the UAV is in flight [8, 9].

10.5 Futureproofing

While we probably will be able to fly with an older flight controller, we see it as a huge advantage to have a FC that is up to date. A more complex code makes the UAV fly steadier and more responsive. In addition, it has more processing power to be able to continue building our platform in the future. Support for GPS/waypoint navigation and telemetry is also an advantage for troubleshooting and for collecting data.

10.6 FINAL DECISION

We choose the Open Pilot Revolution flight controller. This is based on price, availability, performance and because it is a proven platform with consistent quality that is widely used and there is lots of support for it. Most of the smaller flight controllers are stripped down to the essentials and aim more towards the FPV racer. We need a flight controller with a good gyro that has a fast loop time. Fast loop time aids in cancelling out noise because of vibrations. A mechanically complex UAV such as ours is subject to more vibrations than the average UAV with one motor per propeller and fixed pitch. It also supports telemetry, and other peripherals such as GPS and Sonar [10, 11].

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11 Setting up the flight controller

11.1 Control motor mixing

When using a frame that is not equidistant to a center point, like an X-frame, motor mixing is needed. This is to adjust for the balance of the quadcopter and optimize its performance. If the frame is quadratic, a custom motor mixing has no purpose.

Control motor mixing is helping the flight controller to measure how much thrust each individual motor needs to the given operations. In our case, how much pitch angle.

If one rotor is closer to the center, it might need more pitch angle to complete the same distance as a rotor that is further away that needs less pitch angle to the propellers.

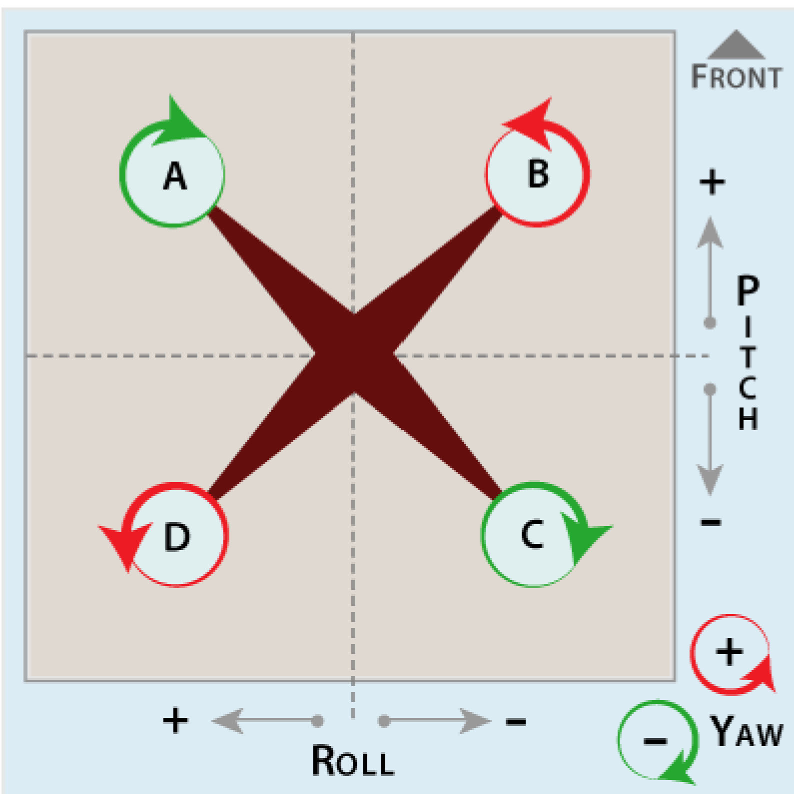


Figure 11.1: Positive and negative direction for pitch, yaw and roll

The scale is from -1 to 1. The number indicates the percentage of force magnitude and the +/- sign indicates the direction of movement [fig. 11.1].

Yaw indicate the direction of the propellers. CW has a negative value and CCW has a positive value. Pitch is positive when the quadcopter is tilted forward, and negative with backwards tilt. Roll is positive when the quadcopter tilt to the left and negative when tilting right.

Throttle is 1 for the motor, but pitch, yaw and roll can have variable values between -1 and 1, depending on the placement of the rotors.

These values have different meanings depending placement. 1. Indicates 100% [1].

11.2 CALCULATIONS

Calculation helps us to create a custom mix for our quadcopter. Motor mixes vary for different distanced multirotors. It is all about the moment of force. A rotor that is further away from the centre needs less energy to stabilize the quadcopter, than a rotor that is closer to the centre.

When calculating these values, the longest distance between the rotors (not diagonally), is used as a denominator to describe the total length or size from a whole. The other distances between the rotors, is divided by the denominator with reference to the pitch- and roll axis. We are looking for the ratio between them in both pitch- and roll axis separately. The given ratios give us information whether we need to reduce or increase the force on the particular axis to get the drone in equilibrium [2].

11.2.1 Online motor mixing calculator

Calculations with the motor mixing calculator online calculates by measuring the distance between the rotors [3], [fig. 11.6]:

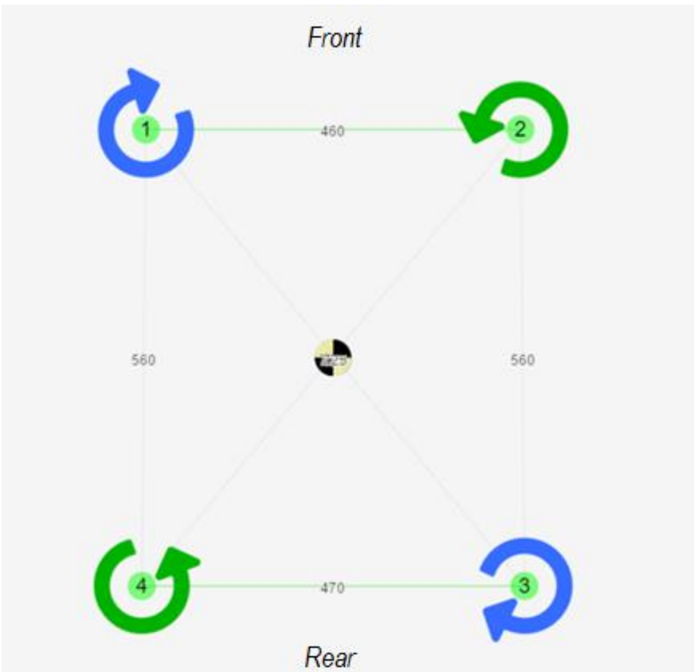


Figure 11.2: The frame size dimensions are put into the motor mix calculator

Custom motor mixing table comes in this order [fig. 11.3]:

mmix [motor number] [throttle] [roll] [pitch] [yaw]

```
mixer custom
mmix reset
mmix 0 1 0.821 -1 -1
mmix 1 1 -0.821 -1 1
mmix 2 1 -0.839 1 -1
mmix 3 1 0.839 1 1
```

Figure 11.3: The outcome values of the motor mix calculations

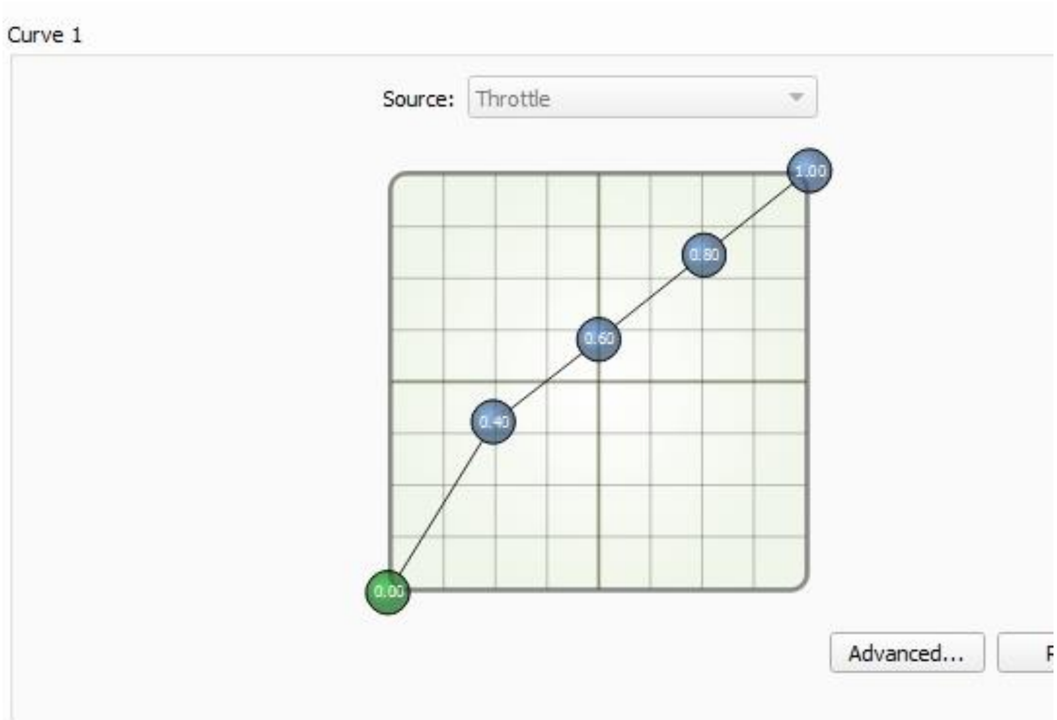
11.2.2 Values used in LibrePilot

Each mixer value in the LibrePilot software is represented as a signed 8bit integer. Because of this the value for motors range from -128 to +127. The range for servo mixing spans from -64 to +64. To get the correct mixer value in LibrePilot we had to multiply this number by the weighting factor from the mixer calculations. [table 11.1]

LibrePilot Mixer	Servo 1	Servo 2	Servo 3	Servo 4	Motor
Throttle/collective	127	127	127	127	127
Roll	53	-53	-54	54	0
Yaw	-64	64	-64	64	0
Pitch	64	64	-64	-64	0

Table 11.1: Mixer calculations multiplied by the total value in the LibrePilot mixer, gives us our values

When the correct values are established, they have to be updated in the LibrePilot GCS mixer.



	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5
Curve 1	0	0	0	0	127
Curve 2	127	127	127	127	0
Roll	53	−53	−54	54	0
Pitch	64	64	-64	-64	0
Yaw	-64	64	-64	64	0

Figure 1.11.4: Custom mixer values

The values for yaw, pitch and roll are both positive and negative. The positive or negative sign in the mixer determines the direction the servo is moving. The signs we get from the mixer calculator is not necessarily the correct. It depends on what way the servo was mounted on the frame. It is therefore important to do a visual inspection to see that the servo moves in the correct direction. The direction is easily changed by changing the sign.

11.2.3 Calculations with Pythagoras:

From figure 11.6, we can see that the dimensions in the front and rear of the quadcopter are not equal. Therefore, the motor mixing is necessary. There are some unknown angles and lengths that needs to be determined before we can proceed with the values used in the motor mixing. The length a and d are known, and there are two length that needs to be determined before proceeding with the motor mixing values; the lengths b and c [fig. 11.4].

It is not given that the gravity point is in the center. We know that the lengths to the roll axis are the same, but the length (b and c) to the pitch axis may not be equal from one another.

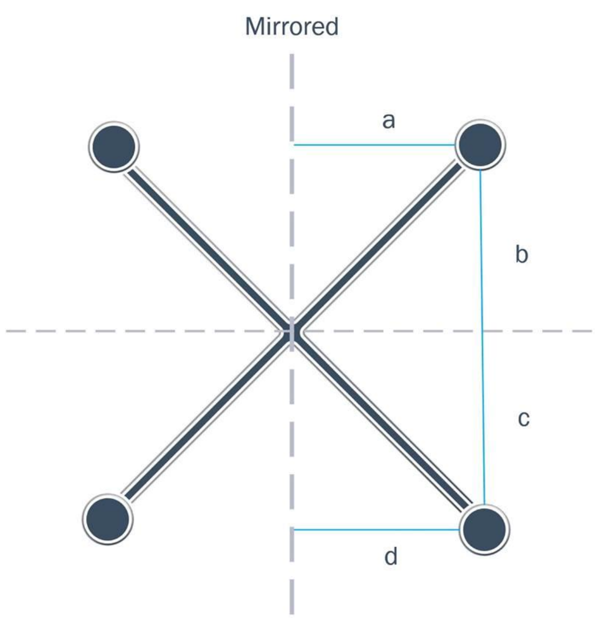


Figure 11.5: Length a, b, c and d, pitch-and roll axis

<u>Preliminary calculations:</u>

To determine the lengths b and c, we are using Pythagoras theorem [eq. I]:

$$CosA = \frac{b^2+c^2-a^2}{2bc} \qquad \text{I}$$

The quadcopter is mirrored along the roll axis, which means that it is similar on both sides of the axis. (Ag=Ag`, Ar=Ar`, Bg=Bg`, Br=Br`)

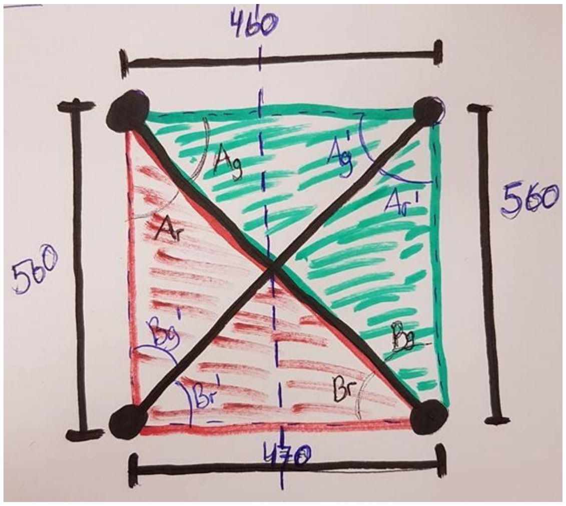


Figure 11.6: Quadcopter split into sections and triangles

Our quadcopter frame can be split into two triangles [fig. 11.5].

Red triangle:

$$CosA = \frac{560^2+725^2-470^2}{2 \cdot 560 \cdot 725} = 0.76148$$

Angle Ar = 40.405 (Ar` is equal)

$$CosB = \frac{725^2+470^2-560^2}{2 \cdot 725 \cdot 470} = 0.63525$$

Angle Br = 50.562 (Br` is equal)

Green triangle:

$$CosA = \frac{725^2+460^2-560^2}{2 \cdot 725 \cdot 460} = 0.63512$$

Angle Ag = 50.570 (Ag` is equal)

$$CosB = \frac{560^2+725^2-460^2}{2 \cdot 560 \cdot 725} = 0.77293$$

Angle Bg = 39.382 (Bg` is equal)

Since the quadcopter is not equal on both sides of the pitch-axis, both sides b and c are unknown.

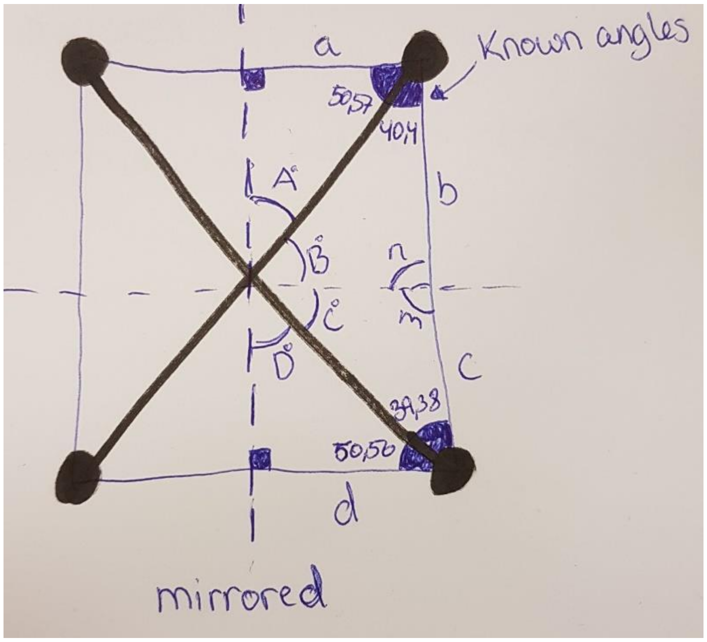


Figure 11.7: Half a quadcopter with sections of triangles to help calculate

The mirrored side of the quadcopter gives us two right-angled triangles with angles A and D. These are given with straight out calculations:

A = 180-90-50.57 = 39.43

D = 180-90-50.56 = 39.44

To find hypotenuses in h_1 and h_2, with using angles A and D:

$$\sin \alpha = \frac{opposite}{hypotenuse} \rightarrow Hypotenuse = \frac{opposite}{\sin \alpha} \qquad \text{II}$$

$$h_1 = \frac{230}{\sin(39.43)} = 362.13$$

$$h_2 = \frac{235}{\sin(39.44)} = 369.92$$

The pitch and roll axis are perpendicular to each other, which states that A+B and C+D both equals to 90 degrees. We now have two other angles B and C:

B = 90-A = 90-39.43 = 50.57

C = 90-D = 90-39.44 = 50.56

Which gives us angles n and m too:

n = 180-50.57-40.40 = 89.03

m = 180-50.56-39.38 = 90.07

Finally, we can use the law of sines to find the lengths b and c [eq. III]:

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \qquad \text{III}$$

$$\frac{b}{\sin B} = \frac{h_1}{\sin n} \rightarrow b = \frac{h_1 \cdot \sin B \cdot}{\sin n} = \frac{362.13 \cdot \sin(50.57)}{\sin(89.03)} \approx 280$$

c = 560-b = 560-280 = 280

The length difference in the front and the back did not have a high impact on the center on our quadcopter. The difference is not sufficient, and we can assume that sides b and c are equal.

Now that we have all the necessary values, we can determine the ratios for pitch and roll.

<u>Motor mixing calculations:</u>

Motor 1 and 2:

Roll: $\frac{230}{280} = 0.8214$

Pitch: $\frac{280}{280} = 1$

Motor 3 and 4:

Roll: $\frac{235}{280} = 0.8392$

Pitch: $\frac{280}{280} = 1$

These calculations give us custom motor mix values [table 11.1]:

Motor (Rotor)	Throttle	Roll	Pitch	Yaw

mmix	1	1	0.821	1	-1
mmix	2	1	-0.821	1	1
mmix	3	1	-0.839	-1	-1
mmix	4	1	0.839	-1	1

Table 11.2: Custom motor mixing

11.2.4 Motor mixing calculation conclusions

We can conclude that the motor mixing calculated by hand and by the online calculator, gives the same values.

The values from the motor mixing calculator get typed into the flight controller, using Librepilot, which will reduce the need for correcting by the flight controller itself. The values for yaw, pitch and roll are both positive and negative. We do not need to worry about these signs, because in our case they may not be the same as the calculations show us. This is because we are using servos laying sideways, which gives us two possibilities of direction. The servo output it either on the left or on the right. This affects the positive or negative value we get from calculations.

11.3 LIBREPILOT

Librepilot is a software used to give control inputs for applications like vehicle control and stabilization, in unmanned autonomous vehicles and robotics [4].

11.4 CONFIGURATION OF MULTIROTOR AND HELICOPTERS

A conventional multirotor has one motor per propeller. It changes altitude and attitude by increasing or decreasing the propeller speed to increase/decrease thrust at the given rotor. The pitch of the propeller blades is fixed.

A helicopter has one motor. To control altitude and attitude it uses between two and four cyclic servos on the main rotor (swashplate) to control pitch and roll, for collective pitching the servos have to adjust simultaneously (lift the swashplate collectively). A helicopter controls yaw with its tail rotor, yaw is controlled by a servo that changes the pitch of the tail blades.

Our quadcopter is a hybrid between a helicopter and a quadcopter, therefore we have to use the custom mixer in LibrePilot to combine both concepts.

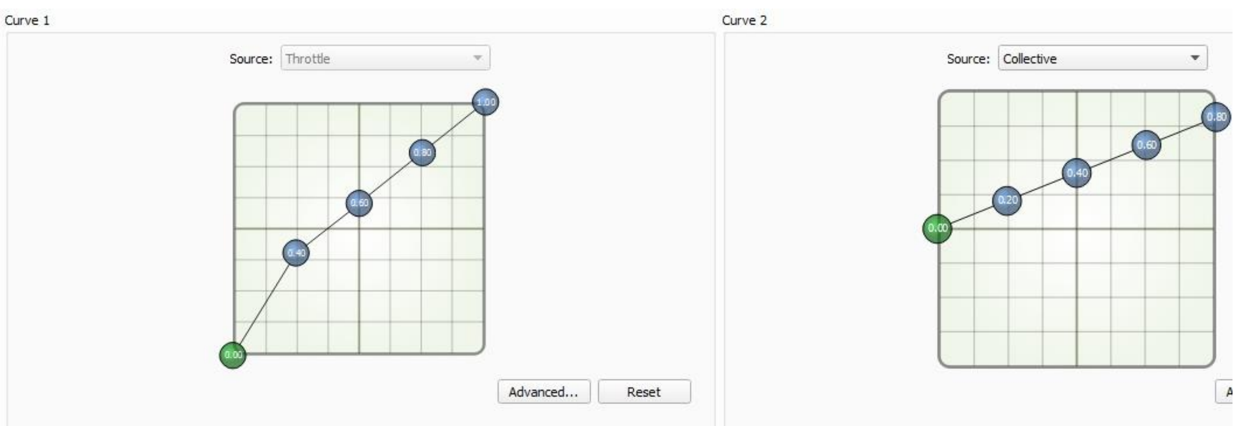
11.5 CONFIGURING FLIGHT CONTROLLER

There are several steps to go through to configure the flight controller, they are all dependent on what you are configuring. There is five different “tabs” in the LibrePilot GCS software: “multirotor”, “fixed wing”, “helicopter”, “ground vehicles” and “custom”.

Since we are building a collective pitch quadcopter, we have to use the custom tab and configure the mixer for a hybrid between a multirotor and a Heli. Throttle and Collective (Pitch) are controlled separately, each with separate output channels. The throttle and collective (pitch) are set to be controlled by the same input channel from the transmitter (TX). When the throttle stick moves up both the RPM of the motor and the angle of the blade increases simultaneously. The throttle stick input control two curves, one linked to the throttle and one linked to collective. The curves can be set individually. The curves decide what happens at the assigned outputs at a given stick input. The curves are weighted to tell the flight controller how much authority it has over the different control parameters. Curve 1 is throttle fig. [11.9], this only controls the motor. This curve is set a little steeper at the start to accelerate faster to hover. The throttle curve is weighted at maximum value, 127. This is because the sole purpose of the motor is to follow the curve. Curve

2 is for collective, meaning; it moves all the servos simultaneously the same amount to increase pitch. Curve 2 starts at 50 percent, that means the servos starts at neutral with zero stick input. If the curve had been set to 0 percent, the blades would have had full negative collective pitch at zero stick input. This would also mean that at 50 percent throttle the collective would have been at neutral therefore not producing any lift. At 50 percent stick input we want to have the multirotor at a hover.

We have adjusted the curves as seen in figure 11.9. Notice that the collective, curve 2 is set to 80 percent at full stick input. This is because we need the 20 percent left for the other output channels to control pitch, yaw and roll.



	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10
Curve 1	0	0	0	0	127	0	0	0	0	0
Curve 2	127	127	127	127	0	0	0	0	0	0
Roll	53	-53	-54	54	0	0	0	0	0	0
Pitch	64	64	-64	-64	0	0	0	0	0	0
Yaw	-64	64	-64	64	0	0	0	0	0	0

Figure 11.9: Throttle and Collective curve

The curves show us the percentage at y-axis and position of throttle stick on x-axis. Minimum to maximum throttle/collective is, 0/50, 40/65, 60/70, 80/75 and 100/80.

11.5.1 Configuring inputs

The first input tab is remote control configuration. This is where we assign the inputs from the radio transmitter (TX) and assign the different channels to functions such as throttle, roll, yaw, flight modes, etc. As seen in fig. [11.10] both the throttle function and the collective function is set to input channel 3. This is the vertical axis on the left stick of the remote controller. This is set to control both motor RPM and collective pitch. Notice that the pitch input is reversed, this could have been adjusted on the TX, but is easier adjusted in the GCS. The channels need to be corrected in the input tab, before proceeding to the output tab. This is important because when flying in stabilized mode the flight controller needs to correct movement in the right direction.

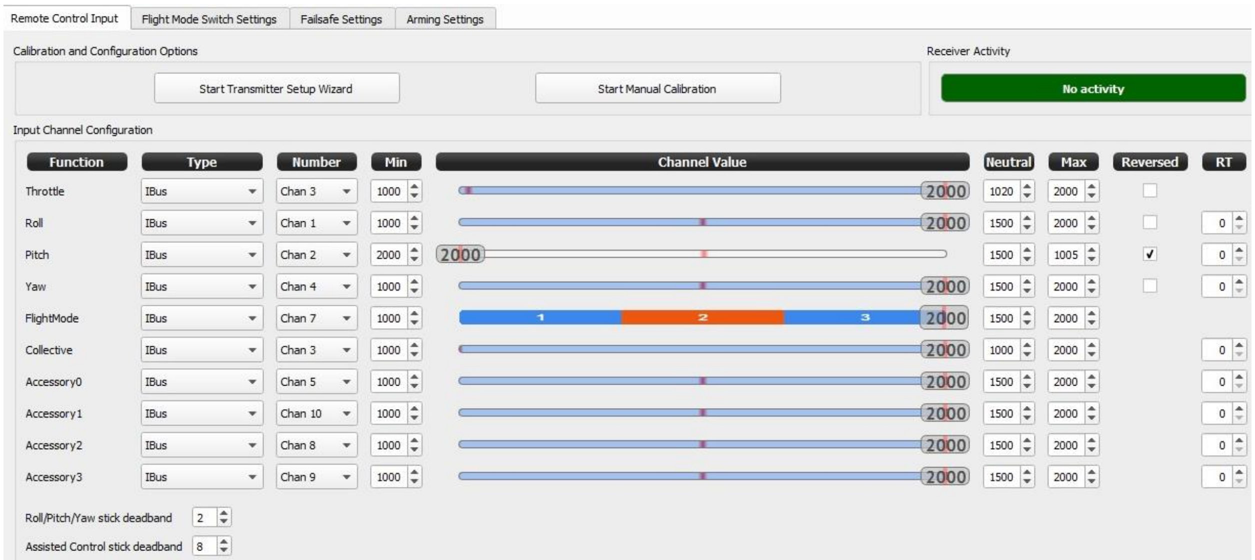


Figure 11.8: GCS Remote control input tab

Before proceeding to the output configuration, we want to assign the flight mode switch. We have used the three-position switch to select flight modes. This gives us three different flight modes to choose from figure11.9. Switch position 1 is set to stabilized1, switch position 2 is set to stabilized2 and switch position 3 is set to stabilized3. We have chosen all flight modes to include stabilizing. Manual or rate flight modes could have been selected as well, we decided not to because novice pilots are bound to crash if they try flying the quadcopter with no stabilization. Stabilized1 is the default flight mode, you will have to arm the multirotor in this flight mode. In this flight mode, you have full control over the multirotor. Stabilized2 is attitude hold, this holds the multirotor at the height you activated it and is a good flight mode for novice pilots because they will maintain altitude and only control attitude. The barometer sensor that measure altitude has a tolerance of about 10cm drop in height. Stabilized3 is similar to Stabilized2 but here you can adjust altitude with the throttle stick.

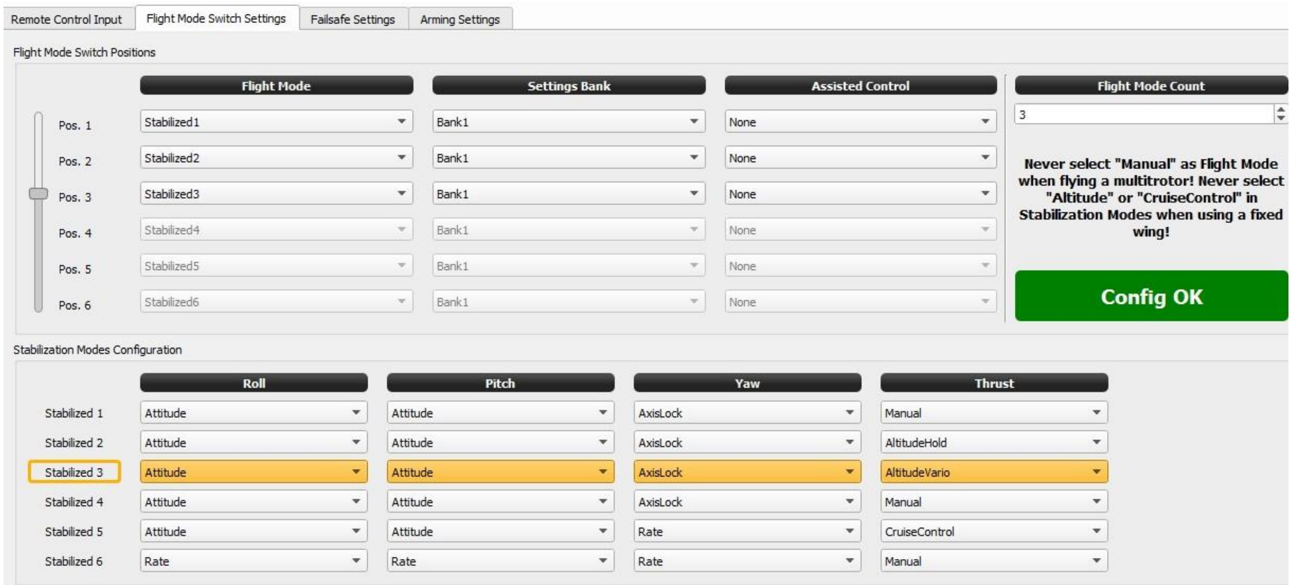


Figure 11.9: Flight mode switch settings

11.5.2 Configuring outputs

The output configuration tab [fig.11.10] is for adjusting output channel min/max values. The output channels use different banks to store values. Some banks are used by several channels. The important thing here is to have the motor on a separate bank than the servos. This is because the servos have a different refresh rate than the Electronic Speed Controller for the motor (ESC). The servos run an update rate of 400Hz, while the ESC run PWMSync (500Hz). The servo travel has been adjusted to limit the travel of the pitch mechanism in negative direction. Therefore, you can find that the minimum value has been set higher than the channel minimum. The maximum value has also been reduced from 2000 to 1900. The reason for this is to limit the servo at the end of its travel. The output signal for servo 2 and servo 4 have been reversed. They are reversed because their position on the multirotor is opposite than that of servo 1 and servo 3. The output signal for Servo 2 and servo 4 have to be reversed in order to move the pitch mechanism in the correct direction. There is one more value that have to be set, that's the neutral of the servo outputs. The neutral is when all the TX sticks are centred, we want to make sure all the pitch mechanisms are adjusted on the multirotor as evenly as possible. The fine tuning of this is done in the LibrePilot GCS. As in figure 11.10, the neutral sliders are not even. We have adjusted them in the GCS so that they are as close as can be physically on the multirotor. The values are different because of variations in manufacturing and tolerances. The flight controller will compensate for this in

Stability mode, but if flying manual or rate-mode you would have to compensate this with stick input. Therefore, we calibrated them as close as we could get.

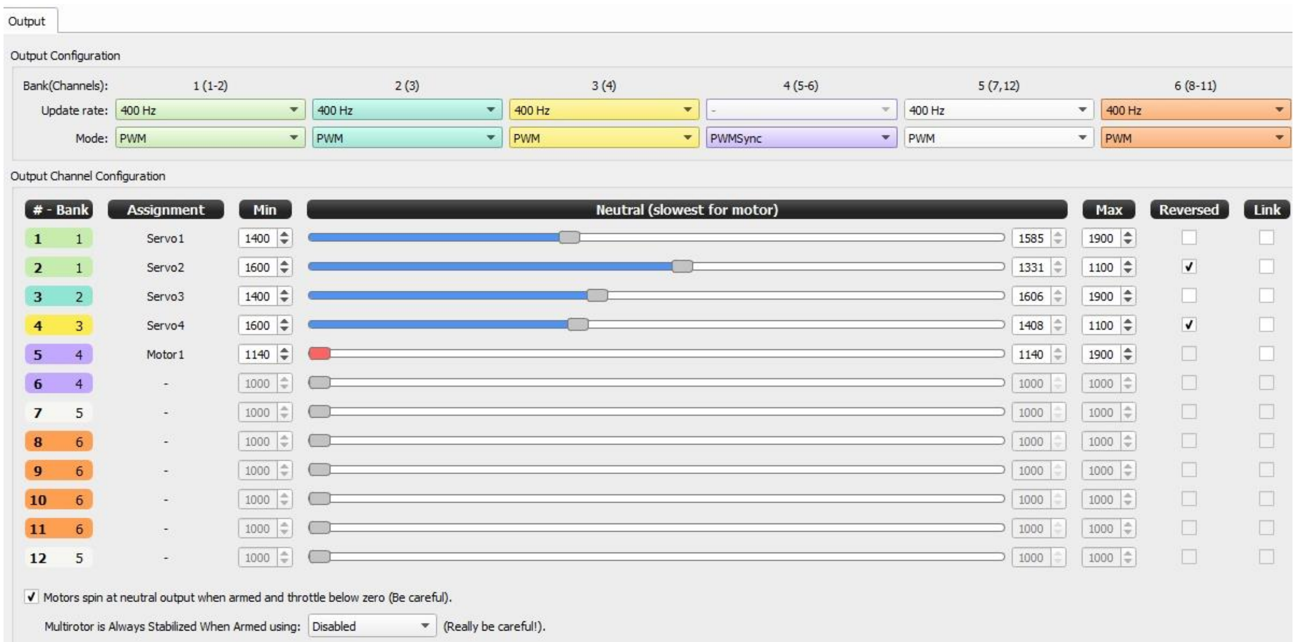


Figure 11.10: Output configuration tab

11.5.3 STABILIZATION

A PID controller part of the flight controller, is a control loop feedback mechanism. It corrects output values in proportional (P), integral (I), and derivative (D) process variables. It reads sensor data, and tells how fast the propellers have to spin and how much the blades must variate. The values go directly to the feedback loop, and start over again with corrected values.

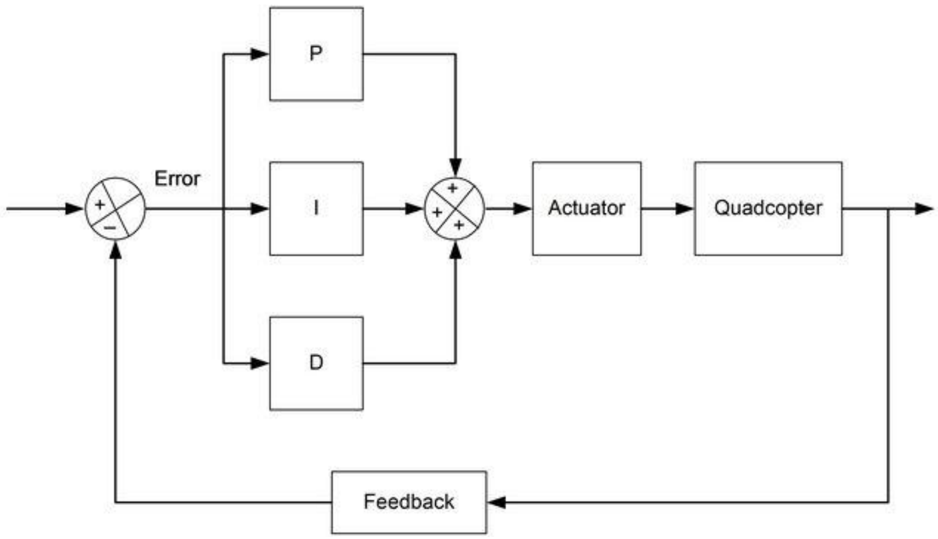


Figure 11.11: PID feedback loop

There are three different values. P, I and D. They are values for the past, presence and tense.

P depends on the present error, I on the past errors that has occurred, and D is values of the future based on the previous values and corrected errors [6, 7].

There are several tabs to adjust the values for PID's. We are only going to use the basic tab for adjusting.

- Inner loop
- Outer loop
- Gyro filter
- Multirotor response Moderate, snappy, insane, exp curve.

The PID values we adjusted was not very far from the default stock values in the flight controller. We increased the P value for both roll and pitch in the Rate stabilization (Inner loop) from 40 to 45 and the I value to twice the value if P to 90 for roll and pitch. For yaw, we left the P value at 72 (default) but we increased the I value to 144 [fig.11.12].

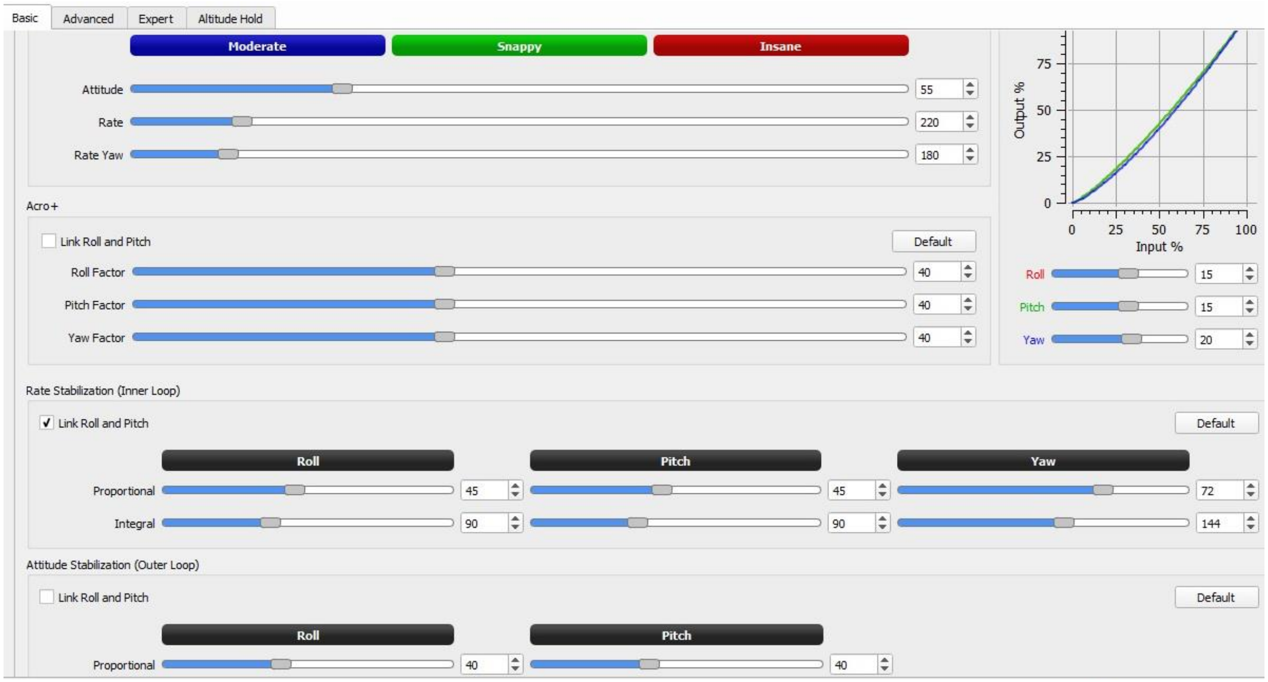


Figure 11.12:

11.5.4 GYRO NOISE FILTERING

Because of many moving parts there is a possibility of vibrations, the gyro in the flight controller is sensitive to vibrations. If the sensitivity of the gyro is too high it will sense all the small vibrations and constantly trying to correct. We ran the motor with the flight controller connected to LibrePilot so we could read the gyro sensor input from the scope tab [fig.11.13]. Adjustments were then made to the gyro noise filter [fig.11.14]. We lowered the sensitivity of the gyro, to where the gyro input had a smoother curve on the oscilloscope and ended up with a value of 0.017.

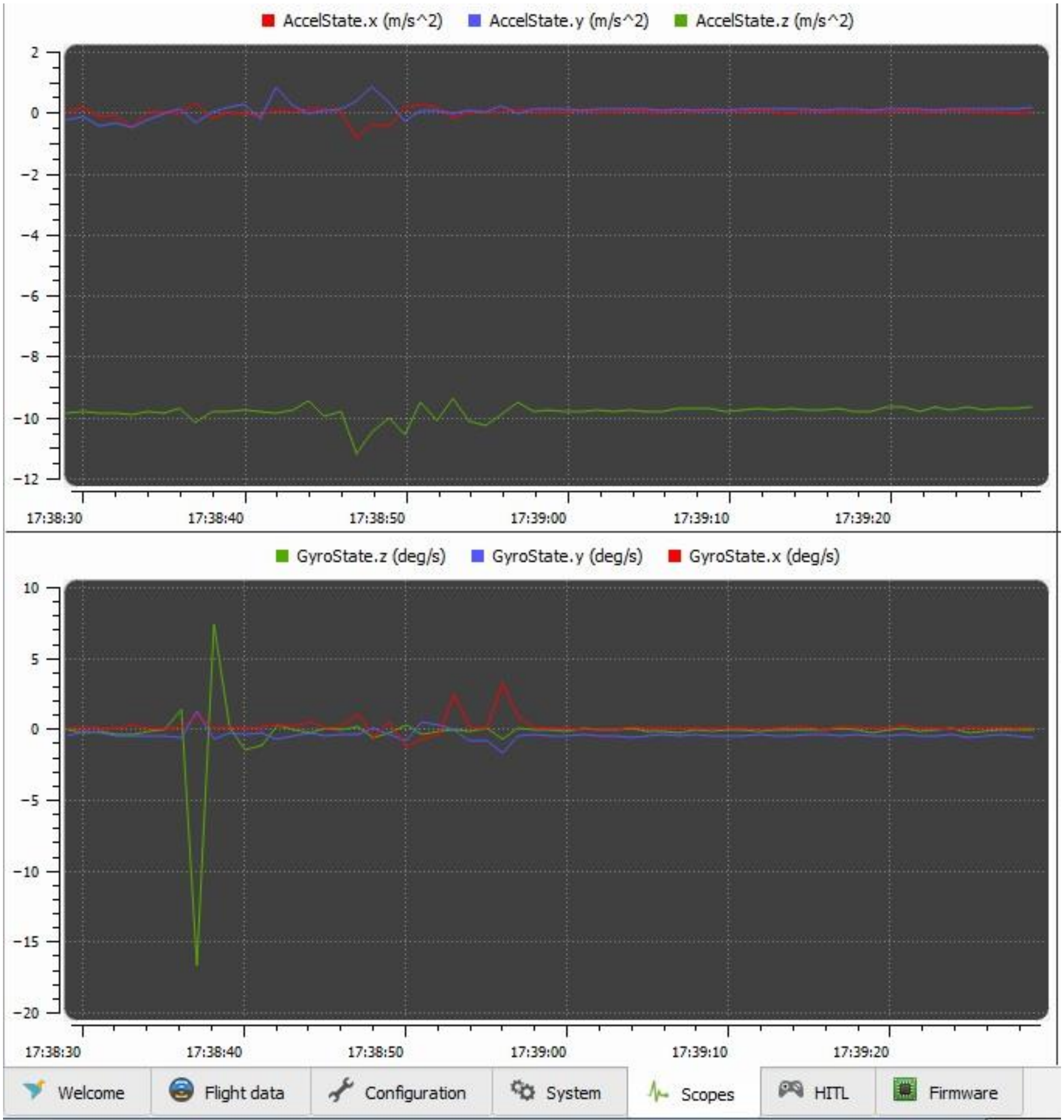


Figure 11.13: Ocilloscopes in LibrePilot for reading sensor data

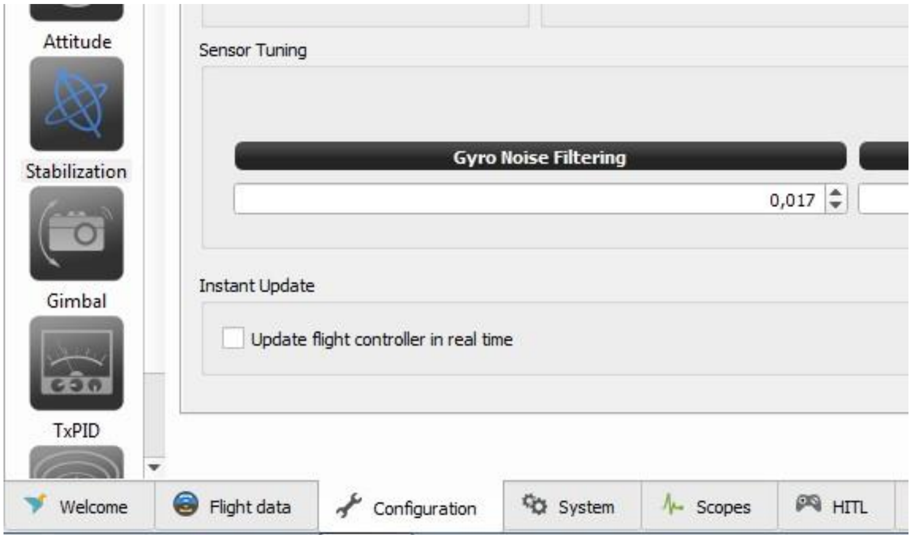


Figure 11.14: Gyro noise filtering in the expert stabilization tab

11.5.5 KILL SWITCH

Our system is set up with an arming switch, this is for arming the multirotor. It also doubles as a kill switch. If disarming in flight the motor will stop and shortly thereafter, the rotors will stop. This The flight controller also has a failsafe setting in its input configuration which we can use to control what the multirotor does if there is a break in the connection between the transmitter and receiver.

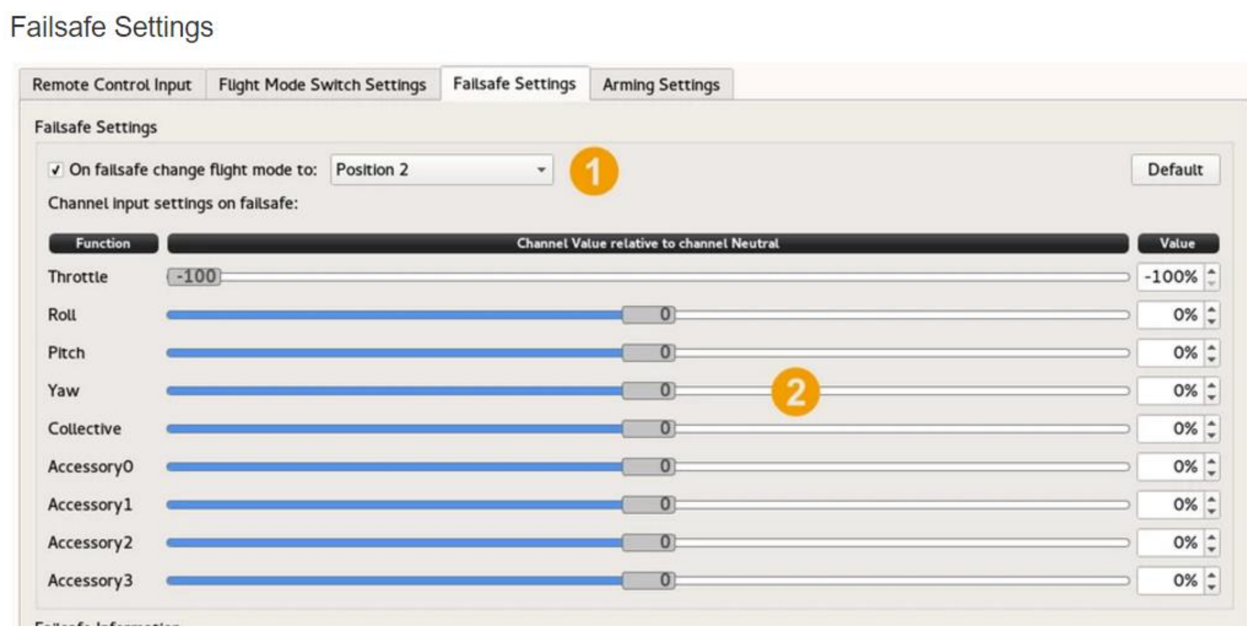


Figure 11.17: Failsafe Setting in LibrePilot

The failsafe is enabled when the connection between the transmitter and receiver is lost. If the connection is lost, the flight mode changes into another position. This flight mode to zero throttle. [5].

When setting up the failsafe, it has a custom timer, which delays the failsafe to trigger. This is because if a mistake or failure breaks the connection between the receiver and the transmitter, we would not want the quadcopter to shut off. The flight controller will stick to the last command given. Bibliography

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12 WIRING THE QUADCOPTER

Because of the nature of a drone and the environment it operates in, it is beneficial to protect wires and connectors to make sure that they will not move. Having a wire disconnect or break connection during flight will have devastating consequences to the quadcopter because it will crash.

We have relocated the power input pins on the flight controller, via a pigtail connector socket mounted on the side of the rotor arm. This aids in ease of access for plugging/unplugging the flight controller battery. It also removes the problem of electrocuting the flight controller due to opposed polarity connection. The plug on the extension lead will only fit one way, there for ensuring that the polarity is always correct.

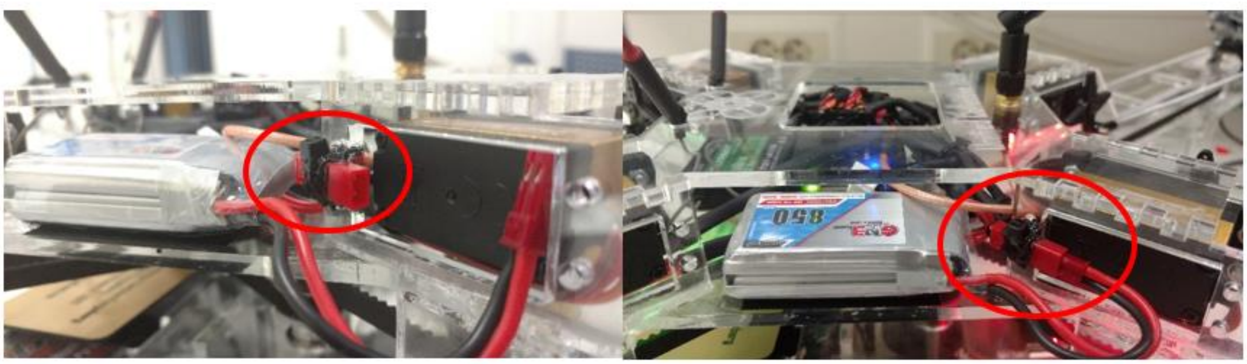


Figure 12.1: Battery connector placement

As seen in the picture below there is a Velcro strip for attaching the battery. Securing the battery with Velcro has several benefits. It simplifies detaching the battery for replacement and ease of access to USB port (the USB port can be seen by the blue light in the picture below). For the pilot to easier orientate himself about the front and rear of the quadcopter in flight, we have installed different colored LED’s in the front and rear. The LED’s are mounted underneath the servos so they are easily seen from underneath the quadcopter as well as around the sides of the quad. Green is to indicate the front of the quadcopter and red to indicate the rear. The two Receiver (RX) antennas (Red and black heat shrink top left in picture below), are designed to have the best signal strength and least interference if they are mounted 90 degrees apart. Therefore, they are in a 90 degree v-configuration on top of the quadcopter front. Since the flight controller have a built in 433MHz OP-link radio (Open Pilot link) we decided to mount the antenna on the rear of the quadcopter top plate, this so that if for future use the quadcopter can be connected wirelessly to a computer for telemetry, data acquisition, control, etc.

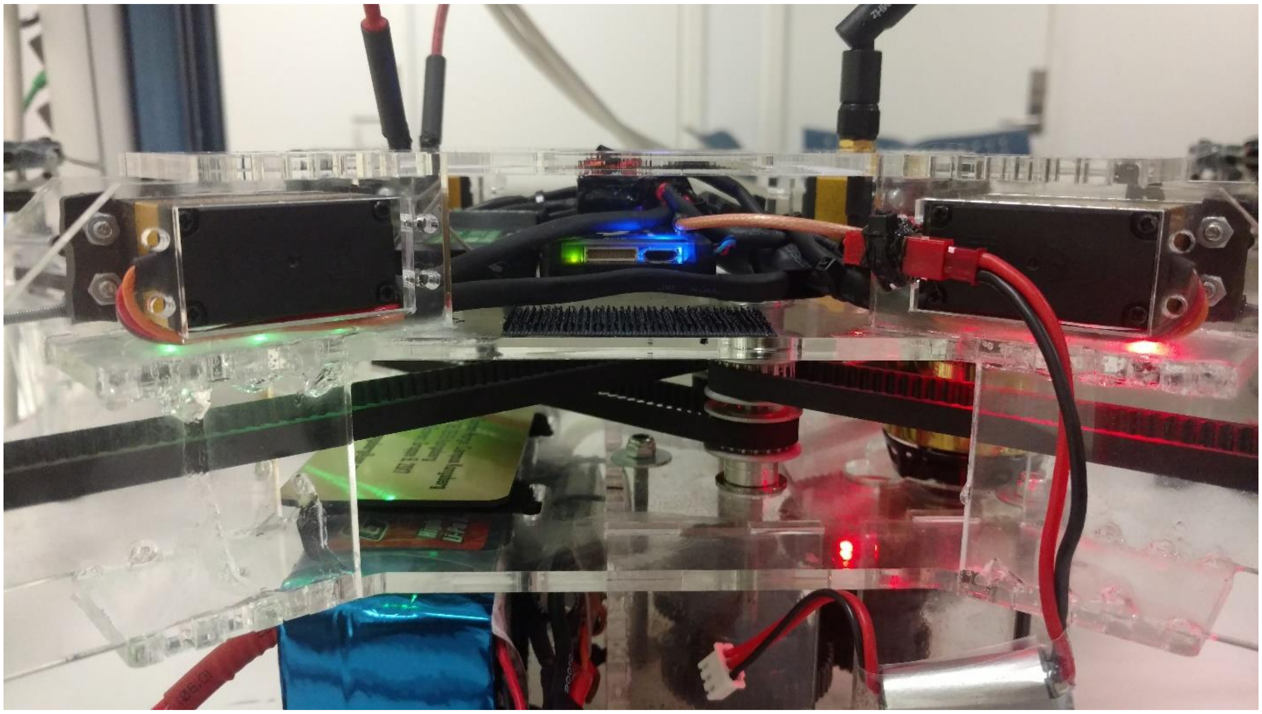


Figure 12.2: Velcro strip and access to the USB port (blue light) is shown in the picture, as well as RX antennas and OP-link antenna

The wires are wrapped in heat-shrink to give a uniform look and to have an extra layer of shielding from abrasion if the wires rub against each other, the wires are tied together by zip-ties to minimize wiring clutter and reduce their movement. A small amount of hot glue has been added between the flight controller connectors to make sure they stay put on their connecting pins during flight, but is easily removed with a Xacto knife (or similar hobby knife).

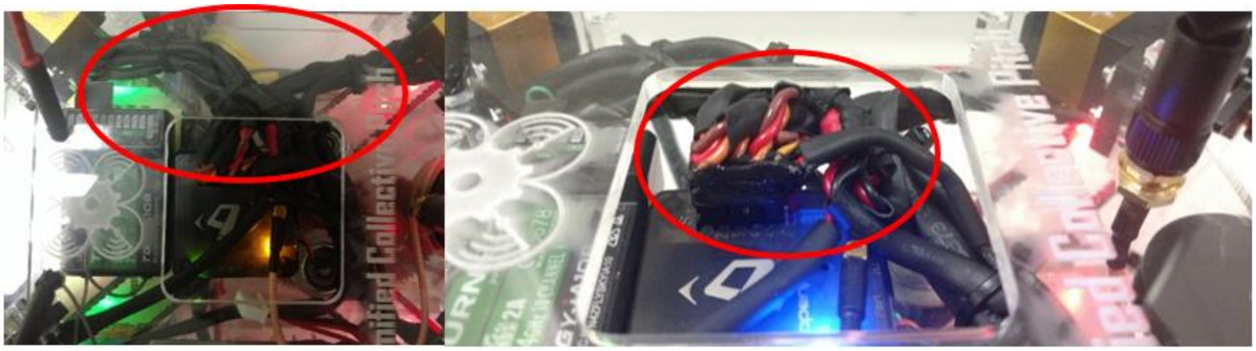


Figure 12.3: Wires are tied together in a wiring harness; on the left. A closeup of the connector and the hot-glue bead; on the right

12.1 VOLTAGE SENSOR

We made a voltage sensor for the flightcontroller to measure the battery voltage in-flight, the sensor is a voltage divider with the appropriate valued resistors for the flight controller. The voltage sensor works by sending the differential voltage over resistor 2 (R2), to the input labled PWR on the flight controller (this is the port for voltage/current sensors). The PWR input can handle a maximum of 3.3 volt therefore we scaled down the voltage with the voltage divider.

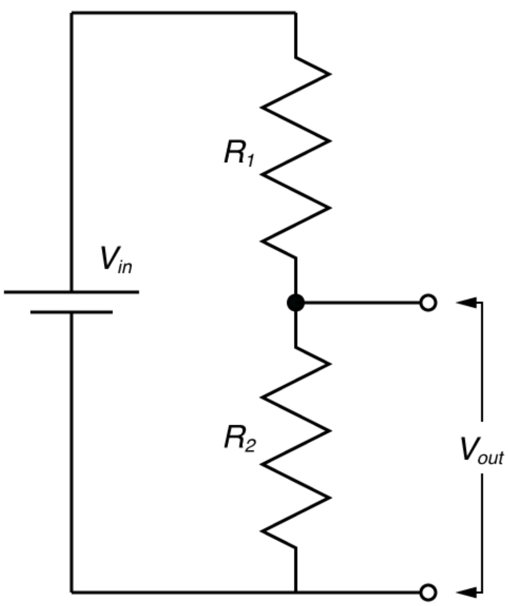


Figure 12.4: Schematic of a voltage divider

Full battery voltage is at 25.2v, we need 3.3v or less at the input.

The voltage divider equation states; to find the voltage **V**out over R2, you divide the value of R2 over the sum of R1 and R2, and multiply this with the source voltage **V**in (battery voltage in our case).

$$\boldsymbol{Vout} = \frac{R2}{R1+R2} * \boldsymbol{Vin}$$ I

By trial we put R1= 15KΩ and R2=2.2KΩ we get:

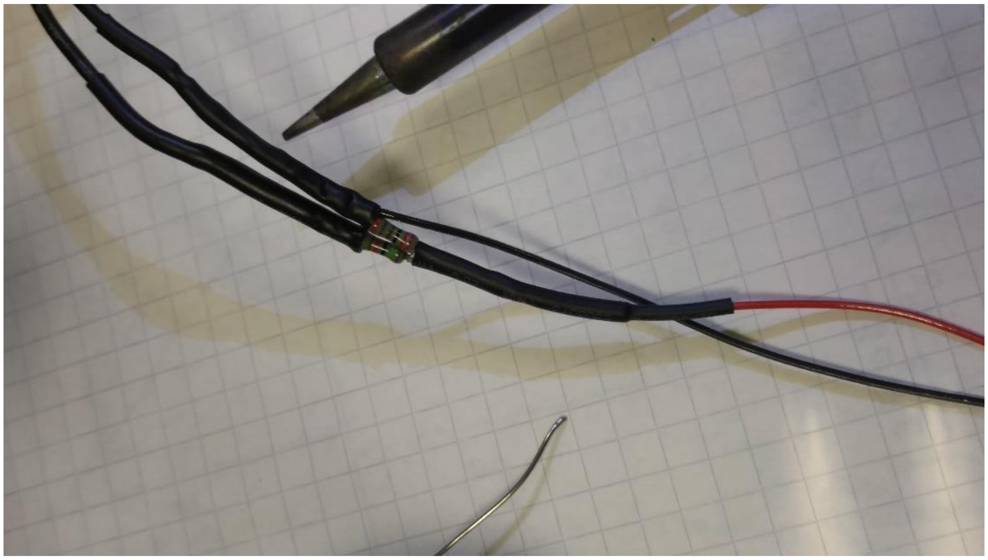
$$\frac{2.2K\Omega * 25.2v}{2.2K\Omega + 15K\Omega} = \boldsymbol{3.22326v}$$

3.22326volt is less than 3.3volt so it is within specified maximum voltage.

$$\boldsymbol{Vin} = \boldsymbol{V}battery = 25.2v$$

$$\boldsymbol{Vout} = \boldsymbol{V}pwr = 3.22326v$$

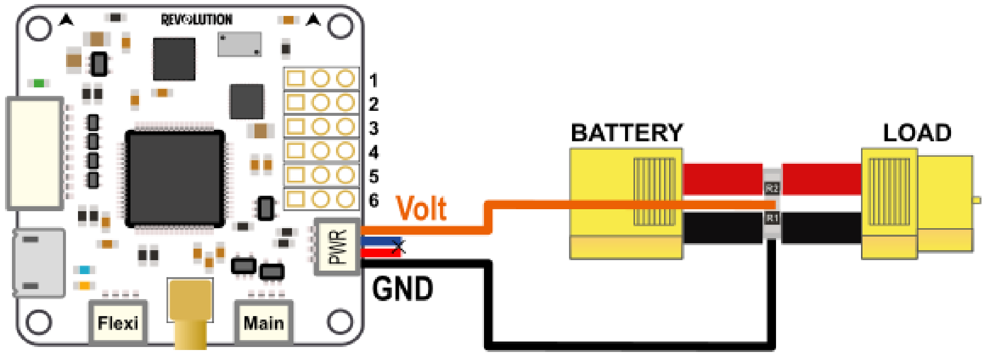
After the resistor values were determined, the voltage sensor was soldered together.



The two resistors in the voltage divider/voltage sensor (15KΩ left and 2.2KΩ to the right)

12.2 Wiring Diagram for the Flight Controller

There are two wires from the voltage sensor, a black wire (battery negative), and a red wire, PWR out (voltage divider output). The red wire is connected to the amber **voltage-In wire** on the PWR 4 terminal connector, and the black wire is connected to the black **ground wire** on the same connector.



12.3 Voltage Factor

Since we cannot run the battery voltage straight to the flight controller, we need to calculate a scaling factor to multiply the signal from the sensor so that the flight controller will measure battery voltage correctly. If the battery is fully charged at 4.2v per cell times 6 cells, we have a total of 25.2v, the PWR voltage at full battery is 3.22326v dividing the battery voltage over the PWR voltage we get a voltage factor

$$\frac{25.2v}{3.22326v} = 7.81817$$

This gets us pretty close to the actual battery voltage measured by a voltmeter. By adjusting the value to correct the error margin between the measured battery voltage and the voltage given by the flight controller we could do small increments to get the value as close as can be. The Voltage Factor ended up being 7.815

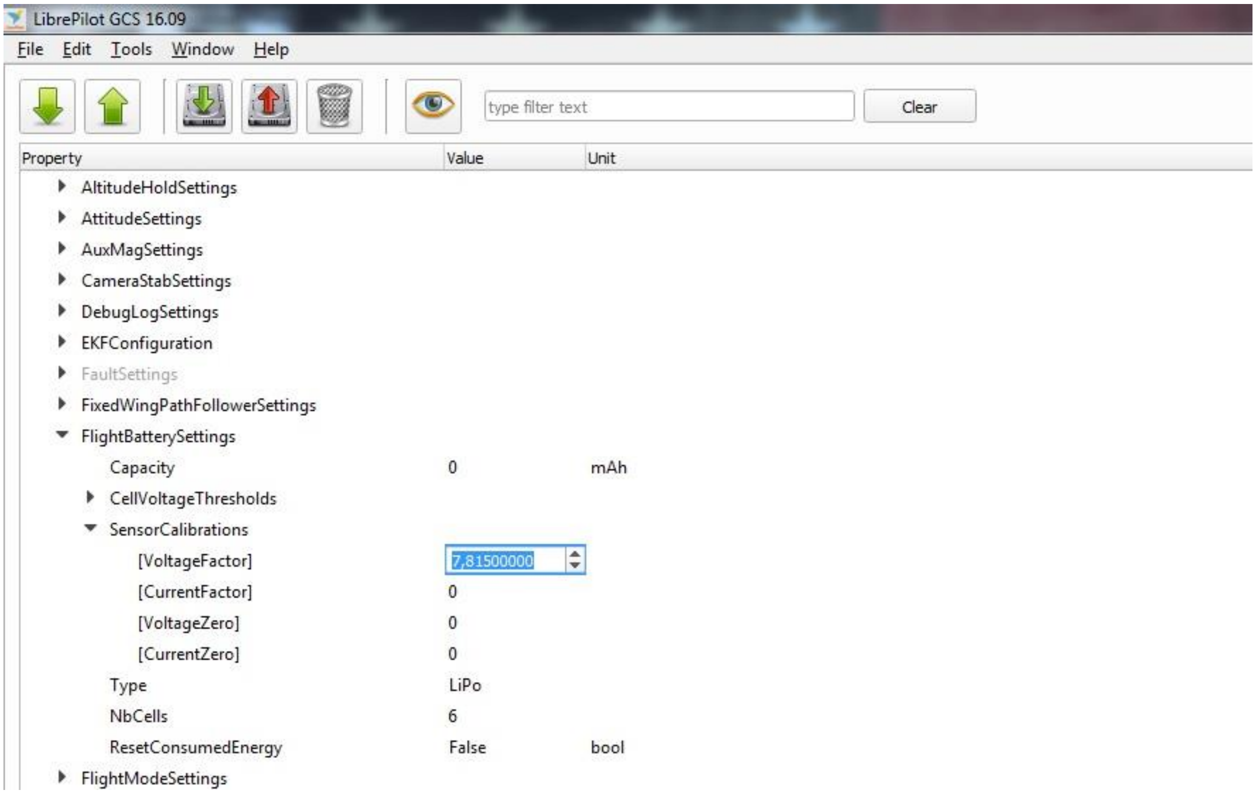


Figure 12.5: Battery voltage is seen in the top of the screenshot of the GCS after the voltage sensor had been calibrated

Battery voltage is seen in the top of the screen of the Ground Control Station (GCS) after the voltage sensor had been calibrated (in the pic).

Figure 12.6: Screenshot of the GCS with battery voltage showing in the highlighted circle

13 MOTOR, BATTERY AND ELECTRONIC SPEED CONTROLLER

When choosing a motor for the system, we have to do some calculations. We need to figure out what power is needed. From the momentum theory, also known as disk actuator theory [1, 2], following the conservation of energy principle: power consumed is equal to the energy flow rate out, minus the energy flow rate in. This gives us:

$$P = \frac{1}{2}M \cdot Vh^2 - 0 = \frac{1}{2} \cdot (M \cdot Vh) \cdot Vh = \frac{1}{2}T \cdot 2Vh = T \cdot Vh \qquad \text{I}$$

$$P = T \cdot Vd$$

Where,

$Vd = Vh$ (For a hovering rotor)

Vd: Velocity of disc

Vh: Velocity of a hovering rotor

P: Ideal power required to produce rotor thrust

T: Thrust

ρ: Density of air = $1.225 \frac{kg}{m^3}$

A: Area of the disc that the rotor produces =$2\pi r^2$ = $0.227 m^2$

V_0=0

$$Ve = Vo + 2Vh = 2Vh \qquad \text{II}$$

$$Vd = \frac{Vo+Ve}{2} \qquad \text{III}$$

Vd , at hover is therefore equal to Vh

$$T = 2 \cdot \rho \cdot A \cdot Vh^2 \qquad \text{IV}$$

$$Vh = \sqrt{\frac{T}{2 \cdot \rho \cdot A}} \qquad \text{V}$$

$$P = T \cdot Vh = T \cdot \sqrt{\frac{T}{2 \cdot \rho \cdot A}} \quad \text{VI}$$

$$P = \sqrt{\frac{T^3}{2 \cdot \rho \cdot A}} \quad \text{VII}$$

Plotting the values for thrust into the equation above, we get:

4000rpm, 4.5 inches of pitch and a rotor size of 15" · 4 rotors, gives us 32.8N of thrust = 252W

6000rpm, 8 inches of pitch and a rotor size of 15" · 4 rotors, gives us 98.8N of thrust = 1317W

The values for thrust is calculated from the static thrust equation in section 7.6. At a head speed (speed of rotor) of 6000 RPM the motor will need to deliver about 1500W of power.

Percentage of maximum continuous power	Power, W	Revolutions per minute, RPM
100%	1660	35520
90%	1494	31968

At 90 percent, the motor will have to generate 1494 W of power, at 31968 rpm.

$$\left(\frac{32000}{6000}\right) = \left(\frac{X}{4000}\right) \rightarrow X = 21333\ rpm \quad \text{VIII}$$

Rounding up to 32000 rpm

60%	996 W	21312 rpm

Taking into consideration how much power we ideally need for max thrust (within the constraints set), considering the losses and giving us a little "headspace", we end up with a motor producing 1500W. Brushless motors are typically 85-90 percent efficient. The chosen motor has a Kv of 1600, Kv is the number of revolutions per minute that the motor turns per volt (v), which means the motor should have sufficient power for our UAV. [3], [4]

With our modular system, it is easy to change to a different motor depending on what you want the UAV to do and to tailor the performance accordingly.

We are going to run this motor with a 6s battery (22.2V, 6 cells with 3.7V/cell), this is because it's a good compromise between capacity/voltage for our UAV. A 1600Kv motor on 6s (22.2V) yields 35520 RPM at 100%, the motor is most efficient in the 20000 to 30000 rpm range as seen in the data plot below. The plot is of similar motors to the one we will be using.

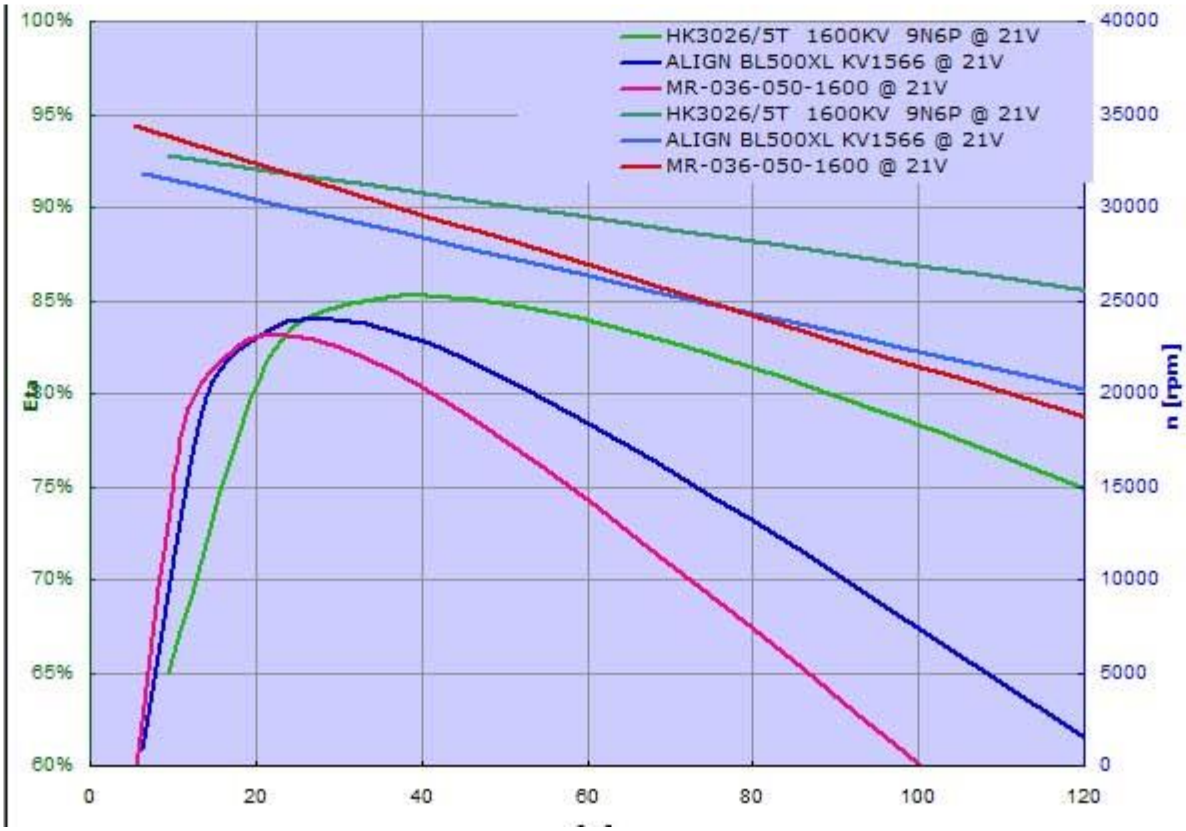


Figure 13.1: Efficiency VS. Current draw (Curves) and RPM VS. Current draw (straight lines) for 3 popular 1600kV heli motors

We chose the Rotorstar 4249 1600Kv motor as seen in figure 12.1; we chose this motor based on; low cost, low weight, and its performance. [5]

13.1 ESC

We want to have an ESC (Electronic Speed Controller) that has a higher current rating than the motor chosen has. This is because the motor is not going to use more power than its maximum rating, having a smaller ESC will result in the motor struggling to reach maximum power, while generating heat in the ESC, wasted heat equals wasted power which leads to lower performance and less efficiency. The ESC we selected is a YEP 80A ESC.

13.1.1 Calibrating the ESC

For the ESC to work correctly it needs to be calibrated. The ESC is calibrated by activating live motor testing in the GCS [Fig.12.2]. It is important remove the propeller blades when performing this calibration; this is for safety reasons in the case that the motor suddenly will start spinning.

Step 1: Adjust throttle output to max, before connecting motor battery.

Step 2: Connect battery and wait for two confirmation beeps. Throttle max is now stored in the esc.

Step 3: Set the throttle slider to min, and wait for two confirmation beeps. Min value is now stored.

Step 4: Is to adjust soft start. Soft start accelerates the drivetrain slowly to give a smooth start, this is good for heavy gear train because you have to accelerate its mass. We set the throttle slider at about 30 percent since we will be higher than 30 percent when hovering. Two configuration beeps are heard and the ESC is now calibrated.

Step 5: Unplug the battery and turn off live motor testing.

Since we are using a separate battery for the flight controller, we are not using the voltage supply from the ESC. Therefore, the red VCC (supply voltage) cable on the ESC is removed from the servo connector plug.

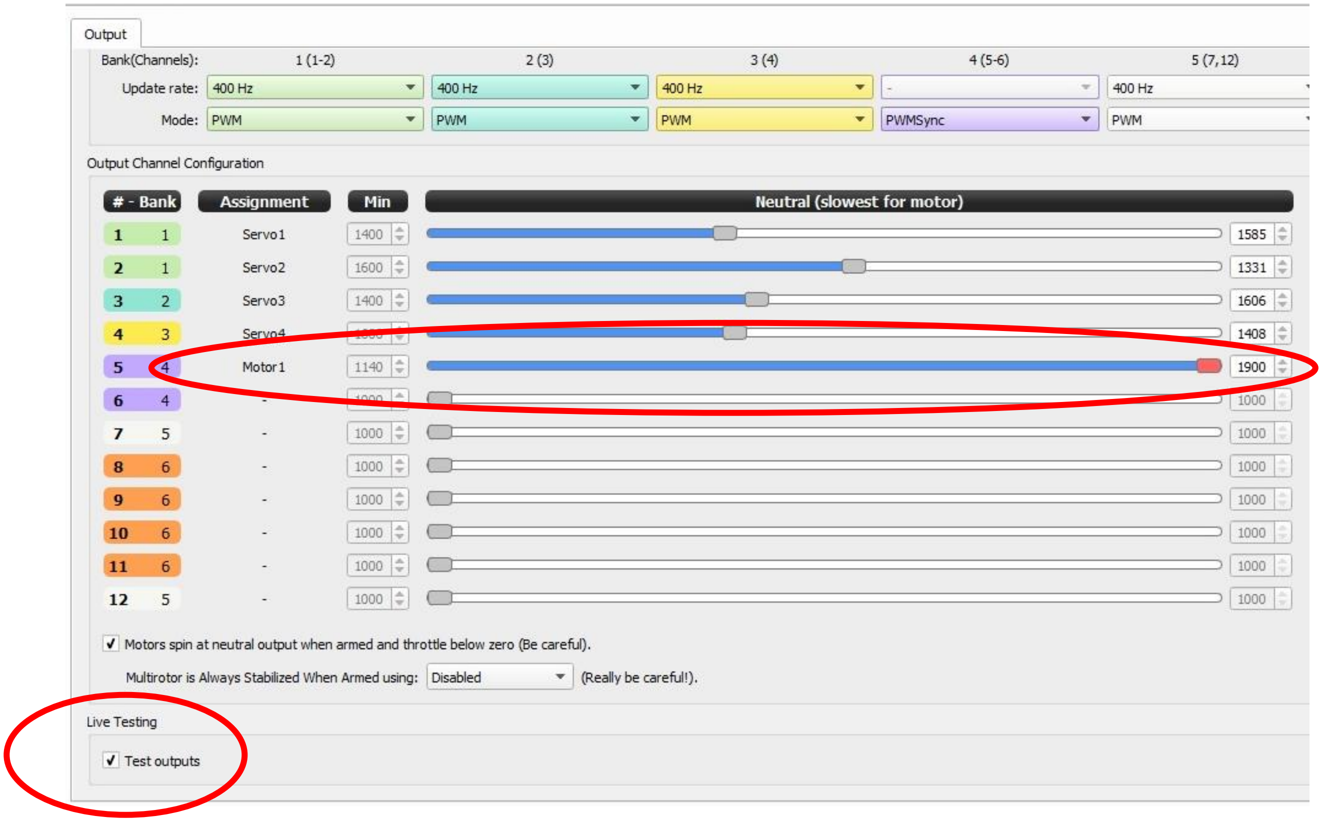


Figure 13.2: Live testing checked and throttle at max

13.2 Battery

The battery for the motor needs to have the same current rating as the motor or more for optimum performance. There is of course a balance between too low amperage, and too high, because too low hinders performance, and too high makes the battery heavier than it has to be.

The battery we are using is a Gens Ace 3700mAh, 6s LiPo battery with a capacity at 35C Fig. [12.3]. Weighting in at 597g.

The capacity of the battery is determined by the capacity rating multiplied with the amperage.

$$3.7A * 35C = 129.5A$$

This is more than sufficient for our quadcopter.

Figure 13.3: The LiPo battery we use

13.3 BIBLIOGRAPHY

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Appendix A: Composite Production Report

TABLE OF CONTENTS

1 WHAT IS COMPOSITE

A composite material is different from the conventional homogeneous material. Currently, composite materials refer to materials containing strong fibers – contiguous or noncontiguous – embedded in a weaker material or matrix. The matrix keeps the geometric arrangement of fibers and transmits to these fibers the load acting on the composite component. The resulting composite material is capable of intermediate mechanical performance, that is, superior to those of the matrix but lower than those of the fibrous reinforcement. The two materials work together to give the composite unique properties. However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other.

Composite materials are not new - they have been used since antiquity. Wood, straw, and mud have been everyday composites.

There are three different composite types depending on matrix type:
- Metal Matrix Composite (MMC)
- Ceram Matrix Composite (CMC)
- Polymer Matrix Composite (PMC)

1.1 CARBON FIBER

In our laboratory, we are using Carbon Fiber Reinforced Composite (CFRC), which is a category of PMC [fig. 2.1].

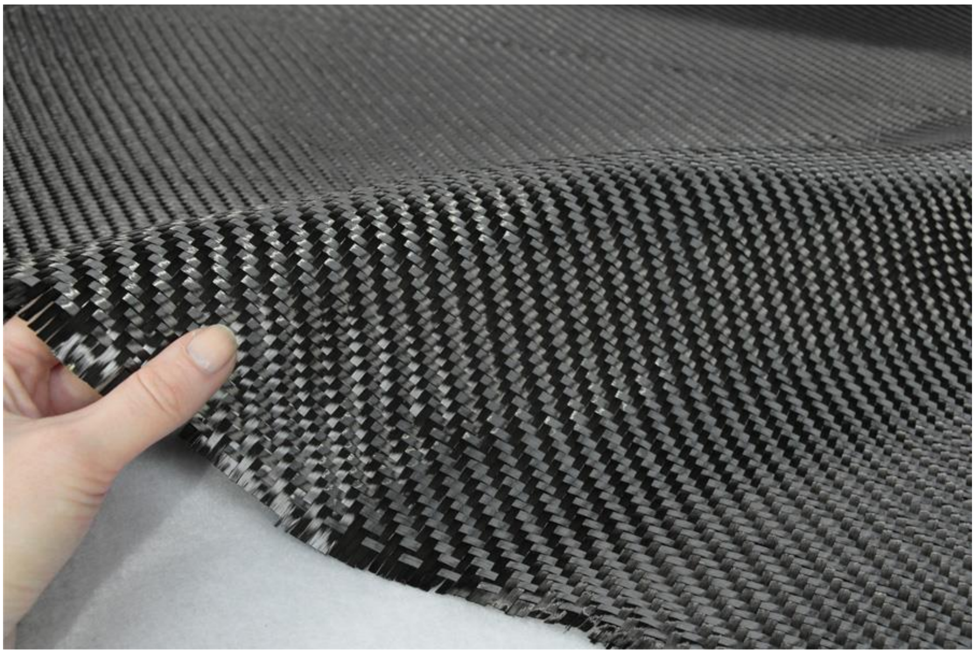

Figure 1.1: Carbon fiber cloth

Carbon fiber consists of filaments of polyacrylonitrile or pitch [here: a viscoelastic material that is composed of aromatic hydrocarbons]. It is obtained from residues of the petroleum products, oxidized at high temperatures (300 °C), and then heated further to 1500 °C in a nitrogen atmosphere. The high modulus of elasticity is obtained by stretching at high temperature. Fibers consist of several hundreds of thousands of filaments, each of them having a diameter of between 5 and 15 µm. The fibers have to be as thin as possible because their rupture strength decreases as their diameter increases [1].

1.2 THERMOSET RESINS

Epoxy resins are commonly used in the industries. Most because of their high mechanical properties and high corrosion resistance. It also shrinks less than other materials (1.2-4.9%) which indicates its bond ability. They are also widely used because of their easy curing process that can be achieved at any temperature between 5 to 150 C°. In general, uncured epoxy resins have poor mechanical, chemical and heat resistance properties. However, good properties are obtained by reacting the linear epoxy resin with suitable curatives to form three-dimensional cross-linked thermoset structures. This process is commonly referred to as curing and is done by adding a correct type of hardener which works as a catalysator and contributes to polymerization process.

If excess resin exists in the laminate, the laminate will have more of the properties of resin only. If too little resin exists, places where the reinforcement is dry will cause weak spots. To optimize the resin content, the entire reinforcement must be saturated with resin with as little excess as possible. The technique of "squeezing out" excess resin to obtain a maximized fiber-to-resin content is the theory of vacuum bagging and vacuum infusion [2].

1.3 FIBERS AND ORIENTATION

If delamination occurs, it splits the layers or splits the fibers from the matrix.

For our carbon plates, we are using 4 layers of 0/90 carbon fiber sheets. Cutting them into 0/90 and +/-45 sheets. The orientation is: 90/45/45/90, which can be noted as: $(90/45)_s$, gives us an even number of plies arranged symmetrically about the midplane, with an equal number of plies oriented at + (angle) and at -(angle), meaning our composite plates are both balanced and symmetric.

2 PRODUCTION OF COMPOSITE LAMINATES

There are four different manufacturing processes when making carbon fiber plates. They give us different strength on the carbon plates. The different processes are hand lay-up

2.1 HAND LAY-UP SHEETS

The hand lay-up technique is the simplest and most widely used process. It involves manual placement of the dry carbon fiber sheets. Normally an aluminum or a glass surface plate is used to create CFRC plate. The glass surfaces have to be prepared with a release agent (like Loctite) to be able to separate the bottom plate and the final carbon fiber plate when it is done.

First the resin is brushed or hand-rolled on the mold plate before the first layer of reinforcement is put on the plate. A combination of brushes, to wet out the fiber as much as possible, and squeegees to try to squeeze out the air bubbles as much as possible is used. This process is repeated on every layer. After wetting the layers of interest, a peel-ply sheet is placed on the top. It is used to absorbed some of the resin that will not go into the fibers.

It also got an advantage of making the fiber surface nice and smooth. The curing of the layers of carbon fibers and resin is usually accomplished in room temperature.

2.2 VACUUM BAGGING

Like the hand lay-up method, the carbon fiber sheets are lubricated with resin by hand when using vacuum bagging method [fig. 2.3-2.5]. To make the sheets even stronger, vacuum is used to create mechanical pressure on the laminate during its curing, making the atmospheric pressure act uniformly over the carbon fiber laminates. A peel-ply is used in vacuum bagging as well to absorb the resin from the composite. Using vacuum bagging, the fiber-to-resin ratio gets optimized which makes it a better mold than hand lay-up mold [3].

Figure 2.1: Manometer to confirm vacuum gauge

Figure 2.2: Vacuum bagging system

Figure 2.3: Vacuum bagging process 1

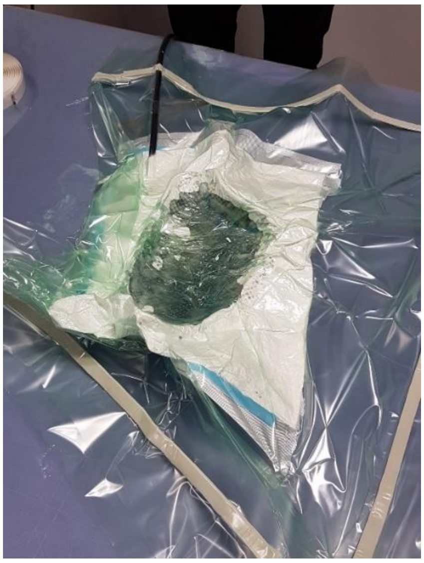

Figure 2.4: Vacuum bagging process 2

2.3 VACUUM INFUSION

Vacuum infusion, also called resin infusion [2.6], is a fabrication technique that uses vacuum pressure to drive resin into a laminate. This method makes a stronger structural sheet, than vacuum bagging. Dry materials are laid into the mold and the vacuum pressure is applied before resin is introduced. Once a complete vacuum is achieved, resin is forced into the laminate via vacuum tubing. The vacuum infusion process offers a better fiber-to-resin ratio than hand lay-up and vacuum bagging, because it forces out the air bubbles from the resin [4].

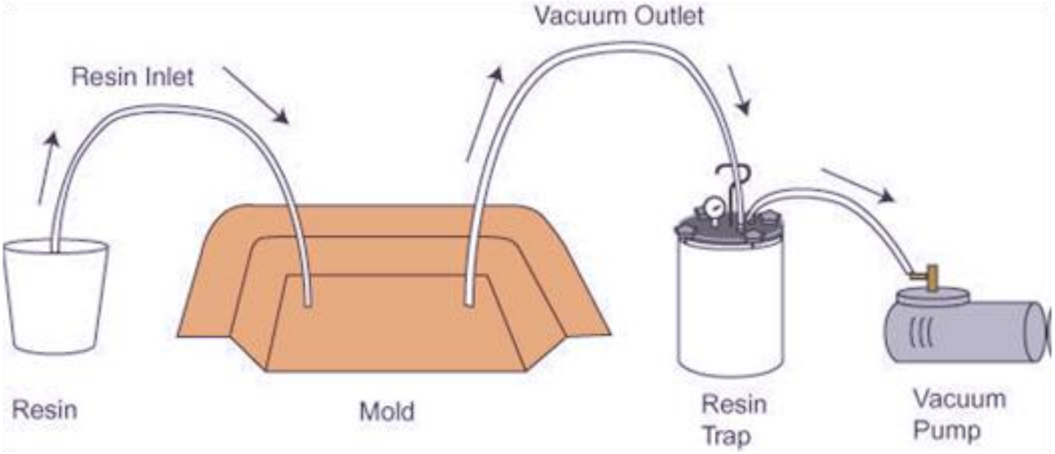

Figure 2.5: Vacuum infusion system

A helpful tool is a leak-flow indicator between the resin trap and the vacuum pump to insure us of having a perfect sealed bag [fig. 2.7]. If the bag has a leakage, the leak-flow indicator will spin.

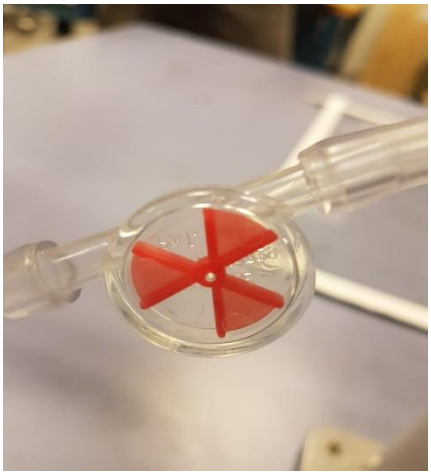

Figure 2.6: Leak flow indicator

2.4 AUTOCLAVE PROCESSING

Autoclave processing are used for manufacturing of high quality, complex parts. Autoclaves are high pressure valves [fig. 2.8] which provides a greater pressure than the vacuum technique, and gives greater compression. The gas is being introduced onto the bag externally inside the autoclave simultaneous as the temperature rises to initiate cure of the polymer [5].

Figure 2.7: Autoclave in "Krag" laboratory

2.5 Manufacturing at School Laboratory

At our composite laboratory at school, we can use vacuum infusion [section 2.3]. We have chosen the following materials to make our composite laminates for the frame.

Material	Type	Density, g/cm^3	Elastic Modulus, GPa	Tensile Strength, MPa
Matrix	SvaPox 110	1.10	3.5	84
Reinforcement	HexForce® 48600 1300	2.45	71	3000

Table 2.1: Material properties from data sheets

Summary vacuum infusion procedure

1. Prepare the mold
2. Large flange area to stick the sealant/bagging tape
3. Prepare the mold with release agent
4. Special vacuum bagging tape around the corners
5. Put layers of carbon
6. Tape to hold it in place
7. Infusion mesh ply with release film: helps the resin to get distributed through the part and stops the rest of the bagging set to stick to the part
8. Infusion spiral and resin feed silicone connector, extra infusion mesh for flow balance, vacuum line silicone connector
9. Vacuum bag itself: oversize bagging film to allow for pleating

2.5.1 Procedure in more details: manufacturing report

At first, we prepare the surface of flat mold (glass plate) with release agent and position bagging tape along the corners. Release agent provides smooth releasing of solidified composite product. In our laboratory, we use Loctite Frekote® 700-NC™. It offers excellent release properties for the most demanding applications and is a great all-purpose release agent. Frekote 700-NC releases epoxies, polyester resins, thermoplastics, rubber compounds and most other molded polymers. Then cut necessary carbon fiber mats and set then in order 90/45/45/90 as shown in figure 2.9.

Figure 2.8: Carbon fiber sheets

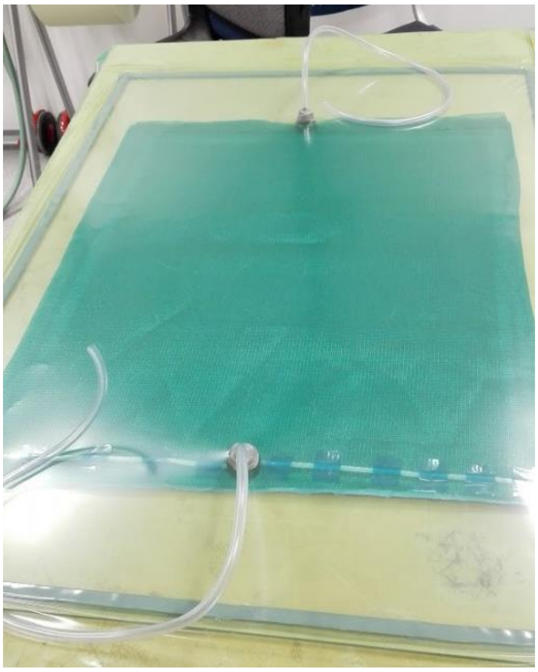

Figure 2.9: Bagging

We set a mesh ply with release film. It secures us a thorough resin infusion and ease of release process when composite is solidified. Then we position infusion spiral, resin feed silicone connector, extra infusion mesh for flow balance and vacuum line silicone connector and cover everything with vacuum bag as tight as possible [fig. 2.10]. There is no room for leakage.

When mixing the epoxy and hardener, we stir slowly in about 2 minutes. We have 70 minutes before the mixture start to harden. After that time, the mixture develops a chemical reaction and gets warm very quickly. The temperature gets as high as 160°C or more and it cannot be used.

Figure 2.10: Infrared thermometer

Then the mix is put in degassing process in a vacuum bulb to suck out all the air bubbles in the liquid. The air bubbles raise to the surface and pop. Elimination of bubbles secure least possible porosity of matrix. For the final composite, it results in higher strength.

Figure 2.11: Vacuum bulb

In our lab, we did not have the right hardener for this process, thus degassing process was not relevant. The problem was that vacuum could not get the air out because of the high viscose of the liquid. The hardener we supposed to use, a less viscous hardener which would have given us less surface tension, had to be ordered from Germany (D-hardener). Therefore, we had to continue with what we had (TL-hardener).

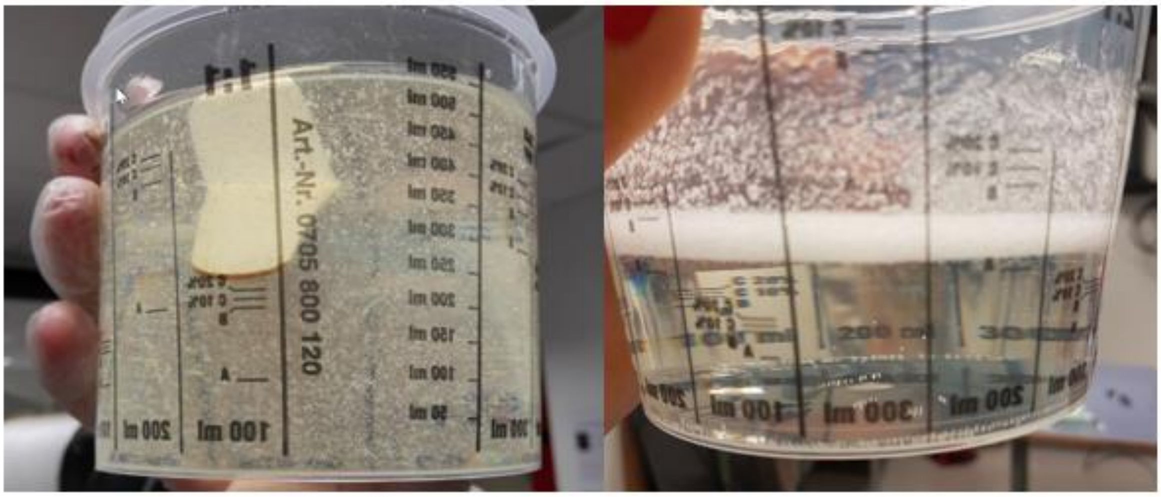

Figure 2.12: Epoxy mixed with hardener, formation of bubbles

Resin mixture is ready. Connectors are sealed tightly and we connect the vacuum pump and feed bucket with epoxy and hardener mixture.

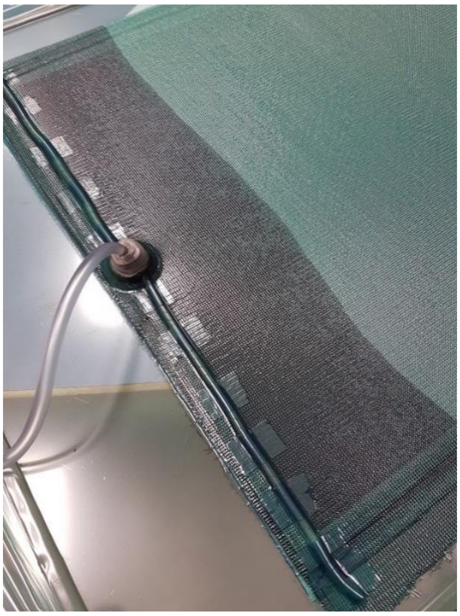

Figure 2.13: Vacuum infusion in process 1

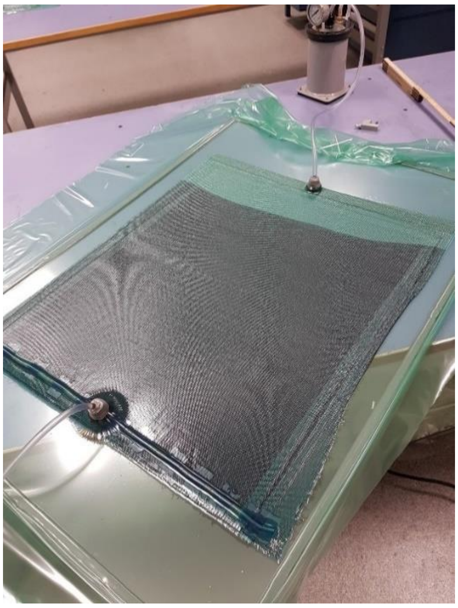

Figure 2.14: Vacuum infusion in process 2

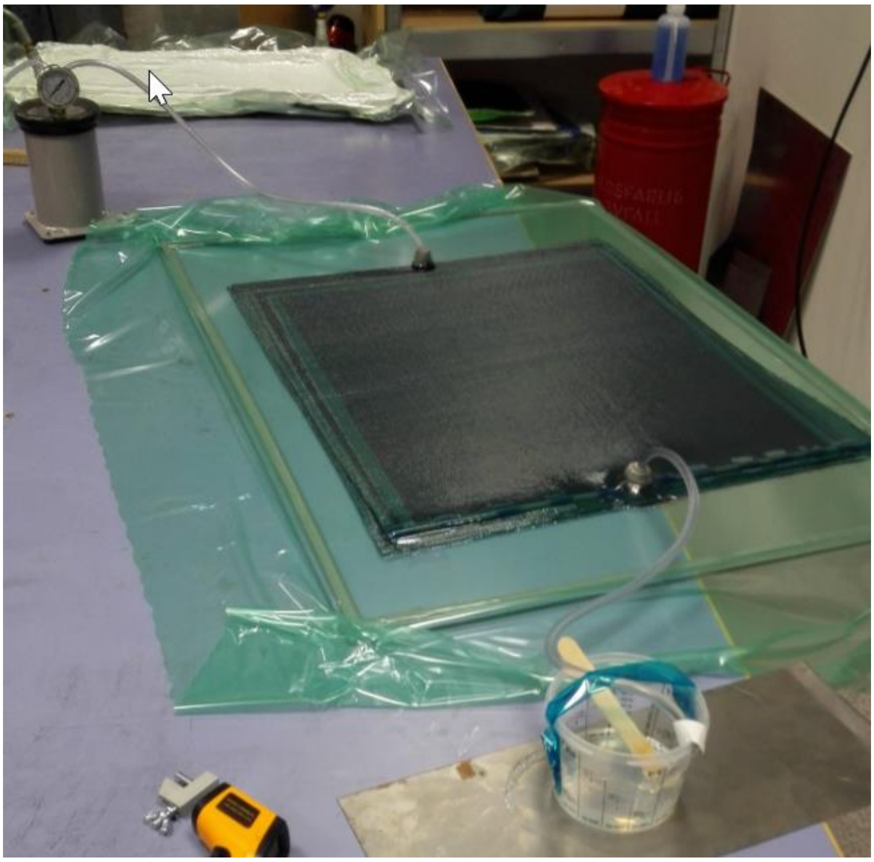

Figure 2.15: Vacuum infusion at a final stage

It took about 3 hours for the vacuum infusion to be completed. A bit more than expected, again because of a denser hardener. The resulting composite plate has become even better than expected with the following dimensions: 600x500x2.5 mm [fig. 2.17]. Perfect and even surface justifies that we followed the procedure as accurately as possible.

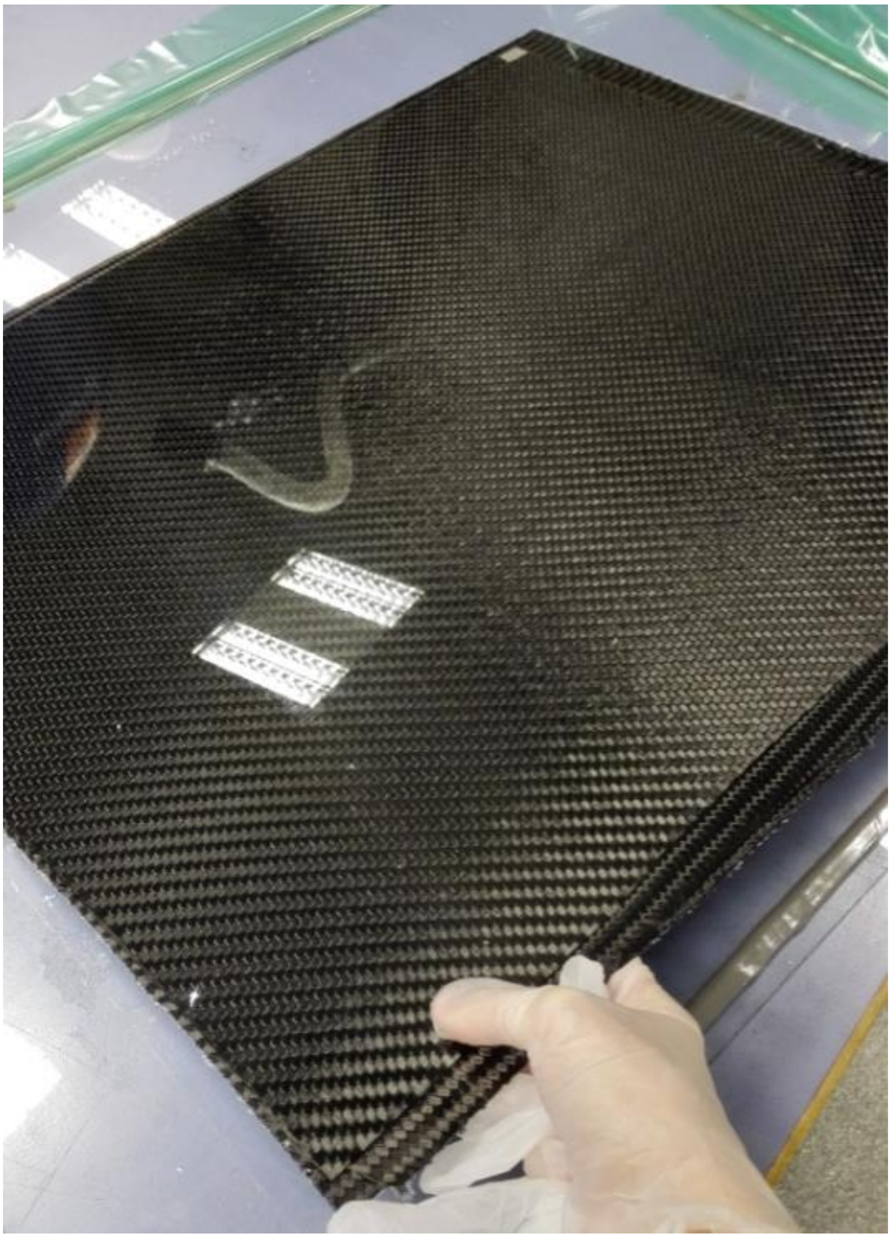

Figure 2.16: Composite plate after complete solidification

Right after release followed the process of cleaning and polishing the surface with a special polishing liquid.

2.5.2 PLATE CUTTING

The CNC machine has a maximum capacity of 20x30x25cm plates, so the composite must be cut into smaller pieces for the machine to operate them. To cut carbon fiber, we can use hacksaw, dremel, angle grinder and jigsaw, to mention some of the tools. The cutting tools should be made from diamond or tungsten carbide, or else the cutting would not be optimal for neither of the involved parts. The carbon fiber is a strong material so one can be damaging the cutting tool instead of cutting the composite plate. Diamond is the hardest natural material and is often used for cutting tools for this reason [6]. Unfortunate, there are limits in available tools in our laboratories. Only two tools were available with diamond blades; an angle grinder and a dremel. Figure 2.18 shows cuts with both dremel and angle grinder. With the dremel, we got a nice cut but did not go all the way through the plate, and with the angle grinder the cut was much coarser but we were able to go all the way through the plate for sure.

Figure 2.17: Cutting the carbon fiber plate with two different tools: a dremel and an angle grinder.

Since we will use the CNC machine to cut out our pieces, we decided to continue with the angle grinder, because the edges would be trimmed accorded to sketches in CNC machine afterwards.

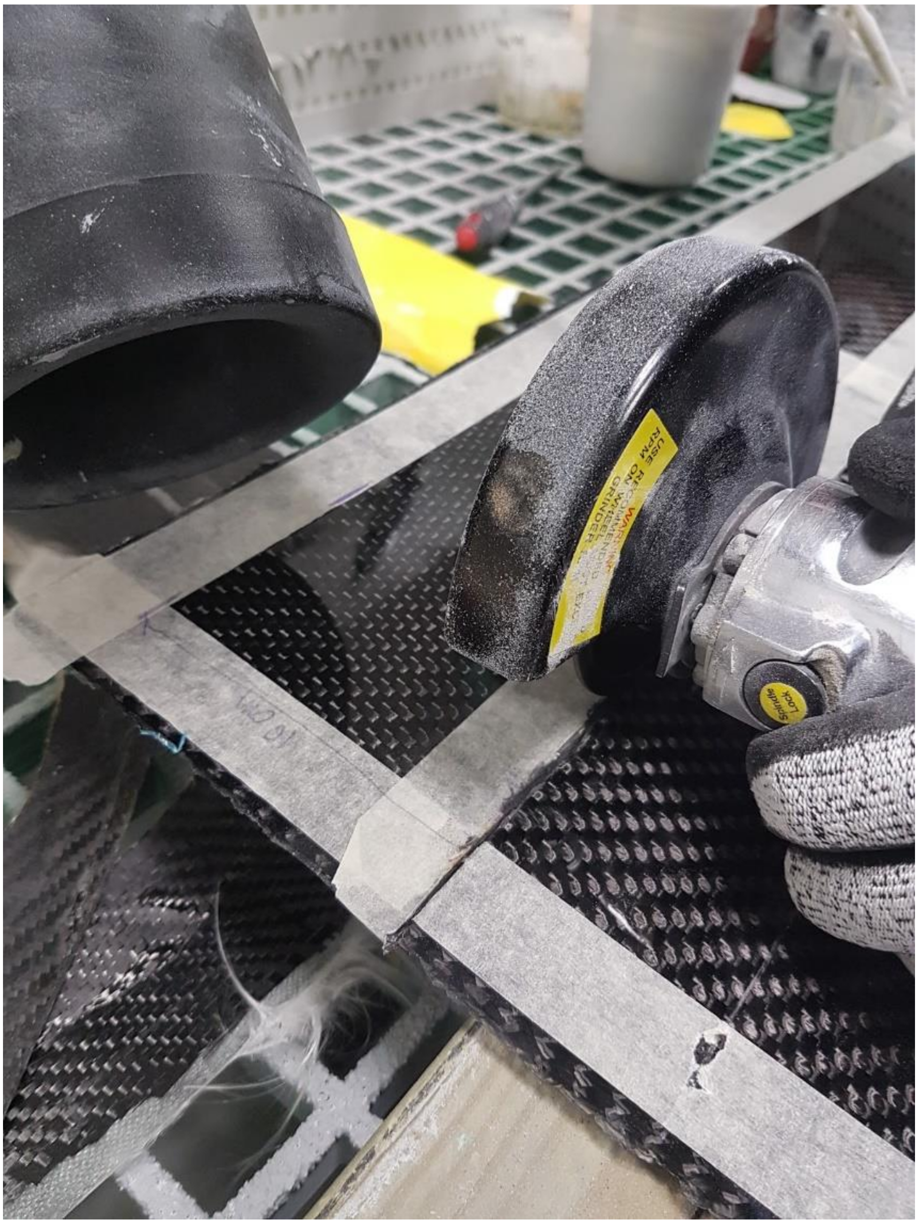

Figure 2.18: Trimming the carbon fiber plates into smaller pieces

2.6 CALCULATIONS

2.6.1 THEORETICAL CALCULATION OF STRENGTH AND RULE OF MIXTURES

We have received density, elastic modulus and tensile strength values from data sheets for materials [7]. All other necessary calculations can be made based on these data.

Material	Type	Density, g/cm^3	Elastic Modulus, GPa	Tensile Strength, MPa
Matrix	SvaPox 110	1.10	3.5	84
Reinforcement	HexForce® 48600 1300	2.45	71	3000

Table 2.2: Material properties from data sheets

At our composite laboratory at HSN we have chosen the following materials:

1. Matrix: epoxy + hardener (SvaPox 110 + hardener TL) (938.6+296.4)
2. Reinforcement: carbon fiber HexForce® 48600 1300

Tensile Strength is the maximum stress that a material can withstand, while being stretched, before if fails. Some non-brittle material distorts before breaking, but Kevlar, Carbon Fiber and E-glass are brittle and fail with almost no distortion. Tensile strength is measured in force per unit area: Pa or Pascals. Ultimate tensile strength or ultimate strength are terms also used.

Modulus of elasticity or Young's modulus is a measure of the stiffness of an elastic material and is one of the ways used to describe materials. It is defined as the ratio of the uniaxial (in one direction) stress over the uniaxial strain (distortion in the same direction).

Strain is the ratio of total deformation to the initial dimension of the material body, which is a dimensionless value.

$$E = \frac{\sigma}{\varepsilon}, where \qquad \text{I}$$

$E - Young\ modulus, GPa$

$\sigma - stress, MPa$

$\varepsilon - strain$

In other words, materials with a high Young’s Modulus are stiffer than materials with lower Young’s Modulus.

A high modulus of elasticity is sought when bending or deflection is not wanted, while a low modulus of elasticity is required when flexibility is needed. [8]

Composite stiffness can be predicted using a micro-mechanics approach termed the rule of mixtures [9].

Assumptions:

1. Fibers are uniformly distributed throughout the matrix
2. Perfect bonding between fibers and matrix
3. Matrix is free of voids
4. Applied loads are either parallel or normal to the fiber direction
5. Lamina is initially in a stress-free state (no residual stresses)
6. Fiber and matrix behave as linearly elastic materials.

What means that:

1. Hook's law applies:

   $\sigma = \varepsilon \cdot E$, tensile stress σ is linearly proportional to its fractional extension or strain ε by the modulus of elasticity E
2. Equal strain in materials, what means that we have a perfect bonding between matrix and fiber and both are strained to the same extent:

   $\varepsilon_c = \varepsilon_m = \varepsilon_f$
3. Static equilibrium requires that the total resultant force on the element must equal the sum of the forces acting on the fiber and matrix:

   $F_c = F_m + F_f$

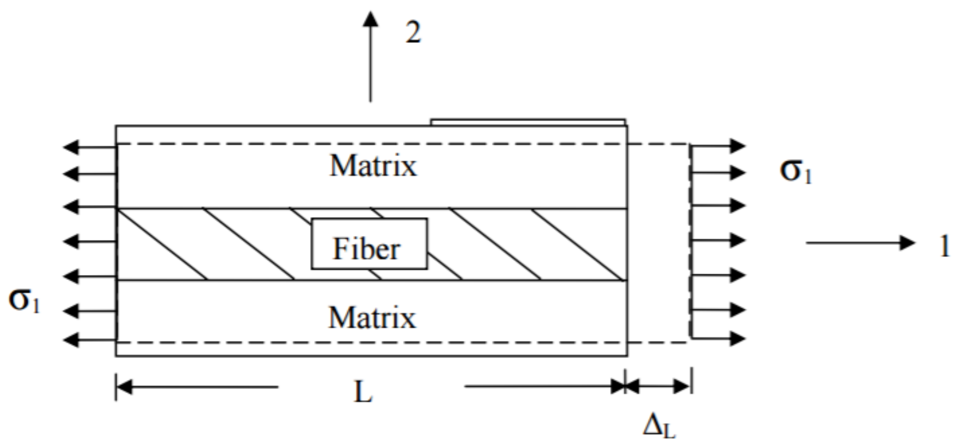

Figure 2.19: Longitudinal tensile strength on composite

$m_m = m_c - m_f = 1336 - 830 = 506\ g, where$

$m_m - mass\ matrix$

$m_f - mass\ fiber$

$m_c - mass\ composite$

Fraction of matrix in a composite material:

$$\frac{1336}{100} = \frac{830}{x}$$

$x = 62$ %

Recommended target for matrix content is 60%. Dry spots are weaker, that why resin content is higher than dry fiber content (that should be around 40%). Calculations show that we have hit the target very accurate.

$f_c = f_m - f_f = 38 + 62 = 100$ %

$F = \sigma \cdot A, where$ II

$\sigma - stress$

$A - cross\ sectional\ area$

$\sigma_c \cdot A_c = \sigma_m \cdot A_m + \sigma_f \cdot A_f$

If we divide the whole equation with A_c,we get the fraction (f) of each component and the following:

$\sigma_c \cdot A_c / A_c = \sigma_m \cdot A_m / A_c + \sigma_f \cdot A_f / A_c$

$\sigma_c = \sigma_m \cdot f_m + \sigma_f \cdot f_f$

So, theoretical tensile strength of a composite material is:

$\sigma_c = 84 \cdot 0.62 + 3000 \cdot 0.38 = 1192.1\ MPa$

When fracture values are known, it is easy to find modulus of elasticity also:

$E_c = E_m \cdot f_m + E_f \cdot f_f = 3.5 \cdot 0.62 + 71 \cdot 0.38 = 29.15\ GPa$

Besides we can calculate density and volume values:

$$V = \frac{m}{\rho}, where \quad \text{III}$$

$V - volume, cm^3$

$\rho - density,\ g/cm^3$

$$V_f = \frac{m_f}{\rho_f} = \frac{830}{2.45} = 338.8\ cm^3$$

$$V_m = \frac{m_m}{\rho_m} = \frac{1235}{1.10} = 1122.7\ cm^3$$

Overall density of the final composite:

$$\rho = \frac{m_m + m_f}{V_m + V_f} = \frac{1235 + 830}{1122.7 + 338.8} = 1.41\ g/cm^3$$

Material	Mass, g	Density, g/cm^3	Volume, cm^3	%	Elastic Modulus, GPa	Tensile Strength, MPa
Matrix	1235	1.10	1122.7	62	3.5	84
Reinforcement	830	2.45	338.8	38	71	3000
Composite	1336	1.41	937.52	100	29.15	1192.1

Table 2.3: Material properties (from data sheets and calculations made)

Having done the calculations, we have received the reference tensile strength of the resulting composite sheet tensile strength.

2.6.2 Simulation of composite in SW

We have made a simulation of composite arms in 2 and 4 plies in SW to check whether composite arms can withstand stresses applied when accelerating vertically and hovering.

For a reference stress, we have used the actual weight of the drone and have assumed vertical acceleration of 1.7 m/s^2. The top and bottom edges of the arms are going to be subjected to this type of load – presser load along the edge face. Stress is a bit higher for the arm with 2 plies, as the cross-sectional area is smaller.

$$\sigma = \frac{F}{A} = \frac{3kg \cdot 1.7m/s^2}{2.5 \cdot 300\, mm^2} = 6.8 \cdot 10^{-3}\, N/mm^2 = 0.0068\, MPa, \text{ arm with 4 plies}$$

$$\sigma = \frac{F}{A} = \frac{3kg \cdot 1.7m/s^2}{0.625 \cdot 2 \cdot 300\, mm^2} = 0.0136\, N/mm^2 = 0.0136\, MPa, \text{ arm with 2 plies}$$

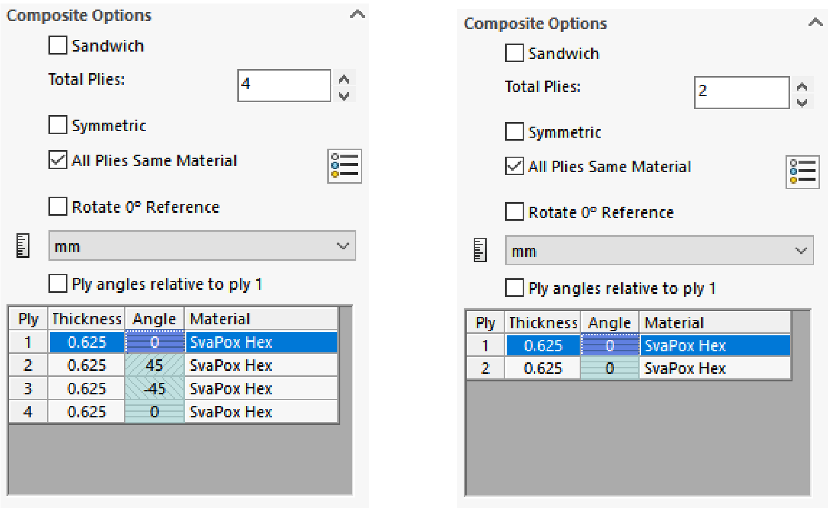

Figure 2.20: Composite with 4 and 2 plies SW

The simulation for the arm with 4 plies has shown [fig. 2.22] that the stresses the part is subjected for are spread in the range 0.008604 MPa to 0.005166 MPa.

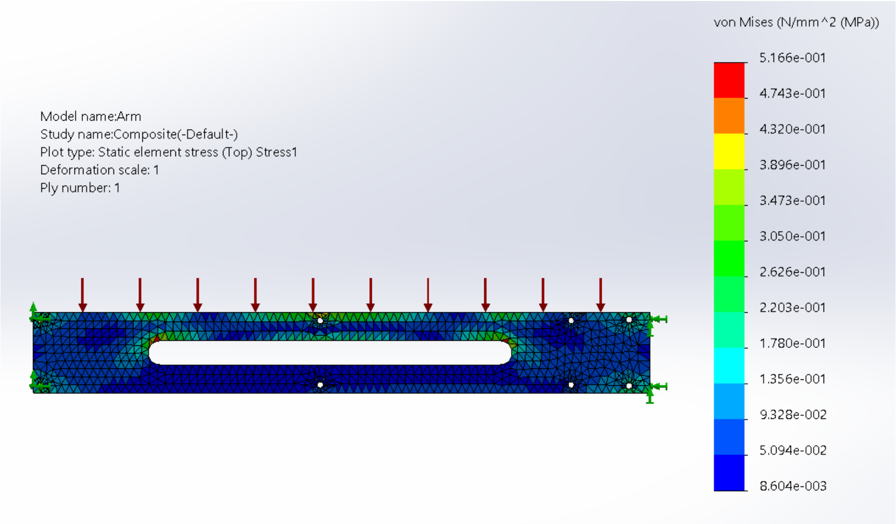

Figure 2.21: Simulation with 4 plies

The same simulation has been performed with 2 plies [fig. 2.23]. The stress results give the following values: 0.01721 - 1.033 MPa. These values are vastly smaller than composite strength previously calculated - 1192.1 MPa. Meaning that arms made in carbon are very strong for our system with 4 and 2 plies as well.

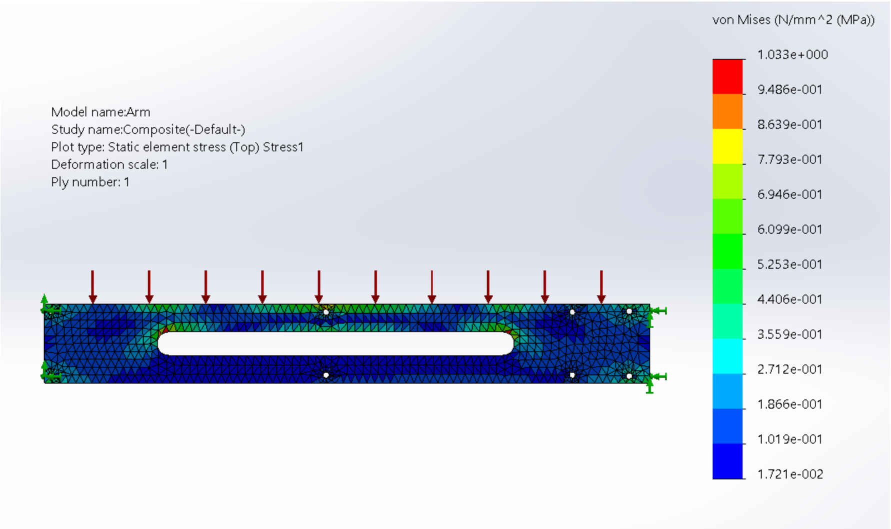

Figure 2.22: Simulation with 2 plies

2.7 MACHINING OF CARBON FIBER

Machining of carbon fiber is generally done with a router; however, standard metal machining methods can be used.

There are some details which should be taken into account when cutting carbon fiber. Machining carbon fiber requires higher spindle speeds than metals, but lower feed rates. The feed rates need to be adjusted to minimize the heat in the part while machining. Carbon fiber has a low thermal conductivity and the majority of the heat remains in the part since there are no chips to help dissipate the heat when machining. This heat from cutting can cause damage to the resin. Since coolant might not be permitted when machining carbon fiber, the tool path and tool must be used to control the heat in the part while machining. Additionally, fracturing of the fibers creates considerable abrasion on the cutting tool, so special tooling is required when machining carbon fiber.

Due to the features described above, cutting carbon fiber in CNC machine at school was very questionable, though we were advised to do so.

Another thing was delamination. Carbon fiber is abrasive and will wear down tools quickly. When a tool loses its sharpness, it can catch fibers and pull them from the part instead of cutting them. To avoid this, tool life must be monitored during machining as cut quality will decrease quickly. The best way to do this is to monitor the machining time on the tool and change it before it becomes dull.

There are several types and shapes of cutters for different applications, but they are generally made from two materials: carbide and polycrystalline diamond (PCD). Carbide provides good wear resistance, but is more applicable to smaller jobs. PCD cutters offer better wear resistance and are the cutter of choice for several composites machine shops. However, the benefit of PCD cutters does come at a significantly higher cost compared to carbide.

Diamond coated grinding wheels are also a staple of the well-rounded composite machine shop. They allow precise dimensional control, reasonable tool life-expense ratio, and effective heat management [10].

2.8 CNC CUTTING OF COMPOSITE: FIRST TRIAL

As a test, we cut a standard test specimen from our self-produced composite, to see the results from the CNC machine. In the first attempt to produce the quadcopter airframe, we wanted to machine the designated parts out of carbon fibre composite plates on a CNC machine.

2.8.1 HARDWARE

CNC is an abbreviation for Computer Numerical Control. CNC machines are used for data management of drills, grinders, welding machines, mills and the like in mechanical workshops. A CNC operator uses a computer to control mechanical machines to process material [11].

Figure 2.23: CNC machine

The available CNC milling machine at the university college of Southeast Norway, Campus Kongsberg, is the HAAS super mini mill [fig. 2.23]. This is a compact vertical machining centre ideal for schools and small shops. Standard features of the super mini mill include a 10000 rpm spindle, 15 hp (11.2 kW) vector drive, belt drive, coolant pump kit with 151 litre tank, 1 GB program memory and a high speed tool changer capable of holding 10 tools. The milling area is 40x30x25cm [12, 13].

Since none of the group members has training on, or are qualified CNC operators, the machine had to be operated by Richard Thue. In general, the CNC operator's job includes [11]:

- Receiving materials
- Plan the work, for example, by selecting cutting tools and cutting data
- Perform maintenance of the machines
- Participate in the development of new products and production processes

We still had to provide the computer program used to control the machine and plan the execution of the milling of the carbon fibre parts, including how the stock material should be clamped.

2.8.2 SOFTWARE

To produce the computer program for the CNC machine we downloaded and installed a software called HSMWorks, provided by Autodesk. HSMWorks is a Computer-aided manufacturing (CAM) solution for Solidworks, that is integrated as an add-in inside the

Solidworks design environment [14]. The software lets us use the familiar graphical user interface(GUI) of Solidworks to generate toolpaths, choose tools, adjust feed rates and more.

2.8.3 SETUP

According to general recommendations for machining carbon fibre composite we set up the CAM job with a feed rate (how fast the tool is translated in the xy-plane) of 500mm/min, a plunge rate(how fast the tool is translated in the z direction) to 50mm/min, and a spindle rate(how fast the tool spins) to 9000 rpm. For our first attempt the machine was equipped with a 3mm high speed steel (HSS) end mill, and a 3mm HSS drill. To make sure the tools was going all the way through the stock 2.5mm composite plates, a bottom offset of -0.5mm was added to the plunge rate. The compensation type was set to “on computer” allowing adjustments to be made on the HAAS Super mini mill media display, if desired by the operator. Stock material was also added to the Solidworks model to aid in visualizing the part before machining, and placement of the clamps.

When the setup was complete, the software lets you simulate the resulting machining operation, making it easy to visualize the process. Figures show the partially finished [2.24] and finished [2.25] simulation of the toolpaths necessary to machine one arm of the quadcopter frame. Note how the green stock material is removed during the operation to produce the part.

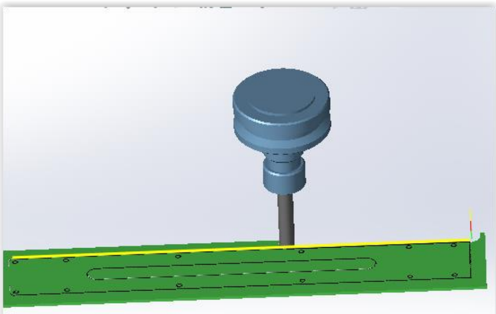

Figure 2.24: Simulation of toothpaths

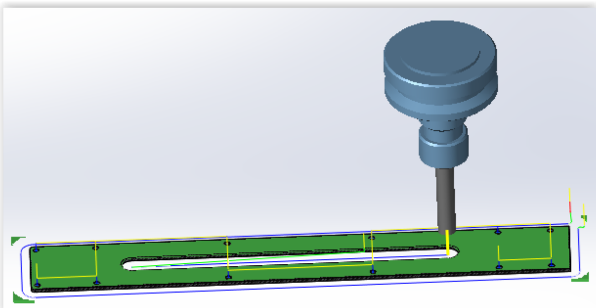

Figure 2.25: Simulation of toothpaths

When we were happy with the simulation, the postprocessor of the HSMWorks software compiled the CAM setup to a program in G-code [fig 2.26 shows part of the g-code for the test specimen].

G-code, which has many variants, is the common name for the most widely used numerical control (NC) programming language. It is used mainly in computer-aided manufacturing to control automated machine tools like a CNC machine [15]. “G-code is a language in which people tell computerized machine tools how to make something. The "how" is defined by instructions on where to move, how fast to move, and what path to follow. The most common situation is that, within a machine tool, a cutting tool is moved according to these instructions through a toolpath and cuts away material to leave only the finished workpiece” [15].

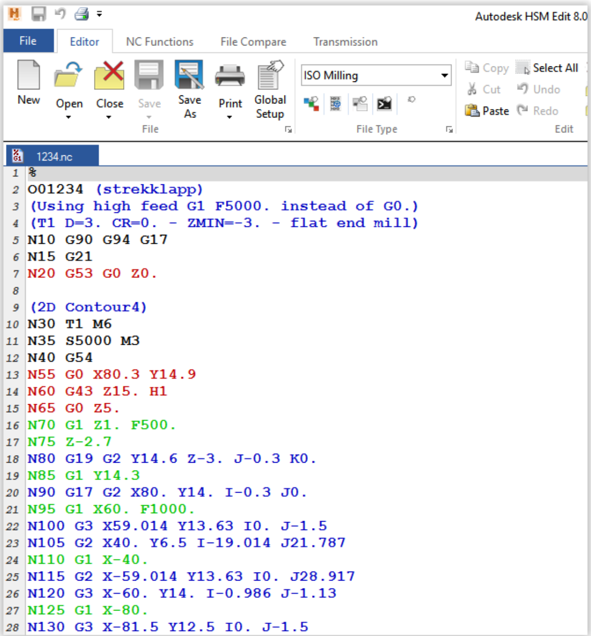

Figure 2.26: CAM setup to a program in G-code

To make sure our settings were right and the tool [fig. 2.27] could do the job, we first tried to machine a test specimen. To prevent damage to the machining table, a plate of machinable plastic was laid down, before the composite plates was clamped in a sturdy position, and the job was initiated.

Figure 2.27: High-speed steel end mill

The end mill we have available is made of high-speed steel without any coating. A general rule for cutting composite is that special coating is necessary, but we do not have such tools at school and they are quite expensive. So, we decided to try with this end mill. We were not so thrilled with the outcome.

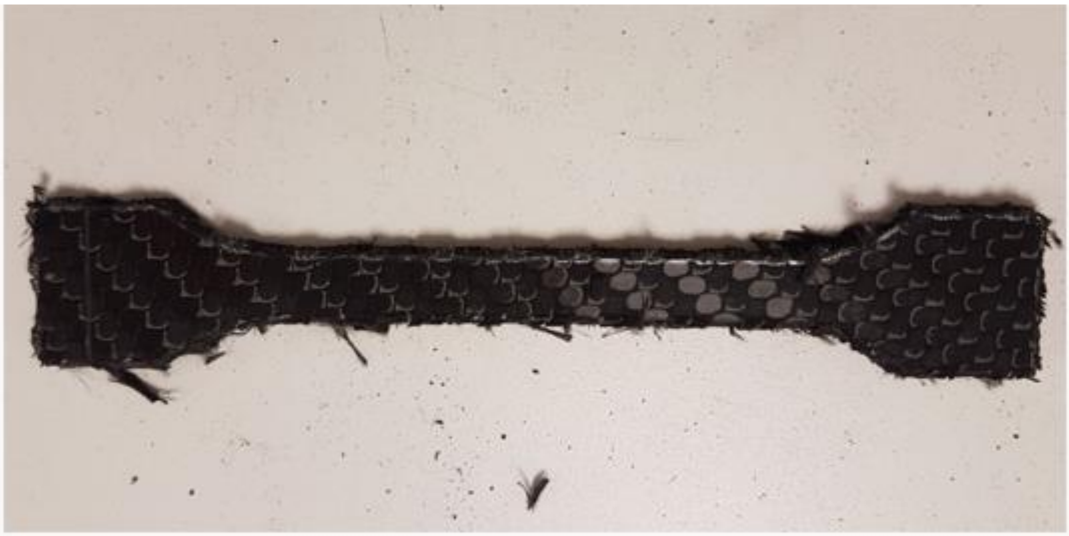

Figure 2.28: First trial with high-speed steel mill

Even though everything looked fine when the machine was running, a closer inspection afterwards revealed a very unsatisfying result, with lots of fibre pull out and delamination. This was probably a result of the type of cutting tool used, in this case a HSS end mill as mentioned above. A second attempt was made a couple of days later with mills provided by Kongsberg Defence and Aerospace, but this attempt was not satisfactory either.

2.8.4 External companies

As a backup plan for the frame, we have a few options to choose between and they can easily be manufactured by the laser cutter. But first we wanted to explore some other options to make our carbon fiber quadcopter realized.

We have been in contact with "Kongsberg Defence & Aerospace AS" (KDA) and they could supply us with composite cutting tools. Since 1992, KDA has produced parts in complex composite materials and build up technology on prepreg-composites.

They wanted a negotiation about the diamond coated cutting tools with our laboratory responsible in HSN. We have been informed that the diamond coated cutting tools they use in manufacturing, cost about 9000 NOK per item and last for 13 minutes, then the cutting tools get replaced with a new one and discarded.

Figure 2.29: Mills from KDA

So, we have received some tools KDA have used to cut composite materials. We decided to try them in our CNC. These tools have no datasheets, as they were taken from disposal box. But we have found out using numbers on the tools, that some of them are made from carbide. Carbide provides good wear resistance and is more applicable to smaller jobs, so that suited or purpose.

2.8.5 CNC CUTTING OF COMPOSITE: SECOND TRIAL

In the second trial test, we have tried one of carbide cutting mills.

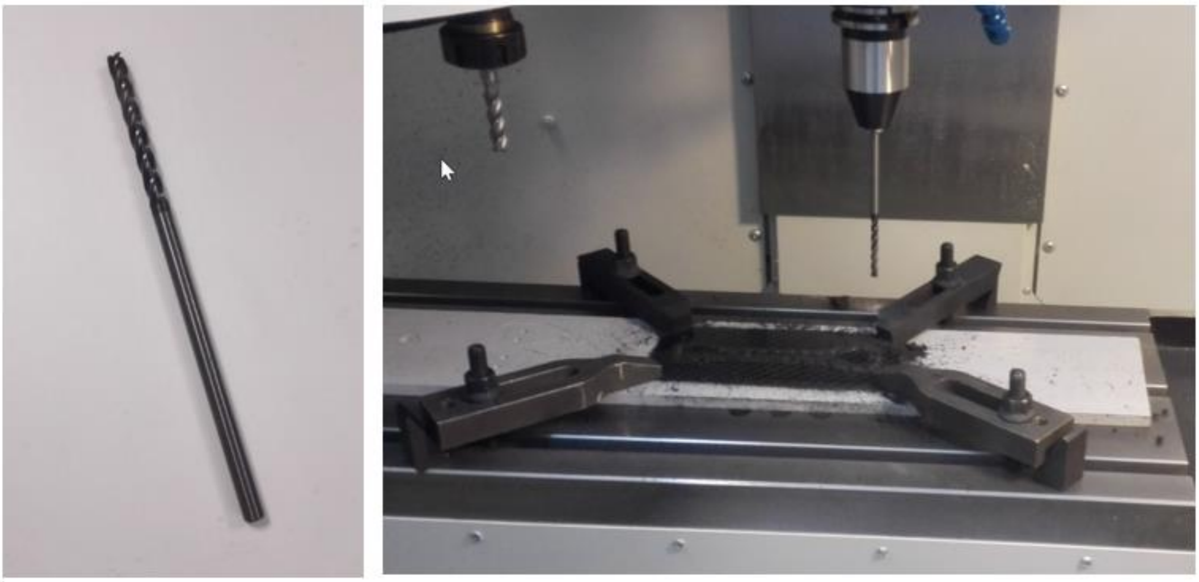

Figure 2.30: Carbide cutting end mill from KDA

Carbine mill was adjusted in the machine and we received the following result:

Figure 2.31: Second trial with carbine mill

We can see that the fibers were drawn from the matrice. The reason for this can be, as discussed above, that carbon fiber is abrasive and will wear down tools quickly. The tools we received were worn out. When a tool loses its sharpness, it can catch fibers and pull them from the part instead of cutting them.

2.9 CARBON FIBER – NOT GIVING UP YET

Simultaneous as we work with the Plexiglas frame, we will be working with our composite frame – by hand. We have put a lot of effort in the carbon fiber and will not let it go to waste, yet.

First, the quadcopter plates were cut out in MDF by the laser cutter, as a template for the desirable design. Then we used double sided tape to clone the design on the composite plate. The holes were cut out first, with the MDF plate on the top and the outlines were peeled into the carbon fiber.

Figure 2.32: Boring holes

Figure 2.33: Cutting plate with jigsaw

With the samples from the MDF plate trimmed in the laser cutter, a jigsaw was used to cut the carbon fiber in the desired measurement. Then the sides and corners were trimmed with sandpaper.

Figure 2.34: Grinding the plates with sandpaper

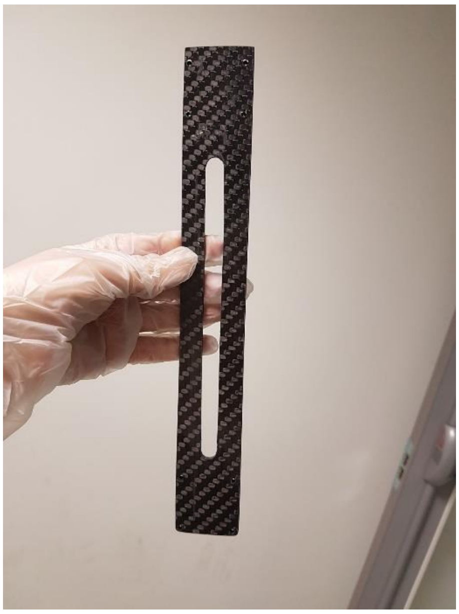

Figure 2.35: Carbon fiber shape

We are satisfied with the result, but the carbon arms are not accurate enough for the components to fit together. It will be time-consuming to make the parts accurate.

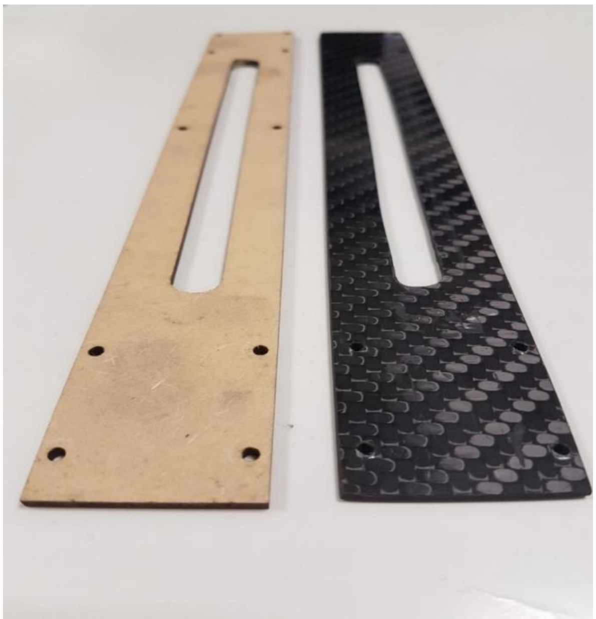

Figure 2.36: MDF and carbon fiber arms

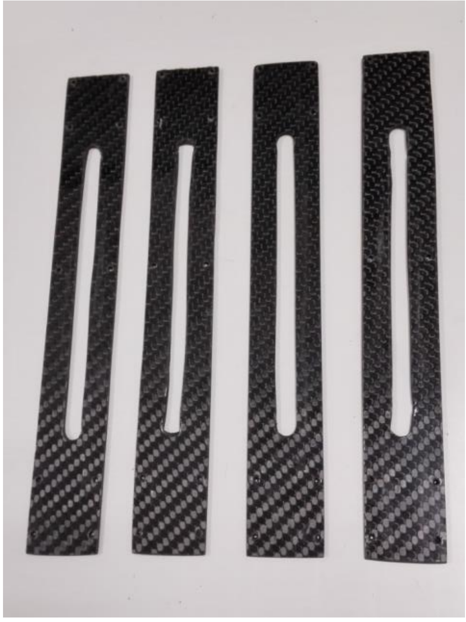

Figure 2.37: Carbon fiber arms

Summarizing the results of these 3 trials with composite plates, the project group have decided not to proceed with carbon fiber composite. Although we had belief in this material both due to its strength to weight ratio and appearance, manufacturing and cutting of composite materials demand special tools and experience.

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[15] https://en.wikipedia.org/wiki/G-code

System Test Plan

Project Name	Unified Collective Pitch Quadcopter
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Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Joakim Thorvaldsen, Severin Myhre, Daniel Christian Torsvik

TABLE OF CONTENTS

1 ABSTRACT

The System Test Plan is a document that describes how we plan to test and evaluate our system to make sure it meets its requirements. The test and evaluation (T&E) of a system, is generally referred to as qualification and/or verification and validation (V&V). The purpose and goal of the System test plan is to make sure that every requirement in the project is tested and documented

2 DOCUMENT STRUCTURE

2.1 DOCUMENT HISTORY

Version	Date	Description	Author
2.0	23.03.2017	System test specification completed	Severin, Daniel Christian
2.1	21.04.2017	Formatting, proofreading, figures added, priorities updated in tests, test tables updated. T04, T05, T26 updated	Severin, Daniel Christian
2.2	12.05.2017	Test Result template added, added Abbreviations and Acronyms, formatting figure names. Completed test T01, T02	Daniel Christian
2.3	13.05.2017	Added a template for every test, ready for test reports. Completed test T08, T17, T19, T29, and T35. Formatting.	Severin
2.4	15.05.2017	Completed test T11, T20, T21, T27	Severin, Daniel Christian
2.5	18.05.2017	Completed test T05, T06, T07, T25. Formatting.	Severin
2.6	19.05.2017	Completed test T04, T22, T28. Formatting.	Severin, Daniel Christian
2.7	20.05.2017	Completed test T12, T23, T26.	Joakim, Severin
2.8	21.05.2017	Completed test T31, T10, T32, T34, T03, T09, T24. Formatting. Added text and test result template to chapter 4	Daniel Christian
2.9	23.05.2017	Completed test T16, T15, T14, T13, T18. T30, T33. Added Chapter 7, together with figures. Appendix A & B are now to separate documents	Daniel Christian
2.10	23.05.2017	Proofreading test doc+appendix A and B. Changed partially passed to partial failure.	Joakim
3.0	23.05.2017	Final release	Joakim, Daniel Christian, Severin

2.2 Abbreviations & Acronyms

A & A	Explanation
CI	Configuration Items
COTS	Commercial Off the Shelf
HSN	University College of Southeast Norway
RVM	Requirements Verification Matrix
SE	Systems Engineering
SRD	System Requirements Document
T&E	Test and Evaluation
TBD	To Be Determined
TBR	To Be Resolved
V&V	Verification and Validation
EM	Electrical Motor
ICE	Internal Combustion Engine
RC	Radio Controller
MMS	Modular Motor System
NA	Not Applicable
FEA	Finite Element Analysis
FOS	Factor of Safety

3 Verification and Validation

Several systems engineering books define the words testing, verification and validation, but few as simple and elegant as Terzi [1] (p. 117-118)

"***Testing*** is an activity undertaken by using well-established procedures to obtain detailed measurements and data about the performance or characteristics of the product, its systems, subsystems, or components. The collected test data are analysed to determine if the product, its systems, subsystems, or components meet their stated requirements (i.e., specified during the design process) Thus, a test can be conducted at the product, system, subsystem, or component levels to determine if one or more of the requirements at its corresponding level are met. A test can be performed by using computer models, simulations, prototypes, or physical working samples of the hardware representing the product, its systems, subsystems, or components. Testing methods can be used for verification or validation purposes."

Further Terzi [1] (p.118) gives a very good definition of verification and validation;

"***Verification*** is the process of confirming that the product, its systems, and its components meet their respective requirements. The aim of the verification is to ensure that the tested item (product, its system, subsystem, or component) is built right, that is, it meets its requirements.

Validation, on the contrary, is the process of determining whether the product functions and it possesses the characteristics as expected by its customers when used in its intended environments. The aim of the validation process is to ensure that the right product is designed and the product can be used and liked by its intended customers."

These definitions of testing, verification and validation will be the basis for our project group in this project.

Several systems engineering sources defines the common methods for T&E, where the word method can also be interpreted as test or type of test. The methods are Inspection, Analysis and Simulation, Instrumented test, Demonstration or Field Test, and Certification.

Following is a short description of the different methods used in verification and validation: (First four from Buede [2] p.361, last one from Engel [3] (p.66))

- ***Inspection***; is a static test where you compare system attributes to requirements
- ***Analysis and Simulation***; is the use of models that represent some aspect of the system. (in our case Solidworks simulation and/or Simulink)
- ***Instrumented test;*** is the use of instruments to measure the system's outputs. (e.g. a calliper or weight)
- ***Demonstration or Field Test***; is to exercise the system in front of reviewers in expected system environment. (E.g. final flight test)
- ***Certification***; verification based on a signed certificate of compliance (from the producer) stating that a delivered item is a standard product. (typically for a commercial of the shelf product(COTS))

4 DOCUMENTATION PROCEDURE

All project requirements' needs verification and validation testing. For each test, we have a System test specification, and all tests should be accompanied by a test report so that the test itself can be verified. In some cases, the system test specification itself can be sufficient to document the test.

A system test specification template has been made to describe each test. Please note that the same template will be used to describe both verification and validation tests.

Test specifications can be found in appendix A, while the accompanied test results to each test specification can be found in appendix B. In an effort to make it easy to understand which test result follow which test specification, each test got the same ID number at the end. E.g. Test ID T11 got a test result with Test Report ID TR11 where you can see a more detailed overview of the test result.

4.1 TEST SPECIFICATION TEMPLATE

REQUIREMENT TEST SPECIFICATION					
Test ID		Corresponding Requirement ID		Author	
Test Report ID		Priority		Test date	
Test performed by					
V&V Method					
Requirement description					
Test description					
Acceptance criteria					
Result					

Figure 4.1: Test Specification Template

4.2 TEST REPORT TEMPLATE

TEST RESULT					
Test Report ID		Corresponding Requirement ID		Result	
Corresponding Test ID		Priority		Test date	
Test performed by					
V&V Method					
Purpose					
Equipment					
Conclusion					

Figure 4.2: Test Report Template

4.3 TRACEABILITY

To trace the system requirements vs the verification and validation process we want to use a Requirements Verification Matrix (RVM) as proposed by (Engel [1] p.65-67)

		Verification Method						Verification Stage				
System Test ID	**Requirement traceability**	None	Analysis	Inspection	Demonstration	Test	Certification	Definition	Design	Implementation	Integration	Qualification
T01	C01			●					●			
T02	C02				●						●	
T03	C03				●						●	
T04	C04				●							●
T05	C05	●										
T06	C05.1			●								●
T07	C05.2					●					●	
T08	C05.3			●					●			
T09	C05.4				●							●
T10	C05.5				●							●
T11	F01		●						●			
T12	F01.1				●						●	
T13	F02				●						●	
T14	F02.1				●						●	
T14	F02.2				●						●	
T15	F02.1.1				●						●	
T16	F02.1.2				●						●	
T17	F02.3			●						●		
T18	F02.4				●						●	
T19	F03			●					●			
T20	F04			●						●		
T20	F04.1			●						●		
T21	F05			●						●		
T21	F05.1			●						●		
T22	F06				●						●	
T23	F07				●						●	
T24	F08				●						●	
T25	F09				●						●	
T26	F10					●					●	
T27	FC01				●					●		
T28	FC02				●						●	
T29	NF01			●					●			
T30	NF02					●					●	
T30	NF03					●					●	
T30	NF04					●					●	

System Test ID	Requirement traceability	Verification Method						Verification Stage				
		None	Analysis	Inspection	Demonstration	Test	Certification	Definition	Design	Implementation	Integration	Qualification
T31	NF08					●					●	
T32	NF13		●		●						●	
T32	NF14		●		●						●	
T33	NF15		●								●	
T33	NF16		●								●	
T34	NF17			●						●		
T35	NF20			●						●		

Figure 4.3: Requirement Traceability

Following is a description of the elements in the RVM derived from (Engel [3] p.66-67):

- *Requirement ID*: Identification number for each test requirement
- *Requirement Traceability*: Traceability to an appropriate document, and or specific requirement.
- *Verification method*: Typically, there are five types of verification methods:
  - Analysis
  - Inspection
  - Demonstration
  - Test
  - Certification

In addition, “no verification” is also an option in the RVM. For a more detailed description of the verification methods please refer to section on verification and validation. (See section 5)

The RVM can also refer to the validation of a system but a separate validation requirements matrix might be added later, to better ensure validation traceability.

5 TEST STRATEGY

The project group have decided to go for a combination of top-down and bottom-up testing in accordance with the CAFCAR+ model.

Buede [2] (p.351) specifies the top-town verification and validation process as "Top-down integration begins by examining the top-level core of the system, is followed by adding major components to this core and testing, and ends by adding the individual configuration items (CI) to the cores of the components and testing."

Based on this we believe that the top-down approach can be very useful on an early stage in the design process, using analysis and simulation tools like SolidWorks simulation and Simulink. Some variant of Black box testing might be implemented when using this strategy.

When it comes to bottom up testing Buede [2] (p.346) writes: "a bottom-up process that combines multiple CIs into components, and multiple components into subsystems, and multiple subsystems into the system. At each level of integration, the appropriate interfaces and models of the external systems, components, and CIs must exist for this subset of the system. These interfaces and models are stimulated by defined sets of inputs and tested to determine if the appropriate outputs are obtained. In addition, the physical combination of the CIs, components, or subsystems is examined to determine that the fit of these system elements is acceptable."

As the inner workings and modules of the system are mapped White box testing and interface testing are applicable tools in the bottom-up process.

6 Resources

Following is a short description of resources necessary for testing, verification and validation of the system.

6.1 Facilities and Equipment

Available facilities for the evaluation i.e. testing, validation and verification of the system are the HSN laboratories at Kongsberg, namely the composite lab, machine/prototype lab and Dronesonen. Some testing might also be performed outdoor in a big open space e.g. behind the campus.

Following is a table of suggested tools, equipment and software necessary to perform various parts of the testing process:

Tools:	Equipment:	Software:
Scale	Safety net	SolidWorks
Baggage weight	Rope/string	Simulink
Vernier or digital calliper	Weights	Excel
Multimeter	Camera	
Stroboscope	Stopwatch	
Strain gauge	Measurement grid	
Torque wrench	Electrician tape	
Tool set		
Wrench		

Figure 6.1: Tools, Equipment and Software used in the testing process

7 Test Result Overview

Test ID & Test Result ID	Test Result	Test ID & Test Result ID	Test Result
T01 & TR01	Passed	T19 & TR19	Passed
T02 & TR02	Passed	T20 & TR20	Passed
T03 & TR03	NA	T21 & TR21	Passed
T04 & TR04	Passed	T22 & TR22	Passed
T05 & TR05	Partial Failure	T23 & TR23	Passed
T06 & TR06	Passed	T24 & TR24	NA
T07 & TR07	Failed	T25 & TR25	Passed
T08 & TR08	Passed	T26 & TR26	Passed
T09 & TR09	Passed	T27 & TR27	Passed
T10 & TR10	Passed	T28 & TR28	Passed
T11 & TR11	Passed	T29 & TR29	Passed
T12 & TR12	Passed	T30 & TR30	NA
T13 & TR13	NA	T31 & TR31	Passed
T14 & TR14	NA	T32 & TR32	Passed
T15 & TR15	Passed	T33 & TR33	Passed
T16 & TR16	Passed	T34 & TR34	Passed
T17 & TR17	Passed	T35 & TR35	Passed
T18 & TR18	Passed		

Figure 7.1: Test Result Overview

Passed	NA	Partial Failure	Failed
28 / 35	**5 / 35**	**1 / 35**	**1 / 35**

Figure 7.2 Test Results Divided into Categories

8 BIBLIOGRAPHY

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[2] Buede, D. M. (2009). The engineering design of systems: models and methods. Hoboken, N.J, Wiley.

[3] Engel, A. (2010). Verification, Validation, and Testing of Engineered Systems. Hoboken, Wiley.

[4] Revolution Board Setup, LibrePilot / OpenPilot, last updated May 2017, http://opwiki.readthedocs.io/en/latest/user_manual/revo/revo.html#technical-description

Appendix A: System Test Specification

REQUIREMENT TEST SPECIFICATION					
Test ID	T01	Corresponding Requirement ID	C01	Author	Severin
Test Report ID	TR01	Priority	A	Test date	11.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	The system shall have a single motor for propulsion				
Test description	Inspect the propulsion system				
Acceptance criteria	One engine is powering the system				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T02	Corresponding Requirement ID	C02	Author	Severin
Test Report ID	TR02	Priority	A	Test date	12.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	The system shall be able to use an electric motor for propulsion				
Test description	Demonstrate that an electric motor can power the drone				
Acceptance criteria	The propellers can be driven by an electric motor				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T03	Corresponding Requirement ID	C03	Author	Severin
Test Report ID	TR03	Priority	C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	The system shall be able to use an internal combustion engine for propulsion				
Test description	Demonstrate that an internal combustion engine can power the drone				
Acceptance criteria	The propellers can be driven by an internal combustion engine				
Result	NA				

REQUIREMENT TEST SPECIFICATION					
Test ID	T04	Corresponding Requirement ID	C04	Author	Severin
Test Report ID	TR04	Priority	A	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Requirement description	The system shall take-off and land vertically				
Test description	Demonstrate that the system can both take off and land vertically				
Acceptance criteria	The system can take off with zero translational velocity and land with less than 10 cm/s translational velocity				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T05	Corresponding Requirement ID	C05	Author	Severin
Test Report ID	TR05	Priority	C	Test date	18.05.2017
Test performed by	Severin Myhre				
V&V Method	None				
Requirement description	The system shall be compliant to CAA classification RO1				
Test description					
Acceptance criteria	All other RO1-related tests are passed				
Result	Partial Failure				

REQUIREMENT TEST SPECIFICATION					
Test ID	T06	Corresponding Requirement ID	C05.1	Author	Severin
Test Report ID	TR06	Priority	C-A	Test date	16.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Inspection				
Requirement description	The system shall be clearly marked with the operator's name and telephone number				
Test description	Inspect the system for the operator’s name and telephone number				
Acceptance criteria	The operator’s name and telephone number is clearly marked on the system				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T07	Corresponding Requirement ID	C05.2	Author	Severin
Test Report ID	TR07	Priority	C-A	Test date	16.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Instrumented Test				
Requirement description	The system's take-off mass shall be ≤ 2.5 kg				
Test description	The system is placed on a weight and its mass is measured				
Acceptance criteria	The system's mass is below 2.5 kg				
Result	Failed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T08	Corresponding Requirement ID	C05.3	Author	Severin
Test Report ID	TR08	Priority	C-C	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	The system shall be equipped with an instrument for measuring altitude				
Test description	Inspect the flight controller for an instrument capable of measuring altitude				
Acceptance criteria	The flight controller is equipped with an instrument capable of measuring altitude				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T09	Corresponding Requirement ID	C05.4	Author	Severin
Test Report ID	TR09	Priority	C-C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	Maximum speed shall not exceed 60 knots				
Test description	Fly the system at maximum translational velocity outdoors when the wind conditions are 1 or less on the Beaufort scale, and record maximum achieved velocity using a GPS module				
Acceptance criteria	Maximum speed of the system in relation to the air is below 60 knots				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T10	Corresponding Requirement ID	C05.5	Author	Severin
Test Report ID	TR10	Priority	C-C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	The system shall be equipped with a kill switch				
Test description	Demonstrate that the power to all propellers is terminated when the kill switch is activated				
Acceptance criteria	Power to the propellers is discontinued within one second of activating the kill switch				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T11	Corresponding Requirement ID	F01	Author	Severin
Test Report ID	TR11	Priority	A	Test date	14.05.2017
Test performed by	Severin Myhre				
V&V Method	Analysis				
Requirement description	The propeller blades shall be replaceable				
Test description	Analyse that the propeller blades can be inserted into and removed from the propeller mounting hub using CAD interference detection				
Acceptance criteria	The propeller blades can be replaced				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T12	Corresponding Requirement ID	F01.1	Author	Daniel Christian
Test Report ID	TR12	Priority	A-A	Test date	20.05.2017
Test performed by	Joachim Krøvel Vikanes, Severin Myhre, Joakim Thorvaldsen				
V&V Method	Demonstration				
Requirement description	A layman shall be able to replace a propeller blade within 2 minutes using only basic tools				
Test description	Have a person with no significant technical experience or education change a propeller blade, and measure time from start to completion using a stopwatch				
Acceptance criteria	The demonstrator replaces the propeller blade in under 2 minutes				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T13	Corresponding Requirement ID	F02	Author	Daniel Christian
Test Report ID	TR13	Priority	A	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	None				
Requirement description	The drive unit shall be changeable by a layman				
Test description					
Acceptance criteria	Test T14 is passed				
Result	NA				

REQUIREMENT TEST SPECIFICATION					
Test ID	T14	Corresponding Requirement ID	F02.1 & F02.2	Author	Daniel Christian
Test Report ID	TR14	Priority	A-A & A-C	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	A layman shall be able to change between propulsion systems $\leq$ 30 minutes A layman shall be able to change between propulsion systems $\leq$ 15 minutes				
Test description	Have a person with no significant technical experience or education change between propulsion systems, and measure time from start to completion using a stopwatch				
Acceptance criteria	The demonstrator switches between propulsion systems within 30 minutes and 15 minutes respectively				
Result	NA				

REQUIREMENT TEST SPECIFICATION					
Test ID	T15	Corresponding Requirement ID	F02.1.1	Author	Daniel Christian
Test Report ID	TR15	Priority	A-A-A	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik, Joachim Krøvel Vikanes				
V&V Method	Demonstration				
Requirement description	A layman shall be able to attach the power system assembly to the support structure within 15 min				
Test description	Have a person with no significant technical experience or education attach the power system assembly to the support structure and measure time from start to completion using a stopwatch				
Acceptance criteria	The demonstrator use less than 15 minutes to attach the power system assembly to the support structure				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T16	Corresponding Requirement ID	F02.1.2	Author	Daniel Christian
Test Report ID	TR16	Priority	A-A-A	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik & Thomas Huse				
V&V Method	Demonstration				
Requirement description	A layman shall be able to detach the power system assembly from the support structure within 15 min				
Test description	Have a person with no significant technical experience or education detach the power system assembly from the support structure and measure time from start to completion using a stopwatch				
Acceptance criteria	The demonstrator use less than 15 minutes to detach the power system assembly from the support structure				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T17	Corresponding Requirement ID	F02.3	Author	Daniel Christian
Test Report ID	TR17	Priority	A-A	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	The drive units shall be fastened with non-permanent fastening mechanisms				
Test description	Inspect the drive unit and check what type of fastening mechanism have been used				
Acceptance criteria	The drive unit can be removed without the use of power tools				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T18	Corresponding Requirement ID	F02.4	Author	Severin
Test Report ID	TR18	Priority	A-A	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	A layman shall be able to change between propulsion systems by using basic tools only				
Test description	Have a person with no significant technical experience or education change from electric to internal combustion propulsion systems and vice versa with only basic tools available				
Acceptance criteria	The system remains fully operational after the demonstrator has changed the propulsion system by using only screwdrivers, Allen keys and wrenches				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T19	Corresponding Requirement ID	F03	Author	Daniel Christian
Test Report ID	TR19	Priority	A	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	The system shall have a variable pitch mechanism				
Test description	Inspect the system for a mechanism for changing the pitch angles of the propeller blades				
Acceptance criteria	The system is equipped with a mechanism for altering the pitch angles of all propeller blades				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T20	Corresponding Requirement ID	F04 & F04.1	Author	Severin
Test Report ID	TR20	Priority	A & A-A	Test date	15.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	Screws shall comply with ISO standard Screws shall have either Phillips, Pozidriv or Hexagonal type sockets				
Test description	Inspect all screws and record their type and dimensions				
Acceptance criteria	All screws either have Phillips, Pozidriv or Hexagonal sockets, and their dimensions are in accordance with the ISO standard				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T21	Corresponding Requirement ID	F05 & F05.1	Author	Severin
Test Report ID	TR21	Priority	A & A-A	Test date	15.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	Bolts shall comply with ISO standard Bolts shall have either Phillips, Pozidriv or Hexagonal type sockets				
Test description	Inspect all bolts and record their type and dimensions				
Acceptance criteria	All bolts either have Phillips, Pozidriv or Hexagonal sockets, and their dimensions are in accordance with the ISO standard				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T22	Corresponding Requirement ID	F06	Author	Severin
Test Report ID	TR22	Priority	B	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Requirement description	The system shall be operable by one person				
Test description	Demonstrate flying the system three meters in the transverse direction by having one person operating the radio controller unassisted				
Acceptance criteria	The flight is performed without damage to the system or its surroundings				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T23	Corresponding Requirement ID	F07	Author	Severin
Test Report ID	TR23	Priority	C	Test date	20.05.2017
Test performed by	Thomas Huse, Severin Myhre, Joakim Thorvaldsen				
V&V Method	Demonstration				
Requirement description	The outdoor flight time with electric motor shall be ≥ 10 min				
Test description	Demonstrate hovering the system in an electric motor configuration outdoors from fully charged battery until battery charge is depleted, while measuring the time from take-off till landing				
Acceptance criteria	The time from take-off to landing is more than 10 minutes				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T24	Corresponding Requirement ID	F08	Author	Severin
Test Report ID	TR24	Priority	C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	The outdoor flight time with internal combustion engine shall be ≥ 30 min				
Test description	Demonstrate hovering the system in an internal combustion engine configuration outdoors until fuel is spent, while measuring the time from take-off till landing				
Acceptance criteria	The time from take-off to landing is ≥ 30 minutes				
Result	NA				

REQUIREMENT TEST SPECIFICATION					
Test ID	T25	Corresponding Requirement ID	F09	Author	Severin
Test Report ID	TR25	Priority	B	Test date	18.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Demonstration				
Requirement description	The system shall withstand a vertical free fall to a flat concrete surface on a parallel horizontal plane, from the height of 0,25 meters				
Test description	Drop the system onto a flat concrete surface that is on a parallel horizontal plane from a 0.25 meter altitude				
Acceptance criteria	The system is not damaged by the fall and no functionality is hampered				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T26	Corresponding Requirement ID	F10	Author	Severin
Test Report ID	TR26	Priority	C	Test date	20.05.2017
Test performed by	Thomas Huse, Severin Myhre, Joakim Thorvaldsen				
V&V Method	Demonstration				
Requirement description	The system shall have a payload capacity of at least 250 grams				
Test description	Fasten a 250 grams item to the system frame, and take off				
Acceptance criteria	The system takes off and lands with the payload attached				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T27	Corresponding Requirement ID	FC01	Author	Severin
Test Report ID	TR27	Priority	A	Test date	15.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Requirement description	Flight controller shall receive and interpret 2,4GHz signals from radio control transmitter				
Test description	Use a radio transmitter to send instructions to the system in the form of 2,4GHz radio signals while the system's flight controller is running				
Acceptance criteria	The system reacts to the signals				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T28	Corresponding Requirement ID	FC02	Author	Severin
Test Report ID	TR28	Priority	C	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Requirement description	The flight controller shall regulate pitch angles to the extent that a skilled operator can hold the system within 1 m^3 for 5 consecutive seconds				
Test description	Have a skilled or experienced drone operator fly the system indoors and instruct him/her to keep the system at a fixed hover point. Measure the time until the system has deviated 1 meter or more from the point in any direction.				
Acceptance criteria	It takes at least 5 seconds until the system deviates 1 meter				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T29	Corresponding Requirement ID	NF01	Author	Severin
Test Report ID	TR29	Priority	A	Test date	13.05.2017
Test performed by	Severin Myhre				
V&V Method	Inspection				
Requirement description	The system shall have a mechanical transfer of power to rotate propeller blades				
Test description	Rotate a propeller by hand and inspect if the remaining propellers rotate with it				
Acceptance criteria	All propellers rotate when rotating one propeller				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T30	Corresponding Requirement ID	NF02, NF03 & NF04	Author	Severin
Test Report ID	TR30	Priority	A / B / C	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Instrumented Test				
Requirement description	A mechanical power transmission shall transfer power from motor to rotors with no less than NF02: 70% efficiency, NF03: 80% efficiency, NF04: 90% efficiency				
Test description	Remove the propellers and the motor assembly and apply 0.1 Nm torque to the motor shaft. Use a Torque meter to measure the output torque on one of the propellers.				
Acceptance criteria	Torque in divided by torque out is above 0.7, 0.8 or 0.9				
Result	NA				

REQUIREMENT TEST SPECIFICATION					
Test ID	T31	Corresponding Requirement ID	NF08	Author	Severin
Test Report ID	TR31	Priority	A	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik & Thomas Huse				
V&V Method	Instrumented Test				
Requirement description	The system's thrust to weight ratio shall be ≥ 2:1				
Test description	Use rope to fasten the system's airframe to a scale. Fly the system at maximum power and record simulated mass on the scale				
Acceptance criteria	The measured weight on the scale is above the weight of the system				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T32	Corresponding Requirement ID	NF13 & NF14	Author	Severin
Test Report ID	TR32	Priority	A	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Instrumented Test and Analysis				
Requirement description	Screws and bolts shall withstand 10 hours of flight induced vibrations without unscrewing				
Test description	Use a torque meter to measure the torque required to unscrew five bolts and five screws after the system has been through the previous flight tests. Apply this data to numerical analysis and computer simulation to predict whether the screws and bolts will unscrew or not				
Acceptance criteria	Neither screws nor bolts are predicted to unscrew				
Result	Passed (With the use of different V&V Method)				

REQUIREMENT TEST SPECIFICATION					
Test ID	T33	Corresponding Requirement ID	NF15 & NF16	Author	Severin
Test Report ID	TR33	Priority	B & A	Test date	23.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Analysis				
Requirement description	The support structure shall have a factor of safety ≥ 1,5 The support structure shall have a factor of safety ≥ 2				
Test description	Run a static stress analysis of the airframe using CAD simulation, applying stresses the system will be subjected to when falling at a 10-degree angle from a height of 0.25 meters to a flat concrete surface				
Acceptance criteria	Factor of safety is above 1,5 and 2 respectively				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T34	Corresponding Requirement ID	NF17	Author	Daniel Christian
Test Report ID	TR34	Priority	C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Inspection				
Requirement description	The support structure shall be able to hold both modular motor systems (MMS)				
Test description	Show either in SolidWorks or on the prototype, that the support structure can hold both MMS by attaching them to the drone. This is done by attaching them separately and one at the time. The support structure shall be able to carry one of the MMS, and not both at the same time				
Acceptance criteria	The support structure can hold both MMS, but not necessarily at the same time.				
Result	Passed				

REQUIREMENT TEST SPECIFICATION					
Test ID	T35	Corresponding Requirement ID	NF20	Author	Severin
Test Report ID	TR35	Priority	A	Test date	13.05.2017

Test performed by	Severin Myhre
V&V Method	Inspection
Requirement description	The power storage shall be fastened to the power system assembly without the use of tools
Test description	Inspect how the battery is fastened to the electric motor configuration and how the fuel tank is fastened to the internal combustion engine assembly
Acceptance criteria	The battery and fuel tank respectively are fastened to the system in a manner where they require no tools to be unfastened
Result	Passed

APPENDIX B: TEST RESULTS

TEST RESULT					
Test Report ID	TR01	Corresponding Requirement ID	C01	Result	Passed
Corresponding Test ID	T01	Priority	A	Test date	12.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Check that the quadcopter is powered by only one motor/engine				
Equipment/Tools/ Software	Camera				
Conclusion	By visual inspection we can confirm that the mechanical power transmission works by turning one propeller, and we can see that all the other propellers spin simultaneously in the assigned directions				

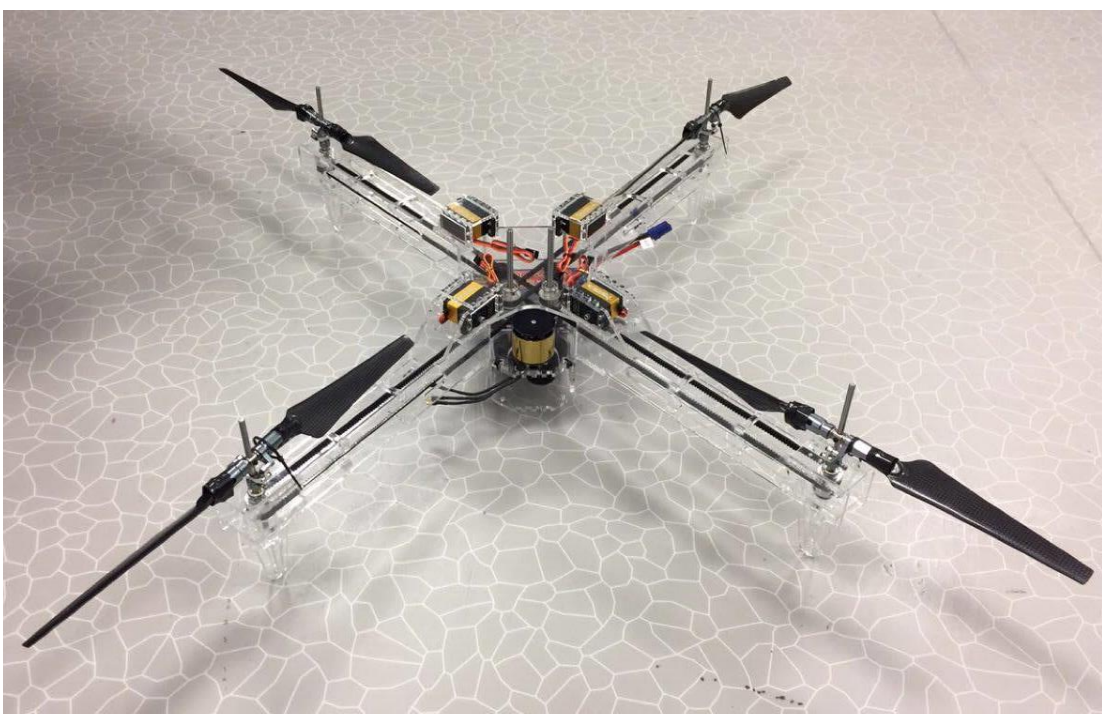


Figure 1: Quadcopter during test T01

TEST RESULT					
Test Report ID	TR02	Corresponding Requirement ID	C02	Result	Passed
Corresponding Test ID	T02	Priority	A	Test date	12.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Purpose	Confirm that the quadcopter can use an EM for power propulsion				
Equipment/Tools/ Software	Camera				
Conclusion	The tester connected the battery to the EM, and started the EM. After receiving a RC command, all the propellers spun simultaneously in the correct directions, thus confirming that one EM can power the drone.				

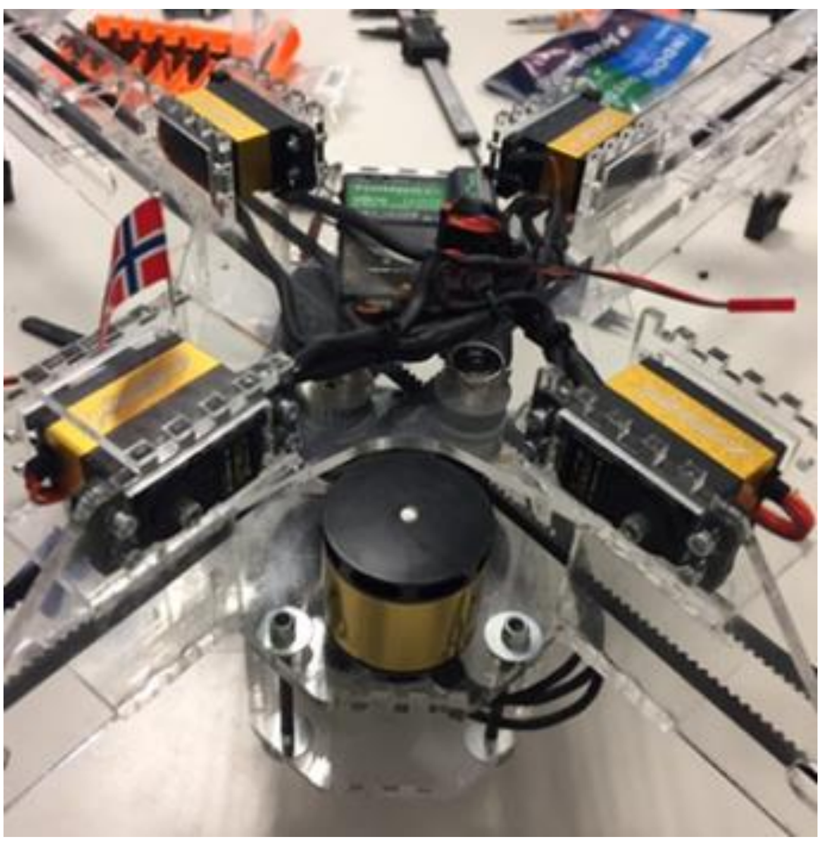


Figure 2: EM connected to the Quadcopter

TEST RESULT					
Test Report ID	TR03	Corresponding Requirement ID	C03	Result	NA
Corresponding Test ID	T03	Priority	C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Purpose	Confirm that the quadcopter can use an ICE for power propulsion				
Equipment	-				
Conclusion	The project team was not able to perform this test, because the ICE modular motor system was never realized, and this was decided relatively early in the process, and has been clarified with the customer. Please see section 4 and 5 in the design decisions document for further clarification We could in theory have performed a test in SolidWorks, but this test would not be sufficient, and the project team would not have been satisfied with the outcome of such a test. It would be hard to prove that it would work just by a demonstration in SolidWorks. With that said we strongly believe that the MMS with an ICE attached, would have worked for power propulsion. We have done the calculations for the EM, [ref. section 4.7.4 in Technical Document] where the biggest RPM is present, and since we got steel gears, we are sure that they will withstand the lower RPM from the ICE, even though the torque is higher.				

TEST RESULT					
Test Report ID	TR04	Corresponding Requirement ID	C04	Result	Passed
Corresponding Test ID	T04	Priority	A	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Purpose	Verify that the drone does not need a runway, and can operate as a VTOL aircraft				
Equipment	Measurement grid, camera				
Conclusion	A grid for measurement was taped to the floor. The grid was used as a reference to measure sideways velocity. From a standstill, thrust and propeller pitch angle was applied until the drone took off vertically. The initial translational velocity was zero. A short flight up to two metres altitude followed, until the drone landed. As it landed, the drone skidded sideways (in the x-direction) with a velocity of 6 cm/s, and a downwards velocity of 5 cm/s.				

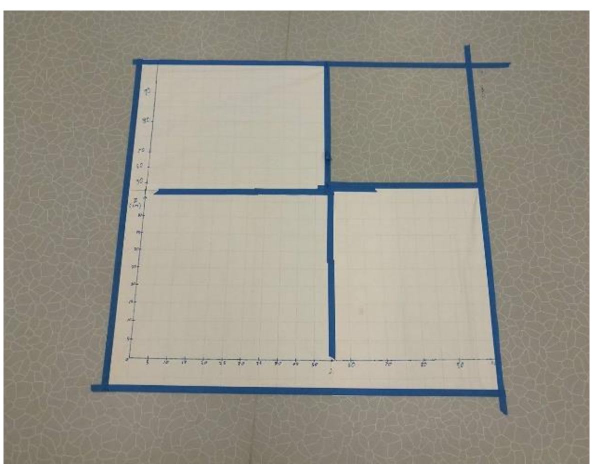


Figure 3: Measurement grid

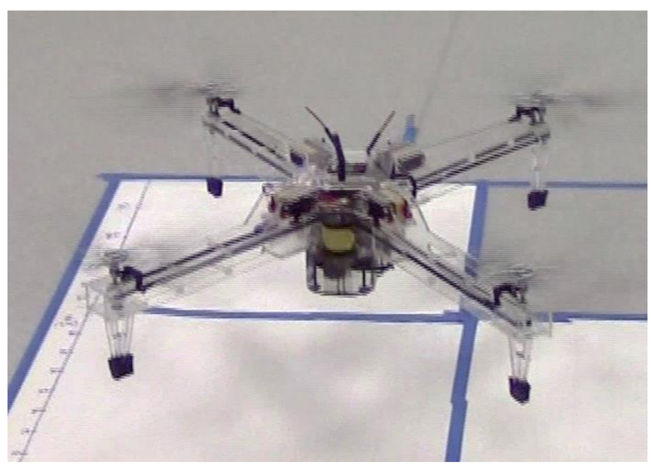


Figure 4: Landing approach

TEST RESULT					
Test Report ID	TR05	Corresponding Requirement ID	C05	Result	Partial Failure
Corresponding Test ID	T05	Priority	C	Test date	18.05.2017
Test performed by	Severin Myhre				
V&V Method	Check results of the other certification-related test				
Purpose	Verify RO1 compliance				
Equipment	None				
Conclusion	T07 is not passed, so not all RO1-related tests are passed. Referring to TR07, T07 is currently failed, but will be met in the final production design of the system. Given that all RO1-related test will be passed in time, we define the result of this test as a partial failure.				

TEST RESULT					
Test Report ID	TR06	Corresponding Requirement ID	C05.1	Result	Passed
Corresponding Test ID	T06	Priority	C-A	Test date	16.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Inspection				
Purpose	Verify that the drone is identifiable				
Equipment	Camera				
Conclusion	A plaque is installed on the upper side of the battery, fastened by Velcro to the same straps that hold the battery. Name of the College University, campus, address, Head of Institute telephone number and e-mail address has been laser engraved onto the plaque. The plaque is a 1.5mm thick “Lasermax Euro Gold” polymer plate made by Rowmark.				

Figure 5: Name plaque, positioned above the battery

TEST RESULT					
Test Report ID	TR07	Corresponding Requirement ID	C05.2	Result	Failed
Corresponding Test ID	T07	Priority	C-A	Test date	16.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Instrumented test				
Purpose	Verify that the system complies with RO1 certification				
Equipment	Scale (Menuett kitchen scale, 1g deviation) & camera				
Conclusion	The prototype drone with all its components was put on a scale and its mass measured. The mass was 3400g. This is 0.9 kg above the RO1 classification, and the test was failed. The added 900g is due to the more massive gears and the airframe being made of plexiglass, not carbon fibre. [Ref. section 5 in Conclusions & Recommendations document and Appendix A - Weight Budget], the final EM production model will weigh 2416g, and is subsequently within the RO1 certification. The ICE configuration is in the RO2 certification due to its combustion engine, and is not subjected to the 2.5 kg weight requirements. The current prototype has failed the test, but in accordance with the aforementioned documents, the final production model will pass. This has been discussed and approved with the customer at an earlier stage in the project. Please see section 6.1 in the Systems engineering document for further clarification.				

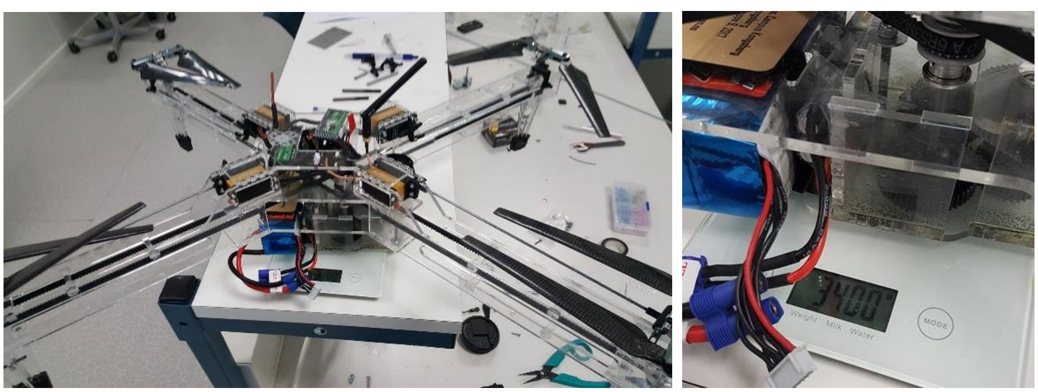


Figure 6: The drone on the scale

TEST RESULT					
Test Report ID	TR08	Corresponding Requirement ID	C05.3	Result	Passed
Corresponding Test ID	T08	Priority	C-C	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Give the operator a way of checking flight altitude, and to allow for altitude-hold and future capabilities such as telemetry.				
Equipment	Camera				
Conclusion	The flight controller is equipped with a barometer. A technical description of the barometer can be found in the bibliography [4] and section 11 of the Technical Document.				

Figure 7: OpenPilot Revolution

Figure 8: MS5611 Barometer

TEST RESULT					
Test Report ID	TR09	Corresponding Requirement ID	C05.4	Result	Passed
Corresponding Test ID	T09	Priority	C-C	Test date	21.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	Demonstration
Purpose	Prove that the system is within the R01 regulations by not being able to reach a maximum speed that exceeds 60 knots
Equipment	-
Conclusion	Since the drone is still in the prototype stage, and add the fact that the frame is made from Plexiglas it would be very bold of us to try such an extreme test as explained in T09. It could very easily end in a very unfortunate event of a broken quadcopter which would be devastating for the project and the project group at this stage. It would also be a dangerous test to perform for the operator, and for other people which is needed to perform the test. The priority of this test is also a C-C, thus being the lowest priority in our priority scale, and it is simply too much risk involved. With this said, we have done the calculations and can prove that the drone can't exceed the R01 regulations of 60 knots [ref. section 10.1 in Technical Document] and knowing that the practical numbers would be even lower than this, we can conclude that the drone meets the acceptance criteria

TEST RESULT					
Test Report ID	TR10	Corresponding Requirement ID	C05.5	Result	Passed
Corresponding Test ID	T10	Priority	C-C	Test date	21.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	Demonstration
Purpose	Check that the system is equipped with a mechanism that turns of the system if the RC unarms it, or if the system loses the signal from the RC
Equipment	Camera
Conclusion	The test was done while the drone was on the ground to prevent any dangerous situations, but in a good enough manner that the acceptance criteria was met. As figure 8,9,10 & 11 show, we armed the drone in a normal manner and when giving throttle command with the RC, the propellers spun as intended. Then we unarmed the drone while giving the same amount of throttle, and the propellers stopped. If this is done while mid-air, the drone will crash to the ground, and prevent dangerous situations in case of loss of control. It is possible to program a failsafe mode, which is a bit more sophisticated method to control the drone in case of loss of signal from RC. If this mode exists the failsafe mode will activate automatically, and switch flight mode where the drone is ordered to a position that we have set up. This will control the drone, and not just crash it to the ground. This failsafe mode will be set up in the future.

*Figure **Error! No text of specified style in document.**9: Unarmed, no throttle* *Figure 10: Armed, with throttle*

*Figure **Error! No text of specified style in document.**11: Armed, with throttle while propellers spin* *Figure 12: Unarmed, with throttle but the propellers stop*

TEST RESULT					
Test Report ID	TR11	Corresponding Requirement ID	F01	Result	Passed
Corresponding Test ID	T11	Priority	A	Test date	14.05.2017
Test performed by	Severin Myhre				
V&V Method	Analysis & Inspection				
Purpose	Verify that the propeller blades are replaceable				
Equipment	SolidWorks CAD software, camera				
Conclusion	The CAD model shows that the propeller blades are fastened by one bolt. The propeller blades can be replaced by unscrewing the bolt and replacing the blade. This is verified by physical inspection.				

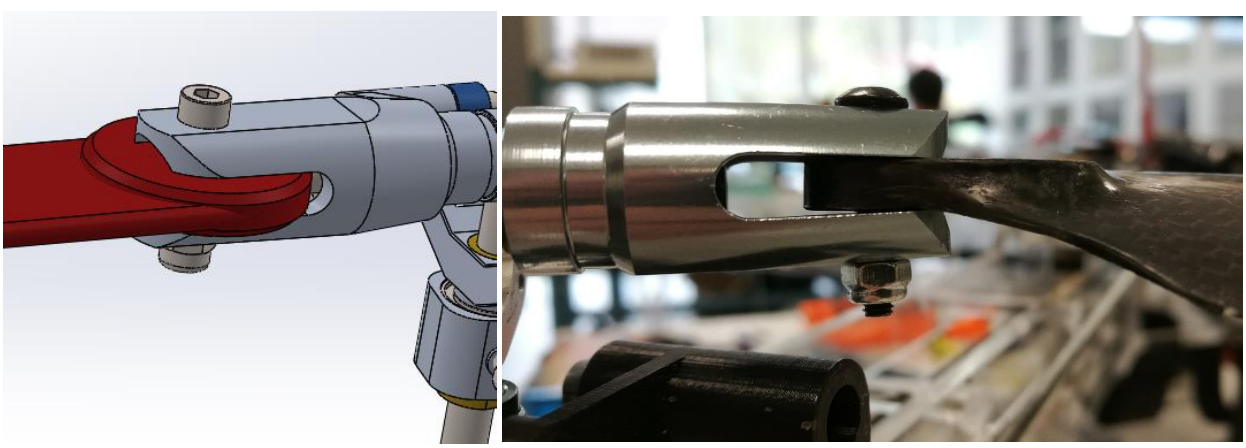


Figure 13: CAD model and picture of the propeller mounting hub

TEST RESULT					
Test Report ID	TR12	Corresponding Requirement ID	F01.1	Result	Passed
Corresponding Test ID	T12	Priority	A-A	Test date	20.05.2017
Test performed by	Severin Myhre, Joakim Thorvaldsen				
V&V Method	Demonstration				
Purpose	Verify requirement F01.1				
Equipment	Stopwatch, camera, wrench				
Conclusion	An external layman, Joachim Krøvel Vikanes, was brought in. He is a Bachelor in Business Administration and Management student with no previous technical experience. He was given an allen key of the correct size and a wrench. He was then instructed to remove a propeller bolt, remove the propeller, reinsert the propeller and then refasten the bolt. The stopwatch was started as the layman lifted the tools, and stopped when he put the tools down after completing the tasks. The time until completed replacement of the propeller blade was one minute and 53 seconds. After the test, a team member used the tools to check that the bolt was properly tightened. The test was passed.				

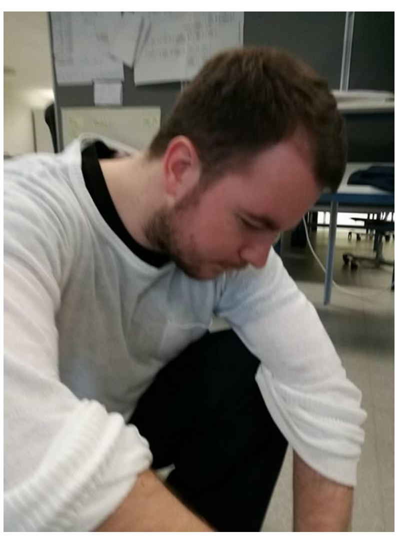


Figure 14: Test start

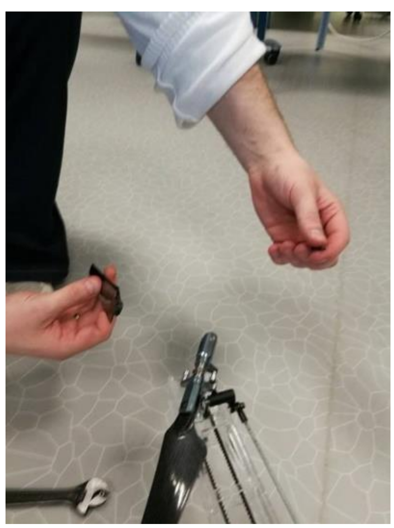


Figure 15: Removed blade

Figure 16: Blade replaced

TEST RESULT					
Test Report ID	TR13	Corresponding Requirement ID	F02	Result	NA
Corresponding Test ID	T13	Priority	A	Test date	22.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	None
Purpose	Show that it is possible to switch between the different MMS with EM and ICE configurations, for a person with no significant technical experience. No time limit
Equipment	Camera, stopwatch, wrench, torque wrench, tool kit
Conclusion	This is a test which the project group won't be able to implement before due date. The reason behind this is explained more in detail in test result TR03. This is basically because we do not have a prototype with an ICE configured MMS at time being, and won't have it before the end of project either. We are very confident that we would pass requirement F02, [ref. conclusion in TR14] if we had the ICE configured MMS available. But since this is not the case, and that T14 which this test is based on got test result NA, the result of this test naturally becomes NA too.

TEST RESULT					
Test Report ID	TR14	Corresponding Requirement ID	F02.1 & F02.2	Result	NA
Corresponding Test ID	T14	Priority	A-A & A-C	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Purpose	Show that it is possible to switch between the different MMS with EM and ICE configurations, for a person with no significant technical experience within certain time limits				
Equipment	Camera, stopwatch, wrench, torque wrench, tool kit				
Conclusion	This is a test which the project group won't be able to implement before due date. The reason behind this is explained more in detail in test result TR03. This is basically because we do not have a prototype with an ICE configured MMS at time being, and won't have it before the end of project either. But looking at some of the other satisfying test results where attachment and detachment of the MMS is done [ref. T15 and T16], we are very positive in regards of passing this test in the future. The layman in T15 and T16, managed to detach the Electrical Motor configured MMS in 4 minutes and 16 seconds, while attaching it in 4 minutes and 55 seconds. Adding these numbers together and you will get approx. 9 minutes and 10 seconds. And even though we only used the EM configured MMS in these tests, and not both the EM and ICE configured MMS, the difference should be in the same ballpark. The reason behind this assertion is that there is only four bolts difference between the EM configured MMS and the ICE configured MMS when it comes to attaching and detaching it from the rest of the drone. It is a three-bolted operation on the EM configured MMS, and a seven-bolted operation on the ICE configured MMS. Note that the four bolts extra in the ICE configured MMS, is smaller and easier to mount than the three needed on both MMS. And since all the tubing, wiring, correct gears for correct RPM, is already handled inside the MMS itself, the process should be quite similar. More info on the MMS can be found in section 4.2 of the design decisions document To summarize, we are very confident that we would pass both requirement F02.1 & F02.2, if we had the ICE configured MMS available. But since this is not the case, we set the test result as NA.				

TEST RESULT					
Test Report ID	TR15	Corresponding Requirement ID	F02.1.1	Result	Passed
Corresponding Test ID	T15	Priority	A-A-A	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik, Joachim Krøvel Vikanes				
V&V Method	Demonstration				
Purpose	Show how fast it is possible to attach the MMS for a person with no significant technical experience, confirming how simple the MMS design is				
Equipment	Camera, stopwatch, wrench, torque wrench				
Conclusion	An external layman, Joachim Krøvel Vikanes, was brought in. He is a Bachelor in Business Administration and Management student with no previous technical experience. He was given a wrench and torque wrench, and basic instructions of how to attached the MMS. Seeing that there are only three bolts, with nuts and discs, that needs to be fastened before the MMS is attached to the drone, this is a quite novice operation. The stopwatch was started when the layman lifted the tools, and stopped when he had completed the task. The time until the task was completed was 4 minutes and 16 seconds, and this is within the acceptance criteria of 15 minutes. This result was about 40 seconds faster than it took to detach the MMS. The explanation for this might be that the external layman had just performed T16, and through this experience had acquired new technical knowledge about the task in hand. But we do not think this affected the result noteworthy, and chose to approve the test.				

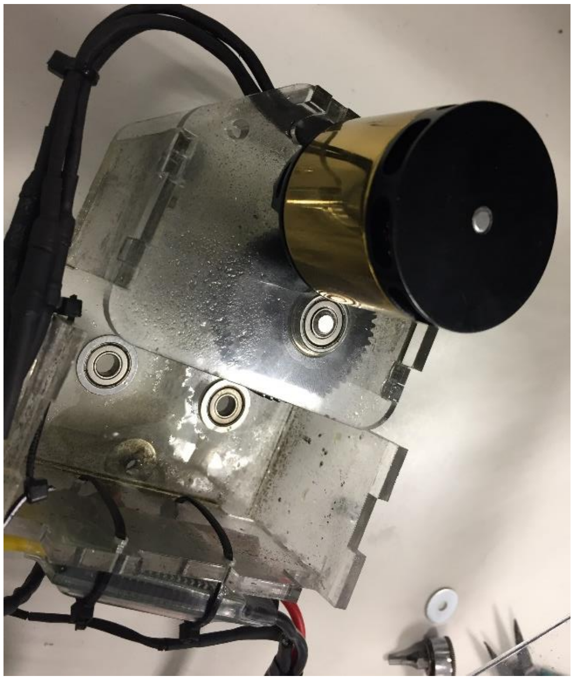


Figure 17: Test start, MMS is detached

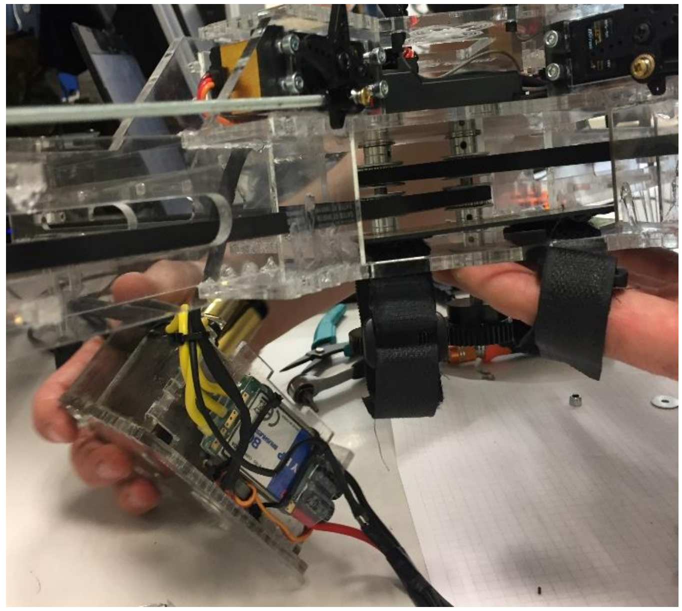


Figure 18: Test underway

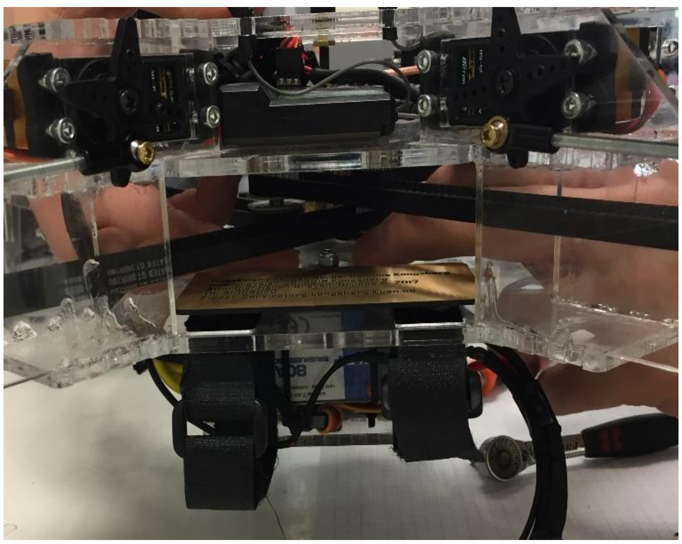


Figure 19: Test done

Figure 20: Stopwatch result

TEST RESULT					
Test Report ID	TR16	Corresponding Requirement ID	F02.1.2	Result	Passed
Corresponding Test ID	T16	Priority	A-A-A	Test date	22.05.2017

Test performed by	Daniel Christian Torsvik & Thomas Huse
V&V Method	Demonstration
Purpose	Show how fast it is possible to detach the MMS for a person with no significant technical experience, confirming how simple the MMS design is
Equipment	Camera, stopwatch, wrench, torque wrench
Conclusion	An external layman, Joachim Krøvel Vikanes, was brought in. He is a Bachelor in Business Administration and Management student with no previous technical experience. He was given a wrench and torque wrench, and basic instructions of how to detach the MMS. Seeing that there are only three bolts, with nuts and discs, that needs to be removed before the MMS is detached from the rest of the drone, this is a quite novice operation. The stopwatch was started when the layman lifted the tools, and stopped when he had completed the task. The time until the task was completed was 4 minutes and 56 seconds, and that is well within the acceptance criteria of 15 minutes. Afterwards Thomas Huse, did the same procedure, and clocked in at 2 minutes and 35 seconds. This is a very satisfying result, and proves how clever and simple the MMS is.

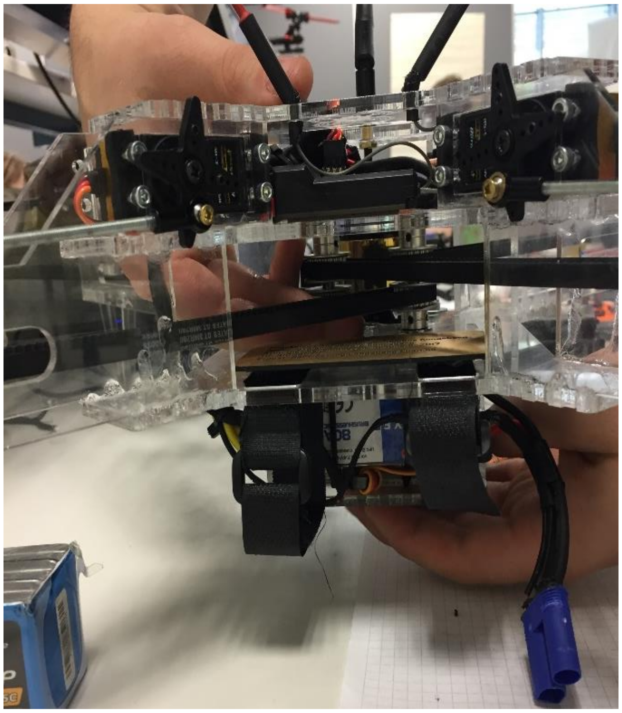


Figure 21 Test start

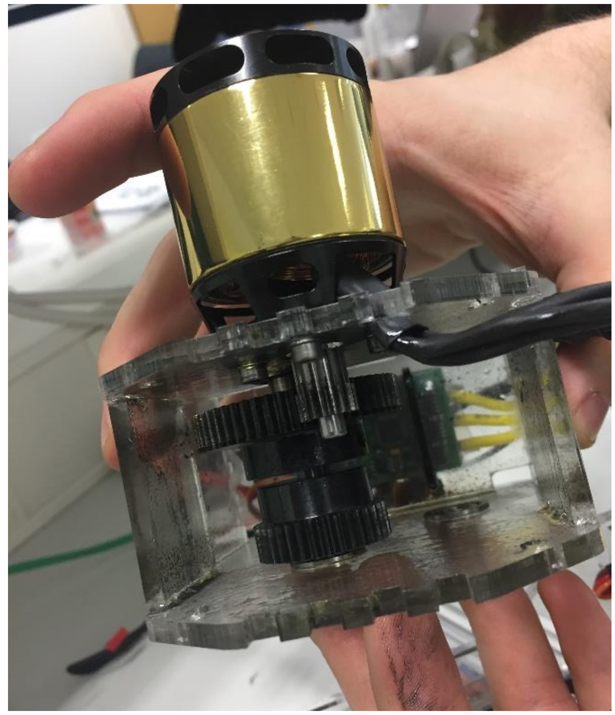


Figure 22: MMS detached, test completed

Figure 23: The three bolts

Figure 24: Stopwatch result

TEST RESULT					
Test Report ID	TR17	Corresponding Requirement ID	F02.3	Result	Passed
Corresponding Test ID	T17	Priority	A-A	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Verify that the drive unit can be removed and refastened				
Equipment	Camera, SolidWorks CAD software				
Conclusion	The EM is fastened to the airframe with four M3 screws with hexagonal heads. The ICE motor is fastened to its support bracket (red) with four M3 bolts with hexagonal bolt heads. The support bracket (red) is fastened to the airframe with four similar screws.				

Figure 15: Fastening of the EM and ICE drive units

TEST RESULT					
Test Report ID	TR18	Corresponding Requirement ID	F02.4	Result	Passed
Corresponding Test ID	T18	Priority	A-A	Test date	22.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	Demonstration
Purpose	Verify that it is possible to change between propulsion systems by using basic tools only
Equipment	Camera, SolidWorks CAD software, wrench, torque wrench, Allen key
Conclusion	We have demonstrated in previous tests [ref. T13 & T14] that it is possible to attach/detach the electric motor configured MMS with the use of basic tools such as a wrench and a torque wrench only. And it is also possible doing the same operations with the use of only a wrench and an Allen key. The drone remained fully operational after these tests, confirming that the system still works. But because we have not built the ICE configured MMS it has not been possible for us to demonstrate that it is possible to change between the different propulsion systems with the help of basic tools only. With that said, we have designed both MMS to meet this requirement, and it shall be possible to attach/detach both systems with basic tools only. We also got a SolidWorks models to confirm this assertion. In the SolidWorks model, there are three bolts needed to fasten the EM configured MMS, and seven bolts needed to fasten the ICE configured MMS. [ref. TR17] All the bolts got hex sockets, allowing for the use of an Allen key and a torque wrench with the correct bit. Since it is proven that we can attach/detach the EM configured MMS with the help of basic tools only, and we can show the SolidWorks model of the ICE configured MMS, where we only use hex socketed bolts as fasteners, [ref. TR17] we approved this test.

TEST RESULT					
Test Report ID	TR19	Corresponding Requirement ID	F03	Result	Passed
Corresponding Test ID	T19	Priority	A	Test date	13.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Confirm that the drone can regulate the thrust delivered by each propeller, by altering each blade's pitch angle				
Equipment	Camera				
Conclusion	The system has a working mechanism on each blade for pitch angle adjustment.				

Figure 26: The variable pitch mechanism

TEST RESULT					
Test Report ID	TR20	Corresponding Requirement ID	F04 & F04.1	Result	Passed
Corresponding Test ID	T20	Priority	A & A-A	Test date	15.05.2017

Test performed by	Severin Myhre & Daniel Christian Torsvik
V&V Method	Inspection
Purpose	Only a basic metric bit kit should be needed for repairs
Equipment	Precision tool set with different bit sizes
Conclusion	There is a total of 44 screws and 25 locking screws. All screws are metric and with either hexagonal, Phillips or Pozidriv sockets. The screws are: Six per pitch mechanism 24 in total 1.5mm hexagonal socket One per lever arm (rotor) 1 in total 1.5mm hexagonal socket One per threaded rod (servo) 4 in total 2.5mm Pozidriv socket Four to fasten motor 4 in total 2.5mm hexagonal socket One per lever arm (airframe) 1 in total 2.5mm hexagonal socket One per servo motor 4 in total 3.5mm Phillips socket The locking screws are: One at the motor pinion gear 1 in total 0.9mm hexagonal socket One per inner pulley 4 in total 1.5mm hexagonal socket One per rotor locking ring 4 in total 1.5mm hexagonal socket Two per propeller pulley 8 in total 2mm hexagonal socket One per pitch mechanism 4 in total 2mm hexagonal socket One per gear 4 in total 3mm hexagonal socket

TEST RESULT					
Test Report ID	TR21	Corresponding Requirement ID	F05 & F05.1	Result	Passed
Corresponding Test ID	T21	Priority	A & A-A	Test date	15.05.2017
Test performed by	Severin Myhre & Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Only a basic metric bit kit should be needed for repairs				
Equipment	Precision tool set with different bit sizes				
Conclusion	There is a total of 31 bolts. All bolts are metric and with hexagonal socket. The bolts are: One per blade — 8 in total — 2.5mm hexagonal socket Four per servo motor — 16 in total — 2.5mm hexagonal socket One per threaded rod (rotor) — 4 in total — 2.5mm hexagonal socket Three for the MMS — 3 in total — 3mm hexagonal socket				

TEST RESULT					
Test Report ID	TR22	Corresponding Requirement ID	F06	Result	Passed
Corresponding Test ID	T22	Priority	B	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Purpose	Verify that only one person is needed to operate the system				
Equipment	Camera				
Conclusion	The system was flown with one person operating the radio controller. The system travelled across the room where the test was performed twice. The system travelled a total of seven meters in the transverse direction. The system was under control the entire duration of the flight, and no damage was done to the system or its surroundings.				

Figure 27: Test in progress

Figure 28: Test in progress 2

TEST RESULT					
Test Report ID	TR23	Corresponding Requirement ID	F07	Result	Passed
Corresponding Test ID	T23	Priority	C	Test date	20.05.2017

Test performed by	Thomas Huse, Severin Myhre, Joakim Thorvaldsen
V&V Method	Demonstration
Purpose	Verify the flight time of the drone with electric motor
Equipment	Stopwatch, camera & Low Voltage Buzzer Alarm
Conclusion	Both batteries – the main and the servo batteries – were charged. The main battery had a voltage of 24.9 V, and the servo battery had a voltage of 8.27 V after charging. The drone was then placed in the "Dronesonen" testing room at the College University. The camera was started, the drone took off, and the stop watch started, in that order. The Low Voltage Buzzer Alarm was connected to the main battery, and set to go off when the most discharged of the six cells reached 3.3 V. The drone was flown until the Low Voltage Buzzer Alarm signalled for low voltage, and the drone was subsequently landed. The duration of the flight was 00.10.50 hours, or ten minutes and 50 seconds. The acceptance criteria were exceeded with 50 seconds. The voltage of both batteries was logged after the flight. The main battery had a voltage of 21.0 V, and the servo battery had a voltage of 7.61 V. The critical voltage of the servo battery is 6.4 V, and 19.2 V for the main battery. This means that the drone could have flown for a longer duration, but the test was ended to prevent any potential damage to the batteries. Based on these results, we deem the test to be passed. An independent observer, student Jardar Gran Østern, was present during the test. The entire test was filmed. The film can be provided upon request.

Figure 29: Test 23 in progress

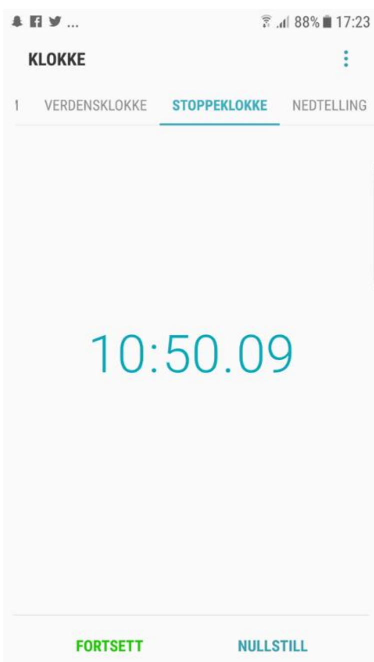


Figure 30: Duration of flight

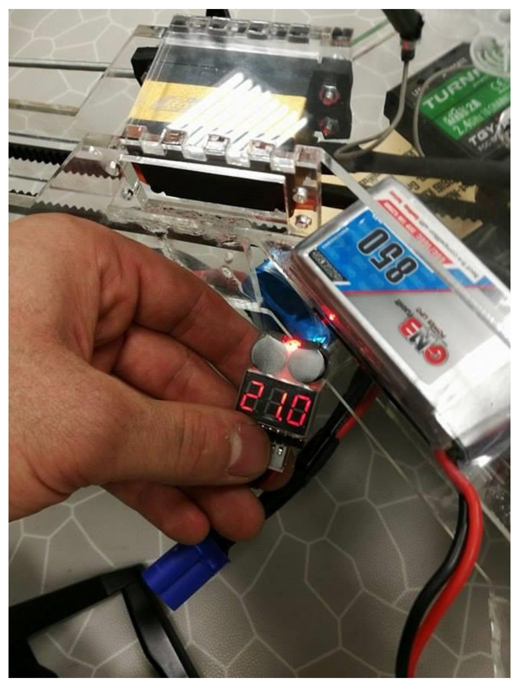


Figure 31: Main battery voltage after flight

TEST RESULT					
Test Report ID	TR24	Corresponding Requirement ID	F08	Result	NA
Corresponding Test ID	T24	Priority	C	Test date	21.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	Demonstration
Purpose	The purpose with this test is to figure out how long the drone can hoover before all the fuel is used.
Equipment	Camera, stopwatch
Conclusion	This is a test which the project group won't be able to implement before due date. The reason behind this is explained more in detail in test result TR03. This is basically because we do not have a prototype with an ICE configured MMS at time being, and won't have it before the end of project either. If we would have realized this feature, it would not be any issue to perform such a test as this, but it would only be speculation saying that we believe that we would pass such a test.

TEST RESULT					
Test Report ID	TR25	Corresponding Requirement ID	F09	Result	Passed
Corresponding Test ID	T25	Priority	B	Test date	18.05.2017
Test performed by	Joakim Thorvaldsen & Severin Myhre				
V&V Method	Demonstration				
Purpose	Verify requirement F09				
Equipment	Ruler, camera, scale, steel rod and mock-up model				
Conclusion	We built a mock-up of the drone airframe from 3mm thick plywood. We used a mock-up as this is inherently a destructive test, and the mock-up allowed us to complete the test without potentially damaging the prototype. Plywood is a relatively cheap material with comparable properties to plexiglass, which the prototype is made of. To simulate the mass of the drone, we used a massive steel rod to weigh it down. The rod was placed in the centre of the airframe. The entire assembly weighed 3461 g. This is a comparable mass to the current prototype. The lowest point of the airframe was at a height of approximately 30 cm to a linoleum coated concrete floor when the airframe was dropped. Results: - One leg broke. - One leg fell off. - All four top cover plates fell off. - No other structural damage to the airframe. The structural integrity of the airframe was on inspection not damaged. There was no visible damage to the arms or body of the airframe, and it was held together. The fact that one leg broke was expected, as the mock-up's legs were not reinforced. The legs of the prototype are reinforced with cross-sectional bracing. One leg falling off is because the legs were not glued or permanently attached to the frame, and is not a concern with regards to the structural integrity of the airframe. The legs are designed to be inexpensive and easily replaceable. The cover plates falling off was expected, as they were just resting on the airframe. This is not a concern, as they can be easily				

	reattached. The prototype's top cover plate is not permanently fastened for easy access to electronics. The overall structural integrity of the airframe remained intact. All damages were related to the construction of the mock-up and/or easily replaceable parts. Based on these results, we consider the test to be passed.

Figure 32: Weighing

Figure33: Before the drop. Ruler in the background

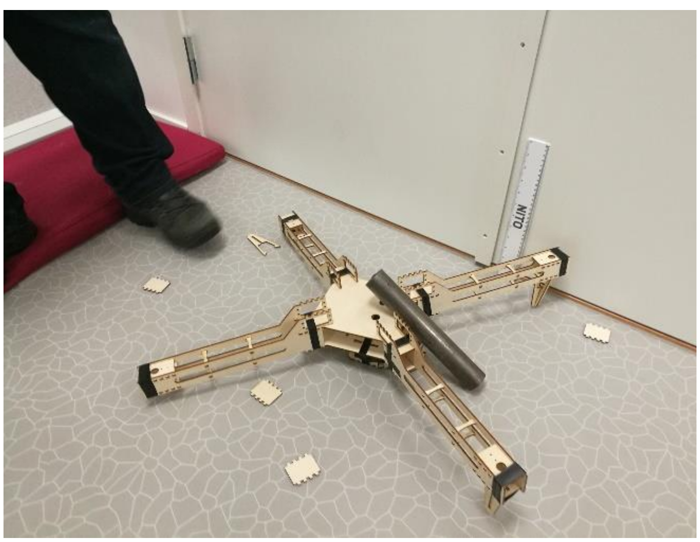


Figure 34: After drop

Figure 35: Broken leg

TEST RESULT					
Test Report ID	TR26	Corresponding Requirement ID	F10	Result	Passed
Corresponding Test ID	T26	Priority	C	Test date	20.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Severin Myhre				
V&V Method	Demonstration				
Purpose	Verify that the drone can carry a payload of at least 250 g				
Equipment	Mass simulator (tool kit), scale & camera				
Conclusion	An item with at least 250 g mass was identified. This was a Würth tool kit, and weighing it showed its mass to be 253.7 g. The tool kit was then mounted on top of the drone. The pilot applied thrust until the drone lifted off, flew to an elevation of approximately 1.5 meters, then landed. The test acceptance criteria were met.				

Figure 36: Weighing of payload

Figure 37: Mounting of payload

Figure 38: Flight with payload

TEST RESULT					
Test Report ID	TR27	Corresponding Requirement ID	FC01	Result	Passed
Corresponding Test ID	T27	Priority	A	Test date	15.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Demonstration				
Purpose	Confirm that the FC can receive and interpret the signal sent from the RC				
Equipment	Camera				
Conclusion	From a neutral position, we gave full pitch and yaw on the radio controller. The propeller blades changed pitch angle accordingly, verifying that the flight-controller can receive and interpret signals sent from the radio controller.				

Figure 39: Receiver with 2,4GHz

Figure 40: Pitch angle changed on RC

Figure 41: Pitch angle changed on propeller

TEST RESULT					
Test Report ID	TR28	Corresponding Requirement ID	FC02	Result	Passed
Corresponding Test ID	T28	Priority	C	Test date	19.05.2017
Test performed by	Thomas Huse, Joakim Thorvaldsen, Daniel Christian Torsvik, Severin Myhre				
V&V Method	Demonstration				
Purpose	Verify the stability of the system during flight				
Equipment	Measurement grid, camera, stopwatch				
Conclusion	We flew the system above the measurement grid, while the operator tried to keep a constant position. The time until the system deviated approximately one meter from the centre of the measuring grid was measured, using a stopwatch. The drone operator never had any problems operating the system within the given test conditions. The time was 20.46 seconds when we decided to stop the test, as we had passed the acceptance criteria by a factor of four.				

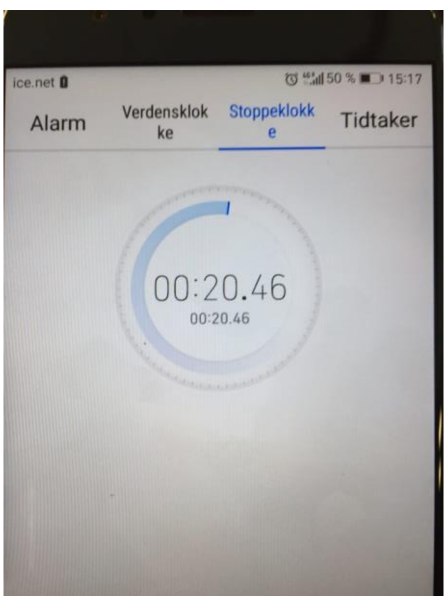


Figure 42: Timer

Figure 43: Test in progress

TEST RESULT					
Test Report ID	TR29	Corresponding Requirement ID	NF01	Result	Passed
Corresponding Test ID	T29	Priority	A	Test date	13.05.2017
Test performed by	Severin Myhre				
V&V Method	Inspection				
Purpose	Confirm that the power transmission functions as intended				
Equipment	Camera				
Conclusion	When rotating one propeller, both the transmission system and all propellers rotate with it.				

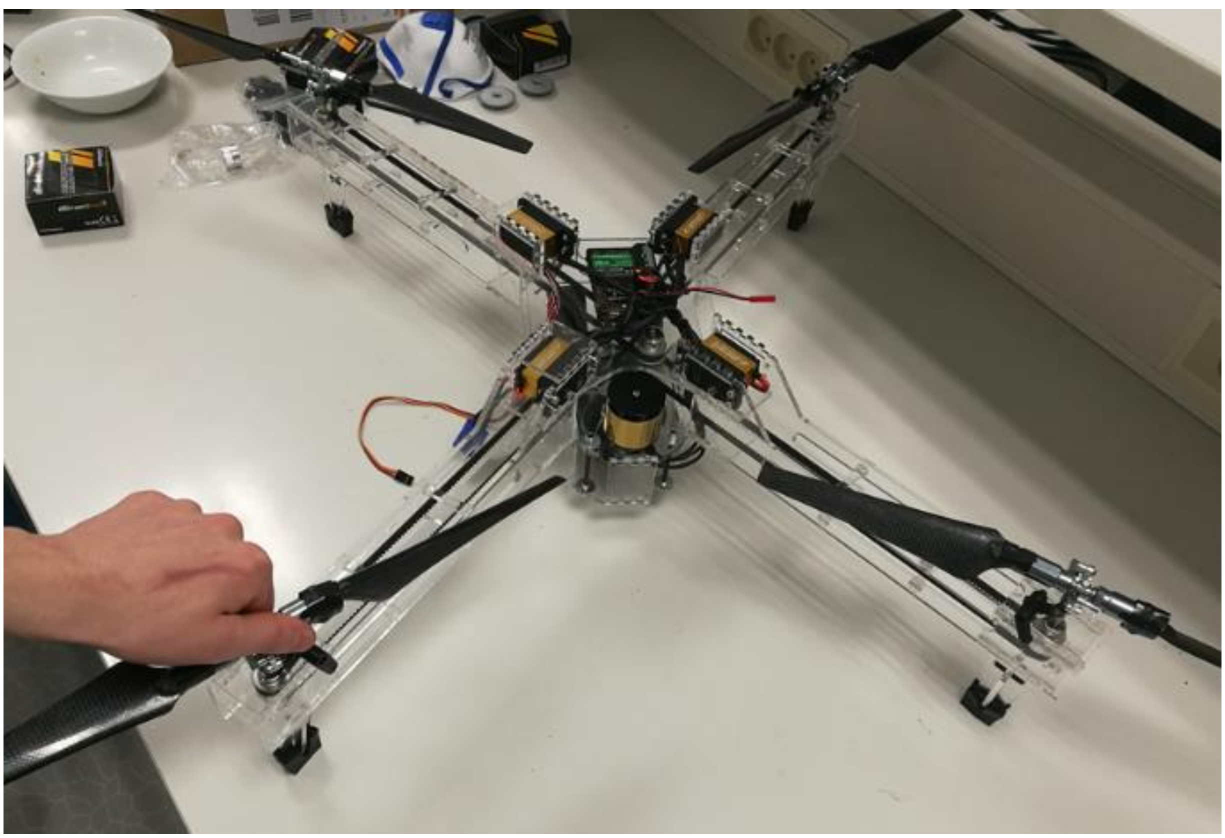


Figure 44: Test T29 in progress

TEST RESULT					
Test Report ID	TR30	Corresponding Requirement ID	NF02, NF03 & NF04	Result	NA
Corresponding Test ID	T30	Priority	A / B / C	Test date	22.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Instrument Test				
Purpose	Figure out the efficiency of the mechanical power transmission from motor to rotors				
Equipment	-				
Conclusion	This is a test which the project group won't be able to implement before the due date. There are two reasons for this, the first reason is that the test description is very specific, and the project group cannot complete the test with the tools available to us. The test would also become very challenging to complete, even if we had the needed tools at hand. The second reason is that the other methods we could use to get an acceptable result, simply is too time consuming at this stage of the project. But if we look at the requirements of efficiency strictly theoretically we can get an idea of what the efficiency of the mechanical power transmission operates with. First, we simplify a bit, and assume that all the energy loss is either from slip between the belts and the belt pulleys, vibrations or friction (heat). Because the belts got "teeth" and fit perfectly with the pitch angles of the belt pulleys, the belt drive itself got no slip, and with synchronous belt drive, we get an efficiency of 95% or higher [ref. section 4.6 Technical Document]. Since timing belts are a type of synchronous belt drive, we can assume we get the same efficiency. In the spur gears used in the mechanical power transmission, where most of the friction is, we got an efficiency of 98-99%. [ref. section 4.7.1 Technical Document]. Since vibrations are primarily energies oscillation between kinetic and potential energy, and add that there are very little vibrations when the motor is spinning at the RPM needed for flight, the efficiency loss because of this can't be very large. With this theoretical view of the efficiency in mind, we can conclude with high certainty that the efficiency of the mechanical power transmission is higher than the 70% efficiency requirement, which got priority A. And even though we believe the efficiency is higher than 90% as well, meaning that we would pass all the tests, and reaching all the requirements within, we can't prove this by demonstration. Therefore, we set this test as a NA.					

TEST RESULT					
Test Report ID	TR31	Corresponding Requirement ID	NF08	Result	Passed
Corresponding Test ID	T31	Priority	A	Test date	21.05.2017

Test performed by	Daniel Christian Torsvik & Thomas Huse
V&V Method	Instrumented Test
Purpose	Check that the system got a thrust to weight ratio ≥ 2:1
Equipment	Baggage weight, camera, electrician tape
Conclusion	The first thing we did in this test was to remove the propellers on three out of four arms, this made it possible for us to do a safe test which would give us a good enough test result. As you can see in figure 45 we managed to get a lift of 1350g on the single propeller, multiply this by four, and we got a total lift of 5400g. This is above the acceptance criteria of 2:1 thrust to weight ratio for the final quadcopter which will weight under 2500g. Since the test was done with our prototype and with some factors we believe can have affected the result negative, we believe we could have gotten a better result with more time and a better test rig. Negative factors: • The battery had 25.0 V when we started testing • The FC may have tried to compensate and therefore adjusted pitch automatically to correct the difference in lift from each propeller • The baggage weight may not have been accurate enough • Dirty air with a lot of turbulence could have affected the lift • Three out of four legs were still on the ground • Didn’t use pitching to get lift, we only used max RPM

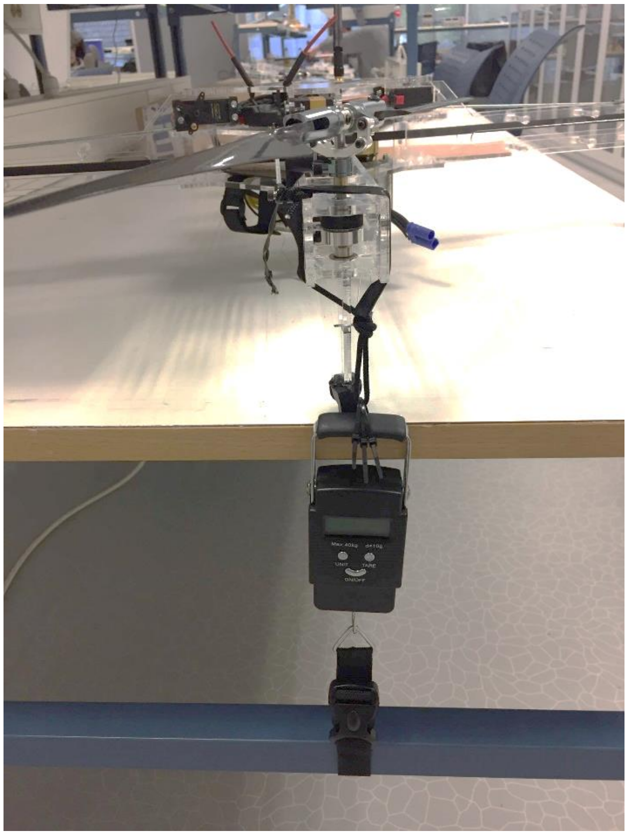


Figure 45: Test bench

Figure 46: Test result, 1350g

TEST RESULT					
Test Report ID	TR32	Corresponding Requirement ID	NF13 & NF14	Result	Passed
Corresponding Test ID	T32	Priority	A	Test date	21.05.2017

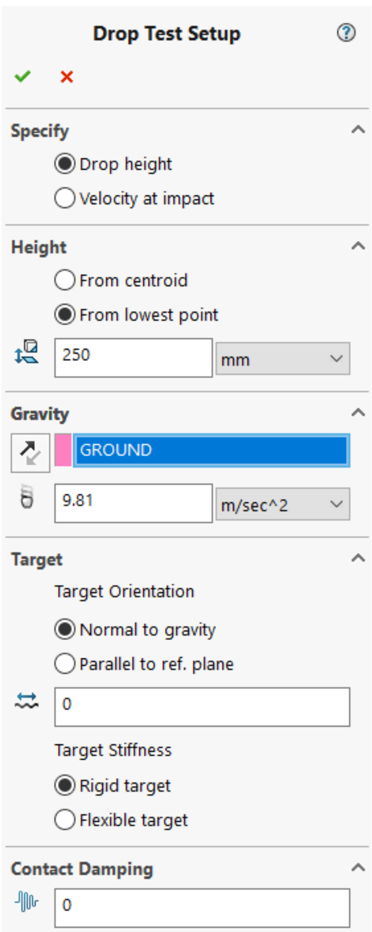
Test performed by	Daniel Christian Torsvik
V&V Method	Inspection
Purpose	Check that the screws and bolts can withstand 10 hours of flying without unscrewing
Equipment	Camera, screwdriver
Conclusion	It was intended for this test to be carried out in the accordance with the T32, where the V&V method was instrumented test and analysis, but this was not possible for us to achieve with the number of tools available for us within the time limit. Instead we chose to do an inspection of the system. Accumulated flight time per 21.05.2017 is approx. 2 hours, and even thought this is only a portion of the requirement we chose to run the test at this stage. Even though a more accurate test is needed to be done in the future to get a more accurate test result, but this is not possible because of time constraints. After close inspection and by using a screwdriver we could confirm that the screws and bolts were smilingly as taut as before flight. And knowing that thread lock is only used on a small portion of the screws and bolts, and that we run the test on a prototype, we are sure that the screws and bolts on the final quadcopter will pass the acceptance criteria. This is because we will use lock thread on every screw and bolt and that the final system will have a less brittle frame than this prototype.

TEST RESULT					
Test Report ID	TR33	Corresponding Requirement ID	NF15 & NF16	Result	Passed
Corresponding Test ID	T33	Priority	B & A	Test date	23.05.2017

Test performed by	Daniel Christian Torsvik
V&V Method	Analysis
Purpose	Check that the factor of safety of the support structure is at least 1.5
Equipment	SolidWorks CAD software
Conclusion	Running a finite element analysis (FEA) drop test on the SolidWorks model of the drone was a difficult and time consuming process. The reason for this is that the final assembly of the drone is huge. The final model contains 69 parts, and 21 of these are sub-assemblies, with a total SolidWorks assembly with 365 parts! This means that you will need a monster of a computer to run the test, and there is at least a thousand of things that can go wrong and cause an error, while running the drop test simulation. Since we didn't have a computer capable of running such a complex test at school nor at home, we had to do a lot of simplifications before we could even run try to run a test. And even after simplifying the model quite a bit, we still got countless of errors. After yet another handful of simplifications we finally got a support structure simple enough to run a drop test on. At least that was our initial thought. Even after stripping the support structure down to the bone, we still encountered problems. When meshing the support structure, we noticed that we needed to supress any fillets and chamfers on the model, to be able to mesh it properly. And we needed a very fine mesh to even get through the meshing without getting an error, and the finer the mesh, the more detailed result you will get. That is all well and good, but this also means that the test will take longer time to run, and at one point we had an expected test result to be ready in no less than 24 hours. This wasn't acceptable, and we had to rerun the meshing, yet again. We also encountered problems with the choice of material, seeing that we use carbon fiber and carbon fiber isn't a completely defined material in SolidWorks. Therefore, we had to search the internet for a data sheet that matched our "homemade" composite sheets. But even though this should

work properly, it is no guaranty for this, because SolidWorks and composite isn't exactly a perfect match.

Then, finally, after tens of errors running the simulation, we got a test result, with a seemingly accurate result. We defined a factor of safety (FOS) plot, and got a FOS of 2. This is within the requirements, ergo enough to pass the test. With this said, it was a very simplified test, and the test result need to be addressed accordingly.



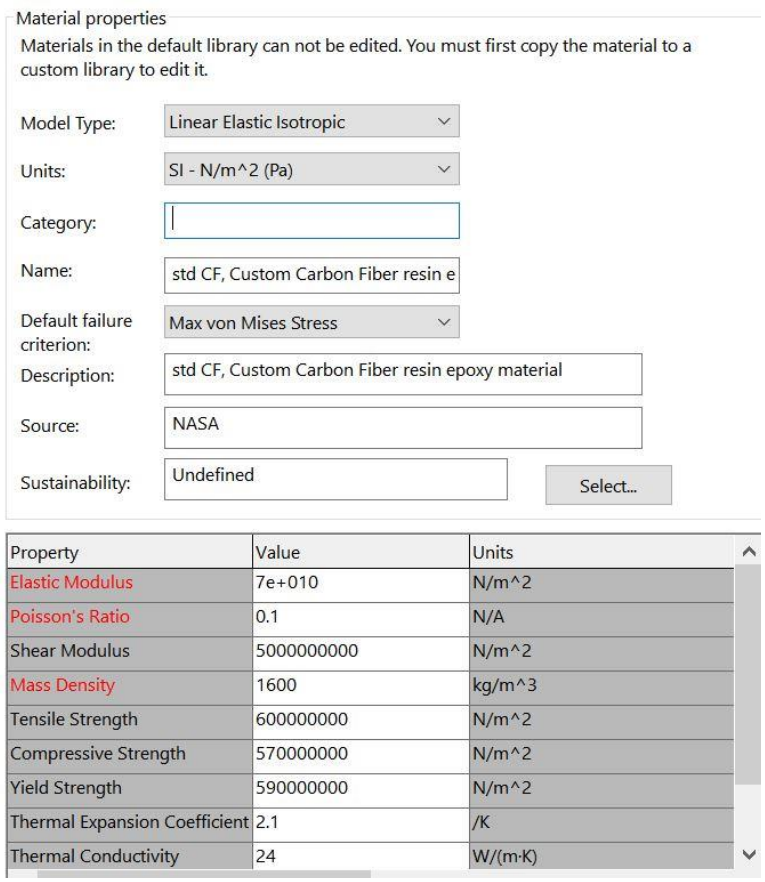


Figure 47: Drop test setup

Figure 48: Test underway

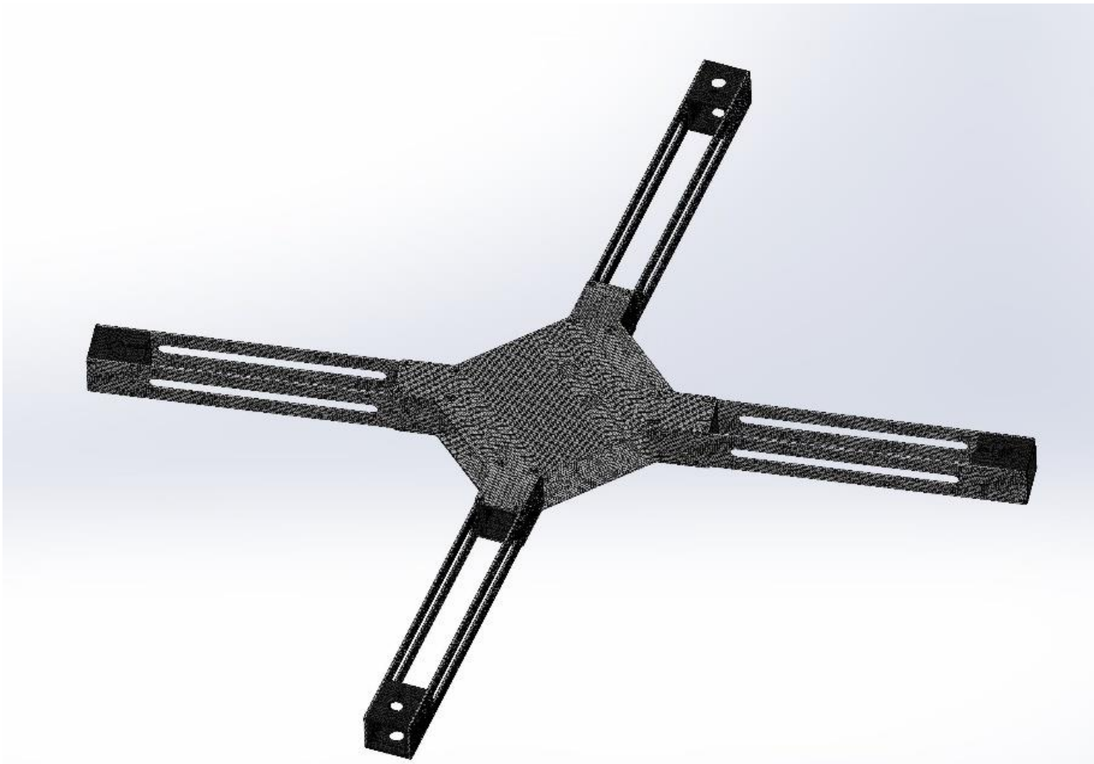


Figure 49: Fine mesh of model

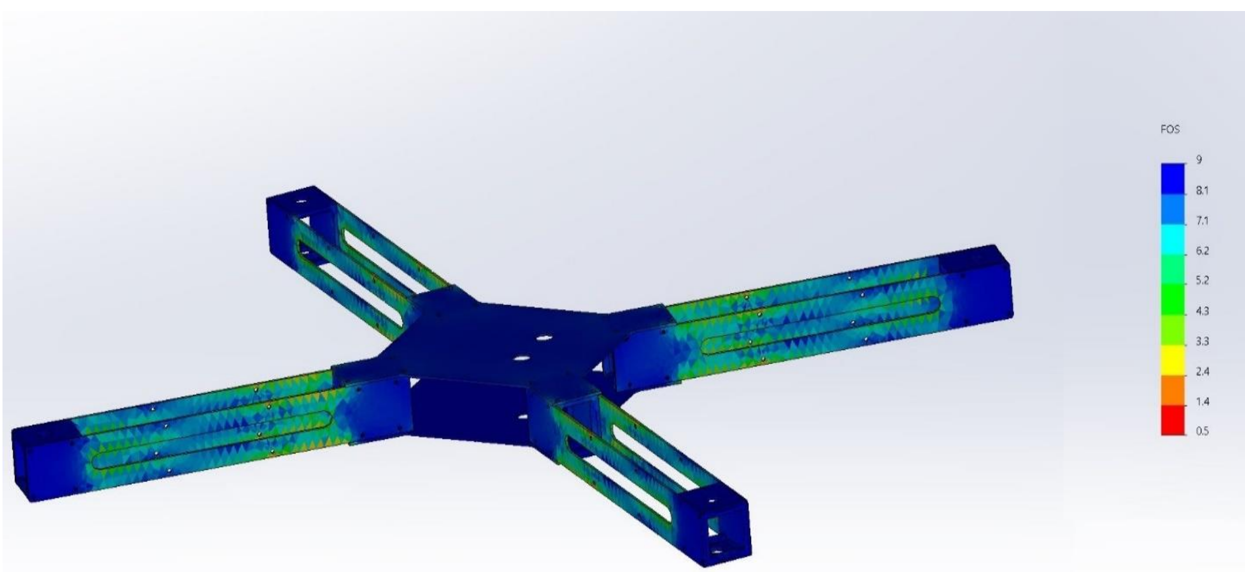


Figure 50: Result of FOS

TEST RESULT					
Test Report ID	TR34	Corresponding Requirement ID	NF17	Result	Passed
Corresponding Test ID	T34	Priority	C	Test date	21.05.2017
Test performed by	Daniel Christian Torsvik				
V&V Method	Inspection				
Purpose	Check that the drone can in fact carry the two different modular motor systems, allowing it to use both electric and internal combustion drive.				
Equipment	Camera, SolidWorks CAD software				
Conclusion	The drone was designed with the purpose of being able to carry different MMS to make it more versatile, and this was done very early in the design process. After building a prototype, we have been able to see that the support structure can carry a MMS outside of SolidWorks, at least for the MMS with an electrical motor. The MMS with an internal combustion engine was never realized, and is therefore only proven on a model inside of SolidWorks. But this is a good enough proof that the support structure can support both MMS, and the acceptance criteria is passed.				

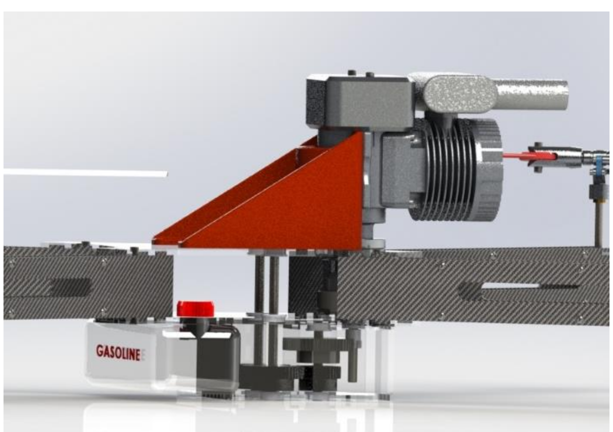


Figure 51: ICE MMS on frame

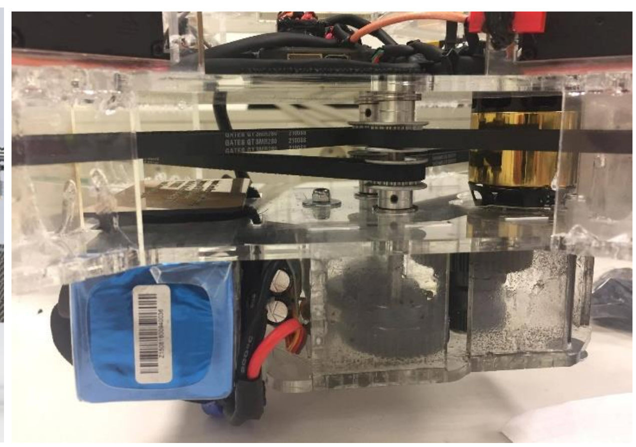


Figure 52: EM MMS on frame

TEST RESULT					
Test Report ID	TR35	Corresponding Requirement ID	NF20	Result	Passed
Corresponding Test ID	T35	Priority	A	Test date	13.05.2017
Test performed by	Severin Myhre				
V&V Method	Inspection				
Purpose	Fast swapping of battery and fast refuelling				
Equipment	SolidWorks CAD software, camera				
Conclusion	Both the battery on the EM configuration and the fuel tank on the ICE configuration are fastened with Velcro. The battery and fuel tank share a common mounting place on the airframe, using the same two strips of Velcro. CAD rendering was used to inspect the fuel tank. Only loosening the Velcro straps is needed to remove both the battery and fuel tank.				

Figure 53: Picture of battery, EM configuration

Figure 54: CAD rendering of fuel tank, ICE configuration

Unified Collective Pitch Quadcopter

User Manual	
Project Name	Unified Collective Pitch Quadcopter
Version	1.0
Number of Pages	22
Date of Publication	23.05.2017
Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Daniel Christian Torsvik

TABLE OF CONTENTS

1 Document Structure

1.1 Document History

Version	Date	Description	Author
0.1	26.04.2017	Creation of document. First outline/draft, introduction added. Warnings added	Daniel Christian
0.2	02.05.2017	About the system added, FAQ added, Abbreviations and Acronyms added, Maintenance chapter added, Warnings added	Daniel Christian
0.3	04.05.2017	RC chapter added, Figures added. Formatting, modular motor system chapter added	Daniel Christian
0.4	10.05.2017	Warnings updated, Figures added to MMS chapter, updated bibliography, text added in some of the chapters, proof-reading	Daniel Christian
0.5	19.05.2017	Formatting titles, UCPQ picture added, proof-reading, FAQ updated, Abbreviations in text fixed	Daniel Christian
0.6	20.05.2017	Added chapter 11 about recycling, figure added, updated bibliography	Daniel Christian
0.7	23.05.2017	Added 2D-drawings, Exploded View, BOMs etc. to chapter 6	Daniel Christian
1.0	23.05.2017	Final Release	Daniel Christian

1.2 Abbreviations & Acronyms

A & A	Explanation
HSN	University College of Southeast Norway
BOM	Bill of Material
EV	Exploded View
UCPQ	Unified Collective Pitch Quadcopter
FC	Flight Controller
ICE	Internal Combustion Engine
EM	Electric Motor
MMS	Modular Motor System
RPM	Revolutions Per Minute
VLOS	Virtual Line of Sight
EVLOS	Extended Virtual Line of Sight
BLOS	Beyond Line of Sight
UAV	Unmanned Aerial Vehicle
IMU	Inertial Measurement Unit
TX	Transmission (Telecommunications)
RPAS	Remotely Piloted Aircraft System
RC	Radio Controller
AFHDS	Automatic Frequency Hopping Digital System
dBm	Decibel-milliwatts
ASWA	Always Stabilized when Armed
LiPo	Lithium polymer
FAQ	Frequently Asked Questions

2 The Unified Collective Pitch Quadcopter

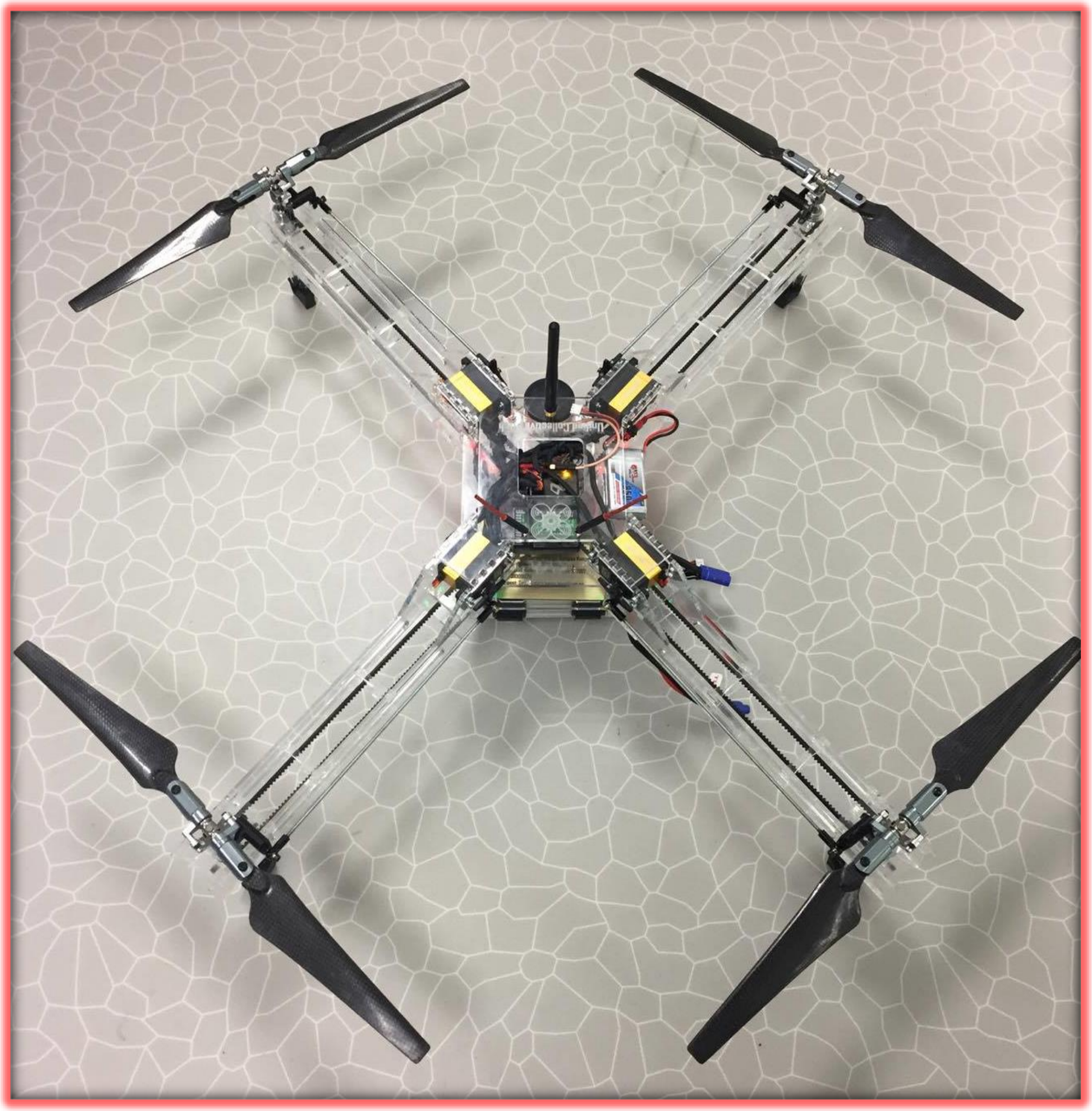


Figure 2.1: The Unified Collective Pitch Quadcopter

3 WARNINGS

Figure 3.1: Warning in different languages

- The Unified Collective Pitch Quadcopter (UCPQ) is not a toy, and must be handled with care! It is not suitable for children under 14 years of age
- It requires proper assembly and setup to avoid accidents and it is the operators' responsibility to operate the quadcopter in a safe manner
- The operator must always operate the quadcopter in Virtual line of sight (VLOS)to ensure safe flight, extended virtual line of sight (EVLOS) and beyond line of sight (BLOS) is not allowed if the operator doesn't have RO2 licence, or higher
- It is recommended that the quadcopter, because of its size and weight, is used outdoors preferable in a large, wide-open area
- It is recommended that if the operator is in any doubt of his/her abilities, should seek assistance from experienced people in this field, before trying it out for themselves
- If the UCPQ is equipped with an internal combustion engine (ICE), the system must be operated by a person with RO2 license or higher
- The quadcopter is to be used in daylight and with little or no wind. Windy conditions may overcome the flight controller (FC), causing possibility of damage or loss.
- While flying the UCPQ, keep it away from other electrical equipment, magnetic objects or radio devices, to avoid accidents caused by interference with each other
- While flying the UCPQ, keep great distance from airports and their runways
- Keep your hands, face, and body away from any revolving parts.
- It is illegal to use this system under the influence of alcohol
- Charge the product using the charging system provided with the battery and controller

Figure 3.2: Warning

4 INTRODUCTION

Congratulations, you are now the proud owner of the ground breaking Unified Collective Pitch Quadcopter (UCPQ)! The UCPQ is a great choice even if you are a beginner new to the hobby, or an intermediate 3D-flight pilot. With that said it is important for you to note that the UCPQ is quite different than the vast majority of quadcopters on the civilian market which use four engines, one engine per arm, directly connected to the propeller. Because of this difference, it will require more from you as an owner/operator, both pre-flight and during flight. The operator of this system when powered by an electrical motor (EM), does not have to have to have a specific license to be allowed to fly the UCPQ because the quadcopters take-off mass is less than 2.5kg. But we strongly recommend that the operator of the UCPQ reads and understands the regulations set in country of use, before first flight, this is very important. A radio controller (RC) with Helicopter programming is recommended to be used with this system for the best flight result. No spare parts are included in this package.

5 DESCRIPTION OF THE SYSTEM

The UCPQ is a single engine quadcopter with variable pitch mechanism, and that combined with its X-shaped design and Modular Motor System (MMS), makes it quite a unique quadcopter. By using one engine instead of one engine per arm, the quadcopter will not only be more efficient than its peers, but it is also much more manoeuvrable. The power transmission solution is also carefully planned and designed to make it possible to power the quadcopter with an EM or an ICE, whether it be nitro or gas. To make the transmission of this aforementioned finesse go as smooth and fast as possible, the quadcopter is equipped with a unique MMS. This MMS, enables the user to switch between propulsion systems without having to disconnect/connect all the tubes and wires needed for the different propulsion systems to work. By simply connecting the MMS where for instance the ICE is mounted, with the fuel tank and tubes already connected and assembled, configuring the system becomes nearly effortless.

The power transmission from the EM or ICE, which is assembled on to the MMS uses different gears to decrease revolutions per minute (RPM) given from the engine/motor, to the correct RPM needed to fly the UCPQ. Then the power transmission from the gears, is transmitted via belts and belt pulleys, to the propellers and gives them the correct speed and spin direction needed for flight.

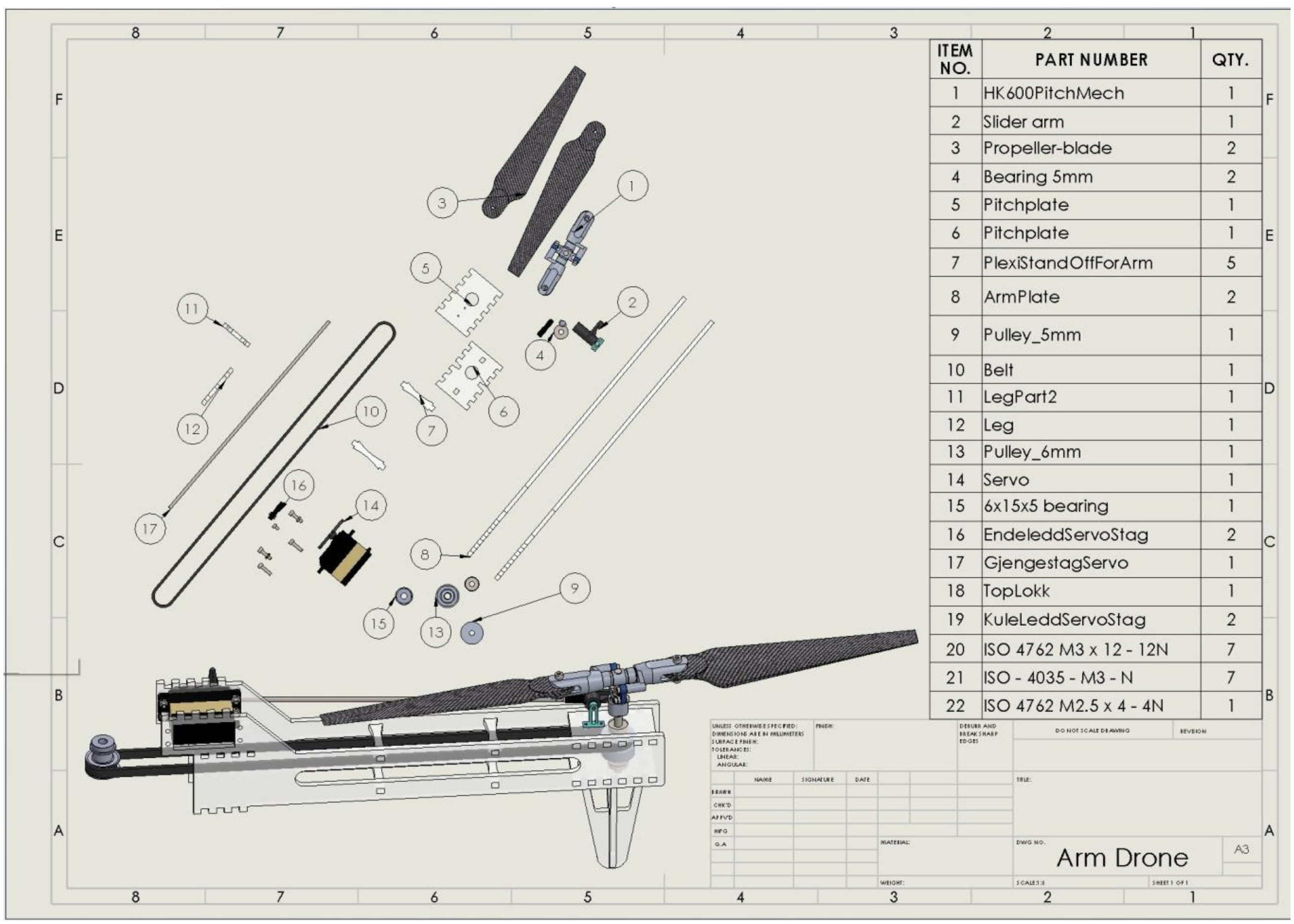
The UCPQ is below 2.5 kilograms, and therefore the operator of this system does not have to have a license to fly it. But this only applies if the UCPQ is used with an MMS with an EM attached. If the UCPQ is to be used with an MMS with an ICE attached, the operator will need a license to fly the system.

6 BILL OF MATERIAL & EXPLODED VIEW

As you know the Unified Collective Pitch Quadcopter is a complex system and consist of a lot of different parts and sub-assemblies. To make it easier for you as a user to understand the system,we have made 2D-drawings, bill of materials and exploded views of the different bulks of the system.

6.1 DRONE ARMS

In figure 6.1 you can see a 2D-drawing of one out of the four arms on the quadcopter, and an exploded view of this. Together with the bill of material (BOM) on the right side of the drawing, we hope to give you an overview of what and how many parts that are inside of the Unified Collective Pitch Quadcopter. As this is only one of the four arms, you must multiply the quantity in the BOM by four, to get the correct number of parts. Note that multiple instances of the same item are not marked with an annotation.



ITEM NO.	PART NUMBER	QTY.
1	HK600PitchMech	1
2	Slider arm	1
3	Propeller-blade	2
4	Bearing 5mm	2
5	Pitchplate	1
6	Pitchplate	1
7	PlexiStandOffForArm	5
8	ArmPlate	2
9	Pulley_5mm	1
10	Belt	1
11	LegPart2	1
12	Leg	1
13	Pulley_6mm	1
14	Servo	1
15	6x15x5 bearing	1
16	EndeleddServoStag	2
17	GjengestagServo	1
18	TopLokk	1
19	KuleLeddServoStag	2
20	ISO 4762 M3 x 12 - 12N	7
21	ISO - 4035 - M3 - N	7
22	ISO 4762 M2.5 x 4 - 4N	1

Figure 6.1: 2D Drawing, Exploded View & BOM of one of the four arms

6.2 Electric Motor Configured MMS

In figure 6.2 you get a detailed overview of all the parts of the EM configured modular motor system, and the quantity of these. This will give the user a good understanding of the structure of the MMS. This can be helpful in many ways, for example if the MMS needs repairing and the only way to fix it is that the user must take it apart.

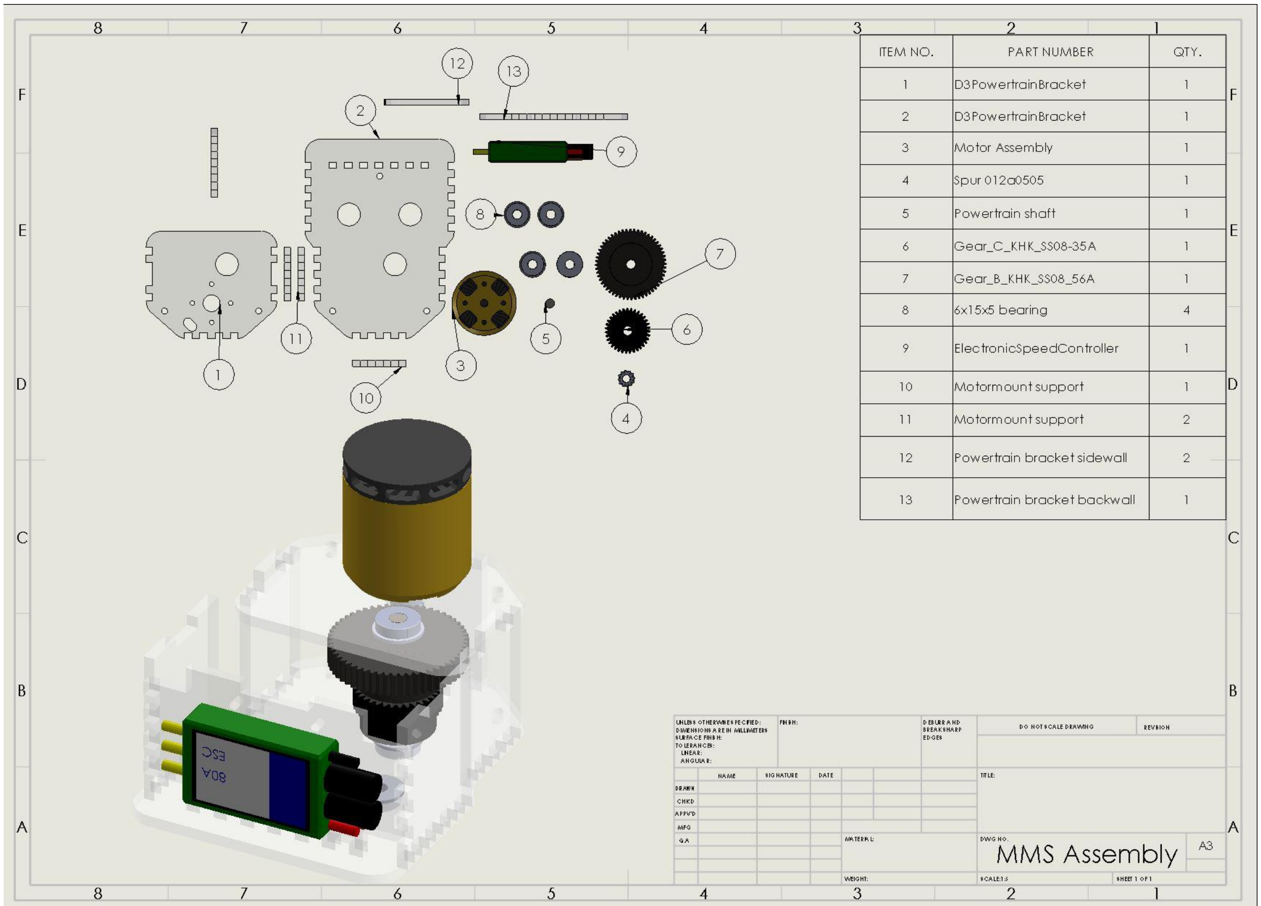


Figure 6.2: 2D drawing, Exploded View & BOM of the MMS

6.3 INTERNAL COMBUSTION ENGINE CONFIGURED MMS

In figure 6.3 you get a detailed overview of all the parts of the ICE configured MMS, and the quantity of these. This will give the user a good understanding of the structure of the MMS. This can be helpful in many ways, for example if the MMS needs repairing and the only way to fix it is that the user must take it apart. Note that the frame of the MMS, with no annotations is identical to the frame in the EM configured MMS.

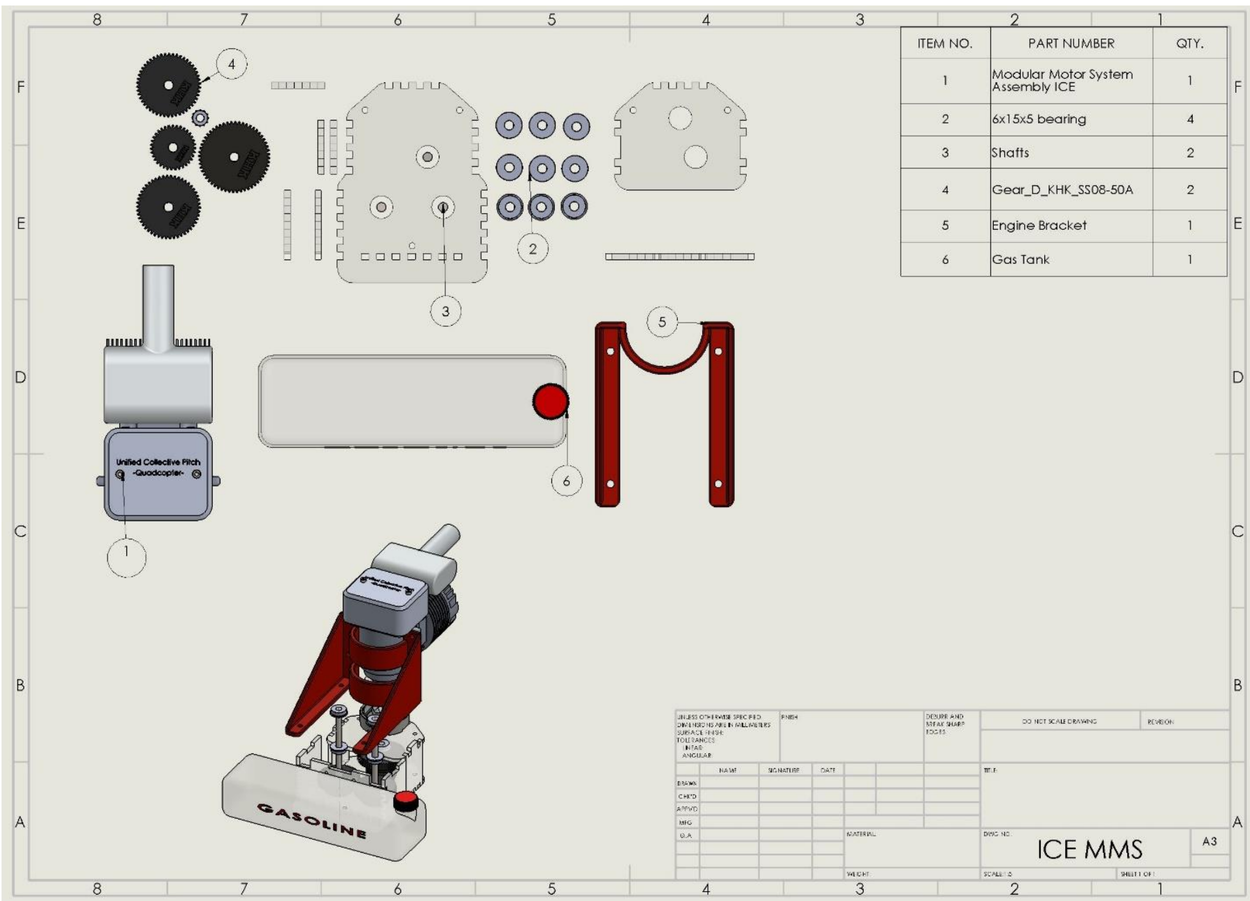


Figure 6.3: 2D drawing, Exploded View & BOM of the MMS

6.4 MIDSECTION

In figure 6.4 you can see a 2D- drawing, an exploded view and a bill of material of the midsection of the drone. This midsection would be a bit more complex than this because of wires from the receiver, flight controller, lights and so forth, but the principle of this 2D-Drawing is on point. Put all these 4 bulks, or sub-systems section 6.1, 6.2, 6.3 & 6.4 together, and you will have the complete overview of the different parts the UCPQ consists of.

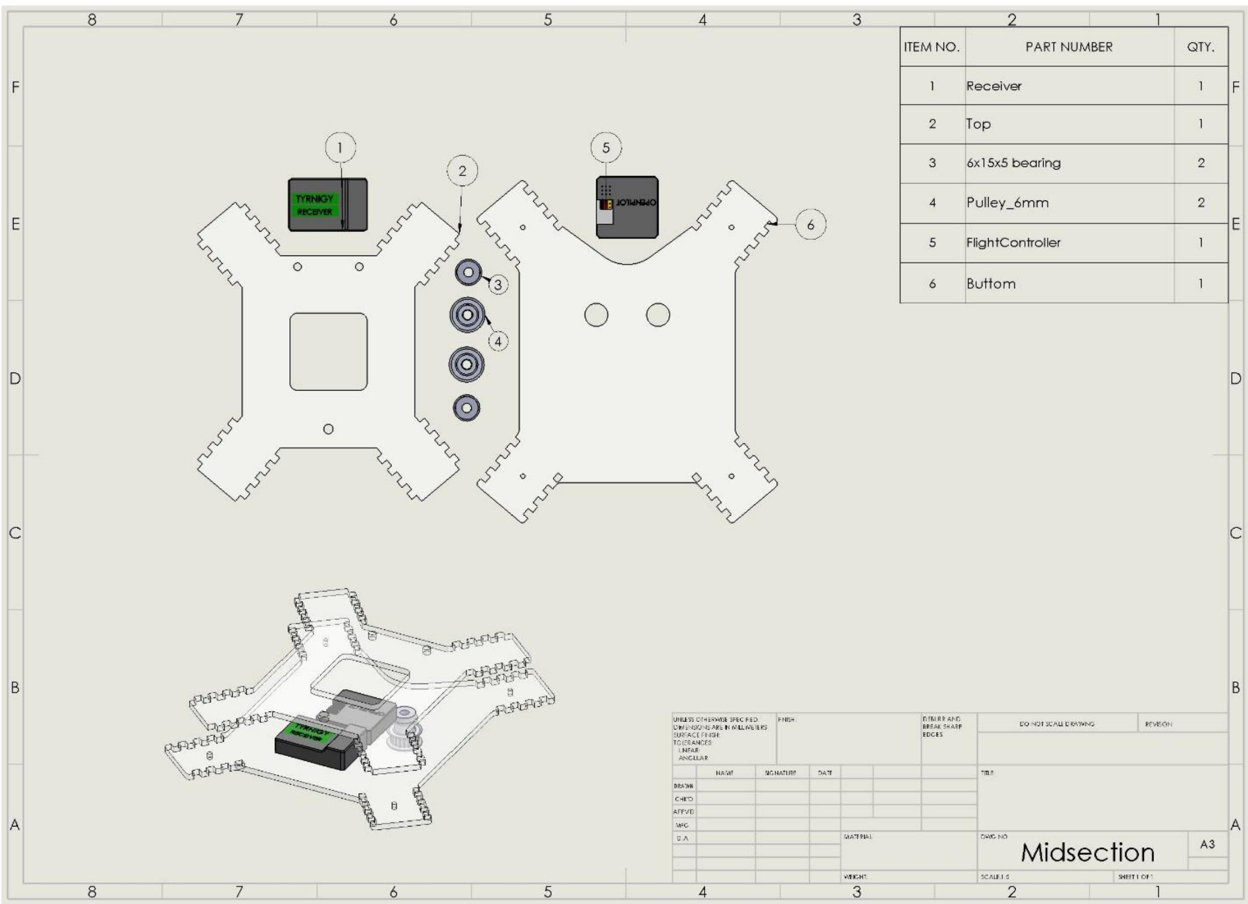


Figure 6.4: 2D drawing, Exploded View & BOM of the Midsection

7 RADIO CONTROLLER

The UCPQ can be controlled by many different radio controllers, and it is up to you as the owner and user of the quadcopter to choose which RC you want to use. The only thing you should keep in mind is that you use an RC made specifically for RC Helicopter/Multicopters with a minimum six channels. The reason behind this is that you must be able to control the steering mechanisms such as throttle, yaw, pitch, roll. And you will also need to be able to arm the quadcopter and chose flight mode. Albeit a RC was not included when you bought the UCPQ, we have modified it to use a Flysky FS-i6 RC Helicopter Multicopter, and therefore it will be most convenient for you to get your hands on one of these. As previously mentioned, this doesn't lock you to use this type, you can still buy another of your liking, and with some small modifications it will work just as well.

7.1 SPECIFICATIONS

7.1.1 FLYSKY FS-I6 2.4G 6 CHANNEL TRANSMITTER WITH LIQUID CRYSTAL DISPLAY

- Bandwidth: 500 Kilohertz
- Radio Frequency power: Less Than 20dBm
- Radio Frequency receiver sensitivity: -105dBm
- 2.4 Gigahertz System: AFHDS
- Sensitivity: 1024
- Low voltage warning: Less than 4.2 Volt
- Power: 4x 6 Volt 1.5AA

7.2 RECOMMENDED RC

Figure 7.1: Radio Controller for RC Helicopter/Multicopter. Flysky FS-i6

7.3 OPERATING INSTRUCTIONS

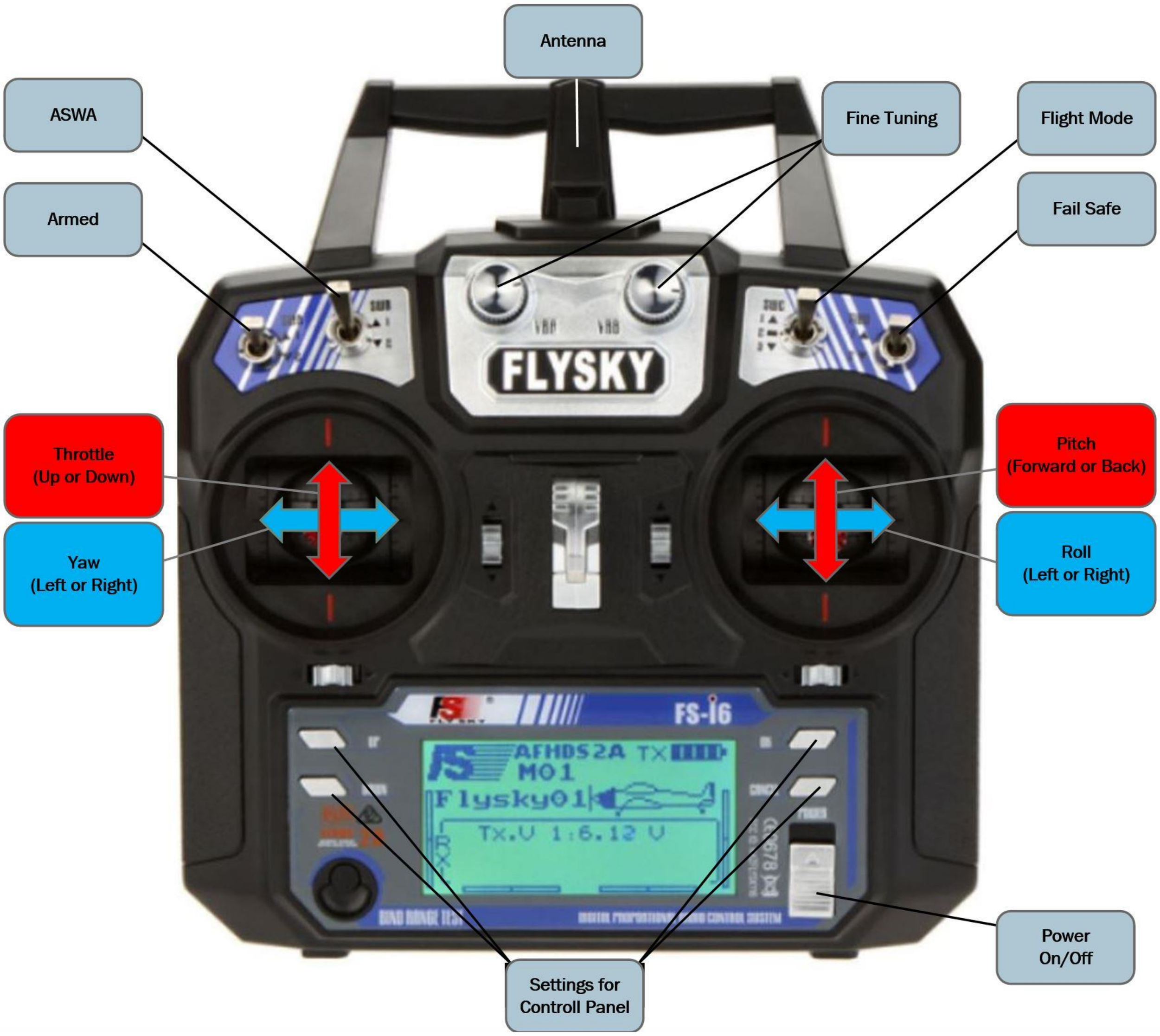


Figure 7.2: Operating Instructions Flysky FS-i6

7.4 CONTROL METHOD

Thottle Up	Push the left stick up, the rotational speed of the propellers increase, and the UCQP begins to ascend
Throttle Down	Pull down the left stick, the rotational speed of the propellers increase, and the UCQP begins to descend
Yaw Left	Push the left stick to the left, this rotates the UCQP left, this helps with changing directions while flying
Yaw Right	Push the left stick to the right, this rotates the UCQP right, this helps with changing directions while flying
Pitch Foward	Push the right stick forward, this tilts the UCQP, which manoeuvres it forwards
Pitch Back	Push the right stick backwards, this tilts the UCQP, which manoeuvres it backwards
Roll Left	Push the right stick to the left to roll the UCQP, which manoeuvres it to the left
Roll Right	Push the right stick to the right to roll the UCQP, which manoeuvres it to the right

Figure 7.3: Controller Instructions Explained

7.5 READY TO FLY

- Turn on the RC
- Set the UCPQ on a clear area of ground and connect the battery if powered by an EM, or start the engine if it is powered by an ICE
- Make sure there are no obstructions, power lines, animals or people nearby
- Step about two meters away and make sure the rear of the UCPQ is aimed towards you
- Make sure that the left stick on remote is at its minimum position
- Get ready for take-off

8 MODULAR MOTOR SYSTEMS

The MMS is a unique feature found in the UCPQ, which is made to make the transition from an EM to an ICE or vice versa, go much faster and smoother. This feature will make it less of a hassle and it makes sure that less things that can go wrong in the assembling. E.g. wrong wiring or tubing. There are different gears attached to the MMS, and this makes sure you get the correct RPM to the propellers. Because of this you can simply mount the MMS with the propulsion system you want, to get the flying experience you want, when you want it, without having to clear your calendar to do so.

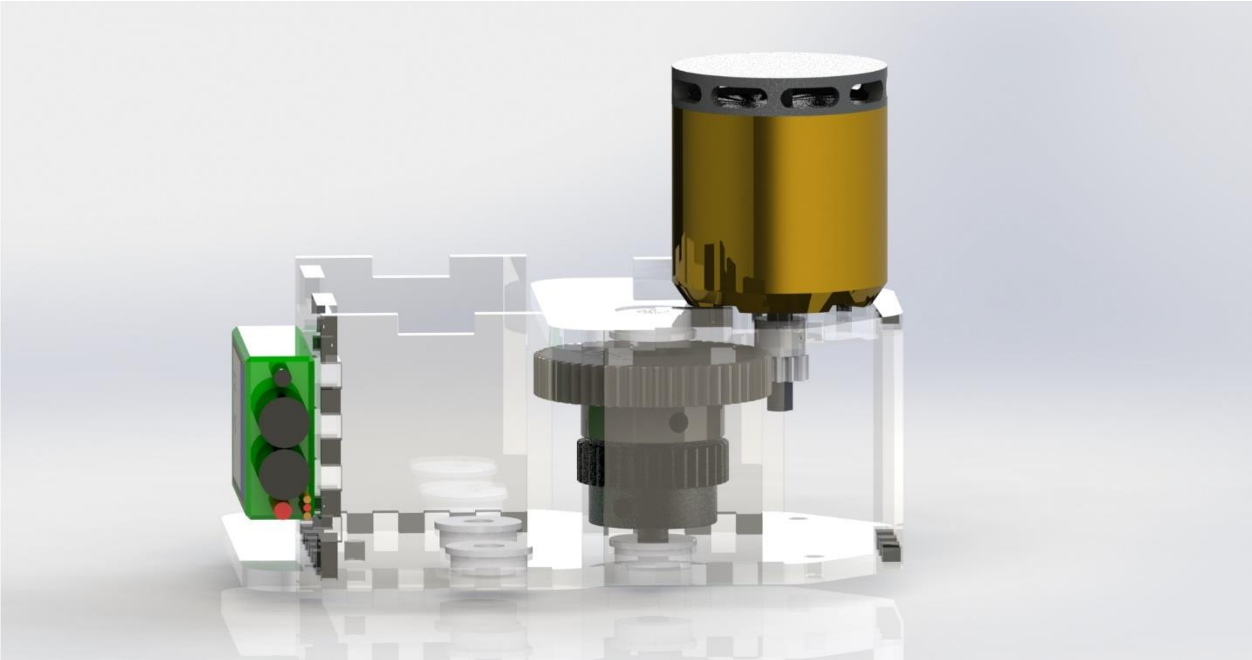


Figure 8.1: Electric Motor configured Modular Motor System

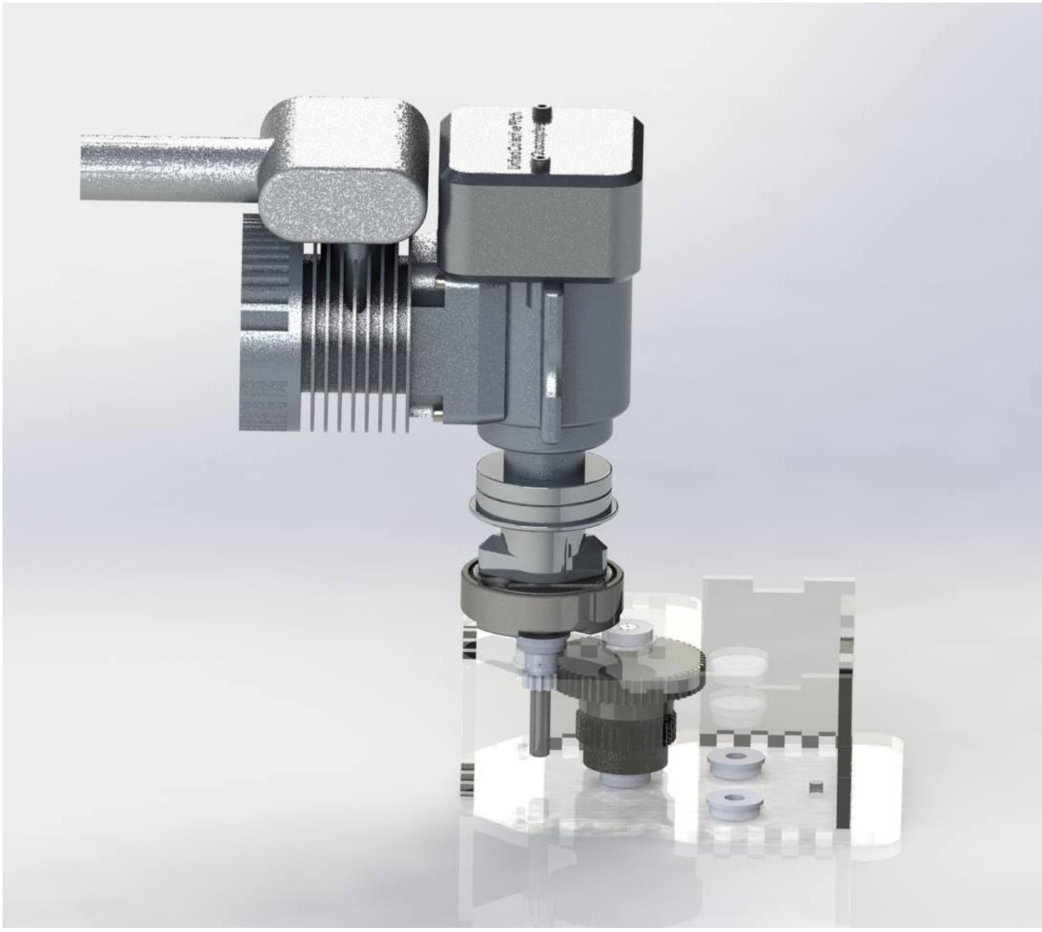


Figure 8.2: Internal Combustion Engine configured Modular Motor System

9 MAINTENANCE

Drones and quadcopters are delicate systems, and even thought the UCPQ is a robust quadcopter compared to many of its likes, it is still a complex system with many moving parts, which need to be maintained properly and regularly. The reason you as a user should take this seriously and use considerable time on maintaining the system, is to be sure the system is safe for you or others to operate, and of course to reach longest possible life span of the system. Maintenance is in other words important concerning both your safety and with your wallet in mind.

"Flying the UAV for commercial use is roughly 10% of the actual job, the other 90% is made up of UAV maintenance/monitoring" [3]

9.1 MAINTENANCE CHECKLIST

9.1.1 BEFORE & AFTER EVERY FLIGHT (EM)

- Check condition of propellers and the variable pitch mechanisms
- Check if the motor is freely spun by hand
- When powered up and idling confirm no unusual noise or vibration from motor
- Check condition of battery connectors and data pins recording the flight battery voltage

9.1.2 BEFORE & AFTER EVERY FLIGHT (ICE)

- Check condition of propellers and the variable pitch mechanisms
- Use fuel filter when fueling to prevent any debris to entering the engine
- Check condition of the fuel line

9.1.3 EVERY WEEK OR EVERY 10TH FLIGHT

- Visual inspection of composite sheets and other components for cracking/damage
- Check tightness of motor or engine retaining screws
- Check if belts are thigh enough for safe flight
- Check TX & IMU calibration state and if all battery cells have good balance
- Oil the variable pitch mechanisms and gears
- Take the engine head apart, then clean and grease the thrust bearings and dampeners (ICE)

9.1.4 Once a Month

- Check the state of all wiring.
    - That plugs are fully seated
    - Condition of all solder joints is okay
    - Condition of visible circuit boards and wiring runs
    - That the quadcopter is generally clean and got no debris/loose items
- Replace the dampeners if needed (ICE)
- Check for firmware updates for the RC

10 Retirement of the UCPQ & its sub-systems

The Unified Collective Pitch Quadcopter is a complex system, and contains many different components such as electronics and LiPo batteries, as well as a carbon fiber frame. And seeing ourselves as an environment friendly company it is important for us that the UCPQ is handled correctly when it comes down to the retirement of the system, or its sub-parts. Therefore, we strongly recommend you as an owner and user of the system, to follow guidelines given from your local authorities regarding where to throw away different components which is harmful to the environment.

The retirement for sub-systems will arrive sooner or later, take LiPo batteries for instance ¨LiPo batteries have a limited cycle life, every time you charge and discharge, it is 1 cycle. The battery will begin to lose punch (internal resistance increasing), and capacity. It's said a Lipo battery could be used over 300 cycles if looked after properly" [6] Old or damaged Lipo batteries should be disposed of properly, and there are many companies out there that know how to handle electronics and batteries in the best possible manner. And we know for a fact that most electronics stores got a delivery point where the customers can throw away waste electronics. Please be kind to use this or any similar options out there.

The recycling of carbon fibers is not that available, but there are companies who recycle composite waste, such as a broken carbon fiber frame which is installed on your very own UCPQ. Seeing that carbon fiber is expensive to produce and got a very long lifetime, it would be a shame throwing it in the garbage at home or even worse in to the wild, both from an economic and environmental perspective. The Adherent Technologies, Inc. [7] is an example of a company who recycle and reclaim carbon fiber, visit their homepage for more information about composite waste recycling.

If you get tired of the UCPQ, which in some rare cases can happen, even though it is a very farfetched thought. Or the UCPQ got some broken parts you just simply don't have the time or energy to fix, we recommend sites such as conservationdrones.org [8] and dronegeneral.com [9], where you can donate your drone to other drone lovers out there. Selling your drone to the highest bidder is also an option you have.

Figure 10.1: Dispose of Waste Electronics Properly

11 FAQ

Question: Can I use the system indoors?

Answer: There is nothing stopping you from using the UFPQ indoors if you power it with an electrical motor. With that said, we strongly recommend that you use it outdoors.

Question: Do I need a license to fly the UCPQ?

Answer: You do not need a license to fly the UCPQ if you power it with an EM and follow all the guidelines. E.g. fly it in VLOS. But if you power it with an ICE, you will need a license.

Question: How do I switch between propulsion systems?

Answer: See chapter 7 in this user manual for the instructions, this chapter explains it well. If you still struggle, call support and they will guide you through it step by step.

Question: What do I do if the one or more propellers get broken?

Answer: We strongly recommend having some spare parts, such as propellers at hand whenever you're out flying the UCPQ. You never know when you will need it.

Question: Can I use another RC than the one described in this user manual?

Answer: Yes, if you buy a RC designed to be used on RC Helicopters/Multicopter there shouldn't be any problems.

Question: Can I mount a camera to the UCPQ? If yes, are there any limitations of what I can film/take pictures of?

Answer: Yes, that is possible. But remember that the UCPQ weight, including payload, can't be greater than 2.5 kilograms, if the UCPQ is to be used without a license. For now, normal privacy laws would seem to apply to image and audio capture from drones that apply in general. For the most part, one can record or photograph in contexts where there is no "reasonable" expectation of privacy. We recommend that you don't record video or take photos in contexts where there is an "expectation of privacy." [10]

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Unified Collective Pitch Quadcopter

Conclusions & Recommendations

Project Name	Unified Collective Pitch Quadcopter
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Project Team	Thomas Huse, Severin Myhre, Ann-Mari Snekkerhaugen, Joakim Thorvaldsen, Anastasia Timofeeva, Daniel Christian Torsvik
Authors	Severin Myhre, Anastasia Timofeeva, Ann-Mari Snekkerhaugen

TABLE OF CONTENTS

1 ABSTRACT

This document summarizes all advantages of our quadcopter, as well as a plan for further development of the project. In addition, the document describes the main challenges the project group have met during this semester, what we have put together, and what we would have done differently if we could.

2 Document structure

2.1 Document history

Version	Date	Description	Author
0.1	09.05.2017	Document is created, section 5 added	Anastasia, Ann-Mari
0.2	17.05.2017	Section 4 added	Severin
1.0	23.05.2017	Section 1 updated, 2, 6 added, section 3 added, updated 2.2, Formatting.	Anastasia, Ann-Mari, Severin

2.2 Abbreviations & Acronyms

A&A	Explanation
UCPQ	Unified Collective Pitch Quadcopter
RPM	Revolutions per minute
UAV	Unmanned aerial vehicle
EL	Electrical
ICE	Internal combustion engine
R&D	Research and Development
GPS	Global Positioning System
MMS	Modular Motor System
RO1	Remotely Operated 1, Norwegian Civil Aviation Agency classification

Term	Definition
Project Group	Students who are working under the project
Customer	Employer, University College in Southeast Norway
Project	Task that students received from customer
System	Unmanned aerial vehicle that students are designing

3 ADVANTAGES OF UCPQ

The Unified Collective Pitch Quadcopter (UCPQ) is a unique creation representing new possibilities to the world of unmanned aircraft. It has been design by a dedicated team with flexibility of use and exploring technology as key efforts.

As a direct result of having variable pitch propeller blades, the drone is more responsive to control inputs than conventional quadcopters. Conventional quadcopters must increase the rotational speed of the propellers in order to accelerate, and the inertia or the rotors means that there is a considerable delay from control input to the drone responding. At the same time, the UCPQ needs only turn a servo motor to adjust the propeller pitch angle and increase or decrease thrust. The propellers are mechanically connected to the same propulsion system and run at the same revolutions per minute (rpm). As the rpm is kept constant during acceleration, the rotational inertia of the propellers is also kept constant. The mechanically adjusted propeller thrust levels of the UCPQ allows for agile manoeuvres, and a responsiveness not seen in conventional quadcopters.

The flight controller of the UCPQ is equipped with a barometer, allowing for attitude hold. The attitude hold is activated with the flick of a switch on the radio controller. This makes it very easy for the pilot to maintain altitude while in flight, and adds to the user friendliness or the system.

Other collective pitch quadcopters are commercially available, such as the “WL-toys v383”, “Aeritech 3DQ”, “Hobbyking Assault Reaper” and “Curtis Youngblood Stingray 500”. These collective pitch drones use belts for power transmission like the UCPQ, but unlike the UCPQ their belts are twisted. They all use an H-configuration propulsion system with a central shaft and belts going out to the rotors. Their belts must then be twisted 90 degrees in order to connect with the rotor pulleys, as shown in figure 3.1. Twisting the belts cause dynamic stress concentrations in the belts, reducing longevity.

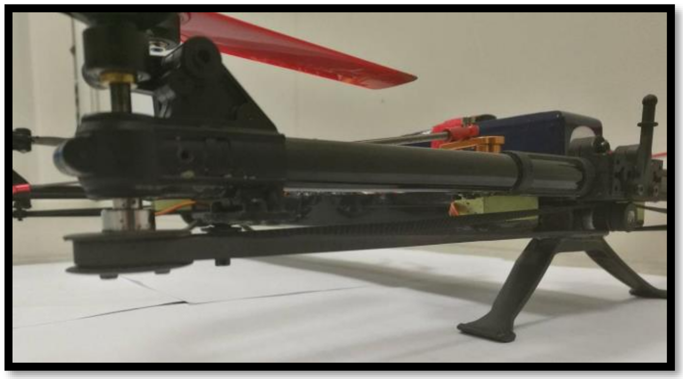

Figure 3.1: Twisted belts of the commercial WL-toys-v383 quadcopter

We have given the UCPQ a more elegant power transmission architecture with straight belts. By mounting the motor shaft in a vertical position, all shafts have equal orientation, and the belts can connect the rotors to the central pulleys whilst remaining straight. No twisting of the UCPQ's belts is needed, and stress concentrations in the belts are avoided [fig. 3.2]

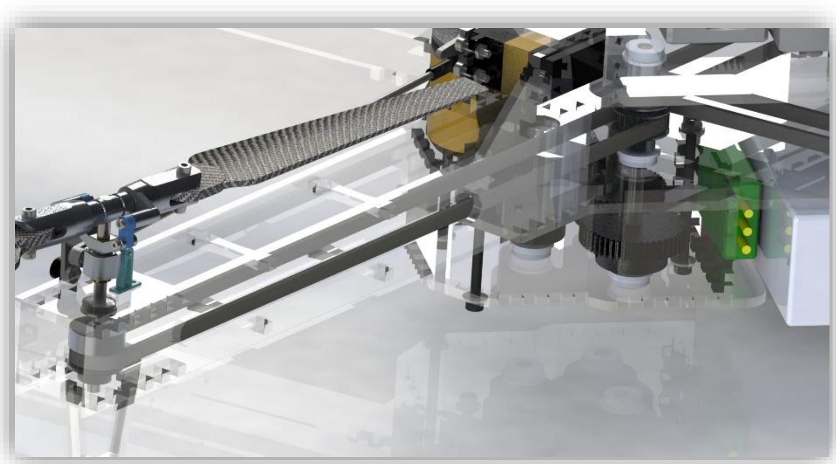

Figure 3.2: The straight belts of the UCPQ

One of the most striking features of the UCPQ is the Modular Motor System (MMS). The MMS is a bracket assembly containing the motor and all gears. The result of this system is that the entire motor with gears can be removed simply by unscrewing the three bolts attaching the MMS to the airframe. The MMS allows for transitioning from an electric motor to an internal combustion engine in a straight forward manner. As a function of the MMS, the UCPQ is inherently more customisable than comparable drones and offers the ability to configure the system to your needs. Only a wrench and an M4 Allen key is needed to install the desired motor [fig. 3.3].

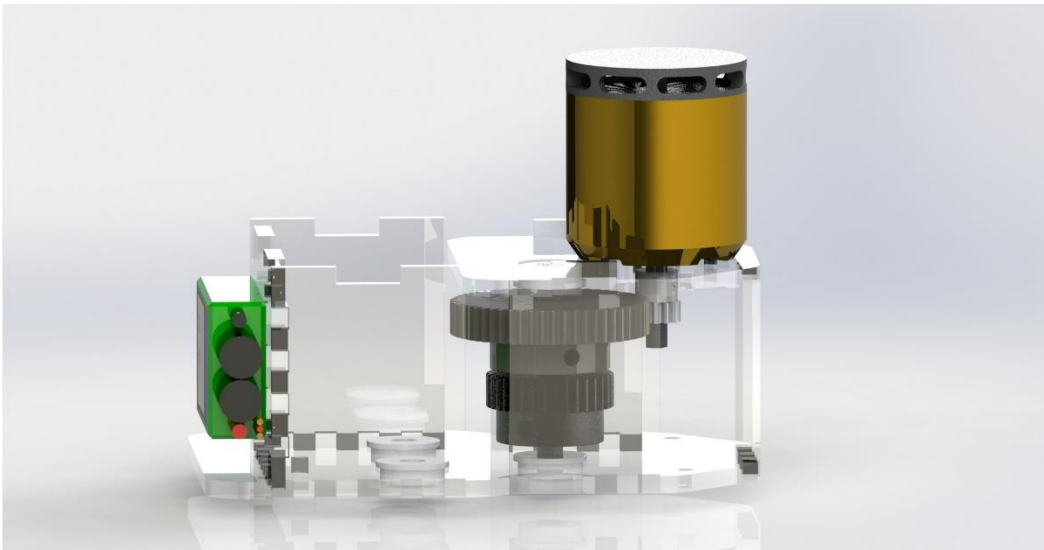

Figure 3.3: The prototype's MMS

4 THE ROAD AHEAD

4.1 STAGE ONE

- With the experience gained from the prototype, we will design and build the final production version of the drone. This includes using the original gears intended for the drone, which are lighter compared to the ones used in the prototype. In addition, the entire fuselage will be made of carbon fibre. Based on prototype testing, weight reduction of the airframe will be made wherever appropriate. This final design with these changes will have a mass of 2416 kg, which is within the RO1 certification [see Appendix A- Weight Budget].
- The ICE configuration of the drone will also be built. It will act as a demonstrator and commercial tool for the drone, showcasing its capabilities and flexibility. Please see the Design Decision, section 5 for further understanding.

4.2 STAGE TWO

- The internal combustion engine configuration will burn fuel as it is flying, meaning the mass of the system will decrease. Required thrust is reduced with reduced mass. We will add a way for the system to self-regulate motor power output, so that the output can change as the mass of the system changes. This will be done through an algorithm based on estimated fuel use per unit time, or with measuring the vertical acceleration during hover, having an algorithm regulate the engine output power such that the minimum power is delivered to keep the vertical acceleration zero. A third way is to add a fuel gauge in the form of a float connected to a potentiometer. As fuel is burnt and required thrust is reduced, the engine output power is reduced accordingly. The result is increased flight-time.
- The flight-controller has an input port for GPS antenna and an integrated 433MHz radio with antenna input port. The 433MHz antenna is already installed, only the receiver is needed. Installing the GPS antenna and acquiring the 433MHz antenna will drastically increase the controllable range of the drone. Through the computer program LibrePilot GCS (Ground Control System), the drone can be controlled from a PC. Through the PC interface, waypoints can be set and the drone will fly to the coordinates using GPS. Waypoint navigation combined with an internal combustion engine with a large fuel tank will create new uses for the system.

4.3 STAGE THREE

- Measure market interest. Based on the public's response to the drone, register a company, and make plans for commercial production or alternatively use it as a demonstrator / testbed for future drone technology.
- If commercial production, the system will be sold in both its EL and ICE variant. They will be sold ready-to-fly out of the box, "factory certified".
- Check potential for registering patents.

5 SUGGESTIONS FOR PROJECT IMPROVEMENTS

5.1 WEIGHT CHALLENGE

The current take-off mass of the drone is over 2.5kg. The reasons and possible solutions for this challenge are described underneath.

As calculated before, each propel produce of 4 kg [section 7.6 of the Technical Document], making the overall thrust for the quadcopter 12 kg. We have calculated and designed the power transmission system based on these thrust data. The conclusion was that the main components as gears, shafts, bearings should be made of steel, and some (like pulleys) can be made of aluminium. This is due to high stresses developing in rotational parts at high rpm (for more details see section 4 in Transmission System of Technical Document).

We have checked several suppliers of small mechanical components for our system around the world, including Norway, US, UK and China. We found out, there is a vast variety of products of different dimensions in polymer, but very few in steel and aluminium. Finding the right products has also been challenging, because some suppliers do not deliver the products to Norway.

The two requirements below are related to the mass of the system:

I.D.	Requirement	Priority	Origin	Reviewed
C05	The system shall be compliant to CAA classification RO1	C	Customer	20.04.17

I.D.	Requirement	Priority	Origin	Reviewed
C05.2	The system's take-off mass shall be ≤ 2.5 kg	C-A	Norwegian CAA	20.04.17

As soon as we have received most of the parts, we have compared the estimated weight budget (see more details in Iteration Protocol of Systems Engineering Document: Iteration 2, section 2.4 Technical Budget) with the actual weight budget [see Appendix A - Weight Budget]. We have found out that our preliminary estimations were quite low, as we assumed at the beginning that transmission system could be made of polymer items. Afterwards, having made thorough calculations regarding torques and stresses in the system, we concluded that the main transmission system components should be made of steel.

In bending stress calculations, we have found out that with safety factor 3.22 bending stresses range between 300-400 MPa (see 4.7.4 Material for gears of Technical Document). We have been in contact with "Eie Maskin AS" and "Tandhjulsfabrikken AS", who specialise in manufacturing gears to specific customer requests. However, purchasing gears made to a tailored order would have been outside of this project's financial budget.

From the table below you can see that tensile strength is highest for titanium, but it is most expensive. So, steel at a reasonable price and enough strength has become the most optimal solution. As a result, the weight budget has increased with steel parts.

Material	Density, g/cm^3	Specific Gravity, -	Tensile Strength, MPa	Young Modulus, GPa	Bending Strength, MPa	Cost, USD/pinion gear, 12 teeth
Acetal	1.57	1.40	75.80	3.10	89.6	50
Nylon	1.64	1.14	82.70	2.93	103	50
Aluminium	2.70	8.00	310	68.9	310	10
Stainless steel	7.81	7.70	505	200	505	30
Titanium	4.51	4.5	800-1200	115	600-1200	200

Table 5.1: Comparison table: material properties

5.2 SOLUTIONS TO REDUCE WEIGHT

5.2.1 GEARS

The first gears we ordered, were sold out at our supplier - SDP/SI. We had to estimate the weight using Solidworks and material properties, as the weight data were not specified in the data sheets. The estimation was within the weight budget. Then it turned out, that waiting time was approximately 4-6 weeks before the items could be sent from the US. The parts wouldn't reach us in time. That was the reason why we had to cancel the order and find other items/suppliers.

Gears	Material	Mass properties from SW, g	Pitch diameter, mm	Face width, mm	Supplier
Spur D, 2 items	Carbon Steel	134	40	4	SDP
Spur C	Carbon Steel	23	28	3	SDP
Spur B	303 Stainless Steel	75	44.8	5	SDP
Spur A	303 Stainless Steel	5	9.60	5	SDP
Total weight		237			

Table 5.2: First order from SDP

Then we had to find other products. We looked at gears with the same module, same pitch diameter and same number of teeth.

We were quite satisfied with SPD and KHK in the US, but they were sold out in SPD, and KHK did not ship to Norway. But with further research, we found a subcontractor of KHK in the UK where we found gears with the same criteria that we were looking for.

The only and most crucial detail we missed when placing the order, was the width of the gear (thickness of the item). The gears turned out to be much heavier than we estimated with the previous gears in Solidworks.

Gears	Material	Actual weight, g	Pitch diameter, mm	Face width, mm	Supplier
Spur D, 2 items	Carbon Steel	222	40	8	KHK
Spur C	Carbon Steel	63	28	8	KHK
Spur B	Carbon Steel	129	44.8	8	KHK
Spur A	303 Stainless Steel	5	9.60	5	SDP
Total weight		419			

Table 5.3: Actual gears ordered

Figure 5.1: Gears ordered from KHK

Our possibilities for reducing the system weight are:

1. Cut and turn the gears in a lathe
2. Order gears at a special order at some manufacturing company
3. Order new gears from another supplier with smaller width
4. Continue the process with the gears we have received

Possibility 1:

Weight of the gears can be reduced in a lathe. The width of the gear hub can be reduced, and holes can be made without affecting the gears, see figure 5.2 for an understanding of the gear reduction.

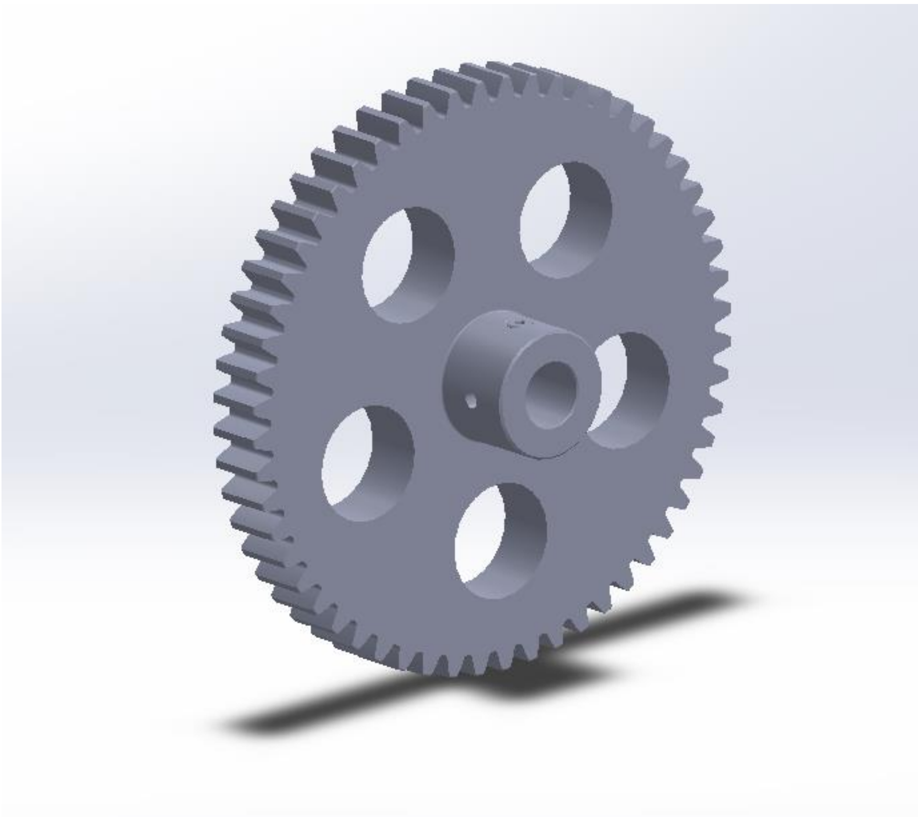

Figure 5.2: Solidworks representation of weight reduction in a gear

It is possible to reduce up to 50% weight using this method. Although, there is a risk of making a mistake when operating the lathe, and in worst case we could be standing there without any gears at all, which would make our quadcopter non-functional.

Possibility 2:

We could have ordered custom designed gears with our dimensions at one of the companies we took contact with. But again, restrictions coming from cost budget and time for this project don't allow us to proceed with this option.

Possibility 3:

Another option is to order new parts. We have already got experience with this kind of task. It is hard to both find the right products for our use, and find manufacturers who ship to Norway. Afterwards, recalculation of the whole transmission system is needed. As this would be our second time doing it, it wouldn't be a problem. But with recalculating, finding the parts and wait for the delivery, it would take a lot more time than we have available for the current project.

Possibility 4:

Realizing that we couldn't achieve our requirement in the RO1, and taking option 1 and 2 into consideration, our best option is to continue with the project as it is.

As soon as we have received the gears and observed the problem, we appointed a meeting with the customer to discuss it. After a customer meeting, we agreed to proceed as planned with the gears we received. Because even if we managed to reduce weight of gears with 50%, we wouldn't meet the requirement of 2.5 kg with the current project.

5.2.2 Other parts

As it is shown in the weight budget [see Appendix A – Weight Bugdet], we could have met the requirement C05.2, if gears weight was reduced twice and with some reductions in frame.

1. Pitch mechanism with propeller
   Per now we have ordered 15inch carbon fiber propeller blades. The choice of the blades was based on thrust calculation [see Technical Document, section 7.6] where diameter of the blade is an essential parameter. The reason why we have calculated thrust F=4 kg per propeller was C03 requirement from the customer:

I.D.	Requirement	Priority	Origin	Reviewed
C02	The system shall be able to use an electric motor for propulsion	A	Customer	20.04.17
C03	The system shall be able to use an electric motor for propulsion	C	Customer	20.04.17

At the early stage of research and development (R&D) phase, we made an estimation regarding internal combustion engine with all necessary equipment. The estimation of engine total weight with accessories was 623 g, in addition to that, we need a clutch, about 100 g, and a full gasoline tank, about 500-600 g. Totally, for the whole ICE system about 1300 g, thus together with the drone itself – 3.5 kg. It was the reason why we have oversized the entire system from the beginning – to meet the requirement for change between ICE and electric motor.

When regarding pitch mechanism with the current pitch mechanism with blades of 97 g per item, we have found out that it is the only solution for our project, as there are very few other opportunities available at the market. All others do not suit due to lack of necessary mechanisms present, as rotor hub. Thus, for simplicity reasons we have chosen, not the lightest, but the most complete variant of it.

2. Frame with diverse

   The first estimation for the frame with diverse screws, nuts, standoffs taken from Solidworks was 843g in plexiglass.

   As we have made a prototype in plexiglass for demonstration and check of design, we have estimated the frame in composite also with 4 plies. One arm weighs 37g, we have 8 arms, and 3 middle plates, altogether 600g.

   We could have done composite plates with 2 plies, as there is enough strength with composite [see Appendix A to Technical Document – Composite Production Report]. Then the frame weight would be at a value of about 400g.

   Given the use of correct gears and the carbon fibre airframe, the final production design will be within the weight requirement and the RO1 certification, as discussed in the previous section 4.1.

5.3 Possible improvements

Here is the summary of what could have been improved in our project if we had started the project again from scratch.

Although thorough project planning is essential, it is only an advantage to begin with prototyping at the initial stages of the project. Especially, if the project aim is to deliver a functional product as a result. Prototyping often requires extra expenses. Due to this fact, it can be worth taking contact with potential sponsors of the project and investigating collaboration opportunities for all parties involved. Both financial, equipment and service support can be very helpful.

According to the Project Schedule provided to the first presentation, we were planning to build a partial prototype right before the second presentation as a part of R&D process in the 5th iteration. The project group had to revise the plan [see Project Plan, section 5.4.2]. We received a request from the customer to present several design concepts of the system before we could order parts to build a prototype. Design and calculations are time consuming activities. Therefore, the ordering session was moved to a later stage, and first and final prototype was scheduled to May, 12.

Starting early with prototyping is a very useful decision. When making prototypes, design decisions can be checked, evaluated and re-designed. It contributes to final quality of the product.

6 Lessons learnt

This bachelor project has been challenging and exciting experience for our project group. We have tried to summarize the most important outcomes of this intense and productive semester.

As mentioned before, we are 6 mechanical engineering students. Everyone with their own individual background and expertise. Every team member has been a vital unit in achieving a common goal. Everybody has contributed to the project to their highest potential and shared knowledge and views.

There have been both ups and downs during the work process. Implementation of certain features didn't always go smoothly, rather badly often. Some of the scope deviated from the original plan, and we had to cope with constant changes and re-evaluation, as well as considering several back up plans simultaneously.

We have learnt to:

- do a comprehensive and scientifically reliable research
- apply our knowledge to practical problems
- see practical aspects of design, such as constructability and designing to a budget
- consider not only computer-aided design, but how to put things together in an efficient and practical way
- be prepared to handle things going wrong, as it happens more often than people tend to think

We have gained valuable experience in:

- teamwork and ways to achieve common goals
- communication, including oral, graphic, written and presentation skills

We have found out that:

- good communications skills are vital
- every team member has their strengths, the trick is to detect them and embrace for the benefit of the project

It is important to:

- make sure that project group and the customer are both on the same page and are updated
- consider budget and timeline
- ensure effective communication between all parties involved
- be flexible when things go wrong
- treat problems as an opportunity to find a better solution, rather than as a distraction

Appendix A – Weight Budget

	Weight Budget, updated with actual weight of parts received									
		Plexiglass frame, original gears				Half weight for gears, carbon fiber frame 2 plies				
Nr.	Part Name	Weight, g	Nr.items	Total Weight, g		Weight, g	Nr.items	Total Weight, g		
	Pitchmechanism with propeller	63	4	252		63	4	252		
	Servo with wires	70	4	280		70	4	280		
	Receiver	20	1	20		20	1	20		
	Flight controller with antenna and wires	36	1	36		36	1	36		
	ESC	65	1	65		65	1	65		
	Motor with pinion gear	233	1	233		226	1	226		
	Battery flight controller (estimated)	50	1	50		50	1	50		
	Battery motor (estimated)	578	1	578		578	1	578		
	Gear d=40mm	111	2	222		55,5	2	111		
	Gear d=44.8mm	129	1	129		64,5	1	64,5		
	Gear d=28mm	63	1	63		31,5	1	31,5		
	Pulley bore d=6mm	13	4	52		13	4	52		
	Pulley bore d=5mm	8	4	32		8	4	32		
	Shaft d=6mm (estimated)	47	2	94		47	2	94		
	Shaft d=5mm	37	2	74		37	2	74		
	Timing belts (4 pieces)	50	1	50		50	1	50		
	Frame with standoffs, div screws, nuts, washers, wires	1166	1	1166		400	1	400		
				3396				2416		980
	Maximum allowed RO1			2500						
	Overweight			896						