Covering the Gap between Advanced Control Theory Design and Real Time Implementation Using Simulink

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Abstract

New developments in sensor technology and control actuators make it viable to monitor and regulate more process variables, providing an opportunity to apply advanced multivariable control techniques. Although modern control techniques allows the implementation of true multiple inputs – multiple output controllers, there has been a big gap between theoretical developments and real life applications. At the University of Southeast Norway, we proposed a bachelor level course aimed to students who have had a previous introductory course to classic control, to teach them the fundamentals of modern multivariable control techniques, including state feedback, LQR and linear MPC. The use of Simulink is integrated with the course, to analyze and design modern controllers for two real multivariable experimental processes. We advocate the use of advanced simulation and data acquisition tools to help to cover the existing gap between the development of modern control algorithms, and their implementation with real processes. The experimental testing and final tuning of the controllers are an important part of the course.

Keywords: Control Education, Control Design, Control Simulation, Multivariable control, Simulink.

1 Introduction

Several authors have pointed to the big gap existing between theory and application of advanced multivariable control techniques. One popular claim is that most industrial regulatory control needs can be satisfied by using several single PID control loops, combined in different configurations (cascade, feedforward, ratio control, etc.), so modern techniques for advances multivariable control are not required.

A fundamental advantage of using PID control is that it does not require an explicit, accurate model of the process. Simple models can be fitted by using "bump" tests, or the controllers can be tuned by using closed loop "in situ" techniques like the classic ultimate gain method or several of its variations. In addition, several PID systems offer now the possibility of auto-tuning options, by automatically running a short test on the system to find appropriate controller parameters. It can also be argued that processes are designed having in mind traditional PID systems, and that more efficient processes could be designed if modern control techniques were considered from the design stage (Bernstein, 1999).

On the other hand, academia focus on the formal teaching of classic control techniques using Laplace transform, poles and zeros location, and frequency domain analysis, and modern control techniques using state space representations. All of these methods require an explicit model, which can be obtained from first principles modelling, or from carefully designed experiments and using system identification techniques (or a combination of both). These models can be nonlinear and require linearization, and the analysis and modern control design techniques are laborious and more suitable to handle using appropriate control software tools. Implementation on the real process requires the use of data acquisition hardware, and it is communally done using software tools different than the ones used for the system analysis and controller design.

The final tuning of the controllers requires a trail and error testing procedure. The common approach in academia is to demonstrate the controllers using simulation tools, and seldom actually testing them on real multivariable processes. While the theory is sound and mature, the design process is laborious, and most industrial control systems do not facilitate the direct application of the resulting algorithms. This situation explains why there are very few reported applications of multivariable control in real experimental or industrial processes.

2 Experimental systems in academia

For many years instructors in academia have used experimental single input – single output control systems, like level control of a single tank, temperature control for air or water heaters, and different kinds of flow control systems. While these systems are extremely valuable to teach the fundamentals of classic control and practice different methods for tuning PID, they are not multivariable, nor challenging enough to justify the use of modern control techniques.

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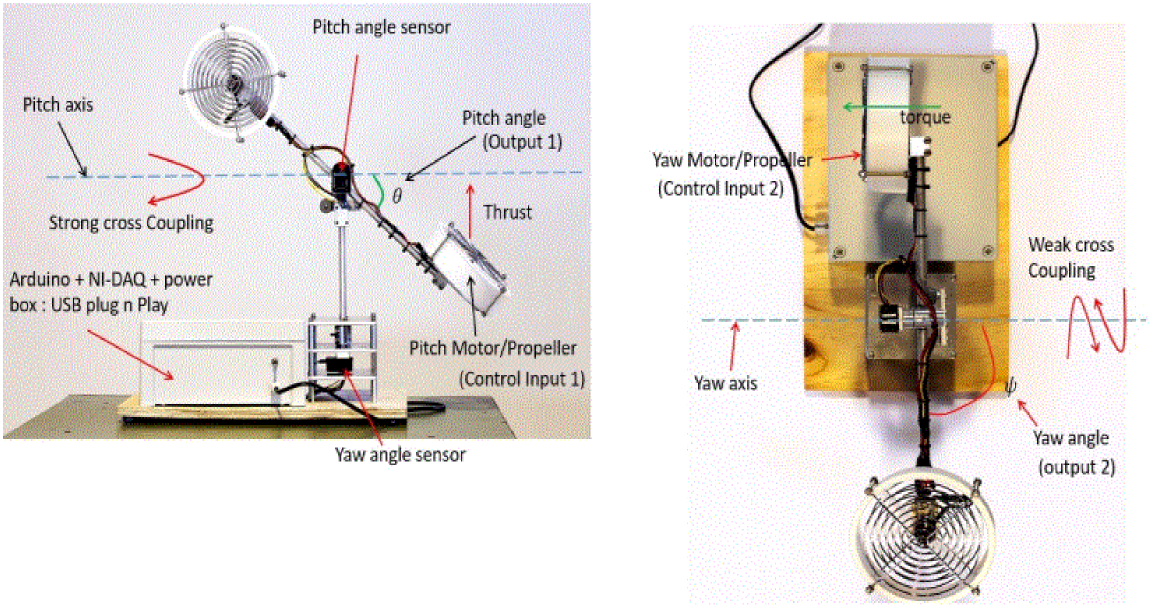

Figure 1: Two degrees of freedom helicopter prototype.

Figure 2: Pilot scale four tanks system.

In recent years, two true multivariable systems have become popular to use for teaching and research in academia: a helicopter prototype with two degrees of freedom (Neto, 2016), and a quadruple tank system for level control (Johansson, 2000; Pfeiffer, 2011).
Both systems present different challenges: the helicopter is an open loop unstable system, highly nonlinear with strongly coupled input-output variables, and it requires very fast sampling times. The four tanks system is moderately nonlinear, but can be operated in different configurations to show challenging behaviors like inverse control and different degree of coupling among the input and output variables. Both of these systems are good candidates to demonstrate the use of modern control multivariable techniques. At the University College of Southeast Norway (USN), we have developed a prototype for the two degrees of freedom helicopter system (Figure 1), and pilot size prototype for a four tank model is under construction (Figure 2), to be used with the course.

2.1 Experimental system models

Helicopter system: the goal for the helicopter system prototype is to control both the pitch θ and yaw Ψ angles, by modifying the input voltage to the front and rear motors, V_{mp} and V_{my}.
The model for the two degrees of freedom prototype is shown in Figure 3 (Qunasar Inc, 2011), with the corresponding parameters description in Table 1.

$$\frac{d\theta}{dx} = \omega_\theta$$

$$\frac{d\Psi}{dt} = \omega_\Psi$$

$$\frac{d\omega_\theta}{dt} = \frac{K_{pp}V_{mp} - K_{py}V_{my} - B_p\omega_\theta}{J_{eq,p} + m_h l_{cm}^2} - \frac{m_h \omega_\psi^2 \sin(\theta) l_{cm}^2 \cos(\theta) + m_h g \cos(\theta) l_{cm}}{J_{eq,p} + m_h l_{cm}^2}$$

$$\frac{d\omega_\psi}{dt} = \frac{K_{yp}V_{mp} - K_{yy}V_{my} - B_y\omega_\psi}{J_{eq,y} + m_h l_{cm}^2} - \frac{2\, m_h \omega_\psi \sin(\theta) l_{cm}^2 \cos(\theta)\, \omega_\theta}{J_{eq,y} + m_h l_{cm}^2}$$

Figure 3. Two degrees of freedom helicopter’s model.

Table 1. Parameters for the helicopter model.

Parameter	Description	Units
l_{cm}	Distance between the pivot point and the center of mass of the helicopter	m
m_h	Total moving mass of the helicopter	kg
$J_{eq,p}$	Moment of inertia about the pitch axis	kg m2
$J_{eq,y}$	Moment of inertia about the yaw axis	kg m2
g	Earth gravity constant	m/s2
K_{pp}	Torque constant on pitch axis from pitch motor/propeller	Nm/V
K_{yy}	Torque constant on yaw axis from yaw motor/propeller	Nm/V
K_{py}	Torque constant on pitch axis from yaw motor/propeller	Nm/V
K_{yp}	Torque constant on yaw axis from pitch motor/propeller	Nm/V
B_p	Damping friction factor about pitch axis	N/V
B_y	Damping friction factor about yaw axis	N/V

Four tanks system: the systems has two control inputs, V_1 and V_2, representing control voltage inputs to two variable speeds pumps controlling the input flows. The flow from each pump is split using a three-way valve, with the splitting fraction defined by γ1 and γ2 for the flows from pump 1 and pump 2 respectively. The system outputs are the tanks levels given by h_1,h_2,h_3 and h_4 The system diagram is given in Figure 4.

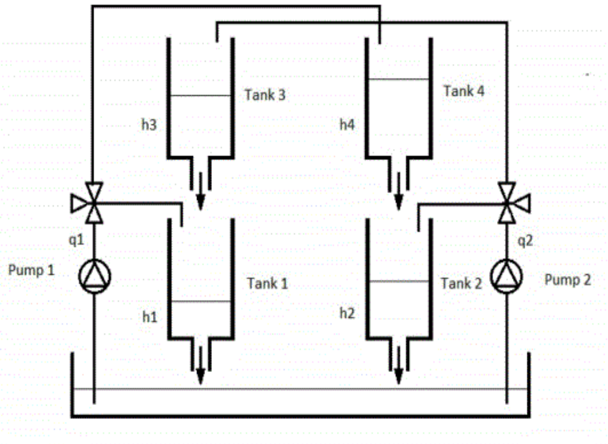

Figure 4. Four tanks control system.

The model for the four tanks system, assuming the pumps dynamics is much faster than the tanks dynamics, is included in Figure 5 (Pfeiffer, 2011), with the corresponding parameters description provided in Table 2.

$$\frac{dh_1}{dt} = \frac{c_3\sqrt{2gh_3} - c_1\sqrt{2gh_1} + \gamma_1 k_1 V_1}{A_1}$$

$$\frac{dh_2}{dt} = \frac{c_4\sqrt{2gh_4} - c_2\sqrt{2gh_2} + \gamma_2 k_2 V_2}{A_2}$$

$$\frac{dh_3}{dt} = \frac{-c_3\sqrt{2gh_3} + (1-\gamma_2) k_1 V_1}{A_1}$$

$$\frac{dh_4}{dt} = \frac{-c_4\sqrt{2gh_4} + (1-\gamma_1) k_1 V_1}{A_1}$$

Figure 5. Four tanks system model

Table 2. Parameters for four tanks model.

Parameter	Description	Units
c_1, c_2, c_3, c_4	Constants depending on the areas of the exit orifices.	m^2
γ_1, γ_2	Flows split fractions.	----
k_1, k_2	Pumps gains.	m^3/v
g	Earth gravity constant	m/s^2
A_1, A_2, A_3, A_4	Torque constant on pitch axis from pitch motor/propeller	m^2

3 Course Description

3.1 Course requirements

The course “Simulation and Control of Dynamic Systems” has been designed for bachelor students who have had a previous introductory course in process control.

Additionally, the course requires calculus and fundamentals of programing. Most of the programing is done in MATLAB/Simulink, which uses a graphical and highly intuitive programming style.

3.2 Topics

The course topics are presented sequentially from modelling, simulation, analysis, design of multivariable controllers, testing in simulation, and testing with the real systems. Both the helicopter prototype and the four tanks system are used from the beginning of the course to demonstrate the different control concepts and techniques. The modelling requires using ordinary differential equations, linearization using Taylor series and model parameter fitting using least squares techniques. These operations are handled using MATLAB. The course follows with the representation of MIMO systems using transfer functions matrices and state space realizations. The concepts of controllability, observability and stability analysis using state space realizations are explored and analyzed using MATLAB.The effect of dead-time on closed loop stability is discused and simulated using Simulink. Common non-linear characteristics in real processes are also discussed and simulated, including saturation, hysteresis, dead-band and backlash.

The analysis and simulation of systems with inverse response is discussed using the four tanks systems as an example. The course follows with an introduction to state space representation, controllability, observability

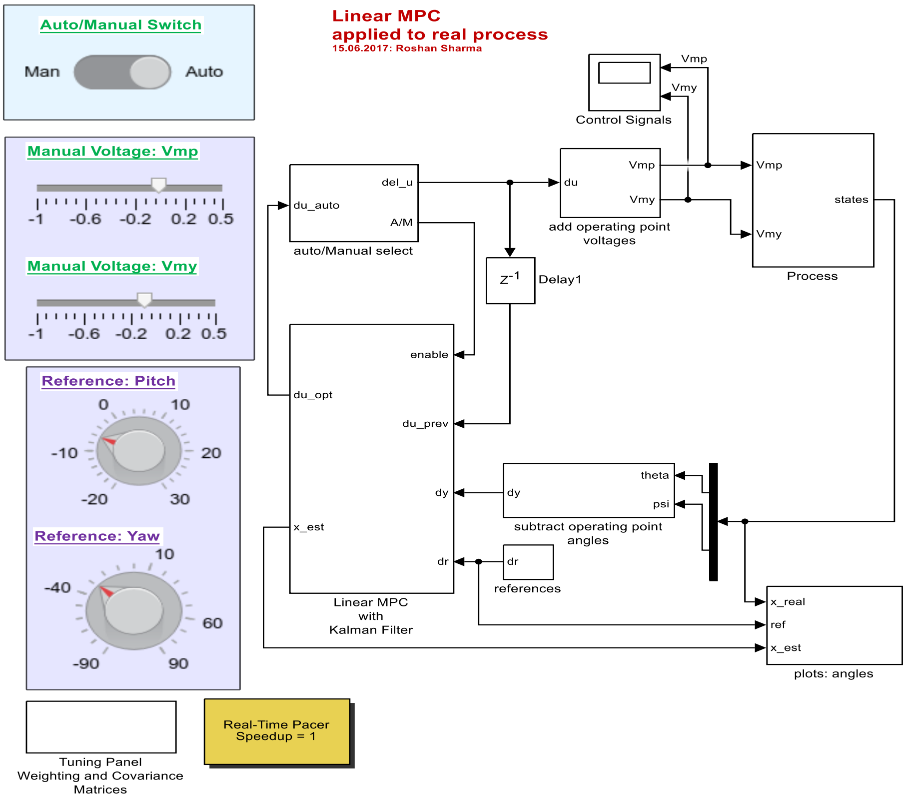

Figure 6: Simulink real time helicopter control system.

and stability analysis using state space realizations, observers, state feedback and the Kalman filter.

The course finishes with a hands on presentation of Linear Quadratic Regulator control and Model Predictive Control techniques, with the students simulating the controllers in Simulink and testing them on the real processes by using data acquisition modules with Simulink to connect to the processes interfaces.

An example diagram of the final implementation of MPC in Simulink to control the helicopter prototype is shown in Figure 6. Experimental results comparing different control methods for the 2-dof helicopter systems are provided in (Sharma and Pfeiffer, 2017).

4 Conclusions

An advanced bachelor level control course has been proposed to teach students at USN modern control techniques for multivariable processes. The course covers modeling, simulation, analysis, control design and implementation using MATLAB/Simulik with the control and data acquisition toolboxes as an integrated platform. All the topics are demonstrated using two real multivariable process: a two degrees helicopter system, and a four tanks level control system. The use of MATLAB/Simulink as an integrated platform facilitates the steps from the system analysis to the controller implementation and final tuning refinement, helping to reduce the gap between the advanced modern control theory and real world applications.

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