Conceptual learning of control and state estimation
through a mobile cart project

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Conference Key Areas: Engineering education research, Education concepts specific for engineering education, Novel education tools for engineering programs

Keywords: Control, state estimation, conceptual understanding, system thinking

INTRODUCTION

Control and state estimation are essential in the typical electrical and mechanical engineering curriculum. Obtaining a conceptual understanding on these subjects has proven to be difficult however. Moreover, using the learned concepts to provide an integrated solution for a real-world setup is even more challenging. This paper describes a mobile cart project that promotes conceptual and deep learning of (feedback and feedforward) control and state estimation (Kalman filter) in a master

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course on control theory. The overall goal for the students is to control a LEGO Mindstorms robot such that it follows a predefined path using the robot's encoders and an ultrasonic sensor measuring the distance to two perpendicular walls. Additionally this paper identifies typical challenges students encounter when faced with such an integrated real-life project integrating control and estimation.

1 RELATED WORK

1.1 Feedback and feedforward control

Bernstein states that control education must be both conceptual and experimental: abstract concepts are powerful but learning is always enhanced by direct experience, concrete examples, and real-world relevance [1]. Additionally, Bernstein provides 21 suggestions (encompassing modelling, control, technology, and cultural issues) to enhance undergraduate control education in the hope to enhance the teaching and appreciation of control [1]. The project proposed in this paper is built on 13 suggestions. In particular we want to give the students practical experience with feedback and feedforward control and state estimation on a real-life setup.

1.2 Kalman filter

A common framework for state estimation is the Kalman filter. The concepts of uncertain dynamical systems, model uncertainty, and measurement noise, are merged by the Kalman filter. This offers both an opportunity to get an overall understanding and a challenge to avoid possible confusion. An intuitive and didactical approach of the Kalman filter is presented in [2,3]. A Java tool for educational purposes was presented in [4]. Finally, De Schutter et al. present a Kalman filter tutorial including a mechanical analogy, which is particularly interesting for mechanical engineering students [5].

1.3 Lego mindstorms in education

A LEGO Mindstorms NXT module consists of an ARM microcontroller interfacing a set of four inputs to connect a wide variety of electronic sensors, including ultrasonic sensors, gyroscopes, and accelerometers. Its versatility and reasonable price makes it a popular platform for educational engineering activities, such as in control system design [6], signal processing courses [7], as well as in more challenging robotic and control applications [8]. An example of state estimation via a Kalman filter was implemented on a LEGO mobile robot in [9].

Markovsky proposed a LEGO Mindstorm project that is similar to the one proposed in this paper [10]. The project uses LEGO Mindstorm robots to teach both state estimation and PID controller tuning. The goal of the project is to keep the cart at a constant distance from a moving object. In contrast to the project proposed in this paper, the problem is simplified to a one dimensional problem. Moreover, a simple moving average filter is used as state estimator. Finally, the students have to implement the microcontroller in C, which is beyond the scope of our project.

Recently, a free and open-source MATLAB toolbox, called “RWTH – Mindstorms NXT Toolbox”, was developed by the RWTH Aachen University [11]. This toolbox enables a host computer to remotely control to the LEGO Mindstorms robots using MATLAB, avoiding the need to program the microcontroller in C. Developing algorithms in a MATLAB environment helps students to apply theoretical knowledge to a practical engineering problem.

2 PROBLEM ANALYSIS

2.1 Overall setup: control and state estimation of a mobile cart

The goal of the project is to ***control*** a mobile cart to follow a reference trajectory. The *inputs* to the mobile cart are the left and the right wheel velocities. The *state* of the cart, i.e. its position and orientation, is not known however and has to be ***estimated*** from the interoceptive sensors measuring the wheel velocities (odometry) and the exteroceptive sensors, in this case ultrasonic sensors measuring the distance to two known perpendicular walls. The students have to design and implement a *feedback and feedforward controller* such that the mobile cart reliably follows the reference trajectory; and a *probabilistic state estimator* (a Kalman filter) to estimate the cart's state from sensor measurements.
In the next sections we will highlight the typical challenges students encounter when faced with a project as described. We identified challenges related to control, state estimation (Kalman filter), and the integration of the control and state estimation.

2.2 Control difficulties

The students have to design and tune a feedback and feedforward controller such that the cart reliably follows the reference trajectory. The *open loop control*, called *feedforward*, applies a velocity reference to the cart wheels without knowledge of the state cart, based only on the trajectory reference to follow. The *closed loop control*, called *state feedback*, applies a correction using the difference between the reference state and the estimated state. This difference is projected into the cart coordinates and multiplied by a state feedback gain matrix. The state feedback law is similar to the one implemented in [12].
Conceptual understanding of feedback and feedforward control and applying it to the real world cart example is challenging:

1. **Understanding the influence of the control design:** While students learn on the properties of particular controllers (feedback and feedforward), using this knowledge to design a controller for a real-life setup and to predict the behaviour of the controlled system is challenging.

2. **Understanding meaning and influence of parameters:** Each controller has parameters (control gains) that influence the behaviour of the controlled system. Applying the learned theory in practice for choosing parameters is challenging. In particular, students have to learn how to tune the parameters in a theoretically founded way such that the controlled system realizes the desired behaviour, while still being robust to unforeseen changes, which are inherent to real-life setups. Moreover they have to understand the physical meaning of the gains and the effect they have on the dynamics and the performance of the system.

3. **Interpreting the results:** After a simulation or experiment students have to be able to interpret the results and reflect on the different aspects that contributed to this behaviour. Moreover, if the result is not yet as desired, this reflection has to result in a concrete plan on what to change and how, building on the understanding gained on the meaning and influence of the parameters.

4. **Influence of disturbances and modelling errors:** When faced with a real-life setup students are immediately exposed to unforeseen disturbances and modelling errors. Understanding the influence of the disturbances and modelling errors and coming up with an approach to reliably handle these is challenging.

2.3 Kalman filter and difficulties

A Kalman filter is a probabilistic, recursive estimator, which provides an efficient computational tool to estimate the state of a system based on the knowledge of the

system model and its uncertainty, as well as some available measurements subject to noise. The Kalman filter works in a two-step process. In the prediction step, or time update, the algorithm estimates the current state, along with its uncertainty. In the correction step, or measurement update, once measurements are available (possibly corrupted with some error or random noise), the estimated state vector is updated using a weighted average, with more weight given to estimates with higher certainty.
Conceptual understanding of the Kalman filter and applying it to a real world example is challenging:

1. **Modelling:** The first challenge is to make a good model of the problem at hand and in particular to make a good and relevant probabilistic state space representation of the system process and the measurement process. Multiple solutions, each with their own advantages and disadvantages, are possible.

2. **Separation between simulation and estimation:** On top of developing an estimator to estimate the state of the real world system, the students have to develop a simulator of the real world example. This simulator allows the students to cheaply test their estimator in a safe simulated environment without the need for the actual hardware. The simulator is probabilistic of nature, i.e. it uses probabilistic models to capture on the one hand the intrinsic uncertainty of the system and measurement processes involved and on the other hand the modelling errors. Typically students have difficulties to separate the simulator and the estimator, in particular when they use similar equations and parameters.

3. **Understanding meaning and influence of parameters:** A Kalman filter is probabilistic of nature and all parameters involved therefore have a probabilistic meaning. Typically students are not familiar with probabilistic modelling and have difficulties to understand the meaning of the parameters. Moreover, all parameters have an influence on the behaviour of the Kalman filter estimator. Understanding how the parameters influence the behaviour is even more challenging.

4. **Interpreting the results:** The Kalman filter provides a probabilistic estimate (a mean and a covariance) of the state. The covariance provides an important insight on the convergence of the Kalman filter and on the uncertainty of the state estimate. Students have no experience in interpreting probabilistic results, therefore interpreting the covariance in particular is challenging. Moreover, the influence of the number of measurements, the timing of the measurements, and the observability of the system is important.

5. **Influence of non-linearities and modelling errors:** The Kalman filter is an optimal linear estimator. Any non-linearity or modelling error will result in non-optimal behaviour. Understanding the influence of the non-linearities and modelling errors is challenging. Furthermore, students have to learn the best ways to adapt the Kalman filter parameters to handle the non-linearities and modelling errors.

2.4 Integration of estimation and control, difficulties

While developing the controller and the estimator by themselves causes challenges, integrating the two on a real-life setup introduces extra ones:

1. **Separation between controller and estimator:** The project involves a controller and an estimator that interact: the controller uses the estimated state to decide on the control action while the measurements that the estimator uses depend on the action the cart takes. As such, the overall behaviour is influenced by the controller, the estimator, and the interaction of the two. This causes confusion on the influence of the controller and the estimator.

2. **Understanding interaction between feedback controller and state estimation:** Since the feedback controller uses the estimated state, the dynamics of the estimator will influence the closed-loop system behaviour. Therefore, students have to adapt the estimator and controllers parameters such that overall behaviour is stable and reliable. As an example: measurements from ultrasonic sensors are typically available at a low rate (lower than the control rate). When the estimator receives a measurement it often causes a "jump" in the estimated state. This jump however can result in a saturation of the control low. Therefore, students should adapt the estimator (higher measurement uncertainty – slower estimator) and on and/or adapt the controller (low state feedback gain – slower controller).

3 PROPOSED APPROACH AND RESULTS

3.1 Situating the course

The KU Leuven is a university in Flanders, the Dutch speaking part of Belgium. The engineering curriculum consists of three Bachelor and two Master years. The course "Control Theory" (5 ECTS) is part of the first year of the master program (first semester) and is mandatory for all students in the master of mechanical engineering. The number of students attending the course in 2012 was around 110. The authors are already teaching the course for several years. The project counts for 25% of the total evaluation. The goals of the course related to the mobile cart project are situated in three domains: knowledge, skills, and attitudes. Concerning the *knowledge* the students have to be able to analyse continuous and discrete time system; analyse the stability of systems, controllability, and observability of state space models; and know the difference between the different types of stability. Concerning the *skills* the students have to be able to derive a mathematical model of a dynamical system based on a simplified physical model description, and based on that state space model description; apply the basic modelling and analysis methods for linear dynamical time invariant systems, and to interpret the obtained results critically; linearize a nonlinear system, that is, to derive an approximate linear model for a given or to be determined equilibrium state; design a state feedback controller, including a closed-loop state estimator; design a feedforward controller aiming at eliminating state tracking errors for different types of reference signals. Concerning the *attitude* the student have to be able critically evaluate the abovementioned designs and reflect on the physical meaning of all parameters etc.

Fig. 1: LEGO Mindstorms robot for mobile cart project

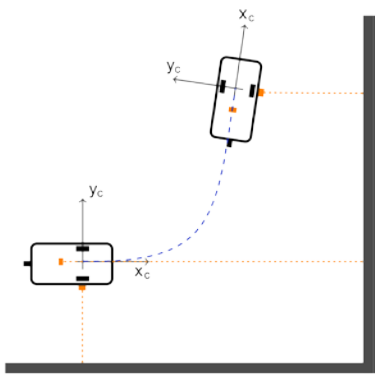

Fig. 2: Schematic view of robot with ultrasonic sensors

3.2 Proposed approach

This paper proposes a mobile cart project using LEGO Mindstorm robots to teach students about state estimation and control. The project confronts the students with a real-life problem, which challenges their knowledge in both control and estimation.

Since our students are already familiar with MATLAB, we use the “RWTH-Mindstorms NXT toolbox” [11], which enables them to perform advanced numerical computations in order to understand, analyse, and design controllers and estimators and easily test them on the robots. The LEGO Mindstorms configuration used in the project consists of a processing unit, two motors, two ultrasonic sensors, and one gyroscope. The system input is the velocity of the wheels and there is a sensor on each wheel to measure its rotational velocity (*Fig. 1*). The information about the cart’s position, velocity, and orientation are obtained from the two ultrasonic sensors measuring the distance to two perpendicular walls and a gyroscope (*Fig. 2*). The use of the gyroscope measurement information was optional.

*Table 1***.** Integrated approach for mobile cart project

	format	number of Students (total 100)	timing (hours)	goal	instructions	graded	evaluation
theoretical introduction	plenary lecture	100	1.5	obtain theoretical background	-	no	no
exercise session 1	exercise session	10 teams of 2 or 3	2.5	analyse system (block diagram)	written & oral	no	no
exercise session 2	exercise session	10 teams of 2 or 3	2.5	analyse controller & Kalman filter	written & oral	no	no
home preparation	self-study	teams of 2 or 3	1.5-3	preparation of experiments	written	no	no
hands-on session	laboratory session	8 teams of 2 or 3	2.5	experiments on LEGO Mindstorms	written & oral	yes	continuous & oral
written report	self-study	teams of 2 or 3	4	show insight in controller and Kalman filter	written	yes	report

The mobile cart project is founded on an understanding-experiment-report strategy. Using code prepared by the lecturers, students have to understand the overall system, design an experimental strategy to answer conceptual questions, perform the actual experiments, and answer the questions in a report. *Table 1* provides an overview of the approach including the format of the teaching and the type of evaluation. Students were confronted with the theory during a *plenary lecture*. During subsequent activities, students were divided in groups of two or three. At the *first exercise session* they were asked to build a block diagram containing the physical system (mobile cart and generation of ultrasonic measurements), the Kalman filter, a feedback controller, and a feedforward controller with a provided desired trajectory as input. The aim was that students would understand the role of each function block and the connection between them. *Fig. 3* shows a simplified version of the block diagram. At the second exercise session the controller and estimator were mathematically formulated. In the self-study assignment the students had to analyse and understand an existing Matlab implementation of the different function blocks of the system. Furthermore they had to use the implemented simulator to design experiments, to find or verify the characteristics of the closed-loop robot system, and to find appropriate parameters for the estimator and controller. During the *hands-on session*, students performed the designed experiments independently. During the experiments they acquired hands-on experimental skills in systems, control, and estimation. Finally, the students had to prepare a written report by selecting eight questions out of fourteen and answering them in order to show their understanding of the estimation and control problem. Questions were in different categories related to modelling, feedforward control, measurement modelling, feedback control, performance of controller and estimator, etc. Moreover, students were challenged to come up with their own question and answer. The course material is freely available at http://people.mech.kuleuven.be/~jdeschut/mobileCartProject.

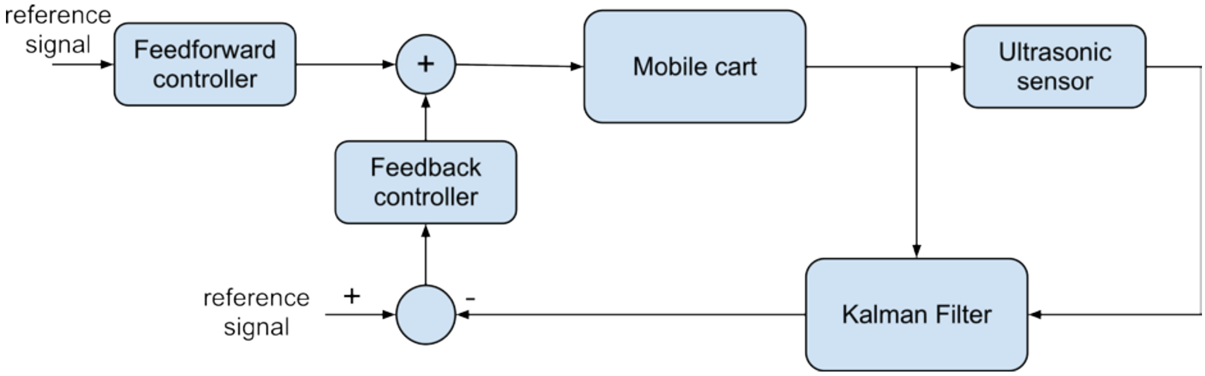

Fig. 3. Simplified block diagram of mobile cart system

3.3 Results

The effectiveness of the proposed approach is evaluated qualitatively. First, the lecturers subjectively observed an increase in the level of conceptual understanding shown during the evaluation and compared with the level shown during previous years when a traditional approach of lectures and exercise sessions was used. Moreover, the lecturers notice that the deeper understanding on these two topics has a positive influence on the overall understanding of control theory. Second, all students were asked to summarize what they learned. Most students stress that they did not only learn about one specific component but also about the overall system. Third, the teaching assistants observed an increase of the level of motivation during the hands-on session with respect to the classical exercise sessions.

4 CONCLUSIONS AND FUTURE WORK

This paper lists the challenges when teaching students (feedback and feedforward) control and state estimation (Kalman filter) in a master course on control theory. Moreover, this paper presents an integrated approach founded on a hands-on project with a mobile robot to obtain a conceptual understanding of control and state estimation. The teachers observed an increasing level of conceptual understanding and motivation of the students. We believe that the project can inspire other teachers and assist them when preparing a hands-on project on control and estimation.

In the future we will on the one hand continue to develop the project and all material involved and on the other hand try to quantitatively measure the conceptual understanding obtained by the students.

5 ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support by KU Leuven's Concerted Research Action GOA/2010/011, the KU Leuven-BOF PFV/10/002 Centre-of-Excellence Optimisation in Engineering (OPTEC), the Belgian Programme on Interuniversity Attraction Poles (DYSCO), European research project EMBOCON FP7-ICT-2009-4 248940, and G.0377.09 of the Research Foundation - Flanders (FWO-Vlaanderen). Tinne De Laet is a Post-Doctoral Fellow of FWO-Vlaanderen.

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