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Low-cost Carry-home Mobile Platforms for Project-based Evaluation of Control Theory ⋆

Armin Steinhauser * Maarten Verbandt *
Niels van Duijkeren * Ruben Van Parys * Laurens Jacobs *
Jan Swevers * Goele Pipeleers *

* *Department of Mechanical Engineering, KU Leuven, Belgium.*
(e-mail: <firstname>.<surname>@kuleuven.be*).*

Abstract: This paper presents mobile platforms that were recently designed in support of an introductory control course. Through dedicated assignments, the students are guided to implement and validate all parts of the course on a setup, ranging from basic time-domain system identification, over root locus analysis and loop shaping PID design, to state feedback, state estimation and Kalman filtering. The platforms are flexible, allowing for numerous extensions and variations; cheap, allowing for a large pool of setups from which the students can borrow platforms to take home; and of sufficient quality, allowing the students to get maximal insight in the course material. The setups are easy to set up and administer using the supporting material provided by the authors.

Keywords: Control engineering education; low-cost laboratory; embedded control system.

1. INTRODUCTION

Teaching a control theory course to Mechanical Engineering students can be challenging. Their primary interests lie in application domains such as manufacturing, thermodynamics, robotics, automotive or aerospace, and they are often impeded by the mathematics involved in control: Laplace and Fourier transforms, state-space models and transformations, etc. In addition, many students struggle with the level of abstraction of the course, which prevents them from appreciating the value of control to their field of application. Hands-on lab sessions are a vital complement to such a course in order to reinforce the students' understanding of the theoretical principles, to strengthen their control design capabilities, and to spark true interest and appreciation for control (Leva, 2003; Feisel and Rosa, 2005; Reck, 2016).

The current paper describes test setups we recently designed in support of the introductory control course B-KUL-H04X3A, a mandatory course in the first year of the Master of Mechanical Engineering at the KU Leuven. We established a pool of 40 setups from which the students can loan a setup to perform experiments whenever and wherever they want. Through dedicated assignments, the students are guided to implement and validate all parts of the course on a setup. They will work on these assignments in teams of two and, as the course evaluation will be based on the assignments, with limited support from the teaching staff.

Recognizing the value of hands-on experience, various control theory teaching teams have developed dedicated lab kits over the last decade (Sarik and Kymissis, 2010; Gunasekaran and Potluri, 2012; Ovalle and Cómbita, 2014; Chancharoen et al., 2014; Hill, 2015; Migchelbrink et al., 2015; Reck and Sreenivas, 2015; Krauss, 2016; Bay and Rasmussen, 2016). Each of these kits has been tailored to the particularities of the course and the aspirations of the team. In our case, the requirements are the following: First and foremost, the setups must enable hands-on experience with as many techniques covered in the course as possible, ranging from basic time-domain system identification, over root locus analysis and loop shaping PID design, to state feedback, state estimation and Kalman filtering. In addition, a diverse set of setups is ambitioned in order to obtain a wide variety of assignments as a safeguard to excessive sharing of solutions and plagiarism in the course evaluation. Therefore a flexible platform was opted for that allows for numerous extensions and variations. The first year we start with two design variants, shown in Fig. 1, while next summer more design variations are planned. In addition, the students are encouraged to be creative and come up with alternative assignments themselves.

Envisaging a large pool of setups limits the available budget per device. As a consequence, the cost of the components is carefully traded off against their quality and the overall robustness of the design. As the setups are

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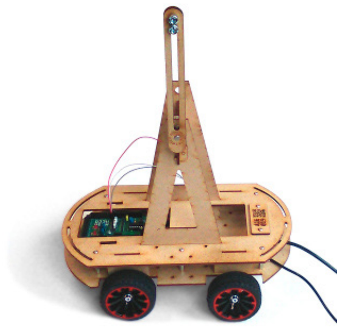
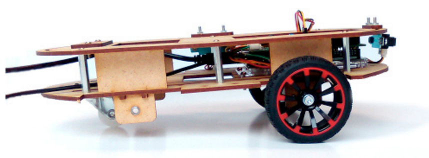


(a) Pendulum version



(b) Swivel version

Fig. 1. Pictures of the two mobile platform variants.

intended to last for a number of years, they should be sufficiently durable. Cheap components with excessive friction or backlash are avoided to prevent students from getting bogged down by irrelevant practical issues and too severe hardware limitations. Laser-cut MDF was chosen for the body parts of the platforms. This can be manufactured in house such that the students can repair broken parts and extend the setups themselves. Finally, the setups are supplied with sufficient on-board computational resources to allow their future usage for sophisticated control experiments in a more advanced control course.

Although an extensive survey of existing lab kits (see the aforementioned references) revealed no direct match with our requirements, it did provide us with invaluable inspiration for our design and hinted us to interesting tools and sources. In a similar way, we hope that this paper will be of value to other teams that are in the process of designing experimental setups and dedicated assignments to their control theory course. To this end, all information regarding the platforms, as well as all supporting material is made publicly available on `https://github.com/meco-group/mecotron`.

In the remainder of the paper we first describe the hardware and software design of the setups. Afterwards, we elaborate on their usage in the course and the corresponding student assignments. We close the paper with concluding remarks.

2. HARDWARE DESIGN

This section discusses details on the hardware of the developed platforms. The first part gives an overview of the specified objectives and the overall platform design. The second part elaborates on the interfaced electronic components and the sensors used.

2.1 Design Overview

To allow for a valuable hands-on experience, a major objective is to make the design sufficiently robust and therefore also easily maintainable, e.g. by replacing broken parts without difficulties. Furthermore, to enable various applications, we aim for two different platforms - a pendulum and a swivel version, which consist to a great extent of identical parts. Somewhat contradictory to these objectives, we additionally seek to minimize the costs, such that the cost per device and therefore the hardware design of the mobile platforms plays a critical role. Trading robustness off against cost by careful selection of the hardware components allows us to keep the total cost per platform as low as € 100 and € 120 for the swivel and the pendulum version, respectively.

Due to the mentioned requirements we choose to manufacture a laser-cut 3 mm MDF frame that is rigid but also inexpensive. Additionally, this enables fast manufacturing of new parts and gives students the opportunity to extend the platforms. An exploded view of the pendulum version is shown in Fig. 2, sharing the majority of the parts with the swivel version. The basis of every platform consists of a bottom (1a) and top (1b) frame that are connected by inserts and spacers. Attached to the bottom frame and the front inserts are two 6 V DC motors (5) - including gearboxes and magnetic encoders - that drive the platform via a pair of RC wheels. The pendulum version additionally includes an A-shaped rack (2) that slides in to hold a pendulum (8). Another pair of wheels is mounted on an axle held by the rear inserts to constrain the platform to linear motions. For the swivel version the rear axle and wheels are replaced by a swivel caster wheel for increased maneuverability. For the purpose of managing a large number of platforms, a numberplate with an identifier and a QR code is fixed to the top frame. The latter is used for automated booking of the platforms in a central database, to keep track of their whereabouts.

2.2 Electronics and Sensors

At the heart of every platform an Arduino MEGA 2560 (3) is used. On top, a custom breakout board - called the MEGA MECO (4) - is stacked that holds a PWM-driven L293D quadruple half-H driver to power the motors and provides easy access to various analog and digital inputs of the Arduino together with a selectable supply voltage for sensors of 3.3 or 5 V. Additionally, a receptacle to connect a Bluetooth module is provided. Unlike using one of the many already existing breakout boards, building our own enables us to tailor the design to our needs, such as placing headers for the motor terminal connectors. Furthermore, the design was kept simple to decrease the chance of defects and the sensitivity to faulty parts as much as possible. The motors of the platforms are equipped with magnetic encoders that are read by two digital inputs of the Arduino, one of them triggering an interrupt on a change of state. Taking the gear ratio of 1:34 into account, this results in 1496 counts per wheel revolution that can be read bi-directionally. Additionally, the pendulum version holds one infrared sensor (6) for distance measurement and an analog-output, multi-turn potentiometer (7) that allows the measurement of the pendulum angle. Using the