A LAB-IN-A-BOX PROJECT ON MECHATRONICS

W.B.J. Hakvoort[1]
Faculty of Engineering Technology, University of Twente
Enschede, The Netherlands

A. de Boer
Faculty of Engineering Technology, University of Twente
Enschede, The Netherlands

J.T. van der Veen
Faculty of Behavioral, Management and Social Sciences, University of Twente
Enschede, The Netherlands

Conference Key Areas*: Challenge based education, maker projects; Interdisciplinary education*
Keywords*: Maker projects, mechatronics, practicals, control*

ABSTRACT

A maker project is combined with theoretic courses on dynamics and control to an integrated module on mechatronics. The combination of theory and practice aims at enhancing student motivation and learning. However, a maker project with a full design cycle (design, realisation and testing) is challenging from an organisational and financial perspective, particularly for large numbers of students. This paper considers the design of a maker project and supporting hardware to enable to overcome these issues. The project follows a structured design cycle to be time efficient. The hardware consists of a lab-in-a-box with reusable standard components and easy-to-produce custom design components. This allows fast realisation at low cost, while offering substantial freedom of design. The results of a student questionnaire show improvement of the student appreciation and report grades show improved learning.

[1] Corresponding Author
W.B.J. Hakvoort
w.b.j.hakvoort@utwente.nl

1 INTRODUCTION

1.1 Background

The Bachelor programme of Mechanical Engineering (BSc-ME) at the University of Twente is organised in thematic modules of 15 EC along the university's educational model [1]. The last module in the second year is *Mechatronic Design*. Mechatronics is an interdisciplinary field combining mechanics, electronics and control. The module consists of two lecture-based courses *Dynamics* and *Systems and Control,* and a *Mechatronics Design* project. In the project the students combine the theory from the courses to complete a full design cycle by architecting, designing, constructing, testing and validating a precision mechatronic system.

1.2 Problem statement

Seeing theory at work and completing a full design cycle in a single project is motivating for Mechanical Engineering students as it appeals to their practical mindset and it provides them with the possibility to autonomously work on the mastery of the material. However, providing the ability to actually realise and test the design is challenging from an organisational and financial perspective. This is particularly challenging by a growth in the number of participants to over 120 students, while the students prefer working in smaller groups.

1.3 Outline

This paper describes how the project and the supporting hardware were concurrently designed to implement this full design cycle project while coping with organisational and financial constraints. First the educational design is discussed, including the learning objectives, the main challenges, the project structure, the supporting lab-in-a-box hardware and the assessment. In the results section, the exam scores and evaluation results are provided and discussed. The paper ends with a short summary of the main results and the potential for future improvement.

2 METHODOLOGY

2.1 Learning objectives

The learning objectives are formulated in terms of what the student should be able to do through and after the project:

1. Design a precision mechatronic system from performance specifications by integral design of a PID-like controller and the nominal and parasitic dynamics of a single degree-of-freedom mechanical subsystem.
2. Design and execute a measurement procedure to obtain the steady-state and frequency response of a mechanical system.
3. Implement and tune a digital PID-like controller for a mechatronic system for the measured response and the specified performance and stability margins.
4. Evaluate the performance of a precision mechatronic system by designing and executing effective experiments and by verification of the performance specifications from the experimental results.

These learning objectives enable students to go through a complete design cycle of a basic mechatronic system. The ability to conceive, design, implement and operate (CDIO) has been identified as the context of engineering practice providing a setting for the education of engineers [2]. It thereby contributes directly to the final qualifications of the bachelor Mechanical Engineering programme.

2.2 Challenges in the project design

Predecessors of the considered Mechatronics project have been running for over 20 years. The project used to combine the aforementioned learning objectives with learning objectives on construction principles for precision mechanisms. At the introduction of the Twente Educational model [1], the project was split in a project on mechanical design and a module on dynamic modelling and control. These projects were allocated to two separate modules. In the time between these modules, the mechanism designs were being produced by a team of technicians. This implementation of the project had several downsides related to the hardware; The realisation of the designs was costly. The students had to be grouped in large teams to be able to timely realise all designs. After production it was hard to modify the design in case of flaws in design or production. Furthermore, the electronic hardware was non-portable forcing the students to work in crowded rooms, while the limited availability of the electronic hardware required time-sharing. These issues lead to poor student appreciation and motivation. An increase in the inflow of students even aggravated these issues.

To overcome the aforementioned issues the project was redesigned. In the end this should increase student motivation and learning. Considering that most issues are related to the hardware used, the hardware had to be redesigned (see section 2.5) along with the educational aspects (see sections 2.3, 2.4 and 2.6).

2.3 Project structure

In 2013, the University of Twente introduced the Twente Educational Model [1]. In this model, the curriculum consists thematic 15 ECTS modules based on project led education. The project thereby has a central place in the 10 week's module. It allows students to apply and practice the theoretic knowledge in the project. Specifically, in the 2nd year's Mechatronics module of the Bachelor Mechanical Engineering programme, the project (5.5 ECTS) requires students to model the dynamic behaviour of a mechanism using the theory from the *Dynamics* course and to control the motion using the theory from the *Systems and Control* course. The students need already quite extensive knowledge from the latter course start with the project. Thereby, the lectures of this course are scheduled in weeks 1-5, while the project is scheduled in weeks 5-9 (see Table 1). The assessment of both courses and project are scheduled in the 10th week. This way the students can use the theory from the courses in the project to deepen the theoretical knowledge before the course's assessments.

In week 2-4 three introductory practicals are scheduled to train the procedure to measure a frequency response and implement a PID controller, learning objectives 2 and 3 respectively. Furthermore the experimental work in the practicals is linked to the theory from the courses. Concurrently students can familiarize with the hardware that is used later for the project. In weeks 5-9 the actual project is scheduled, in which the theory of the courses is transferred to the design and evaluation of the mechatronic system of the project. The project work relates to all learning objectives as detailed in the next paragraph. Through the project work the students can get a deeper understanding of the theory and the relation between the theoretical disciplines involved.

The project is structured along the lines of the V-model [3] (see Fig. 1), which is a well-known model for the systems engineering process and closely links to the previously mentioned CDIO context of engineering practice [2]. This ensures students take the right sequence of steps, which also enhances time efficiency. A concept of operations for the system is provided to the students. Based on this concept, the students have a week to set up the architecture and requirements for the mechanical and control subsystems. Subsequently students have a week for the detailed design of these subsystems, including the implementation of the controller. The hardware (see section 2.5) allows implementation of the mechanism in one day and in the rest of the week the students measure the response of the mechanical system to verify compliance to the design and to retune the controller if needed. Finally, in the last week, the students verify and validate the overall performance of the system and evaluate the design.

Table 1. Schedule of the module

Course\Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Dynamics 2	lectures									exam
Systems & Control	lectures									exam
Project		practical				architect	design	verify	evaluate	exam

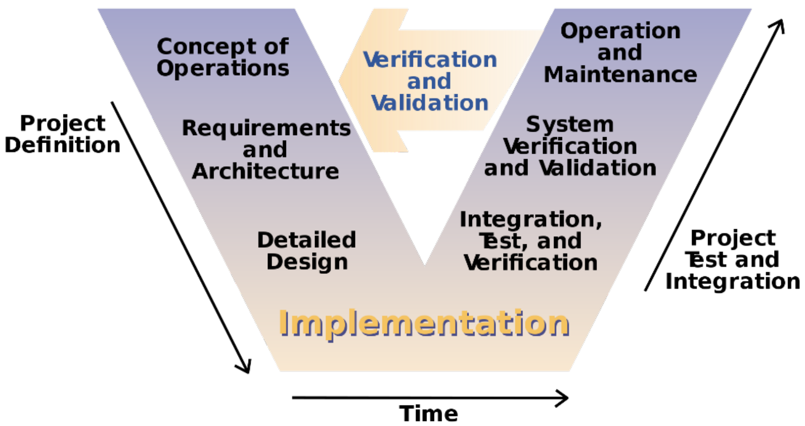


Fig. 1. The V-model of the systems engineering process (adopted from [3])

2.4 Project kick-off and support

Students are grouped in teams of 6. This relatively small group size stimulates student involvement and allows effective work distribution. All groups are provided with the same project description, which includes the assignment and organisational information. The project assignment is specified in terms of the required system behaviour and deliverables. The required system behaviour sets the goal of the mechatronic system to be realised. From the required system behaviour, the students have to architect the subsystem requirements and the way to realise these in a design. Differences in the routes taken by the groups yields different design implementations to reach the goal. The deliverables set the aspects to be considered in the design process and to be included in the project report. The specification of the required system behaviour and deliverables provides freedom in the design and the approach, while the outcomes are comparable for reliable assessment.

The project information is also explained orally in a kick-off lecture with the opportunity to ask for clarification. During the project a weekly lectorial is scheduled. In each lectorial, the deliverables and the supporting theory for the next phase are detailed. Further support is provided by teaching assistants during the experimental work and by question hours with teaching staff for the theoretical aspects. Students are also stimulated to pose questions on the discussion forum of the online teaching environment. Finally, each project group has a tutor, who keeps an eye on the planning, the group dynamics and spots free-riders. Students are free in organising the group work and have ample experience on working in groups from prior projects.

2.5 Project hardware: standard and customised components

Lab-in-a-box hardware is developed to support the project. The hardware allows fast realisation of the design, while it offers substantial freedom in design. This is realised by a combination of modular standard components and easy-to-produce custom design components.

The main modular components are holed blocks of stainless steel with matching fasteners. These blocks are metric versions inspired by the MechBlocks of Motus Mechanical [4]. The use of these components was inspired by the use of MechBlocks in the 2015 Challenge of the American Society of Precision Engineering. These mechanical components are supplemented by a voice-coil actuator and a position sensor to constitute a mechatronic system. The lab-in-a-box is shown in Fig. 2.

The students can design custom components that can be manufactured by laser cutting of steel plate. These components can be produced in one day. Typical custom components are brackets and flexure hinges. Flexure hinges are typically used in precision mechatronic systems as considered in the project. The theory of flexure hinges is learned in the prior module, while it is also an active topic of research in the department [5]. The design of the flexure hinges is important for the dynamics of the mechanical subsystem and the eventual performance of the mechatronic system.

In addition to the lab-in-a-box mechanics, an electronics box is provided. This electronics box can be connected to the actuator and sensor, and its microcontroller can be programmed on the student’s laptop via Matlab-Simulink. The electronics box is also used to control a linear stage during the practical. The lab-in-a-box and electronic box are portable and can thus be used at any convenient location (Fig. 3).

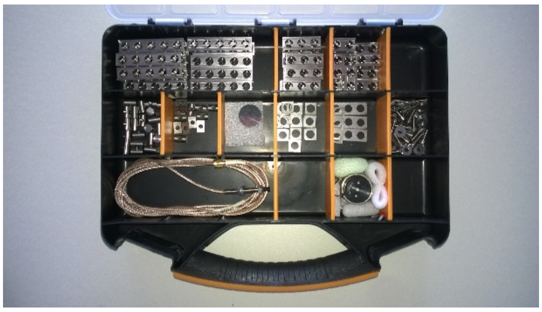
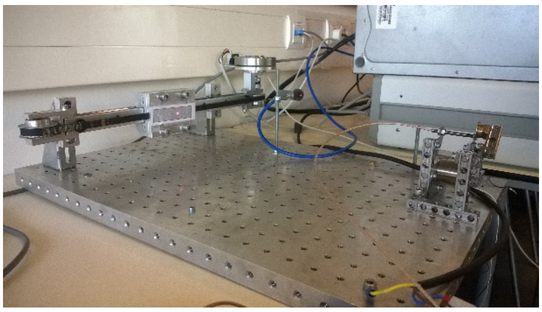


Fig. 2. The lab in a box

Fig. 3. The lab in a box in use

The actual realization of the mechatronic design and the experimental verification provide the students with the experience that reality deviates from theory, typically by unmodelled phenomena. They have to track and explain deviations, which requires them to combine modelling and experimental skills and provides insight in the interrelation of the disciplines. The lab-in-a-box allows adaptation of the design and retuning of the controller to adapt the system to these new insights.

The lab-in-a-box and the linear stage can be reused for various cases over the years. In the last two years they have been used to create a laser tracking system and an XY-plotter (Fig 4). The reusability allows depreciation of the hardware investment (mainly the mechanical blocks) over multiple years. The laser cutting of components are the only low recurring costs. This reduction in cost allowed an investment in sufficient hardware to reduce the group size to the desired number of 6 students even with an increasing number of students.



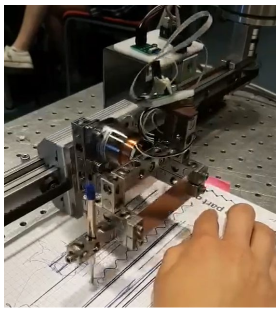


Fig. 4. Examples of design cases. Left: laser tracking system. Right: XY-plotter

2.6 Assessment of the project

The module is assessed through four components. First, the students have to hand-in a practical report to show they have trained the theory before the start of the design project. Secondly, the specified deliverables of the project are to be documented in a report. Major deliverables are on the level of insight, e.g., a discussion of the fundamental limitations in the design, an explanation of the differences between the model and the experimental results and an evaluation of the eventual design. Thirdly, they have to demonstrate the operation of the actual system, to verify the document performance has indeed been realised. Fourthly, the students have to do an individual written exam, to assess the individual achievement of the learning objectives and thereby prevent free-rider behaviour. The individual exam consists of questions on the steps taken during the design process.

3 RESULTS

Table 2 shows the results of the students and the overall student appreciation indicator from the yearly *Student Experience Questionnaire* (SEQ).

The redesigned project has been running since 2018. It has been observed that students are more active and enthusiastic. This is reflected by the clear improvement in the appreciation indicator in 2018. The improvement from 2018 to 2019 are probably related to solving some teething problems and further finetuning, particularly the lectorials and the portable electronics box have been introduced. From the 2019 questionnaire, some quotes from students on the strengths of the module are: “The idea of the practical part of the project is very motivating and interesting.”, “The integration of the different subjects in the project” and “The practical part of the project does give a lot of insight into control systems.” These clearly show the motivational effect and addition insight of having hardware at work, in line with the intended outcome of the project.

Improvements on the achievement of learning objectives are visible from the average grade on the reports. On the other hand, the grades on the individual exam drop severely in 2018. This is probably related to more complex questions in the exam. Splitting compounded questions and a discussion of typical exam questions in the lectorials already improved the exam score in 2019. However, students still feel the exam is somewhat disconnected from the project work. Further improvement on this issue is needed.

Table 2. Results of the exam and evaluation scores for the project

	Students graded	Average grade report	Average exam grade	Students in evaluation	Appreciation indicator
Scale	-	1-10	1-10	-	1-5
2017	104	5.1	6.5	33	2.5
2018	94	5.9	5.3	26	2.8
2019	122	6.4	5.7	31	3.3

4 SUMMARY

The paper shows the design of a project in which students complete a full design cycle, including the realisation and testing of a mechatronic system. The project is meant to integrate and practice theory from courses to enhance insight. The project is aligned with the V-model of the systems engineering process to enhance time efficiency. Realisation of the hardware in limited time is enabled by the use of lab-in-a-box, providing standard components that are combined with easy to produce custom design components. Seeing theory at work is highly motivating as reflected by observations and results from the student questionnaire. The grades on the reports resulting from the project also improved considerably.

As a future enhancement, the introduction of 3D printing is considered. This extends the ability to use custom parts that can be produced quickly. Another potential improvement is the use of e-learning applications for preparation of the practicals [6, 7], which could enhance the learning effect, while reducing supervision workload. The most urgent point of improvement for the project are the individual exams that assess individual performance of the student. Although exam questions are intended to test knowledge on the steps taken in the project, students experience the questions to be difficult and not testing their involvement in the project.

REFERENCES

[1] Visscher-Voerman, J.I.A. and Muller A. (2017), Curriculum development in engineering education: Evaluation and results of the Twente Education Model (TOM), Proceedings of the 45th SEFI Annual Conference 2017 – Education Excellence for Sustainability, SEFI 2017, Bernardino J., Rocha J., Quadrado J.C. (Eds.), Angra do Heroismo, Portugal, pp. 1167-1175.

[2] Crawley, E.F., Malmqvist, J., Östlund, S. and Brodeur, D.R. (2007), Rethinking Engineering Education. The CDIO Approach. Springer.

[3] Osborne, L., Brummond, J., Hart, R., Zarean, M. and Conger, S. (2005), Clarus: Concept of Operations, Federal Highway Administration, Washington D.C., pp. 20.

[4] Smith, S.T. (2018), Motus Mechanical, Motus sponsors 2015 ASPE Challenge, About Motus Mechanical, Retrieved from https://www.motusmechanical.com/about-us

[5] Naves, M., Nijenhuis, M., Hakvoort, W.B.J. and Brouwer, D.M. (2020), Flexure-based 60 degrees stroke actuator suspension for a high torque iron core motor, Precision Engineering, 63, pp. 105-114.

[6] Vreman-de Olde, G.C., Rouwenhorst, C., Alers, J.C. & Veen, J.T. van der (2019). E-learning on the lab with lab education software. Deeper learning & more efficiency? Proceedings of the SEFI annual conference 2019, pp 1261-1270.

[7] Wolbert, B., van der Hoogt, P., Lok, Z. A. J., & de Boer, A. (2007). Succesful teaching of experimental vibration research. Paper presented at 14th International Congress on Sound and Vibration, ICSV 2007, Cairns, Australia.