Enhancing interdisciplinary hands-on education in the field of Magnetic Levitation mobility and Signals Analysis and Control

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Final Report

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Final report

Final Project

I. Project overview: summary of project activities

In this report we provide an overview of the different project activities we have conducted in academic year 2017/2018 in order to meet the project objectives and outcomes of this proposal. In the appendices we also provide further information on how some of the activities have been implemented.

II. Recommendations by the jury

The jury who awarded this project proposal made some recommendations for the implementation of this project. We report below how the project team has integrated the recommendations made by the jury.

1. Interdisciplinary design principles in DBL S&S project. The project team has included interdisciplinary principles from the very first stage of project implementation. First of all, we included some EE and ME content elements in the project such as the extension to the fully digital domain, Z-transform and the pole manipulation in the digital (z-transform) domain. With respect to the Mechanical Engineering field, we added elements such as the frequency domain, recording a Bode plot of the open system, optimizing control action from that viewpoint. Furthermore, students were to start with the system with open loop stable (upside-down configuration: electromagnet is below permanent magnet, pushing the permanent magnet upwards), optimizing and later extending this towards the “normal” configuration, with the electromagnet magnet above the permanent magnet, pulling it up, where the open loop is unstable, and an open loop Bode diagram cannot be recorded. This was meant to work towards assuring that these elements contribute to not only learn new concepts and theory but also that the work-out of these in the project may foster as well trial-and-error way of thinking.

Moreover, the implementation of the interdisciplinary elements took place with only a reduced number of students in the Innovation Space (Gaslab) in order to investigate whether these interdisciplinary elements and the students’ activities have a positive effect on students’ way of working or results.
Finally, we included also some other educational elements into account for the design of the DBL S&S project. We took into consideration the research on Design-based learning available in scientific literature (Gomez Puente et al, 2011). We integrated a number of design steps in the students’ project activities such as problem analysis, build a model, realize graphic representation, and validating the model.

2. Sounding board. The jury recommended the configuration of a sounding board in order to provide feedback on the project activities. The sounding board consisted of the three Program Directors of the three involved departments together with the director of Innovation Space. Advice by the sounding board indicated a closer collaboration towards including the DBL S&S course as part of the choices the AP, EE and ME students make in the bachelor. During the presentation of results of the interdisciplinary DBL S&S project, insights

gained were shared with EE and ME so that the interdisciplinary character can also be integrated in other EE and ME projects as it was the intention of this project proposal. See appendix 1.

III. Objectives and expected outcomes of the project

In this section we report about the achievement of the objectives of this project as well as the outcomes:

- To develop an educational approach to solve problems suitable for interdisciplinary hands-on assignments;

- As mentioned above, the project team has carefully developed an educational approach not only to include the interdisciplinary aspects, in this case of the EE and ME disciplines, but also we have also redesigned some parts of the project that include now interdisciplinary assignments. The approach we have followed is that of integration of interdisciplinary elements into project process and product. In other words, students needed to study and experiment with some EE and ME aspects in order to apply a new step in solving the problem/designing a final product. In addition, the fact that some validated design steps have been used in the design process has strengthened the approach to re-design, or better to say, to adjust the DBL project approach.

- To develop a tailor-made assessment to assess knowledge and skills in interdisciplinary hands-on assignments;

- Since the complexity of the project took some time to define and apply, and due to the fact that there were many new educational elements included in the project, we decided to postpone the assessment part for the following implementation of the project. In addition, as the award of this project was announced in December 2017, and the TU/e deadline to publish course information (i.e. also assessment information) is on August 2018 for semester B, we already had the assessment included in the study guide and was not possible to adjust at this stage. Nevertheless, the responsible teachers are now considering to include digital test to assess knowledge.

- To initiate the collaboration among three departments involved in this proposal (AP, EE & ME) by working towards a hands-on (didactical) interdisciplinary approach for DBL projects.

- With this project, the first collaboration steps have been created among the AP, EE and ME departments. In addition, during the sounding board meeting more emphasis was made among the program director to reinforce the collaboration. As a matter of fact, a new project including the three departments has been developed and there are plans to include the DBL S&S in the curriculum of the EE and ME as electives.

- To create a link with the Innovation Space, as the project will be carried out (at least 3 groups of the DBL Signals & Systems project) in the Innovation Space location in Matrix.

- Following the experience of this first pilot in the Gaslab, we have made efforts to assure that this project course will be implemented in the Innovation Space.

- To create the infrastructure in the Innovation Space so that AP, EE and ME can be challenged to carry out activities in the premises of the Innovation Space.

- Funds made possible by this project have made possible to purchase equipment to create the infrastructure of the DBL S&S project but also for other EE and ME project courses.

Regarding the expected outcomes, we describe below the following:

- Educational approach (to solve problems suitable for interdisciplinary hands-on assignments) has been developed in several courses.

- Based on the first implementation of the DBL S&S project course, results were shared with EE and ME and plans for further introduction of interdisciplinary elements were discussed with the Program Directors. In addition, including this project course into the EE and ME electives curriculum is also considered.

- Assessment method to assess knowledge and skills in interdisciplinary hands-on assignments has been developed and tested in several courses.

- Considerations to assess knowledge in project-education in the following implementation of the DBL S&S project course in 2019 is already included.

- Collaboration has been started among departments in the field of hands-on and interdisciplinary education. AP, EE & ME share knowledge and experiences and educational approach is used in other courses, by dissemination activities (see dissemination plan, section VI in this proposal);

- The AP, EE and ME departments have already discussed an implementation plan to assure that this DBL interdisciplinary course is included in the curriculum of other departments as an elective course. In addition, there are also other plans to integrate EE and ME in this and other courses

- The DBL Signals & Systems project has been implemented in the Innovation Space.

- Based on the successful experience in the Gaslab, the next step is to include this project in Innovation Space in Matrix make in the project available to all students.

- The infrastructure of the Innovation Space has been created that facilitates the implementation of the DBL Signals and Systems (best three groups) and the potential implementation of other EE and ME courses in the Innovation Space.

- This outcomes has already been achieved.

IV. Dissemination and sustainability

The relevance of this project has been expanded to other levels, contexts and even across departments. The importance of showing how the Signal and Systems course can be transformed into a project-based course is high in order to create 'good practices' and examples for other lecturers and departments within the TU/e, but also within the Netherlands and internationally.

Dissemination across departments and levels: even before the implementation of this project, the two responsible lecturers of the DBL S&S course presented the transformation from course to project during the Education Day of the Electrical Engineering department. In addition, the dean of the AP department and one of the responsible lecturers of this project course, has presented the approach in the deans meetings (Lanake).

Dissemination among universities in the Netherlands: The lecturers of this course have presented this experience and results of the interdisciplinary character including the EE and ME components, in the annual ICAB conference of beta education in University of Twente. See appendix 2.

Dissemination in international conference: The first experience of this pilot has been presented at the annual SEFI conference in Copenhagen (Denmark). See appendix 3.

Appendices:

Appendix 1: Discussion with Sounding Board

'Enhancing interdisciplinary hands-on education in the field of magnetic levitation mobility and signals analysis and control'

Review meeting – Sounding board

Gerrit Kroesen, Rudie Kunnen & Sonia Gomez
June 7th 2018

TU/e Technische Universiteit Eindhoven University of Technology

Where innovation starts

4TU. CENTRE FOR ENGINEERING EDUCATION

Agenda

- Objectives of the meeting:
  - Review jury's requests
  - Interdisciplinary set-up OGO Signal & Systems and implementation in Innovation Space
  - Feedback
  - Adjustments and future collaboration between departments

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Introduction: Context OGO S&S

- MAGLEV trains - magnetic levitation - Trains are not resting on wheels, but are levitated in a contact-free and friction-free way
- Electromagnets in tracks and permanent or electromagnets in trains are arranged in such a way that trains are suspended
- Trains can be suspended either by pushing forces (identical magnetic poles) or by pulling forces (opposite magnetic poles)

✓ Assignment: Explore physics, control aspects & hardware aspects, and deliver a model system to demonstrate proof of principle
✓ Project approach: 4 best groups additional interdisciplinary EE & ME components in Innovation Space

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Interdisciplinary approach

- Electrical Engineering topics
  - Extension to fully digital domain
  - Z-transform and pole manupulation in digital domain
- Mechanical Engineering
  - Frequency domain
  - Recording a Bode plot of open system
  - Optimization control action
- Explicit engineering design steps: analysis problem, use graphic representation & build model → *trial-and-error*
- Innovation Space

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Results (1) – Survey, interviews & reports

Table 1. Survey: Overview mean of groups with & without interdisciplinary elements

	Groups without interdisciplinary approach		Groups with interdisciplinary approach in Innovation Space	
	M	SD	M	SD
Q1	2.76	.99	3.31	1.04
Q2	2.90	.99	4.00	.69
Q3	2.65	.87	3.40	1.18
Q4	2.80	1.19	3.54	1.10
Q5	3.77	.75	3.40	1.25
Q12	3.76	1.09	3.22	1.02

- *Q1 – The project is interdisciplinary (i.e. design steps from other disciplines, for instance in designing a solution);*
- *Q2 – The project is interdisciplinary (i.e. there are concepts or topics from other disciplines rather than only Applied Physics);*
- *Q3- The location, Innovation Space/Flux, has inspired me to work in a more creative and innovative manner;*
- *Q4 – The location, Innovation Space/Flux, has inspired me to work in a more collaborative manner;*
- *Q5- The project is open-ended, e.g. there is no one solution given, there are possibilities to look for alternatives, no specifications of the final solutions are given;*
- *Q-12 – The project represents a real-life problem as, for instance, I was working in the industry (question for students in the labs). Working in the Innovation Space resembles better the idea of working in a real-life project representing industry problems (question for InnSpace students)*

- **Students' perceptions (interviews)**
  - Interdisciplinary and trial-and-error approach Innovation Space no major differences in working method
  - EE & ME components used in InnSpa groups but not fully completed - Time constraints
  - Interdisciplinary components influenced hands-on = more experimentation with controller systems, etc.
  - Engineering design steps stimulates hands-on = deeper exploration
  - Collaboration and communication among groups increased in InnSpa

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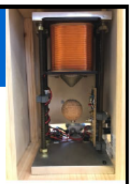
Results (2)



- Analysis of reports (InnSpa vs. FLLUX groups)

- Use of ME & EE interdisciplinary: Bode plot, low-pass filter, discrete transformation
- InnSpa groups follow mainly physics working method
- InnoSpa: 1 group innovation = disturbance of light in the Gaslab
- InnoSpa groups = original display & optimization techniques, e.g. 3-D plots from poles, Ziegler Nichols approach, etc.
- Quality of measurements and simulations not different but quality of analysis InnSpa is better
- InnSpa groups score 1 point higher than FLUX groups

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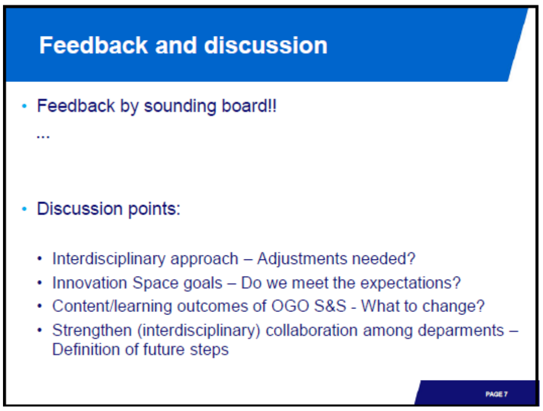
Feedback and discussion
Feedback by sounding board!!
...
Discussion points:
Interdisciplinary approach – Adjustments needed?
Innovation Space goals – Do we meet the expectations?
Content/learning outcomes of OGO S&S - What to change?
Strengthen (interdisciplinary) collaboration among deparments – Definition of future steps
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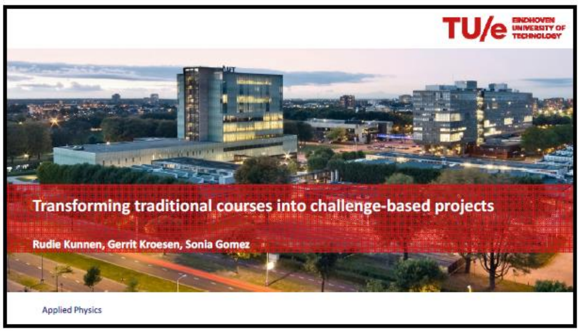
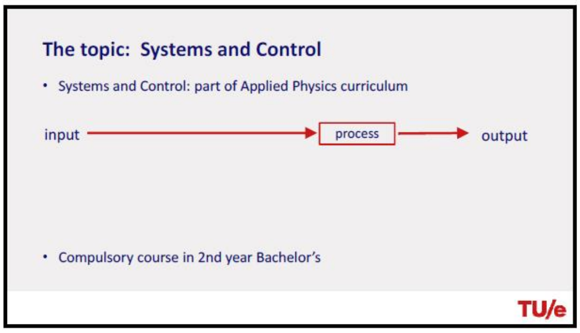
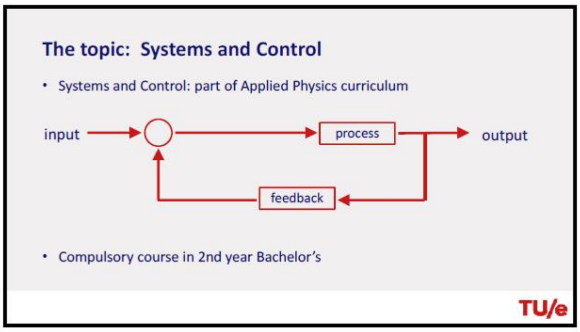
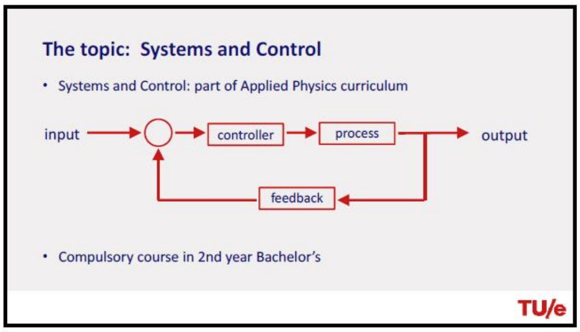
Appendix 2: Presentation at ICAB conference



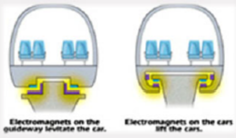


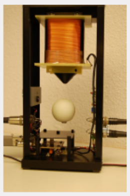




Since 2017: focus on Magnetic Levitation trains

Maglev train:
2 configurations





Control required for a smooth ride.

Which configuration performs "best"?

TU/e

Since 2017: Design-Based Learning course

Students work in groups of 6 on an open-ended design assignment:

Design, implement & test control algorithms for a (model) maglev train

NO lectures, NO step-by-step instruction (we do provide a reader on control)

Students have to master theory & implementation independently

TU/e

Since 2017: Design-Based Learning course

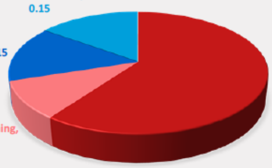
Procedure:

- Weekly group meetings:
  - reporting of progress (short presentations)
  - decision on actions/directions
  - division of tasks for coming week

- Tutor (PhD student) present to monitor progress & act as sounding board (but is NOT leading the group!)
- Teachers and tutors meet once per week

TU/e

Assessment



TU/e

Positive aspects of current approach

- Optimized retention by hands-on experience
- Learn to solve problems of open-ended questions in an iterative process
- Educate students in executing design and multidisciplinary tasks
- Natural embedding of various professional skills:
  - Project planning
  - Presenting
  - Meetings: chair & secretary
  - Working together as a team
  - Writing a report

TU/e

Challenges in current approach

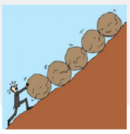
New developments:
(Feb 2019 -)

- Individual component of the grade could be increased
- Hard to test individual retention of knowledge
- There is some "cross-talk" between groups & years
- Accommodation of wide range of skill levels

→ Individual electronic test

→ Develop more experiments

→ Provide multidisciplinary lectures with advanced control concepts



Electrical & Mechanical Engineering are interested in joining!

TU/e

Your challenge

- Consider in groups your own "traditional" course and devise how to convert them into a hands-on project
- If no consensus course, try "Mechanics 101"
- Questions:
  - What does the class gain?
  - Is multidisciplinarity desired?
  - Which skills can be integrated in a natural way?
  - How to assess?
  - ....

TU/e

Appendix 3: Presentation at SEFI conference

Enhancing interdisciplinary hands-on education in the field of Magnetic Levitation Mobility and Signals Analysis and Control

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Conference Key Areas: Curriculum development, Engineering skills
Keywords: Engineering education, Interdisciplinary, design-based learning

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INTRODUCTION

Imagine a world with environmental-friendly, soundproof and safer modern trains. The second-year Design-based learning bachelor project *Signals and Systems* has introduced an interdisciplinary and hands-on approach to let students explore physics concepts of Maglev trains. This type of modern train is not resting on wheels but is levitated in a contact-free and friction-free way. The rationale to integrate interdisciplinary engineering approaches from Electrical and Mechanical Engineering domains is based on stimulating the application of trial-and-error methods in order to enhance out-of-the-box thinking. Physicists, however, apply a mathematical approach to analyze physical models using differential equations and Laplace transformation.

The integration of the interdisciplinary and hands-on approach in this compulsory project of the Applied Physics curriculum at the Eindhoven University of Technology (TU/e) is two-fold: first of all, we introduced more explicitly a limited number of engineering design steps also common to other disciplines, e.g*. analyse the problem, exploring graphic representation of the problem, or building a model*. Secondly, we also included interdisciplinary elements from Electrical Engineering, e.g. extension to the fully digital domain, Z-transform, and pole manipulation in the digital (z-transform) domain. In addition, the Mechanical Engineering input consisted of working in the frequency domain, recording a Bode plot of the open system, and optimizing control action.

In this project, we also have groups of students who carry out the DBL *Signals and Systems* project in the Innovation Space (InnSpace) at the TU/e university campus. This InnSpace location has been specially created to accommodate students' groups working on multidisciplinary collaboratively projects.

In this study, we explore to what extent interdisciplinary elements embedded in the DBL *Signals and Systems* project have influenced the quality of the students' final products. In addition, we examine whether the Innovation Space has encouraged students to work in a more creative and collaborative manner.

Interdisciplinarly in engineering education

Rationale for interdisciplinary education

Interdisciplinary education is becoming more and more an essential component of the curriculum of engineering studies and applied technical programs in higher education. The rationale to pay more attention to interdisciplinary in upper education curricula lies in the fact that the requirements of the industry are more demanding for newly graduates [1]. As the labour market is dynamic so are the developments of new products and equipment, technological processes and applications to meet societal, health, energy and economical demands [2]. These challenges in society claim for a broader approach to work in teams with experts from other disciplines *making use of tools, integrating information and data techniques, and using concepts or theories to solve complex problems* [3].

The need for interdisciplinary education becomes even more relevant as the expected knowledge and skills of both engineers and physicists are framed in accreditation frameworks [4]. This to assure that the output to the industry meets the expected requirements [5].

Theoretical considerations

Definitions on the concept of interdisciplinary in higher engineering education are numerous in the research literature [6]. The differences in the definitions lies in the models and focus of application in education. Interdisciplinary education is interpreted as a mean to teach students to solve problems from multiple disciplines and perspectives [7]. Other modern approaches and supporters of interdisciplinary argue that this type of education is embedded in technological innovations in which interdisciplinary knowledge is essential to resolve complex problems in iterative loops in order to create joint solutions [8].

When applying interdisciplinary approaches into courses and projects to design interdisciplinary education, the level of integration varies by nature depending on different considerations [9]. From an interdisciplinary research perspective, interdisciplinary education can be implemented by applying gradually different knowledge sources (multidisciplinary, interdisciplinary and transdisciplinary) [10]; by the degree of collaboration among the disciplines [11]; by induction as a method to structurally apply in program design [12] or by the so-called design abduction [13]. Furthermore, prescriptive forms of designing education by constructive alignment can provide suitable means to design interdisciplinary education by focusing on the teaching and learning environments [14].

Innovation Space

The Innovation Space (InnSpace) concept is a rather new creation at the TU/e. The motivation to build such a creative environment was generated by models elsewhere such as the Design Factory at the Aalto University in Finland. Inspired by this model, the InnSpace at the TU/e aims at stimulating students to work on hands-on projects in multidisciplinary teams in a collaborative manner while creating linkages with the industry, research organizations and businesses in order to create an ecosystem of technological development. One of the main goals of this macro project is to create a community of students and support them in interdisciplinary engineering projects to generate prototypes together with staff and companies. In addition, the purpose is to *transform prototypes into products and services for society, creating new businesses and valorizing research at the university* [15].

With this vision of interdisciplinary education and innovation in mind we selected a group of students to carry out part of the project in the Innovation Space. Our interest was to identify whether this innovative environment of the InnSpace would have an impact on students' final products.

The design of the DBI signals & systems project

Design-based learning and hands-on education

The aim of the DBL *Signals and Systems* project is to explore systems to maintain a Maglev train levitating by experimenting with repulsion forces between the magnets in the train and the electromagnetics in the track. The assignment is hands-on as students experiment with the levitation of a ball by measuring pull-up and pull-down forces. Students work through the open-ended design-based [16] project by exploring how a control system works, reviewing stabilization time and experimenting with calibration.

2.2 The interdisciplinary design of the DBL *Signals and Systems* project

Grounded in the theoretical considerations mentioned above and more specifically in Biggs & Tangs' constructive alignment theory, we focused on one of the elements of the model of teaching and learning in higher education, i.e. learning environment. Following the constructive alignment theory, we made more explicit a limited number of engineering design steps from engineering disciplines. The engineering design steps are taken from Mehalik and Schunn's taxonomy [17] and these are *analyse the problem, use graphic representation and build the model.* This taxonomy is validated and based on an empirical analysis of engineering design steps that take place in engineering disciplines. For the purpose of our study, we only applied however a few design steps of this taxonomy that fit the content and context of the DBL *Signals and Systems* course.

In addition, we also included Electrical Engineering (EE) and Mechanical Engineering (ME) interdisciplinary elements following Klein's approach on the degree of collaboration among the disciplines. In this regard from the Electrical Engineering field, we integrated topics such as the extension to the fully digital domain, Z-transform and the pole manipulation in the digital (z-transform) domain. With respect to the Mechanical Engineering field, we added elements such as the frequency domain, recording a Bode plot of the open system, optimizing control action from that viewpoint. Furthermore, students were to start with the system with open loop stable (upside-down configuration: electromagnet is below permanent magnet, pushing the permanent magnet upwards), optimizing and later extending this towards the "normal" configuration, with the electromagnet magnet above the permanent magnet, pulling it up, where the open loop is unstable, and an open loop Bode diagram cannot be recorded.

Moreover, following the open-ended approach of the design-based learning educational concept, the integration of the EE and ME elements has not been introduced in the form of a framed assignment. On the contrary, short introductory lectures have served to present new concepts on disciplinary topics in order to widen students' understanding on those. The open-ended character lies therefore in providing students with insights so that they are stimulated to further conduct experiments and analysis, carry out tests and based on results to apply iterations in the models. By doing so, students gather new information and facts in each design step and apply this new knowledge in order to generate and produce new insights [9].

It is worth mentioning that the rationale to integrate EE and ME disciplinary themes was not only based on including elements of these disciplines but also to stimulate a rather trial-and-error approach to problems and look for solutions. On the contrary, the physicists' approach follows rather linear process to analyze physical models using differential equations and Laplace transformation.

Methodology

Research methodology

The methodology we have applied in this study followed a triangular approach. In order to collect students' perceptions on the interdisciplinary elements in the DBL *Signals & Systems* project, we developed a structured Likert-scale questionnaire (1 to 5 scale). The majority of the questions for this survey were taken from a previous research study and has been readjusted for the purpose of this research. The questionnaire has been previously validated [16]. We also interviewed students, tutors and lecturers to identify interdisciplinary elements applied in exploring physics concepts and in delivering a proof of principle model system. Finally, we reviewed the students' reports in order to identify whether the interdisciplinary and hands-on elements have influenced the quality of the products, the approach taken towards solving the problems or the steps followed in order to solve the problem.

Participants

The participants in this study were second year bachelor students enrolled in the Applied Physics study program. The total number of students that followed the course DBL Signals & Systems were 146. For the purpose of this research N= 45 students took part in the study, N= 22 students conducting experiments in the Innovation Space location and N= 23 students working at the AP building premises. The selection of the groups involved in this study was done as follows:we selected four groups at random in order to collect perceptions and observe students' approach to solve the problems within the regular labs. In addition, four other groups were selected to carry out the project in the Innovation Space premises. The selection criteria to choose these four InnSpace groups were based on their progress shown in the first part of the course involving levitation of a ping pong ball emulating the levitation magnets of a train, and in particular representing the effectiveness of a configuration for a train and the system to keep the ball afloat. Likewise, the selection of the tutors was completely arbitrarily done as the tutors were previously randomly distributed among the groups.

Results

Students' perspectives

We collected students' perceptions by a structured Likert-scale survey consisting of 12 questions. For the purpose of this study, we only present the results of the questions pertaining to the interdisciplinary character of the project (Q1 to Q3) and the questions related to the impact of the location, e.g. InnSpace or the regular lab premises (Q4, Q5 and Q12).

Table 1. Overview mean of groups with & without interdisciplinary elements

	Groups without interdisciplinary approach		Groups with interdisciplinary approach in Innovation Space	
	M	SD	M	SD
Q1	2.76	.99	3.31	1.04
Q2	2.90	.99	4.00	.69
Q3	2.65	.87	3.40	1.18
Q4	2.80	1.19	3.54	1.10
Q5	3.77	.75	3.40	1.25
Q12	3.76	1.09	3.22	1.02

The results in table 1 indicate differences in perceptions between the groups that have been exposed to the additional EE and ME interdisciplinary content within the Innovation Space and those that remained in the premises of the AP traditional labs. Looking at the results of some of the questions[2] (Q1, Q2, Q3) we perceive substantial differences in students' perceptions related to the interdisciplinary character of the project, both in the design steps taken from other disciplines as well as the content provided. Regarding the perceptions on whether the location has inspired the students to work in a more creative and collaborative manner (Q4), results indicate that students working in the Innovation Space have a more positive opinion on the influence of this location in the way of working. This due to the fact that the premises at the InnSpace are open extensions in which students work around a table. This provides more opportunities for collaboration among the group members and with other groups as well. There is however little differences with respect to the open-ended character of the project (Q5) as the

[2] *Q1 – The project is interdisciplinary (i.e. design steps from other disciplines, for instance in designing a solution); Q2 – The project is interdisciplinary (i.e. there are concepts or topics from other disciplines rather than only Applied Physics); Q3- The location, Innovation Space, has inspired me to work in a more creative and innovative manner; Q4 – The location, Innovation Space, has inspired me to work in a more collaborative manner; Q5- The project is open-ended, e.g. there is no one solution given, there are possibilities to look for alternatives, no specifications of the final solutions are given; Q-12 – The project represents a real-life problem as, for instance, I was working in the industry (question for students in the labs). Working in the Innovation Space resembles better the idea of working in a real-life project representing industry problems (question for InnSpace students)*

set-up of the course contains ill-defined aspects in the assignments. Finally, the question (Q12) on whether the Innovation Space resembles better the idea of working in a real life problem has not major impact on students' beliefs. Differences in results may be influenced by the fact that the four groups selected to carry out the project in the Innovation Space were chosen based on the quality of the mid-term results (i.e. groups managed to let the ball floating) they produced.

Analysis of reports

We selected specific criteria in order to compare quality of reports and appreciate whether essential elements of the design process and interdisciplinary education have been applied by the students. In the tables below we present an overview of the Innovation Space students and students carrying out the assignments in the labs. Some of the criteria on interdisciplinary cannot be used for comparison as the groups in the labs had not access to additional interdisciplinary education.

Table 2. Overview of students' Innovation Space scores

Groups / Criteria	3	5	7	15
Criteria to make adjustments in the model, or optimize performance	+	++	+	+
Adjustments in the model, or optimize performance and validating the model and analysing	+	+	+	++
(More) iterations as a result of testing different models of EE/ME elements	+	++	++	0
Z-transform, and pole manipulation in the digital (z-transform) domain (EE)	+	+	+	-
Optimizing control action (ME)	+	++	0	0
Group's final grade	9	9,5	9	8,5

Table 3. Overview of students' scores in lab premises

Groups / Criteria	2	4	9	11
Criteria to make adjustments in the model, or optimize performance	+	0	++	0

Adjustments in the model, or optimize performance and validating the model and analysing	++	+	+	+
(More) iterations as a result of testing different models of EE/ME elements	0	0	+	-
Z-transform, and pole manipulation in the digital (z-transform) domain (EE)	*N.A.	N.A.	N.A.	N.A.
Optimizing control action (ME)	N.A.	N.A.	N.A.	N.A.
Group's final grade	8	7	9	7,5

*N.A. Not applicable

From the lecturers' perspective, the Innovation Space groups with additional interdisciplinary input score roughly one point higher than the groups which remained in the AP building premises. However, it is worth mentioning that the InnSpace students were selected based on the quality they produced in the first weeks of the project. Furthermore, it is remarkable that the Innovation Space groups have certainly made more use of the additional interdisciplinary components. As a matter of fact and according to the lecturers' findings students have applied the Bode plot, used the low-pass filter as well as the discrete transformation among others. Surprisingly, students carrying out the project in the InnSpace mainly follow the physics approach during the project implementation and experimentation. Another observation by the lecturers is that the Innovation Space groups also had more possibilities to make use of the newly gained knowledge for instance through the experimentation with the disturbance of the light in the room (disturbing the optical sensor in the setup). In particular, one group even made a special box as this group certainly went deeper into their analysis to protect the floating ball from external factors such as light. Another annotation is that these groups also used more original display techniques and optimization techniques, e.g. 3-D plots from the poles, Ziegler-Nichols approach, etc.

The quality of the measurements and simulations is not very different between the AP lab and the InnSpace groups, but the quality of the analysis by the InnSpace groups is much better.

Students' observations and interviews

Semi-structured interviews with students carrying out projects at the InnSpace premises reflect similar findings regarding the working method. Students both in Innovation Space and in the traditional premises mentioned that the use of a trial-and-error approach is a logical process of testing how for instance the PID controller works when optimizing the system. In addition, the interdisciplinary components of the InnSpace assignment have not enhanced a different approach to work. The InnSpace groups recognize indeed the EE and ME components in the assignments and used for instance the theory on adaptive PID controller or linearization for discrete analysis although these have not been completely practiced by all InnSpace groups. Reasons for this have to do with time constraints rather than with the assignment itself. According to the students, the influence of the interdisciplinary components has indeed enhanced the hands-on aspects of the project as it requires more experimentation with multiple ways of controller systems, the improvement of the systems, adjusting the frequency response and stimulates the options to use different methods. In terms of the engineering design steps, the fact that the InnSpace require more analysis and experimentation in designing the system and building the model implies therefore a deeper exploration of, for instance, how a low-pass filter works and the calculations of the values. This encouraged more iterations in building the model, for example, in making the system more stable with the use of lead-lag compensator. Regarding graphic representation, there is no difference between InnSpace and the other groups. The specific added value of the InnSpace is that the collaboration among group members and the communication with other groups has increased. Students have more possibilities to move around in the open space. This stimulates communication easily.

Conclusions

The implementation of the DBL *Signals and Systems* project has been an excellent opportunity to explore how interdisciplinary components can play an important role in education. Efforts made to embed these EE & ME components are obviously more evident in the InnSpace groups than in the groups working in the labs. Slight differences are also perceived in the analysis of the system and in building the model as the InnSpace groups studied and used additional theory, i.e. the Bode plot, used the low-pass filter as well as the discrete transformation and an adaptive controller in building the system. However, these steps are not commonly applied by all InnSpace groups. Likewise, although a different working approach was expected this has not been always obvious and students still use the physics way of conducting experiments by gaining first the insights from literature, using the linear process in analysing physical models and transforming these into differential equations to apply those in building a model.

The results of this project opens up new venues for further experimentation to design interdisciplinary hands-on projects. Implications for further research imply adjusting the design and set-up of the DBL project *Signals and Systems* by, for instance, including more explicitly the engineering design steps from Mehalik and Schunn's taxonomy. This will reinforce the trial-and-error working method. It will also encourage a more in-depth approach to analyse, experiment and test while building a model. These adjustments in the assignment will ask as well for other forms to assess of students but also in teachers' and supervisors' attitudes in order to align the project more constructively.

Regarding the Innovation Space, this element depends strongly on the new premises being built at this moment at the TU/e. The vision of the Innovation Space is still under construction and the implementation of this ambition lies strongly on making a practical environment in which students can easily collaborate with students from other disciplines, create linkages with the industrial partners and foster creativity and innovation. This will immediately encourage the multidisciplinary vision of the Innovation Space.

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