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Enabling non-engineers to use engineering tools: Introducing product development to pupils using knowledge-integrating systems

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Abstract

Many engineering tasks are supported by tools based on innovative technologies. Powerful tools for computer aided design, simulations or programming permit a wide range of possibilities for engineers in solving complex problems. However, using these tools commonly requires extensive training or specific skills.
Specialized systems that enable tool and technology usage could support novices in solving engineering tasks using embedded knowledge, lowering the hurdle of expertise required for operation.
In the presented case study, knowledge-integrating systems inspired by knowledge-based engineering were developed to allow pupils to solve an engineering challenge without existing skills or prior training. To provide a realistic application context, a teaching module was developed, introducing high school students to product engineering in the form of a conceive-design-implement-operate experience with the learning goal to engage them in the STEM field. Solving the included engineering challenge required the creation, test and iteration of designs for laser cut and additive manufacturing, and code processing sensor signals for motor actuation.
To evaluate the knowledge-integrating systems in their use qualitatively, a trial run was conducted. Participants were enabled to fulfil basic product engineering tasks and expressed engagement in product development and overall satisfaction.

The module's key element is an educational exoskeleton that can be controlled by electromyography signals. It is modified to eventually support a fictional character suffering from monoplegia. The module was realized accompanying the CYBATHLON, a championship for people with physical disabilities in solving everyday tasks assisted by state-of-the-art technical systems.

Keywords: Engineering education; Design education; Technology enabling; Product development simulation;

1. Introduction

Many powerful tools exist to support engineers in solving problems. The classical engineering tasks of designing, building and testing products which tackle problems are accelerated by computer aided design (CAD), simulation tools, fabrication tools and programmable controllers [1,2]. While there are plenty of options to choose from, they usually require the acquisition of specific skills to be employed efficiently.

This problem can be addressed by training users, in this context engineers, to build up expertise on employing these tools. However, time and resources for adequate training are not always given and alternatives are required. Another approach is the integration of expertise in specialized systems themselves, instead of requiring it from the users. This way, users with a low skill level can realize complex tasks. Such systems exist in the specific context of professional product engineering, where they integrate knowledge to automatize tasks and support optimization to reduce time and cost of product development for users [3]. In this specific context, one speaks of *Knowledge Based Engineering* (KBE). Although KBE provides a promising approach for faster and more cost-

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efficient product development, research publications on the topic are still sparse [4].

In this work, an approach is presented on reducing the required skills needed to handle commonly used engineering tools, inspired by KBE. Knowledge-integrating systems were developed that require a low skill level from users with the goal to enable novices to solve an engineering challenge during a realistic conceive-design-implement-operate (CDIO) experience [5]. The approach is introduced in form of an explorative case study.

2. Related work & research gap

Engineering tools are complex and require specific skills to be handled efficiently. The use of CAD systems for example can accelerate product development by supporting design creation, analysis and optimization. However, several limitations to their efficient usage are present: Existing CAD systems were shown to be unintuitive and complex [6,7], requiring extensive training before being able to support design tasks. The required skill level for their usage represents an entry hurdle for users, which eventually limits the tool deployment.

The entry hurdle of required skills and its negative effects can be demonstrated in multiple contexts: In makerspaces, one factor limiting the usage of makerspace facilities was shown to be a lack of training or workshops [8]. Competency, connected to a user's level of expertise, is stressed in the context of makerspaces [9].

In the presented project's specific context, the entry hurdle of required skills limited high school students to solve a realistic engineering challenge during a simulated product development process.

Three possible options to enable engagement in the product development process were identified as feasible, given no prior skills on the use of engineering tools: Increasing competency by training participants, which was discarded due to highly limited time during the challenge. A second approach to increase competency was simplifying the engineering challenge, presented in the product development process, therefore falling back to a strongly simplified assignment like the marshmallow challenge [10] or a project based on Lego [11]. The third approach was to lower the required skills to handle actual engineering tools. Following the potentially beneficial approach of an educational challenge including a realistic engineering challenge instead of a strongly simplified one [12], the third approach was realized for this project.

Therefore, the goal of this paper is to present an KBE based approach on enabling users without any prior skills to use engineering tools and fulfill a product engineering task in the context of a CDIO experience for high school students. Following research questions will be addressed:

- Research question 1: How can engineering tools be adapted to support pupils solving engineering tasks?
- Research question 2: Will the knowledge-integrating systems enable high school students to fulfill an engineering task?
- Research question 3: How will the realistic CDIO experience affect pupils?

3. Application scenario description

To study the usage of adapted engineering tools in a realistic context, an application scenario was developed – an educational module, engaging participants in a simulated product development process with the goal to motivate them for a career in the field of science, technology, engineering and mathematics (STEM) [13]. The product development process was structured as a CDIO experience, including the engineering challenge of modifying an educational exoskeleton. The adapted engineering tools where therein used to support novices in solving the realistic engineering challenge without prior training.

3.1. Educational module

Application context of the underlying project is the educational module. Its learning goal was defined as the transfer of basic principles of product development to participants, and additionally engage them in the topic. According to Bloom's taxonomy of Educational objectives [14], participants should remember, understand and apply basic product development methods in the phases of conceiving, designing, implementing and operating. To reach this goal, participants are provided theoretical input, but also physically engage in a CDIO experience, simulating a product development process.

To develop the module, four units were defined, each containing phase specific theoretical input and product engineering tasks related to a specific CDIO phase.

The module structure was defined together with teaching personnel to ensure adequate time planning and appropriate complexity concerning the theoretical input and assignments, before being tested in a rest run including high school students. Feedback collected from participants, coaches and developers was used to improve the module and finalize development.

The finale module consists of four units, lasting 90 minutes each (Fig. 1). All units start with a brief theoretical input and discussion, which is followed by time for the participants to engage in a product engineering task. The following phases of a product development process are addressed specifically:

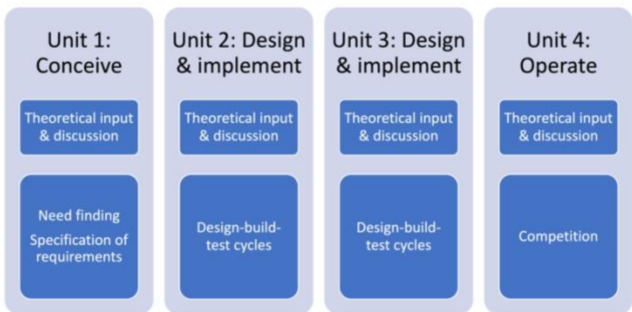

Fig. 1. module structure.

- Conceive: Problem analysis (need finding in the specific context of inclusion, specification of requirements)
- Design and implement: Creation of the product (iterations of designing, building and testing)
- Operate: Application of the developed product (competition)

The last unit includes a competition, in which predefined household tasks have to be completed while the required time is measured, simulating the product application.

Participants are divided into teams of four for the duration of the module. Each team is split again into two sub teams with one focusing on hardware, the other one on software development. The teams are guided through the development process by an education guide, containing graphics, lead questions and basic theory about the exoskeleton, available tools and product development in the context of engineering. The education guide was developed with the goal to enable participants to work freely during the module, providing important information and instructions, however leaving challenges to be overcome by the participants, therefore differing from a simple step-by-step manual. Additional support is provided by coaches, which are familiar with the employed systems and product development methods. In their role, they mainly provide thought-provoking impulses or hints to encourage the participants to find problem solutions themselves instead of demonstrating a complete solution path.

3.2. Engineering challenge

Central element of the module is the educational exoskeleton ‘Flexo’ that can be seen in its initial form in Fig. 2. It was priorly developed by mint & pepper, a project of Wyss Zurich, a center of ETH Zurich and the University of Zurich. Mint & pepper aims to promote STEM to children and teenagers. Its modification provides the realistic engineering challenge.

The exoskeleton consists of a servo motor that supports lowering and raising of the lower arm, two electromyography (EMG) sensors for control signal collection, and a single board computer, a myRIO programmed using LabVIEW, which is used for signal processing and motor control. Users attach it to both the upper and lower arm. The exoskeleton provides several interfaces for the attachment of additional sensors or hardware components. In the module’s project engineering task, participants are asked to modify the exoskeleton to include a gripper, actuated by an additional servo motor, with the goal of enabling the execution of simple household tasks, supporting a fictional character suffering from monoplegia (paralysis of a single limb, the left arm in the presented context). Exemplary tasks are putting laundry on a clothesline, pouring a beverage, attaching a portable hard drive and similar manipulations of objects. Depending on which tasks are selected for a module run, the required gripper complexity can be controlled. This results from the design complexity scaling with the degree of variety of objects that are to be manipulated. Fig. 3. shows the exoskeleton after its modification by the module’s participants.

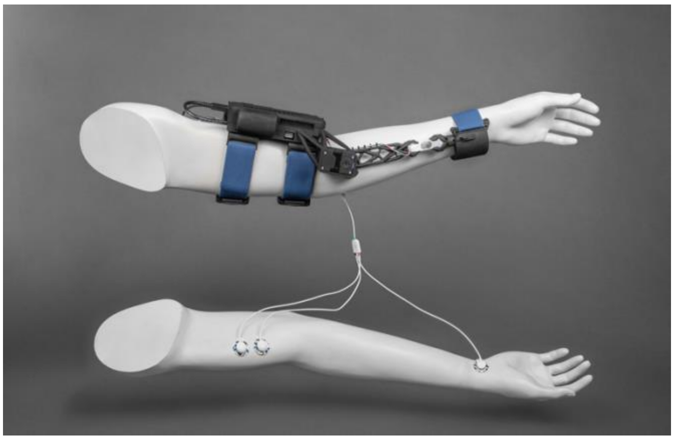

Fig. 2. initial form of the educational exoskeleton ‘Flexo’.

Fig. 3. exoskeleton after being adapted to support gripping of objects.

To solve this engineering challenge, participants are provided with specifically adapted engineering tools that support them in creating designs for laser cut and additive manufacturing (AM) as well as in programming motor actuations controlled by EMG signals. The engineering tools are adapted to embed experts’ knowledge to enable the design and programming tasks to participants without priorly acquired skills on the topic – section 4 describes this in detail.

Created designs are transferred into products using laser cut and a Multi Jet Fusion 3D printer, before they are tested. Additionally, material for paper prototyping and a collection of common workshop tools are provided.

4. Engineering Tools

The key element of the module are the engineering tools, which were developed specifically to enable their use to pupils, considering their lack of skills and highly limited time for training. To develop them, a process loosely based on the development process for KBE applications was followed, answering research question 1: For each of the tools to be deployed in the module, the stages of **problem identification, knowledge capture, application development** and **application deployment** [15] were realized. The following subsections describe this process for each of the adapted engineering tools. Therefore, the problem, the captured knowledge, the developed application and its deployment are introduced in each section.

4.1. Laser cut tool

Coming from industrial applications originally, laser cutters are a tool commonly used in the context of education (makerspaces, trainings, sources) and rapid prototyping. With their use, a variety of materials can be cut automatically into shape.

Design for laser cut parts is usually realized using either CAD or an image manipulation program to create a vector graphic, which is then translated into G-code. Creating designs therefore requires either skills or training in using these CAD tools or image manipulation programs.

To make skills or trainings redundant, a tool was developed to translate sketches drawn by hand into vector graphics. These processed sketches can then be fabricated using a laser cutter. Using the tool, exact sketches as well as free form drawings can easily be translated into fabrication input for a laser cut system.

The developed tool consists of a photo box, equipped with a ring light and a webcam (Fig. 4). It is connected to a computer, which runs an image manipulation script. The script exports a raster graphic, collected by the webcam, into a vector graphic.

Users create a sketch on a A4 sheet of paper, preprinted with reference points used in the digital image manipulation and predefined cutouts to ensure fit of produced parts to the exoskeleton's interface. After finalizing a sketch, it is placed in the photo box. A simple user interface presented on a monitor guides through the steps to create a digital vector graphic from the hand drawn sketch. During the module, the tool is used to create iterations of grippers for the adapted exoskeleton using laser cut.

Fig. 4. tool for laser cut design.

4.2. Additive manufacturing tool

Similar to laser cutters, systems for AM, or 3D printing, are commonly used in industrial fabrication or rapid prototyping. They can be used to fabricate a digital model layer by layer.

The digital model is again created by using CAD tools, requiring specific training or skills in using these tools.

To simplify the use of CAD and limit required preexisting skills to simple computer controls, a web-based configurator was set up. It includes a priorly created parametric design of a connection element that connects the grippers to the exoskeleton, realized with the CAD software Rhinoceros 3D. Providing this adaptable design allows for the pupils to create a customized AM part without CAD training.

The configurator was set up using ShapeDiver: the parametric design is displayed online, together with sliders and text inputs to adapt the design parameters (Fig. 5). If the parameters are adjusted, the displayed design is adjusted accordingly, providing real time feedback for the design task.

Participants of the module adapt the design to fit a user's dimensions, for example the length of his lower arm or the width of his lower arm at wrist height. Using the AM tool, they create a customized part for the exoskeleton.

Fig. 5. configurator for connection element design.

4.3. Programming interface

Programming a motor actuation, triggered by EMG signals, requires programming and signal processing skills.

Learning a programming language or debugging work was made redundant by developing a graphical user interface (GUI), visualizing the current arm position, the signals collected by the EMG sensors (filtered and unfiltered) and the signals sent to the servo motors in real time. Further, dropdown menus and sliders were implemented to apply signal filters and to connect sensor inputs to motor control outputs. To allow multiple combinations of filters, output and input signals, they were realized in the LabVIEW framework controlling the exoskeleton.

Using the interface, module participants can realize various combinations of signal processing changes, for example applying a moving average filter of the EMG signal and setting a threshold, above which a servo is activated, closing the grippers. As soon as the filtered signal falls below the threshold, the grippers will open again.

In a later version, a programming interface using Python was added: predefined functions in combination with a short tutorial, including explanations on basic coding concepts (how to use loop functions or if/else/then statements) and hints with prewritten code snippets enabled participants to code their own motor control scripts.

5. Evaluation

To validate both module and engineering tools, a trial was conducted with sixteen high school students, making up four teams. The participants had no preexisting skills to handle engineering tools or knowledge about product development in general.

5.1. Research question 2: Will the knowledge-integrating systems enable high school students to fulfill an engineering task?

Question 2 was analyzed by monitoring the adapted exoskeletons during the competition concluding the module: All teams reached the module goal of adapting the exoskeleton and were able to fulfill the predefined tasks in the competition, however varying in time. As a further method for evaluation, each module unit was followed by a qualitative feedback session including the module coaches. Since they followed the process of the module participants closely from a spectators' point of view, their insights were considered valuable considering the research question. Each coach formulated their insights on potentials and shortcomings of the module verbally in the format of a moderated discussion. The feedback included technical and organizational aspects, as well as specific insights on the use of the engineering tools. All verbal feedback was documented and used to further improve the module in a development iteration succeeding the module.

All teams were observed to be able to realize iterations of gripper designs to be laser cut and connection part designs to be fabricated using AM. The provided tools were reported to engage participants in the product engineering task, and together with the prototyping materials encouraged iterations of designing, building and testing. The pupils showed motivation and creativity in creating and testing their custom designs with the goal to perform well in the competition concluding the module.

Some groups were reportedly struggling with setting up the motor control code. Difficulties on connecting the EMG sensor inputs to the motor control signals were observed, indicating problems of the participants handling the programming interface. Some pupils wished for a more realistic coding experience. These insights lead to a rework of the GUI to enable motor control programming with prewritten Python functions, supported by exemplary code snippets.

5.2. Research question 3: How will the realistic CDIO experience affect pupils?

Following Kirckpatrick's framework for the evaluation of training programs [16], Question 2 was analyzed using a questionnaire to access the participant's reaction to the module. Table 1 shows the items making up the questionnaire. Each item was rated by the participants, expressing their approval from one ('not at all') to five ('thoroughly') on a Likert scale. Survey items were selected to access participant's perception of the module and gain insights on potentials or shortcomings of the module. The survey was submitted by fourteen participants after completing the module.

Table 1. Survey items for the evaluation of participant's perception of the module.

No.	Survey items
1	Was the procedure of the module clear to you?
2	Were the goals of the module clear to you?
3	Was the educational guide helpful to you?
4	Was working with the exoskeleton helpful to you?
5	How satisfied are you with the module overall?
6	The module encouraged me to participate.
7	The activities encouraged engagement with product development.
8	Discussions were perceived as exciting.
9	I perceived the module as relevant and profited from it.
10	I perceived myself as highly motivated during the module.

Fig. 6 depicts the results of the questionnaire, whereby the variation of participants' answers is visualized using error bars: Most participant's perceived the module's structure and goals as thoroughly clear and felt highly satisfied and motivated during the module. Less distinct, but still highly rated, were the module support by the exoskeleton and education guide, the encouragement for participation in the module and product development, perceived discussions during and relevance of the module.

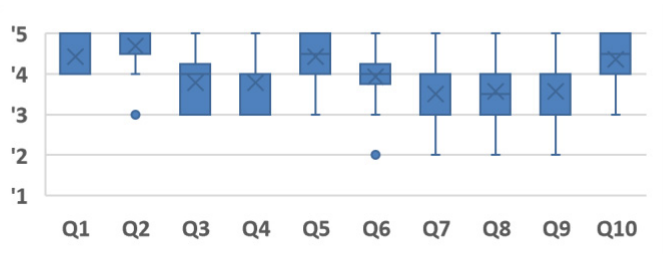

Fig. 6. distribution of participant's approval of the questionnaire items.

Based on these findings, improvements on the educational guide, the robustness of the exoskeleton and the integration of moderated discussions were planned for upcoming module runs, following the approach on developing KBE applications, where findings while deploying the application are used to improve it in following iterations [15].

6. Discussion & Conclusion

Goal of this paper was to present an approach to enable novices to solve a realistic engineering challenge in the context of a realistic CDIO experience. Instead of increasing participants' competency by training or a simplification of the engineering challenge, engineering tools were adapted to specialized systems that require lower skill levels from users.

The development loosely followed the stages of KBE system development.

The presented approach proved to be effective in the specific context of a CDIO experience, developed for high school students. It was shown in the evaluation that the adapted engineering systems enabled pupils to design for laser cut and 3D-print fabrication, and program motor actuations based on EMG signals, allowing them to fulfill the realistic product engineering challenge of adapting a product according to specific user needs. Following the qualitative evaluation regarding the pupils' reaction to the realistic CDIO experience, it was perceived to be encouraging in product development and creating personal gain, indicating a positive effect regarding engagement in product development. This realistic experience was only made possible by using the adapted engineering tools.

The presented approach could support developers of educational modules including realistic engineering challenges (e.g., serious games) or organizations that provide engineering tools to novices (e.g., makerspaces or learning factories) by giving insights on how to adapt existing tools or develop new systems that enable users to tackle engineering challenges whenever preexisting knowledge or training time are limited.

The developed engineering tools can be adopted for other purposes with varying effort in adaptions: The laser cut tool could be used without changes to enable simple prototyping work. The AM tool would need adaptions regarding the included parametric design and the options for modification to enable custom design of other AM parts. The programming interface is highly application specific and cannot be adopted for other engineering tasks without high effort.

Depending on the technology, using the presented KBE inspired approach to create knowledge-integrating systems therefore implicates several limitations that have to be considered:

- Adapting the engineering tools required high effort for development, as it requires time, personnel and expertise in various domains and is feedback dependent
- A limited range of possible solutions that can be created using the systems, restricting creativity
- A prior definition of tasks that would be realized using the systems, limiting them to specific applications

Additionally, the developed educational module could be used as an orientation on how to create a realistic CDIO experience to engage participants in a product development process and transfer product engineering principles, although a validation of the module as a tool for this purpose is to be realized first.

In further steps, the KBE inspired approach of increasing competency by using knowledge-integrating systems and therefore accelerating and supporting product development is meant to be realized in an industrial case study. The presented training module could be evaluated further to gain specific insights on its goal on engaging pupils in product development by analyzing its long-term effects. Furthermore, the presented approach could be evaluated in the context of a makerspace, analyzing its potential on enabling students from non-engineering backgrounds to engage in product development.

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References

[1] Raphael B, Smith IF. Fundamentals of computer-aided engineering. John wiley & sons; 2003 Jun 9.

[2] Camburn B, Viswanathan V, Linsey J, Anderson D, Jensen D, Crawford R, Otto K, Wood K. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science. 2017;3.

[3] La Rocca G. Knowledge based engineering techniques to support aircraft design and optimization; 2011.

[4] Verhagen WJ, Bermell-Garcia P, Van Dijk RE, Curran R. A critical review of Knowledge-Based Engineering: An identification of research challenges. Advanced Engineering Informatics. 2012 Jan 1;26(1):5-15.

[5] Crawley E, Malmqvist J, Ostlund S, Brodeur D, Edstrom K. Rethinking engineering education. The CDIO Approach. 2007;302:60-2.

[6] Riesenfeld RF, Haimes R, Cohen E. Initiating a CAD renaissance: Multidisciplinary analysis driven design: Framework for a new generation of advanced computational design, engineering and manufacturing environments. Computer Methods in Applied Mechanics and Engineering. 2015 Feb 1;284:1054-72.

[7] Szewczyk J. Difficulties with the novices' comprehension of the computer-aided design (CAD) interface: Understanding visual representations of CAD tools. Journal of Engineering Design. 2003 Jun 1;14(2):169-85.

[8] Bill V, Fayard AL. Building an entrepreneurial and innovative culture in a university makerspace. InASEE Annual Conference and Exposition, Conference Proceedings 2017 Jun 24 (Vol. 2017).

[9] Han SY, Yoo J, Zo H, Ciganek AP. Understanding makerspace continuance: A self-determination perspective. Telematics and Informatics. 2017 Jul 1;34(4):184-95.

[10] Wujec T. The marshmallow challenge. Retrieved November. 2010;12:2013.

[11] Masvosve T, Muller E. An exploratory study of how scholarship of teaching and learning (SoTL) inspires the use of the CDIO framework in engineering education. Journal for New Generation Sciences. 2016 Apr 1;14(1):92-106.

[12] Omidvarkarjan D, Conrad J, Herbst C, Klahn C, Meboldt M. Bender–An Educational Game for Teaching Agile Hardware Development. Procedia Manufacturing. 2020 Jan 1;45:313-8.

[13] Malmqvist J, Young PY, Hallström S, Kuttenkeuler J, Svensson T. Lessons learned from design-build-test-based project courses. InDS 32: Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia 2004 (pp. 665-672).

[14] Bloom BS. Taxonomy of educational objectives: The classification of educational goals. Cognitive domain. 1956.

[15] La Rocca G. Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design. Advanced engineering informatics. 2012 Apr 1;26(2):159-79.

[16] Kirkpatrick D, Kirkpatrick J. Evaluating training programs: The four levels. Berrett-Koehler Publishers; 2006.