EXPERIENCE THE RELEVANCE OF TESTING IN ENGINEERING DESIGN EDUCATION

Daniel TÜRK, Bastian LEUTENECKER, Mirko MEBOLDT

Swiss Federal Institute of Technology ETH Zurich

ABSTRACT

Engineering design education imparts students how to Conceive, Design, Implement and Operate complex engineering systems. The „Innovation Project“ at ETH Zurich is a project-based engineering design course, where 456 undergraduate students of mechanical engineering experience the CDIO activities in the freshman year in teams of 4 to 6 students. Starting from an idea, a concept and a design, the project work includes the production of several prototypes with direct manufacturing technologies and the implementation of the final system in a defined operation environment. A main finding of the project in 2013 is that systems being tested at different stages of the product development process showed higher reliability and better performance in the final contest. As a consequence, the learning effects of testing have considerable impact on the projects' success. This paper shows how the relevance of testing can be experienced in project-based engineering design education focusing on the case study of the "Innovation Project" where testing is approached in all four CDIO activities: (1) Testing in Conceiving by the development of low-fidelity prototypes facilitates the exploration of ideas and the verification of the concept. (2) Testing in Design enables the students to identify errors such as part collisions primarily in the context of Computer Aided Design. (3) Testing the Implementation refers to testing the assembly of the parts. Finally, (4) Testing for Operation is conducted by integrating the system in the intended overall system. Based on the results, it is discussed how the relevance of testing can be experienced and imparted in project based engineering design classes.

KEYWORDS

Testing, Prototyping, Engineering Design Education, Standards: 1,2,5,8

INTRODUCTION

The initial design of engineering systems inevitably contains design problems such as mismatches with customer needs, technical design faults or issues regarding manufacturability or maintainability of the product (Qian et al., 2010). Testing is an activity to detect and solve these design problems by generating valuable information. Testing increases design knowledge while reducing uncertainties (Lévárdy et al., 2004). As a consequence, testing is essential to ensure reliable engineering systems.

Both, qualitative and quantitative tests are used in the PDP. Quantitative tests usually require more effort and therefore the test sequence as shown in Figure 1 demands attention. The test case answers the question of what should be tested based on the product requirements.

The test plan consists of the operationalization of the test case and answers the question of how to conduct the test with the aim to ensure its measurability. Furthermore it defines the requirements of the prototype. Prototypes are a precondition for testing. Prototyping and testing are associated activities, being iteratively performed across the product development process. Finally the test is conducted on the prototype, the results are analyzed and further steps (e.g. redesign) are derived.

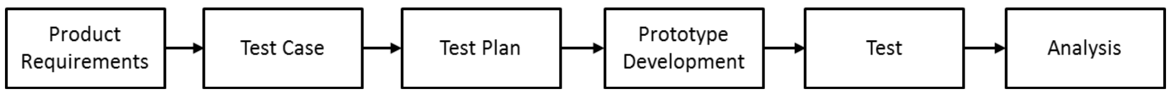

Fig. 1 Test Sequence

The prototype design strongly depends on the test case. Therefore the prototype fidelity varies according to the test case and the project stage. The fidelity of a prototype is defined as the degree to which a prototype corresponds to the product. In engineering design low fidelity prototypes are used to quickly test design hypotheses whereas high fidelity prototypes are a more realistic model of a product. In engineering design it is common practice to consider systems on different functional and hierarchical levels. This extends to testing, and therefore to the design of prototypes. Prototypes can display a range of function from one single function to multiple functions to all system functions. Classifying prototypes according to their fidelity and their level of system integration, allows to focus testing activities on specific system issues and thereby to generate specific design knowledge.
This paper presents an educational concept with a focus on experiencing the relevance of testing by prototypes. Therefore the classification of prototypes according to their fidelity and their functional range is elaborated in the first section. The second section of the paper presents a case study that was recently carried out as a part of the 'Innovation Project' at ETH Zurich with 456 undergraduate students of mechanical engineering. During the 'Innovation Project' students Conceive-Design-Implement-Operate an engineering system. The project work includes the production and testing of prototypes during single CDIO activities. The highlight of the project is the final contest, where the final system is performed in a defined operation environment.
Based on the comparison of conducted testing activities with the performance of the systems in the final contest, the relevance of testing is discussed with a special focus on imparting 'testing by prototypes' in engineering design education.

TESTING BY PROTOTYPES

Testing plays a central role in the development of a reliable product as it is used for the verification of deliverables and the validation of product requirements (Tahera et al., 2012). Designs are continually tested both virtually and physically during the product development process.
However, prototypes are necessary to make newly acquired knowledge available for further design considerations. Prototypes, either physical or virtual, embody design hypotheses, and so enable testing them (Hartmann et al., 2006).
The following classification of prototypes is proposed and displayed in Figure 2: First, prototypes vary in their fidelity and are often referred to as low or high fidelity prototypes, dependent on the degree it resembles the final system (Lim et al., 2006). Secondly, prototypes include a set of functions. They can vary from a single function to full system functions. This section gives a closer insight into the purpose of testing by prototypes varying in fidelity and level of integration.

Testing by Low and High Fidelity Prototypes

Testing can be conducted with prototypes of low and high fidelity. The fidelity of a prototype can be defined as the degree to which a prototype corresponds to the product. The fidelity of a model may vary considerably, ranging from a low fidelity (e.g. paper prototype) to a fully operational prototype, which is almost identical to the product (Blacker, 2008).
Low fidelity prototypes are referred to as funky or paper prototypes and are made of simple and cost-effective materials such as paper, cardboard, foam, wire and tape (Retting, 1994).
Low fidelity prototypes are a resource-effective way to make concept ideas tangible and therefore to support the ideation process. They help to explicitly express and communicate thoughts and ideas since they are physical representations of mental models (Albers et al., 2012). Low manufacturing costs, short production time and particularly the ubiquitous availability of required materials qualify low fidelity prototypes for the use in project-based engineering design education. The development of low-fidelity prototypes enables quick tests of design hypotheses and therefore supports iterative designing and testing.
High fidelity prototypes are more realistic models of a system design. The purpose of functional prototypes is to validate the fulfilment of the required functions. As a consequence, the development of high-fidelity prototypes requires more time and resources such as tools (CAD, fabrication tools), materials (e.g. wood, plexiglass, plastic and metal). High-fidelity prototypes verify the performance of the operating principle. They uncover functional and performance problems and therefore are suitable for the verification and optimization of functional performance factors (e.g. noise and vibration, press fit).

Testing by Single Function and Full System Prototypes

Prototypes are tested on different integration levels. The integration level describes the amount of functions which are integrated into the prototype. A *Single function prototype* is a representation of a specified single system function. A special case of a single function prototype is the *critical function prototype* which calls attention towards focused testing of a critical system function. A prototype which displays all system functions and can be classified as a *full system prototype*.

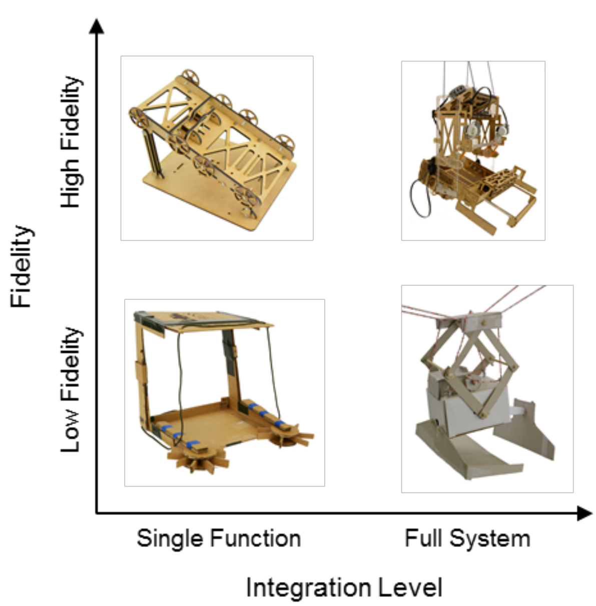

Figure 2. Classification of prototypes according to their fidelity and integration level

TESTING IN ENGINEERING DESIGN EDUCATION

This section presents testing activities in engineering design education. Tests can be conducted in all four CDIO activities. However, the characteristics of the test strongly depends on the current activity.

Testing in Conceiving

Conceiving an engineering system means to understand the needs from different sources. In most project-based engineering design classes the need is formulated in the task. Based on the system goal, students define necessary functions, the concept and its architecture.
Testing in Conceiving mainly consists of the realization of qualitative tests at an early stage of product development process.
Explorative testing generates qualitative but valuable information. Hereby, testing by low fidelity prototypes is a way to explore concepts and express ideas (Houde et al., 1997). For example, paper prototypes allow quick and iterative tests of concept ideas and therefore are claimed to be beneficial for early concept verification. Early testing of identified critical functions actively involves the students with relevant concept issues early in the process. Finally, early tests can be used to validate the product requirements. This includes the assurance that the concept meets the requirements of the customers, stakeholders and users.

Testing in Designing

During Designing, the initial design, drawings and plans of the system are created. Requirements for each component are derived from the system level. Problem solving and creative thinking techniques are applied. Testing in Design is mainly conducted on a virtual level with CAD and simulation tools. As designing is a divergent and convergent activity, various element designs are created until the design converges. Experimental prototypes of low-fidelity are used to support alternating creative thinking and the selection process. Testing by high fidelity prototypes enables to verify the performance requirements of every element. Each part is designed in detail with computer aided design software. Students are encouraged to quantify dimensions of each elements. As a consequence performance tests (e.g. FEM simulations) of the elements can be conducted.

Testing in Implementing

The implementation of a system is characterized by its transformation into a product. This includes the hardware manufacturing and testing of physical parts. Subsequently, the parts are assembled to subsystem and integrated into the system. A selection of the test cases are relevant for the implementation. Testing of the part is a relevant test case, since the transformation of CAD data into hardware is influenced by the characteristics of the manufacturing technology (e.g. resolution, precision, material). Machining tools affect the design, thus tests uncover design gaps between CAD data and the physical part. Assembling the components to subcomponents leads to the detection of mismatches. This might be caused by undetected design errors in the CAD model (e.g. tolerances). Furthermore there is a set of components such as cables which are not considered or misestimated in CAD and therefore can lead to difficulties while assembling.
Finally, the system performance is tested according to the system requirements. Defined test cases (e.g. static load case) are applied to the system with the aim to verify the systems performance (e.g. load bearing capacity).

Testing in Operating

The system is operated in a defined operation environment with the aim to deliver the intended value. Testing in Operation includes without limitation the following aspects: The system is integrated in a defined operation environment. Therefore the interfaces of the operation environment to the system are a relevant test case. Moreover, the system performance is tested in field tests and optimized with respect to measurable product requirements.

EDUCATIONAL CONCEPT OF THE INOVATION PROJECT

This section presents the educational concept of the 'Innovation Project 2013' conducted at ETH Zurich focusing on testing in all CDIO activities. The 'Innovation Project' is a project-based engineering design course with 456 undergraduate students of mechanical engineering.

Framework of the Innovation Project

The 'Innovation Project' is a project-based engineering design course with 456 undergraduate students of mechanical engineering conducted at ETH Zurich. The annually recurring course takes place in the second semester and has a length of one semester. In the 'Innovation Project' students Conceive-Design-Implement-Operate a technical system. That means, that they physically realize an operating system for maximal performance. The performance of the systems is compared to each other in a final contest.
To meet the challenge of large classes, the students are divided into small teams consisting of five members.
A wide infrastructure covering development needs from the ideation to the operation is provided to the students. The infrastructure consists of work spaces, CAD workstations, production machines (laser cutter), and workshops. Provided materials include wood and plexiglas plates with a thickness of 3 to 5 millimeters. Finally, a basic mechatronics kit is placed at disposal.

Figure 3. Operation environment: mountain landscape with ropeway

The task of the ‘Innovation Project 2013’ consists of the development of a gondola for a cargo ropeway that is able to pick up building material (such as steel bars, wooden cubes, wooden beads) from the mountain landscape and transport it to the upper station. The mountain landscape is shown in Figure 3 and has a size of 2500 x 600 mm and a maximum height difference of 1200 mm. In the final competition, the teams operate their systems in the mountain environment. The team with the best performance, that is collecting as much building material as possible and delivering it to the summit station, wins.

Testing in the Innovation Project

During the whole project duration students are encouraged to conduct tests. In the frame of the Innovation Project tests are conducted by prototypes and on the systems. The development of prototypes of different fidelities and system integration levels are part of weekly deliverables.

Testing in Conceiving

In order to raise the students awareness for the importance of testing as a continuous activity across the product development process, low fidelity prototypes were demanded. Most teams developed single-function low fidelity prototypes (e.g. Paper Prototypes) of the collecting mechanisms for the building materials as shown in Figure 4. Most teams consider the function of collecting different materials at different heights to be the most critical. Some teams perfected the single-function prototype to a full function paper prototype. In this context, students test if the full system complies with the available design space of the valley station. Therefore some teams prototyped the relevant test environment which in that case consists of a paper box according to the dimensions of the valley station. Finally, students used paper prototypes to simulate and test function principles for a selected set of system functions. Tangible morphological boxes emerged and served as a way to explore, communicate and discuss ideas.

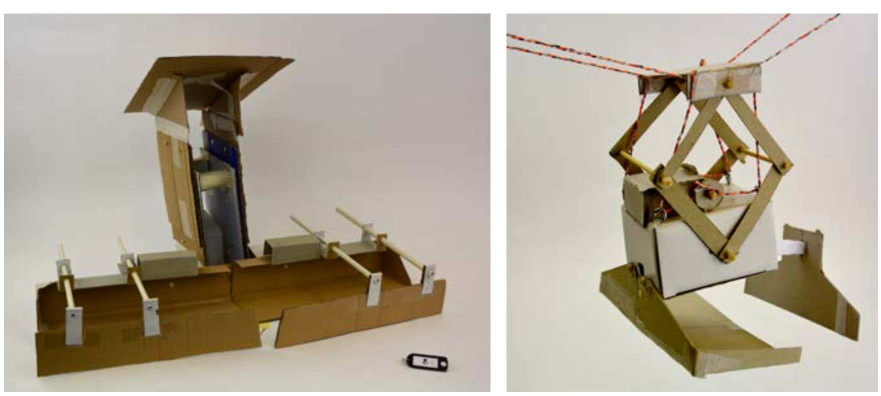

Figure 4. Single function (left) and full system (right) low fidelity prototypes

Testing in Designing

As the project passes in the stage of the detailed design, students create the initial design with CAD as shown in Figure 5. At that point students are encouraged to quantify the dimensions of every component. Students have to consider the design and implementation of basic machine elements such as bearings, gear wheels and gear racks.

The functional interaction of the components is tested virtually. Virtual testing of the assembly leads to the detection of part collisions and functional mismatches between single elements and modules. Moreover varieties of package solutions for the mechatronics can be tested in CAD. Finally, kinematics, such as the mechanism for extension and retraction are tested virtually.

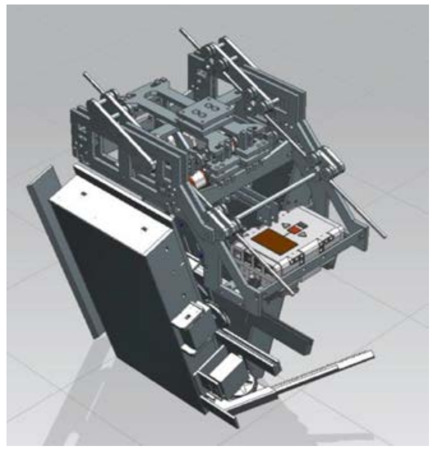

Figure 5. CAD model

Testing in Implementing

The implementation of computer aided designs is executed with laser cutters, a direct manufacturing tool, which transforms the CAD data into hardware. Thus, students are able to quickly manufacture and test the virtual design. At first, test cases have an explorative character since the manufacturing technology and its resolution is new to the students. They first produce parts such as gear wheels and gear racks. Thereby students experience the influence of manufacturing tools on the design.
Laser cutters are direct manufacturing tools and transmit design errors made in CAD to the physical part. The use of laser cutters has two didactical effects with respect to testing: First, some errors become visible when producing and testing the physical part. Secondly, The students take the role of the design engineer and the producer and therefore design and produce their own mistakes. As a consequence it is expected that students understand the reason for the errors and make use of the learnings in the redesign (Meboldt et al., 2014). By assembling the system, students generate knowledge about the importance of tolerances and material properties regarding stiffness and strength. Finally cable management can be tested in the physical prototype.

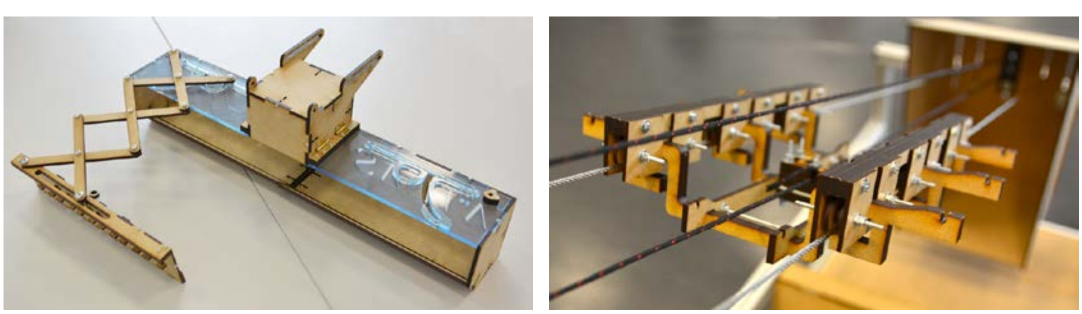

Figure 6. High fidelity single function systems

Testing by high-fidelity prototypes in implementation generates knowledge about manufacturing technologies, the material properties and the system assembly. Iterative testing and manufacturing strategies are used for the high fidelity system in Figure 6. First, one part of the extension mechanism is manufactured. Besides, the interface of the system with the operation environment is tested by a high fidelity single function prototype.

Testing in Operating

In later stages of the 'Innovation Project' the systems are integrated into an operation environment and teams are encouraged to test if the full system delivers the intended value.
Several test cases regarding the performance analysis are identified during the Operate-activity. First, the operation of kinematics, such as extending and retracting movements are tested with the goal to verify the performance and reliability of the collecting function.
Furthermore the system interaction (suspension) with the operation environment (ropes) is tested and pictured in Figure 7. Systems that did not take an operation test did not meet the performance requirements and encountered technical difficulties in the final contest. System failures originate in inconspicuous design errors such as joints, gears and the interface of the system to the hauling rope. Most of the design errors could have been detected by testing the full function system in the operation environment and subsequently corrected by taking redesign actions.

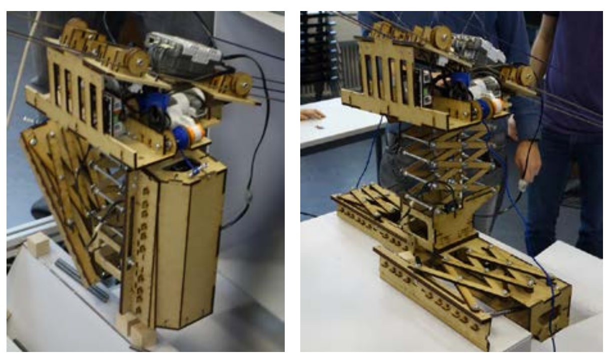

Figure 7. Full System operation test

CONCLUSION AND OUTLOOK

Testing is important to ensure the development of reliable products. The ability to successfully conduct tests is an important competence of engineering designers. Consequently in design education the relevance of testing has to be trained. In order to experience the relevance of testing, prototypes seem to be most suitable. In the educational concept presented in this paper, testing by prototypes of different fidelities and levels of integration, is conducted in all CDIO activities. The relevance of testing is imparted in the 'Innovation Project 2013', a project-based engineering design course at ETH Zurich with around 500 undergraduate students of mechanical engineering.
Key learnings of the students on testing were gathered from students feedback and reports and are summarized hereafter. A main learning was that continuous testing during the project is essential for the development of high performance systems. Conducting tests according to the test case during several CDIO activities generates valuable insights, that are made use of in the design process.

As one student mentioned in the feedback: “Our system perfectly showed that in practice not everything works as predicted in theory. In order to early detect and solve these discrepancies, regular testing is required. Testing is a precondition for developing the optimal solution”.

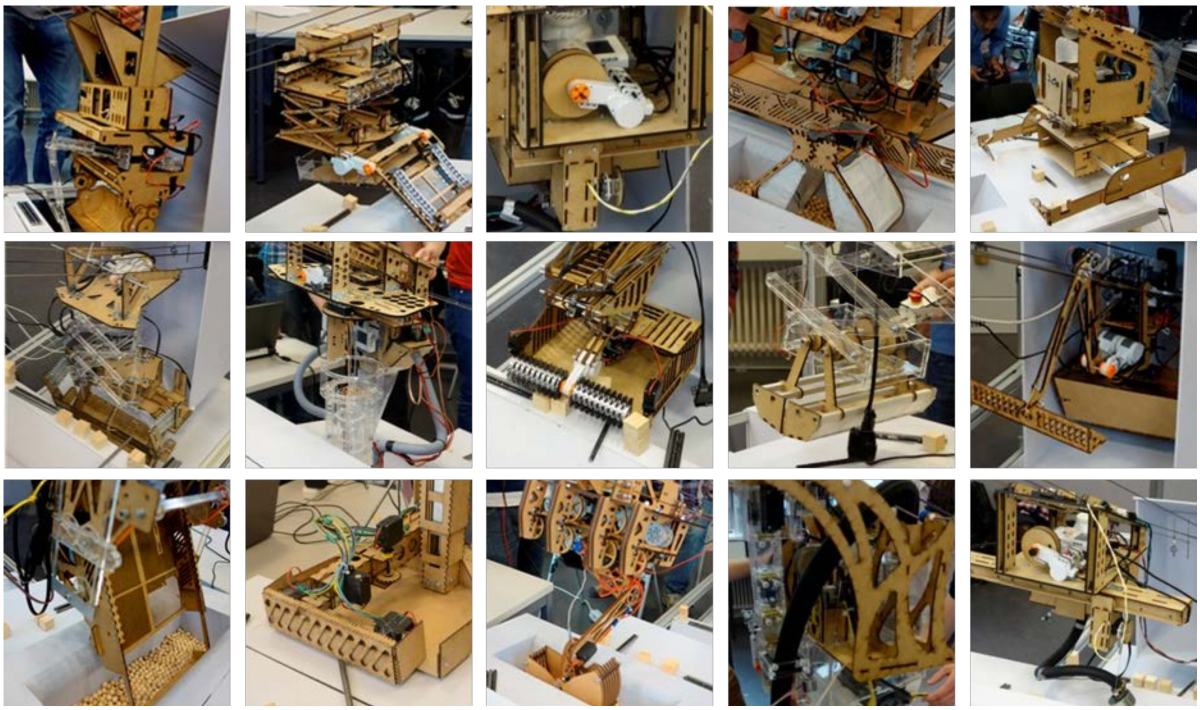

Figure 8. Selected systems of the ‘Innovation Project 2103’

Moreover, the strategy of first manufacturing and testing system with a low level of integration is faster than manufacturing and testing the whole system in one step. This is due, to quick iterations, that accumulate knowledge. Finally, teams that tested their systems during all stages of the PDP, showed a higher performance in the final contest.

The findings of the case study of the ‘Innovation Project 2013’ lead to learnings about the educational concept. By imparting the importance of testing by prototypes, students experience design errors first hand. A student mentioned the following: “I finally became aware of how important it is to plan well and test extensively. I think this is only learnable by personally experience it”. The importance of testing is imparted by engaging students to conduct tests by prototypes in all stages of the PDP. Furthermore an operation environment is provided for testing the operation. Finally, as the goal of the project is to realize a physical system for maximum performance, students have to optimize the performance of the systems.

So far, the educational concept successfully imparts the relevance of testing in engineering design education. However, many teams who did not perform tests on system level encountered technical difficulties as the systems were not reliable. Therefore, in succeeding projects full function system tests will be compulsory in the operation activity two weeks before the final contest with the expectation to increase the number of reliable systems.

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BIOGRAPHICAL INFORMATION

Daniel Türk, Dipl.-Ing. is a Research and Teaching Associate in the Product Development Group Zurich at the Swiss Federal Institute of Technology ETH Zurich currently in charge of the Innovation Project at ETH Zurich.

Bastian Leutencker, Dipl.-Ing. is a Research and Teaching Associate in the Product Development Group Zurich at the Swiss Federal Institute of Technology ETH Zurich in charge of the Innovation Project 2013.

Mirko Meboldt, Prof. Dr.-Ing. is a Full Professor for Product Development and Engineering Design at the Swiss Federal Institute of Technology ETH Zurich. His current research focuses on human centered product development and the development of new technologies and systems.

Corresponding author

Daniel Türk
dtuerk@ethz.ch
T: +41 44 63 33045
ETH Zurich
Tannenstrasse 3, CLA F 21.1
8092 Zurich
Switzerland