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TESTING METHODOLOGY FOR ENGINEERING DESIGN EDUCATION

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ABSTRACT
Testing plays an important role in product development. However, general testing methodology has received little attention in both product development literature and engineering design education. When trying to include testing methodology in engineering design education, the following questions are raised: (1) What are the needs of engineers with regard to testing methodology? (2) Can these needs be addressed with theoretical models? To assess the first question, we surveyed ten graduate engineering design students to evaluate both their knowledge and their needs regarding testing methodology in product development. To address the second question, we developed a theoretical model that links the level of testing activity with the fidelity and integration level of a prototype, which should foster the students' understanding of the role of testing with respect to the maturity of a system function in product development. We evaluated how the model supports the students' understanding with an explorative study in an undergraduate project-based engineering class with 440 students. Furthermore, we analysed how the model can be used to illustrate distinctive approaches students take regarding testing in their projects. This paper presents the results of the pilot survey, a theoretical model on the role of testing in product development and the results of the explorative study. Based on the discussion of the questions presented above we provide recommendations on what to consider when integrating testing methodology in engineering design education.

Keywords: Testing, validation, verification, engineering design

1 INTRODUCTION

The industry recognises that the testing of prototypes and products is a central activity of the product development process (PDP) and probably the most expensive and time-consuming one [1]. The proliferation of dedicated verification and validation units within companies reflects its importance. In addition, the testing of early prototypes is becoming increasingly popular, at the latest since the advent of agile development.

Despite the importance of testing in engineering practice, it is surprising that general testing methodology is under-represented in literature [2] [3] which makes it more difficult to integrate that aspect into the engineering design education. Although the importance is recognised, there are few coherent frameworks or classifications of testing outside the well-established processes of verification and validation. This makes it challenging to address them in the engineering design curriculum.

We recognised the need to include testing into our engineering design education [4], but due to its reception in literature we are confronted with two central questions: (1) What are the needs of engineers with regard to testing methodology? (2): Can these needs be addressed with theoretical models?

Our investigations are structured according to the Design Research Methodology [5]: In our Descriptive Study I, we first conducted a survey with ten graduate students in order to explore the current knowledge and needs of the students with regard to testing methodology. Subsequently, we presented in the Prescriptive Study a model that links testing activities to prototyping activities. Finally, in Descriptive Study II we introduced the model into a project-based course and evaluated the students' reactions to it. Based on these results, we examine the central questions and provide recommendations on how testing methodology can be taken into account in engineering design education.

2 STATE OF THE ART

This section provides background information on literature about testing activities and prototyping upon which the model later presented is based.

Various academic papers recognised in part the role of testing; nonetheless, few classifications or frameworks exist in that regard. Matthiesen et al. presented criteria to distinguish tests within the well-established activities of verification and validation [6]. Boës et al. derived a taxonomy for various testing activities [7], where they classified testing activities into four levels as they typically occur in a PDP. The taxonomy adds to the categories “verification” and “validation” the categories of “trial & error”, which refers to unstructured testing approaches at early stages of the PDP, and “experiment”, which is used with a meaning similar to that used in the fundamental sciences, but is oriented towards a structured approach to evaluate uncertainties with prototypes in a PDP.

In design theory, there are several approaches to classify different types of prototypes. One classification divides prototypes according to “looks like”, “behaves like” and “works like” [8]. Another approach distinguishes among the purposes of prototyping such as learning, communication, integration and milestones [9]. A third classification ties them to stages of a PDP with proof-of-concepts of product, production or manufacturing prototypes [10]. Finally, Türk et al. proposed a classification of prototypes along two dimensions [4]. Fidelity and integration level reflecting the degree to which the prototype (or function) corresponds to the realisation in a product and the evolution from a single function to a fully integrated system. The linkage of the two dimensions implies that development progress is made by optimising a function or integrating a function into a system, preferably sequentially but not concurrently.

3 DESCRIPTIVE STUDY I

In the following, an initial survey with ten students is presented as Descriptive Study I. The goal is to explore their current understanding of testing, the role testing plays in their student projects and their wishes for tools and methods.

3.1 Survey to assess student needs

A survey was conducted in the form of a questionnaire-based interview. The survey included ten graduate mechanical engineering students who were writing a thesis, which also includes the designing and manufacturing of prototypes, at our lab in the field of engineering design. The main questions in the survey were: (1) What did you learn about testing in engineering design courses? (2) How much time did testing occupy as a part of your project? (3) What tools and methods in the area of testing would you wish for?

3.2 Results from initial survey

The analysis of the questionnaires reveals that the students did not receive sufficient theoretical knowledge and wish to learn more about it. On average, the students had completed 10.9 semesters (bachelor’s and master’s programmes combined), were 90% male and were all enrolled in a master’s programme for mechanical engineering at our university. The students reported that testing activities on average take up 32% of their time in their student project. Half of the students reported that they felt that during their studies they had not acquired sufficient theoretical knowledge with regard to testing. This was particularly emphasised by students that had project experience, such as in internships or in yearlong project-based courses. The students’ most frequent replies to the question of what they were missing are summarised in Table 1.

Table 1. Most frequent answers of the ten students regarding wishes for education on testing in engineering design curriculum

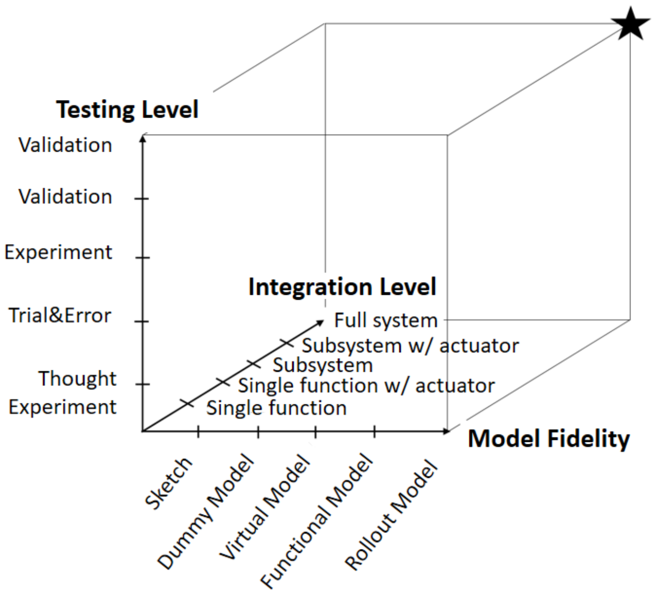
Wishes mentioned	No. of participants
Stress importance of testing in PDP	3
Practical methods and frameworks for planning and conducting tests	3
Illustrate interaction of testing activities with other activities in the product development process	2
Exploration of case studies in lecture	2

4 PRESCRIPTIVE STUDY

Both our Descriptive Study I and our literature analysis revealed that there exists a need to introduce methodological support on how testing interacts with other activities, such as prototyping. The following section presents a model we call the Function Cube, which should help students to better place testing among the other activities of a PDP.

Before the model is presented, we first need to define what requirements this model would have. In Section 2, we introduced an overview of classifications of prototypes and testing activities. We argue that the maturity of a function of a system is determined by both the fidelity of the prototype and the demonstration of its function in a test. The prototype classifications mentioned in Section 2 are not suited to uncover the inherently entangled link between prototypes and testing activities, which occur at different stages of the PDP. Therefore, the model should provide the link between prototyping status and testing activity. Furthermore, the model should help to visualise the evolution of a design project.

Based on the prototype classification by Türk et al. [4] and the taxonomy of testing activities by Boës et al. [7] we present the model called the Function Cube, as depicted in Figure 1, which incorporates three main activities of prototyping and testing revolving around functions and which allows the maturity of a system function to be assessed. Optimising a function, integrating a function in a system and testing a function in various embodiments can be visualised in their interplay with other functions and on various levels. These main activities are represented by the dimensions of the model, which are described in detail in the table shown in Figure 1 on the right. The dimension model fidelity describes the progression of the fidelity of the functional characteristics; the dimension integration level describes how a function is integrated into a prototype. The testing level incorporates the testing levels presented by Boës et al. [7] and adds an additional feature, namely a thought experiment, which refers to a mental walkthrough of a functional test. The upper right point of the cube (indicated with a star) describes the fulfilment of all three dimensions and constitutes a function of a finished product. The lower left point is the initial state when a design project is started. How the Function Cube can be used is demonstrated with an example described in Section 5.2.



Model Fidelity	Integration Level	Testing Level
Sketch: Sketching ideas	Single function	Thought experiment
Dummy model: Low fidelity, paper prototype	Single function with actuator	Trial&Error: Develop basic understanding
Virtual model: e.g. dimensioned model, CAD	Subsystem	Experiment: Identify influencing factors, confirm hypotheses
Functional model: Function fullfilling, but not finally production grade	Subsystem with actuator	Verification: Check achievement of objectives
Rollout model: Production grade	Full system	Validation: Testing under realistic conditions

Figure 1. The Function Cube (on the left) allows the maturity of a system function to be visualised according to the three dimensions model fidelity, integration level and testing level, to which more details are added in the table on the right

5 DESCRIPTIVE STUDY II

This section presents the Descriptive Study II, in order to show the Function Cube in action and evaluate its perception by the students.

5.1 Setup of the Descriptive Study II

The study was carried out at our institution in the Innovation Project [11] in 2017. The Innovation Project is a project-based course for second semester mechanical engineering bachelor students. The goal of the project is to develop and build a fully functioning electro-mechanical system in groups of five students within 14 weeks. At the end of the project each team's system competes against the systems of other teams. In this competition, the teams operate their system and try to score points according to a predefined scheme. In addition, experts evaluate the prototype of each team and issue a design evaluation score that is based solely on the design and not on the performance. This year's task was to develop a robot with locomotion, which manoeuvres on the imitated surfaces of an asteroid and collects probes spread over the uneven terrain.

Each team received the necessary mechatronics equipment, access to 2D-laser cutting, 3D-printing, a fully equipped workshop, weekly coaching [12] and an online collaboration tool for the students to organise themselves within the team and for documenting their progress. Furthermore, the students could define their system functions in templates of the online collaboration tool where the dimensions of the Function Cube were integrated. Throughout the project, the teams were asked to tick off their progress according to the dimensions of the Function Cube. This feature provided a time stamp with every change in the Function Cube, which was trackable and could be retrieved programmatically at the end of the project by the authors. Every two weeks each team had a design review meeting with their coach during which the students reflected on the progress and challenges, also with the help of the Function Cube, and plan the next steps. At the end of the project, each team was asked how it perceived the usefulness of the Function Cube as a model during the project.

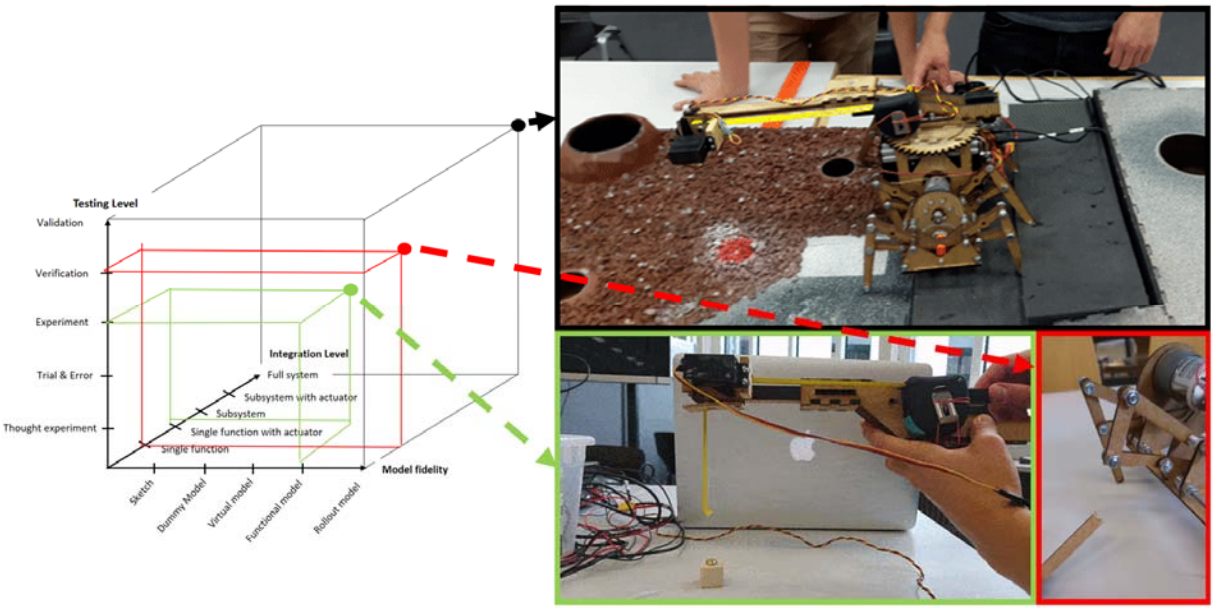


Figure 2. Different stages of the maturity of the functions of a prototype showed exemplarily in the Function Cube (left) and with photos of the corresponding prototype and test (right). The functions "gripping" (green) and "walking" (red) are shown both in a photo and in their representation in the Function Cube. Above: the complete system in a validation test (black)

5.2 Results from the Descriptive Study II

The Function Cube was well received by the students and showed the potential to visualise progress and connect prototypes with testing activities. A total of 82% of the students found the Function Cube helpful for the understanding of the PDP, whereas the remaining 18% of the students either did not find it helpful or reported that they did not have enough time to fill it out. The main advantages pointed out were its potential to visualise project progress and goals: "The function cube enabled us to analyse our progress in the project better, as it made it easier to visualise the progress" and "A good way to graphically set goals". Furthermore, the Function Cube was found to be helpful to set a strategy: "It is helpful for deciding on a development strategy". While the teams were free to divide their system into (sub) functions according to their design, this freedom led some teams to define a set of functions that could not be transferred easily into the Function Cube model, e.g. when the function was not testable. This was negatively received by some teams.

Figure 2 shows how the Function Cube reflects different levels of maturity with the example of the system of one student team. This system uses arachnid locomotion, has a rotating crane with a laterally movable arm and a mechanism for picking up objects by means of a magnet. The photo with the red frame shows the walking function in a load test and the corresponding point in the Function Cube (single function, rollout model, verification) on the left. The photo with the green frame shows the gripping mechanism (single function with actuator, functional model, experiment). The complete system on the playing field of the competition is shown in the image with the black frame and in the Function Cube (full system, rollout model, validation).

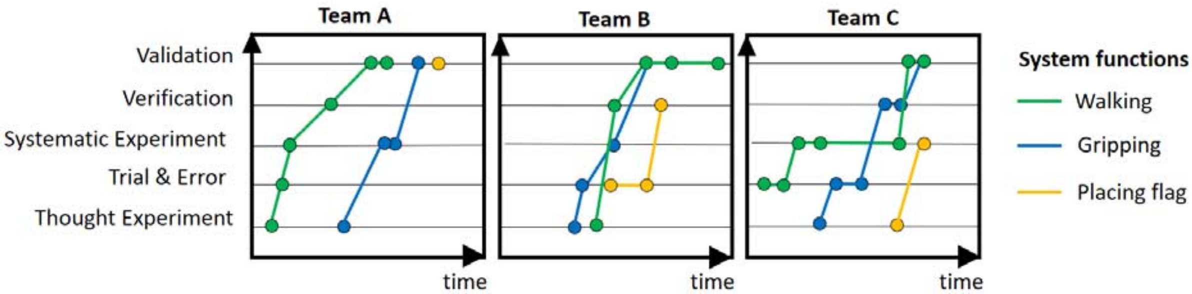


Figure 3. Progress on the dimension testing level of three exemplary teams from the start to the end of the project

Another valuable aspect of the Function Cube is the possibility it offers to retrospectively compare the teams and their chosen development strategies. Figure 3 shows the data extracted from the organisational tool of three exemplary teams to visualise their different strategies. Team A developed the functions and tested them independently one after the other. In contrast, Team B tested their functions concurrently. Team C chose a mixed approach in which they first tested one function to the level of an experiment, then started testing the second one and concurrently tested both of them on higher levels. All of the three teams shown were high-performing teams, which ranked in the top ten (out of 88) at the final competition.

6 DISCUSSION

We set out to answer two questions, which were (1) What are the needs of engineers with regard to testing methodology? (2) Can we address these needs with suitable theoretical models?

Answering (1): Our first survey of graduate students showed a stark contrast between the perceived importance and the abundance of testing in their engineering design education. The students reported that they spent an average of 32% of their project time with testing activities. However, of the ten students, 50% reported that they did not receive any substantial input during their studies with regard to testing. In particular, students with project experience, e.g. from yearlong project-based courses or internships, reported that they would like to learn more about the role of testing in the PDP. The wish most frequently mentioned was to emphasise the importance of testing in education. Case studies, e.g. from industrial practice, was another wish reported by the students. In addition, the survey showed an interest in how test activities could be integrated into the PDP. Overall, these findings confirm the importance of testing in engineering design education in accordance to its initially stated importance in industry.

Answering (2): We designed a model, introduced it to project-based engineering studies and found that the Function Cube was well received by the majority of students. They found it to be helpful and we demonstrated in a study that such models are helpful in promoting their understanding of the inter-relationships among the various testing activities and prototyping embodiments.

In addition, we have analysed how the model can be used to illustrate different approaches that students follow with respect to testing in their projects. The Function Cube allows different development strategies of the student teams to be compared. As shown in Figure 3, various teams took different approaches to testing and integrating their systems. Clearly, the three teams shown in Figure 3 chose very different testing strategies, which nevertheless led to their scoring in the top ten teams at the final competition. Apparently, there is more than one successful testing strategy.

Recommendations: As mentioned by Türk et al. [4], we see advantages in introducing and highlighting the topic of testing in engineering education. In addition, it is advantageous to emphasise the importance of testing activities and it is best to demonstrate them in case studies. Furthermore, tools for the effective planning and execution of tests are required. Finally, the introduction of theoretical models such as the Function Cube has shown to be helpful for students and can provide support in the basic training of engineering design, for example to demonstrate how the various stages in product development correspond to prototypes and testing activities.

Limitations: For the Descriptive Study I the limitations lie in the low number of participants (10) and the specific subset of the population. As those students are pursuing a thesis in the field of engineering design, the results can only be generalised to students within that specific field and their educational experience. For the Descriptive Study II, the limitations lie in the self-assessment of the students to fill out the templates in the online tool, which relied on the student's interpretation of the levels of the Function Cube. In addition, only the testing level was recorded, but not the time each team effectively spent testing their prototypes. Lastly, those students were second-semester bachelor students with limited experience in the field.

7 CONCLUSION

We evaluated students' needs regarding testing with a survey, presented a potential support with a model, the Function Cube, and evaluated the students' perception of the model with another study in a project-based course. We found a stark contrast between the perceived importance and the abundance of testing in the students' engineering design education. Furthermore, we highlighted areas of particular interest for engineering design students with regard to testing. The students considered the Function Cube to be helpful. In addition, it allows the description of a PDP in a distinctive granularity and to study different approaches regarding prototyping and testing as well as their impact on the students' designs and the systems' performance. In a future study, the Function Cube in combination with a measure of the effective testing effort conducted by every team could be used to study successful teams.

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