SUPPORTING VALIDATION ACTIVITIES AND SELF-REFLECTION PROCESSES IN INTERDISCIPLINARY DESIGN TEAMS

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ABSTRACT
In order to fulfil customer demands with today's complex mechatronic products, verification and validation activities are crucial elements within a product development process [1]. These activities comprise the preparation of prototypes, the selection of suitable environmental models, the testing procedure itself, and the acquisition and analysis of the test results. These tests can be classified and distinguished by various factors [2]: (1) use case affinity, (2) system levels, (3) validation purposes and (4) test compositions. The characteristics of all these factors have to match to the actual level of knowledge. To define the suitable test case for a specific validation objective needs a lot of experience [3] and may cause iterations or rework [4].
A new interdisciplinary mechatronic course is established this year at the Karlsruhe Institute of Technology (KIT). Within this course, 40 undergraduate students attend lectures, exercises and perform an accompanying development project. In this development project, the students develop concepts, build prototypes and conduct validation and optimization activities. A web-based tool supports the students in planning and documenting of the test restrictions, the execution, interpretation and reflection. The tool bases on theoretical findings from analyzing different validation activities.
It guides the students through a set of questions and answering options. These questions refer to a general description of the test setup (for documentation), to a specific classification of the test and to interpretation of the results. The specific classification gears towards the above-mentioned four distinguishing factors (1) to (4). The interpretation focuses possible biasing effects on the results (their reliability) and the consideration of existing uncertainties and resulting possible deviations.

Keywords: Validation and certification, x-in-the-loop, project-based learning, test interpretation, team reflection.

1 INTRODUCTION

The innovative capacity of highly developed systems and products are a key factor for Europe's leading economic position. To fulfil customer demands with today's complex mechatronic products, verification and validation activities are crucial elements within a product development process. The demands on today's designers and engineers are rising and it is getting harder for an individual to keep an overview on the whole product development. Additional to that product validation process as well as systems getting more and more complex. For success in today's development projects, engineers have to apply knowledge of the fields of mechanics, electronics and information technologies – called mechatronic.[1] The understanding of the term mechatronics in this paper is as follows:

> *Mechatronics denotes an interdisciplinary development methodology that solves predominantly mechanically oriented tasks by synergetic, spatial and functional integration of mechanical, electrical and information processing subsystems.*

It is expected from mechatronics engineers to have a broad general knowledge and detailed knowledge in a field of specialization. This knowledge should be applied together with methodological expertise to solve complex problems by finding innovative cross-disciplinary solutions. New processes, systems and product should be designed by using mechatronic synergy potentials. The survey 'Faszination Konstruktion' (engl. fascination engineering design) [1] points out the need for so called system engineers that possess knowledge in the fields of mechanical, electrical and information engineering, manufacturing and assembly techniques, project management and creativity techniques. As published by Matthiesen et al. [3] a curriculum for mechatronic engineers has been developed at the KIT. As described above and in Matthiesen [2] the day to day business of mechatronic engineers and the development of industrial mechatronic systems are influenced as followed:

(1) Mechatronic system are developed in **interdisciplinary teams**
(2) Usually development teams are not located in the same office – they are **locally separated**
(3) For develop innovative products a **structured engineering process** is needed
(4) System development requires **development**, **manufacturing** and **testing**
(5) Mechatronic system development needs **continuous validation and testing** with prototypes fitting to changing knowledge base
(6) Mechatronic systems will be developed **under industrial working** conditions
(7) Development of mechatronic systems is not straight forward. Provoke early and cheap **iterations** and reflecting them are very important.
(8) For mechatronic system development projects an **interdisciplinary system modelling** is required
(9) Successful systems are **winning products** on a specific market

2 COOPERATION-FOCUSED EDUCATION

At the Karlsruhe Institute of Technology (KIT) an educational concept for project-based learning, focusing the cooperation in mechatronic engineering teams is developed. The concept was tested in a pilot study and was fully implemented in a mechatronics course in the winter term 2014/2015. It is a project-based teaching approach especially for mechatronic engineering courses, focusing the interdisciplinary cooperation and the development of profession qualifying skills. This concept is designed and carried out from two different departments – the department of mechanical engineering and the department of electrical engineering. It is part of the Karlsruhe Education Model for Product Development (KaLeP) [4], which emphasizes the particular importance of project work in a realistic environment to enable engineering key competencies. By experiencing in specifically created learning situations, students gain competence in solving real complex mechatronic problems.

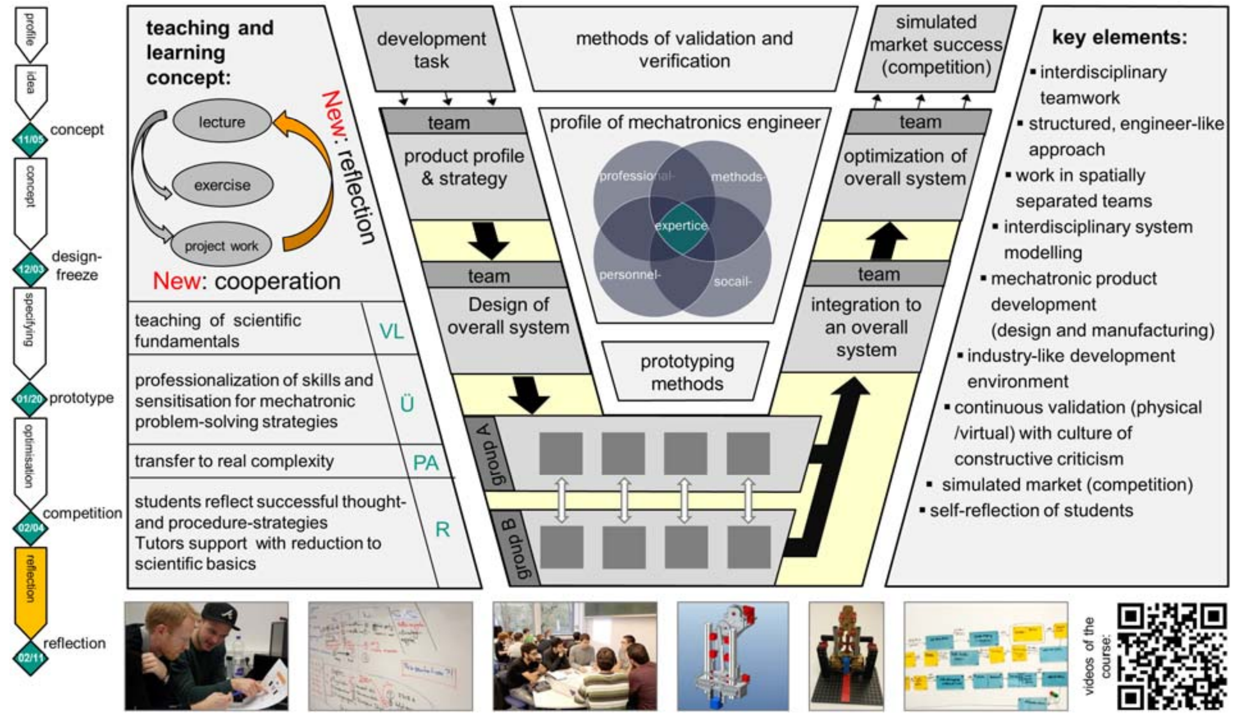

Figure 1. Framework of the course development of mechatronic systems and products

The course '*development of mechatronic systems and products*' consists out of lecture hall sessions with integrated exercise phase's und a development project. The deep expertise from other bachelor courses will be connected and supplemented by tangible and applicable product development competencies (development, production and validation). In order to implement the elements of development of industrial mechatronic systems and to let the students experience product development, a development project is imperative needed. As shown in Figure 1 the project is divided in the stages profile, idea, concept, detailing, optimization and reflection. With this guided stage gate process most parts of the industrial product development process is covered – from strategy over design and manufacturing until the market introduction and measuring the success in the market (time-to-money). One of the key elements of this concept is cooperation – for the final succeeding – two groups (5 persons each with individual responsibilities) have to work together very close as one team. Thus, each group is responsible for its own subsystem, but to achieve the shared goal, the team has to continuously discuss, negotiate and decide about the requirements and constraints for the overall system resulting from their jointly pursued strategy. To simulate more realistic industrial conditions the groups don't work next to each other – they are located in two different working areas on the campus. The team has to develop, manufacture, validate and optimize a mechatronic system to solve the development task. The systems of all teams have to perform on a simulated market against each other. Milestone meetings are carried out to check the project progress. According to the stages the students have to present previously defined development results (strategy, constructions and reasoned decisions) which will be discussed together with the supervisors. Indeed the students have a project plan, best practices and recommendations for each stage, but it's a long and winding road of development, iterations, verification and validation. However, each product development is individual [4] and the students are faced with the decision: In which cases either physical prototypes or virtual models are suitable to support our product development and to demonstrate the functional performance? When does it make sense to test sub-functions or the overall system in the development process? The next chapter gives a closer look at the aspects of validation and its support by the effective use of physical or virtual prototypes. Many project-based teaching approaches doing finally any kind of competition. In this course the competition is not the end of the course. There is a final lecture including a student reflection phase. In this lecture the students reflect the experienced development project based on competition and present and discuss their learnings with the advisor.

3 VALIDATION ACTIVITIES IN PRODUCT DEVELOPMENT PROCESSES

Accompanying validation activities along the product development process are crucial for product engineering. Such tests vary in their specific setup. Albers et al. present four criteria to distinguish different validation setups [6]:

System level: Different tests vary in their system level of the System under Development (SuD). The system level reaches from a single Working Surface Pair (WSP; low system level) to the complete technical system (high system level). Even on the software or mechatronic area, a single software snippet or the overall software can be tested.

Composition: Validation activities vary concerning their proportion of virtual and physical models. The criterion composition distinguishes between virtual tests (i.e. simulations), physical tests and hybrids between virtual and physical tests.

Use case affinity: The use of realistic or abstract test runs and the selection of detailed or reduced models lead to input values of the SuD that either equal or differ from the real use case. Nevertheless, this criterion does not evaluate the quality of the test output. The SuDs input values are described from 'equals the real use case' to 'far from the real use case'.

Validation purpose: The purpose of the validation activities is another criterion to distinguish different tests. On the one hand, a test can examine the fulfilment of the overall customer demand. On the other hand, a test can check the achievement of a quantified technical requirement (like weight or speed). Between these extremes there are the examinations of the desired sub-function and the desired overall function. The four characteristic criteria are transferred into a model, which can be used for test-analysis; test-definition and test-planning (see Figure 3). The test characterization model was provided in the form of an online survey in which the students could document their validation activities. Therein the students were asked for describing the test and rating the four characterization criteria. Furthermore, they could document the results and the interpretation of the same. By filling out the survey, the students had to think about the purpose of their tests, if the test could generally lead to the intended finding and how to interpret the results. From the research's point of view the online survey was a very performant tool to analyze the different validation strategies of different teams, which are presented in the next chapter.

4 VALIDATION STRATEGIES OF MECHATRONIC STUDENT TEAMS

As already described, the basics in the field of development processes, interdisciplinary modelling approaches, importance of iterations to knowledge gaining, different types of testing and the basics of model-based design were taught in this course. The students have incorporated this knowledge directly into the processing of the development task and each team has chosen for himself, at which point sub-functions or the entire system have been validated with prototypes or virtual models. The development project was scientifically supervised and the realized development stages were analyzed. The developed systems are shown in Figure 2. The following procedures and strategies have emerged here:

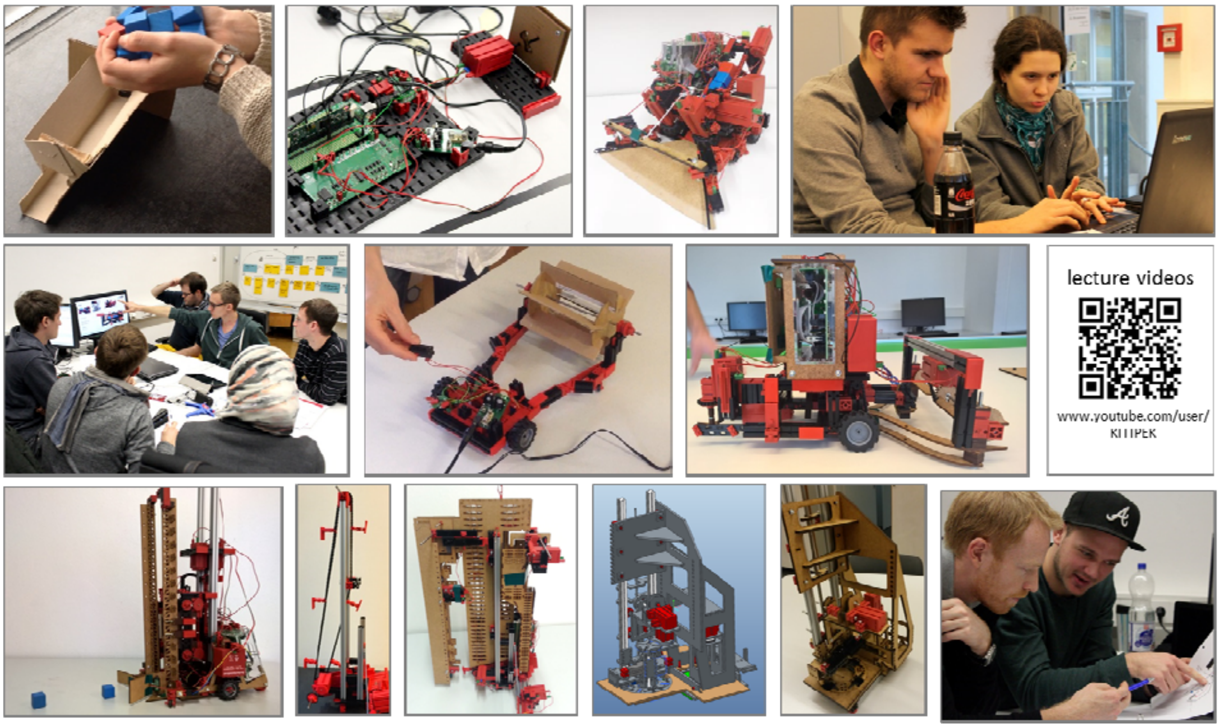

Figure 2. Observation of mechatronic teams during the development project

An Iterative Adaption: This approach is characterized by the fact that there is a large number of iterations, a continuous adaptation of the development depending on a changing knowledge base and a sequential development. The development steps were little thought ahead and the interfaces between the teams were only moderately specified in detail. Virtual models were used only moderately. Pros and Cons: low development risk, as a functional system was always available. However, the development progress was slow and a high use of resources was necessary.

B Focus on the development of subsystems: This strategy is characterized by a detailed analysis of all components. The development of the subsystems was parallel and physical validation of the subsystems was carried out in great detail. The integration of the overall system and its validation (test on overall system level) took place at an advanced stage. Pros and Cons: Each subsystem was developed focused. The late integration is a risk in a sense that the sub-systems do not work together properly and large iterations occur.

C Validation on overall system level: This strategy is characterized by a parallel development of the subsystems and early integration into the overall system. Validation is performed mainly physically on overall system level. Pros and Cons: All subsystems were tested very early in the physical overall system concerning the fulfilment of functions. However, the sub-systems' level of maturity was partly not high enough, so that some sub-systems had to be disassembled again to get optimized.

D Detailed virtual modelling: In this strategy, a top-down approach with integrated SysML modelling can be seen clearly with a distinct definition of the interfaces between the teams, clear responsibilities within the team, a sophisticated CAD design and the advanced utilization of virtual models. The physical validation of sub- functions took place very late. Pros and Cons: All subsystems

were tested virtually and a very fast development progress along a preconceived process could be observed. However, only few functional prototypes have been developed, which is why some critical points were identified very late.
Generally it can be observed, that some of the validation characteristics change over the development phases. Especially considering the system level there is a mayor change from first project phase to the second. In the first phase, the students mainly validate on the level of discipline-specific sub-systems to validate single requirements or sub-functions. On the contrary, in the second phase the level changes to cross-disciplinary sub-systems (see Figure 3). This is comprehensible since the later in the project the more integration of single components into more complex sub-systems has been conducted and has to be validated compare [5].

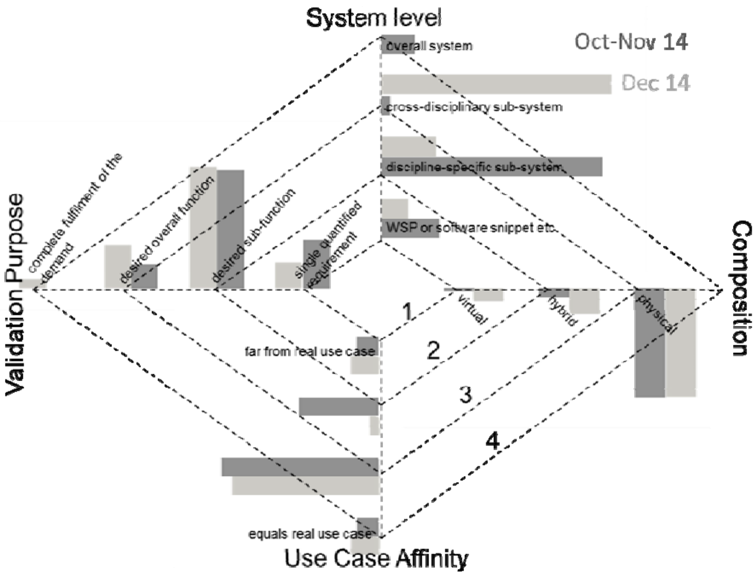

Figure 3. Test characterization model with results from the student project divided into two development phases (first phase – dark grey, second phase – light grey)

5 STUDENT SELF-REFLECTION

Many project-based teaching approaches are doing some kind of competition at the end of the semester. In this case the competition is not the end of the course. However, the goal of this teaching approach isn't the development of mechatronic systems and the best rank in the competition – it is the best possible preparation of the students for their future job. Therefore, one week after the competition a final lecture including a student reflection [8] phase takes place. In this lecture the students reflect on the experienced development project based on the competition results. They present and discuss their learnings with the advisor. The tutors will support the students during their self-reflection and transfer the experiences on general issues and link them to the scientific basics in the lectures. Thus, the control loop of lectures, exercises and development project will be closed and the students can transfer the experience out of this course as good as possible on future challenges. The self-reflection shouldn't be an individual reflection furthermore a reflection concerning the complete project team behaviour. The procedure for doing that is divided in three steps: (I) intuitive collecting of experiences & learnings and searching for specific examples in the development project. (II) Introducing and concentrating of these experiences & learning in the group. (III) Negotiating of experiences & learnings in the team (2 groups) and development of better solutions in future projects. With the goal of a wider variety of experiences & learnings the reflection has to be done in 4 different clusters:

- **Engineering topics**: design, manufacturing, controlling and programming and systemic mechatronic contents.
- **Process topics**: process flow, project planning, strategy, validation iterations
- **Team work and social topics**
- **2 open topics**

Especially in the field of development processes and in particular concerning validation activities the students gained a lot of experience. Particularly the documentation and self-reflection pushed the students to analyze their development and testing process systematically. They recognized testing plays a central role in the development of a reliable product [7].This can be seen e.g. in the following student's statements: *'Our team becomes aware of the importance of prototypes, validation and iteration. Next time we will validate our system earlier and much more target-oriented.' 'We were on the wrong track: We developed and validated only one component in detail and lost the overview of the whole project.*

6 SUMMARY

By solving a real complicated development task in a realistic development environment, the students gain experience and are getting well prepared for future challenges. By pushing those towards systematic validation activities the teams learned to think about the purpose of a certain test and how to interpret the results. By analyzing the validation strategies the following aspects can be observed:

- Validation of the sub-systems took a lot of time, whilst the teams lost sight of validating the function of the overall system.
- Pure virtual validation does not result in sufficient certainty about the functional fulfilment.
- A very late validation on the overall system level brings the risk of late major problems and iterations.

7 OUTLOOK

Besides supporting the students with the test characterization model, the usage within the project provides a comprehensive documentation of manifold validation activities. Specific validation characteristics lead to more effective validation activities in certain development phases. The goal of future research work is to define effective test characterizations for different development phases. The knowledge about such dependencies can support upcoming student generations in their project work. Additionally these results can possibly be transferred to future industrial development processes.

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