Education 4.0 for Mechatronics – Agile and Smart

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***Abstract*— The topic Industrie 4.0 and the transformation of the digital world pose new challenges for teaching university students. In our experience, the students, who will need to advance this development after entering the workforce, have surprisingly little interest in it. In our paper, we will show how to implement different concepts mid- and long-term, to inspire enthusiasm for this topic in students. We will also show which activities are necessary to make Industrie 4.0 a permanent item in the course Mechatronics.**

Keywords—Industrie 4.0; Multidisciplinary Education; Problem Based Learning; Makeathon

I. Introduction and Motivation

Future graduates will face complex challenges in an industrial environment and also on a management level in a industrial region like Baden-Württemberg with its medium-sized businesses. For this reason, it is vital to adress the current developments linked to Industrie 4.0, especially while teaching university students and during the transfer of technology.

Among others, the “Hochschul-Bildungs-Report 2020” of the “Stiftverband für Deutsche Wissenschaft e.v.” indicates clearly the need for “supplementing and updating the traditional educational goals in academia” [1]. Besides specialist skills, which form the basis, the other focal challenges of the Professional World 4.0 mentioned by the report are practical application of both skills and knowledge and the student’s personal development. In the future, both need to play a more important role in higher education.

The objective of the activities presented here is to convey central aspects in an as lasting and as broad as possible manner, and furthermore, to strengthen the connection between learning content to already existing courses and lectures and also to related disciplines. The focus is on the increasing influence of IT on traditional engineering.

The following sections will first present some of the key developments regarding technology and applications connected to the digitalization. Based on this, we will outline the specific challenges this poses for teaching Mechatronics. Next, we will present individual innovative learning concepts and sample projects. They adress the challenges students are faced with and introduce new approaches to aquiring and deepening knowledge for the students of today. Finally, the outlook is meant as a suggestion for developing additonal teaching methods.

II. Technological Developments and Applications

Due to the on-going development of various technologies, the influence of the digital transformation on all areas of life has accelerated greatly. This transformation has impacted daily life and is also having a growing impact on the industrial environment. In the following sections, we present some technological developments which have significantly influenced these changes.

- The complexity and integration density of integrated circuits gets higher and higher. (Moore´s Law, 1965).
- The usage of a communication system increases proportionally to the number of possible connections between the users. Approximately, it’s proportional to the square of the number of connected users. (Metcalfe´s Law,1980).
- Sensors become smaller and cheaper and can be therefore found in many systems.
- The infrastructure for communication keeps improving for wireless and wireline communication.

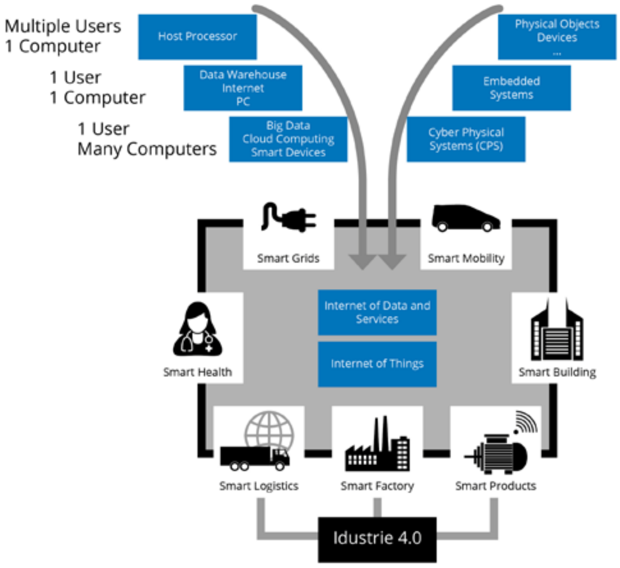

Fig. 1. Two converging development tracks as drivers of innovation. They also offer new perspectives on many areas of daily life and the economic sectors; Application errors of intelligent technical systems [2]

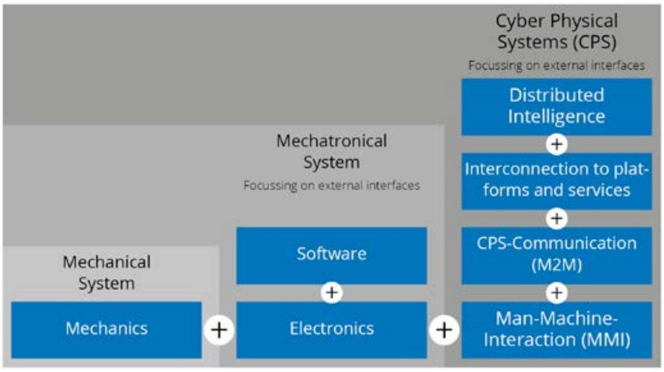

Fig. 2. Change of the system architecture due to increased networking and customization [3]

Two of these converging development tracks are called drivers of innovation and end in the general observation of "Internet of Data and Services" (Fig. 1). By skillfully utilizing and combining these technologies, the systems continue their rapid development. The development began with simple mechanical systems. The next stage were complex mechatronic systems. Today, we're facing the challenge of understanding, operating and developing complex, intelligent, technological systems (also called cyber-physical systems) (Fig. 2).

These intelligent technological systems have led to developing terms in different areas of life like Smart Building, Smart Mobility, Smart Grids, Smart Health, Smart Products, Smart Factory and Smart Logistics. The systems' intelligence regarding different areas of life and economic sectors is due to the interconnection and usage of data and services. Application scenarios for these technologies in daily life are the topics Smart Building, Smart Mobility, Smart Grids and Smart Health (Fig. 1). This is called the Internet of Things (IoT). The application scenarios for an industrial environment are Smart Products, Smart Factory and Smart Logistics. This is called Industrie 4.0 or in the USA, Industrial Internet of Things (IIoT).

The intelligent technological systems or cyber-physical systems form the basis for all "smart" application areas like the Internet of Things or Industrie 4.0. For building intelligent systems, we must already consider integrating individual components sensibly into the system while they are still in development. To understand and effectively develop intelligent technological systems, new development approaches, methods and tools are needed.

To meet the changed requirements in higher education caused by the changes above, it is necessary to test our educational content and teaching methods. It is essential to determine the effects of the digital transformation on the industrial sector. Based on this, we must formulate recommended actions for remodelling our current teaching methods. New educational content must be integrated and new approaches for more flexible training, including self-learn models, must be considered.

From our perspective, the following challenges of the digitalization are barely present in the current curriculum:

- methods for developing cyber-physical systems (Model-based Systems Engineering [4])
- consistent use of modern CAx-tools in product development
- agile development processes for multidisciplinary projects in a global context

III. Innovative Learning Concepts and Sample Projects

A. Goals and basics

By remodeling the curriculum and the teaching methods, we intend to prepare the students for the current issues in today's industry. The teaching methods must be designed to match the student's expectaions, brought over from their personal lives. New teaching methods are designed to appeal to the students and awaken their enthusiasm for technical matters. Giving them the opportunity to have early practical successes during their studies, especially during their first semesters, is meant to motivate them further.

B. Innovative learning concepts

In the following sections, some selected learning concepts will be explained. These learning concepts make it possible to properly adress the dynamic development of the topic Industrie 4.0 during courses both short- and midterm (cf. [5]).

1) Lecture series ("Industriedialog Industrie 4.0") and networking with other universities

So called "lecture series" are an efficient way to permanently integrate the topic Industrie 4.0 into the curriculum and also a good way to make it accessible to interested company employees. Lecturers from industry, politics, associations and universities report on individual key topics ([6]). This event series provides a good overview on the topic from different perspectives and can initiate the necessary communication between the academic and the commercial world.

Basic recommendations for action from Industrie 4.0, Economics 4.0, Work 4.0, World 4.0 are made tangible (and explained). The correlation between technologies and teaching is made clear. Practical examples of application presented by lecturers from the industry introduce students to current issues. In this way, they can adjust the focus of their training accordingly.

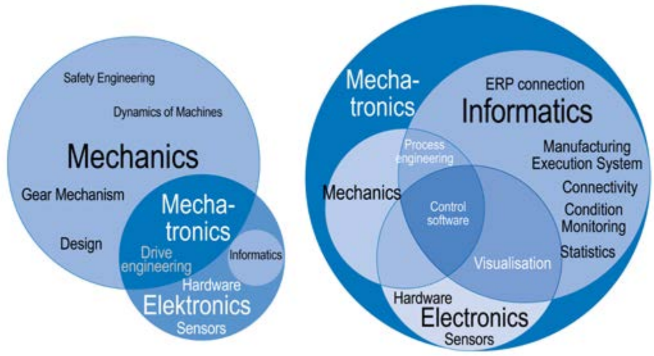

Fig. 3. Paradigm shift in the view on mechatronics ([9])

Additionally, these events offer an excellent opportunity for discussion and are an important contribution to the exchange between the university and the regional commercial world.

Other locations and universities can take part in the lecture event of the lecture series because the individual events were streamed live there. Participants could join the discussion via chat. In this way, a very good and varied selection of lectures was available at multiple locations at once, with a tolerable amount of effort. Actively participating in a live event via chat has a greater learning effect than watching a recording. The participation of partner universities is an opportunity for students to communicate with other locations. In this way, the students can profit by increasing their own specialization and mobility.

2) Problem-based Learning, Coaching and Mentoring

Via joint projects with industry partners, who work on the implementation of Industrie 4.0 applications, a high practical relevance and motivation can be reached among the students. The industrial tasks related to product development can be practiced by the students in a group project. They work on the project together, document it and after completing it, hold a presentation about their results. Besides aquiring specialist knowledge, students also learn practical skills. Additionally, the project offers many opportunities for them to further their personal development in various directions. The students receive support from their mentoring professors by regularly reviewing the development of their project with them. In this way, the students can learn important work methods for the entry into development work. ([7]).

Practical applicability and the advancement of the student's personal development can be integrated well into new learning concepts thanks to the mentoring and coaching available to them.

The students have the opportunity to practice personal skills like "taking responsibility" by working in joint projects with students from other semesters. Students from higher semesters take on coaching and mentoring tasks towards first semester students and school students about to graduate. In this way, the students from the higher semesters support the purposeful job orientation in the early stages of university education.

Within the industrial training, a close cooperation between universities and the federally sponsored Learning Factories 4.0 at commercial schools has become possible. The universities can work on projects which go beyond the usual scope of the commercial schools' curriculum. The results can be used further in joint projects, and also utilized in schools, universities and the industrial companies involved. At the same time, the universities profit from the infrastructure in the commercial schools. On the other hand, the joint projects offer attractive further training for commercial school students ([8]).

3) New courses and adjusting existing courses

To include Industrie 4.0 in the curriculum of the course Mechatronics, we suggest the following three topics as a focus.

- basics
- development methodology
- development tools and software tools

Additionally, the Makethons can be also integrated into the curriculum.

a) Basics

A basic understanding of Industrie 4.0 must be taught at universities. Students must learn when the term was coined, understand what the fourth industrial revolution is and know, which are the key messages for understanding the overall topic. In this way, they will be able to understand the paradigm shift portrayed as a shematic representation in Fig. 3. In the future, IT will have a growing share in mechatronics, because commercial success is significantly influenced by the more flexible ranges of function and the more rapid development cycles.

b) Development methodology

The structure of a mechatronic system described in the VDI guideline 2206 "Design Methodology for Mechatronic Systems" was developed further by expanding the information processing and the networking of systems for an intelligent mechatronic or cyber-physical system ([2]). The cyber-physical systems are the core of Industrie 4.0 and for the Internet of Things (IoT). They connect and synchronize the information in the digital and physical world. The Internet of Things will migrate with the internet of humans (social networks) and the internet of services. These systems are the objective of Industrie 4.0 applications. They require adjusting the methods used for developing these systems.

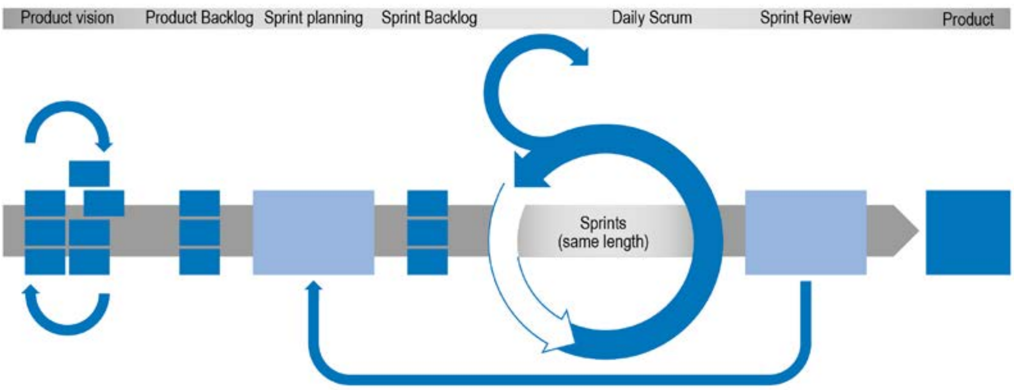

Fig. 4. Agile development processes and their adjustment to mechatronic product development [10]

It is important to consider this advancement of developing mehthods for Mechatronics teaching methods. This also includes modern development methods for software (e.g. SCRUM) and adjusting them in a discipline-specific manner to mechatronic systems ([10], Fig. 4).

c) Development tools and software tools

The plants and products become increasingly more intelligent and interconnected. This is also the reason why the requirements for development tools keep changing. To control the increasing complexity and interconnection of products, and to build cyber-physical systems for the “system of systems”, suitable software tools must be utilized. The students need to be introduced to these new, and admittedly powerful, software tools during their academic education. The “Mechatronic Concept Designer (MCD)” by Siemens or the simulation software “virtuos” by ISG (Industrielle Steuerungstechnik GmbH) are examples of such tools. They can be used, among other things, for constructing a digital twin for the virtualcommission of complex plants and products (cf. [11]).

d) Makeathon

A Makeathon is a teaching method, which contains many important aspects of the digital transformation and its impacts. “Makeathon” is a term derived from “make” and “marathon”. During a Makeathon, something innovative and cool needs to be developed and built, in short: made. To achieve this goal, simple but powerful hardware like Arduinos, Raspberry Pis, 3D printers and many more are used. To carry out the task in the given time, skills like tenacity, endurance, sprinter qualities and perserverance are needed. Students have to work for a long period of time under extreme strain. All these qualities are also necessary if someone wants to participate successfully in a marathon. For this reason, a Makeathon is a good opportunity to do application-oriented coaching (see B.2).

There are different formats for Makeathons. Students continously do creative work together, develop new ideas and build prototypes in a previously defined timeframe of 24 or 36 hours or for three to four days. Especially the combination between the real and digital world poses an interesting challenge.

During a 24-hour nonstop Makeathon at the automatica 2016 fair in June 2016 in Munich, students from different universities were able to prove their skill. The enthusiasm and commitment of the students demonstrated that this teaching method can be used successfully and efficiently ([12], [13]).

A 4-day Makeathon with the slogan “SMART GREEN ISLAND” in Las Palmas de Gran Canaria in September 2016 and Februar 2017 was also very popular with students ([14], [15]).

The goal of a Makeathon is letting the students experience mechatronics by working on specific examples.

C. Sample projects

1) First Makeathon at the Aalen University

The first Makeathon at the Aalen University lasted for three days. In total, 35 first semester students from the courses Mechatronics, Technical Teacher Education and Technical Editing took part.

Students were introduced to mechanics, electronics, computer science and technical editing via practical examples. By the end, they had built and commissioned a simple mechatronic system. After that, every group held a short presentation. Each group described a practical application for a simple robot and reported their impressions by giving feedback on the project.

Fig. 5. Timetable of the Makeathon at the Aalen University

The introduction to

- computer science,
- electronics,
- mechanics and
- technical editing

was done by students from the seventh semester of the bachelor course Mechatronics, students from the master course Systems Engineering and professors.

The first semester students were able to familiarize themselves with these topics by doing easy practical exercises.

By building a mechatronics system, in this case a simple robot, the students practically applied and combined their knowledge from different disciplines. The timetable of the Makeathon is shown in Fig. 5 .

The following parts describe the individual elements of the Makeathon.

a) Computer Science

In Computer Science, students were introduced to creating programs and graphical interfaces. The goal was for each student to learn the structure of a programming language, in this case Python, understanding it and carrying out tasks with it unassisted.

A lecturer introduced the students to programming with Python by using examples. After the basic introduction, the students received the task of programming a graphical interface for the controls of the mechatronic system they would build later. The students were free to use any approach and concept they liked for their interface. This was meant to stimulate their creativity and awaken their enthusiasm for computer science.

b) Electronics

Electronics were meant to help the students in making the transition from pure programming to building physical constructs. The goal was that by the end, the students understood how to program an Arudino board and how electric circuits work and are built.

During the introduction, the students had to conceptualize and build different basic circuits like LED or potentiometer circuits with the aid of a tutor. After the successful completion of these task, each group had to develop and test the source code for the electric circuit of their controls. After that, there were task cards, with which the students could analyse and build more circuits. Everyone was free to decide whether they invented a new circuit or modified an existing one.

c) Mechanics

The students learned how to approach the construction of new components using a CAD assembly. The end goal was for each group to be capable of developing components and creating a 3D model without instructions.

The first step was creating a 3D CAD model for a lego vehicle by using an available technical drawing. With the help of a lecturer, the students learned about the most important methods and tools. In this way, they were introduced to construction programs. By the end, the groups built a complete lego vehicle together. This task was meant to stimulate their creativity and awaken their enthusiasm for constructing new components. The necessary parts for this task were divided among the groups. At the end, the whole assembly containing all components was printed with a 3D printer.

d) Technical Editing

Communication and meta-knowledge were the focus of Technical Editing. The participants explained the contents and goals of the courses and discussed the opportunities for the future offered by each one. The students discussed what content each course provides and what not (meta-knowledge). The goal was creating awareness of future career start and promotion opportunities. In this way, the students could learn how important good communication with clients and collegues will be in their later career. The students learned to explain themselves across disciplines and discuss their visions.

Mechatronics engineers develop products, technical teachers explain products and technical editors make products usable. To achieve this, everyone must look at things from the user's perspective and invent application scenarios. The students developed and worked on an use case and presented the results of the task. Everyone discussed the product ideas and developed them further. The presentations were filmed so that the students could observe their own performance.

e) Mechatronic Systems

After the successful introduction of all four disciplines, a mechatronic system was built, in this case a simple robot. The goal of this task was teaching students the reach and benefit of mechatronics in daily life early on. During this part, the participants needed to already develop the first connections between the mechnical construct and the future controls. After completing the robot, each team had to invent an application scenario in daily life and solve it by using the robot. The participants decided how to solve the problem, which fostered innovation and creativity among them.

f) Final presentations

The groups presented their ideas and how they executed them in a short final presentation. At the end, they reported both particularly positive and negative impressions of the last three days.

This report by a female student shows how innovative even first semester students can be:

"[…] Our team's idea was building a robot with the name "Interbot" (with voice command). He knows all languages or can be switched to any desired language. By languages we also mean dialects like Schwäbisch, Bayrisch and Kölnisch (translator's note: German dialects). We came up with this idea by thinking about illiteracy. I've also worked in a hospital (geriatrics department). Some of the old people there were no longer able to speak all the foreign languages they had learned in the past due to old age. Since medical technology is also starting to include robotics, I think that there's demand for products of this type. Additionally, as a mother, I keep meeting other parents who complain about their kids no longer speaking the local dialect (mother tongue). They are afraid of watching helplessly as their heritage disappears step by step. That's why there's also a market for our robot among children's toys. I hope I managed to explain our idea more. Who knows, maybe one day the first prototype is developed at our university. […]"

2) Showcase Mi5 smart4i-Demonstrator

Challenging development tasks with an international team are worked on with professional tools and processes in the project Mi5 of the company ITQ ([16], [17]).

The smart4i-Demonstrator (Fig. 6) makes Industrie 4.0 tangible and proves, that by efficiently using and composing technical components, Industrie 4.0 production processes are already usable today. Visitors of the fair could order individualized powerbanks online by using the smart4i-Demonstrator. Furthermore, the visitors could also watch the packaging process live. The color, packaging and font could be adjusted according to the client's preferences and wishes (Fig. 7). The order was immediately processed by the demonstrator and the parameters were transmitted to the modules (production with batch size 1). What was exceptional here was the universal networking from the cloud to the field devices, which was guaranteed at all times by the uniform interfaces (OPC UA) and information models. The service-based controls allowed a quick and easy exchange of modules and a comprehensive monitoring of orders. A functional abstraction of the individual modules is created via "Skills".

By using agile mechatronic development methods like for example Scrum, tool-supported engineering and cooperating with industry partners, an inter-disciplinary and international team of 36 students developed this modular production plant in the form of a visible demonstrator in only 36 weeks. The development project for the smart4i Industry Demonstrator shows complexity and interdependency using this specific sample project.

Fig. 6. Showcase Mi5: smart4i-Demonstrator at the VDMA booth of the interpack 2017 fair in Düsseldorf ([18])

Fig. 7. Customized powerbank packaging

During this project, the students learned to use many professional development tools. Part of that was also building a simulation environment for virtually developing and commissioning products (digital twin). Due to that, the students could already assess the overall system in early project phases and develop the hardware and software parallel to it.

Thanks to the international cooperation with multiple teams in different locations and a very challenging schedule, important soft skills, useful for the students' later careers, were also trained.

3) Integration into the curriculum of the course Mechatronics

Fig. 8 shows, how the elements for Industrie 4.0 described in "B Innovative Learning Concepts" have been integrated in the curriculum of the course Mechatronics at Aalen University.

IV. Summary and Outlook

The digitalization poses new challenges for university teaching. Future graduates need to be well prepared for the Professional World 4.0. Based on the methods described in this paper, new lab tests, project works and lecture modules can be created and integrated into already existing courses.

Due to the regular exchange with industry experts, economics experts, associations and science experts, current issues are conveyed to students in a practical and motivating manner. By using specific projects, new development methods and tools can be tested in university teaching. They are therefore important components for achieving longterm learning success.

We want to stimulate the discussion about developing more innovative teaching methods with a few closing keyword propositions.

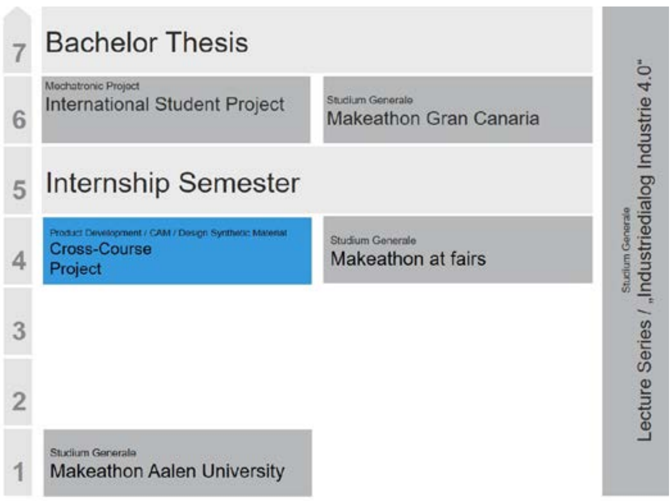

Fig. 8. Integration into the curriculum of the course Mechatronics

A. *Prototypes instead of PowerPoint*

Many real, hands-on experiences and practical application must be realized within a short amount of time without beating around the bush. Building instead of only theoretical development, Hardware instead of PowerPoint.

B. *Interdisciplinary teams instead of uniformity*

The core member of the team is the mechatronics engineer. Additionally, there are programmers, industrial engineers, technical editors, technical teachers etc. who help developing the project. They are often more adept at explaining a concept in an understandable fashion than “pure” engineers.

C. *True visibility instead of theory only*

The tasks and activities must appeal to the students. They must learn teamwork. During large scale events, the opportunity to exchange ideas with foreign students must be possible.

D. *Hands-on education instead of class room lectures*

The new teaching methods must show students that they need to actively particpate instead of only passively listening. Everyone’s prior knowledge influences the courses and projects for everyone’s benefit.

E. *Taking responsibility and inspiring others*

University students will organize workshops at regional schools where they instruct the students working on projects together. The projects are developed at the university in suitable courses. The workshops are meant to inspire enthusiasm for engineering at schools. In this way, school students have the opportunity to learn about engineering early on.

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