Implementation of Task-Centric Holistic Agile Approach on Teaching Cyber Physical Systems Engineering

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Abstract

Industry and academia are facing a significant challenge to address the shortage of required workforce to enable the realization of Cyber-Physical Systems (CPS). To run CPS-engineering projects, engineers are required to have multi-disciplinary technical skills due to the complex nature of CPS that consist of hardware, software and communication systems in a single product. However, having technical skills are not enough since CPS-engineering projects are prone to failure due to lack of social skills of project members. To be prepared for their future work as CPS engineers, students need an opportunity to gather experience in projects in which they face real life situations. This paper proposes a novel task-centric holistic agile teaching approach for teaching CPS-engineering in realistic up-to-date industry-like scenario. This approach especially accentuates the development of social skills. The work presented in this paper describes the implementation of the approach and presents the results of the students’ feedback.

Keywords


Introduction

Cyber Physical Systems (CPS) are intelligent systems consisting of two principal components - physical and computational that are seamlessly integrated with each other. CPS can build up complex systems of systems communicating and collaborating with one another. Examples of CPS are smart cars, smart cities, smart homes, smart factories, smart grids, and other smart systems and things. The current technical developments, such as invention of small and powerful processors and low-cost sensors, expanding information and communication technologies, and networks, together with multidisciplinary engineering skills, allow design and creation of increasingly reliable, adaptable, autonomous, and networked CPS. To meet the growing industry demand in CPS development, skilled engineers with a wide breadth of knowledge in many engineering disciplines and excellent soft skills are needed. Consequently, nowadays the CPS education represents one of the key challenging education areas for academic institutions. To design and develop CPS, engineers need to possess both technical and social skills to run CPS-engineering projects successfully. Interdisciplinary technical skills are increasingly required because the products are getting more complex having hardware, software and communication interface with the surrounding world integrated in a single product. Social skills make an essential contribution to the success of technical projects. In (Bancino and Zevalkink 2007) the authors report that "technology-intensive projects... tend to have failure rates... somewhere between 40 percent and 70 percent". The main reason for
project failures stated by the authors is the lack of soft skills. To be prepared for their future work as CPS engineers, students need to get an opportunity to gather experience in projects in which they face realistic project situations. In this work we propose a novel task-centric holistic agile teaching approach (T-CHAT) for teaching CPS engineering as well as describe its implementation and evaluation.

Background and Related Work

The CPS education is gaining significant interest across academic and research institutes, industries and governmental policies. For example, the report of the Committee on 21st Century CPS Education (National Research Council 2015) reports the need for CPS education from the industrial and the academic point of view. It highlights the essential knowledge and skills needed by CPS engineers and gives hints how these may be integrated into various curricula. The report stresses that the education should focus on core ideas and core principals of CPS.

<table>
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<tr>
<th>Requirements</th>
<th>CPS Engineers need to have knowledge &amp; skills in (National Research Council 2015)</th>
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<tbody>
<tr>
<td>technical</td>
<td>• engineering process,                                                                                       • design, development, test, verification and validation of systems,</td>
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<td></td>
<td>• cross-disciplinary thinking,                                                                               • plant modeling,</td>
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<td></td>
<td>• control system design,                                                                                      • network understanding,</td>
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<td></td>
<td>• algorithm design,                                                                                           • timing and latency,</td>
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<td></td>
<td>• safety assurance, and                                                                                       • communication and sensing technologies</td>
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<tr>
<td>social</td>
<td>• collaboration in a team,                                                                                     • communication,</td>
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<td></td>
<td>• technical writing, and                                                                                       • presentation</td>
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<tr>
<td>business and</td>
<td>• flexibility to manage rapidly evolving technologies,                                                        • definition as well as solving problems,</td>
</tr>
<tr>
<td>entrepreneurial</td>
<td>• entrepreneurship, and                                                                                       • public policy implications</td>
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<tr>
<td>attitudes</td>
<td>• creativity,                                                                                                 • innovation,</td>
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<td></td>
<td>• leadership,                                                                                                • motivation,</td>
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<tr>
<td></td>
<td>• curiosity and persistent desire for continuous learning, and                                               • critical thinking</td>
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Table 1: Knowledge and skills required by CPS Engineers according to (National Research Council 2015)

CPS spans across mechanical, electrical/electronic, controls, computer software and communication engineering disciplines. Engineering teams for developing CPS are usually composed of engineering from various backgrounds and specializations ranging from generic fields such as electrical and computing engineering, mechanical engineering, systems engineering, and computer science, to more specific engineering fields such as aerospace and health care engineering, and to the field of integration of cyber technology and physical systems (National Research Council 2015). This makes communication among team members very challenging. For effective collaboration with colleagues and effective communication with non-technical customers, CPS engineers need to have strong technical and social skills (National Research Council 2015). Soft skills are particularly required if CPS are developed in globally distributed teams. Additionally, CPS engineers should develop skills to enable critical thinking and understanding the
need of lifelong learning (National Research Council 2015). Table 1 sums up the knowledge and skills that are required by CPS engineers according to (National Research Council 2015).

As the industrial software development is increasingly organized in distributed manner (Monasor et al. 2014) and software has a central role in CPS, the CPS education should also conclude the aspects of distributed software development.

This paper proposes that to fulfill the current needs of industry for CPS talent, the academia needs to offer curricula and courses that accentuate both technical and social competences. However, based on our investigation, the current CPS courses (cmp. (Lee et al. 2013), (Cheng 2014), (Wade et al. 2015), (Bauer and Schneider 2013), (Damevski et al. 2013) ) mainly focus on the development of technical skills. The development of social skills has not given appropriate attention so far. As a result of this, the engineering graduates lack the skills required for globally distributed development of complex CPS.

In the following section, a concept of the teaching approach is outlined that aims to instill both technical and social competences in CSP engineering graduates.

The Concept of T-CHAT

To address the challenges faced by the CPS education, a concept of T-CHAT for teaching CPS engineering is developed. Its detailed description can be found in (Maekioe et al. 2016). Holistic approach and agility of the teaching process are the fundamental ideas of the T-CHAT. In this paper, the term “Holistic” refers to the integration and combination of different and versatile pedagogical approaches and teaching/learning methods with the aim to achieve educational goals. Whereas, “Agile” refers to coping "with changing and diverse learning needs" and "with changing research, business, and technology environments" (Chun 2004). Applying this methodology, the tutor combines and varies pedagogical approaches and methods depending on the students’ needs. The central element in the methodology is a CPS development task that provides students the opportunity to learn through practical exercise of CPS development that presents real life scenarios.

Figure 1: Elements of the task centric holistic agile teaching approach T-CHAT

The agile teaching process is organized around a task (cf. Figure 1). The T-CHAT consists of five different pedagogical approaches that may be varied upon demand.

- Perceptual teaching (Kurki-Suonio 2011) is based on the idea that perception plays a fundamental role in all learning. A central role is given to the intuitive perception which is understood as "the creation of meanings (of observations and interpretations)” (Kurki-Suonio 2011). According to perceptual approach, empirical meanings should be perceived before they can be conceptualized. The initial intuitive understanding can be acquired through observations and experiments. Thus, understanding the principles of concept formation forms an essential basis for teaching.
The project-based learning ([Mills et al. 2003], [McDermott et al. 2007]) is a model that organizes learning around projects. It provides self-directed learning in realistic working environment allowing the students apply existing knowledge and learn new things by solving practical problems (Mills et al. 2003). The central element of the holistic approach is the task that is organized as a project.

Problem-based learning serves primarily for acquisition of knowledge and provides student-centered learning (Mills et al. 2003) referring to theory, models, and practice (De Graaf and Kolmos 2003). It trains teamwork skills and experiences improving students' collaboration and communication competences. The task is constructed in such a way that students face problems that they need to solve independently.

Research-oriented teaching (Healey and Jenkins 2006) enables acquisition and advancing of disciplinary and interdisciplinary knowledge and competences. Furthermore, it introduces the key features and the process of research as well as provides an ability to ask questions and find solutions using scientific methods. The task is designed so that the main topic is combined with an up-to-date research question.

In face-to-face teaching, often referred as traditional teaching in which a teacher defines what should be learnt and how, as well as causes learning to occur (Wood et al. 1978). This pedagogical approach is applied, e.g., to introduce complex theoretical topics or to provide an overall picture in a form of short input presentations.

Table 2 summarizes the objectives of the pedagogical approaches that are used in T-CHAT.

<table>
<thead>
<tr>
<th>Pedagogical approach</th>
<th>Objectives</th>
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| **Perceptual**       | • Give an intuitive understanding of complex topics.  
                       • Enable forming of conceptual structures through perception of empirical meanings (Kurki-Suonio 2011). |
| **Project-based**    | • Provide application of knowledge (Mills et al. 2003).  
                       • Provide self-directed learning (Mills et al. 2003). Develop practical engineering skills that allow learning by doing.  
                       • Provide teamwork skills and experiences (Mills et al. 2003).  
                       • Provide realistic working environment (Mills et al. 2003). |
| **Problem-based**    | • Provide acquisition of knowledge (Mills et al. 2003).  
                       • Provide student-centered learning (Ertmer 2015).  
                       • Provide teamwork skills and experiences (Mills et al. 2003).  
                       • Provide reference to theory, models, and practice (De Graaf and Kolmos 2003).  
                       • Provide students enjoyment from the work (De Graaf and Kolmos 2003). |
| **Research-oriented**| • Enable acquisition and advancing of disciplinary and interdisciplinary knowledge and competence.  
                            • Provide ability to ask questions and find solutions using scientific methods.  
                            • Introduce key features and the process of research. |
| **Face-to-face**     | • Introduce complex theoretical topics.  
                            • Provide an overall picture. |

**Table 2: Teaching methods of T-CHAT**

The following sections describe the implementation and evaluation of T-CHAT concept.

**Implementation of T-CHAT**

To validate the T-CHAT, a teaching course of CPS was developed collaboratively by the University of Applied Sciences Emden / Leer, Germany and ITMO-University St. Petersburg, Russia. This course was run in the winter semester 2016/2017. Seven German students studying computer science and eight Russian students studying instrumentation and control engineering participated in the course supervised
by German and Russian tutors from both of the universities. In this course, the students were required to design, develop and validate a CPS that emulates a small factory with several robots transporting building blocks from a source palette to a goal palette while cleaning and painting them. Solving this task was carried out as a project running in an environment, in which the tutors functioned as customers ordering a CPS from a "manufacturer", in this case the students. The students were responsible for setting up a technical infrastructure for CPS development, project management and communication, forming project teams, and organizing the project work. This course was planned and conducted implementing the methods of T-CHAT as well as applying the following key principles that are significant for the course success:

- effective communication and collaboration within technology-intensive projects are crucial for their success (Bancino and Zevalkink 2007), and
- active students’ participation in learning process as well as students’ motivation are the key success factors for effective learning (Dera 1984).

The following section presents outline of the course structure and describes the applied pedagogical approaches and teaching methods.

**Course Structure**

The project was started with an opening workshop in which the project members participated physically. This took place from September 5, 2016 till September 8, 2016 at ITMO University, Russia. During the workshop, the students developed a common understanding of the task, acquired foundation knowledge of the topic, and established personal contacts needed for friendly and trustful project atmosphere. At the end of the workshop, the students were requested to fill out a questionnaire for evaluating the course and effects of teaching, skills, knowledge as well as social competencies acquired. Afterwards, geographically separated, they formed two teams, a German and a Russian one, and continued the project work. Tutors supervised the project status to give feedback and support to the students with little interference in the students’ work. For evaluation of the project settings and organization, we conducted a qualitative research using interviewing method (Holliday, 2007) for data collection. At the end of the project, a closing meeting was held to finalize the CPS development and to summarize the course results. This took place from November 28, 2016 till December 5, 2016 at University of Applied Sciences Emden / Leer, Germany. At the end of this meeting, the students were asked to fill out the same questionnaire as for the opening workshop. At the end of the course, the German and Russian teams gave a joint presentation of the project results.

**Teaching Methods**

During the course, we used the pedagogical approaches contained in T-CHAT applying some teaching methods that are described in this section. The opening workshop addressed the following four critical objectives 1) the students from both universities should get to know each other well and establish personal contacts; 2) the students should be provided with a substantial task in the field of CPS; 3) the students should get background knowledge in the areas of CPS technology, global software engineering, and project management through multiple short face-to-face teaching sessions; and 4) the students should carry out the draft planning of the project.

The workshop aimed at mobilizing and motivating the students to give them feel of competence, autonomy and social integration. The workshop was structured according to the sandwich principle (Strittmatter-Haubold and Ehail 2012) in which collective and individual learning phases change permanently. This allowed the participants to conceptualize the perceived empirical meanings (cp. Kurki-Suonio 2011)) and to place the new learning content into the cognitive structures they have already developed, at their individual pace. Communication games, short impulse presentations for knowledge transfer, and work in small groups were used as teaching methods. The opening workshop was evaluated through students’ daily written feedback. The feedback analysis showed that communication was considered by the students to be a key success factor for the project. The students recognized that gaining the same awareness of a task or a problem needed considerable efforts of every participant because each project member understood the presented stuff in a different way.
At the opening workshop both groups, German and Russian, nominated a project coordinator responsible for the project management as well as for communication between groups and with the tutors, i.e. “customers”. To evaluate the project organization and management as well as to get a reflection about the progress of the project and the atmosphere within the groups, the project coordinators were interviewed. Table 3 presents the questions they were asked. These interviews provided a precise picture of the project structure and organization, technical tools used, communication and the mood within the project team.

### Table 3 Interview questions

<table>
<thead>
<tr>
<th>Questions</th>
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<tbody>
<tr>
<td>What is the project organization?</td>
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<tr>
<td>How have been the technical sub-teams formed? What is the structure and competences of the sub-teams?</td>
</tr>
<tr>
<td>Which development process is applied?</td>
</tr>
<tr>
<td>How does project management process work?</td>
</tr>
<tr>
<td>How project communication is organized?</td>
</tr>
<tr>
<td>How the current project status is tracked?</td>
</tr>
<tr>
<td>How new project tasks are generated and assigned?</td>
</tr>
<tr>
<td>How is the atmosphere and mood among the project participants?</td>
</tr>
</tbody>
</table>

At the opening workshop, the students created a capability matrix containing their individual knowledge, skills and competencies. Based on this matrix they formed technical teams that, being international, focused on specific project topics. These teams were 1) architects and developers, 2) testers, 3) graphical interface designers, and 4) documentation writers. An important issue in the project was the communication. In the beginning, the project members decided that communication between both groups should run via the project coordinators. In the course of the project, it turned out as impracticable because communication within the international technical teams needed to run direct and smoothly. Three types of communication were used during the project: 1) asynchronous communication, 2) synchronous telecommunication, and 3) synchronous on site communication. Asynchronous communication was used mostly within technical teams to collaborate on the same topic. Synchronous telecommunication was used for weekly project meetings where both groups participated. Synchronous communication on site was used inter alia for weekly project status meetings of each group. The project coordinators emphasized that asynchronous communication within the technical teams, especially in the team of architects and developers, posed a significant obstacle for project success. Open points and issues could not be resolved immediately, which impeded the development process. Furthermore, the project coordinators accentuated that communication suffered from the language barrier.

Another essential issue was the work organization within the self-managing teams. Each team conducted regular team meetings to track the progress and create new tasks. Team members picked the tasks they were able to solve. Difficult tasks were discussed and clarified in the team first. All members of teams communicated extensively and mostly worked together, though remotely. Communication between different teams was rather sparse. For example, developers and graphical interface designers discussed the common interface solely at the start of the project.

For the learning success as well as for success of the project and the course, the atmosphere within the project teams and the mood of the students play a major role. Both project coordinators emphasized that by regular team and project meetings the mood of the project participants was very optimistic and positive. The team members were aware of their tasks and so they could contribute to the project success, which resulted in getting the feeling of being useful to achieve a common goal. Some project members were very motivated and showed great initiative. However, in some instances it affected collaboration in team in a rather negative manner, because they took over the job of other team members and so discouraged them. Too much initiative from some members was stated as not implicitly positive for the efficient team work. Project coordinators also mentioned that supervision and feedback of the tutors was
sometimes too rare and wished that the tutors would show appreciation and interest in the student’s work and achievements more regularly.

Indeed, the tutors did not participate in any decisions during the development; they solely supervised the project status. The aim of this was to give students the opportunity to learn managing situations and challenges that may occur during the project.

During the course the students faced some technical problems, for example at integration of software part implementing controlling and supervision of robots with the physical realization of robots. The problems were successfully solved by the project team. The project task was initially devised as an up-to-date research topic. Thus the students, being introduced into current research, actively acquired and advanced their knowledge in the up-to-date CPS technology.

Figure 2 gives an overview of using the pedagogical methods of T-CHAT at various phases of the course.

![Course structure and teaching methods used](image)

**Figure 2: Course structure and teaching methods used**

**Course evaluation**

The non-randomized experiment according to MacGowan’s (2011), Heinsman’s and Shadish’s (1996) approaches was designed as an integral part of the course, so that all students participated in the activities during the class and if required in out-of-class work. The group consisted of 15 students, who registered in the chosen educational path (Babbie, 2001, Katz, et al. 2004). The non-randomized small sample faces less difficulties in sustaining cooperative and synergy outcomes than randomized or larger one (Nosenzo et al. 2015). The procedures undertaken in current study met the requirements and yielded accurate answers according to non-randomized experiment approach (Shadish et al., 2012).

After both of the opening and closing meetings the students were asked to fill out a questionnaire to provide their individual assessment of the course. Both surveys were aimed to investigate the students’ subjective feeling about the course and its outcomes at the beginning and the end of the course. Students evaluated the course, using the novel author’s Questionnaire of Evaluation (QE) based on the theory of human capital (Becker 1985, 1993, Kowal et al. 2011, Simkovic 2013) and on the review of the best practice in teaching technical courses (Speranza, 2017, Admiraal et al., 2017). QE included four dimensions representing effects of teaching: knowledge (EF), skills (SKILLS), social competences (SC), and evaluation of the course organization (EC). All items were measured on a 5-point Likert-type scale: very low (1), low (2), neutral (3), high (4), very high (5). Each dimension was calculated as a mean of points given by respondents to dimension items.

The sample was not random, thus authors conducted statistical analyses using the descriptive statistics, as measures of central tendency (mean, median, mean rank), measures of dispersion, skewness, kurtosis, measures of the correlation as Spearman rank correlation coefficient (Kowal, 1998).
The overall result of evaluation of the course was positive, above the middle point of the scale in both stages (Table 4). However, the global median was slightly less at the end of the course, and the full group was much more differentiated. Probably the students expected easy tasks within this course. Though, some aspects of the course and the method of teaching could be improved. This conclusion confirms educational rule that teaching might require continual development of knowledge and skills of teachers and educators (Admiaraal et. al, 2017).

The results of the whole group related to the dimension of skills are better, higher at the end of the course. As aforementioned, the students seemed to be more differentiated at the end of the course. The most important skills were: 1) ability to use basic theoretical knowledge and practical skills in the subject; 2) ability to understand analyze phenomena and processes on the basis of the methods of the course; and 3) ability to use the knowledge and skills obtained during the course to analyze proposed solutions of concrete problems and to propose new solutions using methodology, techniques and tools of the course.

In the dimension of social competencies, students showed good results and they were more homogeneous and more similar to each other at the end. Most of the students largely eliminated their deficits in social competencies. The most important factors and best evaluated were: 1) ability to cooperate and work in the group taking different roles during preparation common projects, and using methods, techniques and tools of the course; 2) openly speaking also about personal topics; 3) conviction that after the project is over, students would like to have another project with the same team; 4) communication as ability to talk openly about critical issues in the team. These conclusions are important for future work because communication is important in maintaining labor discipline and implementation of the project (Benbasat, & Zmud, 2003). Thus, the approach helped to overcome technological-economic component dominance over social-humanistic one (Ardashkin, & Kirsanova, 2017).

In the dimension of knowledge, students showed good results at the end, but they were more differentiated to each other at the end of the course. That is, it yielded better results in one group of students who were more capable and more versatile. Some students were a little disappointed. However, our method has allowed better differentiate students, among them pick out the best and the brightest. Students were also able to better see whether the proposed course and direction of education meets their expectations in terms of knowledge and its acquisition, and whether it is the right direction for them. These experiences confirmed the need of individualized attention to knowledge development, in order to develop the engineers of the future, to embrace innovative, student-centered practices (Hug et al., 2015). Students emphasized beneficial new knowledge that enables them to choose the adequate methods for the types of problems, to find and compare significant associations and correlations, and to formulate solutions using the methods of the subject. This corresponds to the best practices in teaching technical courses (Speranza et al., 2017).

Conclusions

This paper describes a task-centric holistic approach to teaching CPS (T-CHAT) as well as its implementation in an international setting. The concept focuses on the needs for CPS education identified by the Committee on 21st Century CPS Education. Additionally, critical issues that are discussed in the engineering education literature have been considered. The T-CHAT combines five teaching methods that can be varied by teacher as needed. The concept implies the use of intuitive understanding for teaching.
the fundamental technical principles of CPS. The concept also stresses the social competences in multiple ways.

During the implementation, we focused especially on the development of students' technical and social knowledge and skills. Thus, the task that was implemented during the course was set in a way that the students got an opportunity 1) to learn up-to-date technologies and architectures, 2) to gain and develop communication skills, 3) acquire skills in writing technical documentation and 4) giving oral presentations. Additionally, the international set-up of the project allowed students to get an insight in challenges of distributed industrial project.

As the next step in our work we are planning to improve the T-CHAT approach based on our experience and to organize another collaborative CPS course for winter semester 2017-2018. Additionally, a T-CHAT framework should be created to guide the application of the proposed approach in other subjects as well to improve existent curricula. These future studies will help to improve the teaching of technical subjects in general.

In this study, the results of the T-CHAT approach were not compared with other existing approaches. However, this was the first run of the T-CHAT approach with a limited number of students. A simultaneous run of a control example would have not been possible to organize due to limited available resources. However, the results until now are very promising and encouraging to hold similar courses in the future.

The contribution of this study opens multiple future research possibilities. For example, a future research project could focus on various combinations of the T-CHAT teaching methods depending on the current teaching situation. Also the application of the T-CHAT approach in other subjects, such as economics, need to be studied. The T-CHAT proffers a tool for development of novel CPS courses and curricula considering both the technical skills and social skills in a structured manner.

REFERENCES


