How should embedded systems be taught? Experiences and snapshots from Swedish higher engineering education

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***Abstract*— This paper presents results from a previously published analysis performed on the subject of embedded systems using a didactical approach together with some educational implications. To illustrate the didactical analysis, examples from embedded systems education at KTH in Sweden are given where an exemplifying selection and an interactive communication have been adopted in embedded systems related courses.**

The exemplifying selection means that education in embedded systems would benefit from teaching 'everything of something' rather than 'something of everything', that is, depth rather than width. The interactive communication strongly motivates experimental work, hands-on approaches and problem based learning in general.

***Index Terms*—Embedded systems education, didactical analysis, engineering education.**

I. Introduction

EVEN though embedded systems have been designed for more than 30 years, the academic subject of embedded systems is a new, relatively undefined subject, mostly regarded as an interdisciplinary field combining areas such as computer science, automatic control and electrical engineering. The scope of the subject is continuously discussed, with its implications on research and education.

The aim of this paper is to present results from an analysis performed on the subject of embedded systems using a didactical approach [9]. The purpose of this analysis is to help the establishment of the identity of the subject and to provide further arguments for why the subject ought to be taught in a certain way.

A. Context

The subject of embedded systems is mostly regarded differently among different academic institutions. An example of this is given if comparing the origin of the subject among different universities; in some cases the subject evolved from within departments of computer science, from departments of electrical engineering or from departments of automatic control, which in several cases gives a slight difference between the local definitions of the subject. As a consequence, some universities treat and teach embedded systems as a specialization of computer science, and some departments use the subject of embedded systems to promote education and research in automatic control.

In the examples presented in this paper embedded systems is described and analyzed according to the way embedded systems originally was implemented at the department of machine design, mechatronics lab, at the Royal Institute of Technology (KTH) in Stockholm, Sweden. In this case, embedded systems evolved from within the school of mechanical engineering, specifically the department of machine elements where the microcontroller was introduced as 'a machine element' similar to gears, bearings etc, but with a programmable functionality. Today, 30 years later, embedded systems at KTH is treated as a subject within machine design, with a heavy focus on product development, development of intelligent products.

B. From Education through Research to Industry

The purpose of teaching embedded systems at most universities is to provide the industry with competent staff. The purpose of performing research is to educate doctors in embedded systems, for the same purpose, as well as to create new knowledge in the area of embedded systems, for the industry as well as the common good of the society.

Within the ARTIST and ARTIST2 projects, work has been in progress for quite some time to identify and specify a curriculum for education in embedded systems [1, 2]. In the guidelines published by the ARTIST teams the technical competencies required by an embedded software engineer are well specified, and the need for practice is recognized as 'an essential component for a well-rounded education in embedded systems'. Practice, however, is defined as 'experimental laboratory work' and illustrated by the use of tools such as Matlab/Simulink, running code on real hardware platforms etc. The guidelines do not mention any complementary skills such as teamwork, communication, business, etc.

It is therefore of fundamental interest that the education provided by the universities is deemed relevant and useful by

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the hiring industry, as well as by the industries of the future. One main question then becomes how the universities can understand the needs and requirements of the current hiring industry, how to balance between fundamental knowledge and skills and short-term hot trends as well as predict the evolution of the subject and prepare students for life long learning.

C. *Closing the loop: From Industrial experiences to Education*

By tradition the academic practice is characterized by a narrow viewpoint and a systematic approach, while the industrial practice is characterized by the need for a holistic viewpoint and a, more or less, ad-hoc approach, as in Figure 1. The white arrows show the necessary path to fulfill a better balance in selection and communication (form and content). Industries are constantly struggling to move from an ad-hoc approach towards a more systematic approach, and in the universities there are certainly many initiatives in the direction of reaching a more holistic viewpoint.

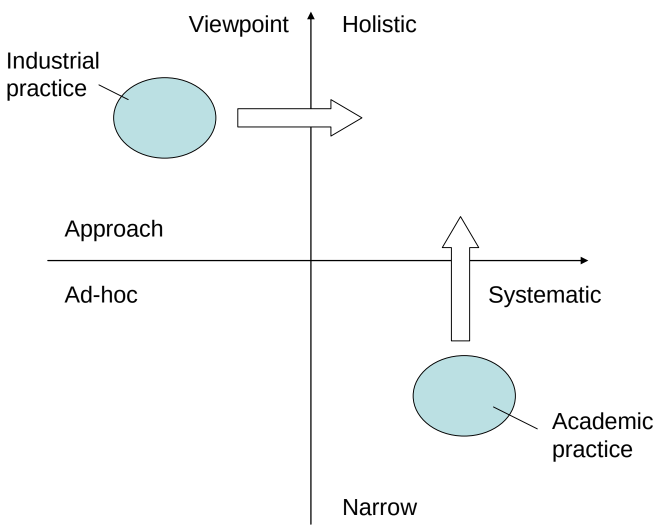

Fig. 1. Traditional differences in practice between industry and academy. The white arrows represent a desirable move to meet discrepancies in legitimacy of the education.

One way to reach a more holistic viewpoint is to focus more on the communication, the form, and, for example, to teach in a more project organized and problem oriented way - both to increase student motivation and also to move towards a more functional approach and thereby hopefully reaching a higher level of understanding. A further motivational factor for the move towards these educational methods is that the project- and problem based educational methods can be seen as preparations for a future professional role as an embedded systems engineer, which require skills such as teamwork, communication etc.

Another example from teaching indicates synergetic effects when giving courses with participants both from industry and university. Industrial participants can contribute along the lines of Figure 1, with experiences that place theoretical pieces in a context, by reflections relating to tacit knowledge and with real-world engineering constraints that are seldom touched upon in the academic teaching [12].

II. A DIDACTICAL PERSPECTIVE ON EMBEDDED SYSTEMS EDUCATION

Didactics is a field of educational studies mostly referring to research aimed at investigating what's unique with a particular subject, and how the particular subject ought to be taught. In this paper we present results from previous attempts of performing a didactical approach to the subject of embedded systems [5, 9]. The didactical analysis is used to identify and describe the identity and legitimacy of the subject (what is the subject of embedded systems and why should embedded systems be taught?) [4]. We also use this analysis to provide insight into the questions of selection and communication (which material should be taught and how?).

A. *The identity of embedded systems*

According to the didactical analysis the identity of a subject could be described in relation to two extremes; as being either disciplinary or thematic, or somewhere in between. Most traditional subjects, with established structures and related organizations, are considered as disciplinary subjects. A closure has then been reached as to the contents and internal relations of the subjects and its domains. With subjects such as embedded systems this closure has not yet been reached. Every university and department considers and teaches the subject differently, and on most conferences the scope and content of the subject is discussed in depth, as is its preferred curriculum for example.

Instead of an established disciplinary identity, themes are used to describe embedded systems, and the themes vary amongst different universities. According to IEEE an embedded system is 'part of a large system and performs some of the requirements of that system; for example, a computer system used in an aircraft or rapid transit system' [10]. From this definition it follows that computer based systems embedded into products like for example TVs, telephones, toys and vehicles qualify as embedded systems, and that the characteristics of these products include their interactions with the environment. Examples of relevant aspects are dependability, performance and cost which implies key areas such as safety critical systems, real time systems etc. Such aspects, areas and applications can therefore be used to describe the subject of embedded systems, as themes of the subject.

However, even if most universities happily agree upon a number of themes, applications and products, discrepancies between how to approach these themes arises. Some universities focus on control aspects of embedded systems, some on developing methods within computer science to reach certain goals while some focus on more general product development of embedded systems.

B. *The legitimacy of embedded systems*

The legitimacy of a subject is defined as the relation between the educational effort performed by the university, resulting in educated embedded systems engineers, and the demands put by the hiring industries on the graduated engineers. According to the didactical approach this legitimacy could be illustrated according to two extremes; as a formal legitimacy or a functional legitimacy. A formal legitimacy is defined as when the demands put by the surrounding actors on the university are expressed in terms of number of credits in specific subjects, which subjects the degree requires etc. In a functional legitimacy instead the actors requires skills and abilities, and expresses these in terms such as capabilities to design controllers etc.

In the case of embedded systems the legitimacy is classified as functional [9]. In Sweden, the hiring industry is primarily interested in functional skills, engineers capable of designing and implementing embedded systems. A study of 21 embedded systems companies in Sweden further motivates this; the companies studied put formal knowledge and traditional courses aside and instead ask for functional skills and complimentary skills such as teamwork abilities and presentation techniques [11].

C. *The selection and communication of embedded systems*

The results from the analysis, the thematic identity and the functional legitimacy, affects the final two dimensions or questions; the questions of selection and communication. These two questions deal with the what and how; what should be taught, and how.

A representative selection means that 'something of everything' is taught. This is often the case in, for example, first year courses in mathematics. The opposite is defined as an exemplifying selection where 'everything of something' is taught. This is often the case in problem based learning or in postgraduate education where the focus is on a narrow field instead of an overview. One example of teaching with a representative selection could be a course in, for example, microcontroller technology that focuses on giving general knowledge on the varieties of the existing microcontrollers, the differences between these, and more theoretical knowledge about microcontroller principles. If instead choosing an exemplifying selection, the course should focus on complete understanding of one single microcontroller. All effort should then be spent on learning this microcontroller, and to become an expert of understanding, programming and using this microcontroller. The basic idea with an exemplifying selection is that the knowledge and skills learned from this selection could be generalized and applied to similar problems and areas.

The final dimension, the question of communication, deals with the preferred method of communicating the subject. In an active communication both parties are active; teacher and student, but in an interactive communication the action by the teacher is dependant on the current status and knowledge level of the individual student or student team.

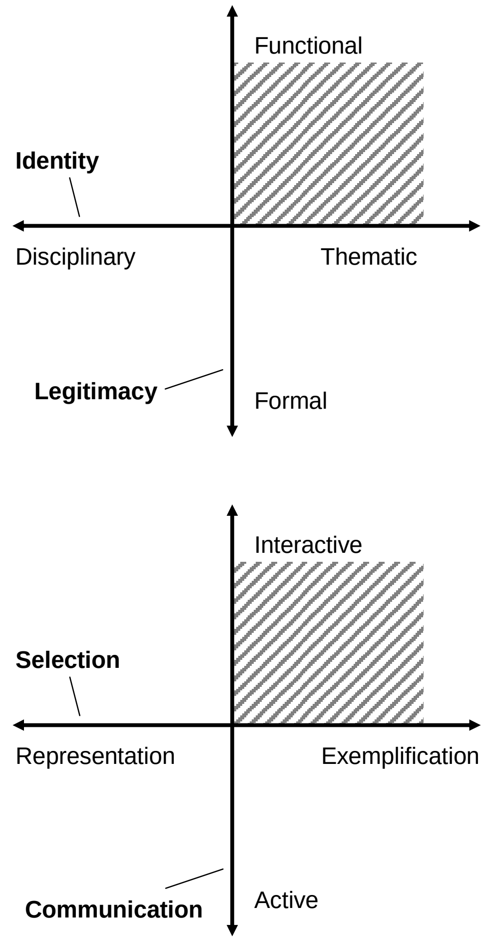

Fig. 2. Illustration of the didactical analysis applied to the subject of embedded systems.

In Figure 2 the subject of embedded systems is mapped according to its identity, legitimacy, selection and communication. The exemplifying selection and interactive communication is a direct consequence of the identity and legitimacy, which also is emphasized in the Swedish study performed on 21 Swedish embedded systems companies [11]. In brief, the exemplifying selection is a consequence of the functional legitimacy; the companies want engineers with in-depth knowledge and functional skills rather than formal knowledge. The interactive communication also facilitates functional skills rather than formal knowledge since such a teaching approach focuses more on hands-on approaches and provides complimentary skills such as teamwork abilities and presentation techniques.

III. Examples from Teaching Embedded Systems with an Exemplifying Selection and an Interactive Communication

The aim of this section is to provide examples and experiences from teaching embedded systems at KTH with an exemplifying selection and an interactive communication. It is important to note though that the examples provided here should be considered in their respective context, as described earlier in this paper. All courses below attract mainly mechanical, vehicle and management engineering students specializing in mechatronics or embedded systems.

A. *Teaching embedded systems according to the CDIO initiative*

The CDIO initiative was established in unison between KTH, MIT and a number of other Swedish universities to move engineering education further from a formal legitimacy towards a functional. The purpose of the CDIO initiative was to create a curriculum that trained students to Conceive, Design, Implement and Operate (C-D-I-O) a system; in this case an embedded system [3].

Course / Skill	Perspectives on D&P	D&P A	D&P B	D&P C	Intermediate thesis project
Analyze technical solutions	•	•	●	◉	
Team work	•	●	●	●	
Written presentations	•	X	X	●	◉
Oral presentations	•	X	X	●	◉
Sketching	•	●	●	●	
Etc.					

• Introduced ● trained ◉ ability requested X occurs unspecified

Fig. 3. An illustration of the CDIO-concept applied to course design at KTH. The illustration shows how complimentary skills are integrated in traditional subject courses, and the three-step model where each subject or skill is introduced, trained and requested over time.

At KTH the CDIO idea is implemented mainly in a capstone course in the fourth and final year of the specialization in embedded systems, a complete problem based and project organized course. In this course, a team of 6 to 15 students are given a task, typically in terms of an industrial development project involving concept evaluation and prototype development, where a corporate sponsor provides the problem, motivation, relevance and funding to the project. The student team spends more than 50% of their time during three quarters of a year in a project that is organized in four phases (C-D-I-O). Complimentary skills such as teamwork skills, project management, economy, language skills etc are interwoven in the project as each student receives two responsibilities, one related to the product and one related to the process. Student responsibilities are cycled in each phase, and after the nine months each student will have practiced skills in embedded systems technology as well as team management, teamwork etc. For more information about the KTH capstone course, see for example [6].

In an evaluation performed by KTH all graduated mechatronics/embedded systems students were asked which course taken at KTH that was most important to them in their professional career. An absolute majority of the former students considered the capstone course most important and useful [5].

B. *The lab in your pocket*

'The lab in your pocket' project was created to implement both an exemplifying selection and an interactive communication in a course in microcontroller technology. The basic ideas of 'the lab in your pocket' concept are the following:

1. Each student has constant access to his/her own set of laboratory equipment.
2. The laboratory equipment can be used at any location, at any time. The only requirement is access to an ordinary PC.
3. With the equipment, each student can perform all laboratory work within the course.
4. The equipment promotes open-ended solutions, meaning that all experiments are flexible enough to encourage creative solutions.
5. The total cost of all sets of equipment does not exceed the cost of the traditional laboratory facilities.

The laboratory equipment consists of one microcontroller, an Infineon C167CS, an I/O-board with a LCD-display, keyboard, buttons, LEDs, a DC motor etc as well as some sensors such as accelerometers and temperature sensors. Also, manuals, C-compilers and examples are provided for all students.

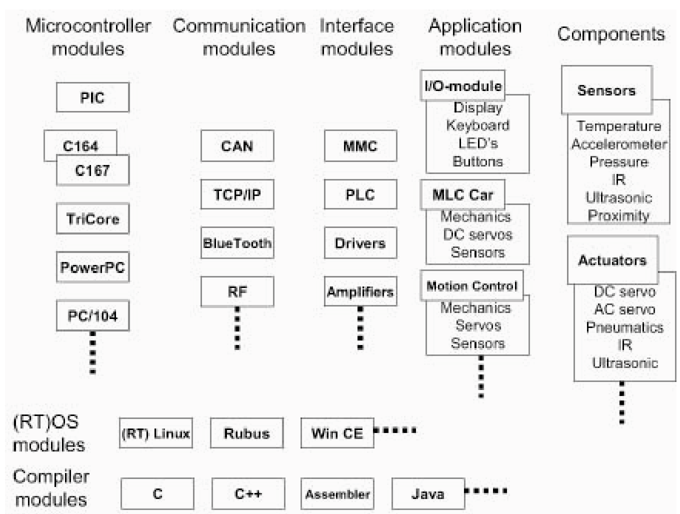

Fig. 4. The Mechatronic Learning Concept, as developed by KTH. Modules for the 'Lab in your pocket' is chosen from these.

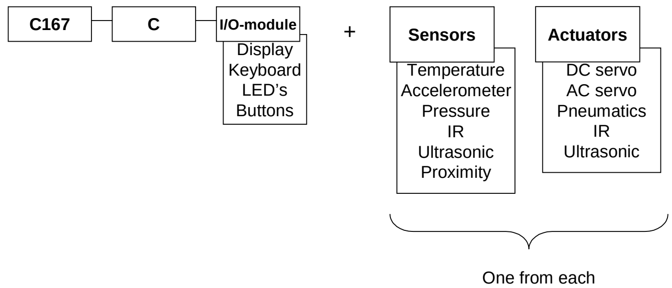

Fig. 5. The modules used in the 'Lab in your pocket'

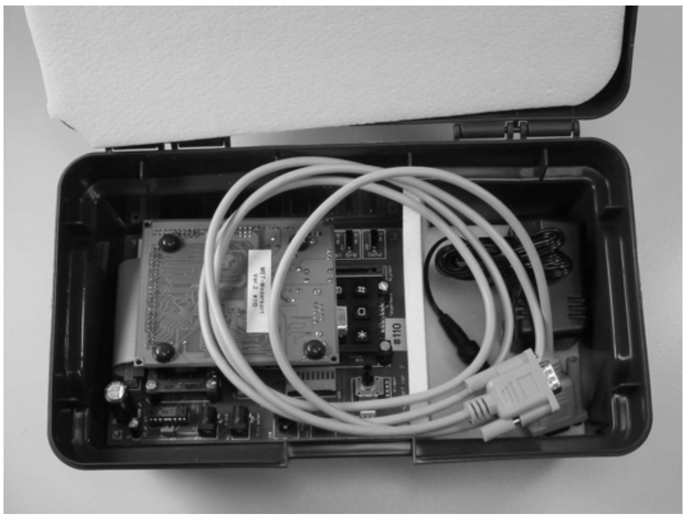

Fig. 6. One set of the 'Lab in your pocket'

In an evaluation of this project we found that the participating students received considerably higher grades, that the students spent considerably more time on experimental work, and that the faculty spent considerably less time on supervision, all this as compared to a traditional experimental course [7]. As a consequence, the total course cost for the university was reduced, again as compared to the traditional course.

C. *Results from project 'Lab in your pocket'*

For an evaluation 30 students constituting a focus group answered a set of questionnaires, and a selection of ten students was selected for interviews. In these questionnaires and interviews the students were asked to describe their approaches towards the experimental work; when, where and how the exercises and projects were done, the overall attitude towards the concept, how much time spent experimenting etc. Another comparison was made between the focus group and the reference group regarding the grades of the projects, the delivery time of the project results, and the overall view of the course. These results can be summarized into the following:

1. Overall course attitudes
    a. The focus group appreciated the exercises, the project and the teachers considerably more than the reference group (grade 4,4[1] compared to grade 3,8)
    b. The focus group attended fewer lectures than the reference group (53% compared to 68%)
    c. The focus group attended more exercises than the reference group (87% compared to 80%)
2. Results of the experimental work
    a. The focus group received considerably higher grades on the projects than the reference group (grade 4,7 compared to 3,9)
    b. In the focus group, only 6% compared to 43% in the reference group chose the projects with the lowest grade. 79% of the focus group chose the highest grades compared to 32% in the reference group.
3. Non-quantified measurements[2]
    a. The average student in the focus group spent considerably more time doing experimental work than the average reference student. The reference group often worked against a deadline, while the focus group worked more spontaneous and at irregular hours.
    b. The faculty spent considerably less time supervising the focus group compared to the reference group. The reference group required constant supervision, while the focus group communicated via the educational web based platform, and collaboratively supported each other.
4. Economical results
    a. The cost of supervision can be reduced since the focus group required considerably less support from the faculty.

The cost of laboratory facilities can be reduced since the focus group did not require any facilities except the portable sets. In this experiment, the annual cost of keeping the laboratory exceeds the initial investment of portable sets.

D. *Education as preparation for future work on a global market*

The functional legitimacy gives at hand that the education ought to be a preparation for future work, and since most companies act on a global market there is a need to also encompass these global aspects into the education. In one example at KTH, this is done within a capstone course that is expanded to cover international aspects [8]. Several modes of international collaboration has been experimented with, either collaboration with a foreign corporate sponsor or collaboration with one or several international student teams.

Among other conclusions, the international collaboration in the studied capstone courses promoted [6]:

1. Improved disciplinary learning and other skills. The international collaboration creates access to

[1] The grades vary from 1 (really bad) to 5 (excellent)

[2] This data is based on the students' own estimates, gathered in interviews.

more resources and gives new and different perspectives to problems. The collaboration also promotes general skills such as teamwork, team management and presentation techniques.

2. Awareness of cultural differences and different educational systems. The collaboration promotes this awareness, which is an important competence in a future career in a global company.
3. Enhanced motivation. The international collaboration itself is seen by several students as an interesting challenge.

In the above, examples can be found of functional legitimacy related to both the subject of embedded systems as well as to general skills related to working in a global company.

IV. Conclusions

The purpose of this paper is to argue for a view on embedded systems education where the results of the didactical analysis are put into focus. Embedded systems, in Sweden, is a subject with a thematic identity and a functional legitimacy, which means that the embedded systems companies are requesting engineers capable of conceiving, designing, implementing and operating embedded systems. The main idea of the didactical approach is not to specify a certain curriculum or a number of courses, but to start with the functionality – to agree upon the idea of primarily educating engineers capable of this rather than engineers with a certain number of credits in a certain number of courses.

Three examples are given from embedded systems education at KTH in Sweden, where the ambition has been to build on the foundation of this thematic identity and functional legitimacy, to create courses with a exemplifying selection and an interactive communication, meaning that the students should learn 'everything of something', with an experimental approach, or in a problem-oriented and project-organized setting.

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