# Experiences from large embedded systems development projects in education, involving industry and research


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**ABSTRACT**: We present experiences from a final year M.Sc. course. The overall aim of the course is to provide knowledge and skills to develop products in small or large development teams. The course is implemented in terms of large projects in cooperation with external partners, in which the students, based on a product specification, apply and integrate their accumulated knowledge in the development of a prototype. This course, which has been running and further elaborated for 20 years, has been proven successful in terms of being appreciated by the students and by the external partners. The course has during the recent years more frequently been carried out in close connection to research groups. Our experiences indicate benefits by carrying out these types of large projects in an educational setting, with external partners as project providers, and in close cooperation with research groups.

Having external partners as project providers feeds the course, students and faculty with many industrially relevant problems that are useful for motivational purposes, and in other courses for exemplification and for case studies in research. Carrying out the projects in close connection to research groups provides synergy between research and education, and can improve the academic level of the projects. A further interesting dimension is accomplished when the projects run in iterations, requiring new groups of students to take over an already partly developed complex system, and work incrementally on this system. The students are then faced with a very typical industrial situation. We advocate that students should be exposed to a mixture of “build from scratch” and “incremental” projects during the education.


## 1. INTRODUCTION

### 1.1 Challenges for Embedded Systems Education and paper outline

The industrial globalization and the competitiveness made possible by embedded systems based products, makes it more important than ever for the educational systems to provide society with competent engineers in the area of embedded systems. However, accomplishing this is a highly challenging task.

The technology and products of the area are evolving rapidly, with products broadening from simple stand-alone measurement/-controlling devices to systems that are internally distributed and also increasingly connected to other devices and users over wired and wireless communication links. The services of the systems are also evolving to include advanced and autonomous functions. The resulting products and systems are as a consequence becoming more complex. The increasing complexity requires that a systems engineering approach is adopted for successful product development, an approach that emphasizes several dimensions including product architecture, enterprise organization and processes. Due to the relative novelty of embedded systems, there is also no established science for embedded systems nor documented pedagogical methods for educating embedded systems engineers. The wide variety of types of embedded systems, with different quality requirements, technologies, and multiple design dimensions and parameters, makes it difficult to agree on a suitable definition on what an embedded system is and how to teach it in a suitable way, (see for example [6]).

At the first Workshop on Embedded Systems Education in Jersey City, U.S., in 2005, two directions and ways to approach embedded systems education were identified:

- *Scientific foundation approach*. In this approach, presented by for example [11], it is suggested that the education has the aim to teach engineering knowledge that lies at the core of embedded systems, including issues such as models of computation and formal analysis.

- *Product development approach*. In this approach, presented by for example [4], the education has many ingredients that are corresponding to industrial product development including project oriented work, team work and problem solving manifesting in a functional prototype.

We consider these two approaches to be complementary, where the former emphasizes knowledge in science and technology, and where the latter provides knowledge and competence in actual system development where several processes and product development activities, as well as team work are central.

The product development approach clearly relies on knowledge acquired in earlier courses such as in mathematics, automatic control, computer science and mechanics.

In this paper we elaborate further on education following the product development approach and focus in particular on a larger project oriented course which is introduced in Section 1.2. In Section 2 we give examples of course instances and in Section 3 discuss experiences from this type of courses from several different viewpoints.. Finally, we conclude in Section 4 by discussing how we would like to further evolve these types of courses and exploit the concept throughout the engineering education.

## 1.2 Project courses in Mechatronics and the capstone course

In this paper the main emphasis is on a capstone course given by the Division of Mechatronics at the Department of Machine Design at KTH. This course, entitled “Advanced course in Mechatronics” (course no: 4F1161, 22,5 ECTS credits), involves a project with a nominal effort corresponding to 60% full time studies over one full semester. The division of Mechatronics at KTH has been conducting such courses since 1984. The overall aim of the course is as follows:

*After the course the student will have knowledge and skills to develop mechatronic products in small or large development teams.*

The underlying motivation for the course is based on the fact that the development of complex/advanced products including embedded systems requires an understanding of the problems involved in the corresponding complex development projects. Thus, apart from specific tasks such as design of mechanics, software, control systems and electronics, central ingredients of the course include requirements engineering, systems architecting and integration, risk management, time and resource planning, interactions within the project team, and with suppliers and the task provider.

The hypothesis behind the course goal is consequently that the corresponding knowledge and skills are best acquired by actually having the students be part of real development projects (before the capstone course, the students have participated in courses which involved smaller projects).

This hypothesis is supported by research on problem based education [2][4][10][13].

Another motivation is provided by Grimheden and Törngren, [6]. Based on the “didactical analysis” they conclude that the subject of embedded systems has a thematic identity and a functional legitimacy, which implies that an exemplifying educational method is preferable, in an interactive setting. An exemplifying selection is facilitated by a problem based setting; each course is built upon a project, the design of a product or a system, for example a control system of an autonomous robot. The functional legitimacy is facilitated by a project organization and problem based setting as well, each student is responsible for the design of a subsystem and will, during a number of projects, acquire a certain set of skills such as project work and administration, PCB design, implementation of control algorithms etc. The motivational factor is further increased by giving the students a high degree of economical responsibility in the projects and by carrying out the projects in collaboration with industry.

Embedded systems typically represent the core enabling technology in the products that are developed. The projects are multi-technological since they also most often involve mechanical design/packaging, sensing and actuating technologies. The main emphasis in the course, however, is on product development.

In the capstone course, the projects are organized as development projects typically resulting in a functional prototype.

The guiding principles for these projects are as follows:

- Students manage the project and take own responsibility as far as possible. Students also manage contacts with industrial partners, suppliers and external contacts.
- During the project, rotation of responsibilities among students takes place in terms of management and technical work roles.
- The educational goal has priority during the project, but has to be balanced with the project/prototype goal
- The project is coached by one to two persons from the academic staff. The role of the coaches is further discussed in Section 3.

It is considered preferable that the project provider is external to the University, since this by experience provides realistic problems and also separates the roles of task provisioning and task coaching/supervision (and examination).

Because of an increasing number of students over the years, starting with about 10 participants in 1984 and with about 40 in 2006, the students are divided into several projects. In 2006 for example, the course was divided into four projects, each coached by one to two faculty members, and each with an external project provider. Complementing the project, there are also parallel common activities which include joint teaching, seminars, and social activities. These activities take place across the projects.

The capstone course, as well as other courses given by the Division of Mechatronics, are currently taken primarily by students from the programs of Mechanical Engineering, Vehicle Engineering, and Industrial Engineering and Management.

Earlier experiences from these courses have been reported in a number of previous publications; see for example [4], [5], [6].

Over the years, more than 50 projects have been performed, see Table 1 for a list of example projects.

**Table 1. Example of capstone course projects, 1984 - 2006**

| Project | Task | Provider (main) |
|---|---|---|
| SAINT1+2 | Automotive software configuration and platforms | Scania / KTH |
| Mucca | Cow milking robot | De Laval |
| FAR | X-by-wire architectures and model based development | Volvo Car Corporation / KTH |
| WARP | Four-legged robot and its control system | KTH researchers |
| Xless | Wireless communication in train distributed control systems | Adtranz |
| Agilis | Fuel-efficient car | Shell-Eco Marathon |
| Balance | Prosthesis and aid for human balance control | Boston University / Harvard Medical School |
| PBLX | Reduction of wiring in cars | General Motors |

## 2. Example course project instances

## 2.1 FAR

In 2002, 30 students specialized in Mechatronics at KTH. Three projects were defined as part of the capstone course, one of them being the FAR project.

The overall purpose of the project was to demonstrate a suitable tool-chain environment, based on adapted existing environments, that supported model based development of embedded control systems and in particular Function and ARrchitecture (FAR) integration. As part of the project, a model X-by-wire car demonstrator and its distributed control system were developed. The project was formulated in close connection to ongoing research projects at KTH, Chalmers and Volvo Car Corporation (VCC). The overall budget for the project was limited to approx. 40k€ which should cover all material and software development costs. KTH and VCC financed academic and industrial staff.

10 students were selected for the FAR project. The project was coached from KTH by one PhD student and one senior faculty member. One research engineer at VCC was responsible for the specifications and contacts with the project team at KTH. In addition, an M.Sc. project involving two students at Chalmers was connected to the project by developing an alternative human machine interface. The project started in November 2002 and ended in June 2003. At the project end the final demonstrator was delivered to VCC (the normal procedure in these courses is to develop a prototype that is handed over to the project provider.

The project adopted a four stage development process. In the initial phase the goals and constraints (e.g. budget and timing) of the project were identified and assessed. Available technology was studied to get input to feasible solutions. The choices of technology and tools were to a large extent limited by the budget and availability of technology. Project as well as product risk analysis were performed throughout the project. An example of the relevance of this is as follows. In the middle of the project, the team faced the challenge to change the networking technology because of an agreement problem with one technology provider. The project team managed in the short time available to change technology. The system specification phase addressed overall solution approaches and structures for functionality, mechanics and electronics hardware were developed. The final phases of the project focused on module development and step-wise integration.

Competition model cars were used as a basis for a mechanical re-design where the individual wheel steering, braking and driving required special attention. The car can be programmed into several modes of operation including manual driving, cruise control and with a simplified collision avoidance functionality. Figure 1 illustrates the hardware components of the demonstrator.

### 2.1.1 *Experiences from the FAR project*

The FAR project indicated the advantages of running this type of student project in close connection to research. The project was one of the first (if not the first) in the world to deploy a TT-CAN network inside a (model) car. The result provided a useful case study in complex systems development, for example adopted in the EAST-EAA project to evaluate modeling concepts for automotive embedded systems, [9].

The software architecture, illustrated in Figure 2, and development approach were seen as quite promising in that it combined component based and model based development with support for distributed systems through the global TT-CAN based clock and the off-line scheduling facility in the Rubus RTOS, [12]. The demonstrator vehicle is still in use at VCC for work on dependable embedded system platforms, see e.g. [7].

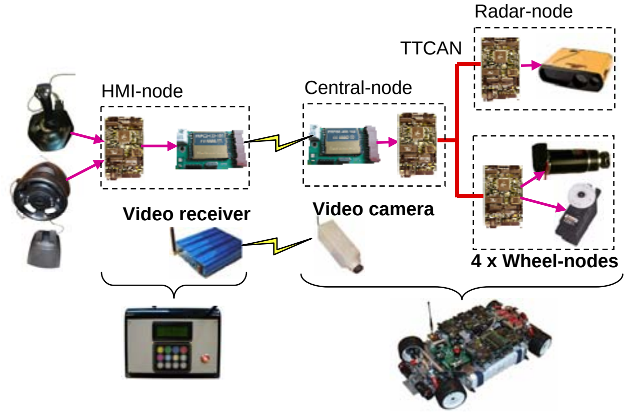


**Figure 1. Hardware part of the FAR demonstrator, illustrating its distributed control system, where the nodes on the vehicle are connected through a TT-CAN network.**

The students responded positively to the project and the experiences it conveyed. The students however also remarked that the workload and goals of the project were set too high. It became clear that the project had a too large scope to meet all the goals set out in the beginning. Although a model car was successfully developed, the desired application level functionality, e.g. collision avoidance could only be rudimentary completed within the duration of the student project. Also, the tool-chain to support distributed control systems development could only partly be tested.

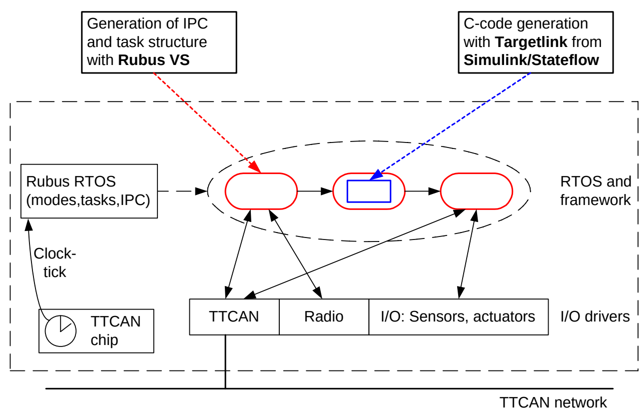


**Figure 2. Software architecture of the FAR demonstrator illustrating separation of concerns between application functionality and the platform.**

These limitations were largely dependent on the limited duration and resources of this project. Given a larger student group, or increased participation of researchers, would have made it possible to push the results somewhat further. Another idea is that of working incrementally on the demonstrator, this gave rise to an idea forming the basis for the SAINT projects.

## 2.2 SAINT1 and SAINT2

The SAINT (Self Adaptive INTelligent truck) project was formulated with a basis in a joint research project between the industrial partner Scania and KTH, and with the experiences of the FAR project in mind. The development of a common demonstrator was of joint interest. It was early decided that the demonstrator and its environments would remain at KTH after development. The budget was limited to approx. 30k€.

The research topics initially considered for study with the demonstrator included function and software configuration, and software platforms/architecture. Whereas modular development of mechanical systems, such as trucks, is rather well studied and supported by established Product Data Management (PDM) tools, the same is not true for software. A current problem in the automotive industry is to fit software efficiently into the product structure and thereby deal with variants and configuration of the EE (Electrical/Electronic)-system. To better support design, reuse and maintenance, there is a need to manage not only hardware and binaries corresponding to software. Traceability of software code, design and analysis models, as well as to requirements becomes increasingly important along with the increasing complexity, [8].

The main purposes of the project included to:

- develop a truck model including its distributed control system
- evaluate the use of PDM tools for function and software configuration, mainly for the production process
- develop a prototype software platform supporting location transparent execution.

The intention was to perform the development over a longer period of time and connect it to the research at the Department. This also turned out to be possible, resulting so far in two subsequent student projects where the second one took over a partially completed demonstrator and finalized its development. The two subprojects are now briefly described.

### *2.2.1 The SAINT1 project*

In 2004, there were 40 students specializing in Mechatronics at KTH. Four projects were defined as part of the capstone course, one of them being the SAINT1 project. 16 students were selected for SAINT1. The project was coached by two faculty members and one industrial PhD student with Scania/KTH.

Given the large scope of the project, the coaches spent quite some time in preparing and evaluating the PDM system such that it could easier be used by the students. The students were also helped in starting to use UML for function modeling, primarily using activity diagrams. Nevertheless the students were faced with the challenging task to develop the mechanics, electronics, software, functions and adapting the tool environment.

The results of the SAINT1 project were quite satisfactory. The truck and its control system, together with a middleware based on the ENEA OSE RTOS were developed together with basic functions. It was demonstrated that the chosen PDM system was adequate for software configuration purposes. In addition, the complete truck was made operational, [3]. See Figure 3 for an overview of the truck.

However, due to the time limitation only basic functionality and one simpler configuration scheme was possible to develop.

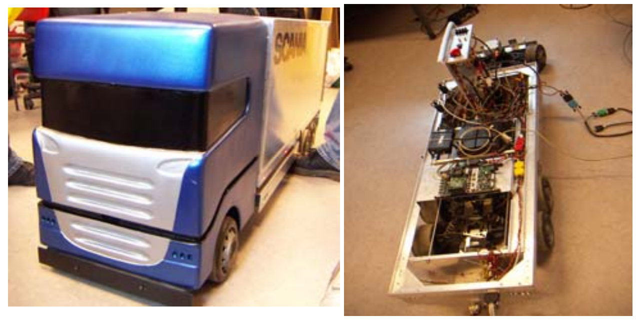

**Figure 3. The SAINT demonstrator after the SAINT2 project. (left), built in scale 1:6, and under the hood (right), including eight microprocessors, CAN networks, electrical motors, laser and ultra-sonic sensors.**

Given this situation and the willingness to continue the project, SAINT2 was formulated.

### *2.2.2 The SAINT2 project*

The goals for the SAINT2 project were essentially to develop more advanced vehicle functions and a more elaborated function/software configuration scheme (essentially those tasks that were not finalized in SAINT1). It was decided to focus on longitudinal motion control and active safety functions including cruise control, adaptive cruise control, anti-spin, emergency brake and collision avoidance. For the configuration, the goal was to be able to perform a complete function/software configuration connected to the PDM database, upon which a software tool automatically would select the appropriate software, allocate it to control units, and then build and download the software for flashing to the appropriate units.

Six students, out of 24 students during the capstone course in 2005, were selected for the SAINT2 project which was coached by one faculty member and one PhD student, in cooperation with Scania. The relatively small number of students was due to the fact that the course that year had fewer students than usual, but still had four projects competing for students.

The results of the project were very encouraging. With the second iteration, a demonstrator including the vehicle and its configuration environment was achieved. Moreover, the educational goals were met and the demonstrator development gave rise to a multitude of new ideas for further exploration.

### *2.2.3 Experiences from the SAINT projects*

In terms of education, the main novelty of the SAINT projects was to perform the projects in an incremental fashion.

When the SAINT2 project idea was first presented there was some initial hesitation. For some of the students the project appeared less interesting because the construction of a mechatronic device including mechanics, electronics and software was already to a large extent accomplished in SAINT1. An earlier negative experience in running a capstone project in two consecutive years with the same external partner resulted in some hesitation from other faculty members. The results of the SAINT2 project clearly indicate the potential of incremental projects. From an educational viewpoint the results were very satisfactory. The students at the beginning of the project faced huge amounts of (not always up to date and consistent) documentation and quickly learnt the value of documentation. The students were faced with multiple subsystems, components, functions and development tools which they had to learn how to use. This was a great challenge and it was not until after approximately 50% of the project time that the students gained control of the project. This experience was in addition to welll known problems of stabilizing and agreeing on the requirements and goals of the project.

However, having crossed this “take-over” barrier, the project team could build upon the already developed platforms – many of which proved possible to build further upon. As a consequence, it was possible in a few months time to develop examples of advanced functionality and to greatly enhance the configuration environment. As a side effect, the complexity of the demonstrator quickly increased due to the more advanced distributed control functions. Although the coaches knew this in advance, the functionality given the support from the existing platforms including the middleware grew faster than they anticipated, resulting in difficulties in distributed systems debugging (feature interaction and multiple fault sources). This turned out to be a good educational experience although it somewhat hampered the completion of the demonstrator. These problems can be alleviated with better support tools for development and debugging.

The external partner acknowledged these experiences as a suitable introduction to real-world engineering. In addition, the project provided technical feedback to the external partner regarding the particular technologies (PDM tools, RTOS, networking tools etc.) used.

The SAINT projects were conduced in close connection to research at KTH. This had the benefits of strongly motivating research personnel at KTH to participate in the teaching activities. As compared to the FAR project, more effort was spent on preparing tool environments for the students. The experience is that this was necessary for the success of the project.

In the SAINT2 project, a PhD student was involved also as subsystem supplier for the project. From the point of view of the project, the involvement of a researcher in the development work was easy to motivate with the small project team. The integration of the subsystem was successful and the example indicates a way in which PhD students, and teams of students, usefully can be part of the same project.

A continuation, in terms of a third SAINT student project is being planned. SAINT is also considered as a strong candidate for case studies and demonstrators in several ongoing research projects.

## 2.3 Boston balance projects

The Boston balance projects are examples of a capstone course project performed in an international setting, with a large number of spin-off projects and products. The original project was formulated in 2001 between KTH and two partner universities in Boston; the Neuromuscular Research Center (NMRC) at Boston University and the Massachusetts Eye and Ear Infirmary (MEEI) at Harvard Medical School. The project attracted twelve KTH students, two KTH faculty members, or coaches, and two Boston faculty members plus a number of Boston students, associates and corporate liaisons from interested companies.

The goal of the Balance project was to develop a prosthesis for use with people with a balance disorder, either relating to a malfunctioning balance organ in the inner ear or loss of sensory impressions from the soles of the feet. Both NMRC and MEEI had rudimentary prototypes realizing aspects of the prosthesis, and the aim of the capstone course project was to integrate these ideas and produce a wearable prototype.

Both NMRC and MEEI perform research in the area of balance prosthesis but had not before collaborated in this sense, neither had access to development resources capable of developing advanced prototypes. The aim of the prosthesis was therefore mainly to enable research on algorithms for balance control as well as feedback signals, sensors and filtering techniques.

The students developed a prototype based on five distributed microcontrollers, 72 actuators, 18 pressure sensors, accelerometers, gyros and CAN communication. The project was organized in four phases, each ending with a cross-atlantic trip – either to discuss ideas or to present results.

After delivery of the prototype, both collaborating institutes continued to use and perform research on the new device.

### *2.3.1 Spin-off projects*

During the four years that has passed since project delivery, a constant collaboration between KTH and NMRC and/or MEEI has been maintained. Usually in the form of KTH students performing M.Sc. projects at one of the partner institutes, but NMRC/MEEI has also hired a number of current and former KTH students for work for between a few weeks up to three years, and academic staff from KTH has also spent sabbaticals at NMRC/MEEI. The balance prosthesis is therefore constantly further developed, and the high level of competence is maintained at both NMRC/MEEI and KTH to enable supervision of new projects. Currently there are even discussions on establishing a KTH center in Boston, to provide a base and permanent accommodation for visiting KTH students and faculty.

### *2.3.2 Experiences from the balance projects*

The five years of collaboration have provided a win-win setting for all partners. The M.Sc. thesis projects offered to the KTH students are highly attractive, both since those enable the students to study in the U.S., but primarily since all projects are highly product development oriented and mostly incremental, and since high competence in the area exists both at KTH and with the partners. Each new student develops an aspect, a new module or a new function for a system that is thoroughly documented.

The partner institutes benefits greatly from being able to both receive skilled students capable of directly contributing, but also from being able to hire professional staff skilled in the area of balance prostheses. Several students so far have been offered a full time job at one of the institutes.

# 3. Experiences from the capstone course

The capstone course has largely been a successful activity. Key factors in accomplishing a successful course and education scheme include the selection/specification of an appropriate project and to have well motivated stake-holders involved in the project (students, coaches and the project providers). Given a well motivated project provider that has sufficient resources and time for the project, often ensures that the students become motivated.

In general, the course is well received by the students. In one evaluation all students that graduated between 1984 and 1994 were asked to specify which courses in their engineering education that they considered most valuable based on their current work as (Mechatronics) engineers. The answer was that the capstone course was deemed as the most valuable course. This is probably related to the fact that the students in the capstone course are both expected to take a large responsibility themselves, but also to the idea that students are expected to utilize knowledge and skills from previous courses rather than being taught new areas – so the course cannot realistically be compared to previous courses in terms of usability.

The course is also well received by the external partners providing the projects. For the Swedish industry, the project courses are seen as a means for recruitment, connection with academic research, and as a means to obtain resources for (cheap) prototype development. Many of the prototypes developed in all the course instances are still in use, including the examples mentioned in Section 2.

However, some projects and course instances have also been less successful and there is still room for improving the course concepts. One important point for improvement has to do with team work related aspects; the objectives for the capstone course state that this should be covered within the content of the course. We have from our experiences found that, with our strong technical background and educational traditions, it is sometimes hard to provide sufficient support for the students to cope with such things as time and resource planning and effective management of the teams.

In this section we first present some general prerequisites and experiences with respect to successful project course implementation. Section 3.2 then discusses the connections to research and use of incremental projects.

## 3.1 General experiences and prerequisites

There are a number of issues that have a large impact on and influence the outcome of the mentioned type of project-oriented courses. We here discuss a selection of these (the reader is referred to [4] for more detail).

### *3.1.1 Conflicting goals: Prototype vs. education*

In basically all projects the coaches and students experience conflicting goals. Typically at the end of the project, students are eager to put more emphasis on the project goals than the educational goals. A typical example would be that, in a critical moment, the task of finalizing the software is given to the student most experienced in programming – not the student most in need of programming practice. However, project progress also motivates the educational goals. A focus on project goals helps motivate students, which then become more easily subjected to learning. The key is therefore to manage the balance between keeping a constant development pace in the project, but also by having all students subjected to exposure from unfamiliar areas and making sure that all students get enough time to learn, reflect and practice new ideas. Team management is therefore crucial, which requires a skilled coach.

As in all projects, the balance between the project goals, the available time and project resources (personnel, budget and technology) is central. It is important that projects with appropriate size and goals are defined. In case the scope is too large, the goals have to be redefined during the project. It is then very important that it is possible for the current group of students to be able to accomplish a meaningful deliverable, e.g. a demonstrator with partial functionality. The corresponding prototype development could continue after the finalization of the project.

### *3.1.2 Homogeneity/heterogeneity and sizes of groups*

Embedded systems course projects are facilitated by, and benefit from, diversity and heterogeneity. This is due to the fact that the students both learn from each others experiences and mainly from the larger number of courses and areas covered by the students combined backgrounds. The KTH projects usually attract students from at least three different M.Sc. programs which together with exchange students usually provide expertise in most covered areas. When creating the teams, a large effort is also made on gender and cultural diversity.

The size of the groups has varied from six to sixteen during the last few years, depending on both the total number of students and the scope of the projects. A large number of students usually requires a more experienced and skilled coach/supervisor, but from experience a small team might also develop conflicts and could require large supervisory resources. A larger team though gives the possibility to introduce sub-teams which could be rotated and changed periodically, which from a supervisory point of view makes the larger team advantageous, even if a small team on some occasions might manage so well on it's own that supervision is superfluous.

### *3.1.3 Team work challenges*

We believe that one of the major challenges is to find a balance between providing the students with knowledge and capabilities about managing an R&D team at the same time as providing them with an environment which fosters sophisticated technical development. In this context we believe that we can learn from the approach and experiences taken in education in Integrated product development [14] which origins from a mechanical engineering tradition. Education in Integrated product development has had a greater focus on work processes, cross-functional teams, and design methodologies than current education in Embedded systems. Since few products nowadays exclude embedded systems and a need to provide the students with more interpersonal and managerial skills have been identified throughout our course, it is well motivated to seek new impressions from neighboring engineering educations.

One Systems engineering principle is the organizational practices which are needed to successfully reach the product development objectives. Since our capstone project currently is one of the last activities and courses (before the student's Master thesis projects) in which the students are engaged, we believe that it is important to prepare them both technically but also organization-wise for their oncoming careers working in complex product development organizations. The ability to understand how the organizational perspective positively relates to the product development performance has been pushed forward by many scholars [17], and the use of cross-functional teams in industrial operations is today rather established.

We believe that by training the students to act in different types of cross-functional teams, such as systems engineering teams, integration teams, integrated product development teams, and product development teams (the reader is referred to [15] for further details on the notion of the different types of teams), will increase their ability to understand what part they play in the complex system, and how they are perceived by other system members. This aspect has been shown to be critical in complex product development [16]. In addition they need an understanding of the whole system and its subsystems and where in the organization they belong and how they are interrelated to other system members.

Due to the rather large projects groups we have an excellent opportunity to address this topic. One way to accomplish this is to have an obligatory re-organization of the project halfway into the projects timeframe, forcing the students to take on a new and different role compared to the first half. This may be counterproductive to the project goal, but we believe that it is very effective in reaching our educational goals of increasing the student's capabilities of acting in complex product development settings.

At the Royal Institute of Technology, education in Integrated product development has from the very beginning had a close collaboration with behavioral scientists in developing and executing the curricula [13]. With their help a rigid support for the student in coping with work group dynamics and the different phases a group experiences have been acquired. The belief is also that the student's ability to build strong teams is enhanced, teams which still endures when internal conflicts arise. This is probably one of the greatest challenges we can identify for embedded systems education, since it is inherently a team work which experiences time, resource and not the least psychological stress during the different phases of the capstone projects. So therefore we encourage the Embedded systems education community to enter new territories by seeking collaboration

### *3.1.4 International projects*

One of the three projects described in Section 2 was performed in an international setting. Currently, the aim is to have at least one project every year, either in collaboration with a foreign university of with a foreign corporate sponsor. The purpose is to educate Mechatronics engineers for the future market; as of today an increasing number of Swedish companies hiring Mechatronics engineers are working on a global market. Engineers thus have an advantage with project work experiences involving an international setting.

The usual method to reach these aims is to spend some time abroad: as exchange student, in an exchange project or to perform a Master's thesis project abroad. In this context however, the capstone course project aims at giving all participating students a similar experience, but without the need to travel.

The international projects have proven to be successful but simultaneously require considerable more resources in terms of coaching, equipment and financing [4]. The projects usually benefit from travels and international meetings, and equipment such as videoconference technology is necessary.

### *3.1.5 Coaching*

Seen historically, faculty supervision has been replaced by team coaching. This is primarily an effect of a larger transformation of higher education: from faculty teaching to student learning, from university- to student responsibility, from lecturing to problem based learning [2]. Coaching means guidance rather than directing, helping rather than telling and basically making the individual student perform at his or her best.

The coach act as mediator between the faculty and the student team, provides resources and directs students towards appropriate faculty experts. A highly valuable property of the coach is his/her previous experience of product development projects and the ability to manage the team in the different phases of the project. As described in Section 3.1.1, the most difficult task of the coach is to balance between the project aims and the educational aims.

At the Division of Mechatronics at KTH, most PhD students and faculty members have acted as coaches at one time or another, but the experience is that this coaching requires much more effort and consideration than what is apparent, and requires industrial experience and years of training and apprenticeship to master.

### *3.1.6 Grading*

Grading is currently subjected to change at KTH, depending on the adaptation process toward the common European system. Previously, the students were basically only given grades of pass or fail, and only students dropping out failed. Today, grades on the ECTS scale, from A to F are given. A considerable amount of research has been performed in this area however, and the actual grading is not as difficult as to design educational aims for each grading level, and to communicate these to the students well in advance.

Some help can also be found in the continuous documentation and presentation processes as part of the project, which can be used as a platform for grading of the entire team. The most important aspect though is to have a continuous discussion between the students and the coach, about the intention of each student and the requirement asked by the faculty to reach the respective aims.

Usually, the process of grading is kept separate from the actual coaching. This has not been the case at KTH so far, but will most probably be adopted in the near future.

### *3.1.7 Course evaluation and evolution*

The number of students applying for the course increased in a rather linear fashion from 1984, with 12 students, until year 2000 with 40 students, and since then the student interest has decreased slightly every year. The same decreasing trend has been identified in most engineering programs in Sweden. Regarding course evaluations and regular improvement, conclusions are difficult to make since the course is heavily dependant on the industrial partner; the partner's area, engagement and the scope of the project. Our experience is also rather that course quality is more a matter of finding the right course coaches and assistants. In some cases, the projects have been closely related to research projects and successfully coached by doctoral students. This further motivates a stronger connection between research and capstone projects, thereby creating synergistic effects between researchers and student projects.

### *3.1.8 Industrial partner prerequisites*

Our experience from industrial partners vary from foreign to local partners, from one-man-companies to large global companies and from companies who show slight interest for either the process or the results to companies who participates daily in the educational activities. Our experience is that neither the locality nor the size of the company matters, neither the field of the company. What matters most is the engagement and interest of the company and primarily the corporate liaison. In many cases this person is a former student of the capstone course, which usually guarantees a good relationship. Of high importance is also the ability of the partner to provide funding for prototypes, tools etc as well as access to the companies own resources.

### *3.1.9 Student preparation*

As to student preparation and requirements, the discussion seems to be everlasting. On one side people advocate for more problem-based courses early on in the education, and on the other side people are considering that more focus on application and holistic courses will reduce the overall disciplinary content of the educational programs. It is obvious that a firm theoretical background is important and has to be established in the early university years. However, this does not exclude having problem-oriented courses as an important complement to provide a systems and synthesis perspective. Regarding the capstone course however, diversity is advantageous, advocating not for a single curriculum in embedded systems but rather that the capstone projects benefit greatly from accepting students with various backgrounds, courses and educational tracks.

## 3.2 Research connections and incremental projects

Over recent years we have noticed a synergetic effect when the projects are aligned or connected to research projects/themes. We have also noticed that incremental projects have a complementary nature as compared to projects that build from scratch.

### *3.2.1 Running the projects connected to academic research*

Aligning the projects with research themes and topics at KTH makes it easier to motivate and involve research staff and doctoral students in the projects. For the researchers a student project can provide extra resources in developing a research prototype. This also motivates extra work in preparing and participating in the project. For example, the SAINT capstone projects described in Section 2 were part of a larger research project where the involved researchers coached the project, assisted in setting up supporting tools, and also in developing the solutions.

We believe that such synergetic efforts can be very important today for the academic staff in view of the overloaded (extremely efficient) University system and to achieve efficient economy and resource utilization.

Connecting the capstone projects to research projects also ensures a connection to state of the art, which can improve the motivation for the students. From a methodological point of view, the research connection has two additional strong benefits:

- Involving researchers in the projects can assist in the adoption of a systematic approach in the development of complex products by e.g. use of systems engineering knowledge and embedded systems theory.
- For the researchers, the projects are an excellent opportunity to learn, and to apply theories on system development and research results on realistic systems. The projects and products developed can also be reused later in research for case studies and demonstration purposes.

As partly exemplified in Section 2, we have had projects that have been connected to external research projects (the Boston projects), cooperative research projects (e.g. SAINT) and internal research projects (e.g. WARP). It has been easier to ensure motivation and a separation of responsibilities when the project/task has been provided by an external partner.

Is there a risk of involving researchers too much in the projects? Similar to industrial prototype development, it is essential that the researchers have sufficiently clear ideas and plans for the research prototype to be developed before a project is started; this to avoid too large project risks. A complete prototype failure may jeopardize the educational goals. There could potentially be a risk of having the academic staff too much involved, but in our experience it has rather been the opposite way – we probably could have included the researchers even more.

### *3.2.2 Incremental projects*

In the examples presented in Section 2, advantages and disadvantages of both incremental and non-incremental projects are discussed. Non-incremental projects provide a strong incentive and satisfaction for the students where they, starting from scratch, end up with a working product. The incremental projects, on the other hand, provide the benefit of accomplishing a more complex and high quality prototype and meet the industrial need for this type of common development.

As with all development processes though, incremental product development fosters incremental innovation rather than radical innovation. One solution is to provide projects varying on the scale from radical to incremental and to clearly express the differences to the students prior to choosing projects.

# 4. CONCLUSIONS

This article puts forward a number of issues dealing with problem based learning in embedded systems education, and specifically in the setting of large capstone projects in collaboration with industry and academic research. The intention by the authors is to investigate and increase synergistic integration between academic research in collaboration with industry and engineering education and to describe and analyze the difficulties and possibilities.

The capstone course projects performed at KTH have varied from radical product development to incremental projects spanning over several years, and among our conclusions are the fact that the incremental projects have proved greatly beneficial in terms of synergy with academic research and long-time collaboration with industrial partners. Some students express initial concern at joining an incremental project rather than starting from scratch, but in the end consider the incremental project advantageous since this project usually contains increased complexity and more advanced applications. In accomplishing incremental projects there is the need for long term arrangements; this can be a challenge if the projects involve external partners. Although our experiences indicate a benefit with external providers of projects, the benefits of incremental projects may still be valid given internal project providers – this is a topic for further investigation.

In a way the project oriented courses, when they take place at the end of the education, act as a kind of exam where the student in their work will reveal what knowledge they really have acquired and are able to use in a concrete development project. This has given us some feedback for earlier courses we are providing, and is one track which could be of interest for further investigation. We believe that achieving synergy between research, education and industry will be of increasing importance for the academic system – and that this topic also deserves further investigation.

Finally, we advocate that students should be exposed to a mixture of build from scratch and incremental project, and that this type of problem based education should be adopted as one of the educational forms throughout the engineering education.

Finally, we must realize the importance of extending the Embedded systems curricula to include more softer skills (in complement to technical skills), since the product development approach we have taken on, explicitly requires team-based development activities. By doing this we believe that the students experiences a greater personal development, hence acquires a greater confident acting in a role as an Embedded systems engineer.

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## 6. REFERENCES


[1] ARTIST2: The European Network of Excellence on Embedded Systems Design. http://www.artist-embedded.org/FP6/ (accessed August 1, 2006).

[2] Barr, R. B., Tagg, J., A new paradigm for undergraduate education. Change, 27, **6**, 1995.

[3] Blixt D, Brikho S, Bråkenhielm E, Cedergren U, Cronebäck Ö, Edvinsson L, Eloranta T, Forsséll S, Hallberg M, Karlsson N, Olsson A, Rödén M, Steiner A, Wängdahl J, Öhlund D, Öhrvall M. 2005. Project SAINT, Technical Report TRITA-MMK 2005:26 ISSN 1400-1179. Royal Institute of Technology, KTH, Stockholm, June 2005. (In Swedish)

[4] Grimheden, M. Mechatronics Engineering Education, Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden. TRITA – MMK 2006:1, ISSN 1400-1179, 2006.

[5] Grimheden, M., Hanson M. Collaborative Learning in Mechatronics with Globally Distributed Teams. International Journal of Engineering Education, 19, **4**, 569-574. 2003.

[6] Grimheden M., Törngren M. What is embedded systems and how should it be taught? – Results from a didactical analysis. ACM Transactions on Embedded Computing Systems; Special Issue on Education, Vol. 4, Issue 3, August 2005.

[7] Johannessen, P. On the Design of Electrical Architectures for Safety-Critical Automotive Systems. PhD thesis, 2004. Diss. CPL 2334, Dept. of Computer Eng. Chalmers.University.

[8] Larses Ola. PhD Thesis. Architecting and Modeling Automotive Embedded Systems. Dept. of Machine Design, KTH, Stockholm. TRITA – MMK 2005:31, ISSN 1400-1179, ISRN/KTH/MMK/R-05/31-SE, Nov. 2005.

[9] Lönn H., Tripti S., Törngren M., Nolin M.. FAR EAST: Modeling an Automotive Software Architecture Using the EAST ADL. Workshop on Software Engineering for Automotive Systems, 26th Int. Conf. on Software Engineering, May 2004.

[10] Leifer, L., Design Team Performance: Metrics and the impact of technology. In: Brown, S. and Seidner, C. (eds), Evaluating Organizational Thinking. Kluwer, 1998.

[11] Pinto A. and Sangiovanni-Vincentelli A.. An overview of embedded system design education at Berkeley. ACM Trans. on Embedded Computing Systems (TECS); Special Issue on Education, Volume 4, Issue 3, August 2005.

[12] Törngren M., Adamsson N. and Johannessen P.. Lessons Learned from Model Based Development of a Distributed Embedded Automotive Control System. SAE World Congress, Detroit, 2004. SAE paper no. 2004-01-0713

[13] Vernon, D., Blake, R., Does problem-based learning work? A meta-analysis of evaluative research. Academic Medicine, 68(7), 550-563, 1993.

[14] Hagman, L., Norell, M., Ritzén, S. (2001) Teaching in Integrated Product Development - experiences from project based learning. Proceedings of the International Conference on Engineering Design, ICED 01, August 21-23, Glasgow, UK. ICED-2001Norell, M., Hagman, L. (1998) Integrated Product Development - in reflective education.Proceedings of NordDesign-98, Stockholm, Sweden.

[15] INCOSE (2004). INCOSE Systems engineering handbook. Version 2a.

[16] Adamsson, N. and D. Malvius (2005). Formal and informal roles in complex product development. Proceedings of the 2005 IEEE International Engineering Management Conference, St. Johns, Canada.

[17] Browning, T. R. (1998). "Integrative mechanisms for multiteam integration: findings from five case studies." Systems Engineering 1(2): 95-112.

[18] Browning, T. R. (1999). "Designing System Development Projects for Organizational Integration." Systems Engineering 2(4): 217-225.