Experiments with Embedded System Design at UMinho and AIT

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Abstract. Nowadays, embedded systems are central to modern life, mainly due to the scientific and technological advances of the last decades that started a new reality in which the embedded systems market has been growing steadily, along with a monthly or even weekly emergence of new products with different applications across several domains. This embedded system ubiquity was the drive for the following question " *Why should we focus on embedded systems design?*" that was answered in [1, 2] with the following points: (1) high and fast penetration in products and services due to the integration of networking, operating system and database capabilities, (2) very strategic field economically and (3) a new and relatively undefined subject in academic environment. Other adjacent questions have been raised such as " *Why is the design of embedded systems special?*". The answer for this last question is based mainly on several problems raised by the new technologies, such as the need for more human resources in specialized areas and high learning curve for system designers. As pointed in [1], these problems can prevent many companies from adopting these new technologies or force them not to respond timely in mastering these technological and market challenges. In this paper, it is described how staff at ESRG-UMinho[1] and ISE-AIT[2] faced the embedded systems challenges at several levels. It starts to describe the development of the educational context for the new technologies and show how our Integrated Master Curriculum in Industrial Electronics and Computer Engineering has been adapted to satisfy the needs of the major university customers, the industry.

1 Introduction

Embedded systems are vital to our own existence as can be proven by their widespread use in automative applications, home appliances, comfort and security systems, factory control systems, defense systems, and so on. This view is nowadays indiscriminately shared by everybody, mainly those who live in developed countries, as well as those that are in charge of developing such systems. Mr. Jerry Fiddler, Wind River Chairman and Co-Founder [3] said: " *We live in a*

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world today in which software plays a critical part. The most critical software is not running on large systems and PCs. Rather it runs inside the infrastructure and in the devices that we use every day. Our transportation, communications and energy systems won't work if the embedded software contained in our cars, phones, routers and power plants crashes". However, this wide diversity along with the increasing complexity due to the multi-disciplinary nature of products and services and heterogeneity of applied technologies demand changes in industrial practices and consequently ask for changes in the educational system. At ESRG-UMinho, the embedded system subject was first taught as a two-hour credit course to mainly promote education in robotic, automation and control. Therefore, it was viewed as an overview course (i.e., a backpack [4]) where students should be first introduced to the main concepts of embedded systems design that would later be combined to provide the embedded systems design big picture. The course was theoretical but due to the growing importance of embedded systems, it was promoted to two three-hour credit courses, allowing the introduction of lab sessions for hands-on activities. Three years ago, our diploma program was revised and the subject promoted to four three-hour courses under a new teaching and research specialization field denominated embedded systems. The embedded systems research group, ESRG-UMinho, was created and a discussion was held within the group to figure out how to attract and keep students in elective courses in embedded systems field. The general objectives should be: (1) exposing students to the industrial project environment of embedded systems design, (2) developing the capacity for teamwork, and (3) highlighting the need to be self-taught. The teaching approach to be followed were based on ideas presented in [1, 2] and was later reviewed overcome some issues faced in the first year. In the remainder of this paper, several questions will be answered, giving special focus on (1) why does the skill mismatch phenomenon exist and how to cope with it and (2) mainly how to drive the whole group in sync by keeping undergraduate and graduate students, teachers and researchers in flow and committed with the ESRG-UMinho vision and outcomes.

2 Embedded System Innovation and Trends

Basically, innovation is a continual process that leads to the introduction of something new and it is a key goal of industry. Apart from software and electronic (digital and analog) components, embedded systems also contain dedicated sensors and actuators, mechanical components, etc, constrained to the design challenges of space, power consumption, cost and weight. Essentially, they differ from the classical IT in several characteristics like [5]: autonomy, flexible networking, fault tolerance, restrictions on user interfaces, real time operation, reactivity, restricted resources, etc. The industry must support the emerging trends in embedded systems in order to stay competitive and among the major ones the following were observed [5]:

1. new generations of applications and products with increasing complexity and high demand for functional safety and security, as well as improved autonomy and usability, and interoperability in network;
2. increasing computational power of embedded processors combined with reduced silicon area and energy, as well as improvements in operating platforms and middleware support for efficient development of reliable systems;
3. new embedded system design methodologies to fill the HW-SW productivity gap, in order to match the software productivity to the speed of HW innovation;
4. merging of application sectors like electronics and IT or telecommunication and consumer electronics to provide multifunctional and more attractive products;
5. embedded systems designers are facing tight time-to-market constraints due to the cognitive complexity of current embedded systems, and so there is a need to balance time-to-market with the quality of the designed product.

To keep up with these trends, the industry is facing new issues and challenges in designing current embedded systems, such as, lifecycle mismatches, skill shortages, low reuse of components, quality concerns, and increased warranty costs [6].

3 Embedded System Challenges

Among the three driving forces of technological advance, Fig. 1, knowledge-push is, along with market-pull the most important. Market-pull is driven by the market and user need for a product and the technology is developed to fulfill that need, while the development of new technology must drive the creation of a business need. In between the technology-push and market-pull will be the knowledge-push, defined in [5] as the continuous application of new technologies to accelerate further technical innovations. However, as pointed also in [5], such continuous application of technologies will be valuable only if the market can create knowledge, share it among all market participants and transfer it into new products, processes and services.

The previously mentioned emerging trends in embedded systems led to several specific challenges for R&D and education in the domain of embedded systems [5–10] that can be grouped into the following three broad categories as pointed in [5]:

1. **Softwareization** to cope with the increasing product functionality and HW-SW productivity gap, by shifting functionalities from hardware to software. To meet this challenge, software engineering elements such as programming languages and compilers, modeling notations with good understanding of semantics, testing methods, and software design processes must be taken into account.

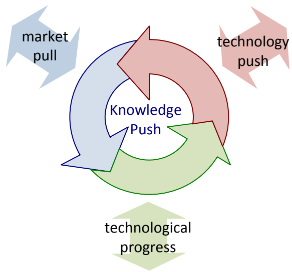

Fig. 1. Driving forces of technological progress

2. **Multi-functionality and flexibility** to deal with the integration of different knowledge fields, integration of hardware and software, knowledge transfer inside a company and among industry sectors, universities and R&D centers. Embedded systems engineers must present simultaneously a deep understanding of some knowledge fields and basic know-how from the other related fields.
3. **Change in innovation drivers** requires knowledge exchange, collaboration, standardization, as well as the incorporation of business aspects and soft skills into the embedded systems discipline. To meet this challenge a embedded engineer needs to master the ability to communicate, understand markets, develop products, and pursue lifelong learning.

4 Embedded System Curriculum

Embedded systems were defined in [5] as invisible computers or programmable electronic subsystems built-in a larger heterogeneous system that help to increase the ease and safety of our life and make our work interesting.

Embedded systems are virtually everywhere and such ubiquity along with the following evidences [2] legitimate them as a discipline of their own:

1. It is the field with the highest and fastest growth rate in industry;
2. It is a very strategic field from economic standpoint: (a) their market size is about 100 times the desktop market, (b) nearly 98% of all 32-bit microprocessors in use today around the world are incorporated in embedded systems and (c) in a near future, nearly 90% of all software will be for embedded systems, and most computing systems will be embedded systems and their importance will grow rapidly;
3. Design of embedded systems is a new and not well defined subject in academic environments [1] and the ”skill mismatch” phenomenon is visible, where the maturity levels of graduates’ skills in the academies don’t meet levels required by key industry sectors.

The "skill mismatch" does exist because embedded systems is a multidisciplinary curricula split into several application domains, and the university education fails to connect them. Coping with it requires completely new embedded systems education where new methodologies for designing embedded systems must be created, consolidated and the knowledge transferred effectively to future graduates. According to the didactic analysis presented in [1] and reinforced in [2], the discipline of embedded systems has a thematic identity and functional legitimacy and so, the academia must:

1. educate engineers with functional skills instead of solely formal knowledge, and find an effective balance between the two, as a high level of formal knowledge might also facilitate the development of new functional skills;
2. provide adequately trained multi-cultural engineers that integrate essential knowledge from computer science, electrical engineering, and computer engineering curricula to facilitate the communication and sharing of experiences inside a company and also avoid fragmented research.

Nowadays, several proposals for education models in the field of embedded systems are found worldwide [11]:

1. Courses on real-time systems in System Engineering and Computer Science undergraduate curricula;
2. Courses focus on embedded systems hardware in Computer Engineering and Electrical Engineering undergraduate curricula;
3. Courses on embedded system design in Computer Engineering, Computer Science, System Engineering and Electrical Engineering graduate curricula;
4. Embedded systems design track in computer science and electrical engineering department;
5. Continuing education and training programs for industrial engineers;
6. Undergraduate curricula in embedded systems engineering.

The first 3 models are used in Europe, the first 5 models in the United States and the sixth model in Asian countries [12–14]. Some universities in the United States [15], Canada [16] and Israel [17] started using the sixth model. A more extensive model for embedded systems field was presented in [18], as it seeks to induce higher interest in embedded systems concepts as early as middle school.

In our diploma program in Industrial Electronics and Computer Engineering, embedded systems education appears as an elective track (among other 3 specialization profiles) consisting of the courses represented by the gray-filled box, Fig. 2.

The courses represented by black-border boxes are taught by ESRG-UMinho teachers/researchers and we bridged them in a coordinated way in order to achieve the depth of embedded systems concepts. This year the diploma program was revised and the course *Advanced Processors Architecture* was included to improve the breadth of embedded systems concepts.

In terms of didactic analysis, a proposal to the "skill mismatch" resolution requires answers to the following questions:

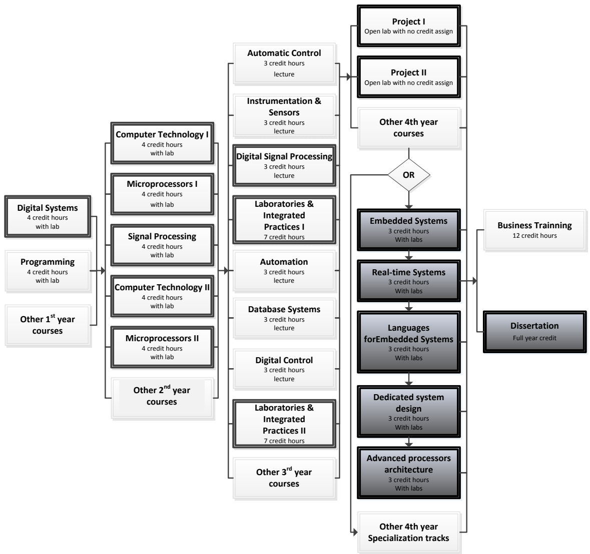

Fig. 2. Industrial Electronics and Computers Engineering course sequence

1. *What about the embedded systems selection?*
Our diploma program focused mainly on electronics and electrical engineering knowledge field, resulting in many engineers with insufficient software background required for embedded systems design. Although, embedded system designers need to handle both software and hardware, the software portion in a system is getting larger than hardware, and so, we must prepare our graduate to face the softwareization challenge. As it is nearly impossible to cover all knowledge fields into our course track in a way to provide students with in-depth understanding across several application domains, our proposal to the breadth and depth problem is to move from teaching "something of everything" toward "everything of something" [1]. Furthermore, at the same time, providing enough high level of formal knowledge to facilitate the development of new functional skills and reduce training in embedded development concepts, thus requiring only the specialization of other application domains. Our chosen "something" or application domain was home automation, the core business of one of our major industrial partners. As we have industrial partners with different core business, the lab sessions of courses like *Embedded Systems* and *Real-time Systems* don't focus in any specific application domain, trying to provide a broad education in embedded systems design. To promote depth to the learning approach, the idea of overlapping coverage using multiple courses with forward and backward references among the courses [15] is followed, providing a deeper understanding of the concepts and also knowledge retention to our students.As pointed

in [15], it will help break down stereotypes associated with hardware versus software engineers. Such significance of good programming and system specification skills will again be emphasized later when students attend the *Embedded Systems* and *Real-time Systems* courses that use reverse reference to the *Programming* and *Computer Technologies* courses.

2. *What about the embedded systems learning communication?*
   We promote an embedded systems education based on interactive communication with strong focus on real world examples and project-based works, to produce skilled graduates capable of engineering embedded systems as required by the hiring industry. Thus, embedded systems concepts are introduced in the course track and the prerequisite courses through lectures, hands-on sessions based on small examples and project-based sessions.
   Lecture sessions: the prerequisites courses provide basic knowledge underneath computer science and electrical engineering and the embedded systems course track provides the design and implementation principles of embedded systems.
   Small real-world examples hands-on sessions: students gain practical experience in programming embedded systems and designing hardware boards, using design tools, development environments and platform targets. Usually they consist of a mix of teaching styles, demonstrator to encourage student participations and facilitator to allow students to explore new options and encourage active and collaborative learning.
   Project-based sessions: students complete a project for a complex system in groups of 2-3 students to gain a better understanding of projects through collaborative efforts. Several home automation and digital security applications will be proposed and the students also have a choice to design and implement their own system.

The *Embedded System* course is a merging of the *ECE 125* course [15] and *Complex Systems Design Methodology* [4] and it was drafted to provide students with a broad overview of the embedded systems design and also to show how the synergistic combination of the broad set of knowledge fields will be explored through backward and forward references to other courses in the curriculum. The other three courses of the embedded systems course track, *Languages for Embedded Systems*, *Dedicated System Design* and *Advanced Processors Architecture* focus on more advanced embedded systems concepts like compiler, processor and System-On-Chip (SoC) design. They are based on a mix of lectures, small real-world examples hands-on and project-based sessions that end with the implementation of a SoC, a C compiler and Linux porting to the new developed platform. Unlike the undergraduate microcontroller-based design course track that strictly follows bottom-up design methodology, the graduate embedded systems course track focuses on high-level abstraction and top-down and bottom-up system-level design methodologies, starting with a knowledge about the system to be developed. All students are forced to always follow the same information flow during systems design, by first transforming the system knowledge into a specification model of the system.

5 Conclusions

The omnipresence of embedded systems altogether with "skill mismatch" phenomenon evince the need and urgency for an embedded systems education that produces skilled graduates capable of engineering embedded systems as required by the hiring industry. At UMinho an embedded systems design course track was designed and several techniques employed in order to fill the "skill mismatch" gap, and also align teaching and R&D activities. Among those techniques we'll emphasize the promotion of: depth to the learning approach by bridging all these courses together, design-for-reuse principles and system-level concepts early at the undergraduate microprocessor-based course track, embedded systems education based on interactive communication with strong focus on real world examples and project-based works, breadth to the learning approach by vertical exemplification teaching approach combined with enough high level of formal knowledge, procrastination avoidance, and integrated learning style but strongly based on kinesthetic learning style. Furthermore, we found the creation of a motivating environment with supportive and high performance culture in course classes and R&D activities are very important, as was visible during the three months staying at AIT where the twelve students were and still are completely in flow and committed with the group vision and outcomes. The assessment of our embedded systems design course track was very positive and manifested by (1) our internal evaluation process with questions to drive further course track improvement, (2) the performance of student coaching lab sessions at UMinho and AIT, (3) the willingness of students to buy their own microprocessor and FPGA boards, (4) the way older students sell ESRG brand, and (5) the increasing number of students attending the elective embedded systems design course track year after year.

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