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Using Professional Resources for Teaching Embedded SW Development

Hector Posadas and Eugenio Villar, *Member, IEEE*

Abstract—In order to prepare the students for their future professional performance, it is necessary to propose complex and realistic practical activities. However, in order to be carried out, this kind of activities typically requires a considerable amount of time, resources, and collateral knowledge. To overcome these difficulties, this paper presents a subject in a Telecommunication Engineering Degree, taught making use of different professional materials. By using these materials, it is easier to transmit information to the students through case-study methodologies. In addition, their use simplifies the preparation of problems and complex projects without generating the perception that the problems proposed are mostly resolved thanks to teaching help instead of student's performance. To demonstrate these ideas, this paper focuses on three experiences covered by the subject: one based on the use of Web resources, one using information from a professional design contest, and the last one focused on technical datasheets and application notes. These experiences have been selected in order to achieve an adequate degree of difficulty and to be attractive for students.

Index Terms—Competences, design contest, technical documents, datasheets, embedded systems education.

I. INTRODUCTION

THE definition of the European High Education Area (EHEA) has placed the acquisition of competences at the center of university education. As a consequence, it is established that university education should focus on professional training which adequately prepares students for entering the labor market. Students must obtain the skills required to perform the procedures applied by professionals to solve real problems. Consequently, the academic world is transforming its methodologies, from purely lecture-based approaches to new alternatives offering a combination of classroom lectures and practical activities with industrial relevance [1]. Thus, the development of active learning methods that encourage students to be more active, participatory and creative is one of the main objectives of the curriculums for the 21st century [2].

However, the development of educational activities capable of obtaining these results is typically a challenge. First, the

time that a professional has in his daily work to find information, understand it and solve the problems that are presented is far from the hours available in a university course. In addition, the solution of such problems often require a combination of knowledge from different areas, which makes them difficult to adapt to the specific agenda of a subject.

To solve these problems, teachers often prepare partial activities, providing students with the information they need to complete them. As a result, the use of these ad-hoc materials can accelerate the acquisition of knowledge. However, widespread use of them may cause problems in the future professional performance of the students, since these materials are quite different from those that will be available in the real world.

Therefore, it is necessary to include in the curricula activities in which students work with professional resources. With them, they can acquire the ability to identify the key concepts and extract the information needed to perform the tasks entrusted. This is especially important considering that usually, the available means that are found during professional performance are incomplete or difficult to understand [3].

Thus, teachers should propose complex activities, but in order to achieve this, they must solve a series of problems:

- First, they need to identify and develop motivating activities that fits the contents of the subject and the knowledge already possessed by the students.
- Secondly, the task must involve logistics that can be used by students in the classroom and even at home, in order to improve their autonomy and interest.
- Teachers should find professional materials that can be used by students to solve the problems proposed.
- And finally, how the autonomous use of these materials is combined with the teacher's help, to get good results in a reasonable time, has to be defined.

In order to solve these problems, this paper proposes the use of professional materials as a constant throughout the teaching of a single subject. These materials are to be used in the development of the teaching activities, as a way to obtain realism and to obtain experiences directly usable by students in their future professional performance. In addition, the regular use of these resources in the subject also makes the students perceive them as something common in the working area, something they must familiarize themselves with, and not as a passing complication imposed by the teacher.

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The authors are with the TEISA Department, Escuela Técnica Superior de Ingenieros Industriales y de Telecomunicación, University of Cantabria, 39005 Santander, Spain (e-mail: posadash@teisa.unican.es; villar@teisa.unican.es).

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To show this idea in detail, the article describes the activities applied in a subject covering the design of embedded systems, offered by the University of Cantabria. This description focuses on three of the activities performed; the ones that have more relevance in the subject. In the first activity, the students use web resources to support the task of compiling and generating binary code. During the second one, the students use resources of a professional design contest [4] to perform optimizations in a target platform, and in the third one, data sheets and application notes are employed to operate a liquid crystal display (LCD) from the target board.

To present that, the article is organized as follows. First, a survey is presented in the context of realistic teaching activities. Second, the objective of teaching and the context in which the activities have been developed is introduced. After that, the three educational experiences described above are presented, one by one. Finally, some conclusions are shown.

II. STATE OF THE ART

Following the ideas presented in the introduction, the integration of realistic activities in university subjects is an increasingly important task in teaching innovation.

In this way, several alternatives have been presented where students develop or manipulate real mechanical and/or electronic systems. For example, the transformation of radio-controlled cars in autonomously guided vehicles has been used in several educational proposals [5]. In that line, the development of control systems of small helicopters or drones has been also covered [6].

Similarly, the use of robots for educational purposes is not new. Several studies have describe the use of various robotic kits and resources that can be used for teaching activities [7]. For example, in [8] a robotic arm with 6 degrees of freedom to be controlled using Python language is shown. In the same line, in [9] a robotic arm used to make drawings on a sheet of paper is presented. This robotic arm is built using LEGO NXT packages, with the objective of creating a control system based on inverse kinematics to move the arm. Moreover, in [10], a robotic arm is used to teach a complete SoC design flow, including the SW to be run on a platform based on an ARM processor.

However, these solutions present two difficulties for educational application. First, the cost of these systems is usually quite high. For example, common prices for robotic systems range from hundreds of euros for simple robots, to several thousands in the case of the more complicated ones [11]. This fact presents several associated issues. First, the costs necessary to assemble a complete laboratory with several posts can be a problem, especially now that the economic crisis has reduced the available budgets. Furthermore, there are additional issues in the maintenance of the lab, and in the possible acquisition of the materials by those students who wish to take their learning further.

The second difficulty is related to the support students require to address the activities proposed by the teacher, which are usually quite complex; such supports limits the autonomy of students.

Alternatively, systems designed with low-cost platforms based on architectures such as Arduino [12], Raspberry Pi [13], Nucleo (ST), Kinetis (NXP) and small FPGAs (arrays of programmable logic placed in the field) has also been used for teaching purposes [14], [15]. With them, it is possible to have an affordable infrastructure, solving some of the problems listed above. However, the definition of both the goals to be achieved and the resources that the student must employ to solve the proposed problems, still depend on teachers. As a consequence, the resulting activities are not very realistic.

As an alternative, [16] proposes the use of white books for teaching activities, but this method is only applicable to a limited set of issues.

To overcome these limitations, this paper proposes to employ different professional resources as a central issue in the teaching methodology of a subject.

III. EDUCATIONAL CONTEXT

As a result of the advances in information and communication technology (ICT), engineers from the areas of electronics and computing are usually involved in designing systems capable of coping with highly specialized and specific applications in various industries, such as aerospace, telecommunications, energy, or in areas related to defense.

In the development of these computing systems it is common to integrate one or more processors together with a group of peripherals. That is why one of the skills that a designer of such systems must have is the ability to design and optimize the SW of the systems, as well as the HW platform and the communications between SW and HW components. As a result, schools of technology are proposing innovative curricula that typically includes the areas of communications, computer networks, system-on-chip (SoC) systems, embedded computing [17], and hardware [18] interfaces, among others.

It is therefore interesting that a modern embedded systems course should include the development of skills related with 32-bit processor [19], of great importance in today's market, and several methodological issues related to the development of embedded systems. As a consequence, it is possible to devote considerable attention to the analysis and design activities [20] which are so fundamental in this area.

However, the design of embedded systems involves a number of features that make their development extremely difficult, especially when it is necessary to handle both functional and nonfunctional requirements, such as runtimes and power consumption constraints. In this context, the knowledge related to the generation of embedded SW, the optimization of the SW and its connection to the outside world are critical capabilities that must be acquired by students.

In this context, this article aims to show how professional resources have been used in the subject "Electronic Systems Information Management", taught in the fourth year of the Degree in Telecommunications Technology.

This subject focuses on the design of HW/SW embedded systems, and their relationships with information and communication technology. It covers the areas of hardware



Fig. 1. Raspberry Pi board.

architecture of embedded systems, embedded SW development, including SW optimization, and HW/SW interconnection.

To cover these areas, the subject is divided into two main parts. The first part is oriented towards HW platforms, and focuses its activities on the design on Microblaze [21] based platforms that can be implemented in FPGAs. These activities are carried out with a Basys2 board and make use of the resources that this HW provides: buttons, switches, LEDs, 7-segment display and VGA connector. With them, students practice the design and interconnection of components to the system bus, using the provided mechanisms and SW description languages to access and operate them from the processor, including reading polling and interruptions. This technical training is achieved through different activities, such as the development of a stopwatch and a simple graphical game chosen by the students, like Tetris, Snake, etc. Such activities are set in motion in a traditional way, mainly by proposing tasks guided with ad-hoc materials.

The second part of the subject focuses on the development of embedded SW, code optimization and external communication. This part has been developed according to the proposal, and therefore the rest of the article will focus on it.

In this second part, the teaching begins covering the area of generation and analysis of executable SW code. For this purpose, an activity based on the analysis and application of the information displayed in a couple of external websites, where the student can find descriptions of the mechanisms to be used for carrying out the practice, has been developed.

After that, the teaching of code optimization techniques is dealt with taking advantage of all the materials provided in a professional design contest proposed during a prestigious international conference.

Finally, input/output communications are covered, analyzing the use of sensors, actuators and display devices. In this case, students have managed an external device using data sheets and application notes provided by the manufacturers as sole source of information.

For the realization of these experiences, the low cost platform Raspberry Pi [13] (Figure 1) has been used. This platform has been selected as it is currently widely used and is valid for both professional and recreational projects. The platform Raspberry Pi is a computer system of the size of a credit card that can work independently or be connected to a TV using a keyboard and mouse as inputs. Thus, it is a small computer that

can be applied in electronic projects and many other contexts for which desktop PCs are not designed for, especially due to problems such as excessive size or power consumption. Raspberry Pi platform can work with or without an operating system. In the latter case, Linux is the most common operating system chosen.

IV. CODE GENERATION: WEB MATERIALS

The first important elements the students have to learn in the development of embedded SW element are the competences on the operation of tools and processes for compilation, code analysis and debugging. To this end, students are taught about the various stages of compilation and its peculiarities in embedded systems, including a study of the various tools provided by the GNU environment: compiler, debugger, binary utilities, “makefiles”, etc.

For practicing with these tools, the subject includes some experiences in which students need to access to one of the resources most currently used by engineers: the information available on the web. As a result, during the experiences proposed, students should understand the information available on an external web page, and apply this information when solving the problems proposed.

A. Description

The use of web pages as a source of information has been implemented in two specific activities. These activities have been developed considering an standard Linux OS, As a consequence, the Raspberry Pi platform is not necessary for the majority of the work. The possibility of using Linux on PC has facilitated their implementation, especially in students’ autonomous work.

First, an activity where students have to create and apply complex “makefiles” has been proposed. To do so, students have to combine the explanations made previously in the classroom with the information provided by GNU on their website (<http://www.gnu.org/software/make/manual/make.html>). This task has been proposed as a deliverable exercise the students must do at home.

Secondly, we have proposed a two-hour lab session where students generate static and dynamic libraries, using them to generate final executables, analyzing their different characteristics, and using the GNU binary utilities to unravel some of their internals. In this case, for the generation of libraries and the corresponding final executables, students have to enter a recommended website (<http://www.yolinux.com/tutorials/LibraryArchives-StaticAndDynamic.html>) and apply the information to perform practice.

B. Results

After the activity, it is interesting to note that all of the students have carried out the set task, requiring minimal support by the teacher for the interpretation of the information available on the websites.

Basically, most of the problems encountered have been derived from the use of pages in English, proving their need

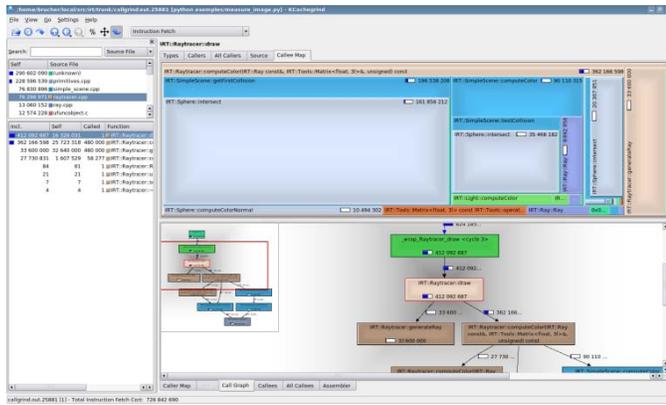


Fig. 2. Valgrind code analysis tool.

to improve the mastery of this language, since these kinds of pages is usually one of the best sources of information on engineering activities.

V. CODE OPTIMIZATION: DESIGN CONTEST

The development of the experiences to make students obtain skills in embedded SW optimization is a difficult task, due to its intrinsic difficulty. First, embedded SW optimization requires large applications that can be analyzed and optimized; otherwise, the need for such optimization will not be appreciated by students.

Moreover, the search for optimization solutions typically requires both experience and imagination. It is not easy to define a simple solution able to obtain the best results from any embedded application. To overcome this problem, some general guidelines on the approach and useful tools (Figure 2) should be combined with specific suggestions so that students can obtain interesting results during the optimization of a specific application.

However, the same problems that complicate the teaching of this area make it very interesting for use in design competitions. Teaching subjects that involve great complexity can register a great benefit from the application of the ideas in professional contests. As a consequence, this proposal can be applied to many other topics of teaching with similar characteristics.

A. Use of the Resources Provided by a Design Contest

Professional design contests usually propose challenging and motivating activities and provide the materials needed to carry them out. In addition, they are designed to allow participation of the maximum number of players, adjusting the effort required to solve the problem and the necessary logistics.

Likewise, the best solutions of the contests are usually published, providing a very useful means that students can use to solve the problems proposed with some autonomy. These solutions are presented in documents oriented towards professionals that include guidelines on how to deal with the contests. Hence, these solutions can improve the acquisition of skills by students.



Fig. 3. Game proposed in the MEMOCODES'14 contest.

Consequently, the use of materials from professional design contests can be helpful in the development of educational experiences as they provide both ideas, codes and documents that can be used directly by the teacher, reducing the effort required for the preparation of the activity and maximizing the effect of realism.

In order to show how the materials proposed by a design contest can be used in a specific teaching subject, the next subsections describe the application of a design competition proposed in the MEMOCODES conference 2014 [4] during the teaching activities of embedded SW design.

B. Description of the Selected Contest

During the MEMOCODES Conference 2014 [4], an international design contest centered around the implementation of the classic game Space Invaders (Figure 3) on the Raspberry Pi platform (Figure 1) was proposed. Space Invaders is a game of two-dimensional fixed shooter in which the player controls a laser cannon by moving it horizontally across the bottom of the screen and shooting the aliens as they descend.

The design problem presented in the contest is based on the fact that the game was developed to run on an Intel CPU 8080. In contrast, the Raspberry Pi is based on an ARM [22] processor, and cannot run the original binary code. To solve this problem, a SW program capable of emulating the 8080 processor in the Raspberry Pi board is provided by the contest. The original version of the emulator is available on the competition website in open source format.

The goal of the design contest is to register a version of the emulator as quickly as possible, reaching the same result as the original emulator after the predefined movement sequences provided by the competition. In this optimization process, the contest only allows modifying the software code of the emulator. Other HW optimizations are not accepted.

In order to simplify its application for the contest, the emulator is provided with two main operating modes, PlayGame and RePlayGame. The first mode enables the user to play the game, recording the events received from standard input.

In addition, this mode allows users to save the final state of the machine.

The second mode permits users to apply the events of previous tries, repeating the game, and to check the resulting output. Thus, it is easy to explore different alternatives for the emulator code and confirm that these modifications have not caused a system malfunction.

In short, it can be seen that the contest has all the features necessary for its application to teaching and facilitates the task of the lecturer. First, the competition offers a complete set of codes and tools that have already been appropriately adapted for their use in the contest. Second, the low cost board (25 e) is affordable for the academic world and enables students who wish to continue their learning activities at home to do so easily.

C. Educational Application

The application of the design contest for teaching purposes on the area of embedded SW optimization has been divided into several stages, as described below.

D. Initial Steps

The application of the design contest in the teaching context requires that students have some prior knowledge. Therefore, the first task to accomplish is to explore how to analyze the execution of SW code and how to integrate hardware and software elements that affect system performance. In particular, the use of tools such as “gprof” and “valgrind” (Figure 2), as a way designers have to analyze the execution of the SW code, has been demonstrated. It has been shown how they can be used to detect the parts of the application that require more time. This analysis is essential to focus optimizations in the most critical sections of SW code, maximizing the benefits obtained.

E. First Stage: Introduction to the Design Contest

Once this prior knowledge is acquired, students start familiarizing themselves with the materials of the design contest. During this first stage, students must access the contest website, read all the information provided, download and execute codes. Moreover, they are asked to analyze the runtime of the application, using one of the analysis tools presented in the previous section.

After this stage, students had obtained an initial idea of the program, its general structure and the more time-consuming functions that must be optimized.

F. Second Stage: Analysis of Documents Provided

After analyzing the code, it is necessary to start with the optimizations. However, this step is quite difficult for a novice designer, and requires additional support.

To address this point, students have to read and analyze the articles written by the contest winners, using them as a source of ideas to perform the activity.

In the first article [23], an alternative implementation of the emulator based on binary translation is presented.

This approach essentially involves the generation of a completely different emulator than the provided in the competition, which register very good results in performance optimization. The problem is that there is not a generic solution that can be applied to other codes and therefore their future degree of application is low.

By contrast, the other two approaches are more suitable for use as general optimization techniques. The second document [24] uses various optimization techniques to increase the performance of the reference implementation. Improvements in the use of data structures and changes in the function calls are some of the changes the authors performed to obtain an implementation that had a speed increase of about 2.5 times over the original code.

Additionally, the third approach [25] presents a practical example of how profiling techniques can be used to obtain valuable information on the implementation of the program, and how this information can be used to perform useful optimizations. As a result, three types of optimizations are proposed in this approach:

- Optimizations aimed at reducing the number of instructions to be executed
- Optimizations to better match the processor architecture
- Optimizations to improve cache utilization

Hence, these two last approaches are fairly generic and interesting in the area of embedded systems, and they are well suited for their use in a teaching context.

Regarding the implementation of the activity, students were divided into groups, in which they analyzed the proposals, subsequently making a presentation to share their findings with other students.

As a result, it was expected that students could identify how to optimize the code and replicate the actions in the next stage. However, the presentations showed that, after reading the papers, the students were not able to apply the optimizations on their own. Consequently, a third stage to overcome these problems before the practical application was defined.

G. Third Stage: Summary of Proposals

Once students presented their analysis of the documents, the teacher led an interactive session where the most important optimization alternatives were identified, demonstrating how they can be applied to some simple examples.

H. Fourth Stage: Applying the Optimizations

Given all the information obtained in the previous activities, in the fourth step, students had to optimize the SW emulator, modifying the original code and checking the resulting impact on execution speed.

I. Fifth Stage: Teacher’s Demonstration

Finally, the teacher introduced a quick survey of some of the enhanced features and their impact on the system performance, explaining the reasons for optimization benefits and eliciting the views of students about their experiences.

J. Results of the Activity

First, the proposal of a game as the basis of the work resulted in some increase in the students’ interest at the beginning of the process.

Second, the analysis of the documents with the winners’ descriptions showed that the management of complex technical documents is not an easy task, and that it requires additional support by the teacher in order to identify the key elements and to enable students to apply to a real problem.

At the end of the process, students had had an interesting experience and learned various alternatives by which a SW code can be optimized to increase performance in embedded systems.

The second and fourth stages were developed in separate laboratory sessions, the remainder being held in the classroom.

VI. I/O COMMUNICATION: TECHNICAL DOCUMENTS

As a third activity presented in this document, an experience that allows to develop skills in the use of system interfaces for input/output communication has been proposed. This activity involved the development of a SW program that implements the operations required to communicate the SW with an external LCD display. This display is of conventional use and can be connected to a multitude of devices. The display can draw two lines of characters with which any system can show information to the user. Students had to use any of the HW/SW communication mechanisms explained in the previous sessions of theory, a summary of which can be seen in [26].

The Raspberry Pi platform was also used as basic infrastructure.

A. Description of the Activity

The control of an LCD display is a complex task. First, the student must understand the procedures required to perform the various activities needed to properly operate the display: initialize the display, write a character, move the cursor, clear the display, etc. Once students understand these procedures, they must generate SW codes that implement them, creating the set of communication services that must be present in the SW interface and a functional executable.

Therefore, the question to be resolved by the teacher is how to make the students understand the procedures in a simple but interesting way.

To do this, the proposal is to use the data sheets and application notes provided by the manufacturers of the LCD. From these professional materials the students have to find all the relevant information required to perform the task.

In order to optimize the results in accordance with the defined objectives, a search among the various technical documents available for the LCD from the different manufacturers has been conducted. Finally, as data sheet the sheet provided by Bolymin Inc. [27] was selected. This sheet describes all the features of the device (electrical, optical, physical, etc.) as well as the use of the different pins available to connect the display to the board. It also lists all the commands accepted by

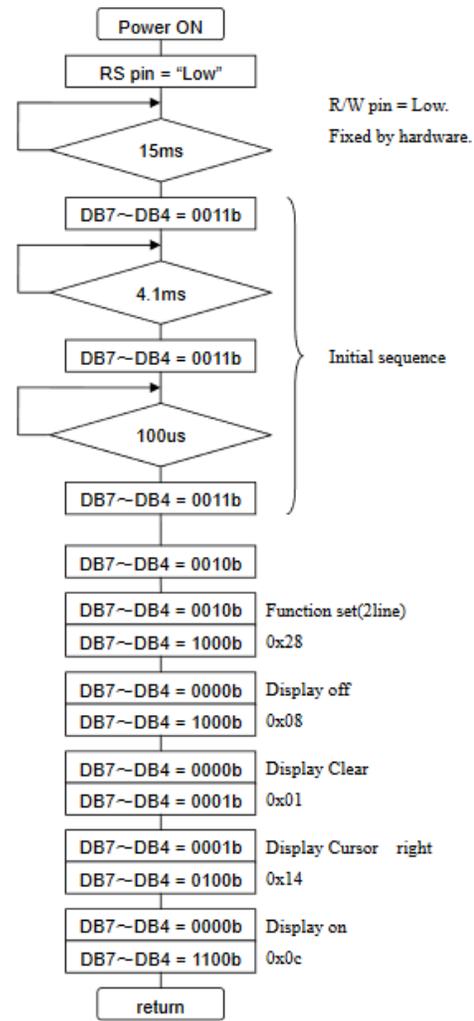


Fig. 4. LCD initialization procedure diagram.

the display in detail. In addition, timing diagrams are included showing how the various procedures should be performed.

With this sheet, students have all the information needed to properly handle the display. However, the exclusive use of the sheet require too much work for the students because they are unfamiliar with these types of documents, especially regarding the sequences described in the timing diagrams. Therefore, together with this sheet, a Fujitsu application note [28] was provided, adding more insight on the operation of the device.

This application note details the procedures required to communicate the display with a microcontroller. For this purpose, they describe each of the conventional methods of using the display (initialization, cursor placement, writing a character, ...) through state diagrams in which the control instructions to be sent to the display are identified, including the necessary waiting times (Figure 4). Additionally, the application note also provides basic SW codes with which to implement these procedures from a processor (Figure 5).

With this information, students can see how they have to implement the code to meet the timing diagrams described in the data sheet. In fact, the analysis of these functions permits the development of two other activities. First, the code

```

/*****
 *
 * NAME: LCD_Initial()
 * FUNCTION: SC1602 Initialization
 *****/
/
void LCD_Initial(void) {
// Port direction
LCD_Control_DDR &= 0xf0; /*Lower 4bit output */
LCD_Enable = 0;
LCD_Register_sel = 0;

mDelay(15); /* delay time */
SC1602LCD_4bit(LCD_DL_8BIT >> 4);
mDelay(5); /* delay time */
SC1602LCD_4bit(LCD_DL_8BIT >> 4);
mDelay(1); /* delay time */
SC1602LCD_4bit(LCD_DL_8BIT >> 4);

SC1602LCD_4bit(LCD_DL_4BIT >> 4);
SC1602LCD_Control(LCD_DL_4BIT |
LCD_N_2LINE | LCD_DH_NORMAL);
SC1602LCD_Control(LCD_DISP_OFF);
SC1602LCD_Control(LCD_DISP_CLEAR_HOME);

mDelay(2); /* delay time */
SC1602LCD_Control(LCD_CURSOR_RIGHT);
SC1602LCD_Control(LCD_DISP_ON);
}

```

Fig. 5. LCD initialization procedure code.

indicates which physical display elements have to be accessed to drive the LCD. These indications enable students to make the physical connection between the display and the processor board. However, these interactions must be adapted to enable the access from the SW running on selected board.

Hence, in a second step students have to solve the problem resulting from the fact that the SW code provided does not have all the functions required for proper operation. Simple functions, such as the procedure applied to wait for certain amount of time (eg “sDelay ()”) or functions required to access the pins input / output (GPIO), must be adapted/implemented by the students, allowing their active participation in the code development.

B. Steps

With the above information in mind, the development of the experience was carried out according to the following steps.

First, at home, students performed the reading of the problem and the preliminary analysis of the data sheets and application notes.

Then, the following steps were performed in the classroom:

- Analysis of the diagrams at their disposal in the application note for implementing the operations of the display and comparison with the information available in the data sheet
- Analysis of the SW code provided in the application note to implement the display controller, obtaining the dependencies between functions, and finding unimplemented functions and variables for HW / SW communication and other codes that have to be adapted.
- Integration of the SW code provided in a real project and implementation of the missing codes.
- SW compilation and board testing

C. Results

As a result, this activity was adequately performed in less than three hours, divided into one hour of work based on

case studies in the classroom, and two hours dedicated to the resolution of the project in the laboratory.

The activity was highly valued by students, contributing to the overall assessment of the course of 5th-year Computer Engineering with 4.41 out of 5.

VII. CONCLUSIONS

This article shows how the use of various professional resources during the teaching of a university subject can facilitate simultaneous development of various skills, involving students in the process.

On the one hand, these documents contain information on realistic use cases, simplifying the development of case-study activities that complement the knowledge acquired by students in other more theoretical steps. Likewise, they facilitate the implementation of teaching methodologies based on the resolution of problems or projects, since these documents provide students with information and assistance without altering the perception of learning and goal achievement by the students.

Thus, these technical documents allow teachers to direct educational experiences towards achieving the specific skills which are sought, and they enable the development of other skills such as information searches on the Internet or the capability of handling professional materials.

The article describes the application of external web pages in two activities related to the process of compilation of embedded SW, and the use of data sheets and application notes for developing communications from the processor to an external LCD display is also shown.

In addition, the article describes an activity that demonstrates the benefits that can be obtained by taking advantage of professional design contests for the development of educational activities. Professional design contests usually propose challenging and motivating activities and provide the materials needed to carry them out, minimizing the effort required for tuning activity. Moreover, the publication of the solutions of the contests provides a useful means that students can use to solve the problems proposed with some autonomy.

These ideas have been applied in a teaching context where students have to solve an optimization problem, using the materials provided by the SW design contest of MEMOCODE'14 conference in order to successfully resolve the whole process.

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