A New Approach to Teach Electrical Engineering Using a Para Didactic Laboratory

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A New Approach to Teach Electrical Engineering Using a Para Didactic Laboratory

Abstract

The objective of this paper is to report the implementation of a Para didactic Laboratory in a private college of engineering in Brazil to improve the training of engineering students so that they can become industry-ready graduates.

A very important component in the education of an engineer is the professional tacit knowledge which is obtained through the interaction with more experienced professionals. This normally takes place after graduation. In order to expose the students to an element of professional tacit knowledge sooner, in lieu of the traditional approaches such as curriculum change and teacher training, we founded a Para didactic Laboratory at our college of engineering where a professional engineering consultant acted as a Mentor/Coach of students while they worked together on real projects. This new approach and environment are designed to prepare the students to:

- Engage and contribute to the process of engineering or technological entrepreneurship sooner.
- Accelerate the process of going from concepts to prototypes and to the final product with confidence.
- Minimize the risks associated with product development phase, reducing time to market.
- Team up with other students from different fields and backgrounds.
- Interact with professionals and participate in meetings with business owners and clients.

The Para didactic Lab also acted as a Local Innovation System, a convergence point for business representatives, undergraduate and graduate students, researchers and engineers, all of them aiming to transform research results and ideas into solutions for real problems and the creation of new products and services. This paper also highlights to the negative aspect of the encapsulation of technology in education, referred to here as the “Aladdin Effect”.

Introduction

The initial motivation for this work came from two publications[1,2] of the CNI/SENAI/IEL (National Confederation of Industry/National Service for Industrial Training/Euvaldo Lodi Institute), from 2006 and 2010 respectively, which reported the impact of problems related to the education of engineering students in their potential to innovate. The documents report data collected and analyzed from 17 public and private colleges of engineering in the country, and suggest strategies and actions to promote the modernization of the educational methods, highlighting education as the motor of the innovation process.

In both documents the situation of engineering education in Brazil is analyzed in the global context, and a number of changes were proposed to encourage a better relationship between academia and industry to prepare a more fruitful path for actions that could lead to wealth creation through innovation. The main emphasis in those documents was on educational initiatives to engage the students in more practical work which could leverage their abilities to transform the knowledge they acquired in the classroom into practical projects.

Since the publication of those documents, very little has happened in terms of concrete solutions, mainly due to the large number of bureaucratic hurdles and the amount of effort required to implement the proposed changes. Meanwhile the economy is still increasingly demanding more qualified engineers both for industry and nowadays for so called technological entrepreneurship, which happens when a technological idea is combined with a business opportunity, a way to market it and escalate its growth. To support this process, resources in the form of capital and talent are paramount. Among the talents necessary is engineering, which has been one of its most important driver[3].

Implementing a new curriculum to develop the student´s abilities to transform the content learned into practical projects implies restructuring a course, with teacher training and changes in the content of the disciplines[10]. The National Survey of Student Engagement (NSSE)[5] reports that students involved in "high impact practices" have higher scores on deep approaches to learning, integrating learned theory into meaningful applications.

Very often, students' contact with practical activities is during traditional lab classes, where the students do hands on work on pre-formatted experiments used to strengthen the theoretical concepts[6], or when they are concentrating on their capstone projects[7,8], where students apply the knowledge acquired on engineering design projects very late, giving them little chance for continued practice[9]. Although there are initiatives to practice engineering design involving freshmen, some of them expose the students to external professional engineering guidance, but only restricted to specific actions[10].

Another problem in training human resources in engineering is the huge rate of growth of knowledge, which makes it difficult to keep up with the pace of change and include it in the curricula, while having limited time to cover the various topics needed for the correct training[4,16]. This additional burden on the faculty can sometimes be relieved by cooperation with external professionals acting as mentors. However, their participation can normally be restricted to specific actions[10] or more intensely later in the course, during the capstone projects[11], which, as we have already said, deprives the students of the continued practice of their engineering design skills.

As a way to educate industry-ready graduates, some initiatives aim to incorporate professional training in the engineering curriculum[13], or even create a College and a curriculum from a blank slate entirely devoted to this[14]. Some initiatives attempt to enhance student contact with the industrial environment using a virtual company simulating real projects[15] while other initiatives focus on the training of professionals with a T-shaped profile[16].

A very important component in the education of a student is professional tacit knowledge which is obtained through continuous interaction with more experienced professionals, needs a suitable environment for its practice[12], and normally happens after graduation. In order to give students contact with professional tacit knowledge sooner, in lieu of traditional approaches such as curriculum change and teacher training, and inspired by the work described by Donald Schön[12,20] we founded a Para didactic Laboratory at our college of engineering. A professional engineering consultant performed his professional engineering design activities and acted as a Mentor/Coach of students while they worked together on real projects. A special environment and a method were designed to support this project. In order to avoid compatibility problems with the regular engineering subjects and the time available for the students, the project was voluntary.

The pedagogical theories

The pedagogical theories supporting the Para didactic Laboratory activities are: i) constructivism as proposed by Jean Piaget; ii) experiential learning according to David Kolb and John Dewey; iii) reflective learning according to Donald Schön and John Dewey. And as support tools: i) the four stages of competence of Noel Burch; ii) the theory of Flow created by Mihaly Csikszentmihalyi.

Constructivism

According to Jean Piaget for the process of learning to be efficient it must take into account the current stage of cognitive development of the students and create situations that allow them to develop new cognitive structures to absorb the knowledge and develop the skills and competences required at each stage of their learning in an ongoing process[17]. The necessary conditions for learning must be developed first[18].

Experiential learning

According to David Kolb the learning process is recursive and begins with a concrete experience providing information and data so that the student can observe, interact and reflect. The result of these reflections is then related to previous knowledge and experiences and transformed into abstract concepts. This new knowledge, now incorporated, form the basis and guide the student to continue working in the real world creating new experiences, going through the previous cycle continuously and generating new knowledge[19].

Reflective learning

Technical rationality says that professionals solve well-formulated problems through the application of techniques and theories derived from systematic research in the form of scientific knowledge[20]. From the standpoint of technical rationality, professional practice should be a process of selection of the best means and methods available to solve a given problem. Real world problems however, do not present themselves in a well-structured manner, rather as complex and ill-defined situations where mostly a process of tedious problem construction needs to be performed well before starting to solve them[19].

Technical rationality, unfortunately, does not prepare professionals to act in situations of uncertainty, and these are the situations which offer the greatest potential for results in areas involving the creation of new methods and processes which are the precursors of innovation[19]. Donald Schön noted that the professionals who excelled in their field were not those who possessed more professional knowledge than others, but instead, wisdom, intuition and professional artistry which were demonstrated when the professional was confronted with situations of uncertainty and conflict[20]. Exactly those situations where a professional trained in the principles of technical rationality faces difficulties. An important aspect of the performance displayed by the professional was the fact that it was tacit, performed naturally, almost unconscious.

Professional tacit knowledge cannot simply be transferred to the students by traditional expositive teaching methods, but the students can be assisted by a coach[20,21]. In his book *The Design Studio an Exploration of its Traditions and Potentials*[12], Donald Schön describes an Architecture Design Studio as the ideal environment for the practice of reflective teaching and learning.

The four stages to acquire any skill

This theory was created in the 1970s at Gordon Training international by Noel Burch[22,23]. According to his theory no matter what skill one wants to learn, s/he must always pass through four stages, usually depicted in four quadrants: i) unconscious incompetence; ii) conscious incompetence; iii) conscious competence; iv) unconscious competence. After practice carrying out one activity, the final stage is when the individual, reaches the point where the activity is performed with agility and unconsciously, sometimes in parallel with one or more activities[22,23]. Viewing the process in stages can help the individual to see where s/he is at any given moment and what it takes to reach the next stage.

The theory of Flow

The concept of Flow emerged in the 1960s when Mihaly Csikszentmihalyi realized that when an artist was executing a job that was progressing s/he felt completely engaged and focused, but as soon as the work was concluded the artist lost interest in the work[24,25]. Research in this area arose from the need to understand this phenomenon in which an activity was motivated by itself, called *Autotelic*, the mere completion of a task is already its own reward, regardless of what may result from its implementation[24]. Some conditions for the existence of flow are: i) challenges or opportunities that are neither above nor below the capacity of an individual, so that s/he can face a challenge at the height of her/his capacity; ii) clear proximal goals and immediate feedback on the progress of the work. One of the research findings is that it is possible to organize a series of challenges that are compatible with a set of skills to create an optimized experience where the individual performing the activity can find a deep state of satisfaction in accomplishing it[24-26].

The approach

The environment proposed for implementing this new approach is a Para didactic Laboratory. *Para* is a prefix derived from Greek, meaning, at, to one side of, beside or side by side. It is used to convey the idea that the Laboratory is not connected directly to the classroom activities, but it runs parallel to them, supports and complements them. The choice of this model was derived from the observation of the difficulties faced during the implementation of some initiatives by the conventional procedures, such as: i) curriculum reform; ii) creation of new courses or modifications to the existing ones and iii) teacher training. The inspiration for its design came from the Architecture Design Studio described by Schön[12].

The Para didactic Laboratory is a community-centered, learner-centered and knowledge-centered environment[27]. There is no formal assessment as the students can show in the practice what they already know during the projects. Assessment is embedded into the process as a Formative Assessment[27], it enables both the students and the Mentor/Coach see what the students know, how they think, their position in the "developmental corridor" and monitor progress[27]. There is, however, a permanent feedback loop between the coordination of the course and the lab. If the students demonstrate a lack of knowledge they should already have, the course coordinator is informed so that corrections can be made.

The first author is a professional engineering consultant and brought his professional activities to the Para didactic Lab also acting as a Mentor/Coach. The students could attend his sessions on a voluntary basis and the Mentor/Coach was responsible for the implementation of the projects and the interaction with the students. In this case, instead of the traditional role of a sage on the stage, he acted as a guide on the side[28].

Some teachers did not feel comfortable engaging in consulting projects, although they have the knowledge to do so. It was then suggested that they could be volunteer tutors for the students so that when these students faced situations where they still did not have the knowledge necessary to solve the problems, they could ask the teachers for their advice in their respective areas of competence. This mode of operation takes the student out of the conventional passive process of Banking Education[29], where they have to wait for the knowledge to reach them at a certain point of the course, most of the time without any practical context.

The students can go at their own pace of learning motivated by the challenge of working on a real project, contributing with their current level of knowledge and actively seeking new knowledge as development problems arose. The knowledge already acquired in the classroom was complemented by directed study or tutoring. The students then become the co-authors of their own education. In fact the framework served both for students who acquired new knowledge, often advancing in the course in areas not yet studied, as well as for teachers who began to see their knowledge put into practice.

The minimum set of skills

The field of knowledge concerning engineering design is large and the techniques involved are not directly present in most electrical engineering curricula. By getting students engaged in real projects without the knowledge or experience necessary to do so, they face the paradox of learning a new skill[30]. They have to learn something that they still cannot fully understand and the usefulness of which is not clear, in this case they have to undertake a "willing suspension of disbelief" in favor of the Mentor/Coach and allow them to "start a journey through uncharted waters"[30,31].

In order to minimize the students´ lack of knowledge and experience, a simplified list of the common approaches used in engineering design projects was created to help the students organize their activities. This sequence is a basic guide and aims to create a minimum set of skills that the students must develop to face the first problems. With practice and through the incorporation of new skills and competencies, they can increase this minimum set until they can develop their own style of problem solving.

This minimum set of skills is necessary for them as a starting point to minimize the frustrations and errors which are common at the stage of conscious incompetence[22,23]. The minimum set of skills are: i) learn how to use a logbook[32,33] (Lab Notebook); ii) learn to search for prior art; iii) learn how to conduct brainstorming sessions[34]; iv) learn to create sketches / napkin sketches/ storyboards[35,36]; v) learn the basics of electronic instrumentation; vi) learn the basics of analog electronics; vii) learn the basics of digital electronics; viii) learn the basics of microcontrollers, hardware and programming; ix) learn how to create proofs of concepts/ prototypes and simulations. This makes up a set of skills that the students can use to face the first problems and continue to develop as a crystal seed, around which they can attach new knowledge, skills and competences and grow at their own pace.

The proposed projects are divided into manageable blocks and offered to students. The manageable blocks offer increasing degrees of difficulty to the students so they can be motivated using the theory of Flow[24-26]. As time passes, they consolidate the previous knowledge passing through the Noel Burch's four quadrants for learning a new skill, to get ownership of the knowledge and turn it into tacit knowledge.

Throughout all the phases of the project, they follow the Mentor/Coach witnessing how the problems, deadlocks, difficulties, and with main emphasis mistakes and failures are managed. Meanwhile, the Mentor/Coach comments and describes what is happening (reflection in the action and reflection on the action)[20]. As a result the students can imitate his behavior, then practice and incorporate this tacit knowledge until they master it, understand it and get to the point where they are able to develop their own style of work and problem solving[12].

Oral and written communication

There is a great need for students to learn to communicate well. The writing skills are stimulated through the use of the logbooks where their activities are documented. Oral communication is encouraged during meetings and presentations of project results to customers or visitors. Another opportunity to practice both oral and written communication is during entrepreneurship or innovation contests, where the students have to present their projects to a panel which will examine their technical and economic feasibility. The judges on the panel are usually entrepreneurs, engineers, angel investors and venture capitalists. The training and experience of making a presentation at such events are important because the analysis, criticism and suggestions provided by these professionals are extremely valuable. The judges make use of methods and procedures used in their professional activities in the real world.

Aladdin effect

W. B. Arthur, in his book *The Nature of Technology, What it is and how it evolves*[37], says that technology generates itself through the process of harnessing natural phenomena, and their subsequent encapsulation into components or operational blocks, which in turn, are once again encapsulated with new discoveries and other inventions in a recurring and complex process. This encapsulation of technology enables users to enjoy their final results and effects such as the use of mobile phones, microwave ovens and computers, controlling them with their fingertips. However, behind the apparent convenience in the use of interfaces which are increasingly friendly to virtually anyone, there hides a technological gap between those who are capable of producing such devices, and those who consume and mostly are not even able to understand the principles of their operation, construction or replication.

The Aladdin Effect is a metaphor created by the first author of this paper derived from one of the tales of *The Book of One Thousand and One Nights*[38], in which Aladdin had his desires fulfilled by simply rubbing his fingers on a magic lamp. He was unaware of the internal process that made things possible. The Aladdin effect draws attention to the negative effect that the encapsulation of technology can have on education. The ease of use of some devices, components and equipment in education seduce the users into blind acceptance and they fail to stop and consider the principles of design and construction behind them and how they operate, creating "Magic Lamp" users but not "Magic Lamp" designers. See also, Beyond Black Boxes[39].

Whenever possible, the students were encouraged to design their own devices, or take apart devices and do reverse engineering to understand their principles of operation and construction. The use of some machines developed by us in the past was also encouraged to demonstrate that it was possible to develop tools and products like commercial ones already in use and which are normally taken for granted.

Approach used in the Para didactic Laboratory		
Pedagogical Theory/Tool	**What is to be achieved**	**How**
Constructivism	The necessary conditions for learning must be developed first.	Minimum Set of Skills.
Experiential learning	Concrete experiences - Observe, interact and reflect.	Divide tasks into small manageable blocks.
Four Stages to Learn any Skill	Unconscious Incompetence, Conscious Incompetence, Conscious Competence, Unconscious Competence.	Repetition of procedures.
Reflective learning	Tacit knowledge transmission from a Mentor/Coach to students.	Work together with a Mentor/Coach.
The Theory of Flow	Create an optimized experience.	Challenges compatible with students' skills.
Risk Management	There is no innovation without risk.	Fail Often, Fail Fast, Fail Smart.
Minimize Aladdin Effect	Learn how things work.	Build things and do reverse engineering.
Oral and written communication	Good communication skills.	Logbook, meetings, innovation contests.

Table 1. Approach used in the Para didactic Laboratory.

Failure management

The typical student comes to university from a school tradition that penalizes mistakes and failures, and this is a heavy burden on his/her ability to take risks. It is an interesting paradox, the student is penalized for making mistakes, is not encouraged to take risks and then is asked to perform an activity that has risk as a premise, which is innovation[40]. There is no technological progress or innovation without risk. It is necessary therefore to play an active role in encouraging calculated risk, and tolerance to failure[42,43]. This was done in the following ways: i) by means of posters on the workbenches saying, "Fail Often, Fail Fast, Fail Smart"; ii) talking to the students about parts which have been designed but proved unsuitable; iii) when the students made mistakes, they were encouraged to reflect on the process as a whole, viewing it as learning steps rather than as an experience which they should be ashamed of or one to be deleted from their memory[40-43]. Table 1. presents the approach used in the Para didactic Lab based on the pedagogical theories and tools presented before.

Case study

The case study presented here is an automated welding machine using the hot plate process. We have developed several projects varying in the degree of complexity, this one was chosen because it includes most of the steps described in the proposed approach. In Fig.9, another automatic machine can be seen in the foreground which was also designed with the help of students.

The project presented was requested by a company that produces polycarbonate sheets that required a method to weld them. The machine was to be a Proof of Concept for a larger one to be installed in the production facility. In this project, two Electrical Engineering freshmen in their 2nd semester and a sophomore from the fourth semester were volunteers. The first author served as the Mentor/Coach, and three teachers accepted the role of volunteer tutors. The resulting product of this project has a patent filed under the number BR112013031937 2 at the Brazilian Patent and Trademark Office-INPI. The students involved in this project were also listed as inventors.

The development of the electronic hardware and the software was carried out by the students in an ongoing process of mentoring and coaching. As this was a real project at some stages the students only accompanied the Mentor/Coach during its implementation. The students already had some programming skills in C and were taking other programming courses. As they lacked some of the necessary knowledge in electronic hardware design, they were mentored by a volunteer tutor during a period of about 90 days prior to this project. During this period, the students received training to develop the Minimum Set of Skills described before.

Dividing the project into manageable blocks

Since the piece of equipment to be built was very complex and the students lacked previous experience, the project was divided into manageable blocks that could work independently, and that could be added to one another incrementally later. The whole process was documented in their logbooks showing the evolution of the project and the learning progress of the students on a daily basis. The students already knew how to use a solderless breadboard prototyping tool, although there were other alternatives for mounting electronic prototypes and this kind of breadboard tool is known to have problems of poor contact, it was used during the project because it would contribute to their learning process.

The first block to be implemented was a serial communication to a Personal Computer (PC), as the device to be built used this interface for communication. For this task, the students researched the state of the art for examples of the technique, circuits and components which could perform this function. A circuit was assembled and tested using a terminal program. A seven-segment LED display was then connected to the newly built serial interface. ASCII characters were sent via the PC keyboard through the serial interface and were displayed as numbers on the LED display.

The next block built was a microcontroller based minimum system. It contained only the necessary hardware for a simple application, the microcontroller, a crystal and a few resistors. The seven-segment LED display driver and the serial interface which had already been developed were attached to this minimal system. This new circuit allowed a user on the PC to send data to the microcontroller via the serial interface, these data were then processed and displayed on the seven-segment LED display. The first software routine was written to control this simple system.

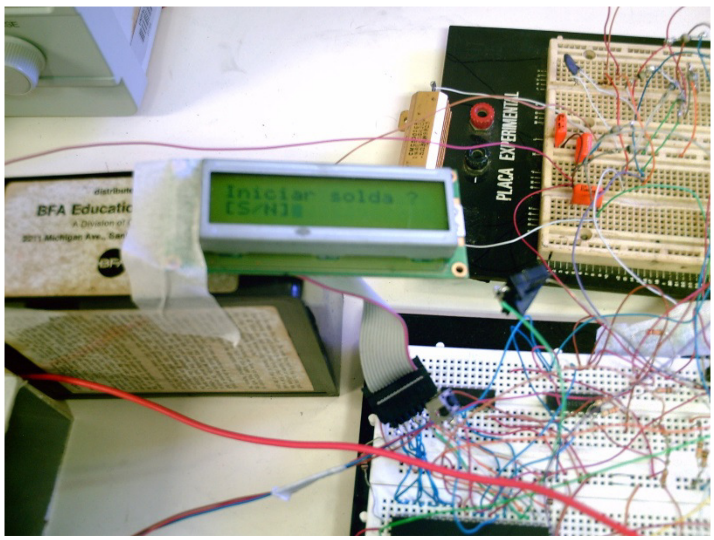

Figure 1. LCD connected to the microcontroller based minimum system.

The next block was a stepper motor driver. Although the final piece of equipment would use DC motors as drivers, stepper motors are easier to control and it served as an intermediate step to demonstrate the principle of driving and controlling motors. This new circuit was then attached to the previous one and tested. The control software written for this new set enabled to control the stepper motor via the serial interface. It was possible to send numerical values through the PC keyboard to control the rotation of the shaft of the stepper motor. At this stage, the students had started to create a library to store routines written in the C language as independent software blocks, so that the next time they needed a routine like this they could use this library.

The next task was to replace the seven-segment LED display with a liquid crystal display (LCD). This new set enabled the PC keyboard to send data over a serial interface, receive them in the microcontroller, decode them and write them on the LCD. Fig. 1 shows in detail the LCD assembled on the new circuit.

The students were then given the challenge of "inventing" a scanning keypad with fifteen keys but using only eight input and output lines available on the microcontroller. This introduced the students to the process of creating a reflective dialogue with a problematic situation, by analyzing it, constructing a problem and solving it[20]. Although the scanning keypad is a classic solution among the designers of embedded systems, for second semester electrical engineering students it was something completely new. The students were able to devise a solution to the problem without any intervention and they also implemented the control software routine. There was also a need to filter the noise generated by pushing the keypad keys[44]

The system so far was composed of: i) a microcontroller system with a serial interface; ii) a 2X16 Liquid Crystal Display; iii) a numerical scanning keypad with fifteen keys; iv) a stepper motor driver. The software routine written for this system allowed the user to type the number of steps required to move the shaft of the stepper motor on the numeric keypad, show the value on the liquid crystal display and immediately perform the desired displacement.

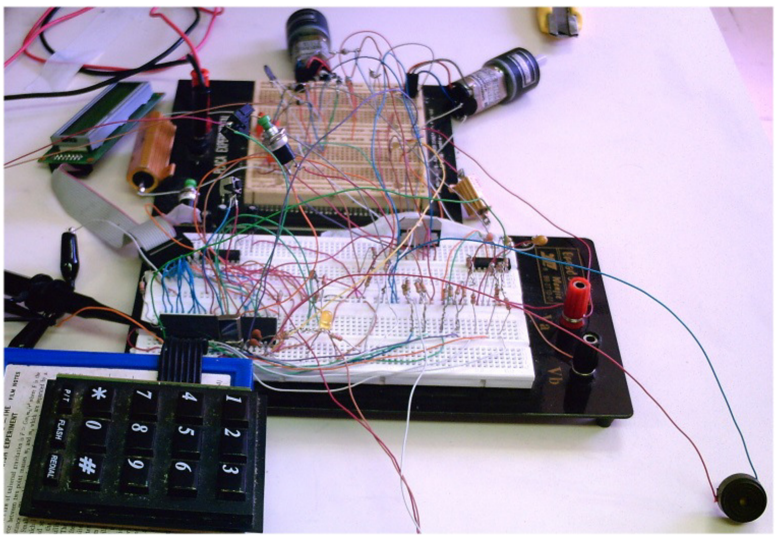

Figure 2. Hot Plate welding machine control system simulator.

The learning process continued with the study of: i) analog / digital and digital / analog conversion; ii) operating principles of DC motors and the use of H-bridges to control them; iii) control methods using Pulse Width Modulation (PWM). This knowledge was obtained through directed study and practical circuit assemblies, the issues that arose were solved by the volunteer tutors who were willing to help in matters relating to the content of the courses they taught. Learning conversion techniques like Analog / Digital and Digital / Analog and the control techniques using Pulse Width Modulation (PWM) were important for processing the signals from the sensors and for controlling DC motors which would be used in the project.

Assembling of a simulator

As the students completed several blocks of the final equipment they were requested to assemble them to simulate the operation of the prototype. They added three push buttons to the circuit to simulate the three main sensors present on the final equipment. With that, they learned how to define initial states for the three buttons by means of pull up or pull down resistors. The sensors that would be used in the actual equipment would be optical switches, however, simulating them with push buttons allowed the students to verify the operation of the hardware and the software routines as well as make changes without the need for connection to the mechanical assembly to prevent damage.

Fig. 2 shows the prototype of the complete control system in the form of a simulator of the final device. The simulator consisted of: i) a scanning keypad to insert the process data; ii) a liquid crystal display for communication with the user and confirmation of the data entered; iii) a buzzer as an audible feedback of the data entered through the keypad; iv) two small DC motors; v) three push buttons to simulate the main sensors. This bench test simulator was used to test all the software routines implemented so far.

The hot plate temperature control

Due to time restrictions, it was decided that the hot plate heating control system would use a commercial temperature controller and a J-type thermocouple as the sensor element. The interface between the electric resistance heater from the hot plate and the temperature controller was a commercial solid state relay. In order to minimize the Aladdin effect, the students did reverse engineering of the solid state relay so that they could understand its working principle.

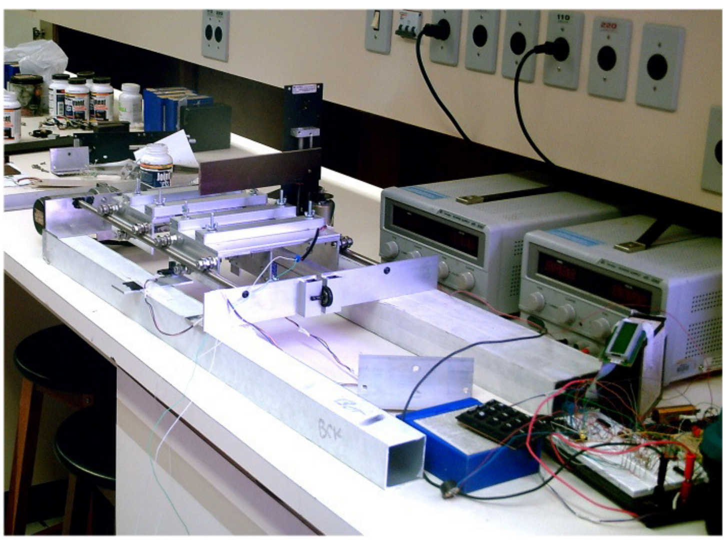

Figure 3. Testing of the mechanical hardware connected to the electronic control simulator.

Testing the mechanical hardware

Once the control circuit shown in Fig.2 had already been tested and optimized, the simulator was connected to the mechanical hardware to check the operation of the system in its entirety. Fig. 3 shows the test of the electronic control system integrated with the mechanical hardware. The main motor had a proportional control system and was implemented in two versions. In the first version a resistor was used as the sensor element which measured the current in the rotor winding. In the second version a load cell was included in the circuit to measure the force that the plates to be welded exerted on the hot plate during the melt phase, and the force each of the plates to be welded exerted over one another during the welding phase.

The complete control system consisted of: i) an embedded computer based on a PIC microcontroller 16F877A; ii) a serial communication interface for firmware update of control parameters; iii) a circuit driver for controlling two DC motors; iv) a commercial solid state relay; v) a commercial temperature controller; vi) a load cell amplifier (designed).

The students not only designed the embedded computer and the control system but also its PCB, see Fig.4. During the layout process of the printed circuit board, the students used some printed circuit boards taken from commercial equipment. The objective was twofold, first to reduce the Aladdin effect by observing products made by professionals and second, to compare with the work they were doing so that they could also develop a sense of what can be adequate, beautiful, elegant and perfect, which is described in a work of Donald Schön as "Appreciation"[20]. The printed circuit board shown in Fig.5 had two layers and was designed using a student version of the Eagle PCB CAD software. The manufacture of the board was also carried out by the students using a PCB Plotter developed by the first author and some colleagues (Aladdin Effect reducing).

Figure 4. Students using the Eagle CAD to design the embedded computer PCB.

The firmware

The machine control software was being progressively developed throughout the project. For each block developed a software routine was written, adjusted and added to the other routines developed previously for the other blocks. Throughout the project, interaction with tutors to ask questions as problems arose was very common. The project was an opportunity to consolidate not only what had already been seen in the classroom, but also what was being seen at that time in other programming courses. The most interesting part of this phase was when students needed to use tools or concepts that had not yet been seen in the classroom, and this meant that they had to seek information by themselves and then approach tutors to ask questions about the practical implementation of the newly learned material.

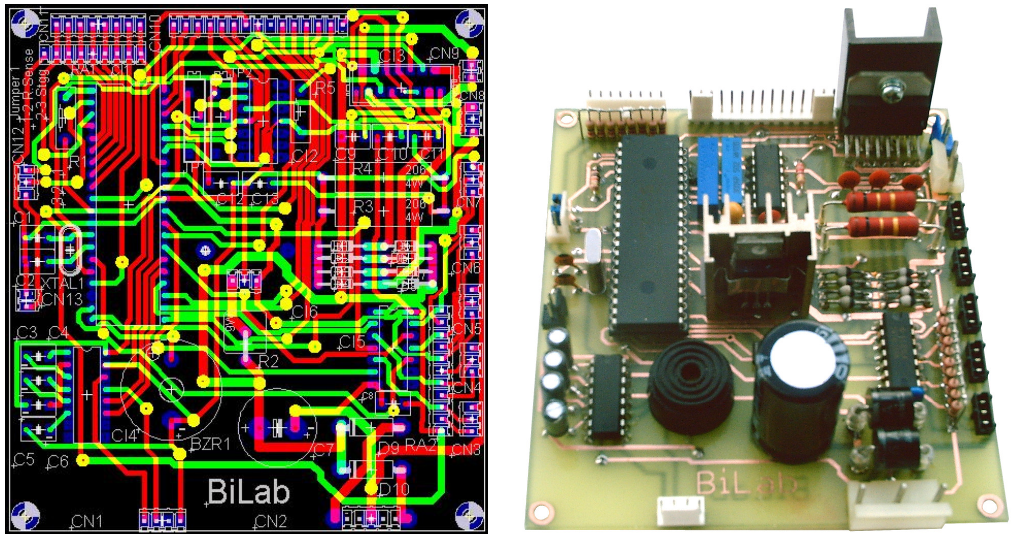

Figure 5. Layout and complete control system printed circuit board.

The complete equipment

Fig. 6 shows the complete piece of equipment in its final version. On the right side of the image, a man-machine interface and the temperature controller can be seen. The hot plate is located in the central part of the machine under a special protective shield. The electronic control system is also located on the right side of the machine, behind the man-machine interface and protected by a transparent polycarbonate plate.

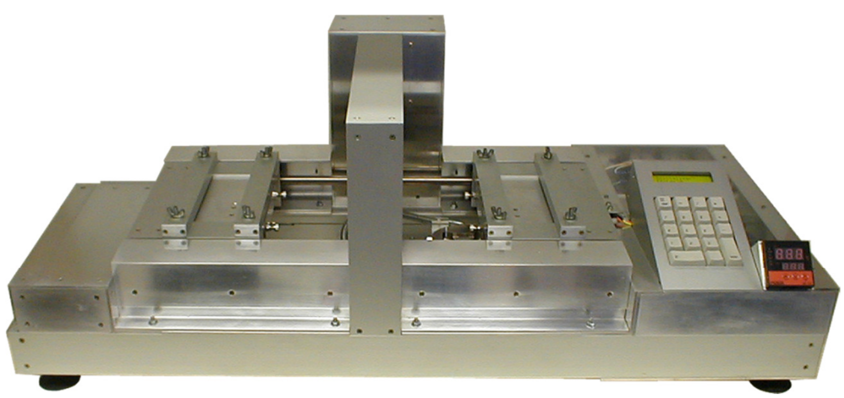

Figure 6. The hot plate welding equipment in its final version.

Throughout the project, the students were encouraged to transform the knowledge acquired into reusable components for both hardware and software. In the case of software, the routines that were developed for each separate block were used to create a library of independent routines that would enable them to implement a proof of concept or prototype of a new project in a very short time. The task would be to divide the project into blocks, associate a routine to every block and then make adjustments to make everything work as a whole.

With regard to hardware, the philosophy was the same, where possible, hardware blocks that could be reused were kept as independent components. They included: i) a numeric keypad; ii) a stepping motor controller; iii) a DC motor controller; iv) a solid state relay (obtained by reverse engineering); v) a load cell interface; vi) a microcontroller programmer.

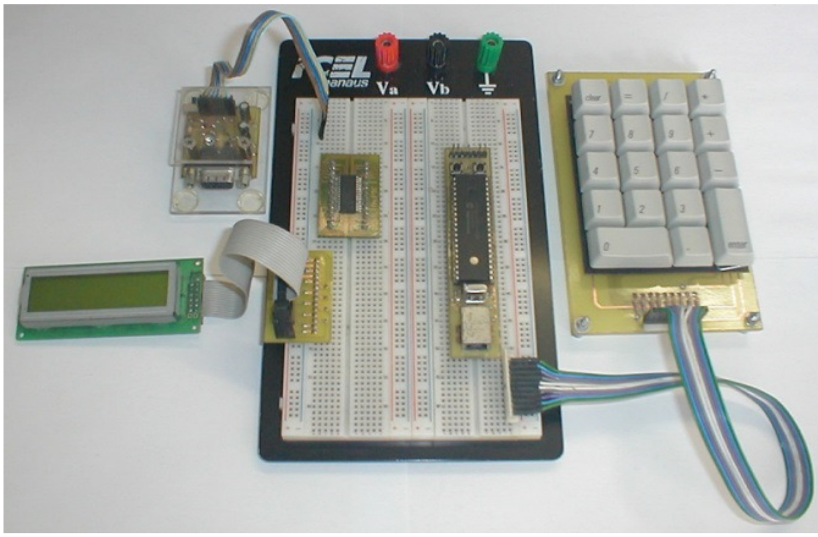

Figure 7. The tools developed by the students.

The tools developed by the students

During the assembly of the electronic prototypes, the appearance of poor contact problems emerged because of the large number of connections needed by some devices such as the LCD (14-pins) and the numeric keypad (8-pins), see Fig.2. When one of the connections failed, it became a problem complex to solve as the system involved interactions between software and hardware. The problems of intermittent connections were becoming more pronounced as the system was growing more complex and the assembly involved a larger number of components. Although there are safer ways to assemble these kinds of prototypes, e.g. prototype matrix printed circuit boards, the use of the solderless breadboard was encouraged so that students could learn about real-world shortcomings.

The students were in charge of the assembly and testing of the prototypes and became increasingly annoyed by the constant connection failures. This also highlighted the importance of looking at problems and barriers that arise during a design project as strong motivators for creating innovative solutions. As part of their training, the students were encouraged to develop reflective dialogues with the problematic situations that arose, constructing problems and proposing solutions[20].

Throughout the project and as the problems arose the students created several tools to solve them. Among the tools, there were adapters that allowed the students to connect some devices directly to the solderless breadboard, avoiding intermediate wiring. Fig. 7 shows the tools that were

created and developed by the students to solve problems encountered during the project. The tools are:
i) an LCD connector adapter; ii) a numeric keypad; iii) a serial programmer for microcontrollers; iv) a multipurpose USB embedded computer.

The tools were designed, developed and built by the students using the knowledge acquired during the project. All the tools developed have connectors that fit into the solderless breadboard as plug and play devices and they assure more reliable connections. Fig. 8 shows a detail for the connector for a 2 x 16 characters LCD.

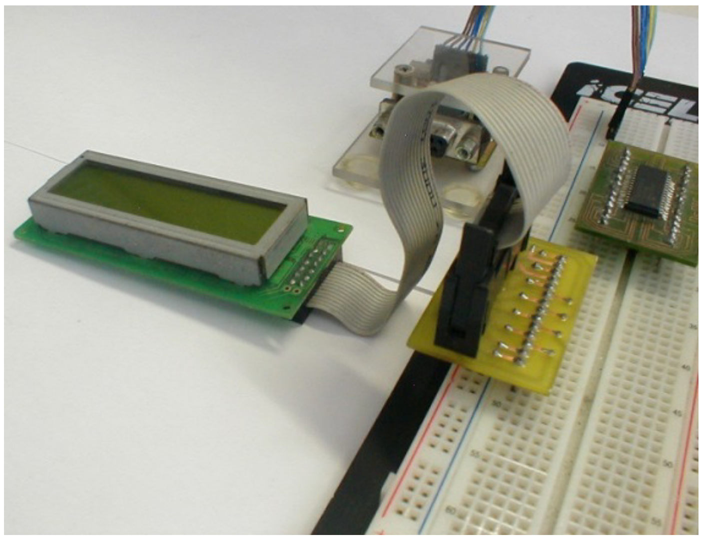

Figure 8. Detail of the connector for a 2 lines x 16 characters LCD.

The internal feedback mechanism

During the firmware programming, it was observed that the students did not know how to make a flow diagram, although they already had a good knowledge of programming in the C language. This was necessary for the prototyping and documentation of the routines and they should have already seen it in the classroom. The course coordinator was informed.

Failure management

During the project, some solutions which were adopted for mechanical and electronic hardware and others which proved unsuitable were described. The solutions that proved unsuitable gave rise to discussion about managing mistakes and failures during the creative process. It was clearly seen by the students how these events are the intermediate steps to arrive at a better solution. The mistakes are stepping stones without which it would be impossible to reach a suitable solution. It was clear through real experiences that we must pay attention not only to the project itself, but also to the opportunities that may arise through the process. Problems encountered during the project motivated students to create solutions that eventually became new tools.

Alignment with the ABET criteria

The activities of the Para didactic Laboratory are aligned with most of the ABET Criteria for student outcomes[45], and contribute to complement the education of the students in the items that have the most impact in the development of the necessary skills to prepare industry-ready graduates focusing on innovation. They are:

(a) an ability to apply knowledge of mathematics, science, and engineering;
(b) an ability to design and conduct experiments, as well as to analyze and interpret data;
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
(d) an ability to function on multidisciplinary teams;
(e) an ability to identify, formulate, and solve engineering problems;
(f) an understanding of professional and ethical responsibility;
(g) an ability to communicate effectively;
(i) a recognition of the need for, and an ability to engage in life-long learning;
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Assessment

The kind of assessment used at the Para didactic Laboratory is Formative Assessment[27]. After compiling experiences over the years we also have developed an assessment rubric based on the ABET Criteria for student outcomes. The proposed assessment rubric can measure whether the learning outcomes are present or not and to what degree using a Likert Scale. The proposed rubric also takes into account the results of the reflective learning which is equally important and which is not tangible and therefore highly subjective. We suggest the following points to be explored:

a) To check how much the student is able to perform a reflective conversation with a problematic situation and construct a problem autonomously;
b) To check how much the student is able to tacitly use the tools and methods learned so far;
c) To check how much the student is capable of solving a problem with little or no intervention from the Mentor/Coach using explicit and tacit knowledge;
d) And finally, verify if the student is able to understand, reflect, use the new knowledge and the analysis tools already learned to construct and solve a problem independently.

Conclusion

The experience in the six years of operation of the Para didactic Lab has shown that the impact on the education of the students is greater if they enter before the second year, after that, they begin to lose interest in the course and focus on "employability". The students' attendance at the Para didactic Laboratory is voluntary which implies initiative, through presenting themselves to work on a project, showing some personal project which they have already implemented, or the desire to put a new idea into practice. The students are generally self-motivated and goal oriented. The usual passive mindset in which students just attend theoretical and laboratory classes and sit exams is discouraged.

The approach described here was originally intended to be applied to electrical engineering students, but due to the multidisciplinary nature of the projects contracted, soon students from other engineering fields such as mechatronics and chemical engineering got involved developing a very diverse and gender balanced environment. Some students clearly demonstrated more natural abilities in some specific areas such as programming, hardware design, electronics or mechanical assembly. The practical integrated activities made them more aware of this and as a result they began to attribute value and invest in those skills while at the same time sharing them with their classmates.

Figure 9. A view of the design and test section of the Para didactic Laboratory.

Normally the implementation of an engineering design laboratory is very expensive due to the specialized equipment necessary. The space used to assemble the laboratory came from a deactivated energy efficiency laboratory. Some desktop computers and all the electronics instrumentation needed were already there. There was a main laboratory and a smaller room used for the evaluation of the energy efficiency of lamps. The Para didactic Lab used the main laboratory to activities of design, assembly of electronic hardware and software programming, Fig. 9. The smaller room was transformed into a workshop, Fig.10. For this second space hand and machine tools were bought.

The hardest aspect to implement was the direct involvement of the faculty in the projects. They did not feel comfortable engaging in consulting projects but their participation was crucial for the success of the endeavor. The way found to circumvent the situation was to assign the staff as voluntary tutors so that the students could ask for their assistance in their area of specialization every time they needed. They felt very happy to help the students contributing with the subjects they teach and they became very motivated when they saw the results of their knowledge being used in practice. As for funding, the college of engineering was responsible for the maintenance costs of the lab and its operations were financed by a percent of the earnings from the projects.

After receiving a suitable basic training to develop the minimum set of skills, the students, even the sophomores or second year, felt strongly motivated to contribute to a real project. They carried out the work with a degree of complexity that was compatible with their knowledge. They also felt very motivated to seek more knowledge and interact with teachers asking for information to be effectively used to solve an immediate problem of engineering. As the process was voluntary it was not possible to guarantee a predictable number of students to assemble many working teams.

Figure 10. A view of the workshop.

The failure management process encouraged the students to establish reflective dialogues with problematic situations which arose during the project. This led to the creation of tools to solve the problems allowing them to do engineering while learning it.

The students became capable of approaching unknown situations, analyzing them and creating solutions, not just reacting to situations which were presented to them. They began to use the knowledge acquired to solve the problems proposed by the teachers in the classroom and also to implement their own ideas. The students also had the opportunity to participate in innovation and entrepreneurship competitions. We see these competitions as an opportunity for students to learn how to present their projects to potential clients or investors, putting into practice their communication skills and the expertise they had acquired in the process.

The feedback with the course coordination was used to communicate that an important component necessary for the prototyping and documentation of the project was missing.
The Para didactic Lab also acted as a Local Innovation System[48], a convergence point for business representatives, undergraduate and graduate students, researchers and engineers, all of them endeavoring to transform research results and ideas into solutions to real problems and to

create new products and services. Some video clips showing the process of design and the final test of the automatic hot plate welding machine can be seen on videos posted on YouTube[46,47].

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