A methodological proposal for the Digital Electronics subject laboratory

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***Abstract*—This paper describes a proposal for teaching the digital electronics laboratory that combines the traditional method based on the assembly of discrete components on test boards with remote teaching using the virtual teaching platform, the use of simulators and programmable logic devices. The aim is to promote autonomy and creativity and to allow greater flexibility in the organisation of learning.**

***Index Terms*—Logic design, simulators, hardware description languages, SSI integrated circuits, FPGA, e-learning platform.**

I. Introduction

The planning of the digital electronics laboratory can be approached on the basis of three methodologies: face-to-face laboratory, virtual laboratory and remote laboratory. The context and the type of teaching (online or face-to-face subjects) will determine to a large extent the technique chosen. In the case of [1] where it is in the context of an online university, the remote laboratory approach is the most appropriate, as it is the closest to the actual handling of components and instruments. In a face-to-face teaching context, there is no doubt that laboratory attendance and real manipulation of components is the best option. In this case, the support of simulators and virtual teaching (VT) platforms allows the student to have a greater predisposition, training and knowledge when approaching practical tasks [2] [3]. A mixed approach based on the use of simulation as individualized homework allows for greater flexibility and enhances creativity, giving the student the opportunity to explore other alternatives to the experiment proposed by the teacher, allowing them to acquire greater confidence when dealing with the handling of the instruments.

In this work, a mixed methodology with classroom and virtual components is proposed for the planning of the laboratory of the Digital Electronic Circuits subject of the first year of the Computer Engineering degree. It also introduces the use of programmable devices (FPGA) in addition to the discrete assembly with breadboards. The rethinking of the digital electronics laboratory will solve some of the drawbacks of traditional methods. It promotes student confidence and trust in the use of the instruments, allows the realisation of complex and versatile designs, encourages personalised work and imagination, and brings first year students closer to more realistic design techniques. Five laboratories are proposed that cover all areas of digital design and are designed to be developed in one term of an academic year, in which the student has a face-to-face laboratory workload of two hours per two-week period.

II. Structuring of content and tools used

As mentioned above, the programme consists of five laboratories. The material is organised in folders on the e-learning platform of the University of Seville (*Enseñanza Virtual* or EV). This platform uses the Blackboard Learn tool which is widely used in many universities and countries all over the world [4]. The tool is very versatile and allows many functionalities. It can be used as online support for traditionally taught courses or to develop fully online courses. It allows for organising content, scheduling activities and exams and having videoconference sessions that can be collaborative.

The contents have been organised in a structured way where each laboratory has a folder in which all the multimedia material necessary for individual and autonomous work is uploaded. This material consists of video tutorials, written documentation and, in some cases, code templates of the hardware description language used, which the student must complete and which serve as a guide for the preliminary work.

The laboratory report is the basic document that explains to the student how to carry out the work and in what order to access the material contained in the laboratory folder. It is structured in the following main blocks:

- Introduction: Tutorial part explaining the work to be carried out and the simulation tools and instruments that must be used to carry it out.

- Pre-study: mainly based on the use of simulators, where students are explicitly instructed to present an explanation of the results obtained in the simulation.
- Experimental study: this is carried out experimentally in the laboratory and must be approved by the teacher, who ensures that the concepts are correctly implemented and understood.
- Personal work: consists of a simulation part and an experimental face-to-face part. It is carried out freely and without templates based on the knowledge acquired in the previous phases. The solutions provided individually are valued for their originality and practical application. This phase is the most directly involved in the promotion of student autonomy.

III. Description of the Laboratories

A description of the proposed sessions is given below. It should be remembered that the programme consists of 5 laboratories, not all of which are carried out in a single face-to-face session.

A. Laboratory 1

As this is the first contact with the usual instruments used in digital circuits, this laboratory is intended as an introduction and presentation of them. A series of video tutorials have been developed for each of the basic instrumentation components: function generator, power supply and oscilloscope. There is also a video tutorial explaining how to use the test strip.

With regard to the simulators used to develop the previous laboratory session in which the student works before the classroom attendance, Tinkercad [5] has been proposed. This is a very intuitive and easy-to-use simulator that does not require installation as it is operated via the web and allows us to reproduce in a very simple way everything that will later be carried out physically. A video has also been produced to explain to the students how to use the simulator. Fig. 1 shows screenshots of some of the videos.

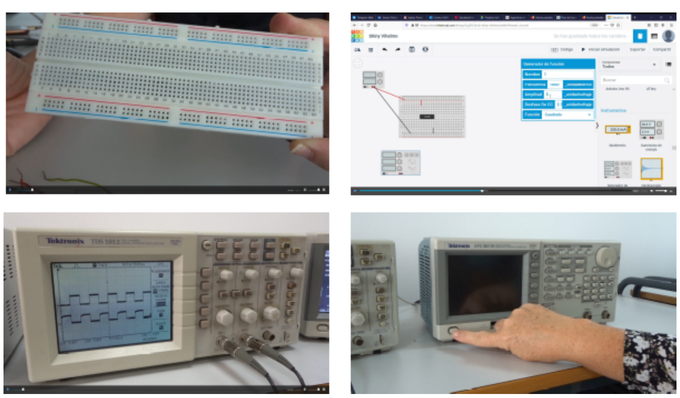

Fig. 1. Examples of video tutorials from Lab 1.

B. Laboratory 2

This laboratory is designed to be carried out in two two-hour sessions. Two concepts are worked on. On the one hand, in the first session, a simple combinational circuit is assembled on the test strip. The operation of the circuit is tested and switching parameters such as delay time are measured.

On the other hand, in the second session, hardware description languages are introduced. The hardware description language chosen was Verilog, because we considered it to be more intuitive, easier to learn and suitable for a first-year subject. The student has to describe the same circuit that has been assembled on the power strip using this language, and can simulate the circuit at home and check its operation.

In order to make it easier for them to simulate and work at home, video tutorials (Fig. 2) are provided with two possibilities. One of them is the EDA PlayGround [6], a web-based simulator that does not require any installation and is independent of the operating system, its use is immediate. The other is Icarus Verilog [7], with the Gtk Wave wave viewer [8], these packages are lightweight and easy to install. Students are provided with videos on how to install it with various options depending on the operating system. The advantage of Icarus Verilog is that it does not require an internet connection.

Fig. 2. Examples of video tutorials from Lab 2.

Students must provide a document explaining how they have carried out the simulation and justify the results obtained. In the classroom session, they must transfer the described and simulated circuit to the FPGA and check its operation.

In order to promote self-learning and autonomy, students are asked to design a combinational circuit with a practical application and implement it on the FPGA. This is individual work and the student, in the laboratory, must justify their design to the teacher.

C. Laboratory 3

The main objective of this practical is to work with general and specific purpose combinational subsystems including arithmetic circuits. It is carried out in two two-hour laboratory sessions. It follows the same dynamics explained in laboratory 2, increasing the level of complexity of the circuits.

In the first session, the student carries out an assembly with medium integration scale integrated circuits (MSI). Specifically, they use multiplexers and decoders. They test their design and measure switching parameters. The design is a simple comparator, as the discrete assembly does not allow for greater complexity in the circuit.

For the second session, the student must, as a preliminary work, describe and simulate in Verilog an arithmetic circuit that performs addition, subtraction and transfer for 4-bit numbers. The description contains the main module that performs the operations and a 7-segment binary converter that will later allow them to visualise the results on the display of the FPGA's Basys board. They are also asked to increase the complexity of the arithmetic circuit provided, incorporating other operations and designing their own Arithmetic Logic Unit (ALU).

In the laboratory, they must incorporate both the basic circuit design and their own design into the FPGA and connect it to the switches and displays available on the FPGA to check its operation. The student explains the work done to the teacher and shows the results on the board.

At this stage of the work developed in the course, the student no longer requires so many explanatory video tutorials, since the same tools described above are used. They only need to learn more about the Verilog code because now the complexity of the language is a little higher because it requires the description of simpler modules that must then be instantiated to design a more complex one at a higher hierarchy level.

D. Laboratory 4

The main objective of this practical is the design of synchronous sequential circuits. However, the use of sequential subsystems, in particular a counter, is also incorporated. The counter is used as a prescaler, since it is necessary to divide the frequency of the clock signal as will be described later. This laboratory is designed to be taught in a single two-hour session. The methodology is the usual one with simulation work at home based on Verilog: the student must complete the description of the circuit and study its behaviour by means of the timelines generated in the simulation process.

We propose the design of a sequential circuit that generates a sequence of 8-bit values that allows the 8 LEDs on the Basys board to be switched on and off alternately. As the frequency of the clock generator on the board is 50 MHz, the direct connection of this clock to our circuit would not allow the visualisation of the switching on and off of the LEDs because it is very fast. For this, the students are offered two solutions: in the first one, a manual clock signal is generated using one of the pushbuttons on the board; in the second one, a prescaler module is added to the design. The prescaler is a one-module counter calculated so that its total counting period lasts half a second. This counter will be incremented by the board clock and will generate an end-of-count signal that will be the clock of our sequential circuit, thus making the switch-on automatic and visible.

During the lab session the student has to test both solutions on the board. As a personal task he/she is asked to modify the circuit to realise other on/off patterns of the LEDs.

E. Laboratory 5

The structure and methodology of this last laboratory differs from the rest, but the work carried out is interesting and has therefore been incorporated into the programme proposed for the subject.

The student uses purposely designed circuit board (Fig. 2) that mostly consists on a counter designed with discrete components and a socket where a ROM memory from a vintage ATARI 2600 game cartridge can be inserted.

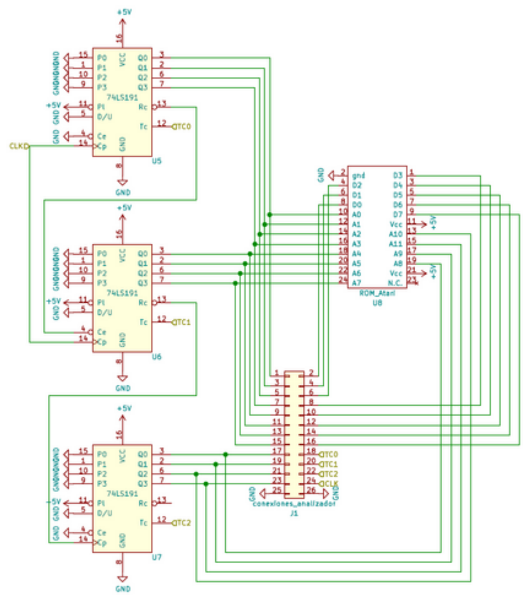

Fig. 3. Design of the board for laboratory 5.

The purpose of this counter is to generate all the address values of a 4kx8 memory corresponding to a game cartridge of the ATARI console.

The memory is removed from the cartridge and inserted into the board. The logic analyser allows the contents of the read memory to be saved and then used in a console emulator that allows the game to be run. The student works on the concepts of sequential subsystems and memory.

IV. Discussion on the Proposed Programme

The proposed programme represents a change with respect to the traditional programmes of digital electronics laboratories, which were always based on the use of breadboards. In fact, not all the teachers of the subject agree with the introduction of circuit design on FPGAs based on hardware description languages. It is argued that the students are not capable of assimilating these concepts and it is decided to introduce them later in the Computer Structure subject in the second term. In our opinion, the way in which the programme is designed allows the gradual assimilation of the concepts, which are introduced with tutorials, starting with very simple examples and gradually allowing the necessary autonomy to be achieved. In fact, it makes it easier for them to face the design of Digital Systems in the second semester subject and does not involve such an abrupt change of methodology in the laboratory. Rather, it motivates them to have tools that allow them to create more complex designs and simulate at home and then move on to hardware in the laboratory.

In order to obtain information on how students view the programme, an anonymous questionnaire was prepared and answered by 30 students from the degree in Computer Engineering, Information Technology (IT) and 13 students from the degree in Computer Engineering, Software Engineering (SI).

Three aspects were surveyed: preparation of the labs, performance of the labs and an overall assessment of what the lab entails in the subject. Each part contains three questions and each question is answered as a 5-point likert scale. Tables I, II and III show the questions on these aspects and the answers provided by the students of both degrees.

TABLE I
PREPARATION OF LABORATORIES.

1. The use of circuit simulators has been useful to me as a preliminary work for the laboratories of the subject.					
Grade	1	2	3	4	5
IT	1	2	3	12	12
SI	1	1	4	7	0
2. The use of circuit simulators to prepare the laboratories has been useful for a better acquisition of the contents of the subject.					
Grade	1	2	3	4	5
IT	2	1	4	15	8
SI	0	1	5	7	0
3. The proposed pre-lab methodology has helped me to be more autonomous in the preparation of the labs.					
Grade	1	2	3	4	5
IT	1	2	6	15	6
SI	1	3	5	4	0

Grades: 1 - Strongly disagree, 2 - Disagree, 3 - Indifferent,
4 - Agree, 5 - Strongly agree.

TABLE II
PERFORMANCE OF THE LABORATORIES.

4. consider it important for the objectives of the subject to know in a practical way the process of design and implementation of circuits based on hardware description languages.					
Grade	1	2	3	4	5
IT	0	1	2	14	12
SI	0	1	3	8	1
5. I find the laboratory practices that implement the designs on FPGA devices more motivating than the traditional practices with wired implementation on connection strips.					
Grade	1	2	3	4	5
IT	0	1	2	14	12
SI	0	1	3	8	1
6. The use of the e-learning platform (EV) is of great help in managing the submission of practical assignments.					
Grade	1	2	3	4	5
IT	0	1	2	14	12
SI	0	1	3	8	1

Grades: 1 - Strongly disagree, 2 - Disagree, 3 - Indifferent,
4 - Agree, 5 - Strongly agree.

TABLE III
OVERALL ASSESSMENT

7. Laboratory exercises provide additional motivation to understand and study the subject.					
Grade	1	2	3	4	5
IT	0	1	2	14	12
SI	0	1	3	8	1
8. Laboratory exercises have helped me to better understand the theoretical concepts of the subject.					
Grade	1	2	3	4	5
IT	1	1	6	11	10
SI	1	2	1	5	4
9. Traditional practices based on breadboards should continue to have a place in the practical programme of the subject.					
Grade	1	2	3	4	5
IT	1	9	5	7	7
SI	1	1	5	6	0

Grades: 1 - Strongly disagree, 2 - Disagree, 3 - Indifferent,
4 - Agree, 5 - Strongly agree.

With regard to the preparation of the laboratories (Table I), the questions were aimed at detecting whether the use of simulators is useful and whether the methodology based on tutorials helps the students to be more autonomous and to have the capacity to prepare all the previous content. The aim is for the student to be more oriented and not to feel lost when facing the work. With regard to the usefulness of simulators, 24 and 23 of the 30 respondents in IT and 7 of the 13 in SI agree with the first two questions respectively, which indicates a clear positioning in favour of the use of this tool. It is also observed that the students perceive that the proposed methodology helps them to be more independent when preparing the work, with 21 of the respondents in IT and 4 in SI agreeing.

With regard to the performance of the laboratories (Table II), the first two questions are designed to test the use of hardware description languages and FPGA implementation. Regarding the first point, 26 students out of 30 in IT and 10 out of 13 respondents in SI are in favour. There is only 1 student in disagreement on this point out of all respondents. 26 students in IT and 7 in SI also find it more motivating to carry out the lab work using the FPGA board compared to 2 indifferent and 2 disagreeing students in IT and 3 disagreeing and 3 indifferent students in SI. As was intuited at the time of proposing the new programme, the new contents increase motivation as well as providing more up-to-date teaching that is more in line with reality. With regard to the use of the virtual teaching platform, the students are not so strongly in favour, with 18 agreeing with its usefulness in IT and 9 in SI, a little more than half of those surveyed.

With regard to the results corresponding to the general assessment shown in Table III, it can be seen that 26 students agree with the motivating nature of the activities that use FPGA chips in TI and 9 in SI. On the other hand, 21 in IT and 9 in SI indicate that it has helped them to better understand the concepts of the subject.

With regard to the use of breadboards continuing to be part of the laboratory contents, it can be observed that in this case 14 students agree in IT and 6 in SI, this number being a little less than half of the respondents.

Fig. 4 and Fig. 5 show the mean and standard deviation of the responses to the questionnaire by IT and SI students respectively. The graphs show that in general the students surveyed are in favour of the new methodology. It can be seen that IT students are more in favour of it, in the case of SI also the means are high but not as prominent. The question with the lowest score and with the most equal distribution between students in favour and against is the one that questions the continued incorporation of the assembly on breadboards in the laboratories.

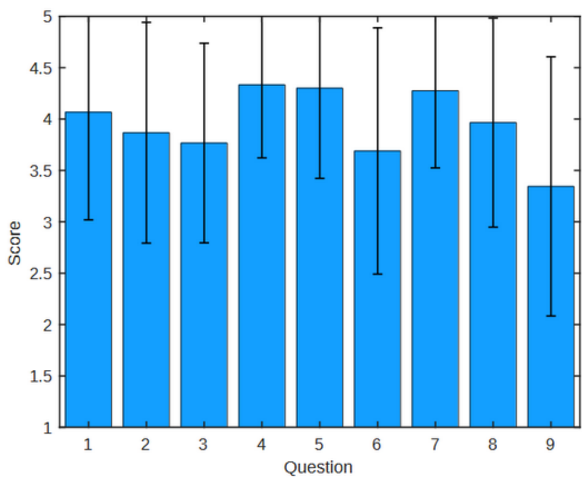

Fig. 4. Mean and standard deviation of IT students' responses to the questionnaire.

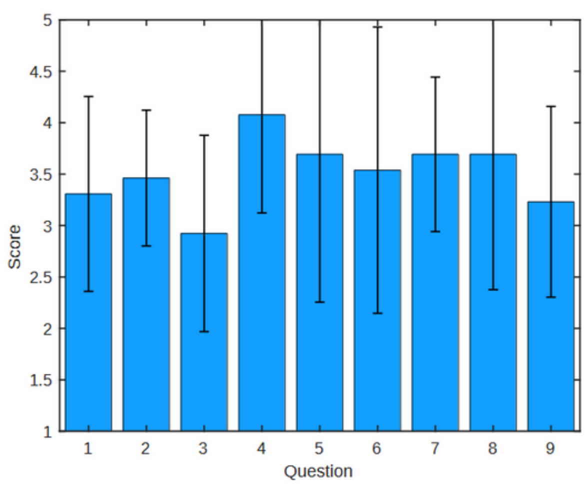

Fig. 5. Mean and standard deviation of IS students' responses to the questionnaire.

V. Conclusions

Although the subjects of digital circuit design are basic and therefore not subject to major updates, there are practical aspects that have changed and that are related to the advance of technology when it comes to implementing the circuits. These advances must be incorporated gradually, so that the student can assimilate the contents without finding them unapproachable. The whole process of redesigning the new programmes must also be evaluated.

The programme proposed in this work has been evaluated during two academic years. It has been monitored how students approach the proposed tasks, it has been seen that they are able to do so with the information provided and that most of them manage to complete the proposed tasks. In addition, the programme allows for many of the tasks to be carried out in an off-site manner, for those situations in which face-to-face classes are not possible.

The survey carried out has allowed us to detect that the students accept the new methodology, which increases their motivation and helps them to assimilate the concepts.

The incorporation of new contents related to hardware description languages, circuit simulation and FPGA implementation are therefore of fundamental importance and should be taken into account when updating the laboratory programmes of digital circuit design subjects.

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