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FPGA-BASED REMOTE LABORATORY FOR DIGITAL ELECTRONICS

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ABSTRACT

This paper presents a proposal of a remote laboratory based on FPGA - Field Programmable Gate Array for use as an instrument to support the practical activities related to the discipline of Digital Electronics in Electrical Engineering & Computer Science courses. The proposed remote lab is based on Altera's DE0 Development and Education Board (kit DE0), on a server that is connected to the internet through the University's internal network and IP camera. Users will be able to evaluate experiment results through video streaming from the use of IP cameras. With the use of the TeamViewer tool, students will be able to remotely access the server and perform the predictable activities or use the platform to test their own projects. One of the advantages of our proposal is that the user does not need to learn to use a new software tool in order to perform the communication between the server and the kit DE0. In addition, since the entire process of configuring and updating the application is based on the quartus_stp package, we do not need additional hardware, based on microcontroller or microprocessor, to send real-time data to the FPGA. We will also present a methodology proposal so that the remote platform can be effectively used as an educational tool. In the proposed environment, the student or teacher has at his disposal a hierarchy of archives containing the pedagogical resources necessary for the adoption of didactic practices based on the principles of active learning methodologies.

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INTRODUCTION

Currently, universities are strongly focusing their actions on introducing the use of modern technologies in the classroom and are increasingly producing online course content to be accessed by both external students and the university students themselves. There is also a tendency for significant investment by universities in the assembly, implementation and application of distance learning (EaD) courses, mainly due to the gradual evolution of the internet in these last decades. According to Moreira et al, one of the great challenges for distance learning courses is the realization of laboratory practices. The author emphasizes that, although there is already available technology, there is still no complete software and hardware solution, combined with an efficient teaching methodology, capable of productively enabling the experimental activity (Moreira, et al, 2008). Engineering education fundamentally needs theoretical activities and experimentation aiming at the insertion of graduates in the labor market.

Practical activities, based on the use of measurement and test equipment, are of fundamental importance for students to develop not only from a conceptual point of view, but also in relation to procedural and attitudinal. Experimental activities can be performed in three different ways: in person, virtual or remote. The implementation and maintenance of the face-to-face laboratory for long periods has a very high cost. This laboratory format is the most suitable to be used in a "classic" Engineering Course (face-to-face). According to Nedic *et al* (2003), the virtual laboratory can be understood as being an environment conducive to the execution of system simulations. Currently, there are several computational tools that can be used for this purpose, and one of its main advantages is that it is a low cost alternative when compared to the others laboratory forms mentioned above. The virtual laboratory can be very useful as a support tool for the engineering course, providing the student with the possibility of carrying out system simulations, aiming to deepen the conceptual understanding on the themes presented in the various areas of engineering.

However, there is a criticism when only this didactic model is used. Macintyre (2002), states that computer simulations are based on mathematical models and these, in turn, are representations or simplifications of reality. If, on the one hand, the ability to understand and build these representations is part of the training of the engineer, on the other, care must be taken so that the excessive use of these models in the classroom does not lead students to forget that models are idealization and therefore, they only correspond to reality when restricted boundary conditions are maintained. Casini (Casini, et al, 2003) define a remote laboratory as an experimental platform on which anyone, with access to an internet connection point, can access and control, in real time, real experiments through a computer. Cardoso and Takahashi (2011) emphasize the use of the remote laboratory by companies, for training of specialized technical staff, and by educational institutions that seek to use such a tool in disciplines that have practical activities. Therefore, the remote laboratory can be seen as a way to optimize the use of resources, as we could have the sharing of the use of experimental resources by several Universities and, consequently, the number of students served would be effectively increased. In addition, it must be considered that the laboratory could be used at different times, only by pre-scheduling. The remote laboratory has become a viable option for educational institutions because it aims to solve some of the usual problems that occur in the vast majority of institutions of higher education. These problems include the allocation of large amount of financial resources for the purchase and maintenance of the equipment necessary for the realization of the experiments. Also, troubles related the physical dimensions of the laboratories, which in most institutions, is not adequate for the number of students in the course. Additionally, the insufficient amount of equipment stands available for the experiment; and the time limitation for the execution of the experiment, often insufficient to complete the work, due to the sharing of the same physical space for several disciplines that need to use the same laboratory. Other factors, not less important than, are:

- The limiting of the use of more sophisticated equipment by students;
- The need for technicians to assemble, disassemble, and maintain experimental equipment;
- The difficulties to adapt activities for students with special conditions.

From the definition of remote laboratory provided by Casini, a possible architecture of this type of laboratory is shown in Fig.1, which consists of the following main systems: a laboratory server, an experiment control platform, an IP camera (web cam) and several objects under control, normally these objects must be programmed to allow complete control of the experiment via software.

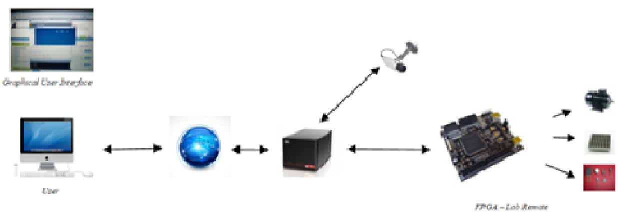

Figure 1. Block diagram of a remote laboratory

In the literature, were found implementations of remote laboratories for teaching Digital Electronics based on FPGA (Drutarovsky, et al, 2009; Ayodele, et al, 2009; Vera, et al, 2012; Karthik, et al, 2014; Garijo, et al, 2016). FPGA-based remote lab typically have three main elements: a configurable platform based on FPGA, server and IP camera. User interfaces are usually built with a programming language like html or Java, or can be implemented using proprietary software such as LabView or Matlab. Students and teachers can evaluate the results of the experiment in real time by means of streaming video using IP cameras, or by accessing user interfaces that have a database stores and makes available the results of the experiment directly on the computer screen. Interactive interfaces of the measurement equipment, coupled to the experiment platform, can also be used to show the results of the experiment. In this article we are proposing the implementation of a remote laboratory based on FPGA to be used as a support tool for the practical activities related to the discipline of Digital Electronics in courses in Electrical Engineering, Computer Engineering, Control and Automation Engineering, and related courses Exact Sciences area. The remote lab is based on the Altera DE0 Board, and is connected to a server via a USB port. The server is connected to the internet through the internal network available at the University. With the use of the TeamViewer tool, students can perform remote access to the server, so they can perform pre-available activities or use the platform to test their own projects. The only restriction of the remote platform is that the developed projects can only use the preexisting interfaces in the Altera DE0 Board (DE0 Kit), as input or output. The entire process of executing the remote experiment can be monitored in real time by the user, and access to the platform can be performed at any time of the day. This article is organized as follows: the section II provides a description of the proposed architecture for implementing the FPGA-based remote laboratory; the section III presents the proposed methodology for using the remote laboratory; the section IV shows the preliminary results of using the platform; and the conclusion and future work are presented in section V.

FPGA-BASED REMOTE LAB: The develop platform for the execution of remote experiments in the area of Digital Electronics has the following characteristics:

- Allows the execution of experiments in real time;
- Enables the execution of experimental activities previously developed in the face-to-face laboratory;
- Allows access at any time, that is, the platform can be online without interruption;
- Enables users to also use of software tools available on the server to perform logic circuits analysis by simulation, i.e., the platform can be used to perform actions virtual laboratory;
- Makes available ways for that projects developed by students to be configured in the FPGA, and then tested and validated.

The main hardware used is Altera's DE0 Development and Education Board (Terasic, 2011). The DE0 kit provides the perfect environment for testing projects implemented in reconfigurable logic, with the FPGA Cyclone III EP3C16F484C6N component that has 15,408 LEs for configuration. The DE0 kit also has 346 I / O pins for users, as well as a variety of connectors that allow the interfacing of the FPGA Cyclone with keyboard, monitor, mouse, keys, buttons, displays, led´s, GPIO bus, among others. The Fig.2 show the photo of the DE0 kit, indicating its main elements and the location of its connectors.
The user interface was developed in Python. The interface module developed has the main function realize communicating between the software tool Quartus II from Intel manufacturer with the DE0 kit that is physically connected to the server. The choice of using the Python language is due to it is really easy to assemble, understand and execute future actions to maintain the interface environment. As well as the possibility of future migration to a web interface.

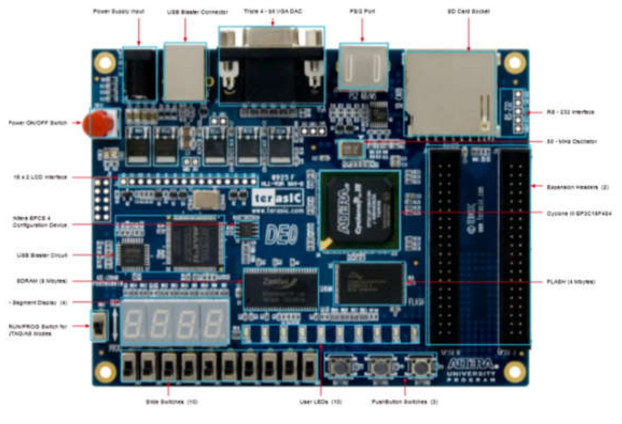

Figure 2. Altera's DE0 Development and Education Board, (Terasic, 2011)

In this application, the Python Kivy (Kivy, 2010) library was used, aiming to facilitate and make the development of graphical interfaces less complex. The program developed for this application offers an interface for the user where, as seen in Fig.3, it is possible view, through a camera, the DE0 kit and also the virtual control panel that allows to control the physical keys (toggle keys and buttons) present in the DE0 kit.

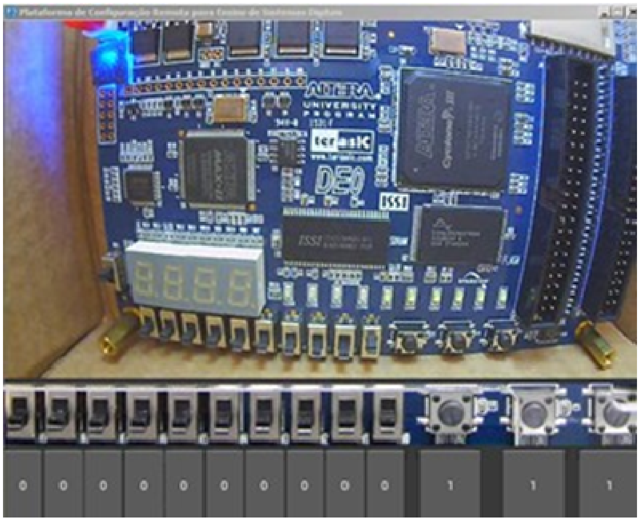

Figure 3.Graphical User Interface developed

The developed software works together with Quartus II through its command-line based tool using the package called quartus_stp (Quartus, 2013). This command loads the TCL packages for a series of tools that communicate with the device through the JTAG Interface. Using the parameter insystem_memory_edit of this tool we obtain commands that read and modify the contents of the memory when this feature is enabled, with this we can change the contents of an internal register, memory block, created initially to store a given value, binary information, such as a constant. In this way, emulating the physical keys present in DE0 Board.

PROPOSED METHODOLOGY FOR THE USE OF THE REMOTE LAB: The remote laboratory can be used to synthesize both combinational and sequential system design directly from a simple graphical user interface, in which few clicks are required for realize the simulate and test of experiments. In the developed distance learning environment of Digital Electronics, the user, student or teacher, has a his disposal a hierarchy of files, in which he can develop predefined activities as well as has the possibility to synthesize his own projects, but limited to complexity of the DE0 kit. In the remote platform there are the following pedagogical resources:

- Laboratory Guide: material containing the objectives and concepts necessary for carrying out the proposed experimental activity.
- Multimedia Material: contains additional information about the practical experiment in a language adapted to digitally available resources, mainly in the form of hypermedia and / or hypertext.
- Virtual Lab: It is a learning object that allows the realization of simulations of virtual experimental digital parameterized systems, so that the user can exercise investigative attitudes about a particular subject. The results are presented in the form of a time diagram, in which the user can at any time intervene by changing the information of the input vectors, and reworking the analysis of the experiment in question.
- Expanding Knowledge: one or more problems are presented in the form of challenge. In the challenges, there are problems that may intrigue and, in fact, motivate the user to look at the proposed issue, getting involved with reading, reflection, discussions and experimentation in search of a solution.
- Remote Lab: It is the item used for the user to configure the DE0 kit with a given pre-established experiment linked to the subject matter indicated in the laboratory guide.
- Complementary Material: Resource that presents the resolution of several problems related to the theme of the activity proposed and executed remotely. This resolution presents comments and discussions can complement the user's study and also help in the learning process these students.

In addition, for the student who developed his own project, a virtual logic block was developed and a script for using it was also created and made available on the server, so that it is intuitive for the student to adapt his project to use the inputs available in the DE0 kit. In this way, the experimental platform will be accessible to a larger number of students through test schedules, being possible to at the start, carry out all the development steps of the project on your own computer, and only perform the final test step in the DE0 Kit remotely. In this perspective, it is possible to adopt didactic practices based on the so-called active learning methodologies. One possibility is the use of the remote laboratory to carry out the Flipped Classroom from on a proposal of hybrid learning. As Schneider (2013) emphasizes, the Flipped Classroom emerged in American high schools from the idea of reversing the logic of traditionally taught classes: instead of students watching expository classes at school, occupying a passive position on the teaching and learning process and carrying out school tasks at home, students are instructed to, on their own, in places and times that they choose, to prepare for classes by reading texts, watching videos, for to carry out a more complex task in class, occupying a more active position, in which the knowledge that was previously studied is then discussed. Our proposal is that, with this remote platform, engineering students can access the experiment beforehand, collect the data, set up their projects and in the classroom, discuss the results, clarify their doubts, in short, take a more active and responsible posture before their learning.

RESULTS

The proposed remote platform offers the possibility of carrying out several experiments, the main constituent elements of this being showed below:

- DE0 kit and server;
- The inputs (keys, buttons, clock) which are directly controlled by the FPGA in the DE0 kit;
- A webcam and a lighting system are present to provide a clear video of the run of the experiment for the user in real time.

All components are allocated in such a way to mount the platform as shown in Fig.4.

Figure 4. Prototype of platform remote

Currently, didactic content is available on the server to carry out various experiments of Digital Systems. Students can choose from fundamental experiments based on logic gates to advanced experiments involving concepts of sequential logic. The Fig.5 shows the content available for the study of the topic of flip-flop and related devices, with some projects / experiments being made available to be performed remotely by the user, such as: ring counter, Johnson counter, BCD counter configured as module counter 24 or 60, pseudo-random counter of 4 bits and a simplified design of a digital clock. Therefore, from these experiments the student will be able to sediment the concepts related to synchronous circuits, such as: What are the characteristics of FFD?; What is difference between synchronous or asynchronous counter?; How project a circuit for realize frequency division?; What types registers are most used in projects of digital systems? That is, the concepts previously presented during the theoretical classes of the discipline of Digital Electronics.
The digital project must be developed with the help of the Quartus II tool, in which the user can choose the best form of input for the description of his project, for example: schematic circuit, state machine editor, or hardware configuration language - VHDL or Verilog. Still in the Quartus II tool, the users can be performing the simulation in order to prove theirs description of the digital system.

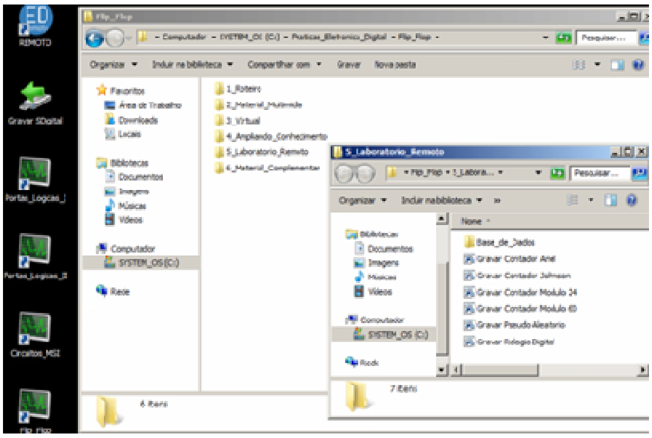

Figure 5. Available material to users on the remote platform server

After validating the project in a virtual way, by simulation, the user must include the module called "DE0_Board" in his project. The DE0_Board module was developed with the purpose of making the control of the keys and buttons present in the DE0 kit accessible, thus allowing total control of the experiment, by the student or teacher, remotely. The Fig.6 shows, as an example, the logic circuit developed to realize the comparison between two words, one provided in decimal format (0 to 9) and the other represented directly by a 4-bit binary vector (called HEXA).

The objective of the experiment is to analyze the operation of the encoder, decoder, magnitude comparator circuits and the interconnection between them. After the execution of the experiment, the student will also be able to describe the function and operation of code converters, in this example a binary to hexadecimal converter was developed, and he will know what precautions to be taken when connecting digital circuits using data bus. The interfaces of the digital system will be: keys, buttons, LEDs and displays of the type 7 segments. Using a priority encoder (74147) the decimal information is converted to the BCD 8421 format and this information is compared with the word HEXA. So we can check if the decimal information is greater than, less than or equal to HEXA information. The result of this comparison is sent to an LED panel, in which only one LED will be active at a time, informing the result of the comparison. The value of the decimal information as well as the HEXA information are decoded and their corresponding values are shown on LED displays of the type 7 segments.

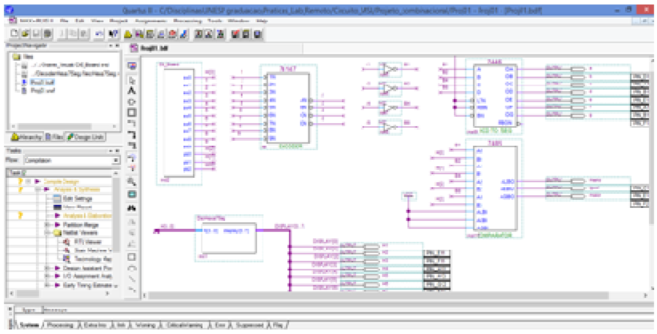

Figure 6. Using Quartus II software in project development

The next step is to configure the project on the remote platform. For this action we use the tool command language (TCL) to automate the use of the Quartus II software programming tool. The Fig.7 shows the screen capture of the automated FPGA configuration process of DE0 Board.

Figure 7. Screenshot showing the automatic DE0 kit configuration process

When the process is finished, the user will have complete control of the keys and buttons of the DE0 board to remotely control the execution of the experiment. The user also has available the simulation results of the proposed circuit on the server. Therefore, the user will be able to make a comparison between the results obtained through the simulation with the real ones obtained from the synthesis of the proposed circuit in FPGA. The result of simulation of the combinational circuit under analysis is shown in Fig.8.

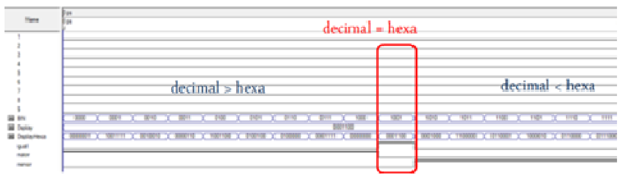

Figure 8. Simulation result of the combinational circuit

In the range of 0 to 2 ms it was established that the decimal value 9 was inserted in the logic circuit, and the HEXA value could assume any of the possible values of its representation range (0x0 to 0xF).

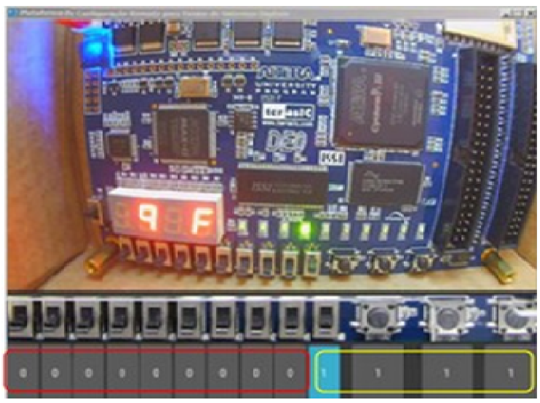

Figure 9. Remote platform operation

In Fig.9, considering the input vectors b "000000000" (decimal input) and b"1111" (HEXA), the values 9 and F will be shown on the displays respectively, and the LED indicating that the HEXA information is greater than the BCD8421 information will be active.

If we change the inputs to b "110000000" and b "0111", the values shown on the displays will be 7 and 7, respectively, and the LED indicating that the information in BCD8421 is equal to the HEXA information will be active, as shown in Fig.10.

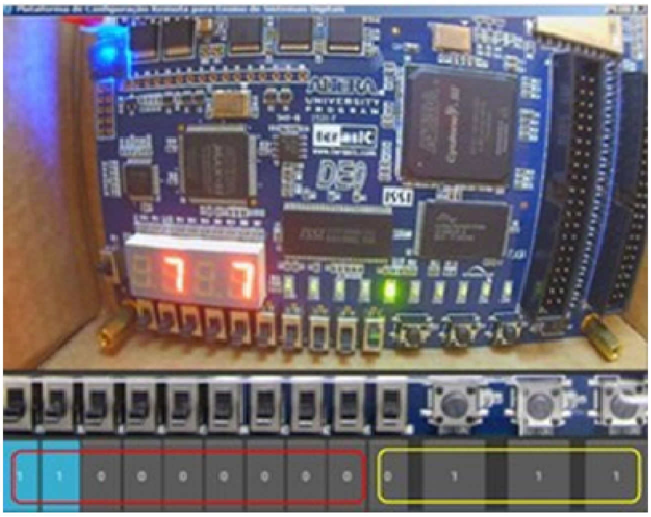

Figure 10. Remote platform operation

As we said before, the remote platform can also be used to solve problems related to sequential circuit designs. There are two more usual ways that the user can use to enter the description of his project in the Quartus II tool, namely: (i) through the graphical interface using the State Machine Editor (Fig.11); or (ii) carrying out the project description using a hardware description language (for example, using VHDL or Verilog).

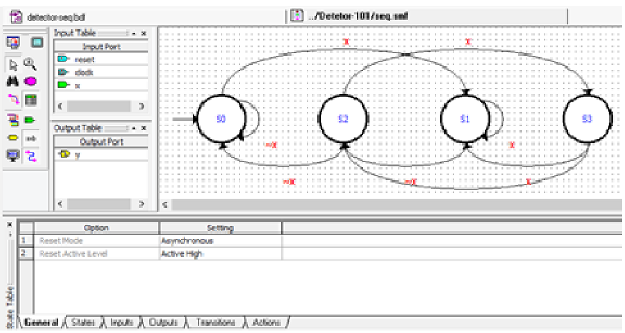

Figure 11. Graphical interface used for description of sequential circuit based on finite state machine

The state diagram shown in Fig.11 represents a sequence detector circuit. When the "101" sequence is identified in an input serial data stream, the circuit output will be activated (ON). After drawing the finite state diagram of the detector, defining which are the input and output signals of the network, the necessary conditions for the execution of the transitions, and how the output must be activated, a VHDL code file (or Verilog) must be generated for the application. Finally, in order to facilitate the development of the application, a symbol file for the project is created, as this will allow the project to be completely described through the graphical interface. The Fig.12 shows the schematic circuit representing the digital pattern detection system, in which additional circuits were inserted to count and show the number of occurrences of the "101" sequence in a given data stream.

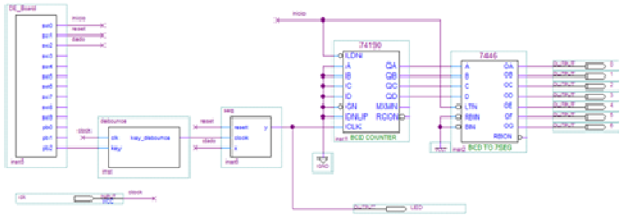

Figure 12. Sequential circuit

For the test to the operation of the circuit it is necessary to have a clock signal to synchronize the operation of the system. For that, we have to choose between one of the three options available on the platform to generate the referred signal, namely:

- Button: The sequential circuit will be controlled by a clock signal generated by a push-button (pb0, pb1, pb2). In this situation, we have a manual sync signal.
- Internal Clock: The FPGA's timing will be controlled by its 50Mhz internal clock signal. This signal is available in the DE0 Kit.
- User-defined clock: The FPGA will be controlled by a clock signal with a user-defined frequency. In this case, the user will have at his disposal a parameterizable frequency divider module that can specify the frequency of the signal in the range of 1Hz to 50MHz.

When the first option is used, it is possible to control the system's synchronism speed, and therefore, it is possible to check the project's operation in more detail (step-by-step). When we use the other options to generate the clock signal, the circuit will be synchronized and will operate automatically. The selection of which sync signal to use will depend on the particular characteristics of each project, and on the needs to be explored by the teacher or student of the application. After completing the sequential circuit project to perform the prototype tests the user must repeat the process of accessing the web server and synthesizing the FPGA. After that, through keys and buttons, the student or teacher will be able to completely interact with the prototype of the developed circuit. The entire process will be viewed through a webcam. The Fig.13 shows the operation of the pattern detector after the detection of two "101" sequences in a given data stream. Therefore, we verified that, from the procedures presented, several digital project, combinational or sequential, can be developed, synthesized and tested through the use of the remote platform, quickly and efficiently.

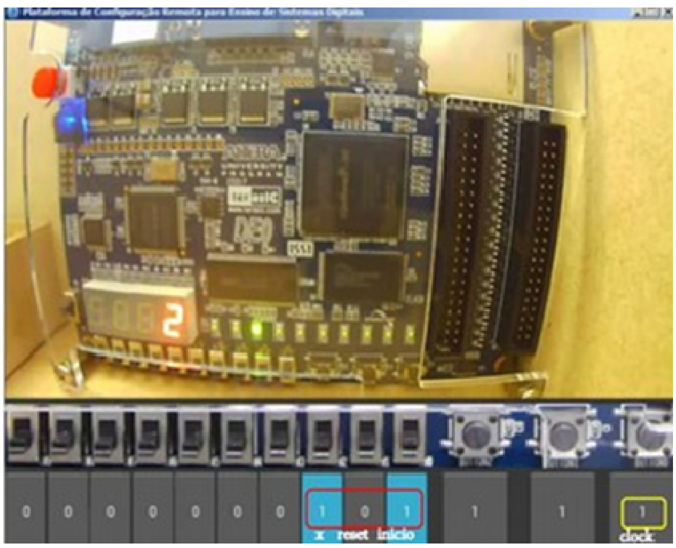

Figure 13. Remote platform operation, test of the sequential circuit (sequence "101")

Comparing our proposal with other remote laboratories cited in the literature (Drutarovsky, et al, 2009; Ayodele, et al, 2009; Vera, et al, 2012; Karthik, et al, 2014; Garijo, et al, 2016), we can say that ours is more efficient because it proposes a simpler way for the user to be able to configure, validate and view the results of the application in real time through a streaming video obtained via an IP camera. For example, in Drutarovsky (Drutarovsky, et al, 2009) solutions are proposed that will require the use of high-cost measurement equipment, which may render their implementation impractical, or the need to purchase data acquisition cards and pre-install proprietary software, such as LabView, to manage the entire process of using the remote lab. In Karthik (Karthik, et al, 2014) there was a need for additional hardware based on the ATmega328 microcontroller to act as an interface module between the computer (server) and the FPGA, managing the data flow between the computer and the FPGA. In this proposal, a graphical user interface was developed in LabView to make the output data available to the user. One of the advantages of our remote laboratory proposal is that the user will not need to learn to use a new tool in order to access and use the remote platform, because there is no need to use a software tool specific to make the system interface (between server and DE0 board). In addition, as the entire process of configuring and updating the application is based on the quartus_stp package, we don't need to design additional hardware based on a microcontroller or microprocessor, to send data in real time to the FPGA, because with the insystem_memory_edit parameter a command is used that modifies the contents of the memory, with this we can change the contents of an internal register of our virtual block, thus emulating the activation of the physical keys of the DE0 kit. And from a streaming video obtained from the use of the IP camera, we can evaluate the results of the experiments also in real time. Finally, and no less important, it was the proposed methodology so that the remote platform can be effectively used as an educational instrument for activities practical in Digital Electronics, presenting the pedagogical resources necessary for the adoption of teaching practices based on the principles of methodologies active learning.

CONCLUSION AND FUTURE WORKS

With the use of the remote experimental platform students can develop their digital projects and also have a way to synthesize and test projects in real way. Therefore, this action allows the student to sediment the theoretical knowledge presented previously in the classroom and / or to reinforce the concepts obtained during the practical classes of the discipline. The platform allows the entire project development process to be carried out directly on the server that controls the entire system, in which case the student must access the Quartus II design tool and follow the steps indicated on the server to be able to test their project directly on a real platform (DE0 Board). Another way to use the remote platform is the student to develop the project completely remotely. In this case, the student must have installed the Quartus II development tool on his own computer. For the project-testing step, the user receives a file (or download) with the instructions to be followed to adapt his project to the needs of the remote platform, and then synthesize and test his project on the development board.The remote platform also provides a mean for students to carry out experiments involving concepts that will still be discussed in the theoretical classes, in order to instigate and / or arouse students curiosity in the field of Electronics. In the future, one goal is to develop a more efficient platform access control, mainly by creating a reserve control of remote platform usage. In that way, it will be possible to control the time of usage of the student. In addition, it will allow multiple users to use simultaneously the platform, but with the condition that only one user is responsible for controlling the experiment, and others can only see what is being executed.

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