A Simulation Environment for e-Learning in Digital Design

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Abstract—**Deeds is a simulation environment for e-learning in digital electronics. The simulators cover combinational and sequential logic networks, finite state-machine design, and microcomputer interfacing and programming. They are integrated together, and therefore allow the design and test of embedded digital systems. The environment guides students' activities by delivering learning materials through specialized browsers. An extensive collection of learning materials is available. This paper includes an example of activity on a problem assignment.**

Index Terms—**Circuit simulation, digital circuits, e-learning.**

I. Introduction

In the field of digital electronics, the explosive development of the last decades has changed component fabrication and design procedures, with profound implications for educational practices. Computer-aided-design (CAD) techniques have evolved from schematic drawing tools to a central part of the design process, covering almost all design phases. They are essential when dealing with complex systems, particularly after the introduction of programmable logic devices (PLDs) [1]–[7].

In the past, the laboratory practice was based on the construction and testing of circuit prototypes. Educational laboratories served many purposes: from demonstrations of principles to practice of measurements and from design and prototyping to testing and troubleshooting. The extension of CAD techniques to the educational field has been a natural evolution.

Information and communication technologies have deeply influenced the framework of education, opening new perspectives, particularly for scientific and technological disciplines [8]. The authors have explored at length the potentialities of hypertexts, author languages, multimedia materials, and, mainly, highly interactive learning tools, with the aim of developing an effective learning environment for electronics [9]. The experience made by the authors has suggested to substitute a quite large set of independent learning tools with a general-purpose simulator.

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At the same time, the diffusion of Internet has shifted the attention toward applications focused on communication and cooperation [10], [11]. The concept of accessing devices via web in order to remotely execute experiments has emerged, and it is now a consolidated practice: Internet-controlled remote laboratories for electronics are already available in many educational institutions [12]–[15]. The use of PLD-based boards [16], [17] allows for the setting up of remote laboratories for digital electronics dealing with relatively complex digital systems. Remote laboratories represent, at this moment, a sort of a middle way between the traditional and simulation-based (or "virtual") digital laboratories, which are the backbone of any current digital-electronic pedagogy.

Existing implementations of virtual laboratories for digital electronics are based either on professional applications or simulation tools designed for educational purposes. A partial list of commercial products targeting the educational field includes the following: Xilinx (see http://www.xilinx.com), Altera (see http://www.altera.com), OrCAD (see http://www.cadence.com/products/orcad), NI MultiSim (formerly Electronics Workbench) (see http://www.ni.com/academic/multisim), Tina Design Suite (see http://www.designsoftware.com), Digital Works (see http://www.spsu.edu/cs/faculty/bbrown/circuits/howto.html), MacroSim (see http://www.engineering-software.com/pr/addProd106.htm), and Proteus (see http://www.labcenter.co.uk/index_uk.htm).

The scenario is more difficult to describe when dealing with simulators developed in a nonprofit perspective: while the commercial packages tend to cover the whole set of digital devices and techniques, it is common to find, in this category, tools dedicated only to specific topics.

WinLogiLab, for example, is a teaching suite for the design of combinatorial and sequential logic circuits, which is composed of a set of tutorials aiming at bridging the gap between theory and practice by mixing together tutorials and simulators [18] (see http://132.234.129.50/WinLLab/WinLLab.html).

Aside from the complete list, the following could also be included: Circuit Shop (see http://www.cherrywoodsystems.com/cshop1.htm), Digital Simulator (see http://www.mit.edu/people/ara/ds.html), EasySim (see http://www.research-systems.com/easysim/easysim.htm), Logisim (see http://ozark.hendrix.edu/~burch/logisim), Digital WorkShop (see http://www.cise.ufl.edu/~fishwick/dig/DigSim.html), and the simulation environment described in this paper.

The authors considered the possibility of adopting a professional simulation tool. They took note of the fact that traditional simulators lack, usually, the capability to interact with the learning material. Moreover, they are oriented to professional users and need proper frame of mind and skills that students of introductory courses generally do not master. In conclusion, the authors decided to develop an environment that, while providing professional simulation performances, would allow the possibility to logically link the simulator operations with the tutorial materials.

In synthesis, the desired target can be looked at from two different points of view: either as learning materials that include general simulation capabilities or as a simulator that is capable of delivering learning contents.

II. Simulation Environment

Deeds (Digital Electronics Education and Design Suite) is a learning environment for digital electronics, which provides an innovative set of tools and resources for teachers and students [19] (see http://www.esng.dibe.unige.it/netpro/Deeds).

Several people in the Department of Biophysical and Electronic Engineering, University of Genoa, Italy, have contributed to the birth of Deeds, with the first prototypes of simulators for digital electronics. NetPro (see http://netpro.evtek.fi), which is a European project of the Leonardo DaVinci Program, running from 1997 to 2003, has served as a catalyst and support for the development of the Deeds toward its current architecture.

Deeds is a set of Windows applications to be installed on the user's personal computer (PC): it has been developed in Delphi Object Pascal. Deeds simulators can run independently or in connection with the web repositories of learning material using the included browsers. Deeds is available, from its Web site, free of charge.

It is extensively used by the students of the first and second years of electronic and information engineering at the University of Genoa to support laboratory activity and project-based courses.

Deeds is composed of three simulators that cover combinational and sequential logic networks, finite state-machine (FSM) design, and microcomputer interfacing and programming at assembly level. They are characterized by their pedagogical orientation but still provide good simulation capabilities. Being fully integrated together, the tools allow the design and simulation of complex networks, including standard logic, FSMs, and embedded microcomputers.

As a consequence, the environment familiarizes the beginner students with current design practices, based on embedded systems, a subject that is receiving a growing attention from the engineering education community [20], [21]. Deeds-based embedded systems, in spite of their apparent simplicity, provide a good understanding of the interaction and tradeoff between hardware and software, building the skills that are the base of current state-of-the-art implementations as in [22]–[25]. The growing complexity of current embedded systems calls for the use of embedded platforms and high-level languages for their design. This process inevitably shifts the focus of attention toward designing at the system level and rightly suggests a top-down approach. The authors are convinced that, to provide good foundations to the education of the professional designer of embedded systems, a bottom-up path, such as the one provided by the Deeds, plays an essential role.

The simulators are integrated with specialized HTML browsers, enabling Internet navigation to find pages with information, exercises, and laboratory assignments. The browsers are used to provide support to students in their work.

The environment helps students in acquiring the theoretical foundations of digital design, together with analysis and problem-solving capabilities and practical synthesis and design skills. Deeds can be adapted to different formats of instruction (lectures, exercises, laboratory assignments, etc.) and can be used at different student levels. To do so, teachers can combine together and personalize the available simulation tools to suit their pedagogical needs by contributing their own learning materials to the lecture space. The simulation tools themselves may adapt to different student levels and provide a subset of their features when used with the beginners.

A question regarding the lack of physical experiments in a Deeds-based laboratory has been frequently asked to the authors [26]. They believe, with the support of several years of experience in introductory courses, that simulation of digital circuits shows many advantages over the previous practical laboratory activity, usually consisting in the breadboarding of circuits with TTL parts. The "construction" of the network, in a schematic editor, is easier and faster than the previous task of breadboard wiring, frustrating, and of dubious pedagogical value for the student. The loss of contact with the physical reality of a digital system is totally acceptable when the sensorial experience is limited to the observation of LEDs as output devices. Of course, things could be different with more complex circuits and sophisticated input/output devices (i.e., a robot arm) or when real measurements are a target of the laboratory activities.

III. Deeds Tools

The simulators included in the Deeds package are the digital-circuit simulator (d-DcS), the FSM simulator (d-FsM), and the microcomputer emulator (d-McE).

The d-DcS has been specifically developed with educational needs in mind, and therefore, it is designed to be easy to use while maintaining quasi-professional features. Its user interface is intuitive, and the choice of digital components available in its library is based on their logical function (not on commercial parts).

The library includes user-definable components that the user can design as FSMs and build with the d-FsM tool. When opened, the d-DcS appears to the student as a graphical schematic editor (Fig. 1).

The library includes an 8-bit microcomputer for embedded applications, which can be connected through standard input/output parallel ports, besides other inputs such as clock, reset, and interrupt request. Using standard logic and/or FSM components, the schematic editor allows the assembly of specialized input/output devices that can be connected to the microcomputer. The firmware can be programmed at the assembly language level (using the d-McE tool).

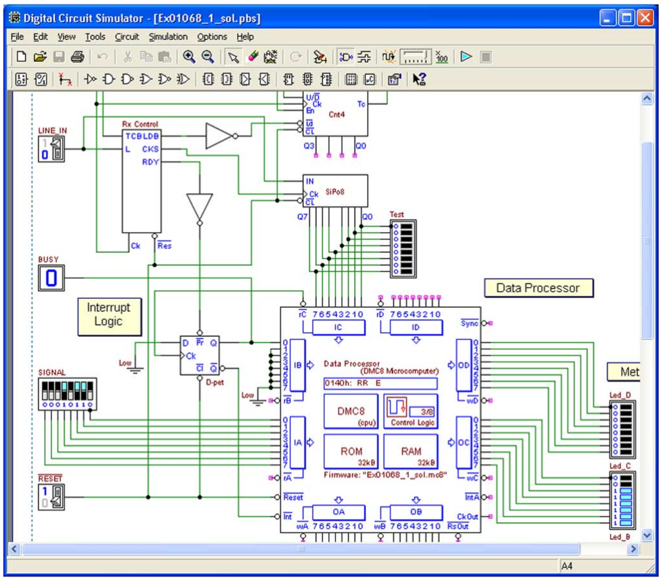

Fig. 1. Deeds d-DcS.

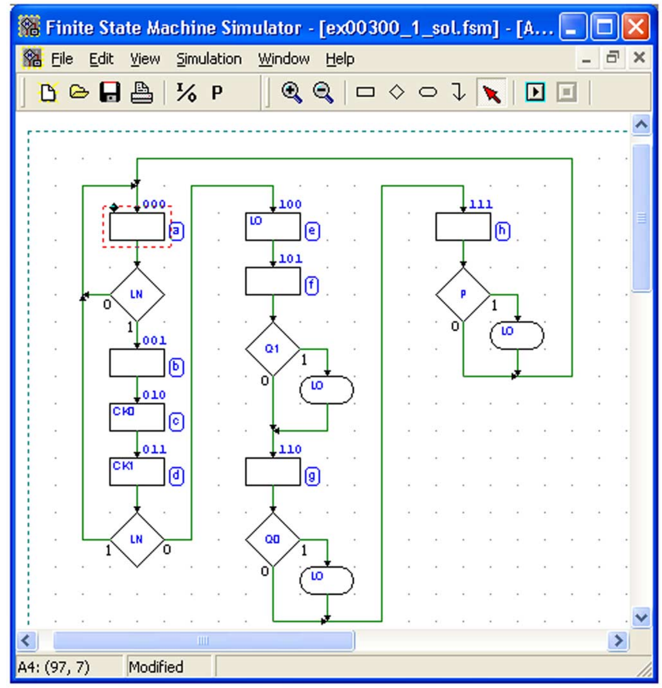

Fig. 2. Algorithmic state-machine chart, edited in the Deeds d-FsM.

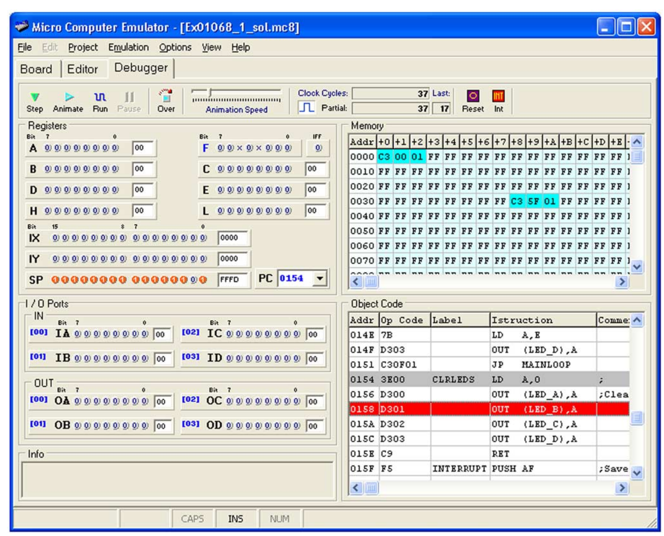

Fig. 3. Interactive debugger of the d-McE.

In the d-DcS, the simulation is event-driven and takes into account the delay times of components. Simulation can be interactive or in a timing-diagram mode. In the first mode, the student can "animate" the digital system in the editor, controlling its inputs and observing the results. This is the simplest mode to examine a digital network, and this way of operation can be useful for the beginners. In the timing-diagram mode, the behavior of the circuit can be analyzed by a timing-diagram window, in which the user can graphically define an input-signal sequence and observe the simulation results. This mode is similar to the one adopted by the professional simulators. Simulation speed is totally satisfactory when using Deeds with its repository of learning material. Since time performance has never been a problem, no comparison with similar products has been made.

The d-FsM tool allows graphical editing and simulation of the FSM components using the algorithmic-state-machine (ASM) paradigm (Fig. 2). The tool is able to functionally simulate the FSM designed by the user, with a runtime display of the relations between states and timing evolution. The components created by the d-FsM can be directly used in the d-DcS and inserted into the digital circuit schematic.

With d-McE, the user can practice microcomputer programming at the assembly language level. The emulated system includes a CPU, ROM and RAM memory banks, parallel I/O ports, a reset circuitry, and a basic interrupt logic. The custom 8-bit CPU, named DMC8, has been designed to suit the educational needs of an introductory course, and it is based on a simplified version of the well-known "Z80-CPU" processor. The possibility of emulating a state-of-the-art processor has been ruled out because its complex architecture would be a formidable obstacle in understanding the basic principles of machine-level programming.

The integrated code editor enables the user to enter source programs, and a simple command permits one to assemble, link, and load them in the emulated system memory. The execution of the programs can be run step by step in the interactive debugger (Fig. 3), where the user can observe all the structures involved in the hardware/software system: the ROM and RAM memory contents, the I/O port state, the CPU registers, and the assembly code in execution.

The files generated by the d-DcS simulator are in proprietary format and cannot be directly exchanged with other simulation tools. The d-FsM tool, instead, can export its files describing the FSM in a hardware description language (VHDL), allowing their reuse in professional design tools. Source programs written with the d-McE emulator are text files and, therefore, are compatible with the standard Z80 assembler.

IV. e-Learning With Deeds

The experience of the authors in the educational use of Deeds dates from several years ago when the first versions of the simulators were released.

A very significant step has been the application of Deeds in the context of the NetPro project. NetPro promoted the project-based learning in the Internet with the creation of models, tools, and services to facilitate communication and collaboration between distant students and to manage access and control of project deliverables [27].

Deeds has been used as a common simulation tool that is shared among different institutions running courses on digital design. The authors tested the NetPro methodologies and tools by running pilot projects targeted to the field of electronics [28] (see http://www.esng.dibe.unige.it/netpro).

Deeds functionalities and pedagogical applications have co-evolved in close contact: the technical evolution of the tools has been dictated mainly by the needs emerged during the educational practice. The more exhaustive experience has been made in what is called a "blended" environment, which is a pedagogical situation where traditional lectures coexist with some form of distance learning. According to Gillet *et al.* [29], blended learning favors the evolution from traditional teaching to active learning, a target that the authors are looking forward to.

Currently, the Deeds laboratory is used in a PC classroom, with a tutorial assistance and in a distant mode, through the Internet. Both cases are supported by Moodle (from www.moodle.org), the Learning Management System (LMS) adopted as a standard by the University of Genoa at https://www.aulaweb.unige.it.

The LMS guides students, at the beginning of each course, to install the Deeds and, then, provides, as resources, a set of guided laboratory sessions, as described in the following.

The integration of Deeds with an LMS provides an added value for teachers and students alike.

Teachers can easily keep track of students' activity, provide news and guidance, have access to the project deliverables, and, generally, take advantage of the LMS features to manage the course. Students gain a large amount of flexibility in the execution of the projects, and they can exchange information with their peers and get help by the teachers through the discussion forums.

Deeds' e-learning features are intrinsic to its main characteristic, i.e., the close association of the simulators with the online learning material, which is obtained through its browsers. The main browser is used to present the problems' lists, while individual assignments are opened in the assistant browser.

A large repository of problems is available with a total freedom of navigation among individual problems (see http://www.esng.dibe.unige.it/netpro/Deeds/LearningMaterials/Index.htm).

Deeds presents a project as an HTML document with text, figures, and other visual objects that can be active, i.e., working as commands to the editing and simulation tools. For example, let us suppose to assign a problem in the form of a schematic

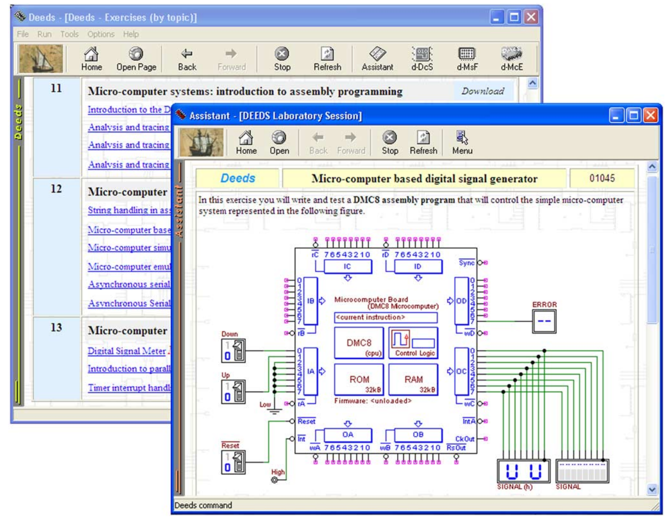

Fig. 4. Distance laboratory assignment proposed by (on front) the assistant browser and (on rear) an index of problems opened in the main browser.

to analyze or modify. When the user clicks on the schematic in the browser, Deeds launches the corresponding simulator and opens that schematic in it. If guidance is needed, the Deeds opens the assistant browser that may provide more information on how to design, explore, or test the circuit itself.

The target of traditional exercises is to help students understand the theory. Usually, a feedback from the teacher on the correctness of the solutions is necessary. A Deeds exercise, instead, is always a project (Fig. 4).

The role of Deeds is to allow students to work out a solution and, at the same time, to check its correctness, i.e., its consistency with the project specifications. Teacher's feedback becomes, if not irrelevant, at least not essential for the students since they must know by themselves if their work is correct. The aforementioned statement is the most important advantage of implementing a project with a simulation tool.

Usually, a laboratory report is requested: a proper template speeds up its preparation and allows the student to concentrate more in the technical work. When learners are satisfied with their work, they use Deeds to deliver the reports through the LMS and the Internet (Fig. 5).

Another important feature of Deeds, making it more flexible in facing students of different technical levels, is the ability to deliver a suitable trace of the solution (i.e., a partial schematic of the solution). Using this approach, students can be guided to the desired level of problem solving, for example, avoiding repetitive tasks.

The d-DcS feature, allowing the saving of input-signal sequences (Fig. 6), provides further pedagogical advantages. Dealing with the acquisition of circuit analysis skills, to facilitate understanding of the proper behavior of the circuits under test, teachers can propose one or more meaningful sets of input sequences, which are included in the same circuit schematic file.

Saved input sequences are useful to learn circuit design, too, by providing to the students predefined sets of input signals. In addition to the system specifications expressed by text, the

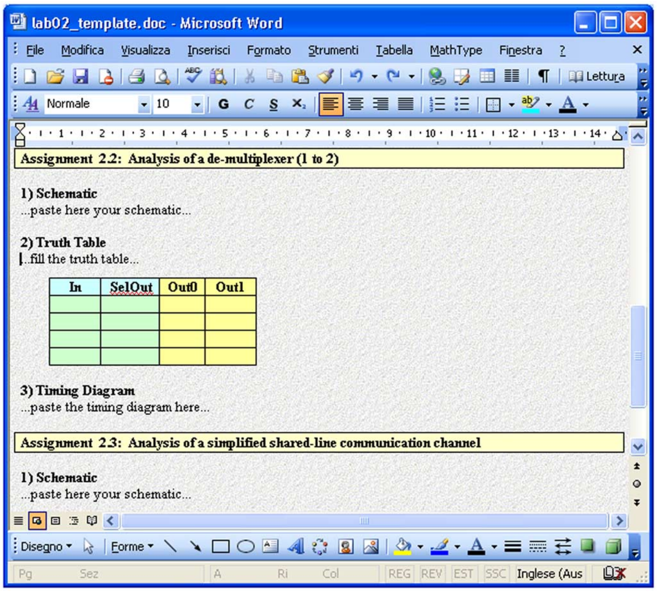

Fig. 5. Deeds laboratory-report template that the student completes and delivers through the Internet.

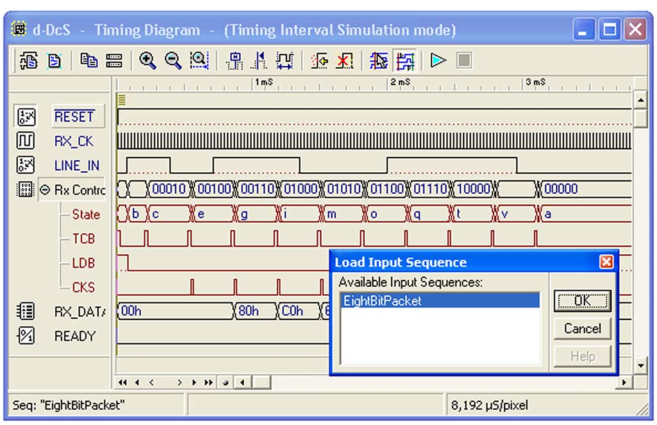

Fig. 6. Example of timing analysis using a saved timing signal set, as proposed by the teacher.

teacher can provide the appropriated input sequences against which testing the implementations, including them into the solution trace. Together with the schematics of the solution, the delivery of proper input test sequences is usually part of the assignments.

Deeds is, by its own conception, a suite of tools aimed at the basic understanding of projects, including both aspects of hardware and software, since the logic simulator can handle a system that is composed of standard digital components, state machines, and microcomputers, as it is the case in contemporary digital design. Deeds allows a low-level total control of the interaction between the logical circuit behavior and the procedural flow of machine-level instruction execution of a microcomputer.

The pedagogical aim of this approach is the understanding of many issues characterizing the embedded systems, like microcomputer interfacing, interrupt handling, real-time operation, and tradeoffs between hardware and software, as a

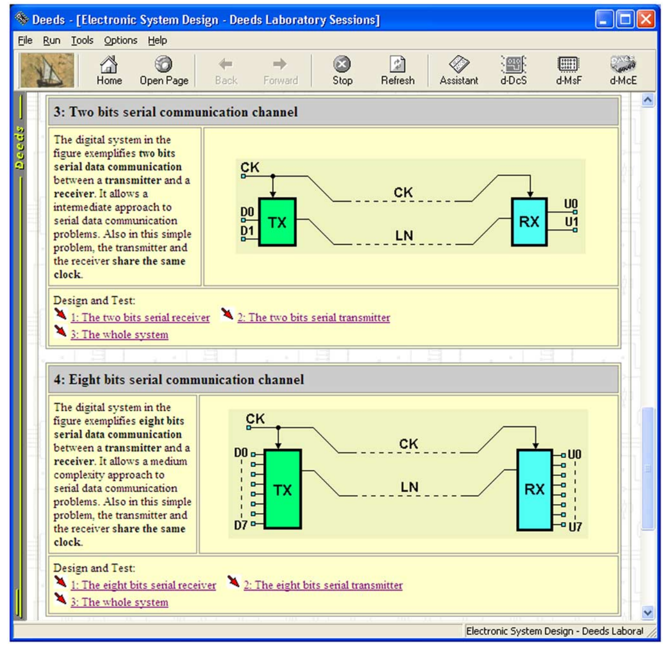

Fig. 7. Deeds main browser shows a list of distance laboratory assignments.

foundation for more advanced digital-design courses. From this point of view, the inclusion of specific tools for the hardware–software codesign and platform-oriented design goes beyond the purposes of the current development phase of Deeds.

V. Example of Distance Laboratory Session

The Deeds structure lends itself very well to support the distance laboratory session, where students develop a digital design project, within the framework of a problem-based-learning constructivist pedagogical methodology. The student groups download the problem assignments from the LMS. An assignment is, generally, a functional description and a set of specifications of a system that students must design and test.

The particular project to develop is only one element of a set of problems, of different difficulty, joined together by the fact that they explore different facets of a main problem. A set of problems starts from simpler problems, introductive to the issues of the assigned project. The learner can move freely within the problems and choose to directly attack the main one or reinforce his knowledge by approaching first the simpler ones. Even if the problems are connected together by their subjects, they can be approached independently one from another. Targets are precisely set, but detailed instructions and explanations are not provided.

The subject of the example reported here is "digital serial-data communication." This topic lends itself very well to explore and master several aspects of digital design.

In Fig. 7, a page with a thematic list of laboratory assignments is opened in the Deeds main browser. The target chosen is the design of an 8-bit synchronous serial receiver (link #1 at the bottom of the figure).

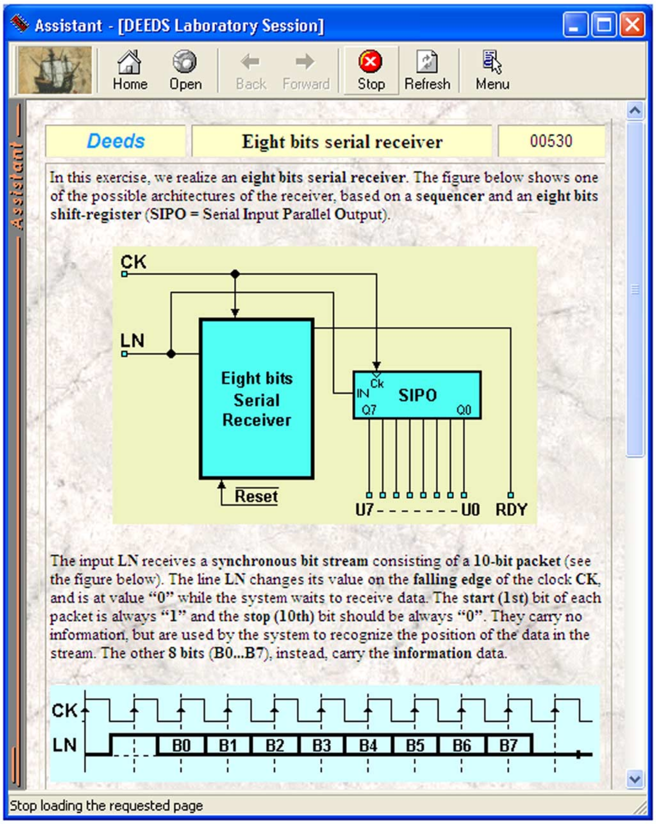

Fig. 8. Specific distance laboratory assignment, as discussed in this paper, opened in the assistant browser.

With a click on the link, the specific assignment will be opened in the assistant browser (partial view in Fig. 8). Since these problems could be approached in different ways, with different circuital architectures, in this problem, the system architecture is set, whereas the control unit design is assigned to the learner. In Fig. 8, the serial receiver is composed of two blocks: a serial-input–parallel-output register, which is in charge of storing the serial data arriving from the input line in parallel format, and a controller–sequencer unit.

The laboratory assignment specifies the simple protocol of the incoming serial-data packets that the receiver must decode. The text continues with the system specifications that the student must implement, designing the circuit control sequencer. Usually, the problem assignment includes one or more files containing partial solution that students can download and open in the specific tool. In this way, they can concentrate on the subject, instead of building the solution from scratch, avoiding the design tasks that are less meaningful at this level. Such option is not mandatory, however, and the student can freely activate the simulator without using the partial-solution files.

In the present example, once completed, the functional description of the sequencer of the receiver, as algorithmic description, will appear as the one shown in Fig. 9, where the d-FsM has been used to design the sequencer behavior.

Users must verify, using the interactive timing simulation integrated in the d-FsM, if their solution matches the correct sequence of output values and state codes. This is accomplished showing, at the same time, the current sequencer state (highlighted on the state diagram) and the corresponding timing sequence, as generated in the timing diagram. This is an important feature because a major difficulty, for the beginners, is the understanding of the relation between the states and the events on the timing diagram.

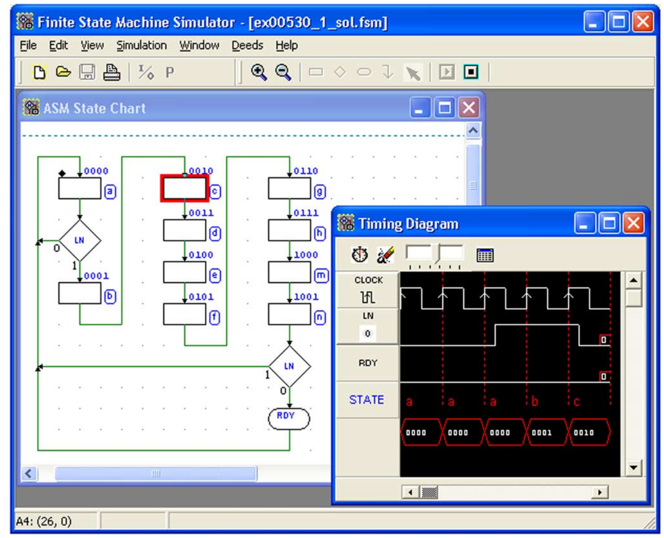

Fig. 9. Algorithmic description of the sequencer, designed and tested with the d-FsM tool.

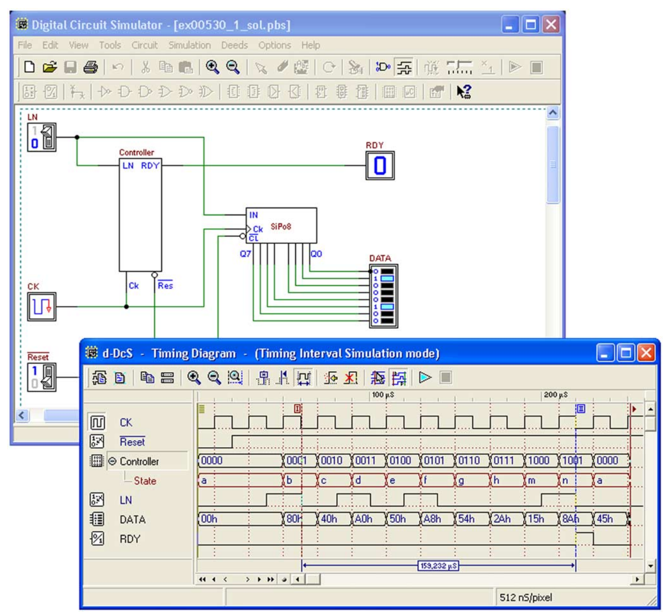

Fig. 10. Completed serial-receiver schematic, and its timing simulation, in the d-DcS.

When the behavior of the sequencer satisfies all the required specifications, the component could be imported in the d-DcS tool. If, as usual, a simple d-DcS partial schematic is provided, the operation is faster without loss of information. Once the schematic is completed, the simulation of the whole system can be obtained in the d-DcS timing simulator (Fig. 10).

A distance laboratory session ends with the uploading of the student report, using the functions of the LMS in use. The student can download and complete a report "template," which is particularly useful for the teacher who will verify all the projects in a standardized format.

VI. Conclusion

Deeds learning material covers, as a whole and at an introductory level, the area of the embedded systems. The Deeds simulation environment is conceived, in accordance with the constructivist methodology, to build in the students the necessary knowledge and skills while developing the problem assignments.

Deeds has now been used by thousands of students at the University of Genoa and other institutions in the first and second year courses of the information engineering curricula. The development team is taking advantage of the continuous feedback from students and colleagues to improve the functionalities and to add new features.

According to the authors, the education results from the use of Deeds are very good. It is very difficult to judge, in an objective and quantitative way, the effectiveness of an educational tool. This statement is particularly true for Deeds that, having evolved and grown for ten years in symbiosis with institutional courses, is now an essential component of their methodology. If the extension of its use is a good indicator, Deeds deserves a good mark. The authors are looking forward to seeing in the future the establishment of an independent evaluation procedure for learning tools [30].

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