

Genuine Lab Experiences for Students in Resource Constrained Environments:

The RealLab with Integrated Intelligent Assessment

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Abstract—Laboratory activities are indispensable for developing engineering skills. Computer Aided Learning (CAL) tools can be used to enhance laboratory learning in various ways, the latest approach being the virtual laboratory technique that emulates traditional laboratory processes. This new approach makes it possible to give students complete and genuine laboratory experiences in situations constrained by limited resources in the provision of laboratory facilities and infrastructure and/or where there is need for laboratory education, for large classes, with only one laboratory stand. This may especially be the case in countries in transition. Most existing virtual laboratories are not available for purchase. Where they are, they may not be cost friendly for resource constrained environments. Also, most do not integrate any form of assessment structure. In this paper, we present a very cost friendly virtual laboratory solution for genuine laboratory experiences in resource constrained environments, with integrated intelligent assessment.

Index Term—virtual breadboard, netlist/simulation, intelligent assessment, neuro-fuzzy classifier, learning characterization

I. INTRODUCTION

Laboratory activities are one of the most important components of engineering education [1]. The value of laboratory experiences is widely acknowledged and physical experiments are indispensable for developing engineering skills. There is need to take advantage of computing facilities to improve laboratory learning because of the low cost, flexibility and versatility of computer systems and the high cost of laboratory equipment. Computer technologies can enhance engineering laboratory education by ensuring a strong correlation between theories and hands-on experimentation [2]. They are able to move beyond the limitations of the traditional laboratory environment since they can provide a wide array of laboratory learning and experimentation tools in a wide variety of forms and formats [3]. Moreover, today's affordable PCs, Object-Oriented Programming (OOP), Graphical Programming, mathematical software tools and other software IT tools now permit the development of interactive and graphical visualization environments that better meet the aims and objectives of laboratory education [4]. The fundamental objectives of engineering laboratory education have been well addressed [5] [6] [7].

“A large number of computer applications are being developed to make learning experience more efficient, flexible, yet at the same time enjoyable” [8]. Computer

Aided (or Assisted) Learning (CAL) tools are learning resources used to assist student in learning a particular concept, subject or experimental procedures through demonstrations, illustrations and simulations [8][9][10][11][12]. The CAL tool is an aid to the overall learning strategy. However, there are a few experiences of using CAL tools for direct practical laboratory experiments. This is exemplified by the current approach of CAL tools in engineering laboratory education, the virtual laboratory. Virtual laboratories emulate traditional experimentation instruments and processes. This new approach is characterized by versatility and low cost, being software based, which makes it possible to give students complete and genuine laboratory experience in situations constrained by very limited resources in the provision of laboratory hardware and infrastructure and/or where there is need for laboratory education, for large classes, with only one laboratory stand. Our work on virtual laboratory is focused, generally, on this challenge.

Basically, there are three types of laboratories: real laboratory (traditional laboratory), remote laboratory and virtual laboratory. All these laboratory types are computer mediated, the major differences being the degree of mediation and the psychology of presence [13]. The real laboratory involves the physical presence of the user in the laboratory where all laboratory instruments are physically set up. The remote laboratories are characterized by mediated reality and are mainly for experimental monitoring and control. Throughout literature, the definition of Virtual Laboratory (VL) is inconsistent and confusing. Virtually every online teaching and learning environment is referred to as VL. However, in this context, we take VL to be software versions of the real laboratory where each experimental setup is implemented in software such that a personal computer can be used to take the place of an entire workbench full measurement and test instruments. Each experiment from signal generation to experimental setup is implemented in software.

The application of virtual laboratory technology has a wide disciplinary spectrum and the majority of the applications are geared towards engineering, with Electrical and Electronic Engineering (EEE) being the most popular. An exhaustive overview of virtual laboratory applications in EEE cannot be given on the limited scope of this paper. However, a few laboratories that demonstrate the feasibility and benefits of virtual laboratories in engineering education deserve to be mentioned. A simulation-based virtual laboratory for teaching power system dynamics and control was

implemented and deployed for use in a number of countries in transition and favourable experiences of the use of the laboratory were reported by users [14]. The laboratory was built by obtaining a simple customized computer application for each laboratory topic using Matlab and Simulink. Other workable virtual laboratories include the Virtual Work Bench for Electronics Instrumentation Teaching by Palop [15] based on a combination of tools (LabVIEW, Matlab, Multisim, Spice and EWB), LabVIEW analogue signal processing virtual laboratory by Hakes [16], Piasni's [17] SWILAB and the Quasi-Stationary Electromagnetics virtual laboratory [18]. Other virtual laboratories are reported by Ubar [19], Zhou [20] and Gopalan [20].

On a higher level, work has been geared towards the implementation of intelligent virtual laboratories and self growing and reconfigurable VLs. The creation of a self-growing VL is oriented towards allowing a continued growing number of new applications over the laboratory aimed at overcoming the limitations of space [21]. The reconfigurable VL is to enable the dynamic reconfiguration of hardware functions too, to ensure instrument versatility in VL [22]. The intelligent universal laboratory (UVL) presents a novel VL approach by integrating an intelligent Tutor in the laboratory environment. The UVL is designed to cater for the experimental needs of both the able and motor disabled, and provides both types of users with a realistic laboratory environment. The disabled user uses a voice recognition device to construct a circuit by voice moving and clicking the mouse and dictating the desired coordinates to place a component [23].

However, most of these existing virtual laboratories are not available for purchase. Where they are, they may not be affordable for resource constrained environments. Their basic building blocks, Matlab, LabVIEW, Spice, Multisim, Authorware and Simulink, are very expensive to license and may not be easily affordable. Our emphasis is not just on building a virtual laboratory but a cost friendly VL that is affordable by even the most resource constrained environments. Also, most existing virtual laboratories do not incorporate integrated assessment structures and there is no common foundation nor agreed upon assessment strategy within the laboratory environment. Student learning is not assessed or characterised, in the virtual environment, with respect to specified knowledge goals, in order to ascertain the readiness of the student to proceed to laboratory activities for the next higher knowledge goal. Assessment in education "describes any processes that appraise an individual's knowledge, understanding, abilities or skills" [7] and equates to testing in order to judge if learning has taken place [24]. Assessment is said to drive learning [25][7].

In this paper, we present a very low cost virtual laboratory solution, with an integrated intelligent assessment structure, for genuine laboratory experiences in resources constrained environments. The rest of the paper is organized as follows: Section 2 discusses virtual laboratory implementation; in section 3, the very low cost virtual laboratory solution, the RealLab, is presented; section 4 addresses how laboratory activities are organized in the laboratory; section 5 and 6 detail the intelligent assessment and student learning level classification; the paper is concluded in section 7.

II. VIRTUAL LABORATORY IMPLEMENTATION

Virtual laboratory are software based and it is software that dictates the overall performance of any system [26]. The language for VL application development is diverse ranging from machine language (Low Level Programming Language (LLPL)) to assembly language to Conventional Programming Languages (CPL) to Object-Oriented Programming (OOP) Languages to Real-Time Programming Languages (RTPL) to Graphical Programming Languages (GPL) to Mathematical/Simulation Programming Environments (M/SPE). Also available are the languages for Web applications such as HTML, XML, etc. and the java technologies. Low level programming languages are mainly used in the development of driver modules. It is up to the user/designer to choose the right software tool for the VL application. Software selection criteria for virtual laboratory implementation has been detailed in [13] some of which are:

- Modularity
- Multi-platform portability
- Compatibility with existing code
- Compatibility with hardware
- Performance
- Intuitive GUI
- Advanced debugging features

VL creation is and should be driven by need. Every implementation depends on the application, the designer and the tools used. No two implementations are exactly alike. However, the basic requirement is that every implementation should be functionally satisfying. The technologies employed in the implementation of the RealLab include Java Applet, JDBC, Java OOP and JavaScript among others.

III. THE REALLAB

The RealLab is a web-based environment able to provide students with an innovative and interactive laboratory learning tools for several undergraduate engineering laboratory courses. In the early years of the EEE degree program, students face the challenge of grasping the basic concepts. In universities offering 5-year undergraduate EEE programmes such as the Federal University of Technology, Owerri (FUTO), one of the target universities for the project, all EEE students take the same subjects in their first three years of study in which they are exposed to the foundations of science and general studies, basic general EEE principles and circuit theory. They begin basic circuit construction activities from second year. As the students enter their 4th and fifth years of study, they concentrate mainly on courses in their areas of specialization. The FUTO EEE department has three areas of specialization: Communication Engineering (COE), Power Systems Engineering (PSE) and Electronic and Computer Engineering (ECE). Some of the general EEE and specific ECE basic courses also serve as major electives for physics students.

Any virtual laboratory that addresses the basic concepts would have contributed in laying a more solid foundation for the students. The nature of the course material for these basic courses need innovative learning skills to grasp and understand the underlying concepts [27]. Hence, the RealLab is a concept to enable EEE students to

A. The RealLab Front-end

The web-based virtual laboratory consists of the front-end and the back-end. The front-end consists mainly of the laboratory's WebPages and the virtual breadboard applet which provides the user with an online GUI to practically construct and simulate electrical circuits. The GUI provides the user with all the components, devices and features to construct a circuit. Components can be clicked and placed on the virtual breadboard and removed and wire connections can be made using stretchable wires of assorted colours. Also, the user has the option of using a single breadboard or two cascaded breadboards depending on the size of the circuit to be constructed (Figures 1 and 2).



- The components panel holds all the circuit components including resistors, capacitors, inductors, diodes, LEDs, wires and transistors.
- The tools panel contains two basic pieces of equipment: the power supply and the function generator. The user can use either positive or negative voltage as desired.



- The function generator can generate square, triangular or sinusoidal signals of different frequencies and amplitude. In the tools panel is

- The workbench holds the breadboard on which the user can undertake circuit construction. The breadboard provides both vertical and horizontal grids numbered A to L and 1 to 28 respectively.
- The Graphical Display panel holds the graphical output from the simulation of the constructed circuit. After circuit construction, simulation is invoked by clicking on the green FIN button, to indicate that circuit construction is complete.
- The result panel displays measured simulation results. For example the value of the voltage across a particular component in the constructed circuit.

At the backend, a number of service programs run including the DBMS and the web server, under XAMPP [28], an integrated server package of MySQL, Apache, PHP and Perl. SPICE OPUS Lite, for simulating the constructed circuit also runs on the server. SPICE OPUS is available in two versions: SPICE OPUS Lite and SPICE OPUS Pro. Analogue, digital, and analogue and digital circuits can be simulated using SPICE OPUS, developed by Faculty of Electrical Engineering, University of Ljubljana, Slovenia. SPICE OPUS Lite is a free version and is available for downloading at [29]. The lite version allows a limited circuit size of 100 nodes, has no user support and optimization tool. SPICE OPUS is invoked when the user clicks the FIN (finish) button on the GUI.

In as much as the virtual laboratory is available to users who wish to carry out any independent work, the laboratory environment contains a number of laboratory activities grouped into sessions. Each session addresses a specific knowledge goal. Bearing the area and level of application in mind, laboratory activities are concentrated mainly on the basics in EEE laboratory learning which have been categorized into a set of knowledge goals, in a prerequisite order. The knowledge goals are a subset of the EEE domain knowledge. Each knowledge goal has a set of outcome concepts and prerequisite concepts. The prerequisite concepts are the concepts the learner should have previous knowledge of in order to fully understand the outcome concepts. Laboratory activities are designed to cover most of the outcome concepts of a knowledge goal. This approach ensures that students carry out concept-based laboratory activities in order to demonstrate and ensure full understanding of knowledge goals whose theories have been learnt in the lectures. In this way, it is hoped to lay a more solid foundation for the neophyte

engineer. Figure 1 highlights a typical knowledge goal and its outcome concepts, Figure 3 is a sample laboratory activity instruction for concept 1 and Figure 4 is the front end diagram of the constructed circuit on the virtual breadboard.

TABLE I.
A KNOWLEDGE GOAL AND ITS CONCEPTS

KNOWLEDGE GOAL: Resistor Circuits		
ORDER	OUTCOME CONCEPTS	PREREQUISITE CONCEPTS
1	Resistors in series	Resistor colour code
2	Voltage dividers	
3	Parallel resistive circuits	
4	Current Dividers	
5	Series-parallel resistive circuits	
6	The Wheatstone bridge	
7	Thevenin's theorem	
8	The maximum power transfer theorem	
9	The superposition theorem	

Five Resistors, R1, R2, R3, R4 and R5, of values 2.2k Ω , 3.3k Ω , 1.0k Ω , 1.2k Ω and 4.7k Ω respectively, are connected in series, in the order R1 to R5 starting from the negative terminal of the dc source. A 5V dc source is connected to the input terminals. Construct and simulate the circuit. Note the value of the voltage across R5.

Reconstruct the circuit of Fig1.1 with the resistors in the following order, starting from the negative terminal, R1, R3, R5, R2 and R4. Simulate and again note the value of the voltage across R5.

Note the observations in your log book and comment on the behaviour of the circuit.

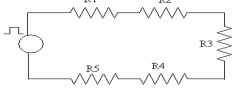


Fig 1.1: Resistors in Series

Figure 3. A Laboratory activity instructions for concept 1

The student must know the resistor colour coding scheme in order to select the right resistors for the project. Also, the student has to select the right dc value, 5V in this case, on the power supply, after switching it on.

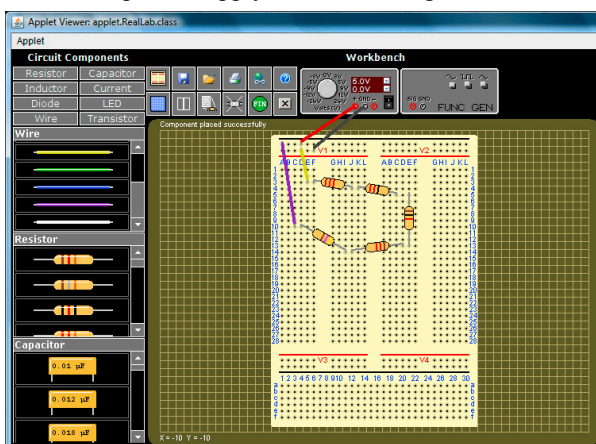


Figure 4. Constructed circuit of a laboratory activity for c1

A. Simulation Steps

As a student constructs a circuit on the breadboard, the schematic data of the circuit is continuously captured and stored. On clicking the FIN button, the netlist generator reads the schematic data and generates a temporary text file. Netlist generation is a very important step prior to the simulation of any circuit. The Netlist holds the circuit information (circuit topology, components types and values) required by Spice Opus for the simulation process. A Netlist verifier checks the temporary Netlist file against various common errors and ensures that it meets the netlist requirements for Spice Opus before the .cir file is generated. Netlist verifier checks the netlist circuit based on the spice opus netlist file format below.

```

Title of the circuit.  ← First line
Circuit description.
Upper or lower case letters.

.control              ← Control block starts here.

Commands for simulation
and outputting results
in only lower case letters.

.endc                ← Control block ends here.

.end                 ← Last line.

```

Source: [30]

It does the check to ensure that none of the following conditions [30] is violated:

- The ground or datum node of the circuit exists and has a number 0 and not letter o or O.
- The circuit does not contain a loop of voltage sources and/or inductors
- Does not contain a cut set of current sources and/or capacitors.
- Each node in the circuit has a D.C. path to ground so, there are no dangling nodes.
- Every node must have at least two connections except for transmission line nodes
- When frequency domain analysis is conducted using ac command, at least one of the sources in the circuit _le must have ac values specified.
- When time domain analysis is conducted using tran command, at least one of the sources in the circuit must have time domain specifications.
- A resistance can not have zero value because this can cause divide by zero error.

V. INTELLIGENT ASSESSMENT IN THE REALLAB

Most course management software packages such as SOAP, WebCT and BlackBoard provide the teacher with some student monitoring and tracking features. Some of such features are also provided in the RealLab. For example:

- the date, login and logout time of each student can be captured.
- a complete history of each student's or the entire class's laboratory attendance can be viewed.

The data can be analyzed in various ways using different criteria. However, these kinds of data do not convey any direct information to the teacher about the actual learning that is or is not taking place. It does not do a learning characterization of a student. Other sources of information must be correlated to derive a characterization

of a student's learning level. Also the weakness of the student with respect to concepts of a particular knowledge goal is not identified. Diagnostic assessment is a very useful tool for identifying student weaknesses.

Hence, the aim in the RealLab is to answer the questions of the types below:

- What is a user's learning level with respect to a particular knowledge goal on completion of a session of laboratory activities.
- Which of the concepts are well understood and which are not.
- Based on a student's learning level for a prerequisite knowledge goal, what should the student do next?
 - Proceed to do the laboratory activities for the next higher knowledge goal?
 - Repeat the just concluded laboratory session?
 - Should be referred back to the tutor to restudy the underlying course
 - Take extra assessment

These questions may not be answered without:

- a characterization of the learning level of a student at the end of the laboratory activities for each session
- determining the areas of weakness of the user with respect to a particular knowledge goal based on diagnostic assessment.

Student modelling is a major tool for student learning characterization and has been referred to as "Cognitive Diagnosis" with three criteria requirements: inputs, procedure for inferring the cognitive state of a student based on the inputs and a description of the generated output [31]. As inputs to the student modeller (classifier), we generate numerical data describing the student's:

- background knowledge
- laboratory performance and behaviour
- cognitive knowledge

The metrics from these assessment measurements are collectively used to characterize a student's learning. This is referred to as authentic student modelling.

"There has been a lot of research and practical implementation of student modelling, especially in the area of Intelligent Tutoring Systems (ITS)" [32]. There are various student modelling techniques [33] [34] [35]. Many of these techniques employ AI approaches and propose different representations of the student knowledge.

A. Background Knowledge Evaluation

The initial characterization of a student is done based on the student's academic performance history in the student's profile, which gives an indication of the background knowledge level. The data in the student profile can be collected from a student himself/herself (through questionnaires) and data gleaned from student records and other sources.

Information contained in the student profile includes:

- GCE/SSCE/WASC scores in physics, chem. and math.
- JAMB and PostJamb scores
- A history of the student's Cumulative Grade Point Average (CGPA).
- Learning styles and preferences.

• Position on the Perry Scheme

Each of these scores and CGPA give an indication of the student's learning level [35]. The student profile is updated at the end of each semester with the current CGPA and other relevant information which ensures that the learning characterization takes into account currently acquired knowledge. In the first semester of first year, the value of the CGPA is null and generalization is based mainly on SSCE and Jamb/PostJamb scores. JAMB and PostJAMB are national university entrance and specific university entrance examinations respectively.

The input variables linguistic fuzzy classifications and a fuzzy rule matrix is constructed (Table 2), in order to associate the inputs with linguistic fuzzy sets describing the student background knowledge.

TABLE II.
FUZZY RULE MATRIX

SSCE CGPA	JAMB/POSTJAMB					
	FAIR		GOOD		EXCELLENT	
WD	VL	VL	SL	SL	H	H
PC	VL	VL	SL	L	H	SH
TC	VL	SL	L	H	H	SH
SL	SL	L	H	H	SH	VH
SU	SL	L	H	SH	VH	VH
FC	L	L	SH	SH	VH	VH

The value of CGPA is in the range 0-5 an indication of the class of degree of a student. The degree classes are spread as follows: 0.00-0.99 (Withdrawal (WD)); 1.0-1.99 (Pass (PC)); 2.0-2.49 (Third Class (TC)); 2.50-3.49 (Second Class Lower (SL)); 3.50-4.49 (Second Class Upper (SU)); 4.50-5.0 (First Class (FC)). WD indicates that the student is within the withdrawal bracket. It is the practice, at FUTO, that any with a CGPA < 1 continuously, for one academic session, may be required to withdraw from the university. A student's CGPA is not final until the last semester of final year. The input variable Jamb/PostJamb scores are singletons in the range 160-400 and associated with linguistic values of FAIR, GOOD, EXCELLENT. It does not start from zero because 160 is the standard jamb pass mark. From the rule matrix, the rules read as follows:

R1: if SSCE is FAIR and JAMB/POSTJAMB is FAIR and CGPA is WD THEN BKL is VL (Very Low).

R36: IF SSCE is V.SAT AND JAMB/POSTJAMB is GOOD AND CGPA is SL THEN BKL is H (High)

BKL is the Background Knowledge Level with possible linguistic values of Very Low (VL), Significantly Low (SL), Low (L) high (H), Significantly High (SH) and Very High (VH). Figure 5 shows the basic configuration of a fuzzy system.

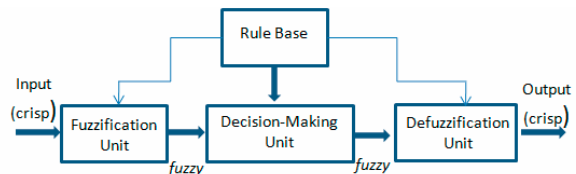


Figure 5. Basic Configuration of a fuzzy system

B. Performance/Behaviour Evaluation

This is a non-intrusive approach of gathering information about a student's behaviour without affecting

the learning process. Student behaviour is any observable action that is used as input to the student modelling process [36]. Their behaviour is characterised by a series of keyboard and mouse actions. In the RealLab, user actions are logged from a number of sources such as:

- The time spent to perform each laboratory activity is measured and evaluated. The time for task completion is a very reliable and powerful predictor of learning [37].
- Component selection/placement/removal
- The noise level as the student works
- The time interval between attendance to the laboratory and the frequency of attendance.

The log file analysis yields a measure of the student behaviour. We generate data describing student behaviour in form of a vector $A = \{a_i\}$, where a_i is a student behaviour variable. A is the student behaviour pattern.

C. Cognitive Knowledge Evaluation

Assessment is one of the most important tasks in the whole teaching and learning process because it has a great influence on learning and learning outcomes. [38]. We conduct a diagnostic assessment in order to identify student weaknesses. The assessment of the learner knowledge is based on two types of information: answers to questions that evaluate the cognitive part of the learner's knowledge and assessment of the results of the student's laboratory activities. The assessment test questions are dynamically generated and can be a combination of different types: multiple choice questions (mcq), fill-in-the blank questions (fib), true/false questions (tfq), short answer questions (saq) and short sentence questions (ssq). Each question tests one or more concepts of the knowledge goal that the learner should acquire and the number of concepts determines the number of questions generated based on which a question-concept mapping is done. For example, from the mapping of Table 3, question 1 tests both concepts 1 and 4, question 2 tests concept 3 only. It takes at least four questions to test a concept. A student is required get at least one question right in each concept test set. The students' results are profiled with a record of the ones answered correctly or wrongly per knowledge goal using a result grid. The challenge is identifying the student weaknesses with respect to the concepts of a knowledge goal, given the result grid and question-concept map [32].

TABLE III.
QUESTION-CONCEPT MAPPING

	Con1	Con2	Con3	Con4	Con5
Quest1	Y			Y	
Quest2			Y		
Quest3				Y	Y
Quest4	Y				

VI. NEURO FUZZY CLASSIFIER

A neuro-fuzzy classifier model (Figure 6) is used to evaluate and characterize a student's learning level in order to make next step decisions. Data from the evaluation of the background knowledge level, behaviour and cognitive knowledge are obtained in linguistic terms and used as inputs into the classifier. The fuzzy stage of the classifier has three sub-stages: a fuzzifier, fuzzy rules/decision and defuzzification that generate crisp

values of the measurements. The second stage of the classifier consists of a Neural Network (NN) that accepts as inputs the defuzzified outputs of a fuzzy stage. The output layer of the NN gives a representation characterizing a student's learning level with respect to BGK, behaviour and cognitive knowledge of set goals. A student's learning level is characterized on a 0-1 scale hence the NN output layer consists of a single neuron.

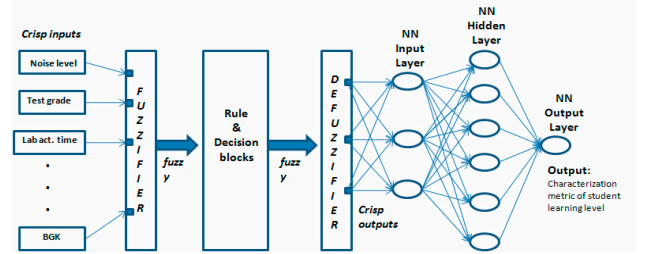


Figure 6. neuro-fuzzy student classifier

At the NN stage, the outputs from the fuzzy system constitute the inputs at the input layer. Vectors leading from the input layer are weighted and the derived values are passed through a function in the hidden layer.

VII. CONCLUSION

The possibilities offered by virtual laboratory as an educational technology has been proven to be feasible and despite its proliferation, there is still a need for further research because:

- Courses and laboratory activities differ in every institution, therefore, custom-built virtual laboratory may still be required most of the time.
- There are still opportunities for improvement and development in virtual laboratory techniques and approaches that may increase student participation and enthusiasm. Moreover, there are ways of learning yet undiscovered.

It is believed that this web-based virtual laboratory environment, the RealLab, will motivate students to challenge themselves with more circuit design, construction and analysis problems. The end result of such engagement will be the acquisition of a number of skills including critical thinking, problem solving, lifelong learning and promotion of experiential learning.

In addition to helping students gain useful engineering skills, the most significant advantage of the RealLab is its very low cost. The laboratory GUI is implemented entirely in java and only freeware third party software packages are used where necessary. RealLab is highly adaptable and portable. Most importantly, on completion, the RealLab will be freely available to Universities in countries in transition at zero cost.

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