

Remote Triggered Photovoltaic Solar Cell Lab: Effective Implementation Strategies for Virtual Labs

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Abstract— Remote triggered laboratories are an excellent way to provide access to costly labs and equipment for students in areas without such facilities. A novel remote triggered photovoltaic solar cell experiment is presented here. This experiment enables the student to learn in a hands-on, practical way about the fundamental characteristics of photovoltaic solar cells. The experiment has a web interface in which the student can turn a number of light bulbs on and off, adjust the load voltage of the solar cell, and view the experiment in real-time via a web-cam. In addition, the characteristics of the solar cells under these various conditions are measured and displayed on the web interface in a spreadsheet and are plotted in a novel and learning-effective manner. This experiment has been hosted on our Virtual Labs website for over a year, with a large number of students using the site. This paper presents implementation strategies and methods used which have proven effective for Virtual Labs, along with a technical description of the experiment and the system used to create and host the experiment.

Keywords— Remote trigger, e-learning, distance education, laboratory setup, photovoltaic solar cell

I. INTRODUCTION

This paper describes the framework and methodology behind the creation of a Remote Triggered Photovoltaic Solar Cell Virtual Lab experiment. It provides descriptions of the student's experience of the experiment and how the experiment works from a technical, behind-the-scenes perspective. It also discusses the novel strategies and methods used for effective virtual learning.

The lab is part of the Virtual and Accessible Laboratories Universalizing Education (VALUE @ Amrita) Virtual Labs project [1], [2]. The project aims to provide valuable laboratory based, practical learning experiences to college and university students across India and the world who may

not have access to adequate laboratory facilities or equipment. These virtual laboratories require only a normal, home consumer grade computer, an Internet connection capable of streaming video and a standard web browser. Details of the multi-tier, scalable network architecture and the Virtual Lab creation and content management tool used are given in [3].

Amrita Vishwa Vidyapeetham University (Amrita University) is part of a consortium of twelve institutions building over two hundred virtual labs covering nine key disciplines in science and engineering. Each lab consists of 8 to 10 experiments. This National Mission project hopes to reach out to India's millions of engineering and science students at both undergraduate and postgraduate levels. The Virtual Labs Project is providing virtual laboratory experiments that directly support the All India Council for Technical Education (AICTE) and the University Grants Commission (UGC) model curricula for engineering and sciences undergraduate and postgraduate programs.

Technologies such as photovoltaic solar cells (also called solar cells commonly and in this paper) are vital for the burgeoning Renewable Energy movement. They offer a myriad of benefits. They reduce dependence on fossil fuels, such as oil, natural gas, and coal and other forms of non-sustainable brown energy, such as nuclear, thereby reducing pollution. Furthermore, they are the easiest and most cost-effective way to provide energy infrastructure to India's and the world's rural areas, since expensive power lines do not need to be run from the central energy generation and distribution plant. Photovoltaic Solar Cells, on the other hand, can be implemented in a distributed and sustainable manner [4].

Not everyone has access to state of the art equipment and technology presented in an expert manner. At the school level, funds may be low and they may not be able to afford laboratories at all, or especially laboratories in more modern technologies, such as photovoltaic solar cells.

In addition, the quality of faculty in less developed areas may not be as high as needed. Their own educations may have been of low quality. The faculty may not have much or any experience with photovoltaic solar cells. Even fewer will have the practical, hands-on experience so necessary for

The VALUE @Amrita Virtual Labs Project is sponsored by the Indian Ministry of Human Resources Development (MHRD) National Mission on Education through Information and Communication Technology (NME-ICT).

understanding and communicating the essential aspects of a technology. Without practical, hands-on experience, one is often unable to distinguish in the theory of a subject what is truly important, what can be disregarded with minor consequence, and when each of these conditions are true. Further training and education are needed. Virtual Labs, when designed properly, provide a strong foundation and background for this further training.

II. PRIOR WORK AND BENEFITS OF OUR SYSTEM

Virtual Labs are computer-based, interactive systems that allow students to conduct laboratory experiments through either simulation, animation, or through the remote control (triggering) of actual lab hardware.

Numerous studies have been conducted and papers written on the effectiveness of using Virtual Laboratories for engineering and science education [5]-[8]. The study [9] looks into various ways of remotely controlling and accessing data acquisition and control equipment for remote laboratory use and implemented one method for four experiments in mechanical engineering. In [10] and [11], previous work has created Remote Trigger Virtual Lab experiments in the area of Biotechnology, involving a similar technological framework as described in this paper [3].

One study, [12], describes a Virtual Lab for teaching Renewable Energy concepts, including solar and wind energy integration into a building, but it has relatively little experimental content and does not use actual remotely triggered hardware. A similar experiment is given in [13], although this experiment is hosted outdoors and is unable to provide accurate results in poor and inclement weather and during the night, limiting its usability. It is also unable to provide multiple, easily selectable illumination levels, as our system does.

Similar work has been reported elsewhere [14], with one fundamental difference being that it requires additional software to be downloaded and installed on the client computer, whereas the work described here operates without the need for any additional software installations, using only standard web browser capability and ubiquitously installed software. A second difference between [14] and the system described in this paper is that [14] only allows selection between a single “dark” and a single “light” illumination level. In contrast, our system allows for the selection of four different “light” illumination levels, which sufficiently covers a range of practical daylight illumination levels closely simulating that found in the natural world. This is helpful for teaching practical engineering.

Nearly every study has proved that Virtual Labs are an effective learning and teaching tool [5] – [14]. The benefits are many. Virtual Lab experiments can be worked on the student’s own time schedule and at their own pace. They can also be repeated as many times as desired.

In order for virtual labs to be effective they must engage the user as much as possible, forcing them to do the bulk of the work necessary to facilitate thorough understanding and learning, just as a well designed physical laboratory experiment does. This engagement and interactivity is what is

often missing in virtual labs. Too often, a mass of information is presented along with an experiment that can be completed in just a few button clicks, leading to little user engagement and in consequence, little actual learning. This study aims to rectify this by creating a more life-like, interactive, and engaging Virtual Labs experience which provides the benefits of a physical virtual lab and more, without the infrastructure requirements and costs.

A. Benefits of Our System

Our Virtual Lab includes three main benefits, which when coupled together form the foundation for an extremely versatile and effective E-learning system:

- 1) No additional software download is required to be installed.
- 2) The Six-step Learning Process, outlined by *Theory, Procedure, Self-Evaluation, Simulator, Assignment, and References*.
- 3) The method of plotting graphs and collecting data in the *Simulator* section is far more natural and life-like in our scenario. This offers particular advantages in learning described elsewhere in this paper.

1) No additional software download required: No additional software is required to be downloaded for using Amrita’s Virtual Labs in nearly all cases, since the software used, Adobe Flash, is already installed in nearly all computers with a web browser. While this may seem like a small detail, since downloading software can be very simple, quick and painless for an experienced computer user, there are numerous advantages that go with a download and installation free Virtual Labs experience.

- a) The software can be simply and easily used by anyone, requiring only a keyboard, mouse, and internet browsing skills. Downloading and installing software can seem to be unknown and risky to inexperienced users. Many people might not even use the system and will find another, rival e-learning system that requires no download. This pertains to people who are even experienced installing software; the most convenient system is often the one used. Installing software also takes up more disk space.
- b) Administrator rights are not required. This is especially important in developing countries where many people do not have personal computers of their own and must go to internet browsing centres or borrow friends or family’s computers for internet access. In these situations the user typically does not have the administrator rights necessary to install software. The owner of the computer themselves may be reluctant to install unknown software on their computers.
- c) Not downloading executable files reduces the risk of downloading an infected executable file and reduces the risk of a virus infection on the computer. Downloaded executables may be bound with or contain malware, or the website could have been hacked and the link may lead to a false and infected download.

2) *Six-Step Learning Process*: Each of Amrita's Virtual Labs, whether in Physics, Neuroscience, or Mechanical Engineering follows a common format. Six page selection tabs for *Theory*, *Procedure*, *Self-Evaluation*, *Simulator*, *Assignment*, and *References* are present for each experiment. This method is modular and comprehensive. The modular format breaks the learning down into smaller, discrete steps which are easy to digest, understand, and complete. It allows for easy repetition of only necessary modules and it is less intimidating for the student since the work is broken into smaller pieces.

The labs are comprehensive in the sense that they have both theory and practical components. A feedback tab is also present for the student user to provide critical feedback for how the experiment can be improved. In this way, the student becomes the teacher and the teacher the student, creating a positive feedback or upward spiral of learning.

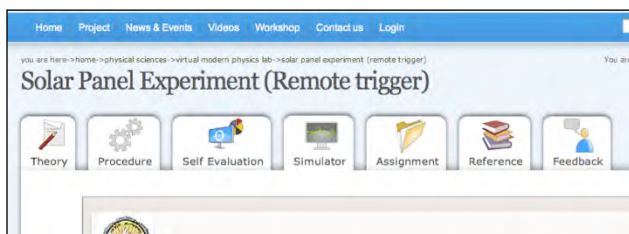


Fig. 1. Six-step learning process tabs (*Theory*, *Procedure*, *Self-Evaluation*, *Simulator*, *Assignment*, and *Reference*, plus the extra *Feedback* tab)

This particular learning format has proven so intuitive and effective that the overall national project coordinators declared its use mandatory for all of the other partner universities within India's MHRD funded Virtual Labs projects. This also provides the advantage that all of India's MHRD funded Virtual Labs have a common look, feel, and format, simplifying their use and providing a comprehensive and cohesive united learning front. This format is actually inbuilt into the Virtual Labs Collaboration and Accessibility Platform (VLCAP) development tool described in [3].

3) *Novel Data Collection and Plotting Methodologies* Collecting and plotting data points is a fundamental and essential component of real-life laboratory experiments. This process creates a situation in which the student must learn the functional relationship of the system being studied. In other words, the student learns how varying the independent variable of the experiment creates changes in the dependent parameter. By collecting individual data points, one at a time, the student carefully observes the nature of the physical process being studied and how this process occurs as the independent variable is modified. By plotting the points together on a common graph, the student learns how the system changes as a whole, over a wide range of independent and dependent parameters. The student learns if the relationship is linear or non-linear, increasing, decreasing, oscillating, etc.. These functional relationships define the system or process being studied; understanding these relationships are key to understanding the system or process being studied.

The nature of the created on-screen graphs, representing data collected from the remotely triggered lab experimental setup are not discussed in the papers reviewed by the authors. It appears that many of the graphs were created in an automated or semi-automated fashion. The disadvantage of these methods is that the user misses out on discovering the shape of the graph. It becomes a mindless mechanical action, requiring little attention, engagement or interaction. As a result, the student contemplates little about the experiment and the relationship among the important parameters.

Amrita's Virtual Photovoltaic Solar Cell Lab employs a method of plotting data points that is unique to the best knowledge of the author. The user is given control over the independent variable, in this case the load voltage, by moving a slider on the screen with the mouse or touchpad. This is analogous to moving a linear slider on a large adjustable resistor, as would be done when the same experiment were performed in person on actual lab equipment. Each time the user moves the slider and brings it to a stop, a data pair is generated. This data pair consists of the value of the load voltage (the independent variable) and the value of the current created at that particular load voltage (the dependent parameter). These data pairs are simultaneously added one-by-one in the displayed on-screen table and plotted on the displayed Cartesian "x-y" graphs. Multiple overlaid graphs are created at four different user-controlled illumination levels. (Technical details regarding the graphs and curves created are given in Sections III and IV.)

The advantage of collecting and plotting data points one by one, at the user's choice, as a user would do if he or she were conducting the experiment in a physical lab, is that the student actively watches the shapes of the curve, the nature of the fundamental relationships of the process being tested, evolve. The student is engaged, and is forced to fill in the missing gaps in her or her data by adjusting the independent variable. The student looks and wonders, "will the results of my experiment match the predicted theoretical results, shown in the *Theory* section?" The entire process becomes much more organic, interactive and engaging. Then the process becomes more like a learning game than "homework". The thrill of interactive discovery enhances the learning process significantly, making it much more engaging of the student's attention. The result is that the student will remember the shape of the plot and the relationships present among the parameters of the system, much more reliably than if it was simply created at the press of a button, especially among poorer students.

Collecting and plotting data points by the above mentioned method also saves considerably on network bandwidth since for each data point request by the user, the system data acquisition and control equipment has to collect, and the network has to transfer, only one data sample.

III. NEED FOR A REMOTE TRIGGERED PHOTOVOLTAIC SOLAR CELL VIRTUAL LAB

For implementing and using photovoltaic solar cells in a practical engineering application, it is essential to understand two fundamental relationships. These, relationships,

illustrated by curves on the Cartesian plane, also illustrate aspects and details of how photovoltaic solar cells operate.

The first of these fundamental photovoltaic solar cell relationships is current vs. load voltage (where load voltage, shortened to just voltage, is the independent variable and current is the dependent parameter), also called the I-V curve. The second fundamental relationship is power vs. voltage, (again, where voltage is the independent variable and power is the dependent variable), also called the P-V curve. It is worth noting that the power is actually the voltage multiplied by the current, at each point along the voltage scale.

Of the two relationships, I-V and P-V, the P-V relationship is the most important, as a large variation in the power produced by the solar cell is created as the load voltage changes. By adjusting the load voltage on the solar cells, the maximum power can be obtained from the cells, thereby significantly increasing the efficiency of the cells and reducing the payback time of the investment in the photovoltaic power system. An automatic electronic device called a Maximum Power Point Tracker (MPPT) is commonly used to achieve this. On solar panels used for power generation, it is usually cost effective to use MPPT's; the extra power produced more than compensates for the added cost of the MPPT.

One of the primary purposes of this virtual lab is to teach students how to empirically plot the P-V curve and how to read the same to determine the maximum power point of the solar cell. This information is also one of the key solar cell characteristics that is given in the manufacturer's data sheet for the solar cell. Knowing how to operate the solar cell near its maximum power point is of the utmost importance for designing real-world, cost-effective solar cell implementations.

IV. USING THE VIRTUAL PHOTOVOLTAIC LAB

In order to use the lab, the student logs into the Virtual Labs website. The student selects the discipline they wish to study, and then choose the particular lab they wish to conduct experiments in. There are normally 8 to 10 experiments per lab, which may be any mixture of simulation, animation, and remote trigger experiments.

For this particular experiment, the *Theory* section provides background information on how solar cells work (photoelectric effect, bandgap, etc.), how they are modelled mathematically, and how to use them practically. The *Procedure* gives specific instructions on the objectives of the lab (how to adjust illumination and load resistance, take voltage and current data, find the Maximum Power Point, etc..) and how to complete the lab experiment. A short video is also given which explains how to use the Virtual Lab. The *Self-Evaluation* tab has a series of questions designed to ensure that the student has properly learned the *Theory* presented and understands the material in the *Procedure*. This ensures that the student has enough background knowledge and understands how to do the experiment and obtain maximum benefit from it. The *Simulator* tab includes the Remote Trigger Photovoltaic Solar Cell experiment itself. The *Assignment* provides follow-up questions and assignments to ensure that

the student has properly assimilated all of the knowledge learned. Finally, the *References* tab includes references to books, articles, and websites for the student to go to for more in-depth information and learning about Photovoltaic Solar Cells. Students are also encouraged to give Feedback in the *Feedback* tab to help improve the Virtual Lab.

After reading the *Theory* section and performing the *Self-Evaluation*, the student performs the remote trigger lab experiment in the *Simulation* according to the online instructions in the *Procedure* and as described in the following.

Through the web interface, the student controls the number of lights irradiating the solar cell (up to four), and hence the amount of virtual sunlight that the cell receives. They also control the load resistance on the solar cell by the slider, as described earlier, and thereby the voltage of the cell. In this way, they collect data samples at four different illumination levels and a wide variety of load voltages. An online spreadsheet is used to record the data measurements; this data can be reviewed or copied to other spreadsheet software for additional analysis. The data is automatically graphed, point-by-point, on an online Cartesian coordinate system, as described earlier.

This creates sets of I-V and P-V curves at four different illumination levels. All of the I-V curves are on one graph, and all of the P-V curves are on a second graph. The pair of curves at each of the four illumination levels are also plotted in a different color. E.g, the I-V and P-V curves with one light bulb turned on are both graphed in an orange color, two light bulbs turned on is graphed in green, three in blue, etc..

The student can then empirically determine the Maximum Power Point of the solar cell at the different illumination levels by finding the maximum values of the P-V curves and the voltages at which the maximums occur. A proper understanding of these curves and the Maximum Power Point comprises the essence of understanding how to implement and use Photovoltaic Solar Cells.

Video feedback is also streamed live to the student on the web interface. This lets the student see the lighting changes on the solar cell that he or she is controlling remotely, providing closed loop feedback and helping to create the feeling of controlling real equipment in person.

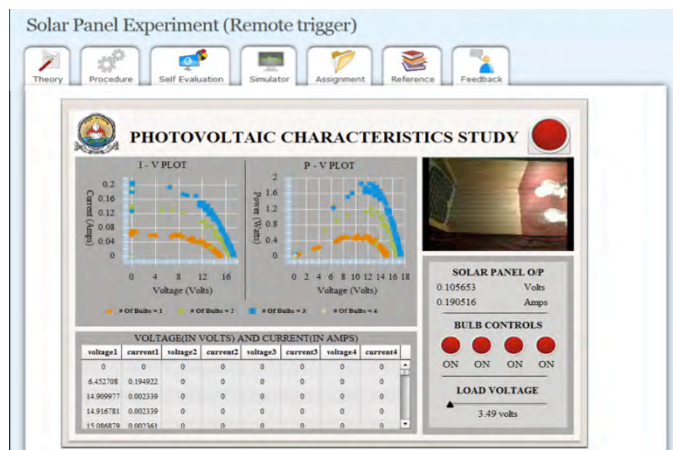


Fig. 2. Screen shot showing the user interface for the Remote Triggered Photovoltaic Solar Cell Virtual Lab. Key components are the Six-step learning

tabs, the bulb control buttons, the load voltage slider, the data table, the I-V and P-V graphs, and the streaming video.

V. THEORY OF OPERATION

A Photovoltaic Solar Cell Virtual Lab setup was created using the following method. The solar panel used is a small, 2.5 Watt, Mono-crystalline Silicon panel with a peak output of about 19 volts, designed to charge a 12 V battery. Data acquisition (DAQ) and control equipment is used to interact with the lab setup. We programmed the DAQ equipment to take a single data sample whenever the user moved the load-voltage slider. This considerably reduced the amount of data transmitted and the network bandwidth required.

The DAQ device is used to measure the voltage and current of the solar cell. Since the voltage and current produced by the solar panel is higher than the DAQ device can directly measure on its analog input channels, a voltage divider circuit was used to reduce the voltage to a level that the DAQ could safely handle without damage (see Fig. 4). The measured voltage value was later converted back to its full value in the software. The current was converted to voltage by passing it through a power resistor of known resistance and using two of the DAQ's analog input ports to measure the voltage drop across the resistor. The current produced by the solar cell is then easily calculated by dividing the measured voltage drop by the known resistance.

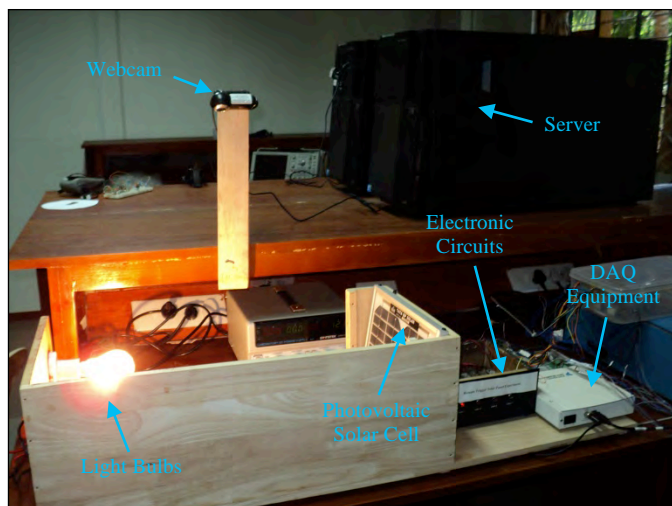


Fig. 3. Physical Hardware setup for the experiment illustrating the photovoltaic solar cell, light bulbs, electronic circuits, DAQ equipment, webcam and server.

Through the four bulb control buttons on the web interface, the user turns the four solar cell illumination light bulbs on and off. This experiment uses standard 100 W incandescent light bulbs since many solar cells do not work well under fluorescent lighting. The digital output ports of the DAQ device turn the light bulbs on and off by switching standard automotive-style electromechanical relays.

The user also adjusts the load voltage for the solar cell through the web interface. The slider on the web interface controls an analog voltage output of the DAQ device which is connected to the Gate of the MOSFET which is configured to act as a variable resistor. This resistance controls the operating point of the solar cell on the I-V curve at that particular

illumination level by determining the load voltage. The load voltage can range from zero volts, representing I_{sc} the short circuit condition, up to a maximum of V_{oc} , the open circuit voltage. These two operating conditions, I_{sc} and V_{oc} are also key characteristics of solar cells, giving the maximum current and voltage the cell can produce, respectively.

Any data acquisition device with three or more analog data input channels, one analog output channel, and four digital outputs will work for this experiment. Many other configurations are possible as well, for example if the DAQ equipment measures current directly.

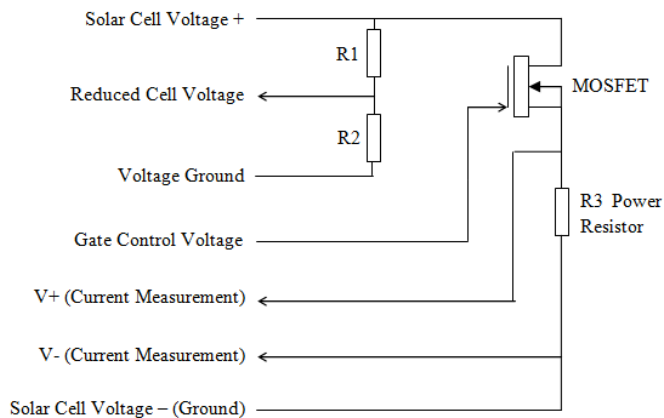


Fig. 4. Schematic of the voltage and current measurement and load control circuits.

Any suitable web GUI software can be used with any data acquisition and control software as long as they can communicate with each other with an intervening network connection.

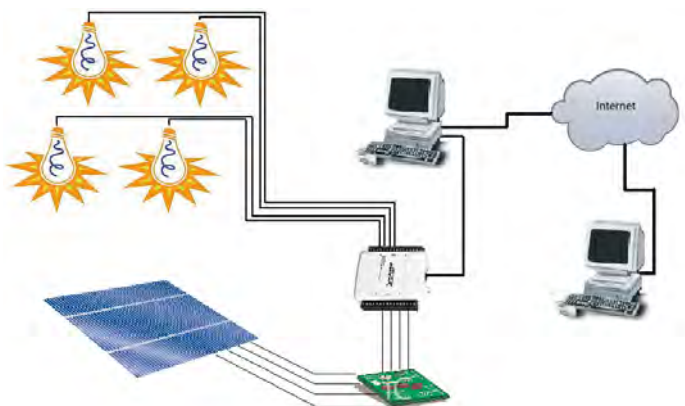


Fig. 5. Diagram showing the system components and their connections. System components include the solar panel, the light bulbs, electronics, data acquisition card (white box in the middle), the server, and the client side computer.

The users control input is collected via the thin client GUI, transmitted over the internet using standard protocols, received by the web server, then given to the data acquisition and control program to control the experiment. The data output from the experiment (raw data) are collected via the data acquisition and control software, given to the web server, transmitted over the internet, and displayed to the user in the thin client GUI interface. The video is taken via a webcam,

streamed over the internet using standard protocols, and displayed using the same GUI. Measured data, control signals, and video are all transmitted in real-time, giving the student real-time feedback and control over the remote system.

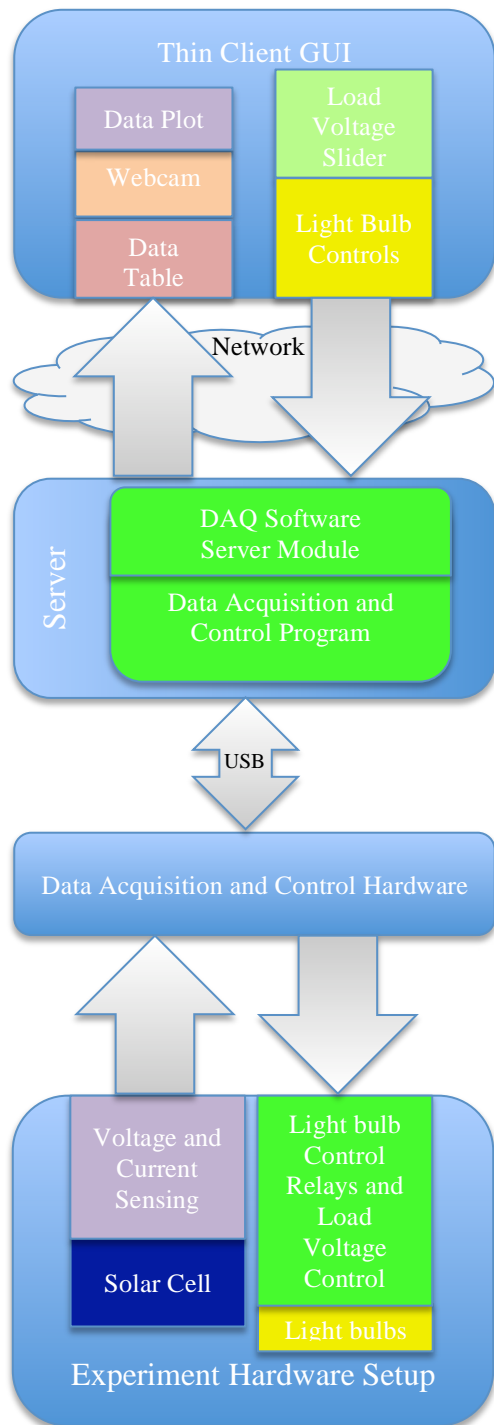


Fig. 6. System flow diagram

In our particular implementation, we have used Adobe Flash as the thin client GUI for the web interface, Labview data acquisition and control software with Labview Web Server enabled, and a National Instruments USB general purpose data acquisition and control card. Data is streamed between the GUI and the Data Acquisition and Control

program through the internet using Labview Web Server and standard http “GET” protocols [15].

Flash is used because it is a readily available package that is already very widely deployed on most computers and is highly optimized for internet content (streamed video, animation, and graphics). Some of our University project groups also have strong capabilities in this area. Common software usage will allow our Virtual Labs to interface cleanly with our widely deployed A-View E-learning software [16]. While this integration is not performed yet, various E-learning synergies were conceived at the beginning of this project that would be more easily possible if common software platforms were used.

Sampling by the DAQ system is performed one time, every time the user moves the load voltage slider. This keeps data transfer to a minimum and reduced the required network bandwidth. The DAQ card sampling rate can also be kept very low, to under 1 sample per second, allowing the use of low cost DAQ equipment.

VI. EFFECTIVENESS OF THE VIRTUAL LAB

The system is able to effectively remotely monitor and control a Photovoltaic Solar Cell lab experiment. The user is able to take data and accurately reproduce the characteristic I-V and P-V curves of the solar cell in an engaging and true-to-life manner. No extra software is normally required to be installed, as long as standard web browsers and the normal ubiquitous plug-ins are installed. The user is led through six modular, sequential, comprehensive steps for effective learning. These elements combine to provide a highly effective virtual lab experience that very closely replicates an actual physical lab for the student.

Furthermore, experience has shown that learning is roughly equivalent to performing the experiment with real equipment and top quality educational materials and teacher support. Learning is significantly enhanced where the option of performing experiments with actual equipment and top quality educational materials/teacher support is not available. Our system effectively gives both.

VII. CONCLUSIONS AND FUTURE WORK

A Photovoltaic Solar Cell Remote Trigger Virtual Lab has been presented here. In addition, methodologies and a framework for an effective and low-cost Virtual Lab, in any subject, has been shown.

System delay is kept below one second, for round trip commands and data feedback, partly due to the low data transmission and the thin-client architectures. Noise has not been a problem thus far. However some experiments, such as those using strain gauges, thermocouples, or accelerometers (sensors traditionally susceptible to noise) may encounter problems.

Scheduling and web security program modules have been implemented over the course of the project in response to issues of multiple users attempting to access the same remote trigger resource at the same time. Because of the nature of the experiment, with the user controlling the illumination light bulbs and being able to see the same on the displayed webcam,

it is necessary to give the user full control over the setup. This necessitates that only one student can use the experiment at a time. Thus, to expand the system to allow simultaneous users, additional parallel sets of lighting, solar cells and electronics would have to be installed. However, we have had success multiplexing numerous Virtual Labs experiments on a single DAQ card and multiple DAQ cards can be hosted on a single server, although more optimization of equipment and resource use can be done in this area.

Future work includes giving the user more control over the load voltage/resistance, for example, by inputting resistance or load voltage values numerically. The unique method of plotting shown in this paper can be tested empirically as well, with the scores on the *Evaluation* compared between this new method and the normal method of producing an entire data series and complete plot with the single click of a button. Other improvements that could be made include adding an Export to External Spreadsheet Program option. The number of unique photovoltaic solar cell experiments can expand as well, to include other relevant topics within this area. Expanded user feedback and analysis and studies on the effectiveness and efficacy of the lab are planned as well.

Expanding the Virtual Labs to run on mobile devices is planned. The Virtual Labs project can be more tightly integrated with Amrita University's other E-Learning projects, such as A-View (Amrita Virtual Interactive E-learning World, www.aview.in), CREATE (Center for Research in Advanced Technologies for Education, <http://research.amrita.edu/create/>) and SAVE (Sakshat Amrita Vocational Education, <http://sakshat.amrita.ac.in/save/>) [17], for an even more holistic and effective learning environment.

Similar Remote Triggered Virtual Labs are being planned and implemented by Amrita in many other areas, specifically, Wind Energy, Solar Thermal Energy, Physics, Solid Mechanics and Dynamics, Neurosciences, and others. These are part of a larger Virtual Labs project sponsored by the Ministry of Human Resource Development, Government of India, which intends to provide quality, effective Virtual Labs in nearly all science, technology, and engineering disciplines through a wide swath of India's top educational institutions (www.sakshat.ac.in).

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