AC 2011-2207: E-QUALITY CONTROL METHOD FOR MEASURING SOLAR CELL EFFICIENCY

Richard Chiou, Drexel University

Dr. Richard Chiou's background is in mechanical engineering with an emphasis on manufacturing. Dr. Chiou is currently an associate professor in the Goodwin School of Technology and Professional Studies at Drexel University. His areas of research include machining, mechatronics, and internet based robotics and automation. He has secured many research and education grants from the NSF, the SME Education Foundation, and industries.

Michael G Mauk, Drexel University
Robin Kizirian, Drexel University

Robin Kizirian completed his M.S. degree in Computer Engineering at Drexel University in Philadelphia and his B.S. degree in Computer Engineering with a minor in Computer Science at the University of Hartford in Connecticut. He is currently serving as a research assistant at the Engineering Technology department at Drexel University. Robin has been involved in various projects funded by Pfizer, NASA, NSF and Department of Education. His areas of research include Embedded Systems, Mechatronics, Efficient Solar Energy Systems, Internet-based Quality Control and 3-D Online Education.

William Peeples, Drexel University

William Peeples is a graduate from Drexel University with a B.S. degree in Mechanical Engineering Technology. He now works in the Engineering Technology laboratory as a research assistant at Drexel University. His interests include Robotics, Vibrations, Controls Systems, Internet-based Quality Control, and Renewable Energy Systems.

E-Quality Control Method for Measuring Solar Cell Efficiency

Abstract

Recent results of laboratory and course development under an NSF, CCLI sponsored project, "CCLI Phase II: E-Quality for Manufacturing (EQM) Integrated with Web-enabled Production Systems for Engineering Technology Education" (NSF Award # 0618665) are presented. This paper discusses an educational effort that incorporates Renewable Energy in a senior design project offered at Drexel University. Renewable Energy science and technology stimulates discoveries and developments that promise to sustain a wave of new technological and economic innovations throughout the world. It is likely that the use of renewable energy will become an increasing national priority that will affect the next generation of college students. The senior design project engages students in their studies on the implementation of an innovative method for measuring the efficiency of solar cells using E-Quality and image processing. There is a need for students to learn how to provide a consistent quality control method for evaluating the characteristics of solar cells in manufacturing. Many methods used so far are contact methods that may damage the cells during inspection. We therefore focused on non-contact measurements for solar cell inspection. By linking the current output of a solar cell to the grain size, it is possible to develop a non-contact method of evaluating the efficiency of solar cells. By measuring the blob size of different grains and linking them to current output, a non-contact system for evaluating solar cells can be created. This project is Internet-based and is an essential resourceful element for engineers who are working in the Renewable Energy industry. A concluding section discusses the experiences from offering such a project.

Introduction

Renewable Energy continues as a national priority in response to the global energy and environmental situation. . Its contribution to total energy supply remains modest, but is posed to increase dramatically in the near future due to the rising prices of non-Renewable natural resources such as fossil fuels and nuclear energy and the increasing consumption and demand for power generation. Renewable Energy includes solar energy, hydro power, wind energy, biomass, etc. Solar energy is in some ways the most popular and widely used type of Renewable Energy[1-4]. The applications of solar technology range from grid electricity generation to running small embedded appliances. The abundance of sunlight every day delivers tremendous amounts of power to the surface of the earth. The solar cell conversion efficiency is determined by the factors related collection and conversion from light energy to electrical energy. Thus, the quality of solar cells is a crucial factor in determining their efficiency. Hands-on renewable energy related classes, labs, and projects promote alternative energy efficiency education. This paper presents the establishment of a renewable energy teaching and research laboratory through a senior design project involving undergraduate and graduate students, and faculty in learning about alternative energy at Drexel University[5-7].

There are many manufacturing variables that can affect the quality and efficiency of a solar cell. Anomalous grain structures, contamination, and surface roughness may lead to unpredictable or compromised output from the cell. In some cases, film uniformity flaws in the anti-reflection coating of the solar cell, such that the surface has a general blue reflection with light blue/purple discontinuities is not only a cosmetic defect, but reduces solar cell performance. Other issues involve electrical defects such as breaks in the contact lines which affect the current output of the solar panel. Due to the production processes currently used, solar cells often show local defects that may affect their life time and efficiency. For this reason, there is a growing interest in solar cell quality control processes. Effective tools and methods are needed designed to assess and measure solar cells[8-13], especially in line during manufacture.

Finished solar cells undergo a variety of tests before they are assembled into modules. It is crucial that low-performing cells are not incorporated into modules. Conventional quality control methods test the current, voltage, and resistance of each of the cells to determine whether it falls short of the required standards. The approaches for measuring solar cell current usually entail using a current conducting probe and touching the conductive buss bar on the cell. This can in turn damage the solar cell which may lead to a decrease in the overall efficiency of the solar cell. Other solar cell tests evaluate their mechanical robustness, e.g., the ability to withstand various vibrations, twisting and hail. The quality measurements are validated from data taken over the operating life of the solar cell modules from the field[14-17].

In this paper, we explore non-contact quality control methods to estimate solar cell performance and detect possible defects that may affect the overall performance of a solar cell. The research involves an educational effort that incorporates Renewable Energy in a senior design project offered at Drexel University. Several approaches are pursued as part of the project. Through image processing, the students have been given means to perform statistical analysis on the grain structure of solar cells and try to relate it to the measured current output. An attempt at measuring the surface roughness of the solar cell has been also performed. Finally, the effects of the angle and the intensity of the light on the solar cell have been studied and analyzed. The paper discusses the steps taken and apparatus used for performing some quality control measurements of solar cells. It is concluded with the future plans regarding the project.

Structure of a Solar Cell

To better understand the nature of our project it will be useful to briefly described the structure of a solar cell. Solar cells can be classified as amorphous, monocrystalline, or polycrystalline. Production solar cells are either made from silicon wafers or in thin-films using vacuum technologies. Silicon solar cells are the most common type of solar cell and are the type tested in this work. The photocurrent reading from a solar cell under illumination from a calibrated artificial light source can is affected by at least several factors. Some of these are the light intensity, angle of illumination, and the wavelength of the light, as well as cell-dependent factors such as the size of the grains that make up the cell, the surface roughness, and the effectiveness of any anti-reflection coatings formed on the front surface of the cells.

The response (current generation) of a solar cell is highly dependent on the wavelength of the illuminating light. This is because the depth of penetration of light into the solar cell depends on the photon energy (i.e., wavelength). Although solar cells are typically used under ‘white’ light conditions (i.e., natural sunlight), their performance under more color lighting is highly informative and often diagnostic for various materials and device problems.

Other losses in efficiency are attributed to the imperfections in the metal contacts on the front side of a solar cell, solar cell series resistance, and shunting paths in the cell. Monocrystalline or 'single' crystalline solar cells have the highest efficiency, yet are also the most costly. Therefore, a large fraction of solar cell production is based on cheaper 'poly' or multicrystalline silicon material characterized by an easily observed grain structure. Not surprisingly, compared to single crystalline cells, multicrystalline solar cells can have more prevalent areal uniformity issues.

As polycrystalline solar cells may have highly variable grain structures, and performance of the solar cell is sensitive to grain structure, a method of characterizing grain structure and correlating it with solar cell performance is very useful. Further, it this type of inspection can be applied to solar cells in various stages of processing, and can be incorporated in line during production, it would prove a useful quality control tool. In this work, we use machine vision, with various controlled illumination conditions, to characterize silicon wafers and solar cells in several stages of fabrication. This work has provided very productive senior design projects for our undergraduate engineering technology students.

Non-contact-based Quality Control Approach

Conventional quality control methods mostly incorporate contact-based solutions for evaluating the efficiency of solar cells. Studies of the structure of a solar cell have shown that the size of the crystals in a polycrystalline cell might be directly correlated to its overall efficiency. This hypothesis motivates assessing the quality of polycrystalline cells in a non-contact-based approach through analyzing their grain structure by machine vision with a CCD camera. A solar cell is imaged under different lighting conditions. By shining light at a solar cell and processing the reflected image, it is possible to determine the size of the crystals and perform statistical analysis on their size distribution.

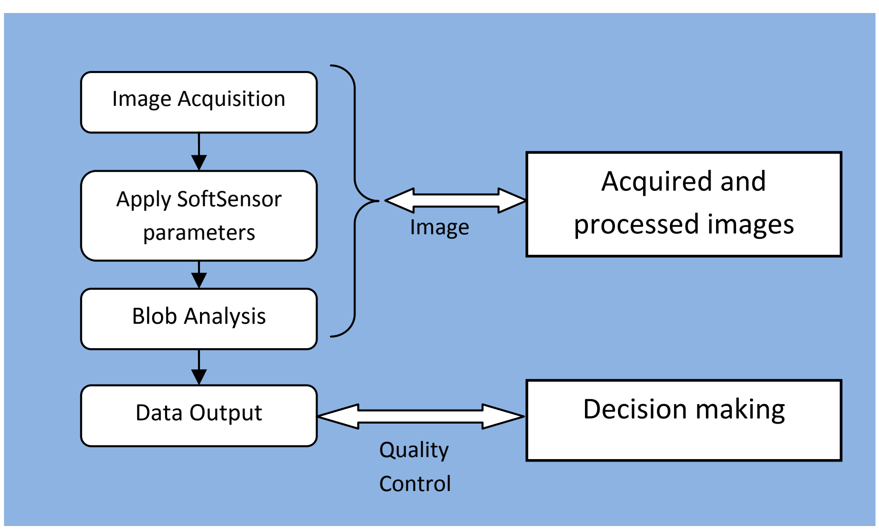


Figure 1: Solar cell vision system processing flow chart

Figure 1 displays the flow diagram for the processing procedure of a vision system. The vision system is comprised of a smart machine vision camera. The camera contains a processor with built-in libraries of image processing tools and filters. Image acquisition and processing is performed through controlling the built-in SoftSensors. The SoftSensor parameters can be controlled and applied through Intellect 1.5.1, the corresponding software for the camera. The camera is also equipped with an Ethernet port which provides it with Internet capabilities. By programming custom scripts, it is possible to design a server-client system that will communicate with the user interface and supply it with the quality control data.

Blob analysis image processing technique is used for distinguishing the individual grains in a polycrystalline solar cell. It accomplishes this task by acquiring an image of varying light intensity values, evaluating each of the pixels in the image, and then comparing them with the neighboring pixels. If the variation in intensity is large, the algorithm identifies an edge or boundary in the image. The pixels that are within the same light intensity region are grouped together and defined as a 'blob'. As such, the embedded blob analysis feature can contribute to the quality control process through distinguishing the brighter and darker regions of the illuminated cell.

Another approach for the non-contact quality control solution is uses surface roughness evaluation system. Surface roughness is a measure of the texture of a surface, i.e., to what degree the surface deviates from a perfectly smooth plane. A certain degree of surface roughness in a solar cell is desired to reduce reflection and induce other favorable optical effects, however, excessive roughness can degrade solar cell performance and complicate some of the fabrication steps. There is therefore an optimum roughness for a solar cell. The roughness inspection is traditionally performed through the use of stylus-type profilometer which correlates the motion of a diamond-tipped stylus to the characteristics of the examined surface. In this paper, a non-contact-based roughness measurement technique is developed to permit rapid surface roughness measurements with accepted accuracy for use in an Internet-based production environment. Through computing the optical parameters of the surface of a solar cell, it is possible to reach to a conclusion regarding the quality of the cell.

Blob Analysis System Design

The blob analysis system consists of three main sections: the vision system, the lighting system, and data acquisition. Figure 2 portrays the integration among all these sections. The machine vision camera is mounted on top of a cloudy day illuminator to block any rays of external sources of light. Inside the dome, a microcontroller-based LED ring is used to illuminate the specimen. The whole system is Internet-based and controlled through a LabVIEW interface running on a PC. The output data is acquired from the vision system and saved to a spreadsheet for further analysis and decision-making.

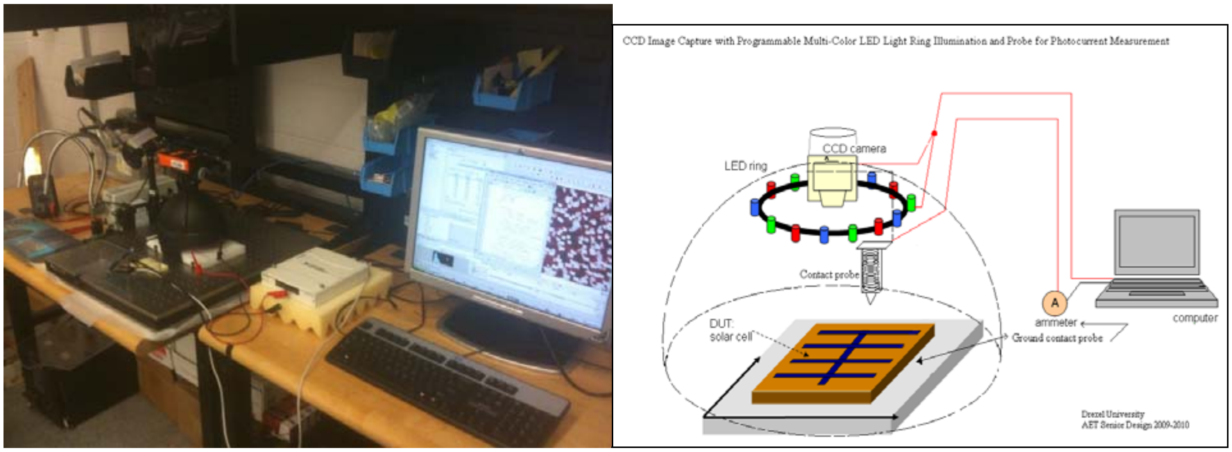
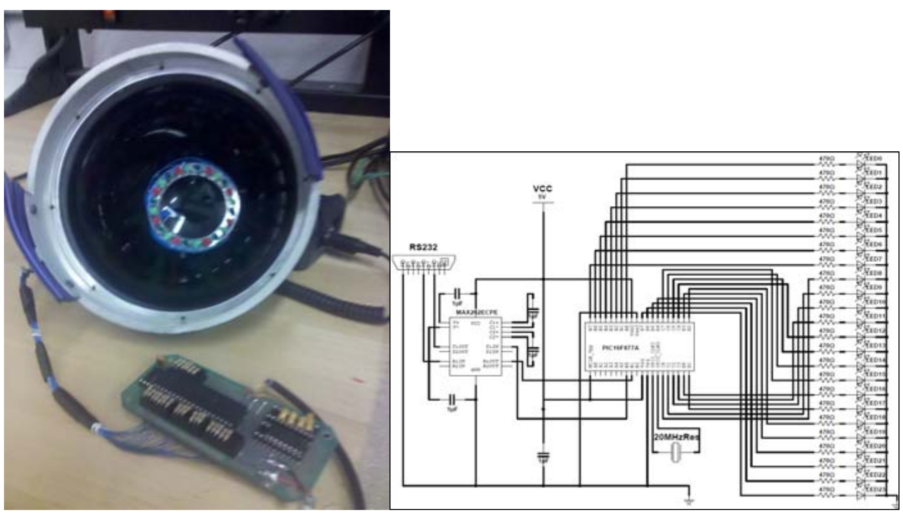


Figure 2: Blob analysis and testing system

The LED ring is constructed using 24 individual LEDs and a circular plastic frame. Each of the LEDs can be turned on and off by the microcontroller. The intensity of the LEDs can also be varied to accommodate the different blob detection tests. The microcontroller receives external commands through its input pins from an RS-232 transceiver chip. The transceiver is connected to a RS-232 to Ethernet control box. This setup will allow a PC to remotely send commands to the microcontroller through the Internet. Figure 3(a) shows the LED ring which is connected to the microcontroller. The schematics for the microcontroller and the RS-232 transceiver are shown in Figure 3(b).



(a) (b)

Figure 3(a) Cloudy day illuminator and (b) Microcontroller schematic

Figure 4 displays the LabVIEW software interface used to control the LED ring through the microcontroller. A virtual ring in the interface allows the user to identify the illuminated LEDs' number and angle. The buttons and knob allow the user to control the state and brightness of each of the LEDs. Due to the insufficient brightness of the LEDs, this system would be useful for blob analysis, but not for measuring the output current from the solar cell.

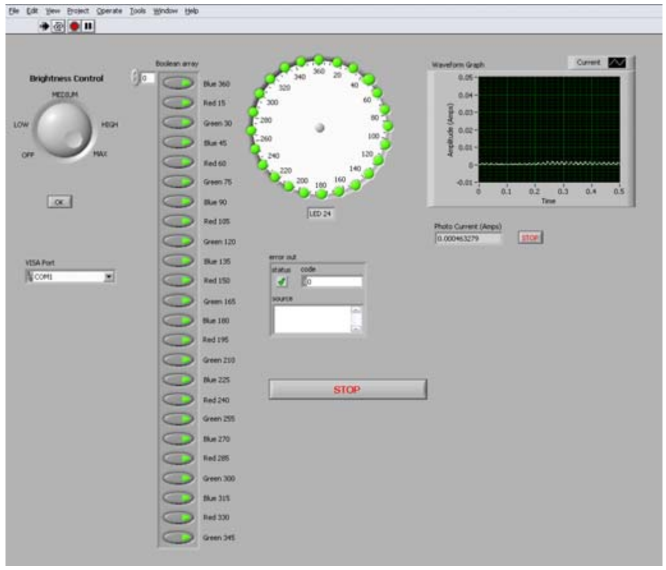
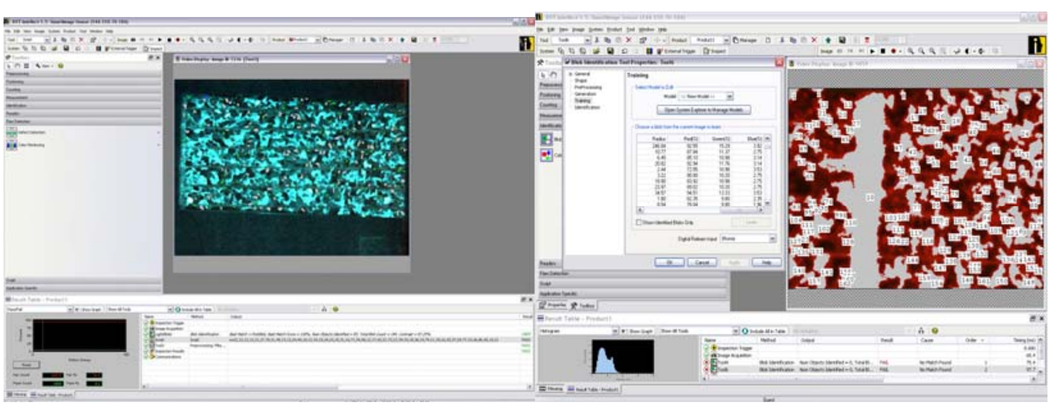


Figure 4: LabVIEW LED controller program

After configuring the LED ring with the specific intensities, the machine vision camera is able to acquire the necessary images of the illuminated specimen and apply the programmed filters onto it. The software used to teach the machine vision camera is Intellect version 1.5.1. Multiple types of filters have been programmed into the camera to enhance the original image. These filters include sharpening the image, fixing the contrast, and performing morphological changes. At this point, the blob filter is applied to the processed image for blob detection. Blob filters are used to detect both light and dark parts of the image. Figure 5(a) demonstrates the Intellect software and Figure 5(b) shows an example of the blob analysis procedure in the camera. The blobs are separated into groups and numbered according to their intensity values. These numbers can be seen in Figure 5 (b).

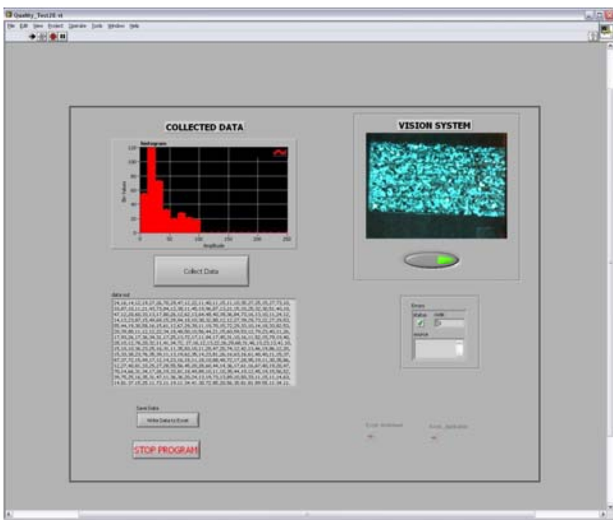


(a) (b)

Figure 5(a) Vision camera software and (b) Blob analysis

The actual data that is obtained from the blob analysis has to be extracted from the Intellect software into a LabVIEW interface to be analyzed. Using the script function, an Ethernet-based server was programmed into the vision camera to accept connections from any Ethernet clients with the correct port. The server script is a background script and is continuously running. During the blob analysis, a separate foreground script is running to extract information from the SoftSensors and save it into global registers that can be accessed by the server script. This script executes only when the camera recognizes the solar cell. As soon as the connection between the server and client is established, the server script transfers the blob analysis data that is available in the global registers to the client.

The LabVIEW client interface has been designed as shown in Figure 6(a). This client is able to communicate with the server in the machine vision camera to request the transmission of the blob analysis data. Using the graphical user interface, the user has the ability to view the examined solar cell and the captured data from the machine vision camera. The interface also displays the data in a histogram format to help the user identify the type of blobs that have been detected. This histogram is a representation of the grain size distribution of the solar cell. For documentation purposes, the LabVIEW interface allows the interaction with Microsoft Excel to export the captured data into an organized spreadsheet that can be used to perform the necessary analysis algorithms. Figure 6(b) represents a sample spreadsheet which contains parts of the blob analysis data.



(a)

	A	B	C	D	E	F	G
1	Area	Perimeter	Avg Intens	Radius	Color		
2	65951	2231.398	13	251.0401	0.084196		
3	65925	2260.992	13	251.0401	0.084237		
4	65942	2257.781	13	251.0401	0.084229		
5	65952	2257.781	13	250.9626	0.084253		
6	65938	2245.602	13	251.0401	0.084179		
7	65916	2259.539	13	251.0401	0.084192		
8	65943	2269.414	13	251.2628	0.084193		
9	65950	2249.477	13	250.9801	0.084196		
10	65947	2261.883	13	251.2628	0.084234		
11	65948	2239.883	13	250.9801	0.084207		
12	65941	2256.852	13	251.0401	0.084214		
13	65916	2274.203	13	251.1001	0.084231		
14	65925	2258.266	13	251.0401	0.084205		
15	65941	2272.305	13	250.9801	0.084204		
16	65932	2262.203	13	251.0401	0.084219		
17	65940	2256.367	13	251.0401	0.084198		
18	65933	2261.781	13	251.0401	0.084211		
19	65959	2242.648	13	250.9801	0.084196		
20	65942	2261.336	13	251.0401	0.084219		

(b)

Figure 6(a) Blob analysis LabVIEW program and (b) Gathered data from Blob analysis

The blob analysis system design demonstrates a possible method for measuring the efficiency of solar cells through image processing techniques. With an effective type of algorithm, the gathered data can be investigated to accurately assess the quality of a newly manufactured solar cell. The final product would include mechatronics and automation components into building an automated blob analysis system. The vacuum suction technology provides delicate handling of the fragile cells, allowing the robots to move them around the system without causing any significant damages to the surface of the cells.

Surface Roughness Evaluation of Solar Cells

In the manufacturing process of a solar cell, there may be issues with the titanium oxide film coating on the top of the cell. The ideal situation is for the coating to be non-uniform and energy absorbent to maximize the current output. The uniformity of the cell can be evaluated through calculating surface roughness parameters. The roughness inspection is traditionally performed through the use of a profilometer which correlates the motion of a diamond-tipped stylus to the characteristics of the examined surface. However, in the case of solar cells, a non-contact method would be preferred to avoid damaging the crystals on the surface of the cell.

The surface roughness evaluation system utilizes a Lasercheck sensor head which is designed to measure various lapped, polished, or grinded surfaces. The calibration of the sensor is a major step in guaranteeing accurate roughness measurements. Due to the fact that a solar cell calibration block is not available for this system, standard calibration for grinding or milling of glass has been used as an alternative. The roughness sensor is operated through its controller that can be configured and calibrated through its own scripting language. The parameter used to calculate the surface roughness is R_a. This parameter is the arithmetic mean of absolute values of the height measured from the laser head, expressed in microinches. The accuracy of the Lasercheck roughness sensor is around 2 microinches.

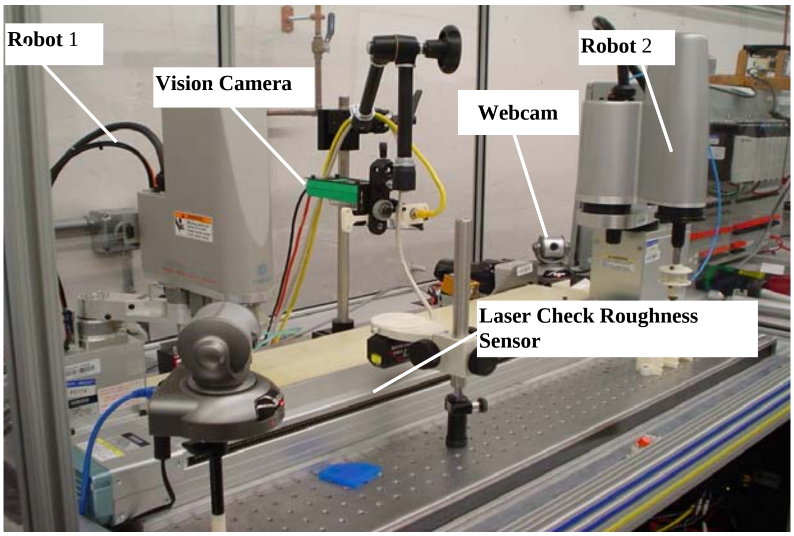


Figure 7: Quality control system incorporating laser roughness system

As shown in Figure 7, the Lasercheck head is mounted on top of a one-axis robot. The one-axis robot positions the solar cell to be placed precisely under the sensor. The controller can be externally triggered by one of the robots or a controlling software package. The surface of the cell is scanned by stepping the one-axis robot in 1 mm increments and the data is captured by the controller. This setup can be incorporated with the blob analysis vision system to encompass a fully-developed quality control procedure to evaluate the efficiency of solar cells. Figure 7 shows how multiple SCARA robots can help in orienting the specimen through the different sections of the quality control system. Two webcams at the edges of the robotic cell are used to monitor the process from a remote location.

A LabVIEW software interface has been designed to communicate through Ethernet with the Lasercheck controller and capture the roughness data that is being measured. The interface allows the user to view the robotic cell through the installed webcams and toggle the data transfer from the roughness sensor. The interface also permits to control the robots and run the experiment remotely. The captured surface profiling data is displayed in a 3D surface plot that is a representation of the uniformity of the surface of the solar cell as shown in Figure 8.

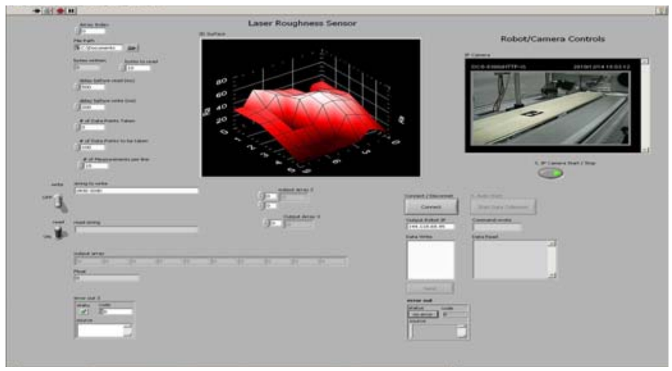


Figure 8: LabVIEW interface for surface profiling

Effect of Angle and Intensity of Light on Current Output

As a supplementary case study, the effects of the angle and intensity of light on the output current have been studied as part of the quality control process for solar cells. A test apparatus was constructed to perform these tests that consisted of an Olympus fiber optic light source, a DAQ 6015 with current conducting probes, and a LabVIEW-enabled PC. Using a protractor, different angles of illumination were possible by aligning the fiber optic light source at varying angles. Using a light intensity meter, accurate measurements of the intensity of the light source have been conducted. A portion of the testing process can be seen in Figure 9. The test solar cell piece has the dimensions of 21 mm length and 39 mm width.

Electrical current output from the solar cell sample has been measured by connecting a DAQ (Data Acquisition Assistant) 6015 connected to two current conducting probes and monitoring the data through LabVIEW. Two sets of experiments have been conducted; the first involves keeping the angle of the light source fixed and changing the intensity values while the other involves keeping the light intensity fixed and changing the angle. Figure 10 is the sample graph for the the experiments displaying the measured currents according to the variable criteria. From these figures, it can be observed that the current output increases as the light intensity increases at certain angle. The experiment shows that at the higher angles of 75º and 90º (vertical), the saturation of the solar crystals in the cell takes place at a lower light intensity. Thus, this confirms this range of angles is the most efficient for the solar cell.

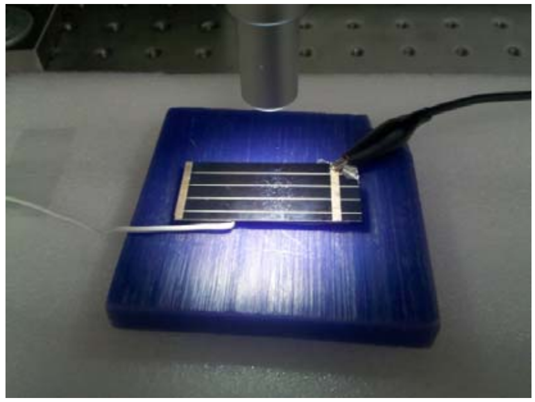


Figure 9: Solar cell current measurement

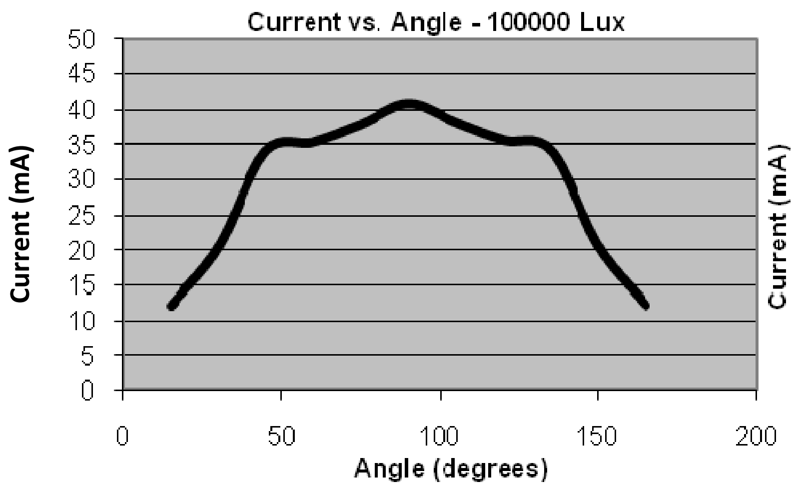


Figure 10: Current vs. angle of illumination at10,000 Lux

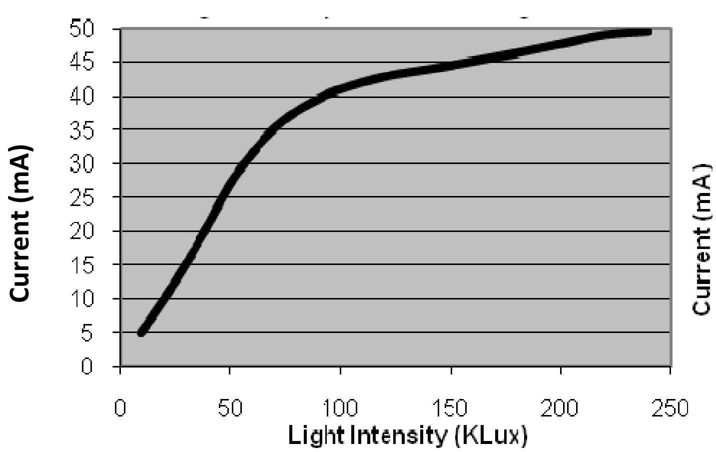


Figure 11: Sample current measurements vs. light intensity at an angle of 90º

In Figure 11, it is also observed that there is a saturation point for a certain solar cell. At the efficient angle of 90º, the current output keeps increasing as the light intensity increases. However, at the intensity of 160,000 Lux and 180,000 Lux, the solar cell becomes saturated and the current output is at maximum value. The Lux unit is the SI unit of luminous power per unit of area or one lumen per square meter. This case study proves that the structure of a solar cell and its correct orientation and position are crucial factors in yielding the maximal current output and achieving the highest levels of efficiency.

Conclusion

Due to the increasing importance of renewable energy, solar cell manufacture is an appropriate topic for the Engineering technology curriculum. We described several senior design projects that gave students hands-on experience with solar cell quality issues that could be addressed with modern methods such as machine vision, image processing, and robotics. The senior design project at Drexel University addresses this issue and encourages students to investigate in possible methods for building quality solar energy efficient systems. It presents a non-contact-based approach to assess certain performance methods and characteristics of a solar cell of solar cells by using E-Quality and image processing. This project is an introductory step to a larger scale mission to develop tomorrow's energy industry.

Acknowledgement

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