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## **AC 2012-4886: ROBOTICS AND MECHATRONICS-BASED SOLAR CELL ROUGHNESS MEASUREMENT LABORATORY**

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# **Robotics and Mechatronics-based Solar Cell Roughness Measurement Laboratory**

## **Abstract**

This paper discusses the design and implementation of a mechatronics-based solar cell surface roughness measurement laboratory for student learning experience in the emerging field of renewable energy. 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. This system is comprised of several subsystems and elements that are together utilized to automate the gathering and processing of solar cell roughness data. While a Programmable Logic Controller (PLC) is used for controlling the I/O between the robots in the workcell and the Laser Check system, a LabVIEW program is responsible for triggering the robotic programs, as well as collecting and processing the data collected by the Laser Check device. A concluding section discusses laboratory development for student hands-on learning experience within the context of a course MET 205 Robotics and Mechatronics.

## **Introduction**

This paper presents the establishment of a renewable energy teaching and research laboratory through an NSF project involving undergraduate and graduate students, and faculty at Drexel University. 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. 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<sup>1-4</sup>. The network hardware and software components are integrated with quality methodologies to achieve maximum effectiveness in teaching Web-based quality concepts in MET 205 Robotics and Mechatronics. In MET 205, a 10-week junior-level undergraduate course was offered that included a classroom component presenting lectures on robotics integrated with automation principles and methods, combined with a hands-on solar cell roughness measurement laboratory session.

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 the quality of solar cells, especially in line during manufacture<sup>5-8</sup>.

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<sup>9-11</sup>.

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 at Drexel University. Several approaches are pursued as part of the project. An attempt at measuring the surface roughness of the solar cell has been also performed. Through image processing, the students perform statistical analysis on the grain structure of solar cells and try to relate it to the measured current output. 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 student learning experience on renewable energy manufacturing with the steps taken and apparatus used for performing measurement of solar cells for quality control.

### **Non-contact-based Quality Control Approach**

Conventional quality control methods mostly incorporate contact-based solutions for evaluating the efficiency of solar cells. 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. Studies of the roughness of a solar cell have shown that the surface roughness of the solar 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.

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. 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.

## Automated Surface Roughness Measurement System

Figure 1 describes the architecture of the remote surface roughness measurement system. The PC-based remote inspection system is composed of a YK250X 4-axis SCARA robot, RCX 140 controller, a F1010-700 1-axis robot, SR1-X robot, a laser check sensor, an IP Surveillance camera, and an Allen Bradley PLC controller. The laser check sensor has a built-in processor which allows it to perform real-time algorithms, along with real-time monitoring. The process is designed to be Ethernet based using TCP-IP communication. After a successful TCP handshake, images and extracted measurements can be sent back and forth remotely between the servers and clients. The laser check sensor is properly programmed with necessary algorithms to calculate the various surface roughness parameters. In the LabVIEW-based graphic user interface (GUI), statistical quality algorithms for remote measurement are calculated. The controller communicates with the robot to instruct it to perform the required operations. In addition, the Internet-based vision system is integrated through the IP surveillance camera, displaying the products that are being analyzed. The most significant part of this automation system is the vision module.

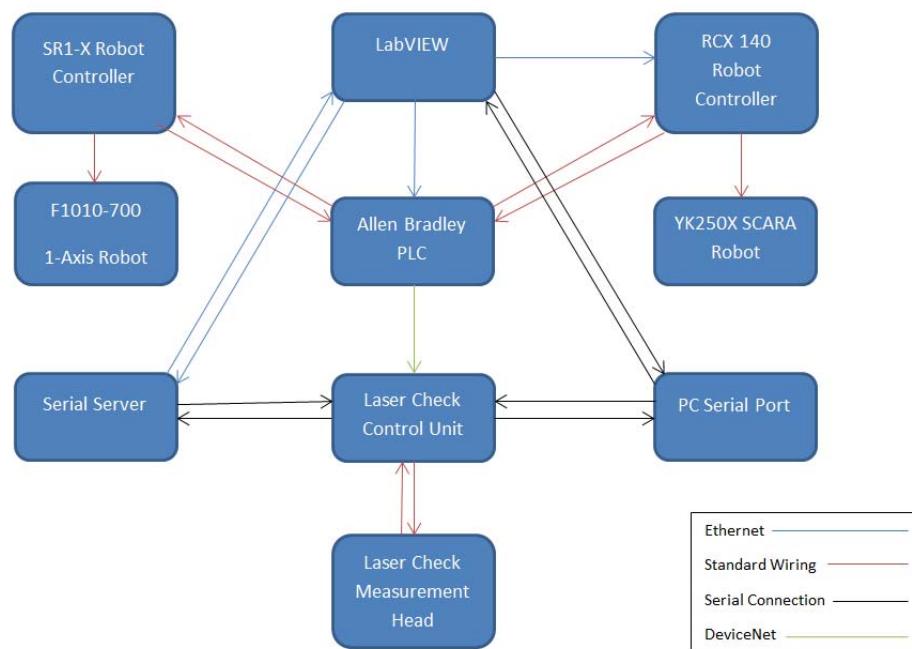


Figure 1: Architecture of surface roughness measurement system diagram

### Laser Check Components

The Laser Check surface roughness measurement gage is the component that performs the actual measurement of a surface's roughness via the use of a non-contact, visible laser. This device consists of a measurement head as well as a control unit, which can be seen below in figure 2.

The measurement head is where the laser and a photodiode array are housed and mounted to the robot. The laser used in this device is a visible red laser with a wavelength of 650nm. The photodiode array consists of 35 discrete elements, of which only 24 are used at any one time to perform calculations. Measurements are taken by triggering the laser, which is aimed at the surface, and the reflected and scattered light distribution is detected by the photodiode array. This distribution data is then sent to the control unit where the  $R_a$  value is calculated for the area measured by the laser. It is key to note that the  $R_a$  measurement is not a measurement of the roughness at a single point, but a calculated average roughness value of the area covered by the laser beam. The formula for calculating the  $R_a$  value is  $R_a = \frac{1}{n} \sum_{i=1}^n |y_i|$  where the units are in microinches. To communicate and collect data from the Laser Check device an RS232 serial cable is connected between the control unit and either a PC or a serial server. The LabVIEW program, that will be discussed in greater depth further on in this paper, can access the data locally via a serial port on the PC it is running on, or over Ethernet when the serial connection is made to the server.

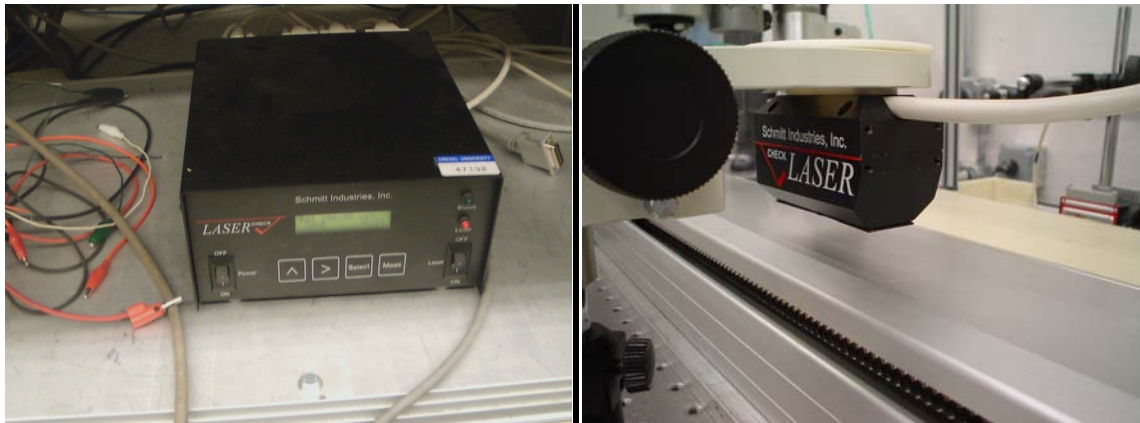


Figure 2: Laser Check control unit

## Robotic Workcell

Utilizing robots in the process of performing surface roughness scanning allows for both full automation as well as precise and repeatable measurements. The two robots used in this cell are the Yamaha YK250X SCARA robot and the Yamaha F1010-700 1-axis robot. The measurement head of the Laser Check system is mounted to the tool arm of the SCARA robot. The robotics cell can be seen in Figure 3.

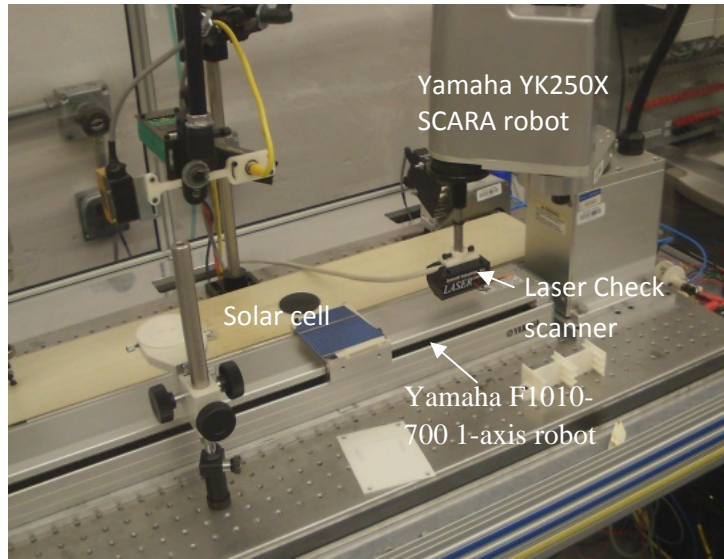


Figure 3: Robotic surface roughness measurement workcell

The piece to be scanned is mounted to the 1-axis robot. The scan is performed by incrementing the 1-axis robot in what shall be designated as the y-axis  $i$  number of times. Once completed, the 1-axis robot moves back to its initial position and the SCARA robot increments in what shall be designated as the x-axis, and the 1-axis robot begins its incrementing cycle again. This process repeats  $j+1$  times,  $j$  being the number of increments the SCARA robot makes. This produces a 2D array or matrix of data:  $\mathbf{M}_{i+1,j+1}$ , which can later be used to plot a 3D graph.

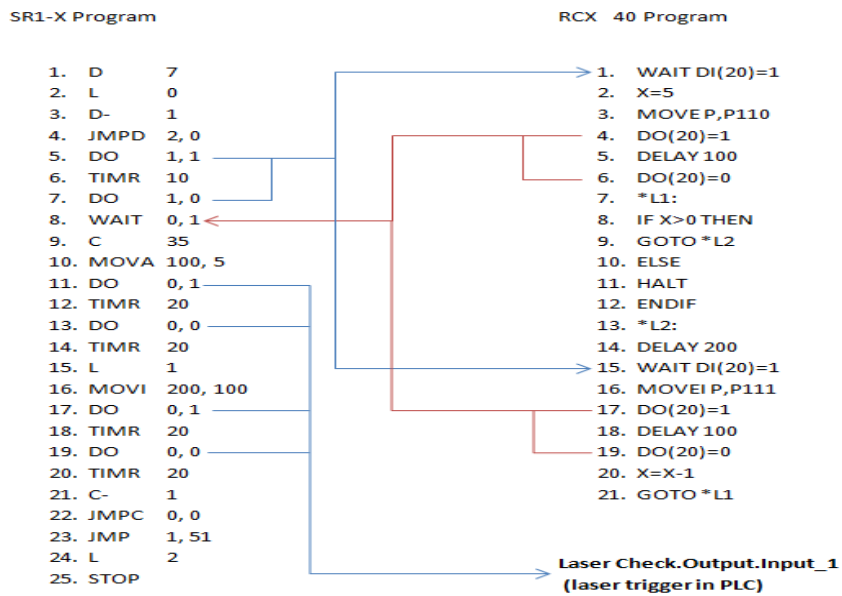


Figure 4: One-axis and SCARA robot programs

The two programs for the robots can be seen on the next page in Figure 4. The program on the left is the program for the 1-axis robot, and the program on the right is the program for the SCARA robot. The basic functionality of both of these programs comes from the use of variables, loops, and incrementing instructions. The variable D in the first program is equivalent to  $j+2$  and is responsible the number of times the entire program loops. The variable C further on down is equivalent to  $i$ . Thusly, if you wanted a matrix  $35 \times 10$  you would make D equal to 11 and C equal to 34. By decrementing these variables and using conditional loops, the desired number of increments can be achieved. Similarly, the program for the SCARA robot also makes use of the same functions. The variable X in the second program is equivalent to  $j$  so that if the number of columns in the matrix is 10 for instance, X would be equal to 9. Again, as in the other program, the X variable is decremented after each cycle and upon completion branches off and halts the program. The lines drawn between the programs in figure 4 represent the connections of I/O between both robot controllers that are made using the PLC.

### Programmable Logic Control

To make the system fully automated, there must be a way for the robots to send and receive signals from each other, as well as to and from LabVIEW and the Laser Check control unit. To accomplish these connections a PLC is used. The type of PLC used for this automation system is an Allen Bradley Control Logix unit. A simple PLC ladder logic diagram is employed to coordinate certain inputs to in turn trigger specific outputs. The ladder logic used in this system is shown in Figure 5.

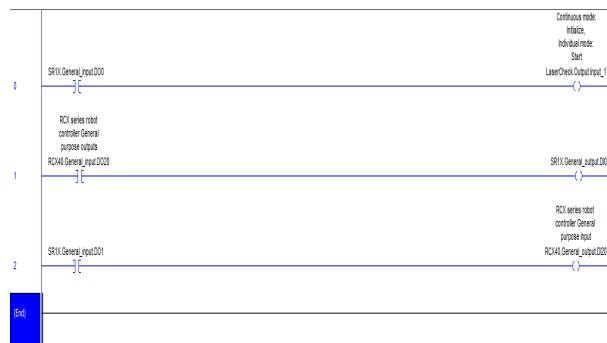


Figure 5: Surface roughness system ladder logic diagram

In this experiment, students learned the basics of using the ROCKWELL Automation “RSLogix 5000” Enterprise series ladder logic software. Students also learned how to set up ladder logic programs, save them on a PLC processor, and run them on the Allen Bradley PLC to control robots and electric actuators. RSLogix 5000 is a powerful industrial software package, which is very similar to many other industrial ladder logic programs in industry. Students program PLC ladder logic, as along with relay ladder logic, although the differences between them are fairly slight.

This ladder logic basically functions as a form of virtual wiring between components. The first rung connects an output from the 1-axis robot to the laser trigger of the Laser Check control unit. Whenever the robot's program sends that output, it turns on the laser. The second and third rungs connect an output and input from one robot to the input and output of the other. This allows the robot's to signal when, for instance, they are both in the initial position and ready to start a scan. The ladder logic is not the only way that the PLC is used in the automation system. The LabVIEW program can access and flip bits in the PLC via an Ethernet connection. These connections are used to initiate the robots' programs remotely as well as control the timing of data flow into the LabVIEW program.

## Data Acquisition

The LabVIEW block diagram for the program is shown below in Figure 6. This program breaks down into two main sections, which can be seen visually by noting the two large while loops that are outside of each other. The first top part of the program communicates with the Laser Check control unit and collects the data from it. Once the data has been gathered, it is then processed in subsequent case structures, which produces the floating point data that is needed. This data is then built into an array and graphed on a 3D plot in the LabVIEW program. The data is also saved externally to a spreadsheet so that external analysis can be done using Excel, MATLAB, or any other analysis software.

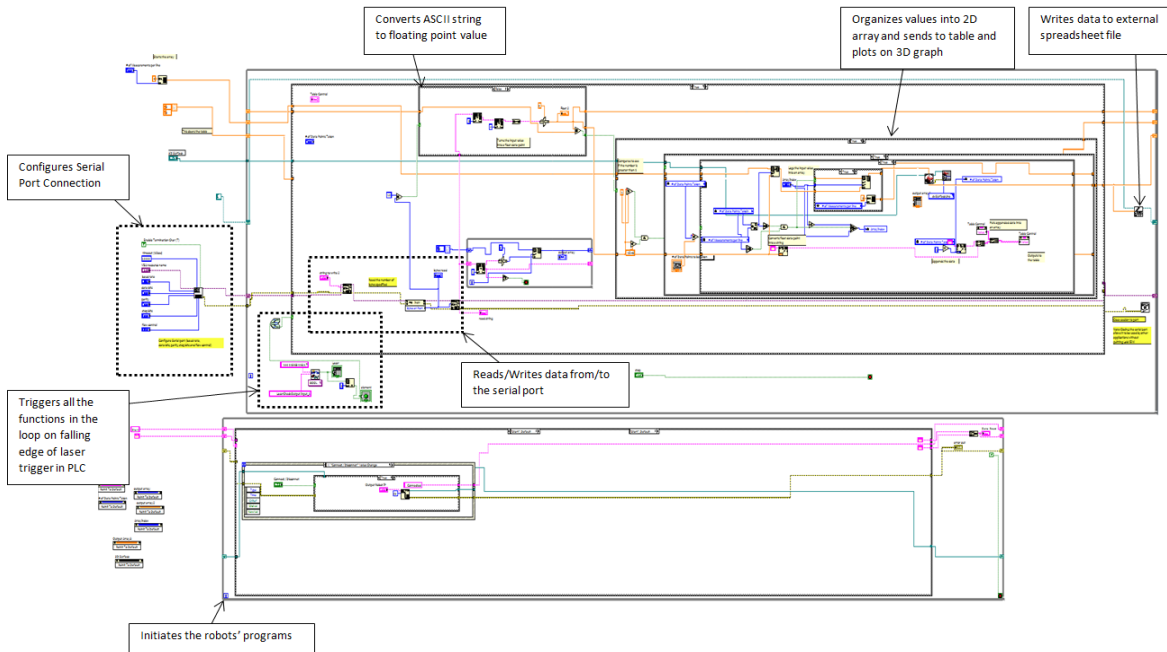


Figure 6: LabVIEW program block diagram

The second part of the program initiates the two robot's programs. The majority of the program is inside the case structure, which is inside the first larger while loop. This case structure has four different cases which it switches through based on button presses on the front panel as well as



internal factors. The connections between the program and the robots are made through both the PLC and through Telnet communication using TCP/IP. The 1-axis robot controller does not support Ethernet connection, and as such, the program is initiated by connecting to the PLC and flipping the bit. The SCARA robot controller can be connected to Ethernet directly using TCP/IP.

To initiate the connection between either the serial port or serial server a configuration block, specific to the type of connection, is used. Once the connection is established, TCP/IP or Serial Read/Write blocks are used to issue a call for data to the Laser Check system and then read the data that comes in. To control the flow of data in, such that data is not erroneously read twice or skipped over, a case structure is employed, which is triggered by the falling edge of the laser trigger in the PLC. This essentially allows the program to read the data only right after the laser turns off. The data that flows in comes in the form of an ASCII string. To convert this into a floating point value, the string is parsed and header and footer values are removed. The remaining value is then converted to a float value using a type cast function. This data is then sent along and placed into a 2D array that is a set of 1D arrays that represent each scan along the face of the material. This array is then sent to the 3D graph and table on the front panel, as well as to an external spreadsheet file.

### Surface Roughness Evaluation of Solar Cells

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. 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: LabVIEW interface for surface profiling

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.

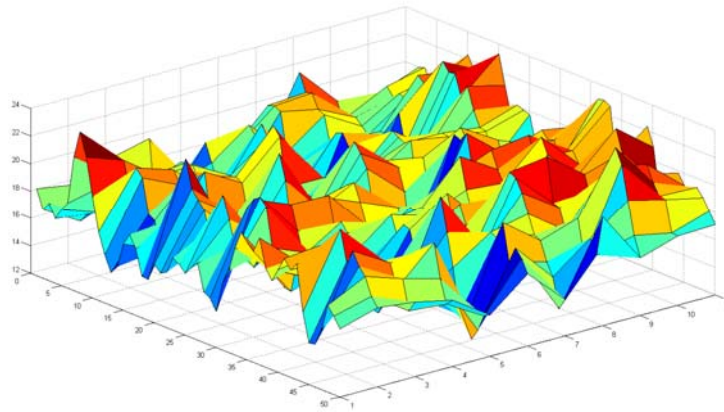


Figure 8: Solar cell surface roughness graphs

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 surface of the solar cell. Figure 8 shows example plots of the data, plotted with MATLAB, collected from the described system. The x and y axes correspond to the rows and columns of data collected, in this case 11 by 50. The z axis displays the measured  $R_a$  values. This data comes from 3 separate scans of the same monocrystalline solar cell.

### **Real-time Solar Cell Quality Experiments for Students**

The solar cell quality control experiment has been developed for the course MET 205 Robotics and Mechatronics as a part of this laboratory development. The course provides the students with a comprehensive knowledge of Internet-based quality control using industrial robots and other mechatronic components as shown in Figure 9. The specific Internet-based quality methodologies chosen are related to computers and networks, robotics, quality inspection, laser check, and sensors. The laboratory assignment was used to reinforce lecture information and to give hands-on experience on solar cell quality. It is believed that the student learning experience about Internet-based solar cell quality control is enhanced. Course reviews by students were very positive. Students commented that they enjoyed hands-on working experience in the lab. An additional benefit to students was that they could claim on their resumes that they had experience on renewable energy quality control integrated with robotics and mechatronics.

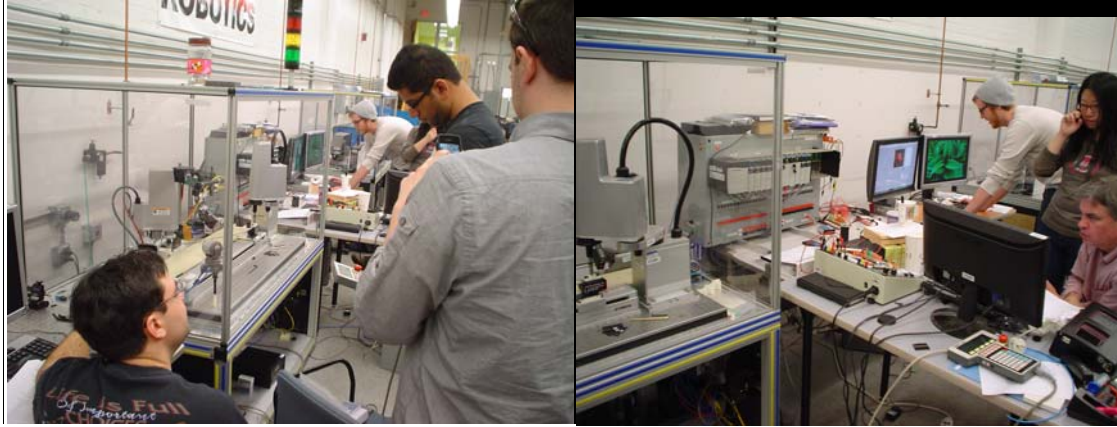


Figure 9: Students performing solar cell surface roughness measurement

## Conclusion

This paper describes laboratory innovations for the enhancement of undergraduate level teaching of a capstone course (MET 205 Robotics and Mechatronics) integrated with emerging technology. The trends in emerging fields of renewable energy have changed the teaching schemes with industrial robots. The new developments allow the students to program, monitor, and control robotic operations through the Internet using the LabVIEW. The 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.

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