

Development of an Automated Measurement System for Checking Irradiation Non-uniformity of Solar Simulators

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Received 02 June 2017; received in revised form 13 June 2017; accepted 23 August 2017

Abstract

Generally, for some solar simulator manufactures, the measurement of irradiation non-uniformity is made by placing a PV cell artificially and point by point on each measuring point on the solar module. It records each corresponding output voltage of PV cell. It is time-consuming and easy to produce measurement error. If either an XY table or a multi-axis robot is applied in this case, it is not only expensive but also difficult to carry and setup. Hence, an innovative and automated measurement system, which consists of both a self-developed smart robot and a monitoring and control system, is proposed in this paper to solve aforementioned problems. The monitoring and control system, i.e., constructed by a PC and a self-developed LabVIEW-based application program, plays the role of remotely commanding the operation mode of a robot, receiving the irradiance data being transmitted from the robot and calculating the irradiation non-uniformity. Once the irradiation non-uniformity is calculated, some operations are made to adjust the irradiation parameters of the solar simulator such that the irradiation non-uniformity can meet the specification, i.e., 2%, 5%, 10% for class A, B or C of solar module, respectively.

Keywords: solar simulator, PV cell, solar module, irradiation non-uniformity, measurement

1. Introduction

Recently, many works of literature have paid much attention to develop or design the solar simulator [1-6]. Polly et al. [1] presented a dual source solar simulator. To test meteorological radiation, Sun et al. [2] designed the optical system of the solar simulator. Domínguez et al. [3] presented a solar simulator for measuring the performance of large area concentrator photovoltaic (CPV) modules. A new economical large-scale multiple-lamp solar simulator has been designed and constructed by Meng et al. [4] to provide a test platform for the simulation of solar radiation at the earth's surface. A low-cost and portable solar simulator by using LED (light-emitting diode) lamps has been proposed by Kohraku and Kurokawa [5]. Besides, Sabahi et al. [6] designed and constructed an efficient large-scale solar simulator to investigate solar thermal collectors. To measure the characteristic parameters, such as maximum power output [7], operating temperature [8] etc., of solar module more accurate, an efficient multiple-lamp solar simulator has been employed to irradiate the surface of the solar module. Before that, the irradiation parameters of the solar simulator need to be checked in advance, such as irradiation non-uniformity, irradiation stability, and so on. The qualification of solar simulator was specified in IEC standard 60904-9, and it specified that at least 64 points irradiance on the surface of a solar module is required to be measured. Generally, the solar module consists of 6 x 10 or 6 x 12 PV (photovoltaic) cell and each of them is 200mm*200mm in dimension. Before checking the irradiation non-uniformity, these 64 points irradiance need to be measured in advance. And then, the irradiation non-uniformity is checked based on these data according to a non-uniformity formula.

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The study of [9] pointed out that the most commonly used irradiance non-uniformity measurement methods were “mechanical scanning”, “optical tracing”, and “reference correction”, etc. However, they can not meet the requirement of measuring the non-uniformity of pulse simulator. In [9], a measurement system based on the “shutter method” has been proposed to accomplish an irradiance non-uniformity measurement of pulse simulator. For some solar simulator manufactures, to measure the irradiation non-uniformity, the measurement of irradiance on the irradiated surface of the solar module is made by placing a PV cell artificially and point by point on each measuring point on the surface of the solar module. And then, it records each corresponding output voltage of PV cell. It is time-consuming and easy to produce measurement error. In the way of “mechanical scanning”, if either an XY table or a multi-axis robot is applied to achieve this automated measurement process, it is not only expensive but also difficult to carry and setup. Therefore, it is urgent to develop a portal and automated measurement system for checking irradiation non-uniformity of the solar simulator.

The purpose of this paper is to propose an innovative and automated measurement system for checking the irradiation non-uniformity of the solar module. This paper is organized as follows. Section 2 gives a profile of the proposed system hardware structure. Section 3 describes the system software, including graphic user interface (GUI), the PC program and the Arduino program. In Section 4, the experimental results are presented to demonstrate that the proposed scheme is capable of checking the irradiation non-uniformity of the solar module. Conclusions are made in Section 5.

2. Profile of the System Structure

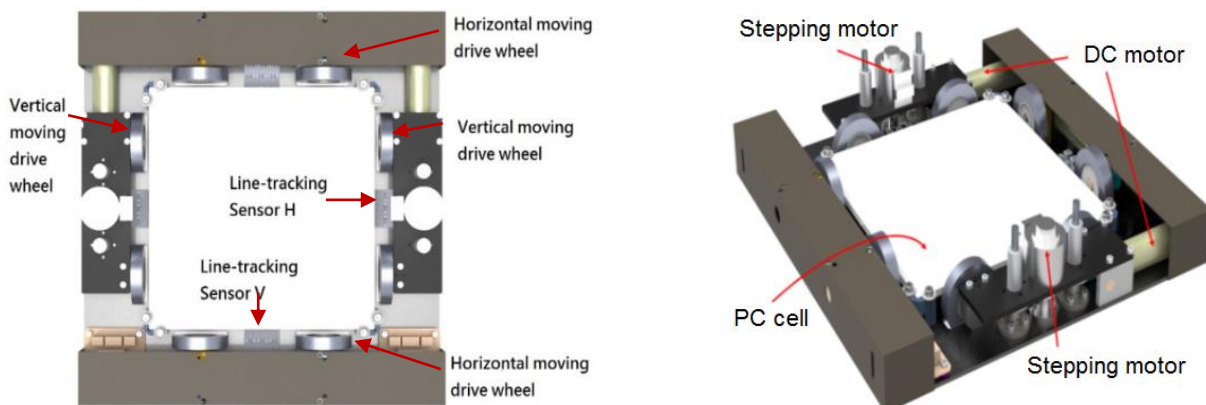


Fig. 1 Sketch of robot

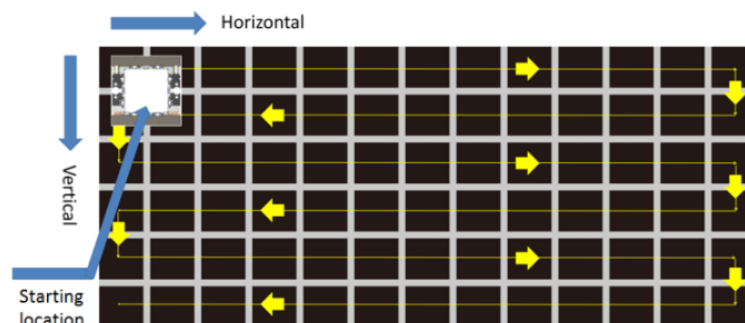


Fig. 2 Moving paths for robot

The automated measurement system proposed in this paper consists of both a small and smart robot (320mm x 320mm x 75mm) and a monitoring and control PC. In a mechanism, the robot has been well designed for only moving along either the vertical or the horizontal path to avoid turning and to promote position ability. Functionally, it is capable of loading a PV cell on its top and moving automatically on a sheet of poster paper which is covered on the surface of the to-be-measured solar module and laid out with several pre-designed tracking paths and position points for the robot. The designed sketch of the robot is shown in Fig. 1, and the poster paper (192mm x 96mm) being laid out with tracking paths and position points are

shown in Fig. 2. In Fig. 2, there are 6 horizontal paths and 12 vertical paths. The line-tracking sensor H and the line-tracking sensor V are, respectively, employed for the robot to move along the horizontal path and the vertical path. When the robot moves along a horizontal path, once the line-tracking sensor V senses the vertical path the robot stops for a moment and the irradiance on the surface of the solar module is acquired and stored in the EEPROM of Arduino Mega [10]. The similar working principle is applicable to move along vertical paths for the robot.

The structure of the proposed automated measurement system is shown in Fig. 3, and serial peripheral interface (SPI) signal between the RF module and the Arduino Mega/UNO [10] is further shown in Fig. 4. The PV cell detects the irradiance on the irradiated surface of the measuring location of the solar module and its output voltage is sent to an analog input (AI) of Arduino Mega. The control signals from the PC include operation mode, i.e., automation mode and manual mode, position location, start/restart measurement, start transmission, DC motor control and stepping motor control, can be transmitted through the RF modules located on both the PC side and the robot side. In Fig. 1, two sets of DC motors including transmission gears are employed to drive four wheels for driving the robot to move along the horizontal direction, and the other two sets of DC motors including transmission gears are employed to drive four wheels for driving the robot to move along the vertical direction. Moreover, two sets of stepping motors including transmission mechanism are employed to control the mechanism which switches either horizontal moving drive wheel or vertical moving drive wheel to contact the floor. Fig. 5 reveals this switching effect. On the other side, the monitoring signal from Arduino Mega like irradiance data being acquired can be transmitted to the PC. Since the RF module only has SPI, the feedback data transmitted from Arduino can not be transferred to PC. An Arduino UNO is used to bridge the SPI of RF module and the USB of PC. An Arduino UNO is used to bridge the SPI of RF module and the USB of PC.

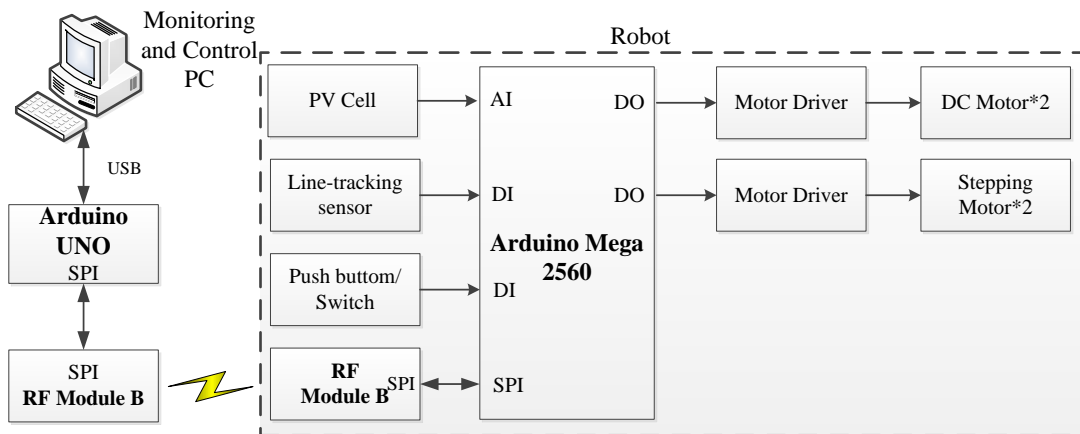


Fig. 3 Structure of the proposed system hardware

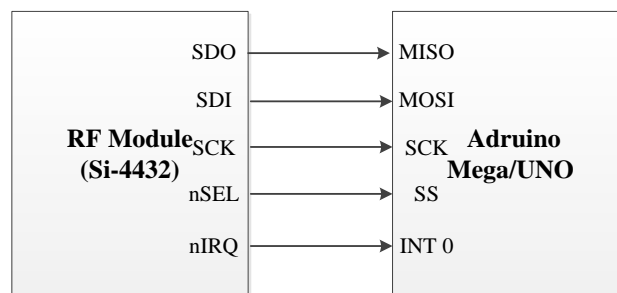


Fig. 4 SPI between the RF module and the Arduino Mega/UNO



Fig. 5 Sketch of the robot

The main facilities and modules being required for the proposed system are as follows.

- (1) One PC is used as monitoring and control station.
- (2) LabVIEW 2015 for the design of GUI and the communication with the Arduino Mega.
- (3) One Arduino UNO connected with the PC via USB and with the RF module (Si4432) via SPI.
- (4) The robot controlled by Arduino Mega makes it move in horizontal and vertical on the top surface of solar module.
- (5) One RF module (Si4432) connected with the Arduino Mega via SPI.
- (6) One PV cell connected with Arduino Mega via AI.
- (7) Two sets of line-tracking sensors connected with Arduino Mega via digital input (DI) are used to sense the horizontal path and vertical path, respectively.
- (8) Two sets of DC motor drivers connected with Arduino Mega via digital output (DO) are used to drive four DC motors for driving the robot to move along horizontal and vertical direction, respectively.
- (9) Two sets of stepping motor drivers connected with Arduino Mega via DO are used to drive two stepping motors for switching either horizontal moving drive wheel or vertical moving drive wheel to contact with floor.

3. Description of the System Software

The system software includes the monitoring and control program in PC and the control and communication program in Arduino UNO/Mega. The monitoring and control program in PC includes GUI and the program of commanding robot and receiving measured data from the robot via wireless communication. On the other hand, the robot is controlled by the Arduino Mega which includes control program and the program to communicate with the Arduino UNO via the RF module B. The Arduino UNO functionally acts as the bridge between the PC and the Arduino Mega. Thus, the program in it is used to communicate with the PC via USB and communicate with the Arduino Mega via the RF module A.

3.1. Description of GUI

The LabVIEW-based GUI builds up the friendly human operation interface and the communication mechanism between the PC and the robot. From the monitoring and control panel in the PC, shown in Fig. 6, the remote connection between the PC and the robot will be achieved immediately once the “Start measurement” button is pressed. The GUI can determine the operation mode of the robot, i.e., automation model and manual mode.

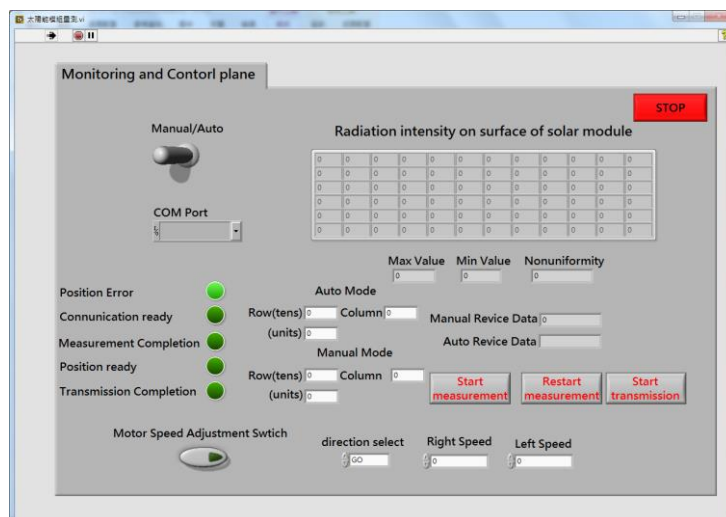


Fig. 6 Monitoring and control panel in the PC

3.2. Illustration of PC programming

The programming of PC is responsible for transmitting the control signals to the Arduino Mega and also receiving data from the Arduino Mega. Besides, the receiving data transferred from the Arduino Mega are also integrated into GUI in PC.

The main procedures in PC are briefly described as follows, and its flowchart is shown in Fig. 7.

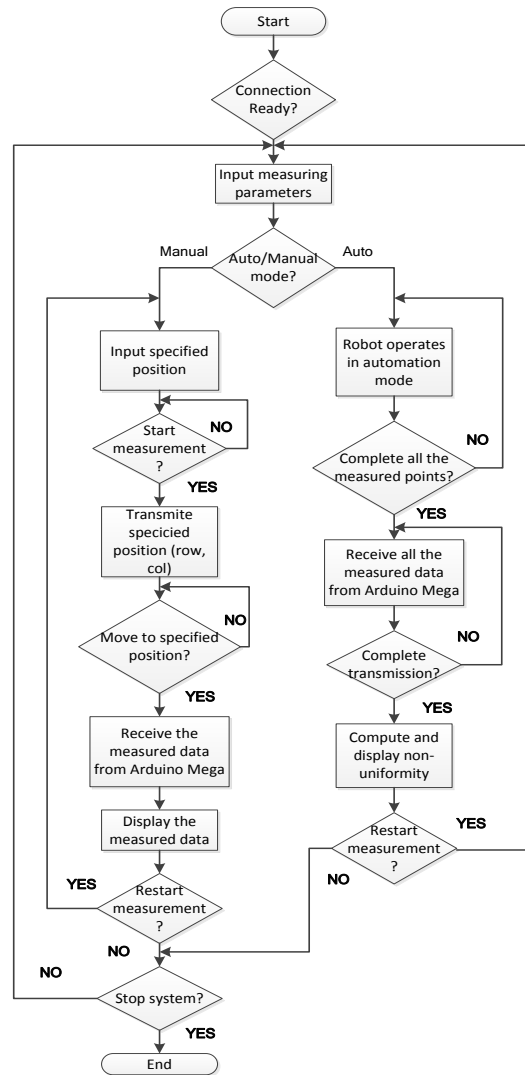


Fig. 7 Flowchart of the LabVIEW programming

- (a) Set COM port for the serial communication and determine the transmission rate, i.e., baud rate (bit per second), as 9600 that need to match the Arduino UNO transmission rate.
- (b) Set the specification of solar module, i.e., the number of PV cells that a solar module includes. For example, 6 rows x 12 columns means that a solar module has 72 PV cells.
- (c) Check if the wireless communication connection is ready. If yes, turn on “Communication ready” indicator and go to the next step. Otherwise, repeat Step (c).
- (d) In this step, two operation branches work independently as follows.

Branch 1: Manual mode

 - (i) Check if the manual mode is requested. If yes, go to the next step. Otherwise, go back to Step (d).
 - (ii) Set the specified position on the solar module, i.e., the row number and the column number.
 - (iii) Check if the “Start measurement” button is pressed. If yes, transmit the manual command code and the specified position to the Arduino UNO and go to next step. Otherwise, the same procedure is repeated.
 - (iv) Check if the specified position is reached. If yes, turn on the “Position ready” indicator and go to the next step. Otherwise, the same procedure is repeated.
 - (v) Receive the measured data from the Arduino UNO.
 - (vi) Check if the measured data is received. If yes, display the measured data and go to the next step. Otherwise, go to Step (v).

(vii) Check if the “Restart measurement” button is pressed. If yes, go to the next Step (ii). Otherwise, go to Step (e).

Branch 2: Automation mode

- (i) Check if the automation mode is requested. If yes, go to the next step. Otherwise, go back to Step (d).
- (ii) Check if the “Start measurement” button is pressed. If yes, transmit automation command code to the Arduino UNO. Otherwise, the same procedure is repeated.
- (iii) Check if the measurement of all the measuring points is completed. If yes, turn on “Measurement completion” indicator and go to the next step. Otherwise, the same procedure is repeated.
- (iv) Check if the “Start transmission” button is pressed. If yes, go to the next step. Otherwise, the same procedure is repeated.
- (v) Receive all the measured data, i.e., the irradiance on the solar module, from the Arduino UNO.
- (vi) Check if all the measured data are received. If yes, turn on “Transmission completion” indicator go to the next step. Otherwise, go to Step (v).
- (vii) Display all the measured data on GUI, compute irradiation non-uniformity and display it, and save the data measured at this time in a file. The formula to compute irradiation non-uniformity is described as follows.

$$\text{Non - uniformity} = \left[\frac{\max \text{ irradiance} - \min \text{ irradiance}}{\max \text{ irradiance} + \min \text{ irradiance}} \right] \quad (1)$$

- (e) Check if the “Stop” button, i.e., the button to stop system, is pressed. If yes, stop the measurement system. Otherwise, go to Step (b)

3.3. Illustration of the Arduino programming

There are programs in both the Arduino Mega and the Arduino UNO need to be designed and their illustration are, respectively, illustrated as follows:

(1) Illustration of the Arduino UNO programming

The Arduino UNO is employed to bridge the communication between the RF module with SPI interface and the PC with a USB interface. The programming flowchart is shown in Fig. 8. The main procedures are briefly described as follows.

- (a) Set the transmission rate, i.e., baud rate (bit per second), as 9600 that need to match the PC transmission rate.
- (b) Check if wireless communication connection is ready. If yes, turn on “Communication ready” indicator and go to the next step. Otherwise, the same procedure is repeated.
- (c) Receive command code (sent from PC) and transmit it to the Arduino Mega.
- (d) Check if the “Start transmission” flag is activated. If yes, receive the measured data from the Arduino Mega and transmit them to PC and go to the next step. Otherwise, the same procedure is repeated.
- (e) Check if the “Restart measurement” flag is activated. If yes, go to Step (b). Otherwise, the same procedure is repeated.

(2) Illustration of the Arduino Mega programming

The Arduino Mega is employed to control the robot for executing manual or automation operation according to the command code transmitted from PC, to acquire the output voltage of PV cell via AI, and to feedback the acquired data to PC. The programming flowchart is shown in Fig. 9. The main procedures are briefly described as follows.

- (a) Check if the wireless communication connection is ready. If yes, turn on “Communication ready” indicator and go to the next step. Otherwise, the same procedure is repeated.
- (b) Compare if the command code is manual or automated. Two operation branches work independently as follows.

(c) Check if the “Start measurement” flag is activated. If yes, go to the next step. Otherwise, the same procedure is repeated.

Branch 1: Manual mode

- (i) Control the robot to move to the specified measuring point.
- (ii) Acquire the output voltage of PV cell, i.e., the irradiance on the solar module, via AI and transmit the acquired data to PC.
- (iii) Go to Step (a).

Branch 2: Automation mode

- (i) Acquire the output voltage of PV cell i.e., the irradiance on the solar module, via AI.
- (ii) Control the robot to move to the next measuring point that is the required point belongs to the programmed path in automation operation.
- (iii) Store the acquired data in the EEPROM of the Arduino Mega.
- (iv) Check if the measurement of all the measuring points is completed. If yes, transmit all the acquired data stored in EEPROM to the PC and go to Step (a). Otherwise, go to Step (i).

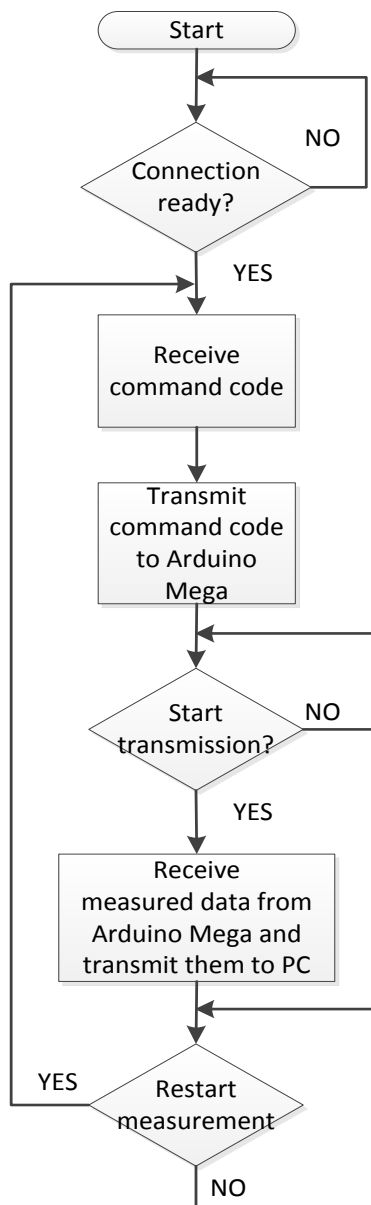


Fig. 8 Flowchart of the Arduino UNO programming

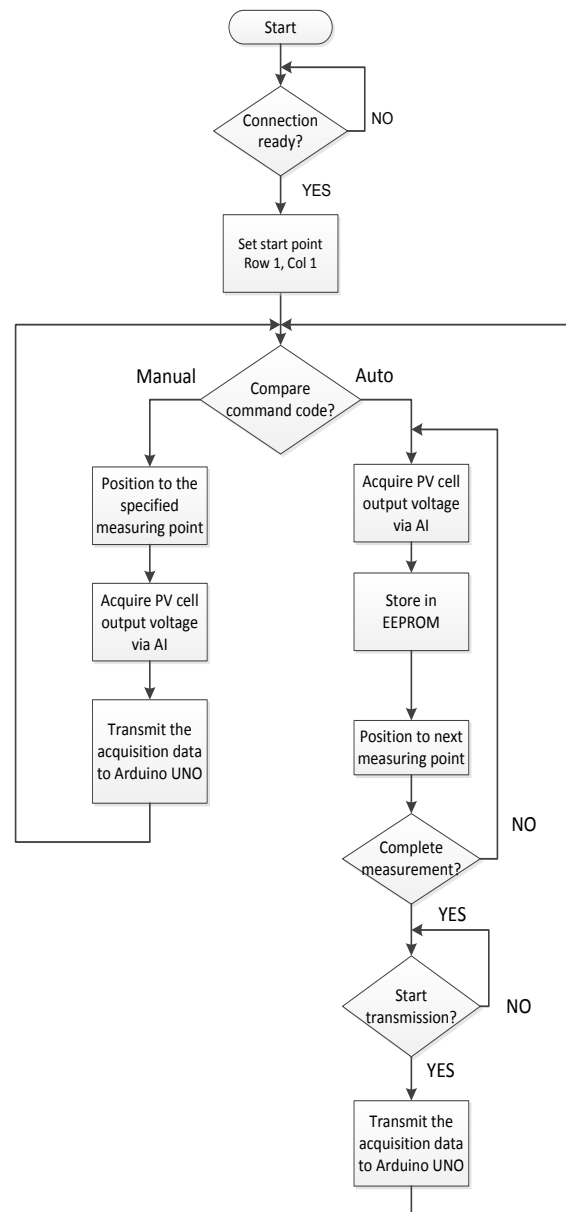


Fig. 9 Flowchart of the Arduino Mega programming

4. Experimental Results and Discussion

The experiment of this new approach is implemented in a chamber which is equipped mainly with a solar simulator used to irradiate the solar module and a platform used to load a solar module. This chamber is shown in Fig. 10.



Fig. 10 A chamber

(1) Connect PC to the robot

The first step to implement the proposed system is to connect PC to the robot. Once the LabVIEW-based GUI is activated, shown in Fig. 6, the connection will be operated immediately whenever the Arduino Mega is standby. Fig. 11 indicates the implementation status after completing this step.

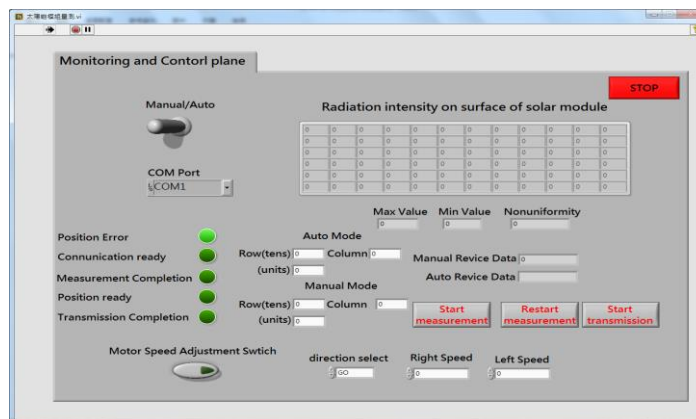


Fig. 11 Setup of the system connection

(2) Implement automation operation

The implementation of the automation operation, shown in Fig. 12, shows the measured data, i.e., the irradiance on the solar module, the maximum and minimum value of them and the irradiation non-uniformity.

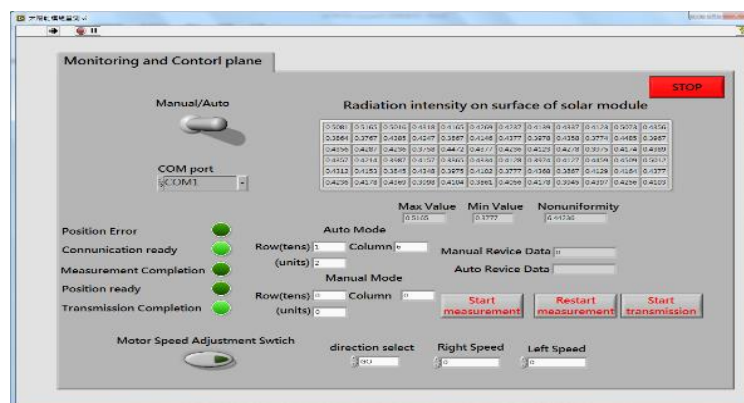


Fig. 12 Operational results of automation mode

(3) Implement manual operation

The implementation of the manual operation is shown in Fig. 13. It shows the number of PV cells, which a solar module has, the specified measuring point (row number and column number) and the measured data from that point are shown in “Receive data” field.

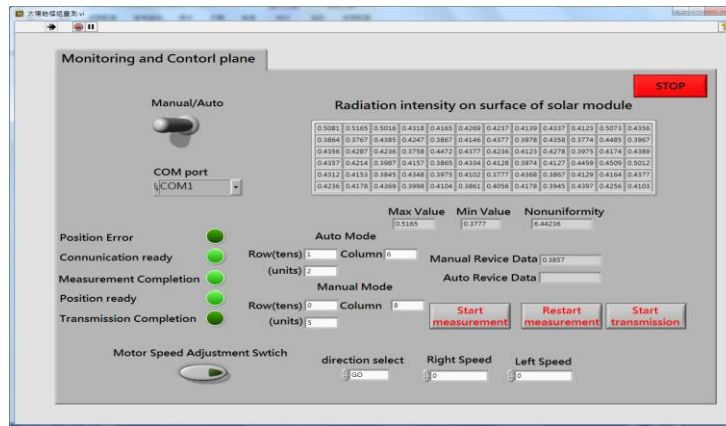


Fig. 13 Operational results of manual mode

(4) Measuring time

The experimental results about the measuring time and the moving velocity which the robot operates in automation mode are shown in Table 1. Generally, if the measurement of irradiation non-uniformity is made by placing a PV cell artificially and point by point on each measuring point on the solar module, each measuring point takes 20 seconds in average to measure. Thus, it will totally need 1440 seconds to complete measuring one solar module which is 6 rows x 12 columns in the specification. The measuring time obtained by using the proposed system is significantly improved as compared with that by artificial measurement.

Table 1 Measuring time and moving velocity

Specification of solar module	Measuring time (sec)	Moving velocity (mm/sec)
6 rows x 10 columns	210	56.47
6 rows x 12 columns	240	56.03

5. Conclusions

In this paper, an innovative and automated measurement system for checking the irradiation non-uniformity of the solar simulator is proposed. The feasibility of this new approach has been demonstrated by implementing the experiment in a chamber with a solar simulator and a test platform. Furthermore, the experimental results have shown that the proposed system has merits of meeting the miniaturization and portability demands, low setup cost and higher measuring efficiency.

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