Robotica (2007) volume 25, pp. 575–580. © 2007 Cambridge University Press
doi:10.1017/S0263574707003463 Printed in the United Kingdom

Auto-laydown robot for space solar module

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(Received in Final Form: February 6, 2007. First published online: March 29, 2007)

SUMMARY

This paper discusses about auto-laydown robot (ALR), which is applied to performing the laydown process of a solar module on earth. The robot consists of an adhesive dispensing mechanism, an auto-laydown mechanism, a pneumatic system and a control system. The method of gripping solar cells is described based on pneumatic technology. Meanwhile, a new method of controlling adhesive thickness and area during dispensing is proposed in this paper. The robot realizes the automatic laydown process of solar modules and can control the laydown pressure effectively. Compared with the manual method, the robot could control the dispensing volume and the adhesive area between solar modules and panel substrates, by means of experiments. The novel ALR greatly improves the laydown quality of solar modules and meets the lightweight trend of solar cells development.

KEYWORDS: Auto-laydown robot (ALR); Solar module; Gripping; Dispensing mechanism.

1. Introduction

The manufacturing process of solar cell arrays (SCA) is very complicated and scrupulous (shown in Fig. 1). Since solar cells are very thin and fragile, a mass of manual labour has been employed during the process. In order to realize automated manufacturing of SCA on earth for space applications instead of manual work, we developed an auto-bonding robot (ABR) and an auto-laydown robot (ALR). In outer space, there are many high-energy particles, and the irradiation is very intensive. The solar cells must be bonded with anti-irradiation glass cover. ABR is developed for automated bonding, which has been presented in refs.[1]–[3]. After the bonding process, the laydown process of solar modules can be implemented by ALR. This paper mainly describes the ALR robot, including the architecture and methods of the system.

Figure 2 shows a photograph of a solar cell integrated connector (CIC) that is 40 mm long and 20 mm wide. One string of solar cells basically consists of 60–80 pieces of CIC welded together, which is called a solar module.[4–7] At present, the laydown process of solar modules on solar panels is totally accomplished by manual labour. The ALR system is hence developed to realize the automatic operation. The existing laydown process of solar panels by manual labour is as follows:

(1) Many special adhesive tapes with lots of rectangular holes are adhered to the solar panel substrate.
(2) The prepared adhesive is spread over the substrate.
(3) Tear out the adhesive tapes, so much adhesive in the shape of a rectangle is left on the substrate.
(4) Adhere solar modules to the substrate and make sure that each cell corresponds to the one rectangular adhesive field.

Obviously, there are some major drawbacks in manual operation. First, the thickness of the adhesive layer cannot be controlled. Then, bubbles form easily inside the adhesive, which is hazardous to solar cells in outer space.[8–10] Furthermore, solar cells may easily get stained by manual work, which will cause lower production rate and difficulty in cleaning operation. Due to these disadvantages, the ALR is developed to realize the auto-dispensing and auto-laydown operation.

Section 2 describes the overall system of the ALR. The gripping method of solar modules is proposed in Section 3. In Section 4, the method of controlling the thickness of adhesive layer is introduced. Section 5 explains the laydown process of solar modules. In Section 6, the advantages of the automated laydown method over the manual method, as proved by experiments, are presented. Section 7 concludes the paper.

2. The auto-laydown robot (ALR)

Our robot, the ALR, consists of the mechanisms of adhesive dispensing and auto-laydown, a pneumatic system and a control system (Fig. 3). Figure 4 is the block diagram of the robot. Figure 5 gives a detailed description of mechanisms of adhesive dispensing and auto-laydown, which are installed, respectively, on the Z-axis and X-axis in XYZ three-DOF (degrees of freedom) auto-moving mechanism. Since solar arrays are usually very large, the largest solar array at present being 4000 mm long and 2000 mm wide, the XYZ three-DOF auto-moving mechanism is employed as support foundation for high position precision. Table I provides the specifications of the three-DOF auto-moving mechanism.

The control system is made up of a 32 bit IPC, with Intel Pentium4 processor and a controller based on PC-bus, which has 16 fixed inputs, 16 fixed outputs, and an additional 16 configurable I/O points. In addition, the controller also provides an expansion slot to accommodate expansion boards. The system is responsible for the motion control of the robot and other I/O controls of the pneumatic system. The windows 2000 OS and control software are installed on the IPC. The computer can send signals to the motion controller. At the same time, the encoders will

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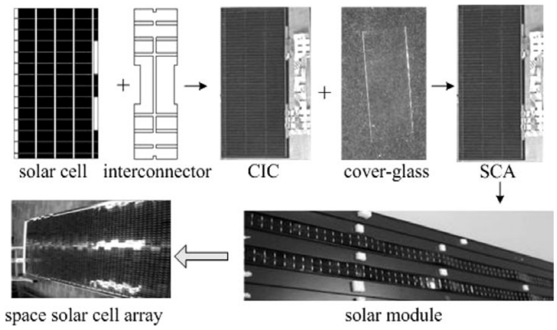

Fig. 1. Manufacturing process of solar cell arrays.

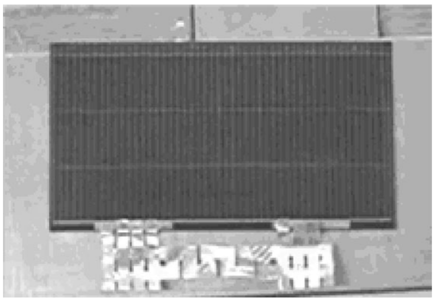

Fig. 2. Solar cell integrated connector (CIC).

provide a feedback on the position information of the motor axes to the motion controller, which keeps a close position control. The control software could harmonize both actions of pneumatic system and moving position of the robot, in different processes. The resolution of all the encoders hereby is $T = 360°/3000$, with an accumulative angle error less than $0.3\ T$.

The whole working process of ALR can be divided into three parts, which are solar-module gripping, adhesive dispensing and auto-laydown.

Fig. 3. Photograph of the robot.

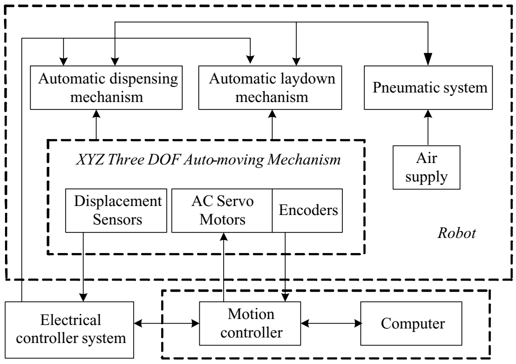

Fig. 4. Block diagram of the robot.

3. Solar-module gripping

Most of the solar cells used in space are made of semiconductors, such as crystal silicon or GaAs. These materials are both light and fragile. Then, suction cups are adopted for the picking job. Since the existing longest space solar string is made up of 80 cells, 80 suction cups are mounted accordingly on the auto-laydown mechanism,

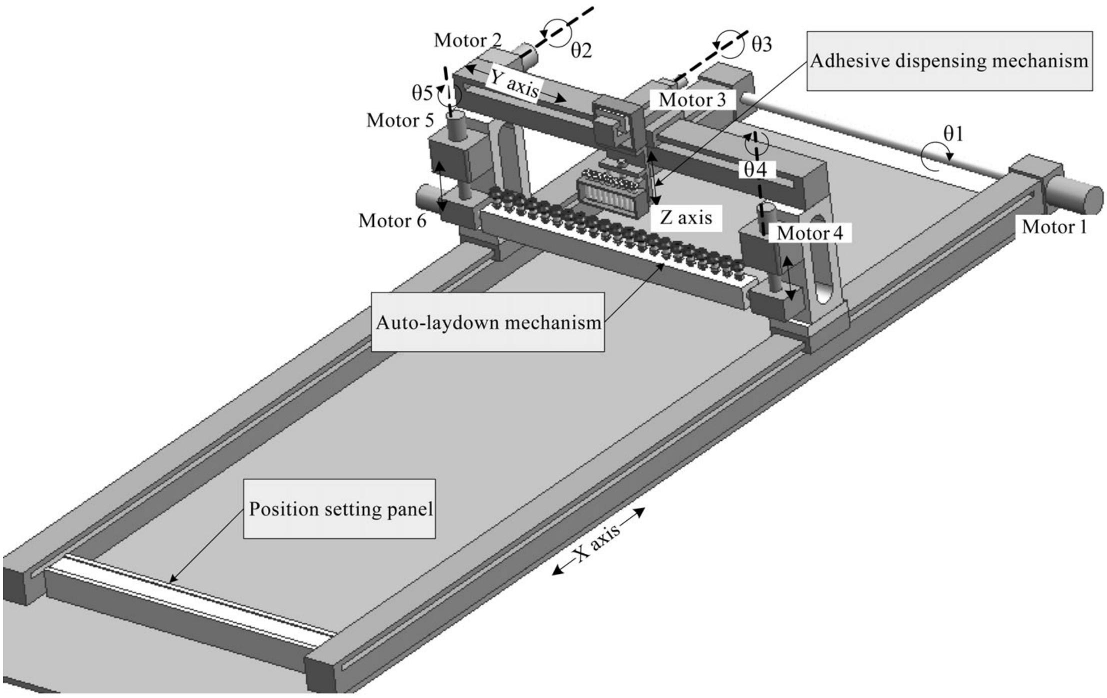

Fig. 5. Auto-laydown robot system.

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Table I. Specifications of the three-DOF auto-moving mechanism.

Axis	Stroke	Motor & driver	Mechanical driver
X	4000 mm	AC servo motor & driver (1000 W)	Belt
Y	2000 mm	AC servo Motor & driver (400 W)	Belt
Z	100 mm	AC servo Motor & driver (200 W)	Ball screw

which makes sure that solar cells could be picked up by suction cups one-to-one. The position setting panel is installed in front of the robot. Also, there is a shallow groove on the top surface of the panel. The width of the groove equals that of a solar cell. Before the robot is powered, a solar module should be put into the groove of the position setting panel. Motor 1 gets powered and drives the X-axis mechanism forward. When the auto-laydown mechanism is on the upper part of the position setting panel, the displacement sensor sends a signal to the motion controller that stops the movement of the X-axis. At the same time, motor 6 drives the auto-laydown mechanism and makes it turn at θ 6, which makes the suction cups fixed on it be opposite to the position setting panel. Then, motor 4 and motor 5 are powered synchronously and turn it at the same angle of θ 4 and θ 5, which ensures the horizontal fall of the auto-laydown mechanism. When the suction cups touch the solar module on the position setting panel, the sensor sends a signal to the controller, and motor 4 and motor 5 are deactivated. Under the control of the pneumatic system, suction cups grip the solar cells. Then motor 4, motor 5 and motor 6 continue the reversed operations in turn and the suction-gripping of the solar modules is completed.

The position setting panel is fixed on a bracket. When gripping the solar modules, the centre of the suction must align to the centre of the panel. And the permissible error of the X-axis movement is ±0.1 mm. Furthermore, the motions of motor 4 and motor 5 must be synchronous, and their angles of rotation, θ 4 and θ 5, must be the same. To ensure the safety pickup of solar modules, the suction cups must be controlled vertically to the position setting panel or the solar modules could not be picked up (refer to Fig. 6 for details). The design of the pneumatic system is described in Fig. 7. Gripping of solar modules is essential for the robot. Through I/O board, electromagnetic valves are controlled by IPC. Basically, the suction cups should keep working normally. Enough negative pressure should be created by the vacuum generator inside the suction cups.

4. Adhesive dispensing of ALR

The quality standard for solar arrays: the thickness of the adhesive layer must be controlled within 0.2 mm, and the area of the dispensed adhesive should be over 80% of a solar cell and no outflow. The dispensing track is determined and shown in Fig. 8. From the figure we can obtain the following information (1) the parameters of the dispensing track, (2) the length h, (3) the width m, (4) the clearance between tracks d, and (5) the rims a and b. All these parameters can be adjusted to meet the requirements on the spot.

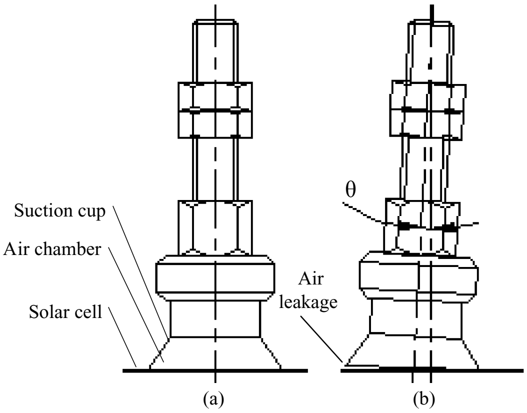

Fig. 6. Suction cup is gripping the solar module. (a) Suction is vertical to the position setting panel. (b) Suction is not vertical to the position setting panel.

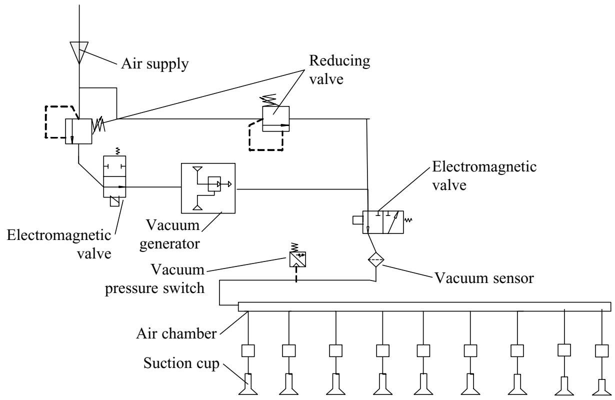

Fig. 7. Pneumatic system for gripping.

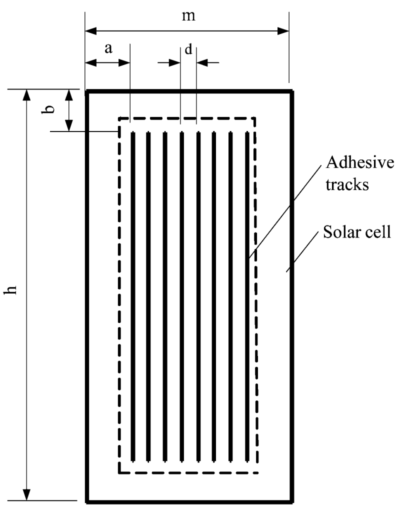

Fig. 8. Track of dispensing the adhesive.

Suppose the movement speed of the syringe needles controlled by the robot is v_0; the length of the whole track

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is:

$$L = (h - 2b) \times \left(\frac{m - 2a}{d} + 1\right). \quad (1)$$

So, the cycle time of dispensing adhesive should be:

$$t = L/v_0. \quad (2)$$

The adhesive dispensing mechanism is fixed on the Z-axis of the XYZ three-DOF auto-moving mechanism. Based on the motions of motor 2 and motor 3, the adhesive dispensing mechanism could move along the Y-axis and Z-axis. Thus, the dispensing track can be obtained. When dispensing the adhesive, the distance between the needle tips and the solar cells gripped by the suction cups must be adjustable. There are two ways to adjust the distance. One is based on the motions of motor 4 and motor 5. Driven by the two motors, the suction cups mounted on the auto-laydown mechanism can move vertically with the solar modules. The other is to turn the screw of the adhesive dispensing mechanism manually, and the needles could be slightly moved relatively with the solar modules.

The next issue is how to dispense the adhesive. We apply the auto-dispensing method through a combination of pneumatic technology and robotics, which could promote high efficiency and precision. 10 syringes full of adhesive are installed on the adhesive dispensing mechanism. Under the effect of air compression, dispensing of the adhesive is performed, as shown in Fig. 9.

The adhesive dispensed on a solar cell must be fixed; the adhesive dispensing is analysed as follows. Based on fluid mechanics, we acquire the velocity field of adhesive flow in needles as:

$$u_z = \frac{n}{n+1}\left(\frac{1}{2\mu}\frac{\mathrm{d}p}{\mathrm{d}z}\right)^{1/n}\left(R_n^{\frac{n+1}{n}} - r^{\frac{n+1}{n}}\right) \quad (3)$$

where, n is the power exponent, μ is the viscosity coefficient, R_n is the radius of a needle, and the pressure gradient is $\frac{\mathrm{d}P}{\mathrm{d}z} = \frac{P_1 - P_0}{L_n + L_t}$. The gas pressure can be determined by trial and error according to the expected adhesive layer thickness. The

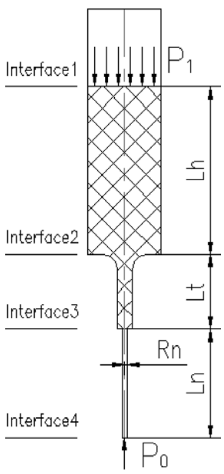

Fig. 9. Schematic illustration of adhesive pipe flow in a syringe.

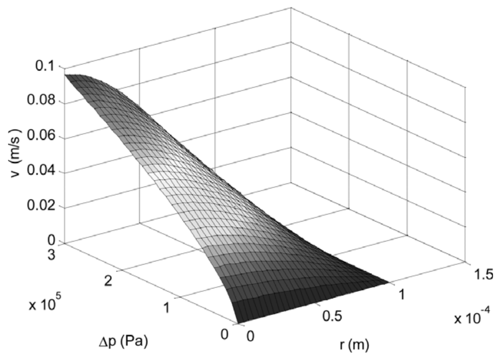

Fig. 10. Flow velocity field of adhesive in a needle.

velocity field of adhesive in one needle could be described in Fig. 10. Thus, the volume of adhesive dispensed on a solar cell in a unit time is also obtained as:

$$q = \int_0^R 2\pi r u_z dr = \pi\left(\frac{1}{2\mu}\frac{\mathrm{d}p}{\mathrm{d}z}\right)^{1/n}\frac{n}{1+3n}R^{\frac{3n+1}{n}}. \quad (4)$$

So, the total volume of adhesive dispensed on one solar cell is:

$$Q = qt = \frac{\pi n\left(\frac{1}{2\mu}\frac{\mathrm{d}p}{\mathrm{d}z}\right)^{1/n} R^{\frac{3n+1}{n}}(h-2b)(m-2a+d)}{v_0 d(1+3n)}. \quad (5)$$

Suppose the distribution area of adhesive on a solar cell is s. Then, the average thickness of adhesive layer is:

$$w = Q/s. \quad (6)$$

5. Auto-laydown operation of ALR

After the adhesive is well distributed on the solar cells, the robot begins to laydown the solar modules on the substrate. Besides gripping the solar modules, the suction cups can also press the solar cells in the presence of elastic distortion during auto-laydown process (Fig. 11). The substrate is installed on the support foundation between the two X-axis slides. Through the combined motions of motor 4, motor 5 and motor 6, the solar modules gripped by the suction cups

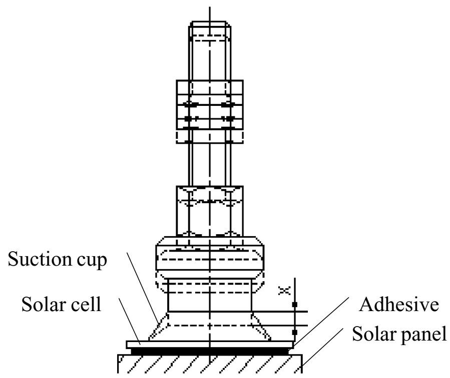

Fig. 11. Illustration of a suction cup pressing the solar cell.

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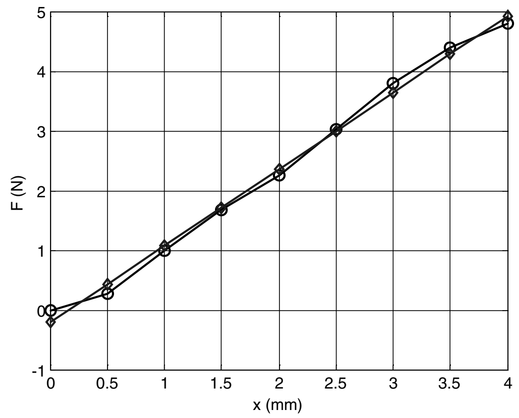

Fig. 12. Action force curve of a suction cup.

are vertical to the substrate. For solid adhesiveness to the substrate, the solar modules must be pressed during the auto-laydown process. Furthermore, pressure force must be controlled within a limited range, which avoids outflow of adhesive. Yet, as the solar cells are very fragile, we use the suction cups to run the press operation. By fitting experiment datum, we obtain the functional relationship between the distortion of a suction cup and the action force (Fig. 12). It could be expressed as:

$$\frac{\mathrm{d}f}{\mathrm{d}x} = 0.0308x^3 - 0.48x^2 + 1.56x + 0.19 \qquad (7)$$

where f is the action force and x is the distortion of a suction cup. Based on Eq. (6), we can control the distortion of the suction cups to obtain the necessary pressure force.

6. Experiment

6.1. Adhesive dispensing experiment

If we adopt the manual way of dispensing adhesive, neither the volume of adhesive nor the position of dispensing could be accurately controlled. Then the outflow of adhesive occurs frequently, which will contaminate the solar cells. Therefore, the wiping operation must be conducted manually, which also brings along the danger of the solar cells fragmenting. Based on robot technology, the auto-dispensing adhesive method will obtain the needed volume of the adhesive, and the accurate position precision of dispensing the adhesive. All the experiment parameters are shown in Table II.

First, we test the total adhesive volumes flowing out of every syringe into respective beaks during adhesive dispensing process. In contrast between test and calculation according to Eq. (5), the validity of the adhesive dispensing analysis is confirmed, as shown in Fig. 13. In terms of Eq. (5), the adhesive dispensing volume through every needle is 78 mm^3. Learning from Fig. 13, the adhesive dispensing volumes tested by experiments approximately equal the volumes calculated according to the fluid equations. Figure 14 shows the photograph of performing adhesive dispension on the solar cells. Apparently, the track and area of the adhesive dispensed on the solar cells could be controlled effectively by this method.

Table II. Experiment parameters for adhesive dispensing.

No.	Test parameters	Values
1	Operating temperature (°C)	22
2	Dispensing track (mm)	$a = 4$, $b = 5$, $d = 1.67$
3	Gas pressure (Mpa)	0.15
4	Diameter of syringe needle (mm)	0.4
5	Speed for YZ axes' movement (mm/s)	1.5
6	Length of a needle (mm)	20
7	Adhesive power exponent	1.5
8	Adhesive viscosity coefficient (Pa·S^n)	1.273

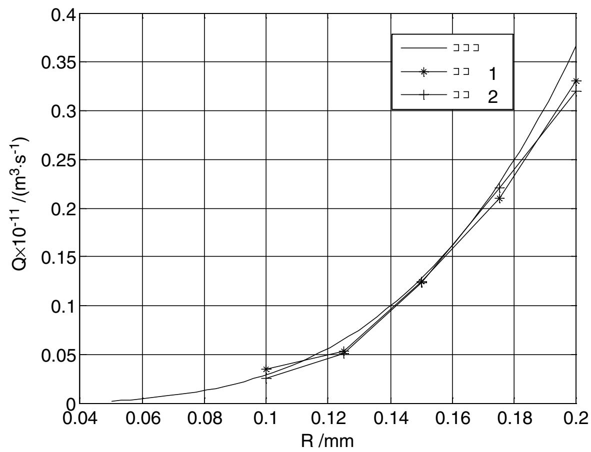

Fig. 13. Volume test of the dispensing adhesive.

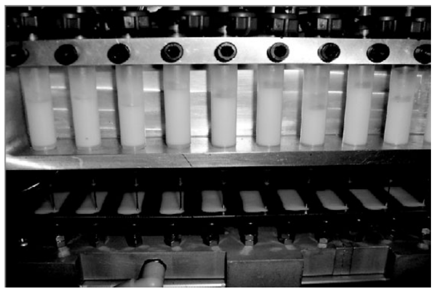

Fig. 14. Photograph of dispensing the adhesive.

6.2. Auto-laydown experiment

The existing manual laydown method cannot control the force acted on each solar cell and often leads to massive adhesive outflow. Furthermore, by this method, the thickness of the adhesive layer could not be determined. The auto-laydown method has solved these problems. In order to inspect experiment results easily, we adopt glass as the panel substrate instead of real ones. Thus, from the other side of glass, we could observe the distribution of adhesive under the solar cells. Learning from these experiments, the auto-laydown method could meet the requirements of position precision and pressure on a solar module. The solar array constructed by this method is shown in Fig. 15.

The performances of solar panels constructed using different methods, by hand and robot, are shown in Table III. The largest solar panel nearly consists of 7000 solar cells. The

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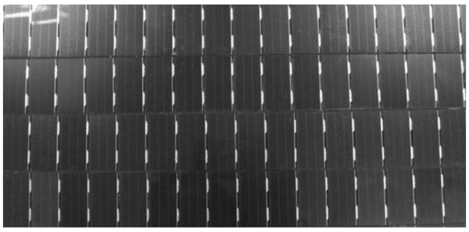

Fig. 15. Photograph of a solar array constructed in the auto-laydown method.

Table III. Performance contrast between the manual method and the robot method.

Method	Fragment rate of solar cells	Position error	Adhesive overflow	Pressure precision
Manual labour	7.6%	±1 mm	mass	$+5\frac{N}{cm^2}$
By ALR robot	0	±0.5 mm	No overflow	$\pm1\frac{N}{cm^2}$

fragmentation rate in manual method reaches 7.6%, which leads to high cost. But, by using the robot there will be no fragmentation. The distance between the adjacent solar modules in the robot method would be less than that in the manual method. Thus, more solar cells could be installed on the solar panel, which could improve the performance of solar arrays. Furthermore, there would be no overflow, thereby avoiding the staining of solar cells.

7. Conclusion

As discussed above, the ALR enhances the quality and improves the manufacturing environment of solar arrays, and entirely satisfies the following technical requirements:

(i) The error of the position precision of the solar modules is confined within the range of 0.5 mm.
(ii) The error of the distance between two solar strings is less than 0.2 mm.
(iii) The fluctuation of action force is within the range of ±1 N/cm^2.
(iv) The adhesive does not outflow and stain the solar cells.

Before the automatic laydown technique is used in manufacturing solar arrays officially, a lot of experiments will be conducted to ensure stability and reliability in processing. The robot has great prospects and wide application possibilities in the manufacturing of solar arrays in the near future.

Acknowledgment

This work was partially supported by National Science Foundation of China under Grant No. 60675040.

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