TECHNOLOGY ASISSTED SMART SOLAR-SYSTEM (TASS)

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Electrical Engineering - Master of Science

2016

ABSTRACT

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This thesis focuses on the design, fabrications and testing of a Technology Assisted Smart Solar-System (TASS) that uses a solar panel both as an energy source and a sensor for tracking. A microcontroller, interfaced to a mini solar-cell array, was used to control and test the systems efficacy to track the light source employing (a) a motorized solar panel and (b) a robotic platform. The TASS packaging and printed circuit boards were designed and fabricated using 3-D inkjet printing. A roof-top TASS was built to demonstrate an inexpensive application. The TASS developed in this work is also applicable to a light-tracking flowerpot for a smart home.

This thesis is dedicated to my great parents, brothers and sisters.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my advisor, Prof. Dean Aslam, for his continuous support, help, patience and encouragement throughout my master study. His office was always open whenever I ran into a trouble spot or had a question about my research or writing. This thesis would not have been possible without his guidance.

I would like to thank Dr. Jian Ren and Dr. Wen Li from the Department of Electrical and Computer Engineering for serving on my thesis committee. I am deeply grateful to them for their motivation and insightful comments.

I would also like to thank Mohammed Alforidi, who as a brother, was always supporting me to overcome life's obstacles.

Last but not least, I am deeply grateful to my parents, brothers, sisters and friends for their tremendous support and encouragement.

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Chapter 1

INTRODUCTION

The rise in the usage of non-renewable energy resources and fossil fuels has led the world to a stage where many governments have started to develop strategies and policies that help in reducing global warming and CO_2 side effects. As an example, each country in the European Union has assumed a goal to complete by 2020 [1], in which they achieve a certain percentage of the use of renewable energy. Fossil fuels cause contamination of the environment due to the chemical reaction involved in their processing. Consequently, renewable energy became a huge research topic recently because it can significantly reduce the cost and produce a permanent energy source without poisoning the environment. The sun can be considered the most important source of renewable energy that is available to use everywhere. As the earth revolves around the sun, the solar incidence in one point at a certain time of the day will not be the same and there is a need to know where the highest energy vector is pointing at a certain time.

The Technology Assisted Smart Solar-System (TASS) research, benefiting directly from the latest developments in Micro and Nano technologies, can help integrate emerging technology components into a Microsystem useful for many applications. A particularly interesting aspect of an inexpensive TASS is the integration of control circuits, wireless interfaces, microsystems components (sensors and actuators), software and power sources into a single mass producible unit using 3D inkjet printing and microfabrication. Examples of TASS applications are energy scavenging/harvesting, solar tracking systems, night light systems, mind-controlled robots and micro drones for surveillance and harsh weather monitoring, and optoelectronic systems [2].

The major goals of this research are revealed in a general concept diagram of technology assisted smart solar-systems (TASS) as shown in Figure 1.1. It consists of a solar tracking panel mounted on a solar tracking robotic platform. The Design of mechanical structures and the system packaging are implemented using a 3-D inkjet printer. TASS design with two tracking capabilities was successfully tested. For tracking, five light dependent resistors (LDR) were utilized, three of them used for controlling the solar panel orientation, and the remaining two used for the robot.

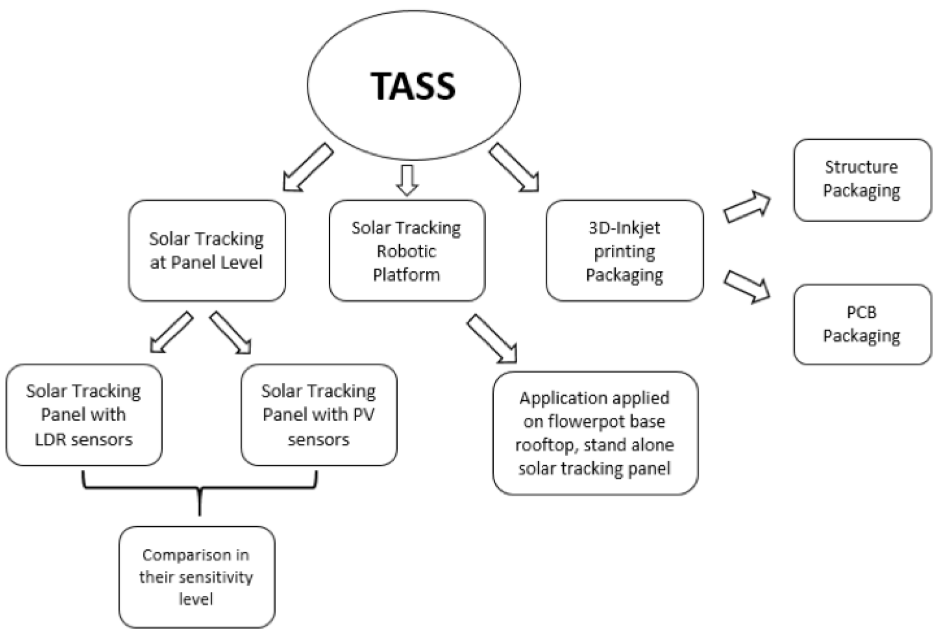

Figure 1.1: Block diagram summarizes TASS project.

The unique aspects of this thesis can be summarized as follows: a) the use of tracking at the solar panel and robotic platform levels, (b) a 3D inkjet printed circuit board and TASS packaging and (c) a solar tracking flowerpot for a smart home and d) the use of solar cells as sensors in replacement of LDRs, and investigating the differences between them in terms of accuracy.

The structure of the thesis will be as follows; Chapter 2, presents a literature review that shows the main contribution in the literature about topics related to the TASS project such as solar tracking systems. Chapter 3, introduces the solar tracking at the panel and robotic platform levels, starting with solar tracking using LDR and solar cell sensors, and going through a comparison between them to show which sensor would be more reliable in the system. Then the results from the solar tracking robotic platform will be analyzed. Chapter 4, will show details of the 3D printed packaging along with some TASS applications. Chapter 5 will include the conclusion and the future work of TASS.

Chapter 2

LITERATURE REVIEW

Recently, extensive research has focused on solar tracking systems and related work [3–31]. Single axis solar tracking using shape memory alloy (SMA) actuator was implemented as shown in Figure 2.1 [3]. At low temperature, the SMA can easily be deformed and then goes back to its original shape when the temperature increases. A lens had been used to focus the solar irradiance to one of the two SMA actuators. The referred solar tracking was designed to have the same lifetime as solar arrays. Other solar tracking using shape memory alloy can be found in [4, 5].

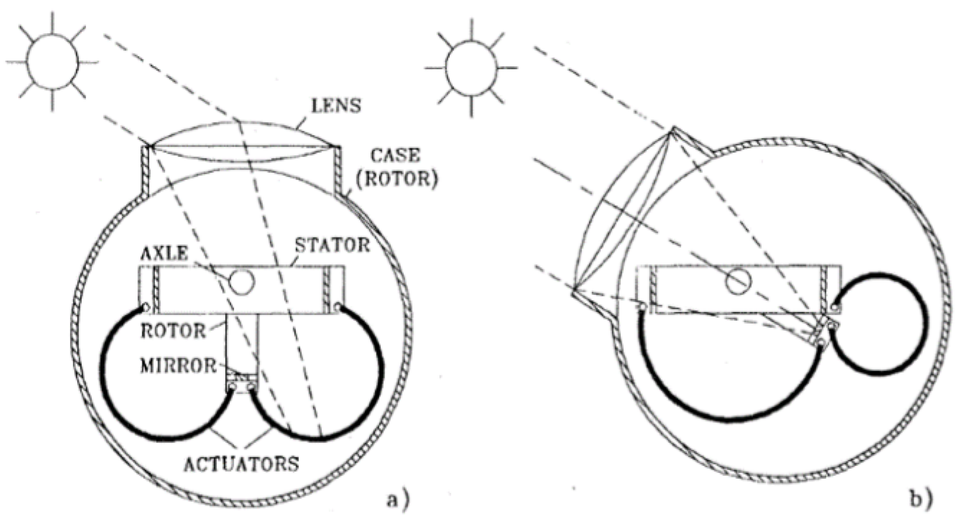

Figure 2.1: Solar tracking using SMA.

A design of two axes solar tracking using micro-optic solar concentrator is presented in [6] which is suitable for some applications. In [7], a dual axes solar tracking was implemented using Keplers equations. The system was designed to move the panel right-left and up-down to properly track the light intensity based on the programmable logic controller. The experiment had a result of an increase in the overall efficiency of 17% - 20% for sunny days and 8% - 11% on cloudy days compared to the fixed arranged module.

Discussion about the control of solar tracking systems for solar thermal power generation industry is presented in [8]. The goal was to explain a genetic based algorithm to improve the control applied to heliostats in solar thermal plants. There are two basis methods for controlling the movement of the panels, the theoretical sun-movement dependant, where the rotation of the panel depends on the Keplers equations, and the sunlight-measurement dependant, where the closed loop circuit uses sunlight sensors to provide feedback to a microcontroller and this one controls the rotation of the panel. The first method lacks the precision and self-control because the movement is fixed, which means that the system is relying on equations that may not take into account the weather conditions, i.e. if there are clouds or it is raining and the second one requires a lot of initial costs since several photodiodes or sensors are to be installed in each panel to make it light-dependable.

Solar tracking was designed using an arrangement of one panel, two axes of movement and five photodiodes to track the movement of the sun and make the system more efficient [9]. The axes of movement are north-south and east-west. The actuators are one linear actuator and one conventional motor. The experiment uses five different sensors pointing in different directions as shown in Figure 2.2.

The purpose of the placement of the four external sensors is to monitor the sunlight from those directions, and the fifth one in the middle is responsible for facing the panel in the direction of the sun.

The electronic components used in this paper are also a basis to study in order to un-

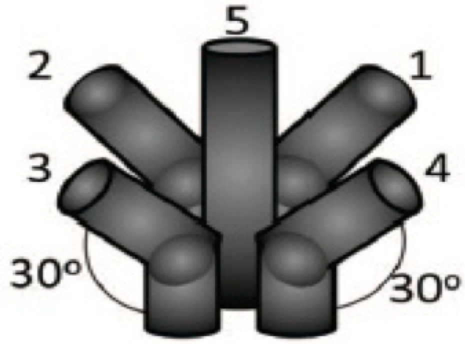

Figure 2.2: Five sensors pointed in different directions.

derstand the basic requirements. For example, the authors used Atmega32 microcontroller to control all components, having the values for the 5 different voltages, they are compared with the database of angles that are stored in the microcontroller. The actuators turn on only if the elevation angle is more than 15 degree or if the azimuth angle is more than 7.81 degree and they are activated until the panel face itself perpendicular to the sun.

In [10], the work shows a theoretical-empirical approach to the tracking issue since it uses the solar-movement equations to drive a solar panel with the help of a Siemens LOGO! Programmable Logic Controller (PLC). The project was about designing, building and evaluating the system and its performance using two axes, one for vertical daily tracking and horizontal seasonal tracking, while comparing the tracking option to the fixed one. The project differentiates itself from the rest by the fact that it does not use sunlight sensors to add precision to the tracking task, it relied entirely on the theoretical equations.

In [11–13], light dependent resistors (LDR) were utilized as sensors to read the voltage changes according to the amount of sunlight. Design and construction of a system for sun tracking was implemented to measure the direct beam solar irradiance by a pyrheliometer [17], in which four-quadrant photo detectors were used to sense the position of the sun and a computer program calculated the position of the sun when it could not be detected by sensors. A Commercial webcam was used as a sensor element to provide a high-precision solar tracking system [18]. The webcam was connected to a personal computer and MATLAB was used to implement a simple image processing algorithm for the incoming frames. In [19], neural networks were applied in a tracking system for solar concentrators to reduce tracking errors. A two-axes sun tracking system was used to investigate its effect on the thermal performance of compound parabolic concentrators [20]. This system was equipped with two photo transistors and it was designed to follow sun light every three to four minutes in the horizontal axis and every four to five minutes in the vertical axis. A sun Tracking system designed to improve the efficiency of photo-voltaic panels using a programmable logic controller was also reported [21]. It was proved that the solar tracking system increases the power output of the solar panel by 20% in comparison with a fixed module.

The applications of solar tracking system can vary depending on the user's needs. For example, in automated systems the tracking device would be significantly important when generating the electricity needed. Taking the recent use of the solar impulse airplane and placing a tracker in it would provide extra capacity for its operation [32]. Also, charging batteries in mobile robots such as lawn mowers would take less time by activating its tracking function. Moreover, the use of solar tracking system car can be in smart houses and offices, mobile self-powered robots and micro-drones.

Chapter 3

Solar Tracking System

This chapter presents one part of a TASS project, which is a solar tracking system at the panel and system level. Firstly, the solar tracking panel will be introduced in which two approaches have been utilized to achieve that purpose, a) solar tracking with Light Dependent Resistors (LDR) used as sensors and b) solar tracking with solar panels used as sensors. Then the sensitivity level of these sensors will be investigated. Finally, solar tracking robotic platform with 5 LDR sensors will be described. Figure 3.1 shows the normal process of a solar tracking system.

3.1 Solar Tracking Panel

3.1.1 Tracking with LDR Sensors

Maximizing light intensity of the solar tracking panel is accomplished by aligning the solar panel toward sun radiation. Photo resistors were utilized to detect the sun position and movement status. As illustrated in Figure 3.4, the base holder of the solar cell is attached to a rod, which is placed on (5V) stepper motors shaft. Three LDRs were placed on the left (L), middle (M) and right (R) side of the solar panel with about 45-degree angle to measure the light intensity by reading their signal that changes based on the amount of light intensity. This information is fed to the microcontroller that then makes the decision in

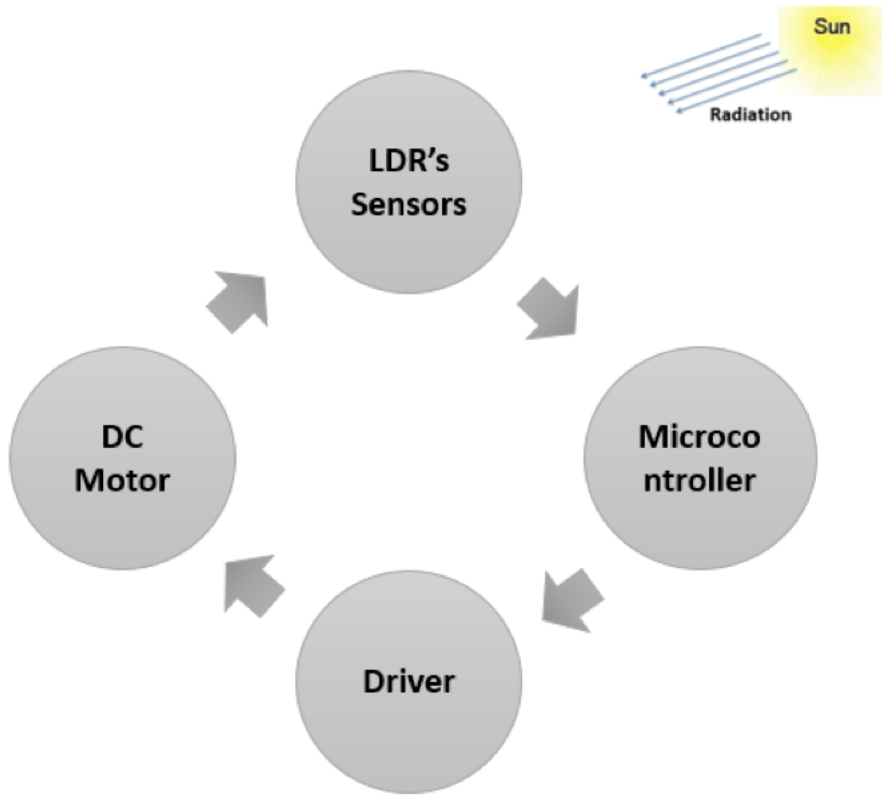

Figure 3.1: Process of solar tracking system.

which direction the stepper motor should rotate. The middle sensor is the OFF sensor, i.e., when it receives maximum sunlight, the motor will shut down. The left sensor is installed on the east side of the panel and the third sensor is installed in the west side of the panel. The movement of the sun will cause a shadow on the middle sensor as well as on one of the side LDRs which turns on the motor. The motor will move toward the highest light intensity thats measured between the left and right sensors. Motor rotation stays on until the middle sensor receives maximum light intensity or all sensors receive low light intensity (night time). The operation conditions are illustrated in Table 3.1. The microcontroller used in this system is ATmega328, which is used in the Arduino board. As can be seen in Figure 3.2, the reading of LDR 1, 2 and 3 are sent to the micro-controller to control the movement of the stepper motor.

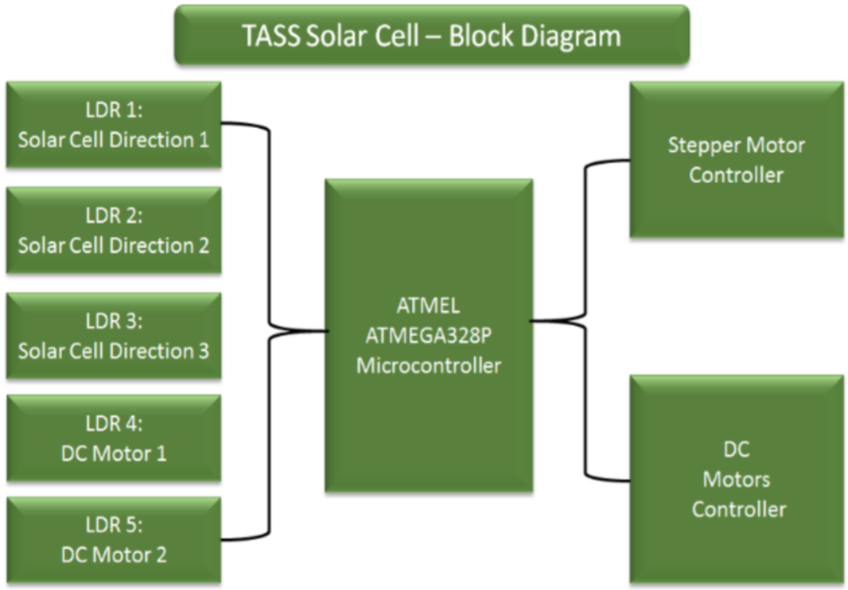

Figure 3.2: Bloack Diagram of a TASS application.

Table 3.1: Operation condition of the stepper motor: where 0 = dark (or less light) and 1 = light (or high light).

L-LDR	M-LDR	R-LDR	Stepper Motor's Action
0	0	0	Do Nothing
0	0	1	Clockwise Rotation
0	1	0	Do Nothing
1	0	0	Counter Clockwise Rotation

The process of the solar tracking system can be described as follows:

- When the left and right LDRs receive no light, the motor does nothing.
- The motor moves counter-clockwise when the left LDR receives a higher amount of light than the middle and right LDRs.
- If the right LDR receives the highest light intensity, then the motor moves in a clock wise direction.
- The motor stops when the sun light strikes perpendicular to the solar cell, in which case the middle LDR receives the highest light intensity.

The first experiment was conducted during a partially cloudy day in which the effects of the presence of clouds to the output of the solar panel can be seen clearly in Figure 3.3.

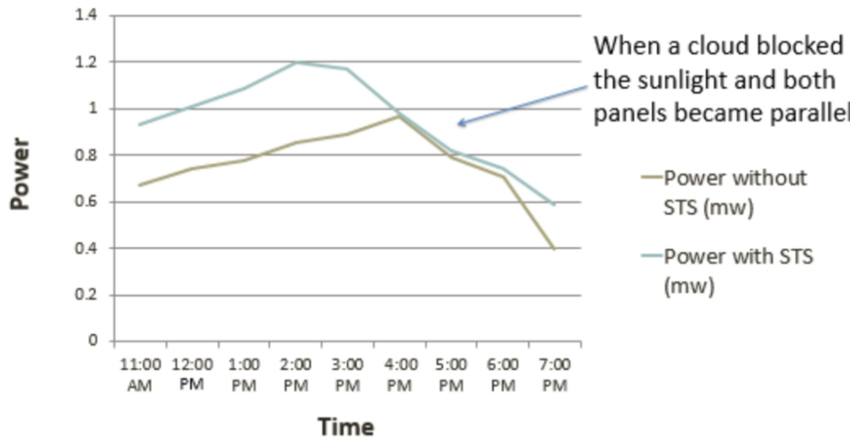

Figure 3.3: Chart of solar tracking panel results in June, 2013.

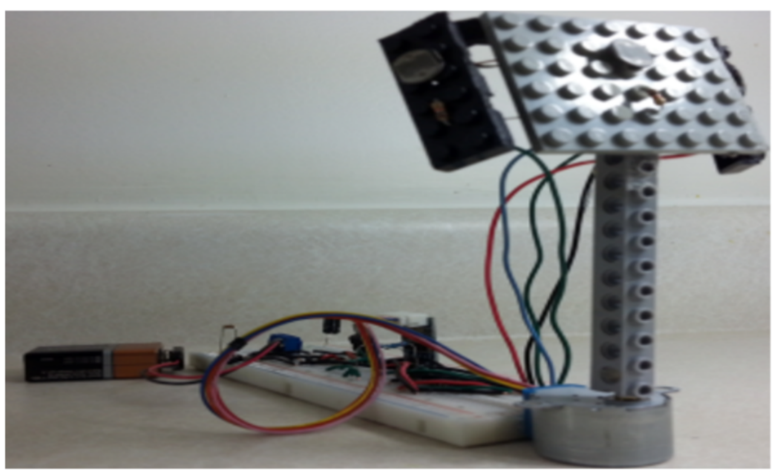

Figure 3.4: First module of a single axis solar tracking system that was built using LEGO parts.

3.1.2 Tracking with Solar Cells Used as Sensors

In the previous subsection, photo-resistors were utilized to read the voltage variation that is caused by the change of the sun light intensity. A combination of mini-solar cells is used to replace the LDRs role as sun light detector. The main principle of this technique is that the movement of the suns directions has high effect to the solar cell, which gives a reasonable amount of variation of output voltage and that allows reading the suns position. Figure 3.5 shows a diagram explaining the proposed system. The four-quadrant mini-solar cells have been tested to find the output voltage under high spectrum light source that mimics the sun spectrum. Figure 3.7 shows the circuit schematic of the implemented experiment. It contains four mini solar cells with 3 V and 70mA each. A Schottky diode was used due to its very low forward-voltage drop and very fast switching speed. It prevents discharging battery voltage at nighttime. In addition, we can easily measure the output voltage of the solar cells separately when they are connected in parallel, see Figure 3.6. Moreover, boost converter with 0.52 duty cycle is used to get 5 V out of 2.4 V from the rechargeable battery. In order to have dual axis tracking with precise movement toward the highest light intensities, two stepper motors are used in the vertical and horizontal axis as can be seen in Figure 3.5.

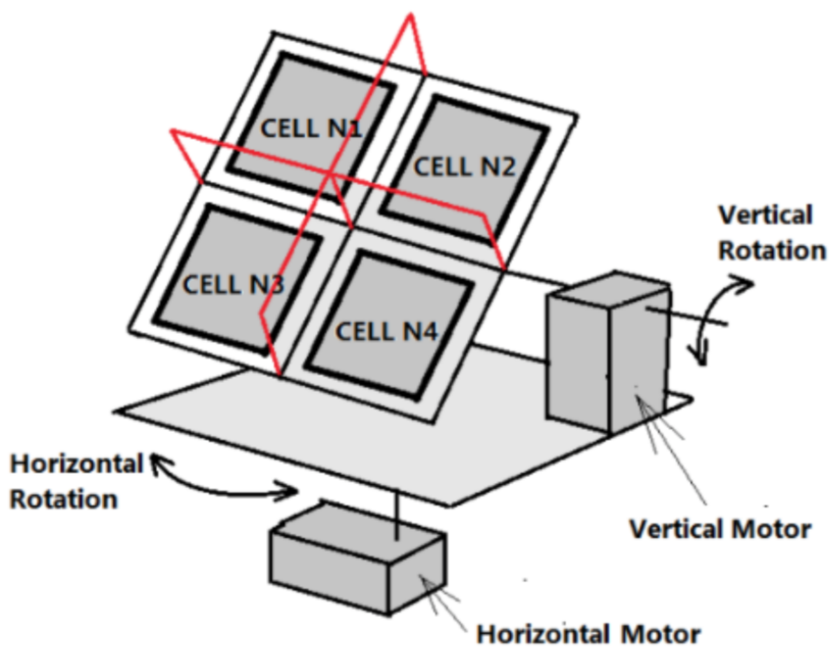

Figure 3.5: Concept diagram of dual axis solar tracking system with solar cell sensors.

The voltage difference between solar cells plays a major role in deciding the position of sunlight. As the sun moves, the reading of solar cells changes and the rotation of the motors also changes accordingly. When the solar cells N1 and N3 receive higher or less sunlight than N2 and N4, then the horizontal motor turns on and rotates clockwise or counterclockwise, respectively. The vertical motor will be turned on when the solar cells N1 and N2 receives higher or less sunlight than the solar cells N3 and N4. A flow chart of the system is shown in Figure 3.8.

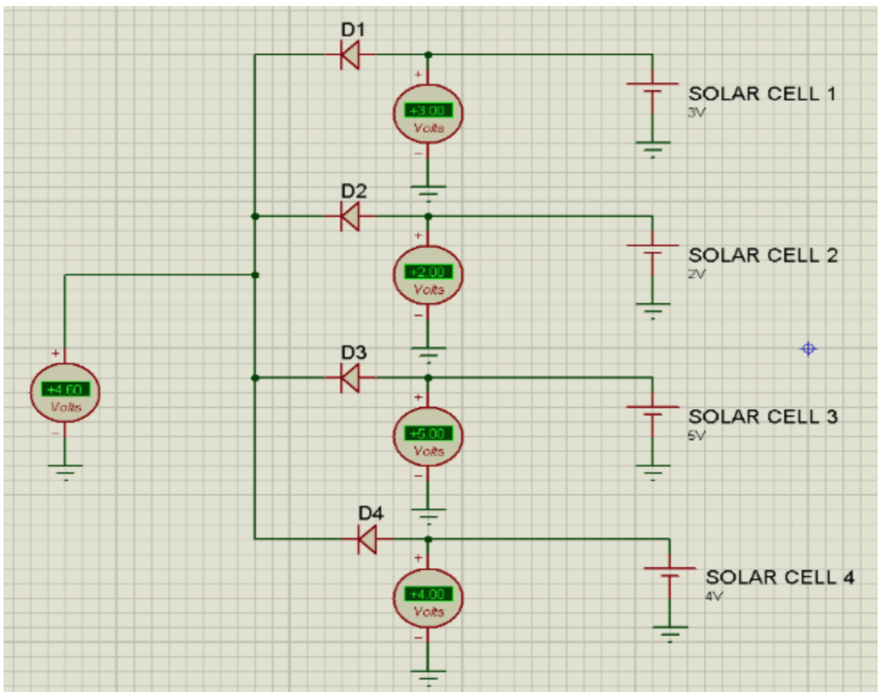

Figure 3.6: Separate voltage measurement for solar cells.

3.1.3 Calibration Method.

From the experiment that has been done to find the sensitivity of the solar cell, the variation between each solar cell is very low compared to the different amount of light intensity falls on their surfaces. Also, It is useful to have a range of minimum and maximum light intensity that is available in the test area. For this reason, a calibration method is used

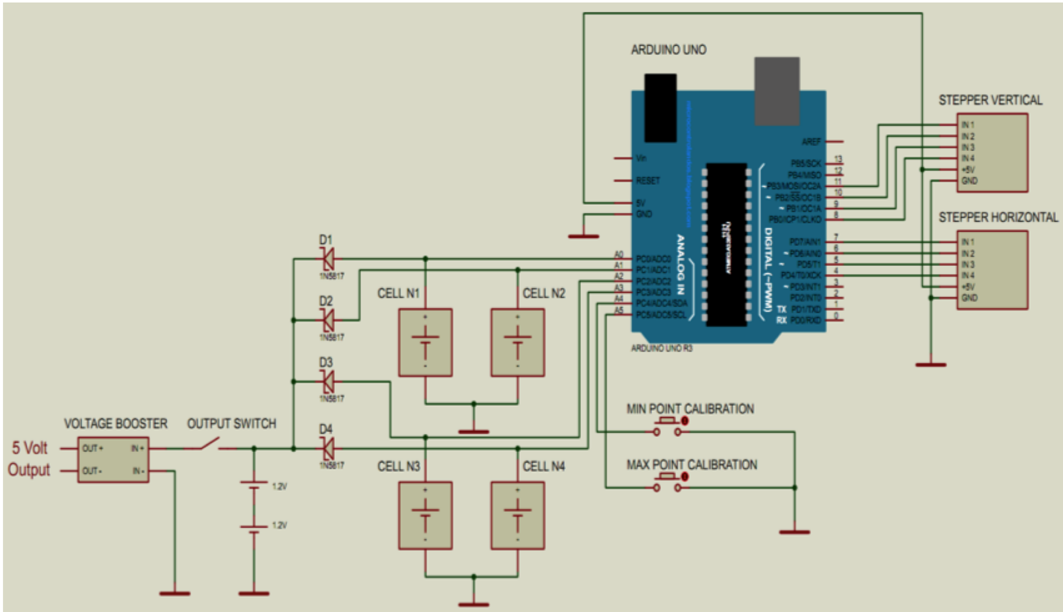

Figure 3.7: Circuit Schematic of a dual axis solar tracking system.

Table 3.2: Experiment results of solar cells output with different light intensity.

Light intensity, Lux (x10)	Cell N1 voltage, V	Cell N2 voltage, V	Cell N3 voltage, V	Cell N4 voltage, V
111	2.48	2.68	2.71	2.73
145	2.59	2.76	2.80	2.79
208	2.73	2.85	2.88	2.87
292	2.82	2.95	2.98	2.94
400	2.96	3.06	3.07	3.08
692	3.10	3.18	3.18	3.17
901	3.20	3.21	3.20	3.28

to be able to read the small amount of changes in light intensity. Table 3.2 shows the results of the test. As can be seen in Figure 3.9, the change of voltage between solar cells does not exceed 0.7 V with high changes in light intensity.

The calibrated table and chart are shown in Table 3.3 and Figure 3.10, respectively.

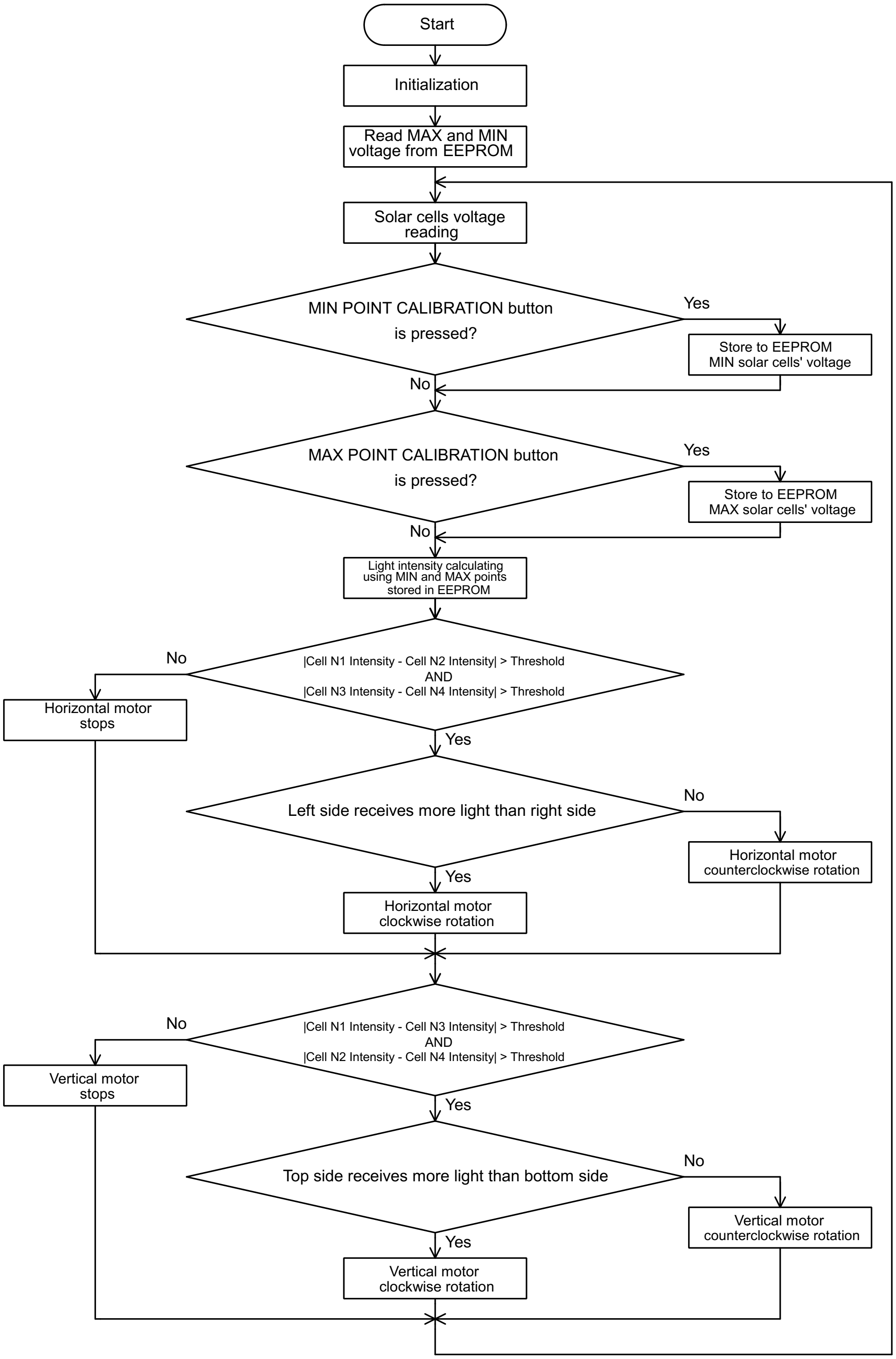

Figure 3.8: Flow chart of the dual axis solar tracking system using solar cell sensors.

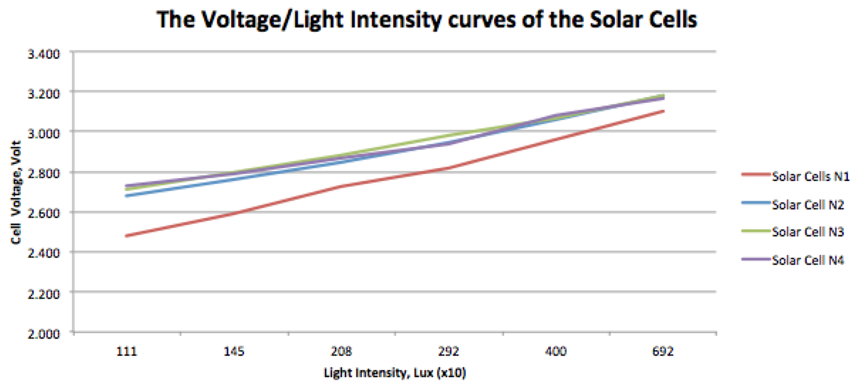

Figure 3.9: Chart shows cell voltage as a function of light intensity.

Table 3.3: Experiment results of solar cells output with different light intensity after calibration.

Light intensity, Lux (x10)	Cell N1 %	Cell N2 %	Cell N3 %	Cell N4 %
280	0.00	0.00	0.00	0.00
309	15.28	15.09	18.37	10.91
350	34.72	32.08	34.69	25.45
423	47.22	50.94	55.10	38.18
503	66.67	71.70	73.47	63.64
605	86.11	94.34	96.33	80.00
901	100.00	100.00	100.00	100.00

3.1.4 Comparison between LDR and Solar Cell Sensors.

Light dependent resistor (LDR) is a variable resistor that changes based on the amount of light. The LDR resistance decreases with increasing incident light intensity. It is made of a semiconductor material. Table 3.4 shows a brief summary between LDR and solar cell. They both have activity with light exposure, but they are designed and used for different purposes.

LDRs and mini-solar cells were both successfully used as sensors in the solar tracking system. However, their sensitivity needed to be explored in order to make a full accurate comparison between them. Although, the use of the solar cell sensor has the advantage of

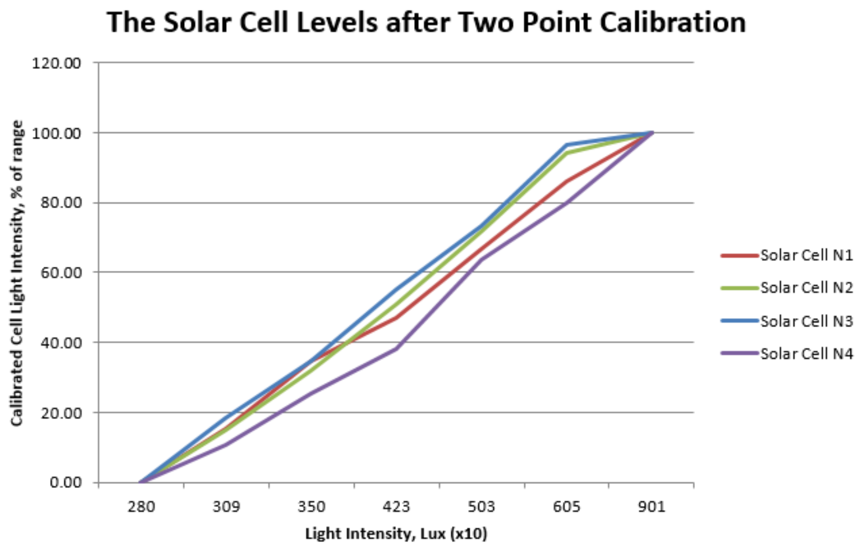

Figure 3.10: The solar cell levels after two-point calibration.

Table 3.4: Comparison between LDR and Solar Cell.

	LDR	**Solar Cell**
Category	Sensor	Power source
Substance	High dark resistance	PV-Junction
Activity in exposing light	Change its resistance from several mega to few hundred ohms	Produce electric power
Sensitivity to light	Very sensitive	low sensitive

reducing the number of components of the system by using it as a power supply as well as sensors, the LDR was found to be more sensitive to the light variation. In the test, a high spectrum light source that mimics sun light irradiance was used. Figure 3.11 shows a diagram of the experiment along with the circuit schematic. Figure 3.12 shows clearly that the difference between LDR 1 and 2 is higher as compared to solar cells 1 and 2. The angle of incidents goes from zero to 180 degree to mimic the movement of the sun from east to west, see Table 3.5. The solar cells output is almost identical and that makes it less sensitive to light variation than LDRs. However, this variation could affect the precision reading that fed to the microcontroller, an isolation frames around the solar cell sensor would make it

Table 3.5: Test Results with different angles.

Angle, Degree	Light Intensity, Lux (x10)	LDR1, V	LDR2, V	SC1, V	SC2, V
0	30	0.723	0.728	0.86	0.899
45	140	2.23	1.901	1.348	1.348
90	205	2.58	2.248	1.476	1.5
135	130	2.253	1.925	1.241	1.295
180	40	2.013	1.642	0.855	0.801

work better as it was implemented in the test of the dual axis solar tracking using solar cells sensors. Solar cells can be used as a power supply as well as sensors for sunlight tracking.

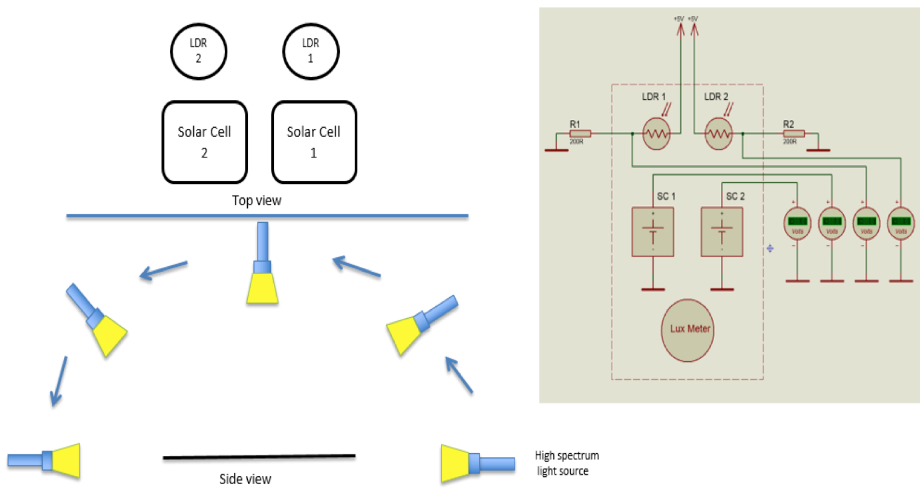

Figure 3.11: Experiment set up to measure sensitivity level between LDR and solar cell.

3.2 Solar Tracking Robotic Platform

3.2.1 Micro-controller based solar tracking robot

The idea of the Solar Tracking Robotic-Platform (STR) is to make solar tracking system mobile and portable. This has a tremendous advantage to enhance the efficiency of the STR in some applications that will be discussed in this thesis. The STR system consists of

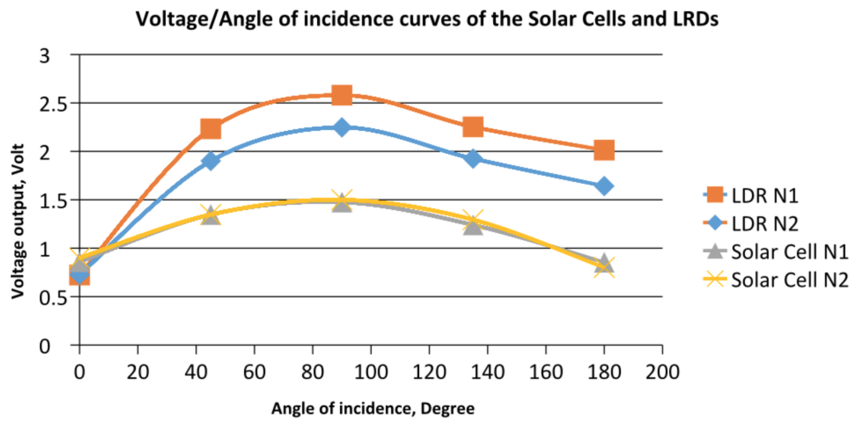

Figure 3.12: LDRs and solar cells output voltage as a result of different angles of light incidents.

two LDR's (4& 5 in Figure 3.2), two DC motors, and one swivel caster. Figure 3.13 shows the combined circuit schematic of the solar tracking panel and the solar tracking robotic platform using LDRs. The stepper motor used for the single axis tracking is controlled by LDR 1,2 and 3. Two DC motors were used to move the whole solar panel and LDR 4 and 5 were used to direct the panel toward higher light intensity. As can be seen in the figure, ATMEGA328 micro controller was used in this system.

3.2.2 Solar Tracking Robot (STR) without using Arduino board

The first attempt in building a solar tracking robot was implemented without using an Arduino board or more specifically a micro-controller. The experiment was successfully tested, but the use of a micro-controller was still needed to implement some intelligent decisions in the system. The circuit schematic that was built is shown in Figure 3.14. The working principle of this circuit is that as both LDRs receives light, motors will not receive enough power to rotate. The MOSFET works here as a switch to turn the motor on and off based on the light intensity on the LDR. When there is no light, the motor will turn on to look for an area with more light intensity. An ultrasonic sensor is needed to avoid

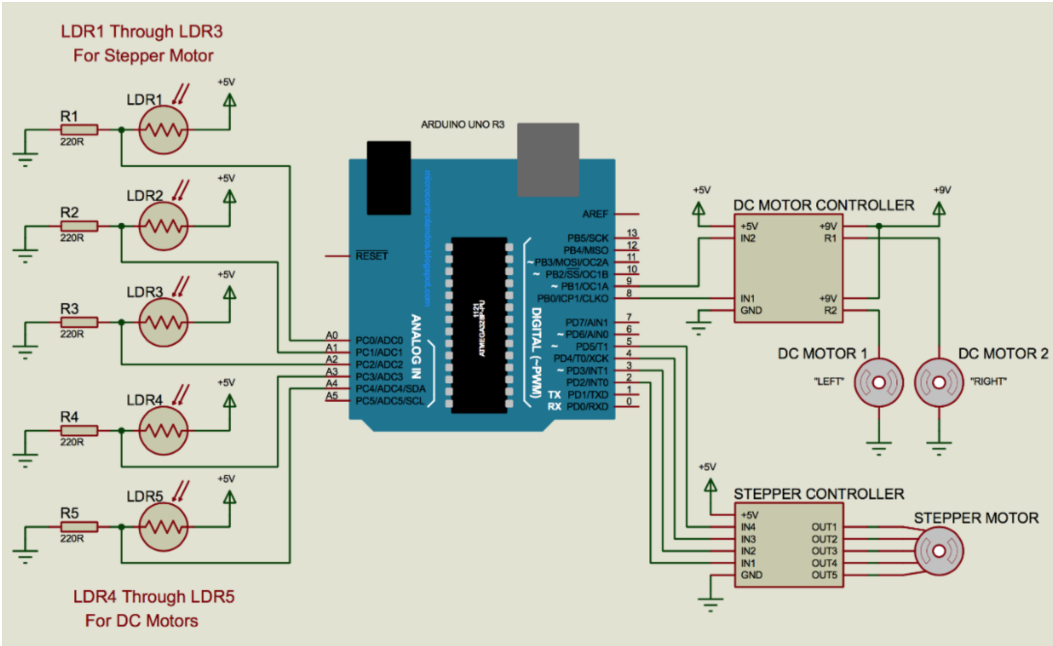

Figure 3.13: Circuit schematic of the solar tracking panel and robotic platform using LDRs.

collision. The experiment was tested to drive the robot using a flash light from one position to another. This robot can be used as a toy for children in which a transmitter and receiver can be added to the circuit to allow LEDs, positioned in front of the LDR, to turn on and off using a remote control.

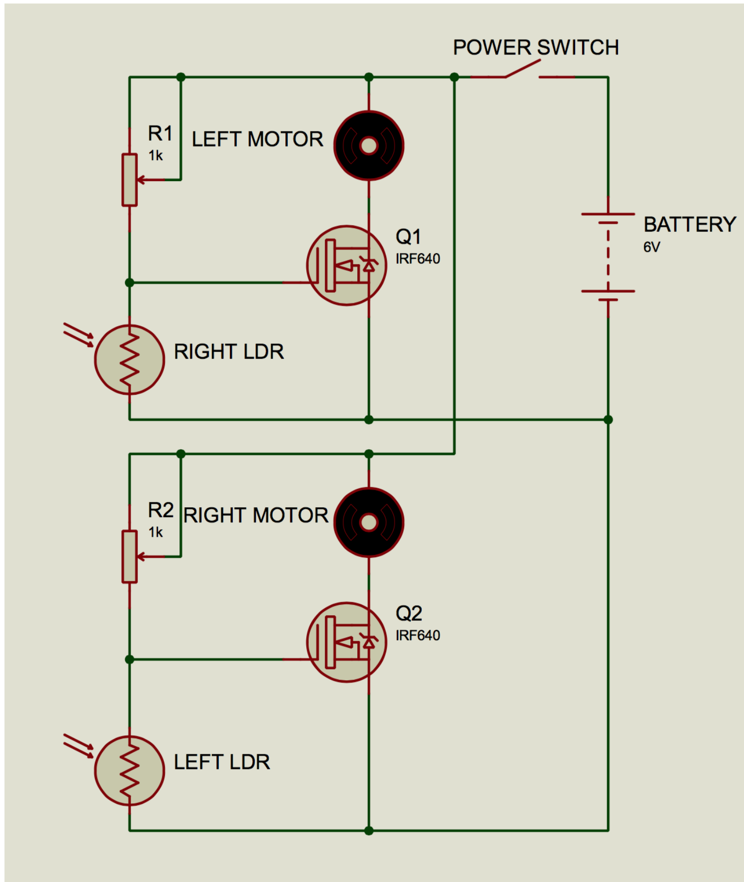

Figure 3.14: Schematic of a STR without using Arduino board.

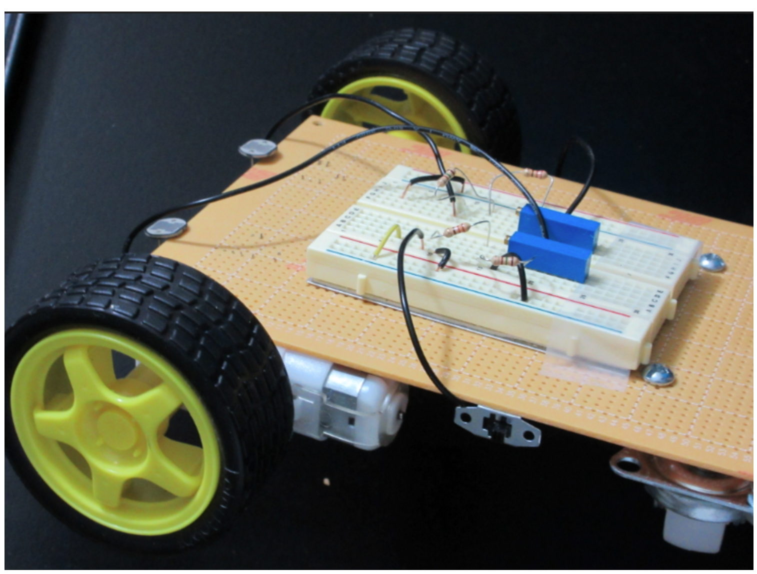

Figure 3.15: STR without using Arduino board.

Chapter 4

3D Inkjet Printed TASS Packaging

4.1 TASS Packaging

4.1.1 3D Printed Solar Tracking Panel

A 3D Inkjet printer was used to print the TASS system packaging. All parts were designed using SolidWorks software based on the system requirements. The components of the solar tracking panel were designed and built as shown in Figure 4.1. The mechanical structure was precisely designed to fit the components that were used in the system. The designed stand pillar that hold the solar cell can fit to any type of motors. The only part that needs to be changed is the small nut that goes on the bottom side of the pillar. It was specially designed to fit the stepper motors shaft used in the system. LDRs sensors were placed around the mini-solar panel with a tilted surface structure to detect the direction of the highest light intensity.

4.1.2 3D printed solar tracking robotic platform

The solar tracking robotic platform was also designed and printed using 3D printer. Figure 4.3 shows the plate where the solar cell is attached, a rod that holds the solar cell plate attached to the motors shaft, two open holders for LDR 4 and 5, a solar car base where all electronics parts are placed, and a swivel caster that allowed the car to move in multiple

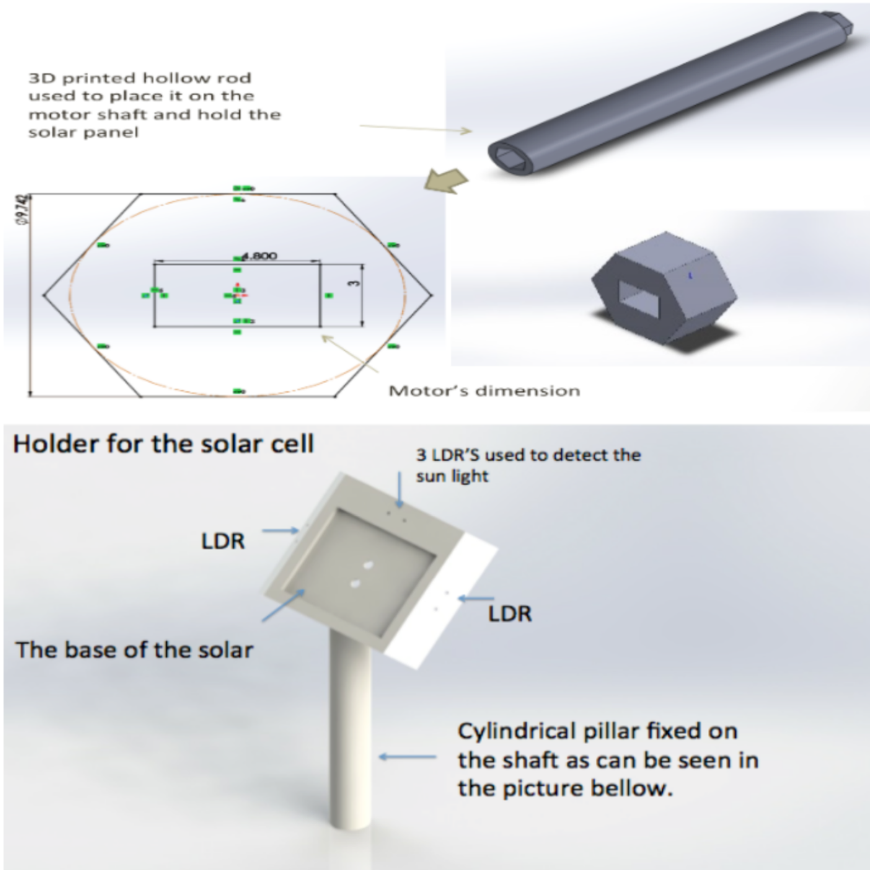

Figure 4.1: Packaging design of the solar tracking panel system.

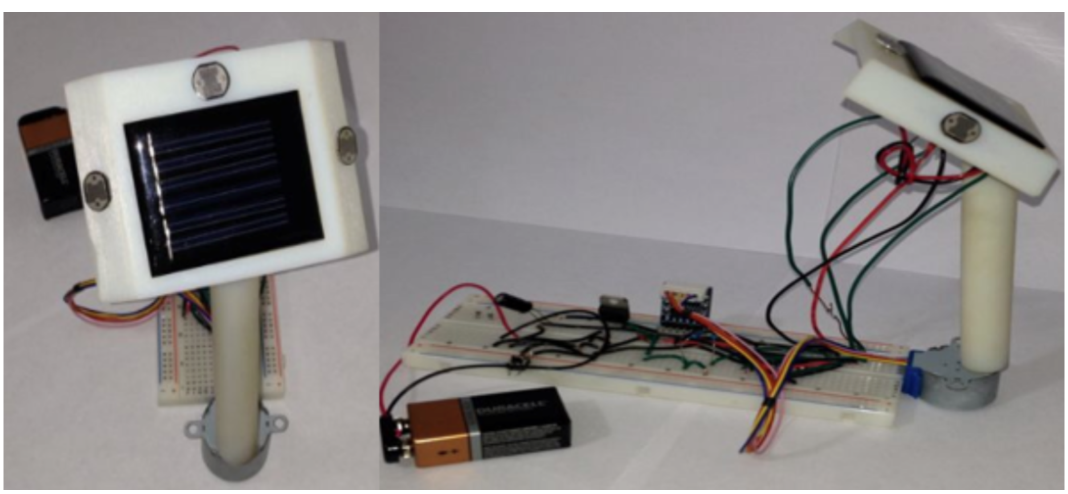

Figure 4.2: Printed packaging solar tracking panel system.

directions. The DC motors are attached to the cars tail and they will be rotating based on the LDRs output. The solar cell panel is equipped with LDR 1, 2 and 3 to control its direction in the same way as in the previous section. This design can be disassembled and used in different applications.

4.2 TASS Applications

4.2.1 Rooftop Solar Tracking Panel

Most of the solar panels that can be seen in some buildings are placed in a fixed position on the top of the buildings reducing the efficiency during the morning or the afternoon because of the movement of the sun. This means that a single solar panel placed with this arrangement may harness most of the energy during the mornings and be almost useless in the afternoons. There is another option which takes this into account, put solar panels on both sides, which increases the initial costs of the project and the future maintenance cost while trying to join the two sources of energy and placing them into one device. In this thesis, a single solar panel, that is able to change its position based on the amount of energy available to be harnessed, is used as seen in the arrangement described in Figure 4.4.

An experiment has been setup to calculate the variation of the efficiency and power output of the rooftop tracker. It is composed of three LDRs, one stepper motor, one mini-solar cell and some LEGO parts to build the structure. In addition, high light intensity source is used to mimic the sunlight. The experiment was conducted in a darkroom where no other light sources existed. The output power of the solar panel was calculated in three different angels (45, 90 and 135 degree) between the flat floor and the light source. The solar panel was successfully following the light source. Table 4.1 shows the output parameters of

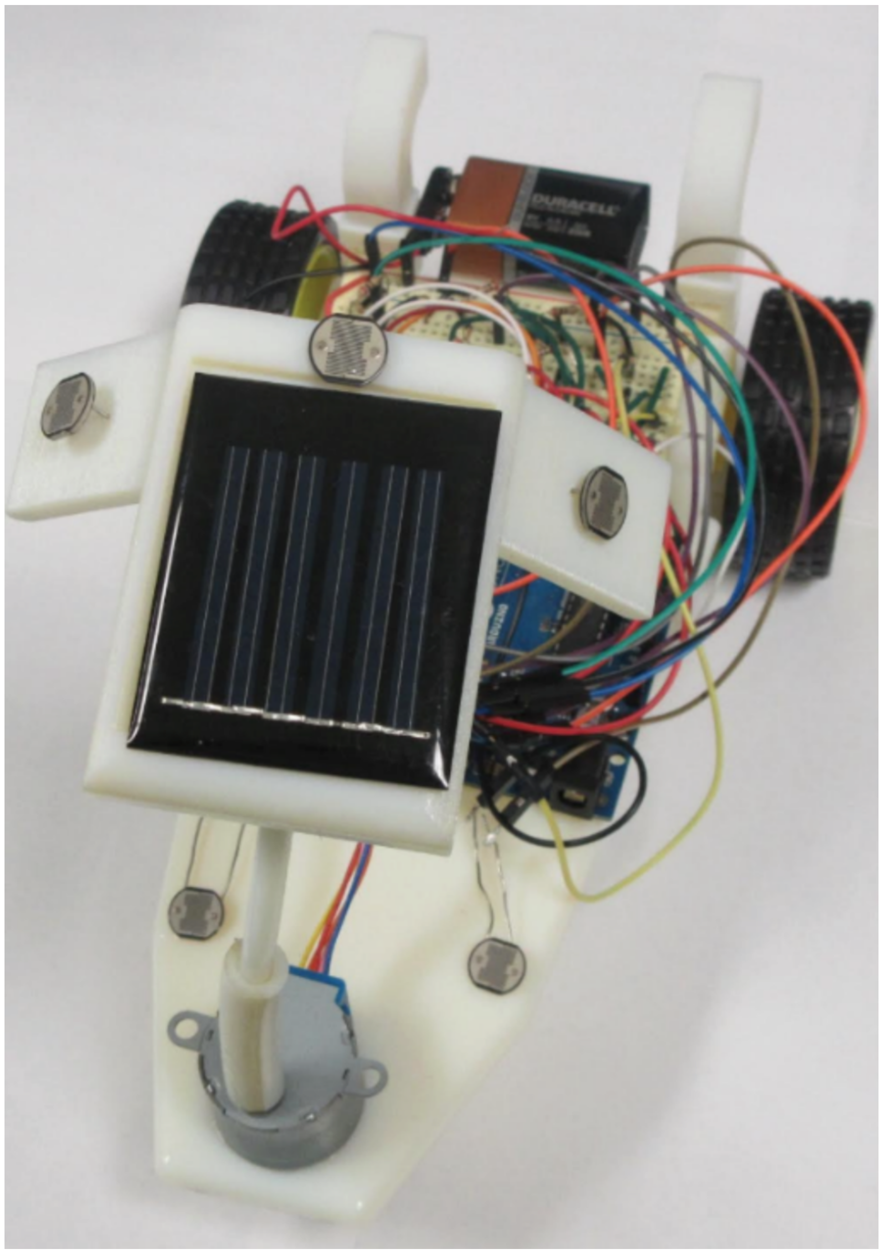

Figure 4.3: 3D-printed design of the system

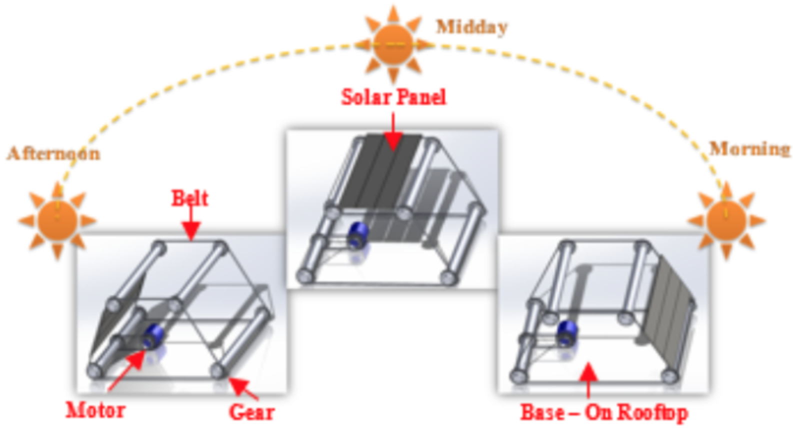

Figure 4.4: Arrangement of rooftop sun tracker.

Table 4.1: Comparison between fixed and movable mini-solar panel within three positions of light source.

Parameter	Solar Tracking Panel			Two Fixed Solar Panels		
	Position 1	Position 2	Position 3	Position 1	Position 2	Position 3
Voltage (v)	1.890	1.705	1.840	2.370	2.230	1.970
Current (mA)	0.89	0.86	0.70	0.600	0.10	0.410
Power (mW)	1.682	1.466	1.280	1.422	0.223	0.80
Avg. Power	1.478 mW			0.815 mW		

one mini solar panel tracking light and two-fixed mini solar panel.

From the results shown in the table, the solar tracking panel on rooftop is more efficient than the fixed solar panel in terms of power and cost. Average power percentage of the solar tracking panel to the two fixed panels is 64%. One mini-solar panel was used in the tracking system whereas two solar panels were used in the fixed one in both sides of the rooftop. The whole design of the experiment is shown in Figure 4.5.

4.2.2 Flower base solar tracking robot for smart home

The TASS shown in Figure 4.3 was also used to build and test a proof of concept for a possible smart home application. A flower pot was mounted on the rear side of the TASS

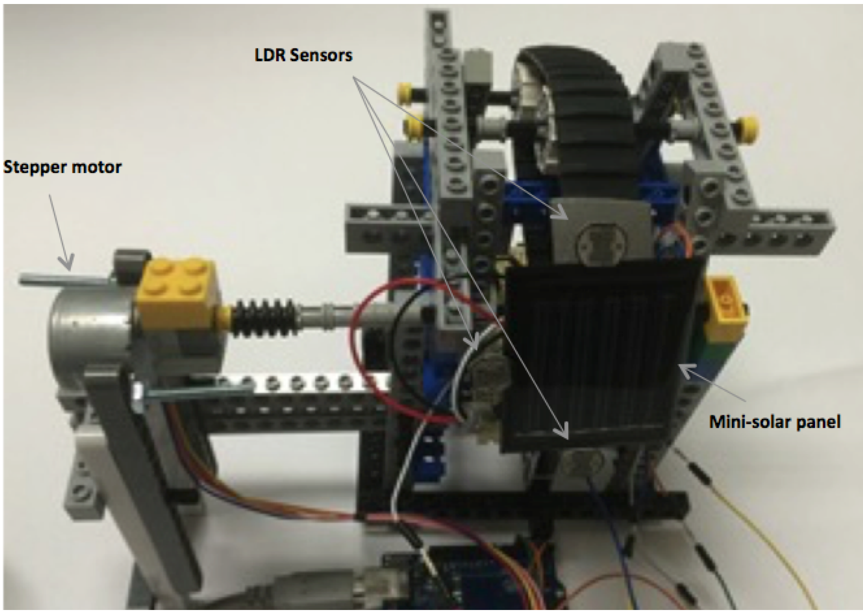

Figure 4.5: Prototype experiment of rooftop solar tracking system.

system as shown in Figure 4.6. Although it shows how this system followed the light coming from a window in the kitchen area, it was tested in different areas of a contemporary home in Ann Arbor area. The use of ultrasonic sensors to avoid objects in the tested areas would enhance the functioning work in this type of projects.

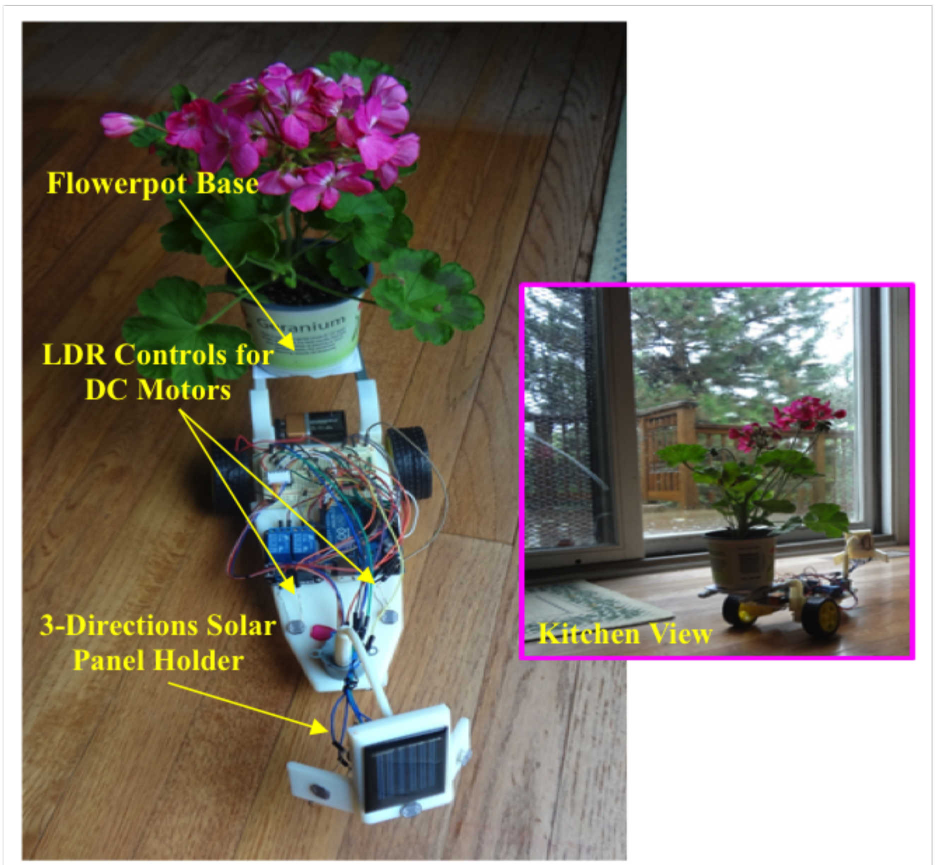

Figure 4.6: TASS flowerpot for a smart home.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The following unique features of the thesis research were demonstrated; a) the TASS concept has been developed to enhance the output energy of a solar system, b) the use of the solar tracking system at the panel and robotic platform levels has been demonstrated, c) two types of sensors, LDR and PV sensors, were used to achieve the goals of the solar tracking systems, d) comparison between the two sensors was investigated, e) 3D inkjet printed circuit boards and TASS packaging were developed, and f) different applications of TASS were implemented and discussed.

5.2 Future Work

- TASS project has a lot of applications in many areas such as energy scavenging/harvesting, night light systems, mind-controlled robots and micro drones for surveillance and harsh weather monitoring, and optoelectronic systems.
- Future applications are expected in, 1) smart street lights, roads and homes lighting, 2) robotic and fixed systems equipped with solar source tracking technologies and 3)

systems equipped with multi-material solar cells using MEMS actuators.

- Building solar tracking cells with each solar panel could help reduce the consumed energy in the tracking process. See Figure 5.1.

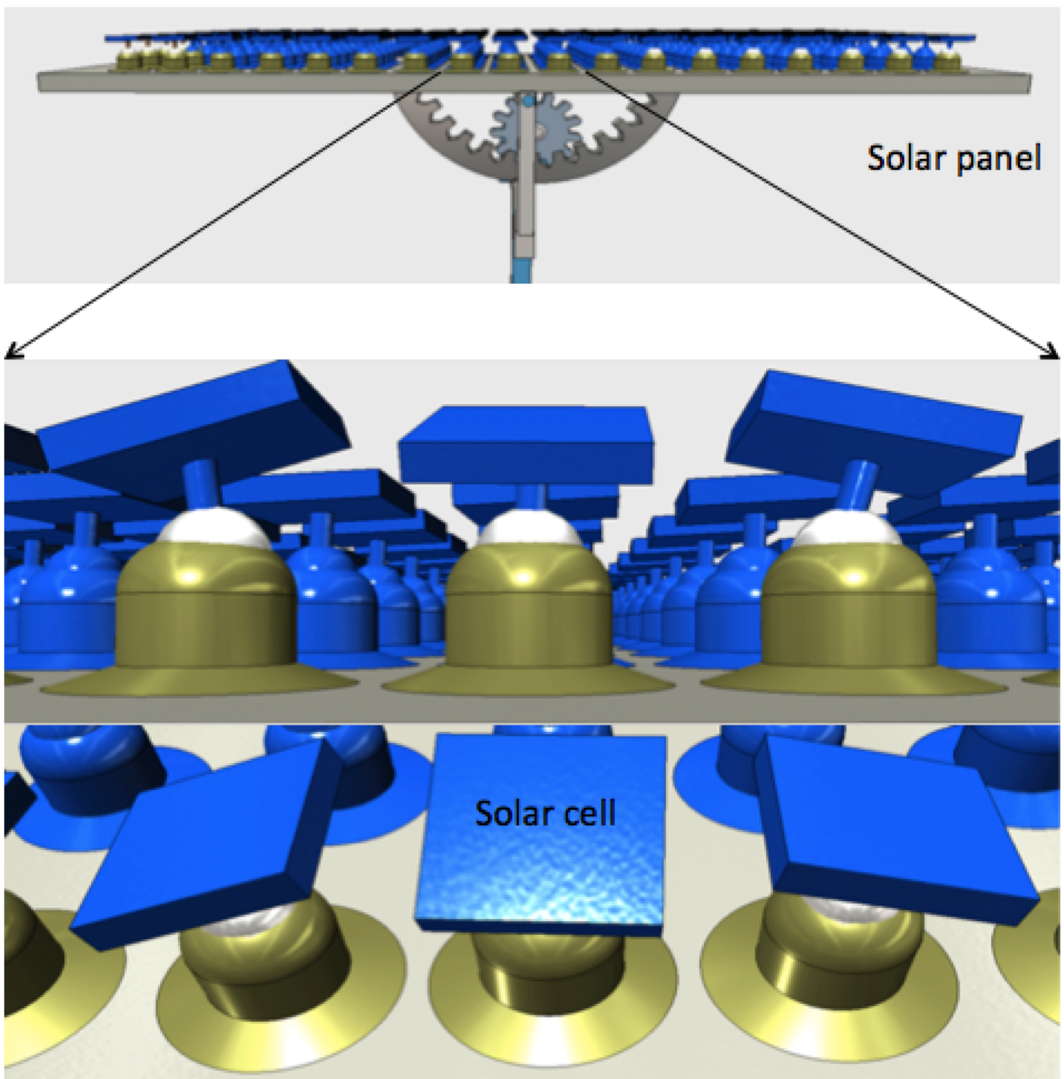

Figure 5.1: MEMS Actuated Solar Array (MASA).

BIBLIOGRAPHY

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[1] the Authority of the House of Lords, "The economics of renewable energy," vol. I, 2008.

[2] D. M. Aslam. (2013, Jun.) The technology assisted smart solar-system. [Online]. Available: http://www.egr.msu.edu/ aslam/

[3] V. Poulek, "Testing the new solar tracker with shape memory alloy actors," in *Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on*, vol. 1, Dec 1994, pp. 1131–1133 vol.1.

[4] S. Degeratu, L. Alboteanu, S. Rizescu, D. Coman, N. Bizdoaca, and C. Caramida, "Active solar panel tracking system actuated by shape memory alloy springs," in *Applied and Theoretical Electricity (ICATE), 2014 International Conference on*, Oct 2014, pp. 1–5.

[5] N. J. Ganesh, S. Maniprakash, L. Chandrasekaran, S. Srinivasan, and A. Srinivasa, "Design and development of a sun tracking mechanism using the direct sma actuation," *Journal of Mechanical Design*, vol. 133, no. 7, p. 075001, 2011.

[6] J. M. Hallas, K. A. Baker, J. H. Karp, E. J. Tremblay, and J. E. Ford, "Two-axis solar tracking accomplished through small lateral translations," *Applied optics*, vol. 51, no. 25, pp. 6117–6124, 2012.

[7] T.-S. Zhan, W.-M. Lin, M.-H. Tsai, and G.-S. Wang, "Design and implementation of the dual-axis solar tracking system," in *Computer Software and Applications Conference (COMPSAC), 2013 IEEE 37th Annual*, July 2013, pp. 276–277.

[8] Y. Gan, "Research on solar tracking composite control," in *2014 10th France-Japan/ 8th Europe-Asia Congress on Mecatronics (MECHATRONICS2014-Tokyo)*, November 2014, pp. 389–393.

[9] M. Haryanti, A. Halim, and A. Yusuf, "Development of two axis solar tracking using five photodiodes," in *Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), 2014*, Aug 2014, pp. 40–44.

[10] O. T. Mahmood, "Programmable logic controller based design and implementation of multiple axes solar tracking system," in *Electrical, Communication, Computer, Power, and Control Engineering (ICECCPCE), 2013 International Conference on*, Dec 2013, pp. 101–106.

[11] M. I. Hossain, S. A. Khan, and M. Shafiullah, "Power maximization of a photovoltaic system using automatic solar panel tracking along with boost converter and charge controller," in *Electrical Computer Engineering (ICECE), 2012 7th International Conference on*, Dec 2012, pp. 900–903.

[12] okpeki U.K and otuagoma.S.O, "Design and construction of a bidirectional solar tracking system." in *International Journal Of Engineering And Science*, Feb 2013.

[13] M. T. A. Khan, S. M. S. Tanzil, R. Rahman, and S. M. S. Alam, "Design and construction of an automatic solar tracking system," in *Electrical and Computer Engineering (ICECE), 2010 International Conference on*, Dec 2010, pp. 326–329.

[14] S. Malge, K. Bhole, and R. Narkhede, "Designing of dual-axis solar tracking system with remote monitoring," in *Industrial Instrumentation and Control (ICIC), 2015 International Conference on*, May 2015, pp. 1524–1527.

[15] S. A. Kalogirou, "Design and construction of a one-axis sun-tracking system," *Solar Energy*, vol. 57, no. 6, pp. 465 – 469, 1996. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0038092X96001351

[16] J. M. Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities," *Materials & Design*, vol. 56, pp. 1078 – 1113, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0261306913011345

[17] P. Roth, A. Georgiev, and H. Boudinov, "Design and construction of a system for sun-tracking," *Renewable Energy*, vol. 29, no. 3, pp. 393 – 402, 2004. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148103001964

[18] M. M. Arturo and G. P. Alejandro, "High-precision solar tracking system," in *Proceedings of the World Congress on Engineering*, vol. 2, 2010.

[19] K. Brown, D.G; Stone, "High accuracy/low cost tracking systems for solar concentrators using a neural network," in *Proceedings of the 28th Intersociety Energy Conversion Engineering Conference*, 1993.

[20] A.-J. N. Khalifa and S. S. Al-Mutawalli, "Effect of two-axis sun tracking on the performance of compound parabolic concentrators," *Energy Conversion and Management*, vol. 39, no. 10, pp. 1073 – 1079, 1998. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0196890497100206

[21] A. Al-Mohamad, "Efficiency improvements of photo-voltaic panels using a sun-tracking system," *Applied Energy*, vol. 79, no. 3, pp. 345–354, 2004. [Online]. Available: http://EconPapers.repec.org/RePEc:eee:appene:v:79:y:2004:i:3:p:345-354

[22] G. Mwithiga and S. N. Kigo, "Performance of a solar dryer with limited sun tracking capability," *Journal of Food Engineering*, vol. 74, pp. 247–252, 2005.

[23] S. Armstrong and W. G. Hurley, "Investigating the effectiveness of maximum power point tracking for a solar system," in *Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th*, June 2005, pp. 204–209.

[24] A. Yazidi, F. Betin, G. Notton, and G. A. Capolino, "Low cost two-axis solar tracker with high precision positioning," in *Environment Identities and Mediterranean Area, 2006. ISEIMA '06. First international Symposium on*, July 2006, pp. 211–216.

[25] M. A. J. Paul, "Design and performance analysis of automated two axis solar tracking system for steam generation," in *Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference on*, April 2013, pp. 432–437.

[26] J. C. Schaefer, "Review of photovoltaic power plant performance and economics," *IEEE Transactions on Energy Conversion*, vol. 5, no. 2, pp. 232–238, Jun 1990.

[27] J. Arai, K. Iba, T. Funabashi, Y. Nakanishi, K. Koyanagi, and R. Yokoyama, "Power electronics and its applications to renewable energy in japan," *IEEE Circuits and Systems Magazine*, vol. 8, no. 3, pp. 52–66, Third 2008.

[28] B. Koyuncu and K. Balasubramanian, "A microprocessor controlled automatic sun tracker," *IEEE Transactions on Consumer Electronics*, vol. 37, no. 4, pp. 913–917, Nov 1991.

[29] J. Roy, D. Pal, S. K. Sanyal, U. C. Sarkar, and R. Nandi, "Design of a microprocessor based radar tracking system using stepper motor," in *ACE '90. Proceedings of [XVI Annual Convention and Exhibition of the IEEE In India]*, 1990, pp. 250–253.

[30] H. A. Sohag, M. Hasan, M. Khatun, and M. Ahmad, "An accurate and efficient solar tracking system using image processing and ldr sensor," in *Electrical Information and*

Communication Technology (EICT), 2015 2nd International Conference on, Dec 2015, pp. 522–527.

[31] X. Xu, Q. Liu, and Y. Zuo, "A study on all-weather flexible auto-tracking control strategy of high-efficiency solar concentrating photovoltaic power generation system," in *Intelligent Systems (GCIS), 2010 Second WRI Global Congress on*, vol. 2, Dec 2010, pp. 375–378.

[32] (2015) Solar impulse. [Online]. Available: www.solarimpulse.com