Insect eye solar tracking

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Abstract

It is well known that solar tracking systems increase solar panel efficiency. The higher demand for energy production requires more efficient systems to harness more energy for useful use. Cloudy weather conditions reduce the solar panel's energy production significantly. The center of study in this thesis is the development and experimentation of an artificial compound insect eye for maximum solar radiation detection even in cloudy conditions to know the best orientation of the solar panel for maximum capture efficiency.

Photodiodes were used as the eye's sensing unit. Printed circuit board were used to connect these single photodiodes. Arduino Mega 2560 was used as the brain to collect data and send them to a computer for monitoring. A hemi-spherical eye was designed using Solidworks and manufactured using a 3D printer Ultimaker 2. The Arduino program mapped the photodiodes to the final output image correctly and used a multiplexer circuit to rotate on all photodiodes. Connection problems aroused and a pervious prototype sensor was used to prove the concept. The sensor was successful in determining the maximum point of radiation even in cloudy conditions where the solar panel's power output increased by 6% by orienting it to the point of maximum radiation given by the eye instead of fixing it in a horizontal position, which is a significant number when applied to large solar power stations.

Keywords— Solidworks, Photodiode, Artificial Insect Eye, Flexible Circuit, Solar Panel, Solar Tracking.

I. Introduction

Nowadays there has been a higher demand of energy production and the depletion of fossil fuel reserves has caused the search for an alternate source of power that is renewable and sustainable. Solar power is one of the best alternative power sources as it is abundant in nature and a renewable form of energy. For harnessing solar radiation, photovoltaic panels have been developed and used throughout the years.

Nature has been one of the most inspiring environment for the majority of engineers, scientists, and designers. From the beginning of human history, it has played a vital role in our creative expression. The lands and waters we rely on for daily survival shape how we view and interpret the world around us. And in turn, the art we create from nature's inspiration becomes part of our personal and cultural identity. Insects, animals, and plants are nature's version of mechanical, mechatronic and energy systems, so studying how these creatures evolved through ages, investigating their different mechanical, energy, chemical, and even neurological systems, and observing their response to different stimuli can be a great inspiration for developing solutions to many problems faced in life. [1]

Since many of the mechatronic energy systems developed nowadays are already inspired by nature and its creatures, such as plane and automotive aerodynamics and many mechanical motion systems, further bio-inspired research and observation will definitely broaden horizons to new approaches for implementing more advanced and complex mechatronic systems. This is the study of bionics. Often, the study of bionics emphasizes implementing a certain function found in nature rather than just imitating the exact biological structure.

In the area of solar tracking, cloudy weather conditions reduce solar panel's energy production significantly [8]. So to try and gain the maximum output of a solar panel in this fact into consideration, an insect eye sensor was developed to detect the maximum point of irradiance in cloudy conditions and orient a solar panel to that point.

Engineering an artificial compound eye is a challenging task, since the angle and alignment of each photoreceptor unit is very important and affects greatly the final output. The center of study in this thesis is the development and experimentation of an artificial compound insect eye for maximum solar radiation detection even in cloudy conditions to know the best orientation of the solar panel for maximum capture efficiency. The reason behind the name compound eye is because they are made up of repeated units, the ommatidia, each of which functions as a separate visual receptor. A single compound eye may consist of thousands of ommatidia located on a convex surface, forming the eye structure, and thus each pointing in a slightly different angle and direction. Although every ommatidium has its own optical and receptor structure, the image perceived is a combination of inputs from every ommatidium in the eye, and thus giving the eye its properties.

However, compound eyes have limited resolution compared to humans' eyes. Since each individual lens is of very small size, diffraction imposes a great limitation on the eyes resolution, and as a result, a compound eye with comparable resolution to our simple eyes needs to be of approximately 11 meters diameter. Insects' compound eye is the structure to be discussed in this thesis. [1]

A spherically shaped structure with photo-detector sensors implemented on its surface represents the sensing element. Moreover, a 2 degree of freedom rotary motion system was be implemented to direct the panel to the correct angle.

A. State of the art

There has been a lot of research going on in the area of solar tracking and tracking of the sun even on cloudy days.

The first part is about the study of the number of axis for solar tracking. There are two ways, single axis and dual axis solar tracking. Single axis is simply moving the panel in only one degree of freedom and dual axis is moving the panel in 2 degrees of freedom. In general solar tracking gives higher efficiencies compared to fixed tilt panels. Dual axis tracking is more efficient than single axis tracking. [2]

Since the aim of solar tracking is to generate more power. It is important to take into consideration that the power consumption of the tracking system should be low. [3]

The second part is the control strategy. There 2 major types of solar tracking strategies, the open loop control strategy and the closed loop control strategy. An open-loop controller uses only the current state and the algorithm of the system to compute its input into a system without using feedback to determine if its input has achieved the desired goal. It is simpler and cheaper than the closed-loop type of sun tracking systems. There is no observation of the output of the processes that it is controlling like in the closed loop controller. Therefore, an open-loop system doesn't have the ability to correct any errors so that it can compensate for disturbances in the system. Closed-loop controllers of solar tracking systems are based on feedback control. Sensors give a number of inputs which detect relevant parameters by the sun to a controller, then manipulated in the controller and yield outputs. [4]

There is also the hybrid control strategy, which is made by the combination of open loop tracking strategies based on solar movement models and closed loop strategies using a dynamic feedback controller, a hybrid tracking system is made. The advantage of the hybrid tracking is that it is cheaper than closed loop tracking with almost the same efficiency. [5]

The third part was to know where the maximum radiation is coming from to be able to point the solar panel perpendicular to that radiation for maximum power output. Most sensors developed today work well in tracking the sun on clear skies, one way is using the combination of astronomical estimates from GPS and vision-sensor image processing. By using image processing, a decision making process is used to differentiate if the current weather condition is sunny or not [6]. The solar tracking system decides whether to use the image processing outcomes or astronomical estimates based on the output. For the tracking method that combines the solar image and astronomical estimates, the solar panel can maintain a normal direction to sunlight. But, in cloudy weather conditions, solar image controlling is not the best case due to the difficulty in locating the sun using images; In that case, operating only using astronomical estimates only is used for tracking. [6]

Other ways is to track the beam radiation other than image processing is using sensors such as Pyranometers [7]. In cloudy conditions, the diffuse component in the global radiation contributes by a significant amount so the energy capture decreases by 23% of the maximum efficiency that can be reached by the solar panel because of inadequacy in capturing most of the diffuse radiation. A controlled tracking system that tracks beam radiation in clear skies and fixes the panel in horizontal position during cloudy conditions has shown to increase the capture efficiency [8]. This is a different method to deal with cloudy conditions than using the astronomical estimates to track the sun on cloudy days.

So in this thesis, a sensor was developed for maximum solar radiation detection in cloudy conditions to know where the maximum radiation is coming from and orient the panel accordingly. The manufactured sensor was hemispherical in shape and had 92 photodiodes. Unfortunately, that prototype experienced some connection problems due to manufacturing, so it gave inconsistent results. As a result, a previous prototype at the DHBW Karlsruhe was used as a proof of concept.

The previous prototype insect eye was made for the purpose of following light indoors and its design was relatively different than hemispherical one. The angle and alignment of each photo receptor unit is very important and affects greatly the final output. The photodiode light sensor was chosen as the detector was successful to represent insect's eye ommatidium to simulate different proprieties of the eye. A micro-controller represented the insects' brain that collects the signals sent from the photodiodes and combine them together to give an output image of the surrounding (32 pixels). Moreover, using 3D printing technology to build the eye model was efficient enough in dimensions aspect. [9]

This prototype was used as a proof of concept to see the reaction of the eye in sunny and cloudy conditions, but it was not integrated with the solar panel movement as its design would not give consistent results. The panel power output was compared in the horizontal position and the oriented position given by the eye. Fig. 1 shows the shape of the previous prototype eye. [9]

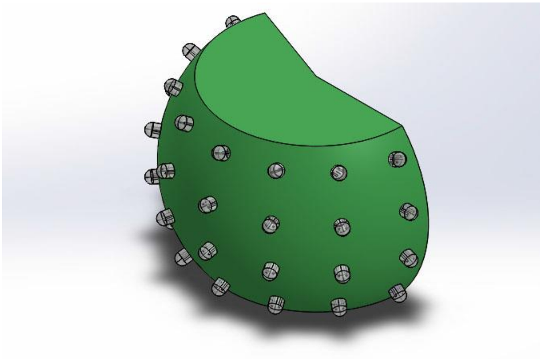

Fig. 1. Previous eye prototype

II. Background Knowledge

A. Eye types

Eye types can be divided into two types, Simple eyes, which have one concave surface containing all photoreceptive cells, and compound eyes, which are composed of many photoreceptive units called ommatidia, laid out on a convex surface. The compound eye is what will be used in this thesis, so it was compared to the human eye. Moreover, a comparison was made between different types of compound eyes. [10]

Compared with human eyes, compound eyes possess a very large view angle, and can detect fast movement and, in some cases, the polarization of light.

Compound eyes generally allow only a short range of vision. For example, flies and mosquitoes can see only a few millimeters in front of them with any degree of resolution, although within this short range they can see detail that we could see only with a microscope.

Dragonflies have one of the most elaborate eyes of any insect, capable of pinpointing the motion of a small prey insect several meters away, even while the dragonfly is traveling fast. Butteries have color vision that is more enhanced than our own, enabling them to locate food from flowers. Honey bees can see in ultraviolet, which allows them to perceive patterns on nectar-laden flowers that are invisible to us. Many insects, including bees, can also detect polarized light, which they use in navigation. A compound eye is what was used in this thesis.

B. Light sensor types

Light sensors convert light energy to an electrical signal output. When converted into electrical energy, the beaming energy within the infrared to ultraviolet light frequency spectrum source can be measured. [15] An important part of this project's realization was choosing the detector to use for this solar tracking application. The choices seemed overwhelming; photodiodes, phototransistors, photodarlingtons, photomultiplier tubes, photoresistors, various hybrids, LED’s as detectors and even thermopiles. Light sensing applications differ widely from specialized scientific instrumentation that needs to detect separate photons to systems that control high speed welding and cutting lasers that produce kilowatts of optical power.

In the end, photodiodes seemed the best choice as they are also cheap and they have a wider spectral range and dynamic range than phototransistors and photoconductive sensors, so they may be more suitable for the application in this thesis. Although photo-multiplier tubes are more sensitive, they are more expensive and they are larger in size.

C. Flexible circuits

A Flexible circuit is a normal PCB but it has a special feature it can be bent and can take almost any shape. There are special components which are also flexible which can also be mounted on the flexible circuit resulting in a total flexible device. Also rigid normal components can be placed on top of the flexible circuit. The material in which these boards are made of differ from one manufacturer to another. However most of them use plastic substrates or a conductive transparent polyester. Devices can contain normal rigid printed circuit board and flexible circuit board. [29]

One of the advantages of the flexible circuits is it is thin which gives it the flexibility. This thin feature gives a possibility for a more integrated design and increasing the density of packages. Flex circuits are used in many application such as smart phones, sensors, LCD televisions, laptops ...etc. There is also a single layer flexible circuit as well as double layer and multilayer flexible circuit board. The only difference between the flexible circuit board and the normal rigid printed circuit board is the material of the routes, pads and vias.

Flexible circuits will be useful to be able to shape the sensor circuit into any shape needed, in this case a hemi-spherical shaped eye.

D. 3D printing

There are three main steps in creating parts or shapes using 3D printing: Modeling, printing and finishing. First modeling a CAD (Computer Aided Design) program is used to first create the part and then converted to a .STL (stereo lithography) file to be read by the 3D printer.

There are many ways of realize the model objects created by the 3D printers. One method use melting or softening material to put the layers on top of each other. Two of the most used technologies are fused deposition modeling (FDM) and Selective laser sintering (SLS). Laying liquid materials that are cured afterwards is another method of printing. The technology with this method is stereo lithography (SLA).

Ultimaker 2 is the 3D printer used in this thesis it uses the fused filament fabrication technique to build the layers to shape the final 3D product. It has a print speed and Travel speed of 30 mm/s to 300 mm/s. Its precision is 12.5 - 12.5 - 5 microns in width, length and height respectively. The layer resolution is 20 microns, the maximum build volume is 223 x 223 x 205 mm in width, length and height respectively. It was sufficient to build and test the prototype also to build the final eye. [32]

E. Solar irradiance

The solar irradiance is the power per unit area reaching a surface, it is in the form of electromagnetic radiation. After atmospheric absorption and scattering, irradiance may be measured in space or at the earth's surface. The irradiance incident on the Earth's upper atmosphere is called the extraterrestrial irradiance (TSI). Irradiance is a function of distance from the sun, cross-cycle changes, and the solar cycle [33].

The energy in solar irradiance comes in the form of electromagnetic waves of a wide spectrum. The shorter wave lengths such as visible light or UV have more energy than longer wavelengths such as infrared. The spectral distribution graph (figure 2-20) shows the spectrum, the relative weights of individual wavelengths is plotted over all wavelengths, measured in W/m^2 (wavelength). Just outside the entry into the earth's atmosphere, the diagram displays the spectrum of a sun ray. In the visible spectrum, the peak of the spectrum is found, but there are shorter and longer wavelengths with significant amounts of energy. [7] Photodiodes were chosen for they can detect wavelengths between 0.2 and 2 µm which is the band of interest in the solar spectral irradiance curve. [20]

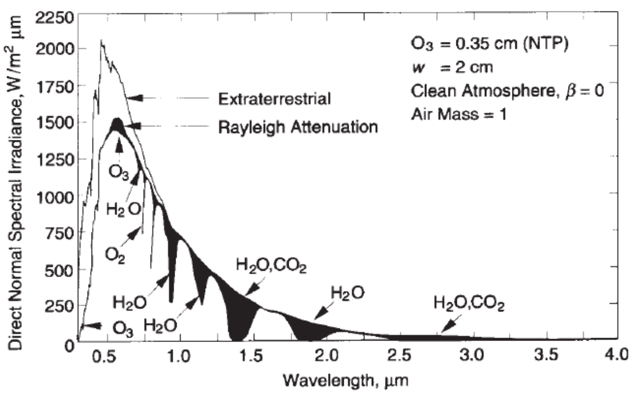

Fig. 2. Solar spectral irradiance curve [7]

When the surface is perpendicular to the sun, irradiance is largest. As this angle moves from the right angle position, irradiance is reduced proportionally to the cosine of the angle.

As described by the horizontal coordinate system, the angle measured from directly overhead to the sun's center is called the zenith angle. The elevation (attitude) angle is the angle between the sun's center and the horizon. The azimuth angle is the angle measured from the south as shown by fig. 3.

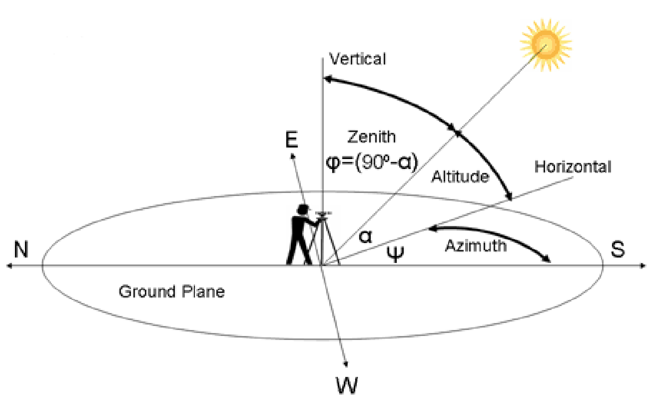

Fig. 3. Zenith, elevation and azimuth angles [34]

If the zenith angle is not zero, for horizontal surfaces, a larger area is required to catch the same irradiance of a surface normal to the sunbeam.

F. Solar cells

A solar cell is a device that converts the solar energy into electricity by the photovoltaic effect. Characteristics such as current, voltage, or resistance, vary according to the irradiance of the sun on earth. They are the building blocks of photovoltaic modules, known as solar panels.

Electrical properties of devices are describe by current-voltage characteristics. It is useful to understand the origin of these current-voltage characteristics in terms of basic physical processes. The electronic functions of solar cells take place within materials called semiconductors. Semiconductors have the capacity to absorb light and to deliver a portion of the energy of the absorbed photons to carriers of electrical current – electrons and holes.

The conductivity of the semiconductors can be controlled (modified) through the introduction of specific impurities, or dopants called donors and acceptors. N-type (electrons are the majority carriers of electrical current). Obtained introducing donor impurities into a semiconductor. P-type (holes are the majority carriers of electrical current). Obtained introducing acceptor impurities into a semiconductor. [35]

A solar cell is simply a p-n junction diode basic structure with emitter region which is the more heavily doped quasi-neutral region. A base or absorber region which is the more lightly doped quasi-neutral region.

The ideal current-voltage characteristics are based on the following assumptions: The abrupt depletion-layer approximation; that is, the built-in potential and applied voltages are supported by a dipole layer with abrupt boundaries, and outside the boundaries the semiconductor is assumed to be neutral. The Boltzmann approximation is valid. The low-injection assumption; that is, the injected minority-carrier densities are small compared with the majority-carrier densities. No generation-recombination current exists inside the depletion layer, and the electron and hole currents are constant throughout the depletion layer.

For the solar cell to operate, photons hit the solar cell, electrons are excited from their current molecular/atomic energy level to a higher level. They can either dissipate the energy as heat and return to the original level or travel through the cell until it reaches an electrode. Therefore a DC current flows through the material and the electrodes. [35]

The short-circuit current, I_{SC}, and dark saturation currents, I_{01} and I_{02} depend on the solar cell structure, material properties, and the operating conditions. These quantities are given by rather complex expressions. A solar cell can be modeled by an ideal current source – I_{SC} in parallel with two diodes – one with an ideality factor of 1 and the other with an ideality factor of 2 as shown in fig. 4.

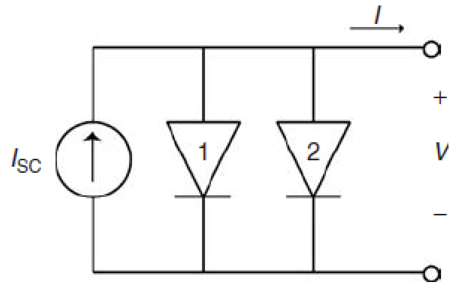

Fig. 4. Simple solar cell circuit model [35]

The current-voltage I(V) characteristic of a typical silicon solar cell is shown by fig. 5.

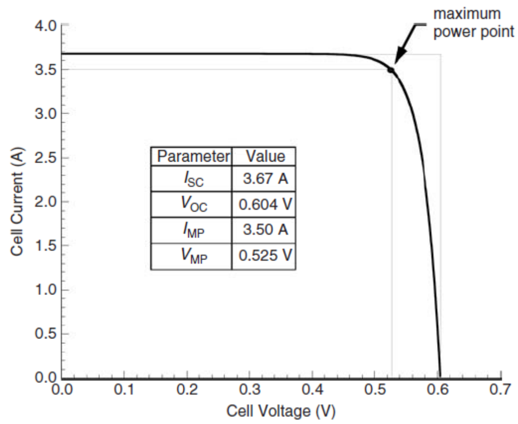

Fig. 5. I-V characteristic curve [35]

The important terms for solar cells: the short circuit-current, I_{SC}, the open-circuit voltage, V_{OC}, the fill factor, FF, and the cell efficiency, η. At small applied voltages ($V \approx 0$), the diode current is negligible and the current is just the short-circuit current, I_{SC}. At high applied voltages, the diode currents becomes significant, and the solar cell current drops quickly. At open-circuit ($I = 0$), all the light-generated current I_{SC} is flowing through diode 1 (diode 2 ignored)

$$V_{OC} = \frac{kT}{q} \ln \frac{I_{SC} + I_{01}}{I_{01}} \approx \frac{kT}{q} \ln \frac{I_{SC}}{I_{01}} \quad (1)$$

Where $I_{SC} >> I_{01}$

Maximum power output point (MPP) on the I(V) curve is where the power produced at a maximum: $V = V_{MP}$ and $I = I_{MP}$. These point defines a rectangle whose area, given by $P_{MP} = V_{MP} * I_{MP}$, is the largest rectangle for any point on the I(V) curve.

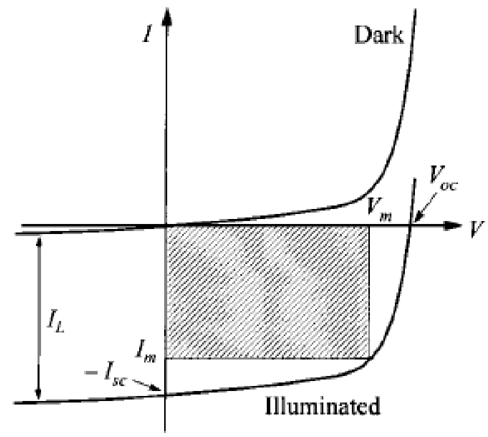

Fig. 6. I-V characteristics of solar cell under illumination. Determination of maximum power output is indicated. [35]

The rectangle defined by V_{OC} and I_{SC} provides a reference for describing the maximum power point. The fill factor, FF, is a measure of the square-ness of the I-V characteristics and is always less than one. It is the ratio of the areas V_{MP}, I_{MP} and $V_{OC}*I_{SC}$.

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} = \frac{P_{MP}}{V_{OC} I_{SC}} \quad (2)$$

The power conversion efficiency, η, is the most important figure of a solar cell, which is defined as

$$\eta = \frac{P_{MP}}{P_{in}} = \frac{FF V_{OC} I_{SC}}{P_{in}} \quad (3)$$

Where P_{in} is the incident power. [35]

III. Experimental Setup and Sensor Design

A. *Mechanical design*

It was required to move the solar panel to the angle of maximum irradiance that is detected by the insect eye. The implementation of the moving mechanism will allow the solar panel to follow the light. The proposed moving mechanism is a 2 degree of freedom mechanism that can rotate about two axis. The structure implemented satisfying the 2 degrees of freedom requirement for solar tracking is the rotate and tilt mechanism shown by fig 7.

The rotating part holding the tilt motor and the solar panel is made using the 3D printer. Also, the I-shaped part holding the solar panel is made using the 3D printer

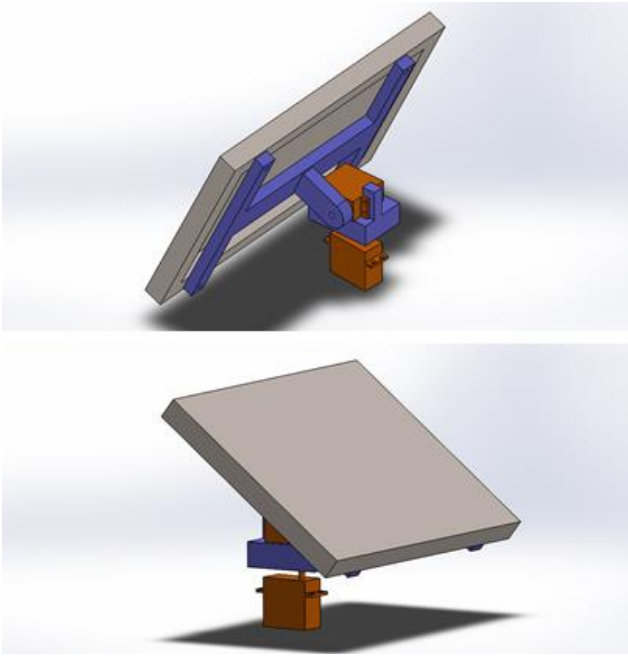

Fig. 7. Rotate and tilt mechanism

B. Multiplexing circuit

This section presents the design of the multiplexer circuit used to rotate on all photodiodes of the eye and read their values.

Eagle is a software used to produce schematics and circuit board designs. This circuit was designed to take in 96 signals or photodiodes in this case and output 3 signals to be read by the Arduino.

To be able to achieve the 96 to 3 multiplexer effect in this circuit, 6 multiplexers of 16 to 1 were used and three 2 to 1 multiplexers. Also, 96 resistors, which were used to make a voltage difference to be measured by the Arduino, were placed in this circuit. The value of these resistors can control the sensitivity of the sensors. The value of each resistor was 1 MΩ. In addition this circuit also had 2 pin headers each with 50 pins. These 100 pins were used to take signals from the sensor where 96 are sensor inputs and the other 4 are output or +5 V supply to the sensors. Also, two 100 nF capacitors were connected to the VCC of each IC.

Another pin header with 10 pins was used as a connection to the Arduino to send the eye readings to the Arduino and receive the control signals from the Arduino. Three output signals to be connected to the analog inputs of the Arduino, 5 control signals as input to the multiplexer circuit to choose the correct bit to output and the remaining 2 are +5 V and GND required to any device.

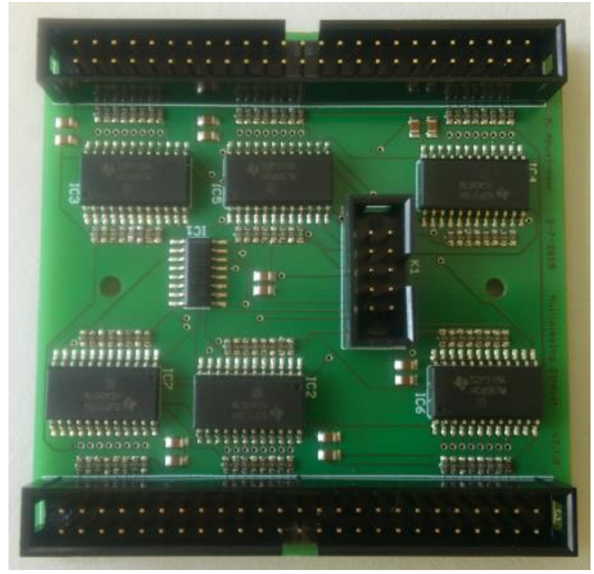

Fig. 8. Multiplexing circuit

C. Hemi spherical eye

Creating a spherical eye was a very challenging task as PCB's cannot normally be bent to take curves in 2 directions even if they are flexible PCB's. But, to produce a hemispherical eye that looks like a normal insect eye, it was required to bend a flat PCB to take the hemispherical shape. The idea began by making several paper stripes that were thin and bend them on a curved surface. From there a flexible circuit was designed using Eagle with the shape shown in fig. 9.

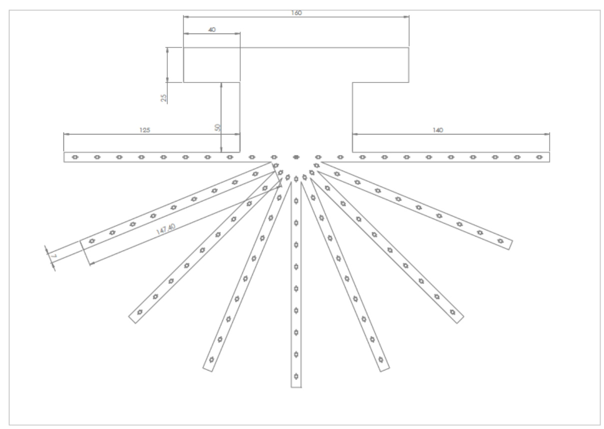

Fig. 9. Sensor stripes to be bent

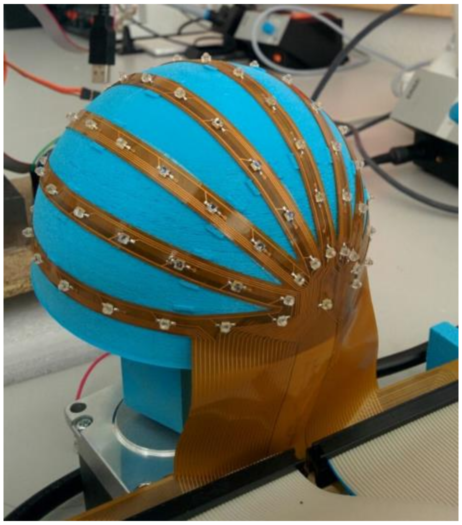

Fig. 10. Final eye

The flexible circuit was attached to a 3D hemispherical eye that has guides for the stripes to have equal distances between the photodiodes and so that they can be distributed all over the hemisphere (fig. 10).

IV. Results and issues

The Arduino Mega 2560 was the brain used in this project. The Arduino was used to interact with the multiplexer circuit to both send the controlling signal also to acquire the image from the sensors and sending the image to the computer to preview it. The Multiplexing circuit used was successful and was able to rotate on all photodiodes and send their values to the Arduino. It takes the 96 sensors and outputs only in 3 signals according to the selection lines. The concept of this circuit can be further used in achieving more pixels in the eye as the Arduino Mega can take up to 5 of these circuits working at the same time as it has 16 analog inputs.

The photodiode’s response to light is noticeable and reliable. The response highly depends on the value of the resistance connected in series with it.

As for the hemispherical eye, several problems were faced during testing that are discussed in the following section. These problems resulted in changing the prototype to a previous prototype that was built for another purpose but can give reliable results as a prove of concept that the eye can be used to detect the maximum point of irradiance.

A. Problems and Issues

In order to connect the multiplexer circuit with the eye, ribbon cables are used. The problem was that the 50 wire ribbon cable is nearly rigid or not flexible enough, so the connection was not robust and not fixed well. Also the pin connectors used in this circuits were large, THT and had sharp edges that affected some tracks in the flexible circuit of the eye. The normal soldering techniques to solder these pads was not robust and was not connected well, so the photodiodes were not connected well to the multiplexer circuit.

After testing the eye for the first time, the diodes were working and the tracks were connected. After some experiments with the eye to be able to map the sensors correctly for visualization, some tracks and some pads were cut and stopped connecting due to the rigidity of the cables and poor soldering, they connected only when pressured by hand but give floating results, so it was very unreliable. One reason for this problem was the long neck of the eye carrying the 2 pin connectors and the other one was the edges of these connectors. Many approaches were used to solve this problem, such as re-soldering and externally connecting the photodiodes using normal wires. However, only the right-outer-pads could be solved, but the inner pads were not very successful. Nearly about 40% of the photodiodes were not connected properly, some gave meaningless values (floating values), others had a very weak response to light and were barely noticeable and some diodes gave large values in no light conditions. Due to this problem, this eye was not useable for either trying to prove the concept of the thesis or integrating it with the mechanical setup to track the sun and of course cannot be compared to commercial sensors.

In the multiplexer circuit, 1 MΩ resistance was used. The photodiode’s sensitivity to light and radiation depends on this value. When the eye was put in direct sunlight, the image given was a white image with no variations which was due to the effect of bad connections and high sensitivity of the photodiodes due to large resistances.

B. Previous prototype results

To be able to have reasonable results and to prove the concept of this thesis, a previous prototype eye was used (fig. 1), which was built for the purpose of tracking the light indoors. The eye is curved circularly in one direction and only slightly curved in the other. So it can only be used to track the sun in one axis, therefore it could not be integrated with the movement of the solar panel too, it would give inconsistent results. Also, it cannot be compared to other commercial sensors.

This eye had resistances of 1.5 MΩ, meaning that the photodiodes were very sensitive to light. To solve this problem a bread board was used and smaller value resistances were used to make it suitable for outdoor experimentation.

The previous prototype eye had a much smaller number of pixels (photodiodes) of 32 pixels, distributed 8 x 4 on the eye’s surface. But, its circuit was handmade so the resistances can be changed, hence the sensitivity could be changed and tested.

The best resistance used to achieve good readings in direct sun light with no clouds was the 5 kΩ which is much smaller than the resistance used in the multiplexer circuit. In cloudy conditions or partially cloudy conditions, a 50 kΩ resistance is used to have good readings. Fig. 11 shows the results on a sunny day while using different resistances each time for the same orientation and position of the sensor in the field. The values used are 50 kΩ, 20 kΩ, 10 kΩ and 5 kΩ, starting from upper left to bottom right.


Fig. 11. Effect of varying resistance during sunny conditions

The Arduino reads analog values ranging from 0 to 255, where 0 means that the photodiode is reading zero light intensity, and 255 means that the photodiode is reading maximum light intensity. White tiles represent the brightest pixels of the value 255 and black tiles represent the darkest pixels of the value 0, all values in between 0 and 255 were represented by the gray scale, the brighter the pixel, the more intensity it reads.

As shown by fig. 11, changing the resistance has a large effect on the sensor’s sensitivity to irradiation coming from direct sunlight. The 50 kΩ was very sensitive during that time and many photodiodes have reached their maximum value, so pin-pointing where the sun is was not successful. Going down to the 20 kΩ and 10 kΩ resistances gave more specific results about the location of maximum irradiation, but still more than one photo diode reached its maximum value.

When the 5 kΩ resistance was used, the maximum point of irradiation has been found out as shown in the bottom right image, and the solar panel was directed manually to that angle.

The values of the solar panel power output was taken in the horizontal position and oriented position given by the eye. The solar panel’s power rating is 5 W.

Solar panel’s power in horizontal position: 3.76 W

Solar panel’s power when oriented according to the eye: 5.16 W

So the sensor was successful in determining the maximum point of irradiance in sunny conditions.

However, in cloudy conditions, the 50 kΩ resistance worked best. Higher resistances than 50 kΩ were too sensitive and gave a white image, lower resistances were very non-sensitive and gave black images. Fig. 12 shows the eye working with 100 kΩ, the eye has only been able to detect that the sun is on its upper right side. Fig. 13 shows the results in cloudy conditions with different orientation of the sensor.

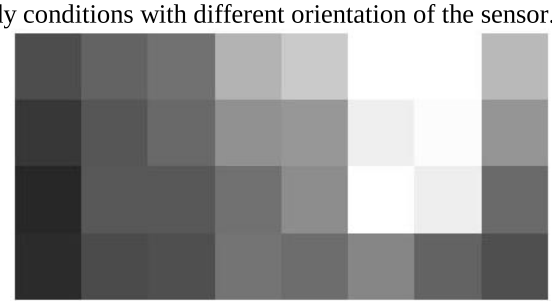
Fig. 12. 100 kΩ resistance results in cloudy conditions

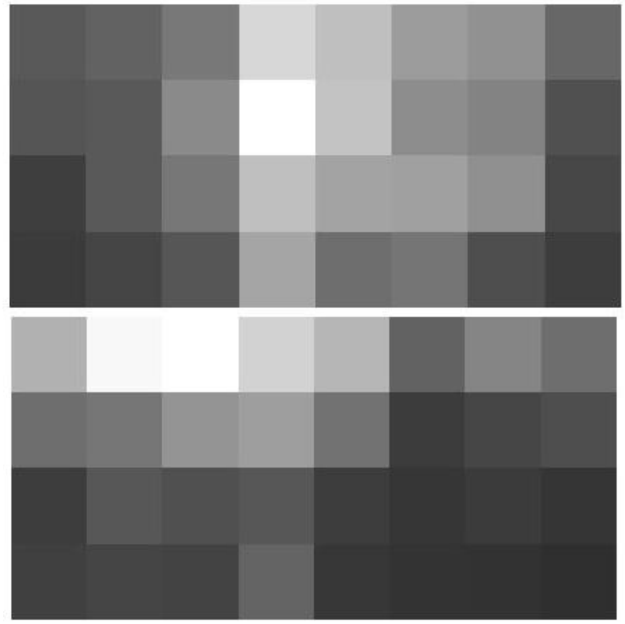
Fig. 13 Cloudy conditions results in different orientations

As shown by fig. 13, the sensor is able to detect the point of maximum irradiation during cloudy conditions. The solar panel’s power output was measured also in both the horizontal position and the oriented position given by the eye.

When the solar panel gave a slightly higher voltage of about only +0.8 V than when it is oriented in the horizontal position.

Solar panel’s power in horizontal position: 1.1186 W

Solar panel’s power when oriented according to the eye: 1.1844 W

The results show an increase of about 6% in the power output. This increase can be significant in large solar power stations and energy production. For example, for a 100 MW power station, assume that the average energy production on a cloudy day is 10000 kWh. An increase of 6% in energy production will give 600 kWh extra, assuming a house consumes 6 kWh/day. This means that the power station can provide energy for 100 more houses on that day.

V. Conclusion and Future Work

A. Conclusion

The Arduino mega was found to be successful in representing the insect’s brain function of receiving signals from the multiplexer circuit that rotates on the photodiodes and combining them to form an image.

Photodiodes have proven their effectiveness in mimicking different properties of the ommatidia. They were successful in detecting the minimal difference in irradiance coming from the sun giving the advantage of detecting the maximum point of radiation using the insect eye sensor even in cloudy conditions. The solar panel’s power output increased by approximately 6% from the horizontal position to the oriented position given by the eye. This increase is significant in large power stations.

B. Future work

1) Variable resistance in multiplexer circuit

A problem faced in this project was the fixed resistance in the multiplexer circuit. The results show that the sensitivity of the photodiodes need to be changed according to the weather conditions. A good field of research would be designing a multiplexer circuit in which the resistance can be varied and controlled to suit the environment outside the eye. This can be seen in the human eye for example, where the pupil enlarges and contracts according to the light intensity in the surrounding environment adapting to it. Using a circuit that imitates this phenomena will achieve tracking in clear and cloudy conditions even when very weak light is present, with the help of a large resistance it can be previewed.

2) Increasing the amount of pixels

In this project a flexible circuit was used to hold the photodiodes. Using the same multiplexer circuit, it is easy to achieve 480 sensors working together or even more. Each Multiplexer circuit uses only 3 analog input pins in the Arduino Mega 2560 which has 16 analog inputs. Using the same ideas, it would be easy to go up to 480 without effort. Increasing the amount of photodiodes gives a higher accuracy in detecting where the maximum irradiance is coming from.

3) Robust connections

In this project THT pin connectors were used in the flexible circuit. The edges of these connectors affected the circuit and cut some routes. One solution could be the use of a rigid-flex circuit, this will eliminate connections between circuits and there will be no need for cables. Rigid-flex circuits may have fixation problems and might be costly. Another solution would be using SMD connectors instead of THT connectors or a built-in connector in the circuit having a shape of a male header at the edges of the flexible circuit or any another type of connection as the connection used in keyboards in laptops.

4) Integration and comparison

This project was successful in forming the steps of manufacturing the sensor and proving the concept of detecting the maximum radiation in cloudy conditions, although some problems aroused, but they could be prevented and improved by further research. The next step in this project is to integrate the sensor with the movement of the solar panel to be able to get accurate results that can be compared with sensors already in the market.

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