FPGA Based Single Chip Controller For Dual-Axis Sun Tracking System

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Abstract

This paper describes the design of an FPGA based controller for dual axis sun tracking. The design is proposing a new approach in sun tracking that can increase the efficiency and reduce the cost and design complexity. The design is location independent, it can track the sun accurately on daily basis without the need for special equipment to determine the position. The controller learns from the collected data and tracks the sun intelligently in such a way it maximizes the overall power gain of the tracking system. The design utilizes one FPGA chip, and four light intensity sensors to keep track of the position of the sun.

1. Introduction

Researchers all over the world are working hard to find efficient methods to extract renewable energy. Solar energy is the most promising renewable energy source, reports suggest that the amount of solar energy we receive from the sun is more than enough to supply the entire world annually [1]. Solar panels made up of photovoltaic cells are used to harvest solar energy, which convert solar energy into electrical energy. The amount of electrical energy extracted from solar panels is mainly affected by the efficiency of the photovoltaic cells and the intensity of sun rays hitting the solar panel. A solar panel need to be perpendicular to the sun rays all over the day to maximize its utilization, hence, sun trackers are used.

1.1 Types of Sun Trackers

Sun trackers can be categorized according to the degree of freedom they allow into single-axis and dual-axis trackers. Single-axis trackers allow the solar panel to track only the daily motion of the sun, from east to west. On the other hand, dual-axis sun trackers allow the solar panel to track both, the daily motion and the seasonal motion of the sun. Furthermore, sun trackers can be classified into closed-loop trackers and open-loop trackers. Closed-loop trackers use feedback signal to track the motion of the sun, while open-loop trackers rely on predetermined algorithm [2-3]. Also, there are hybrid trackers that use a combination of closed-loop tracking and open-loop tracking [4]. An example of open-loop tracking is using trajectory equations and a real time clock to compute the positon of the sun. An example of closed-loop tracking is using light intensity sensors to track the motion of the sun.

Studies showed that closed-loop dual-axes sun trackers are the solution to maximize solar panels' utilization through all seasons [5]

1.2 Industrial Application

Rawabi United Safety Services produces gas detection systems, each gas detection system consists of several gas detection stations. Those stations are usually operating in the middle of the desert, where there are no power lines. A station operating at the middle of the desert is powered by a rechargeable battery, which is charged by a large solar panel. The use of large solar panels increases the cost of each station significantly, and make it hard to move stations from one place to another. Furthermore, during cloudy days, if some of the cells of a solar panel are shaded this will significantly reduce the electricity being generated, or even eliminate it. This is due to the fact that cells of a solar panel are connected as a string (in series), a solar panel could contain one string or more of cells, but small solar panels are usually composed of one string. This issue affects the reliability of the systems noticeably during cloudy days. Therefore there is a need to increase the utilization of solar panels by sun tracking.

1.3 Study Objectives

This paper discusses the design of a low power, possibly self-sustaining solar tracker that have the potential of providing the power gains of continuous tracking systems and the power savings of hybrid tracking systems. Active trackers consume a considerable portion of the extracted energy on tracking the sun, the energy is mostly consumed by the actuators, and secondly by the controller and the sensors. This consumed energy need to be balanced carefully with the power gains of the system to maximize utilization. This work describes the design and potential of a tracking controller on chip and the algorithm it applies to maximize power gains and minimizes power consumption.

2. Design Approach

This design will track the sun using four light sensors mounted on the solar panel and keeping track of the time of the day. The design of the tracking controller will all be implemented on one FPGA chip. Two servo motors will be used to move the solar panel in two axes. Servo motors with analog feedback signal will be used to provide accurate orientation of the solar panel, auto calibration for the orientation of the solar panel and to compensate the effect of the wind or any other mechanical issues.

2.1 Specifications

The table below shows the specification of the hardware that will be used and implemented.

Parameter	Specifications
Tracker Type	Active intelligent dual-axis sun tracker
Tracking Method	Based on light sensors and time.
FPGA Chip	Altera MAX10
Motors	Two closed loop servo motors
Light Sensors Type	Phidgets 1143
Communication Interface	SPI
Operating Temperature	-40°C ~ 85°C

3. Mechanical Design of the Movement System

Figure 1: Mechanical design of the movement system

The main goal of the mechanical design is to provide dual-axis movement to prove the concept of the sun tracking controller. The solar panel used is small, but provides a reasonable performance to allow us to investigate the effectiveness and validity of the idea.

The mechanical design is a dual axis solar panel positioning system that uses two servo motors. The two motors allow the sun tracking controller to rotate the panel along the azimuth and elevation angles of the sun. The mechanical system is mainly composed of a solar panel holder, holder rotator and two servo motors as described below.

3.1 The Solar Panel Holder and its Rotator

The solar panel holder holds the panel using aluminum channels and a hollow aluminum tubing. It allows the panel to move from east to west, i.e. track the azimuth angle of the sun. On the other hand the holder rotator rotates the holder and the solar panel all together using a gear connecting the leg of the holder and a servo motor. It allows the panel to rotate to face north or south, i.e. track the elevation angle of the sun.

3.2 Servo Motors

An efficient sun tracking system needs precise positioning of the solar panel and low power consumption actuators. Servo motors provide the needed positional accuracy, efficiency and low power consumption. Servo motors are high performance alternatives to stepper motors [7], and low cost alternatives for linear actuators.

4. Design of the Sun Tracking Controller

4.1 Design Architecture of the Sun Tracking Controller

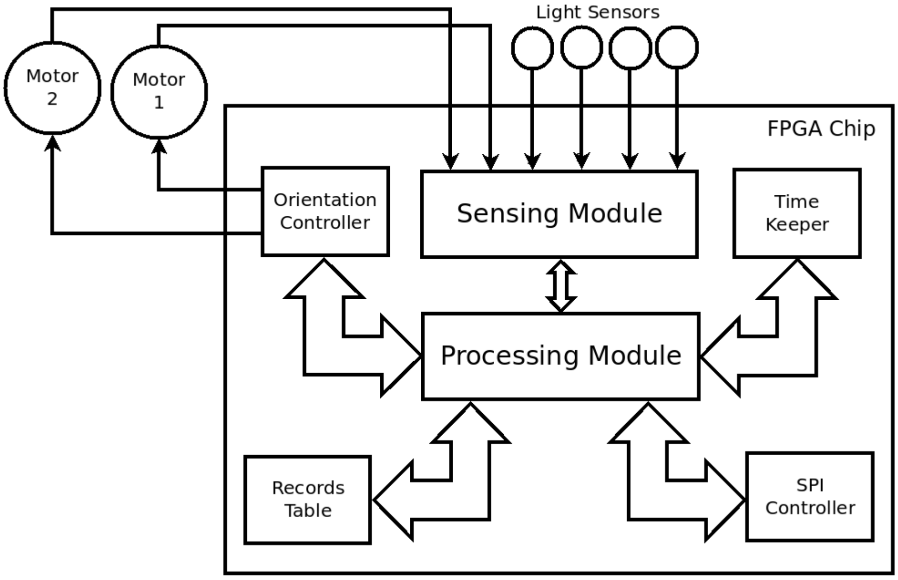


Figure 2: Design architecture of the sun tracking controller

Figure 1 shows the general architecture of the sun tracking controller. As depicted in figure 1, the design of the sun tracking controller can be divide into 6 main modules all to be implemented on one FPGA chip:

1. Sensing Module

   Provides six analog channels to measure the output of four light sensors and two feedback motor signals.

2. Orientation Controller Module

   Controls the movement of the motors and keeps track of the orientation of the solar panel.

3. Time Keeper Module

   Keeps track of the time of the day.

4. Records Table Module

   Will be used by the processing module to store the optimum position of the solar panel for several periods of the day.

5. Processing Module

   - Will process the readings from the light sensors to determine whether it is day time or night time and will send the result to the time keeper.
   - Will process the feedback signals from the motors.
   - Will process the information provided by the time keeper.
   - Will record tracking data in the records table module, and will process this collected data when taking decisions.
   - Will take the decisions to move the solar panel based on the results of the processed data.
   - Will communicate with external systems through the SPI controller to provide live readings of registers and manual control of the position of the solar panel by an external system.

6. SPI Controller Module

   Will be responsible for delivering messages between the processing module and an external system through an SPI bus.

4.2 The Processing Module

4.3 The Time Keeper

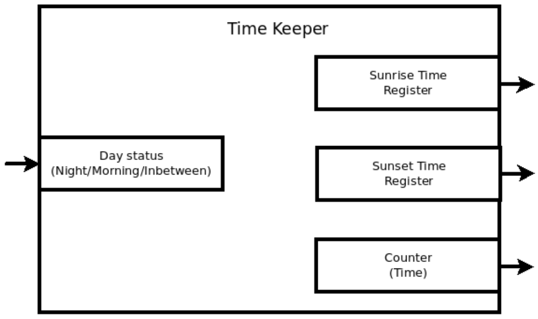


Figure 3: Time Keeper's inputs and outputs

The time keeper will keep track of the time in a fuzzy way, and will provide three registers to be used by the processing module, as figure 4 shows: Sunrise Time Register, Sunset Time Register, and Counter or Time Register. The value stored in the Sunrise Time Register represents the sunrise time of the current day and the expected sunrise time for the following day, with respect to the clock of the time keeper. In the same manner, the value stored in the Sunset Time Register represents the sunset time of the current day and the expected sunset time for the following day, with respect to the clock of the time keeper. On the other hand, the counter register contains the time of day with respect to the clock of the time keeper, it stores the hours and minutes. The time keeper uses the 'day status' signal (night, morning, or in-between) reported by the processing module in the Day Status register, to apply the algorithm that keeps track of the time and determines the sunrise time and the sunset time.

The flowchart below describes the algorithm that will be applied by the time keeper to keep track of time. As the flowchart depicts, the time keeper will calibrate (resets) itself every day at sunrise.

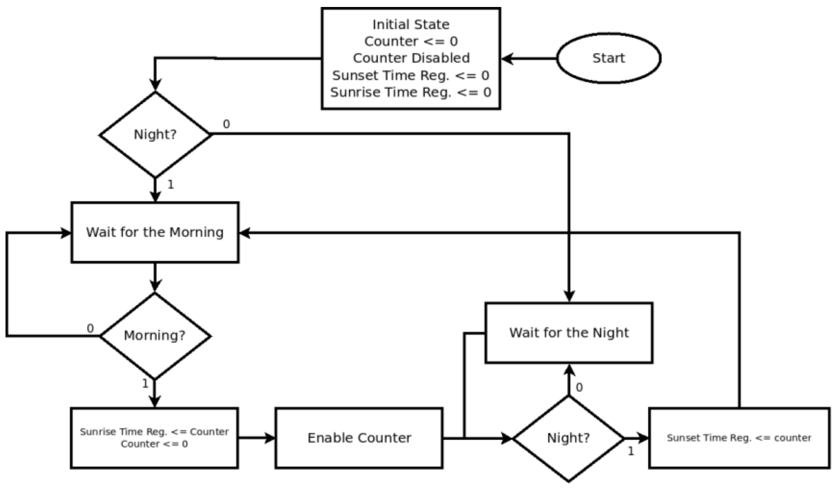


Figure 4: Time keeper's algorithm

4.4 The Sensing Module

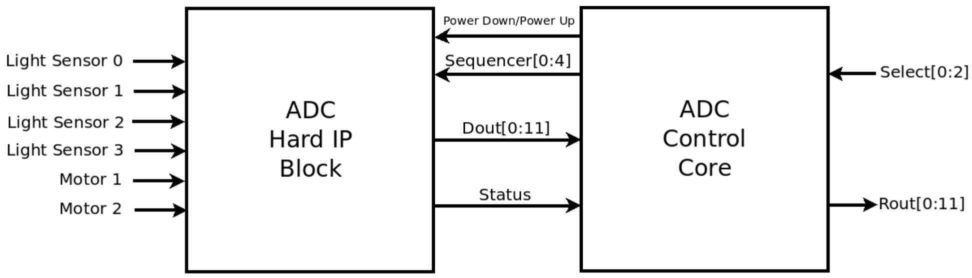


Figure 5: Organization of the sensing module

The sensing module will be used to interface the light sensors and read the feedback signals from the motors. This module is composed of two main components, the ADC hard IP block, and an ADC control core. The ADC hard IP block is a hard part of the MAX 10 FPGA chip that contains the ADC circuit and will get the readings from the analog devices. The ADC control core is a soft block that will be designed and implemented, it will control the operation of the ADC and will act as an abstraction layer between the processing module and the ADC.

4.5 The Orientation Controller

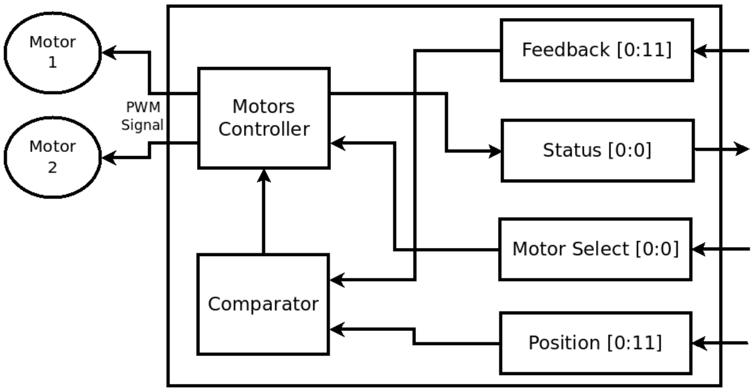


Figure 6: Organization of the orientation controller

The orientation controller is composed of the following main sub components:

a. Motors controller: will generate a pulse width modulation (PWD) signal to drive the selected motor, and will output the Status signal to indicate whether it is busy driving a motor or not.
b. Comparator: will compare the position feedback signal from the selected motor with the required position by the processing module, and based on that comparison will generate a signal to the motors controller to specify the direction of the movement.

4.6 The SPI Controller

The SPI controller will apply the following algorithm to handle the communications between the processing module and the external system through the SPI bus:

- If request is received
- The SPI controller processes the request
- If valid request,
    - If write request
        - The SPI controller sends a register address to the processing module.
        - The SPI controller puts the data on the data bus.

- the SPI controller sends an interrupt signal with a write request to the processing module

A read request will be handled in a similar way.

4.7 Records Table

Hour	Minute	Position X	Position Y	LE	LW	LN	LS
1	00	106	154	2.0	2.0	2.0	2.0
1	15	110	160	2.2	2.2	2.2	2.2
1	30	115	160	2.5	2.5	2.5	2.5
….	….	….	…	…	…	…	…

Figure 7: Records table organization

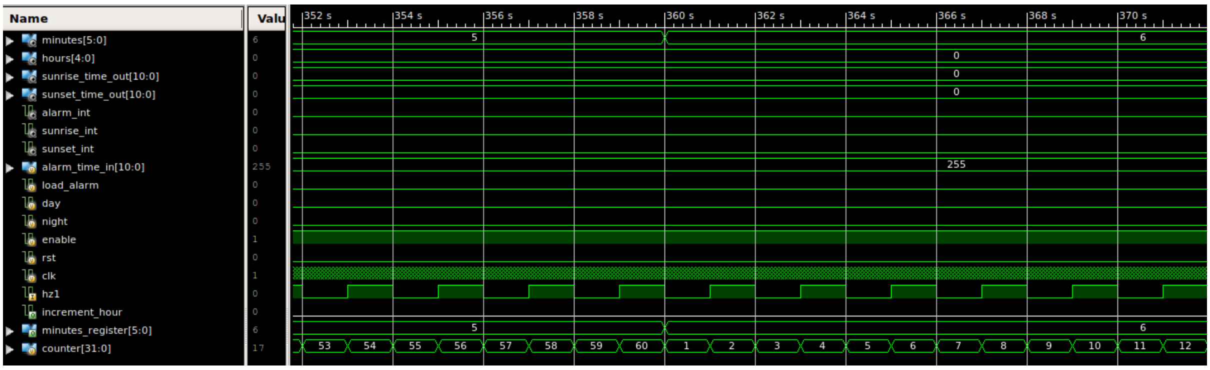
This module will store a table containing the time with respect to the sun tracking controller clock, and the corresponding optimum position for the solar panel and the light intensity readings. The processing module will access a record by passing an address to the records table module through the address register, and reading/writing the content through the data bus.

The records table is stored on the user flash memory (UFM) embedded inside the Altera MAX10. The UFM is composed of 16 pages, each is 16kb.

5. Modules Simulation and Testing

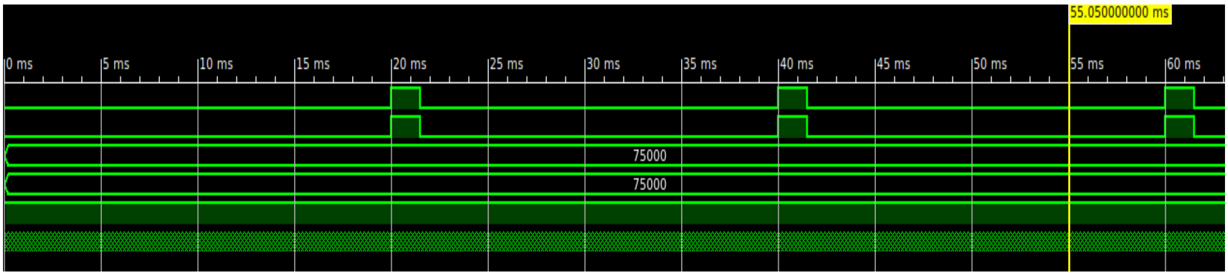
Two modules mainly determine the accuracy of the system, the time keeper and the orientation controller. The time keeper determiners the accuracy of the timings of the operations of the system, hence, any small error here will render the whole implementation incorrect. Also, the orientation controller determines the actual position of the solar panel, mapping incorrect position values into wrong actual positions will kill the purpose of the system. Therefore, those two modules will be simulated to verify their function and accuracy.

5.1 Time Keeper Simulation and Testing

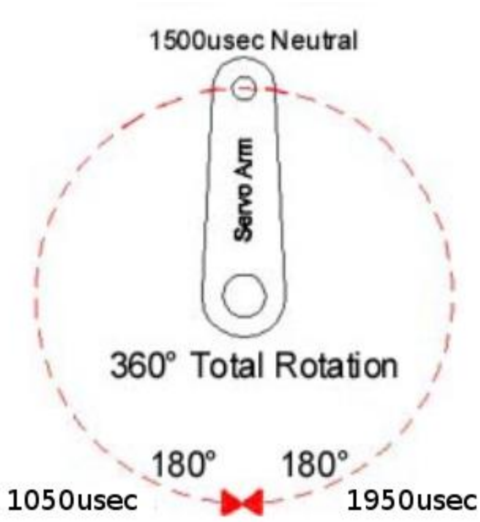


5.2 Orientation Controller Simulation and Testing

The orientation controller receives the required position for the two motors as a value between, where 52500 corresponds to -180 degrees (1.05 ms) and 97500 corresponds to 180 degrees (1.95 ms). The servo motor receives position commands as PWM signal, where a pulse with a specific length need to be sent every 20 ms to keep the motor at the desired position. The length of pulse sent determines the position of the motor.



The simulation shows that module is a able to send a pulse every 20 ms. In the graph, the module is receiving a position value of 7500, which corresponds to the neutral position (the middle) of any servo motor, which requires a pulse of length 1.5 ms.



6. The Tracking Algorithm

6.1 General concept

This tracking algorithm emphasizes collecting data and learning from the environment to maximize the power gain and minimize power consumption. The general concept of the tracking algorithm is that the controller will start its operation by investigating its environment using the light sensors and collecting data, as time passes the controller will start learning from the collected data to estimate the optimum tracking path to maximize the power gain. As it goes through the optimum path, the controller will record the measurements from the light sensors and the corresponding position and time. The following days the tracking algorithm will track the sun based on computations done on the records from the previous days. Getting high readings from the light sensors reflect that the system is absorbing high energy, however, moving the motors is the most power consuming part. Therefore the algorithm will avoid any unnecessary movement, i.e. when the movement during a specific period will cost more power than what the system is gaining.

6.2 Detailed Mechanism

The sun tracking algorithm starts its operation during the first day by collecting data from its environment. The controller will look for the optimum position to absorb energy every preconfigured time period, and will store this optimum position and the corresponding light measurements into the records table.

The next day the controller will start by copying the data for the previous day to the fields of the new day. The controller will process the copied data and detect weak points, where the power gain is lower than expected. A weak point is a point where the power gained is lower than the power gained between two adjacent points. Let's consider a weak point B between points A and C as shown in the figure below.

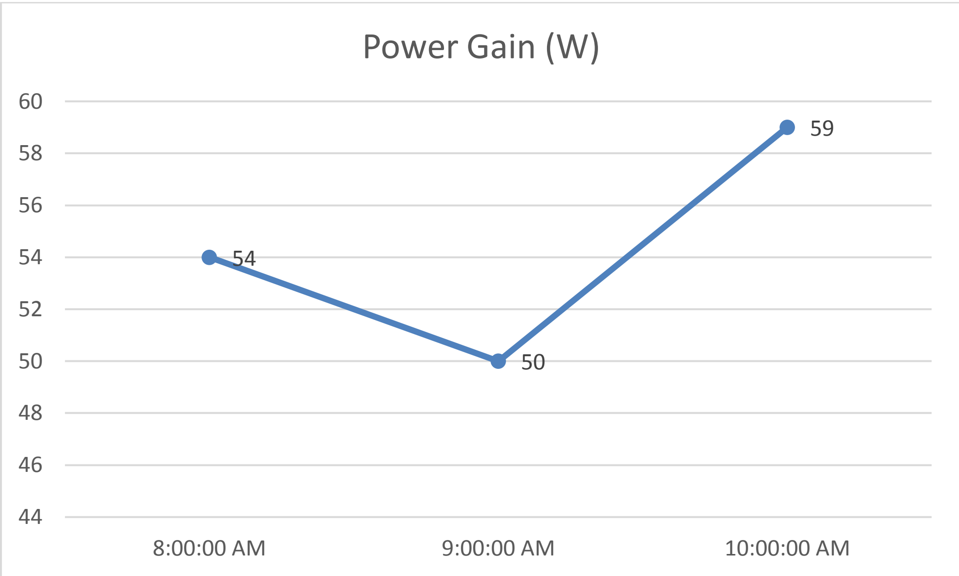


Figure 8: An example of a weak point

The controller computes the power gain difference between A and B, and between B and C. Based on the two differences the controller will decide in which point, A or B, the solar panel should be positioned during that period to maximize the power gain. From the figure we can see the controller should ignore point B, and instead, spends more time at point C. The controller will replace the point B with two new points that can give a higher power gain as show in the figure below.

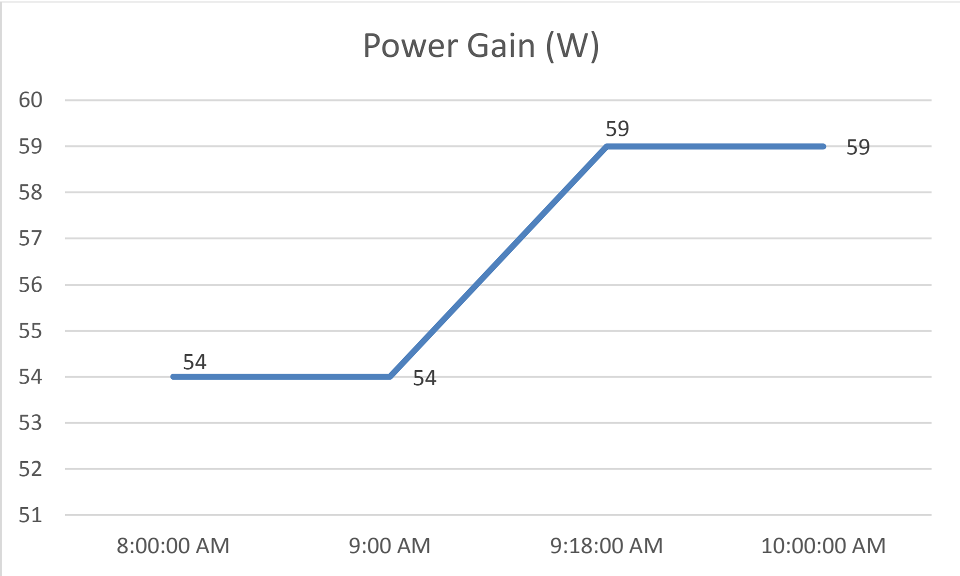


Figure 9: Adjusted weak point to improve the power gain

The two new points can be computed as follows:

$$\boldsymbol{A - B = 54 - 50 = 4}$$
$$\boldsymbol{C - B = 59 - 50 = 9}$$

$$\rightarrow \boldsymbol{The\ solar\ panel\ should\ stay\ at\ A}: \left(\frac{\mathbf{4}}{\mathbf{13}}\right) * \mathbf{100}$$
$$= \mathbf{30.77\%}\ \boldsymbol{of\ the\ time\ of\ period\ B, this\ is\ the\ first\ point}$$
$$\rightarrow \boldsymbol{The\ solar\ panel\ should\ stay\ at\ C}: \left(\frac{\mathbf{9}}{\mathbf{13}}\right) * \mathbf{100}$$
$$= \mathbf{69.23\%}\ \boldsymbol{of\ the\ time\ of\ period\ B, this\ is\ the\ second\ point}$$

6.3 Detecting and Computing the Position of the Sun

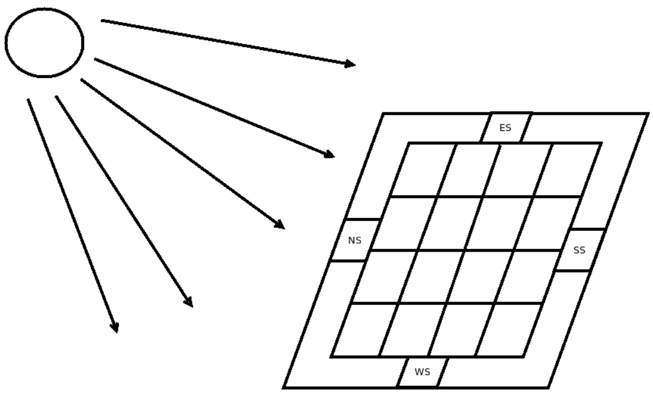


Figure 10: The organization of the light sensors on the solar panel

The sun tracking controller uses the four light sensors, the east sensor (ES), the west sensors (WS), the north sensor (NS) and the south sensor (SS), mounted on the solar panel to locate the position of the sun. The controller receives the readings from the light sensors through the sensing module, the processing module processes the readings and computes the position of the sun based on the differences between the readings. The controller rotates the solar panel toward the computed position of the sun until the difference between the readings from ES and WS is zero, and the difference between the readings from NS and SS is zero.

6.4 Adjusting records

The controller while following processed data will compare the stored light readings against the actual current readings from the sensors. If the stored readings are above the actual readings by a threshold value, the controller will detect that this is no longer the optimum position for this period of the day. Therefore the controller will compute the optimum position based on the readings from the light sensors and will move the solar to that optimum position. Also, the controller will update the record for that period with the new optimum position and the new light readings.

7. Simulation

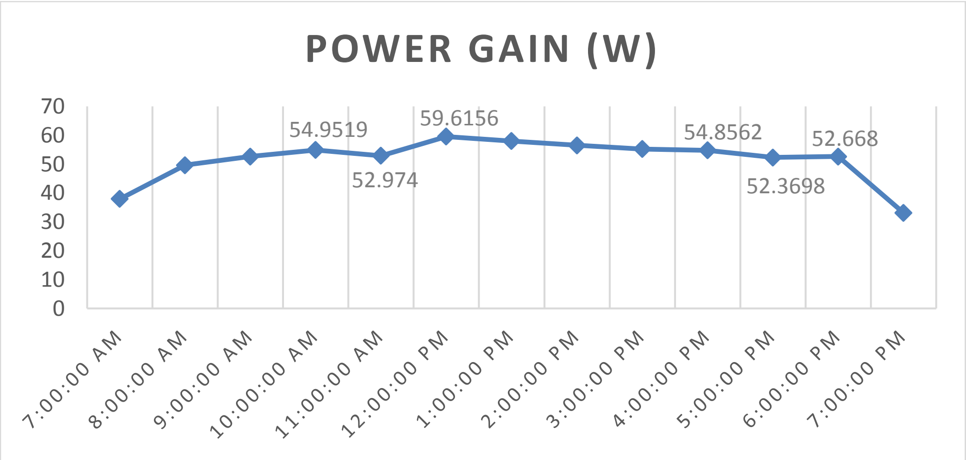
7.1 Simulation Method

In this simulation a random sample from a research paper for a dual-axis tracker will be used to apply the weak point suppression feature of the algorithm. The table below represents the results of simulating a dual-axis tracker that is not applying the algorithm applied in this paper [6]. The power gain presented in the table is not taking into account the power consumption of the motors.

Time	Power Gain (W)
7:00:00 AM	38
8:00:00 AM	49.728
9:00:00 AM	52.701
10:00:00 AM	54.9519
11:00:00 AM	52.974
12:00:00 PM	59.6156

1:00:00 PM	58.0488
2:00:00 PM	56.5687
3:00:00 PM	55.3151
4:00:00 PM	54.8562
5:00:00 PM	52.3698
6:00:00 PM	52.668
7:00:00 PM	33.22
Average Power	51.6167

Figure 11: Simulation Result for Dual Axis Tracker System [6]

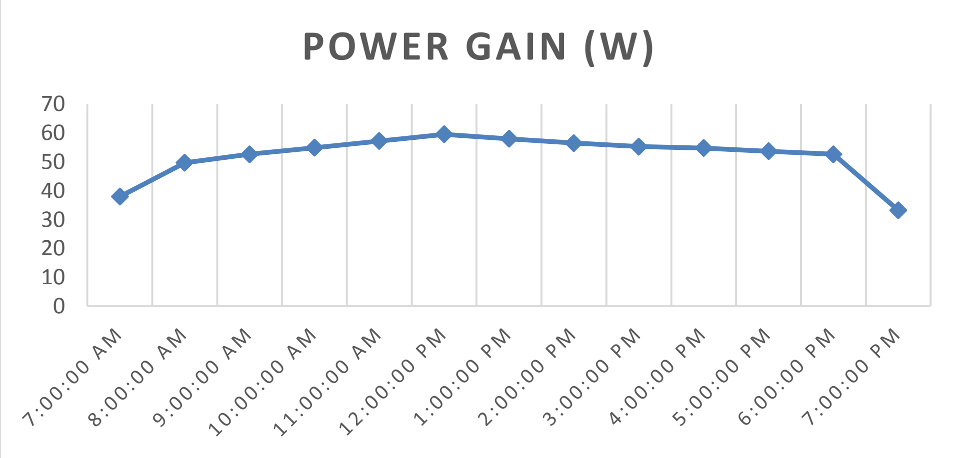


7.2 Simulation Results

The table below shows the results of the simulation when we apply the weak point suppression feature of the algorithm presented in this paper. The results show 0.85% improvement.

Time	Power Gain (W)
7:00:00 AM	38
8:00:00 AM	49.728
9:00:00 AM	52.701
10:00:00 AM	54.9519
11:00:00 AM	57.284
12:00:00 PM	59.6156
1:00:00 PM	58.0488
2:00:00 PM	56.5687
3:00:00 PM	55.3151
4:00:00 PM	54.8562
5:00:00 PM	53.7621
6:00:00 PM	52.668
7:00:00 PM	33.22
Average Power Gain	52.05533846

Figure 12: Simulation result for dual axis tracker system with the weak point suppression feature



7.3 Discussion

The results above show that the algorithm is capable of increasing the power gain for any dual-axis tracking system. Especially when the position adjustment period is short, where the movement will be more frequent which result in more power consumption, but also higher power gain. Therefore, the algorithm shows potential to achieve power gain comparable to the power gain produced by a continuous sun tracker, and it also power savings comparable to the ones of a conventional hybrid sun tracker.

8. Future Work

The design of the controller and the algorithm will be implemented on the FPGA chip and will be tested on real environment with different lengths of adjustment periods to verify the potential of the design.

Conclusions and Recommendations

The paper presented a simple design of a low-power, low cost and self-sustaining sun tracking controller with the potential to surpass the performance of both, hybrid sun trackers and continues sun trackers. The single chip solution presented is an attractive option for small embedded applications that require solar power, and for large scale power generation projects.

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