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Position Control of Solar Panel Receiver by Joint Generated Power and Received Signal Power Maximization

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ABSTRACT

The use of solar cells as photodetectors in Optical Wireless Communications (OWC) systems, is acquiring an increasing attention. This is due to the fact that a solar cell can detect an incident optical signal without the need to be biased by an external dc source, unlike traditional photodetectors. Basically, solar cells are designed to be used in solar energy harvesting systems. However, the solar cells are used during the day time and they remain idle at night. Then, they can be used in other applications, such as optical signal detection during night hours. Moreover, the efficiency of solar systems and solar receivers can be maximized by using dual axis light source tracking, to keep the cell orientation at the direction that results in the maximum electrical output. Therefore, in this paper, a solar cell positioning algorithm is proposed to track the maximum power point of both of the sun at day time and the optical communication signal at night. The proposed system can automatically distinguish between its two operation modes and then provides the necessary control. The proposed system is implemented and tested under realistic outdoor environment. It showed an accurate detection of the operation situation and also an accurate and smooth positioning during the specific operation mode. The measurement of the generated and consumed power by the designed system has emphasized it feasibility.

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السيطرة على توجيه لوح شمسي كمستقبل لتعظيم الطاقة المتولدة وقدرة الاشارة المستلمة معاً

الخلاصة

ان استخدام الخلايا الشمسية ككاشف ضوئي في انظمة الاتصالات اللاسلكية الضوئية اكتسب اهمية متزايدة. هذا بسبب الحقيقة بان الخلية الشمسية يمكن ان تكشف الاشارة الضوئية الساقطة عليها بدون الحاجة الى ان تتحيز من مصدر قدرة مستمر خارجي، على عكس الكاشفات الضوئية التقليدية. اساساً، الخلايا الشمسية صممت لاستخدامها في انظمة تجميع الطاقة الشمسية. حيث ان الخلايا الشمسية تستعمل في النهار اما في الليل فتكون غير مستخدمة. لذلك يمكن استعمال الخلايا الشمسية في ساعات الليل في تطبيقات اخرى، مثل كشف الاشارات الضوئية. علاوة على ذلك، فانه يمكن رفع كفاءة المنظومات الشمسية والمستقبلات الشمسية باستعمال تتبع الضوء ثنائي المحور، لإبقاء توجيه الخلية الشمسية في الاتجاه الذي يؤدي الى ان يكون الخرج الكهربائي من الخلية أكبر ما يمكن. لذلك في هذا البحث، تم اقتراح خوارزمية لتحديد موقع الخلية الشمسية لتعقب أعظم نقطة قدرة كهربائية متولدة من الشمس في النهار ومن اشارة الاتصال الضوئي في الليل. ويمكن للنظام المقترح ان يميز اوتوماتيكيا بين انماط عمليتي التشغيل ومن ثم يقوم بعملية السيطرة الضرورية. تم تنفيذ واختبار النظام المقترح في بيئة خارجية واقعية. تبين ان النظام دقيق في كشف الاشارات الضوئية وتحديد الموقع خلال نمط العملية المحددة. قياسات الطاقة المتولدة والمستهلكة للنظام المصمم اكدت جدوى استخدامه.

1. INTRODUCTION

The advantage of using solar panels as receivers in optical wireless communication systems is that they can convert modulated light signals to electrical signals without any external power requirements. Therefore, they can have used instead of photodiodes (PDs) which need external power to operate. In addition, the use of solar cells simplifies the receiver circuitry by removing the need for a trans impedance amplifier [1].

In 1954, at Bell Laboratories, the modern solar cell

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was invented [2,3], and since then three generations were developed. The conversion efficiency of signal-crystalline and multi-crystalline silicon solar panels is more than 20% and they are currently dominant in the market [2,4]. When using thin film solar cells, the cost can be reduced compared to crystalline silicon panels, but the conversion efficiency falls down to approximately 10% [5]. The conversion efficiency of the current generation of solar panels is up to 40% at a cost comparable to thin-film technology [5-8].

The problem of radio frequency interference and spectrum allocation is getting more difficult as the number of users and service requirements are increasing. A recently developed attractive alternative is the visible light communication (VLC) which is reported to be a promising solution [9]. VLC is safe and does not interfere with the existing wireless communication systems. It offers a wide bandwidth and hence a high speed wireless data communications [10].

A curate orientation of the solar cell towards the source of light can maximize the amount of received light and hence the generated electrical power [11]. Smart microcontroller based sun tracking systems have been successfully used to track the sun light and keep the solar cell in line with the sun for all the day time [12].

In this paper, a solar panel is used in an outdoor environment with positioning control algorithm to operate in two different modes, as follows:

- At day time, it works as a solar energy harvesting system.
- At night, it works as a receiver of optical data signal.

Therefore, an automatic dual axis microcontroller based solar panel positioner is designed and implemented to accurately orient the solar panel towards the sun at day time and towards the communication laser beam at night. This paper consists of seven sections, section two is (Literature Review), section three is (System Model), it describes the proposed system, section four is (Hardware Implementation), it consists of two parts: Solar Cell Positioner and Solar Cell Receiver, Section five is (Software Control Algorithm), it describes the required control algorithm through the flowchart, section six is (Experimental Results), it shows the tested results of the proposed system, section seven is (Conclusion).

2. LITERATURE REVIEW

Kim and Won [13] they proposed a technique to use a solar cell to generate electrical power and receive visible light signal without a photodiode receiver and power supplies. They research the normal for a solar cell and exhibit that a solar cell can receive low-frequency VLC signals and optical energy from daylight simultaneously, and furthermore examine the effect of daylight obstruction on the VLC performance. The cost to implementation the proposed system is low and the transmission distance between the LED light and the solar cell, is 40 cm. The solar cell cannot be tracking the sun and VLC signal.

Chen et al. [14] they presented the use of solar cell as optical receiver for VLC without a photodiode receiver and power supplies. They also proposed using pre-distortion to significantly upgrade the response of the solar cell receiver. A VLC capacity of 0.4 Mbit/s at bit-error-rate (BER) of 10-9 under wireless transmission distance of 75 cm; and a capacity of 0.3 Mbit/s at BER of 10-9 under wireless transmission distance of 125 cm can be accomplished and the cost to implementation the proposed system is low.

Hsu et al. [15] they proposed and experimentally tested an indoor positioning system which consolidates source identity positioning and radio frequency carrier allocation technique in order to reduce the signal interference from close-by light-emitting diodes (LEDs) and enhance the exactness of positioning. Furthermore, the solar cell is utilized as an optical receiver for the obvious light positioning system. Because of the advantages of solar cells, for example, low-cost, high light sensitivity, and ease in integration with wearable devices, the proposed system could be an energy-efficient and environmentally friendly choice for indoor positioning later on.

Malik and Zhang [16] they propose a Signal Conditioning Unit in solar panel-based VLC receiver to regular the input signal which was deformed from output of solar panel. A solar panel acts as photodetector and also powers the receiver circuit by converting the light signal into electronic signal. The frequency response of solar panel is 50 kHz after conditioning. The results show that a data rate of 8kbit/s is achieved at a transmission distance of 50 cm.

Wang et al. [17] they experimentally studied the feasibility of optical wireless communication (OWC) systems with a solar panel as a photo-detector. The frequency response of a solar panel shows that its 3-dB modulation bandwidth is 350 kHz. The results show that for a 1-Mbit/s on-off keying signal, a bit error rate of less than 2×10^{-3} could be achieved when the average irradiance on the solar panel is 3.5×10^{-4} W/cm^2. This corresponds to a transmission distance of 39 cm.

3. SYSTEM MODEL

Generally, the model of the proposed system consists of a solar cell, dual-axis positioner, programmable microcontroller, a receiver, and light sensors, as shown in Fig. 1. The system works in two different situations. At day time, the solar cell must be directed towards the sun to harvest the maximum possible energy and charging the battery. At night, the system is also active. It orients the solar cell towards a photo beam emitted from an optical data transmitter to receive data. The system distinguishes between these two different operation situations through a simple light driven resistance (LDR) light sensor connected to the microcontroller Atmega 328. According to this signal, the controller switches the connection of the solar cell output to the battery, at day time, or to the data receiver, at night.

However, in both of these operation modes, the solar cell has to be correctly positioned to maximize the signal at its output. This is the role of the dual-axis solar cell positioner. It consists of an arrangement of four LDR sensors mounted vertically to the plane of the solar cell and two servomotors for the azimuth (horizontal) and elevation (vertical) movement.

At day time, the positioner works as a dual-axis sun tracker. It determines the position of the sun by calculating the difference between the outputs of the four LDRs. Then, according to a pre-stored software algorithm, the microcontroller determines the required amount of horizontal and vertical movements to direct the front of the solar cell to the maximum power point (MPP). The microcontroller implements these m5ovements by driving the servomotors. This mode of operation continues as long as the Day/Night sensor is sensing sun light. But, once this sensor detects a sun set, the role of the positioner changes. It has to position the solar cell towards the beam of optical data.

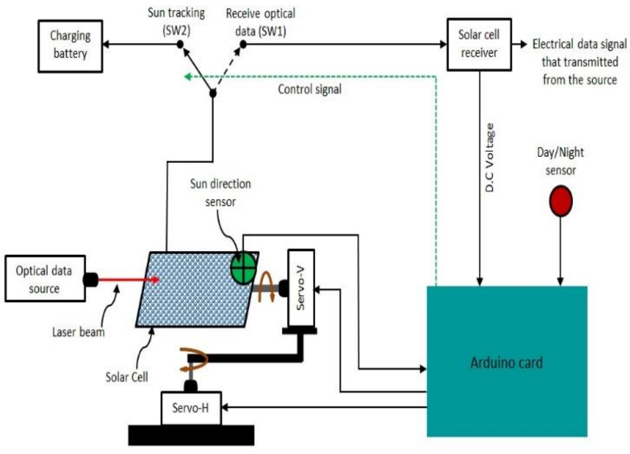


Fig. 1. Proposed solar energy harvester/ optical data receiver.

Without loss of generality, it can be assumed that the position of the optical data source (transmitter) is fixed and initially known to the solar cell receiver. In this case, the positioner can roughly direct the solar cell by resetting the horizontal and vertical servomotors to an origin and then moves them to that known position. Practically, this cannot always guarantee an accurate positioning of the solar cell due to many reasons including the possible losses in the mechanical coupling of the moving parts of the system. Therefore, the role of the designed signal strength detection circuit, described in Section (Hardware Implementation), comes to find the actual direction of the data optical beam and let the microcontroller update the solar cell position to be more accurate.

4. HARDWARE IMPLEMENTATION

4.1. Solar Cell Positioner

The popular open-source Atmega 328 microcontroller within the Arduino Uno development board is used in this system. It is programed by the code of the positioning algorithm, presented in Section (Software Control Algorithm), to read input signals from the sensors and outputs accordingly suitable commands to the servomotors and the battery/receiver switches. The day/night and the four light direction sensors are all implemented by LDRs connected to the microcontroller as shown in Fig. 2.

A two solar cell of the type CP108X39 that generates a maximum DC voltage of 6V, 50 mA are used in the implemented model. It is mounted on the shaft of the elevation servomotor (Servo-V), which is already mounted over the shaft of the azimuth servomotor (Servo-H). These motors are of the type Tower Pro micro servo 9g. They are connected to the microcontroller as shown in Fig. 3. Moreover, according to the day/night sensor, the microcontroller controls two electronic switches to connect the output of the solar cell either to the battery or to the receiver. The 4066 quad-switch is used, and it is connected as shown in Fig. 4.

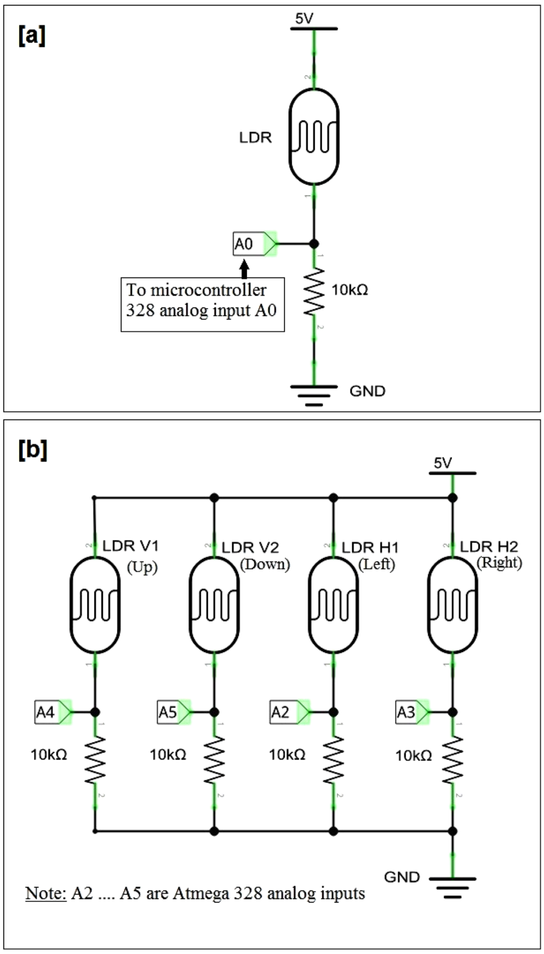


Fig. 2. (a) Day/Night sensor, and (b) Light direction sensor.

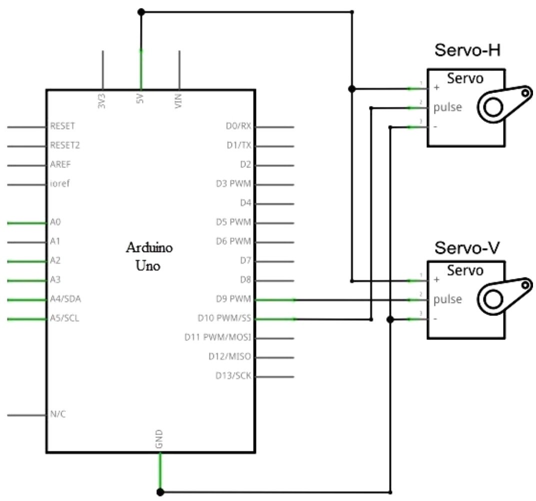
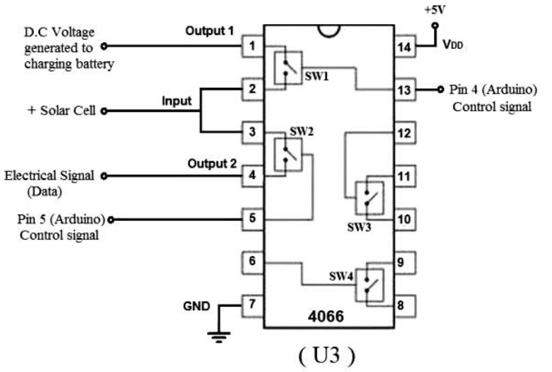


Fig. 3. Servomotor connection.

4.2. Solar Cell Receiver

The signal emitted by the optical data source (transmitter) is implemented as a laser beam modulated by a square wave representing the binary data message, in an ON/OFF keying manner. The proposed solar cell receiver consists of three main blocks, namely, signal amplifier, signal strength detector and data signal sharpener, as shown in Fig. 5. The detailed schematic diagram of the designed solar receiver is shown in Fig. 6.

The signal amplifier is implemented by an inverting amplifier using the LM741 operational amplifier. It provides a voltage amplification gain of 100 times to the output of the solar cell. When the system works at night as a receiver, the pulsive laser light beam incident on the solar cell will cause a noisy and weak (Vpeak ≐ 100 mW) pulsive electrical signal at its output. The amplified signal is still noisy and the transitions between the binary levels of the message signal are not sharp. Therefore, an inverting zero-crossing LM 741 based comparator is used to produce a clear replica of the original binary data message.



Control Signal from Arduino		U3 (4066)		Mode
Pin 4	Pin 5	SW1	SW2	
0	0	OFF	OFF	No mode
0	1	OFF	ON	Received optical data
1	0	ON	OFF	Sun tracking
1	1	Not used		

Fig. 4. The 4066 battery/ receiver switch connection.

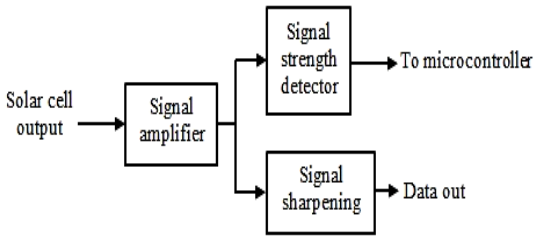


Fig. 5. Proposed solar receiver diagram.

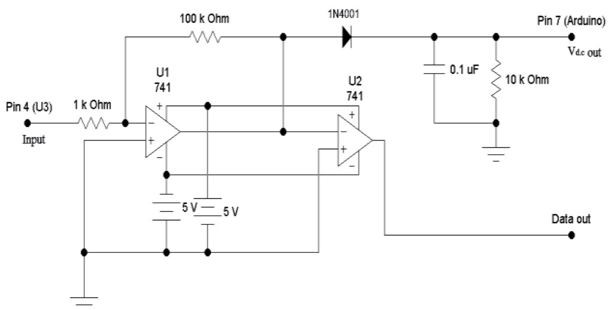


Fig. 6. Proposed solar receiver circuit diagram.

However, the whole operation of the designed solar receiver is governed by the availability of a strong enough received signal. This task is implemented by a simple envelop detector whose output is conditioned and fed to the microcontroller to let it monitor the received signal strength. This signal can then be used to control the connection of the recovered data output to the destination device. The actual implemented system is shown in Fig. 7.

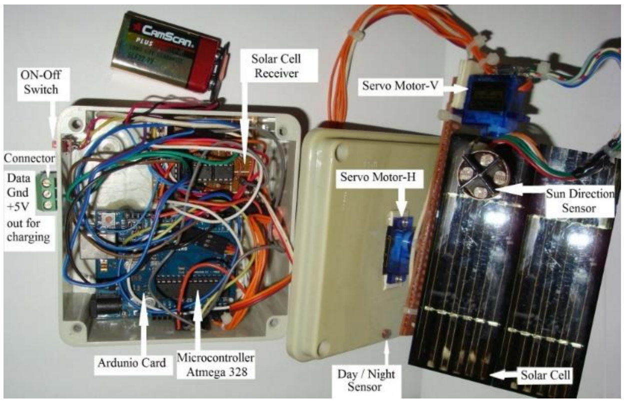


Fig. 7. Implemented solar energy harvesting/optical data receiver.

5. SOFTWARE CONTROL ALGORITHM

The microcontroller is the control part in the designed system. It has to be initially programed by a software to implement the required control algorithm. The detailed flowchart of the proposed system is given in Fig. 8.

Basically, the algorithm starts with the required initializations including the determination of the functions of each used hardware pin and the proper definition of software variables. The dynamic operation mode of the system starts by reading the day/night sensor, according to which the execution control is branched between the energy harvesting mode or optical data receiving mode. For the former case, the switches SW1 and SW2 are controlled to disconnect signal receiver and connect the output of the solar cell to the battery.

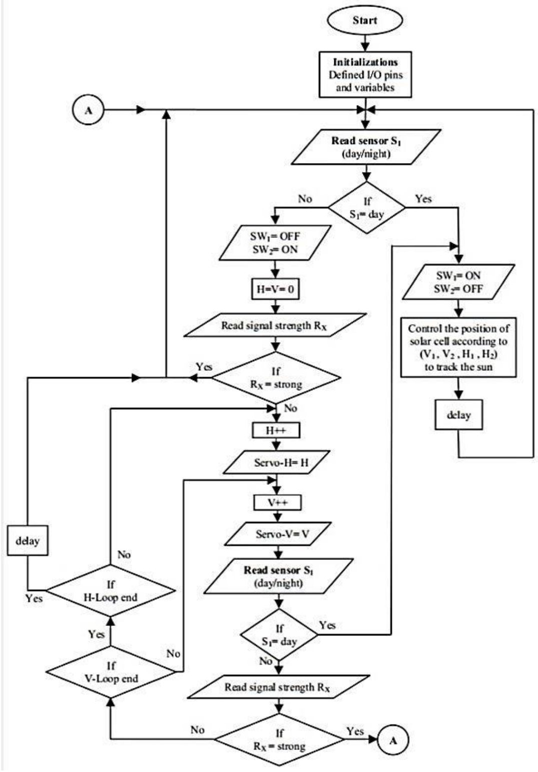


Fig. 8. Software control algorithm.

Then, a usual dual-axis sun tracking algorithm is performed, as described in Section (System Model). However, between each two cycles of updating the position of the solar cell, the day/night sensor is examined. Once this sensor changes status, the execution will switch to the mode of signal receiving. At this mode SW1 and SW2 are switched to disconnect the battery and connect the solar cell output to the signal receiver. Then, the microcontroller reads (measures) the strength of the received signal. If it is greater than a predefined threshold, then it is strong enough and the process of signal receiving continues. Otherwise a light beam tracking algorithm is started to correct the orientation of the solar cell, depending on measuring received signal strength. When an acceptable level of received signal is detected, the tracking system locks on the incoming laser light beam.

Any possible drift in the direction of the laser beam can be compensated for by the tracking algorithm. In this mode the day/night sensor is also periodically monitored. Such that when the night time ends and the sun rises, the system is switched to energy harvesting mode automatically.

6. EXPERIMENTAL RESULTS

The implemented system is tested in an outdoor environment. At day time, it showed a smooth movement and accurate tracking to the sun, and generated an electrical output near its maximum limit. However, the amount of the generated electrical energy depends on many parameters including the type and dimensions of the solar cell (panel), weather conditions, the season, the position on earth with respect to the equator, …etc. The accuracy of the tracker in finding the MPP is a dominant parameter. It can maximize the generated output energy at a given operation situation. Then, the output can be used to charge a battery or supply a connected load. On the other hand, the electronic and electric components of the system will consume part of the generated energy. This amount depends on the type and size of these components.

For the designed system, the average power consumed by each component is measured as shown in Table 1. At a sunny day, the system generated an average of (300 mW) and the total average consumed power by the sensors, controller, and the servo motors of the tracker was (162.75 mW).

Table 1
System power consumption.

Component	Average power (mW)
LDRs	11.25
Microcontroller	150
Servomotors	1.5
Solar receiver	34

This shows the feasibility of the designed system in the energy harvesting mode of operation. At night, the system responded by switching to the signal receiving mode. A laser beam is modulated by a 1 kHz square wave as the binary data signal. The designed system easily found the laser beam and locked to its direction. The recovered data signal was a pure replica of the original data signal. The test is repeated with a 6KHz data signal. The results are shown in Fig. 9.

At the next day sun rise, the system automatically suspended data reception since the sun light has become stronger than the laser beam and saturated the solar cell. The system switched to the energy harvesting mode again.

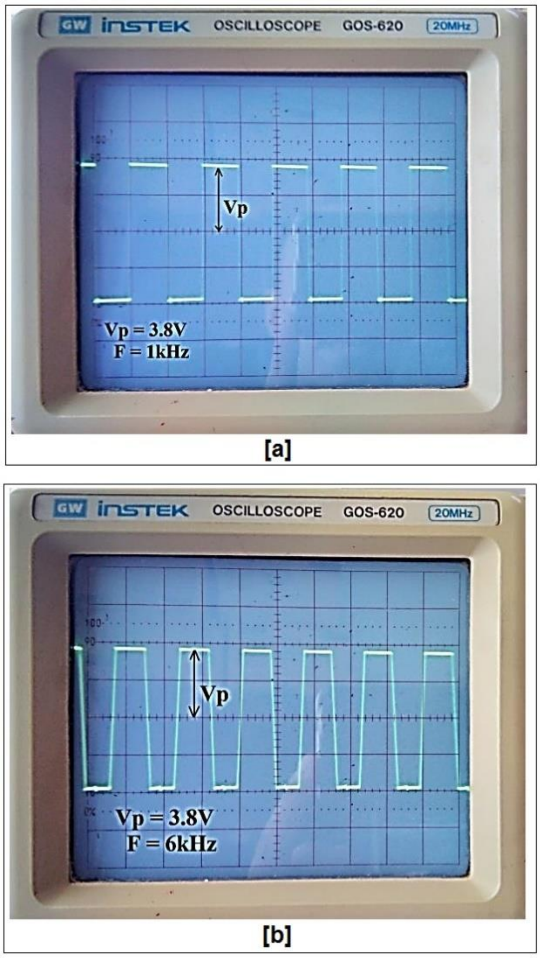


Fig. 9. Recovered data signals.

Table 2
Comparison with previous works.

Proposed work	Previous works
Used at night for receive optical data signal.	Not used at night.
Transmission distance is more than 2m , depend on the power of laser beam.	Maximum transmission distance is 1.25m.
Used dual-axis positioner tracking, programmable microcontroller.	Not used tracking technique.
Used in an outdoor and indoor environment.	Most works used in an indoor environment only.

7. CONCLUSIONS

In this paper, a dual task solar cell system is proposed, designed and implemented. The solar cell harvests solar energy at day time whereas at night it is used to receive optical wireless data, unlike usual solar cells where they stay idle during night hours. In order to find and direct the solar cell to the point of maximum power, for both day and night operation modes, a dual axis light tracking system is used.

A software control algorithm is proposed to control the system hardware to achieve the required performance. The system is tested under realistic outdoor environment. It showed a fast and accurate detection of the operation situation and an accurate and smooth positioning during the specific operation mode. The measurements of the generated and consumed power by the designed system have emphasized it feasibility.

The comparison between the proposed system and the previous works as shown in Table 2, show that the proposed system is beter in terms of the communication distance, it works during day and night, with a dual axis tracking for signals both indoors and outdoors.

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