Automatic Dual Axis Solar Tracker for Landmine Detection Robots

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***Abstract*-This paper presents a two axes automatic solar panel tracking system installed on an automated mine detection robot to support the robot batteries with electrical energy. The tracking system is controlled using a microcontroller programmed with astronomical algorithm to keep the solar panel at right angle with the incident sunrays, in order to improve the performance and to maximize the output power of the solar panel delivered all over the day hours and during the robot's motion in the field. Tracking system mechanism is rotated around two axes, tracing the sun angles from the sunrise to the sunset. The new positioning tracking system includes one photovoltaic panel of 90-watt output power. A liquid capacitive inclinometer chip is used for measuring the tilt angle of the solar panel with respect to ground and robot's inclined angle within 0 to 90 degree range. Electronic compass issued for adjusting the azimuth solar angle direction for any movement of the robot on the ground. A Pulse Width Modulation controlled DC-DC charge controller Boost converter is used along with the automatic tracking system for enhancing the solar panel's output power under variable insolation conditions. Control of the overall system has implemented using PIC 18F452 microcontroller circuits. Practical results show the superiority of the illustrated design.**

Keywords-Component; Dual Axis Tracking; Mine Detection; Boost Converter; Astronomical Tracking

I. INTRODUCTION

To insure a remote permanent green, unlimited and reliable energy sources to supply electrical power to the mine detection robot that performs searching, detecting, catching and working in a minefield. An effective and harmless energy source that assures this objective is the solar energy, especially because Egypt belongs to the global Sun Belt. Egypt is a country that has advantageous position for generation of solar energy; it enjoys 2900-3200 hours of sunshine annually with annual direct average normal energy density of 4000 kWh/m2 [1].

To collect the solar energy, an important factor concerning the efficiency of photovoltaic system output energy is the angle of incidence of sunlight on the surface of the panel. In the case of fixed panels, sunlight hits the solar cells at an oblique angle for most of the day. Maximum of electric energy is achieved only when sunlight strikes the cells perpendicular to their surface (at noon). It is simple to mount solar panels at a fixed tilt and azimuth direction and just leave them there on the robot's board assuming that the robot does not move or moving only straight ahead on a clear smoothing ground. Unfortunately, this is not true because the robot moves according to a searching path that may be in a certain position makes the solar panel out of angles and does not face the sunrays. With different observation location and time, the sunlight direction is different; therefore, sun's position must be tested and located first if the sunlight needs to be tracked. Using a dual axis solar tracker is therefore much more beneficial as it has both the azimuthal and altitude tracking and always has the sun nearly perpendicular to the solar panel. There are four main kinds of solar tracking technologies. They are as follows:

1) Relative method of sunlight strength to photo resistance for detecting sunlight strength:

It is one of the common methods using light dependent resistor (LDR), it is a passive device, whose resistance is a function of the light falling on it. Its resistance decreases as the intensity of light falling on it increases. In LDR based solar tracking systems, three or more sensors are arranged in different ways at the ends of the panel or closed to each others to locate the position of the sun. Generally, 4 LDR sensors are placed closed together separated by dark partitions, with one LDR sensor in each partition. The readings obtained from different LDR sensors are compared to determine the relative illuminance and hence find the position of sun relative to the panel. LDR based trackers have a positional feedback system which keeps a regular check on the current position of the panel. The disadvantage of this method is that it is not very accurate in cloudy of foggy weather also, if the set up is hanged on movable surface as the robots, the system tends to enter hunting and unstable mode which results in substantial consumption [2]-[4]; 2) image processing Camera Bases Tracking systems use a sensor or a camera to obtain the image of the sun, the image is processed by a computer using complex image processing algorithms. Accurate position of sun obtained. This method though very accurate, it is not used generally because of the heavy computational requirements of the system [5]; 3) observe algorithm which also known as the Hill climbing algorithm. It is characterized by a simple logic and does not require complex calculations to work. It measures power at each step and moving forward only if an increase in power is recorded in the next step. It keeps doing so until it reaches the point where a step ahead results in fall in value of power. The point thus obtained is the point where maximum power obtained [6]; 4) Astronomical coordinates method, it is one of the most widely used methods for solar tracking systems. It makes use that the path of the sun has a pattern. The path of the sun as viewed from a location on earth can be calculated by using the parameters of latitude and longitudinal position, day of the year and time of the day. The position of the sun is calculated and this position is converted to angular movement of the panel to keep it aligned to the sun. This method provides a reasonable degree of accuracy if misalignments due installation errors and effect of wind or any motion, can be avoided. Coordinates method has the complexity of the control circuit but gives more accuracy though the precision of control system is superior. This method checks power loss by preventing the system from entering hunting mode, which is a common problem for real time tracking methods. Astronomical method does not have any feedback mechanism hence it is not preferred in conditions where possibility of misalignment is high [2], [4].

In this paper, we designed and implemented a dual axis solar tracking system installed on board of the movable mine detection robot to supply the robot with the electric energy achieving a simple circuit utilizing high accuracy in the sun tracking using two feedback sensors. The tracking system is controlled using a PIC microcontroller programmed with astronomical algorithm to keep the solar panel at right angle with the incident sunrays by calculating the Instantaneous difference between the coordinates of sun and robot to maximize the output power delivered all over the day hours and during the robot's motion in the field. A charger controller DC-DC Boost converter is used along with the automatic tracking system for charging 24 volt batteries enhancing the solar panel's output power under variable insolation conditions This research work also makes a comparison of this proposed dual axis solar tracker with single axis tracker and stationary type. Fig. 1 shows the block diagram of the proposed system.

II. TRACKING MECHANISM USING ASTRONOMICAL COORDINATES METHOD.

Due to the robot continuous motion and changing of directions so the coordinates, method is the most applicable method to be applied in the robotic behavior. That means the solar tracking system can set with any position to aim with the sunrays from its own axis.

Changing of the angles of the sun across the sky influences the major parameters that affect the tracking algorithm. These parameters are the altitude and the azimuth angle. Altitude is the angular distance above the horizon and measured perpendicularly to the horizon. It has maximum value of 90° at zenith, which is the point overhead. Azimuth is the angular distance, measured along the horizon in degrees corresponding to the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere of the earth. Azimuth starts from exactly north, at 0 degree, and increases clockwise.

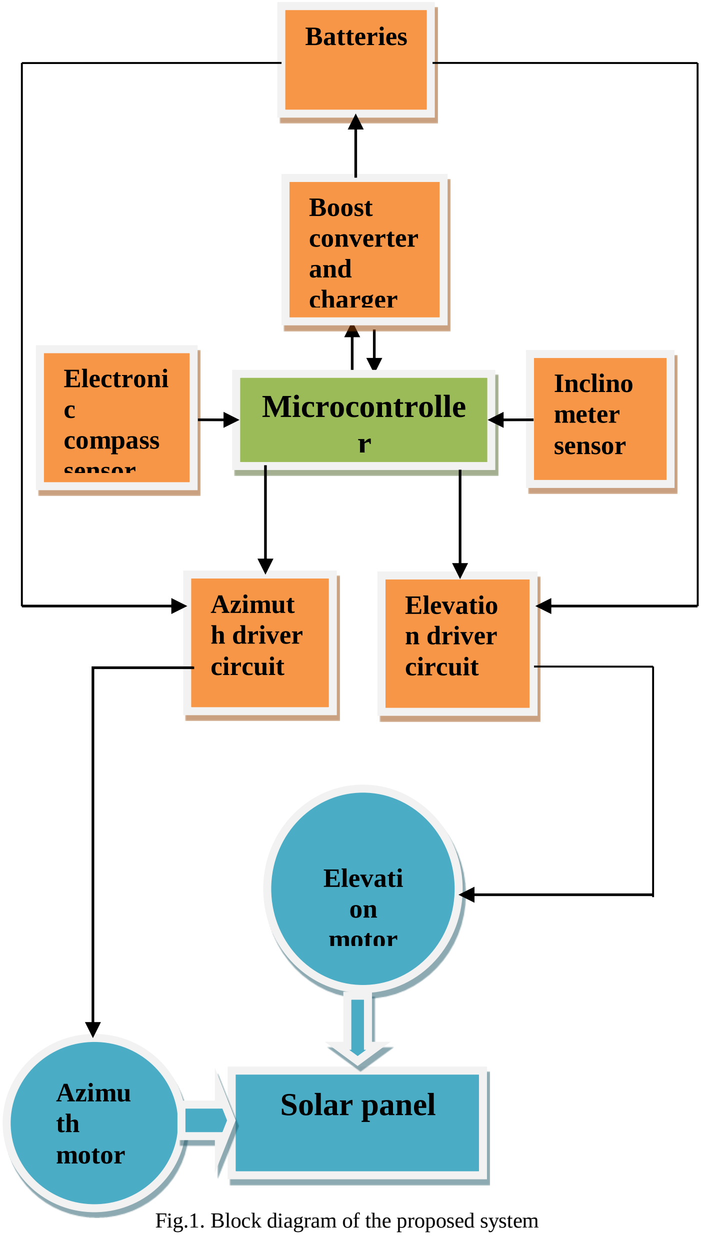


Fig.1. Block diagram of the proposed system

The altitude is symbolized by (Ɣ) starts from the horizon, which is measured using the liquid capacitive inclinometer chip, while (Z) symbolizes the azimuth angle, starts from the South Pole and travels clockwise. Fig.2 shows that the sun is higher in summer more than spring and winter, and the direction of looking into the sun is the south. So, photovoltaic panels are positioned at the true south direction facing the sun with tilt angle depends on the region at which it is located. In the north halve of the earth as in Egypt The tilt angle varies seasonally because the sun is higher in the summer and lowers in winter.

The sun's paths are different due to factors such as:

1) Location (local latitude) which in Egypt directed to south and the corresponding is declination angle.

2) Rising and setting position based on time of the year and on the season (tilt angle).
3) Duration of the day and night from east to west

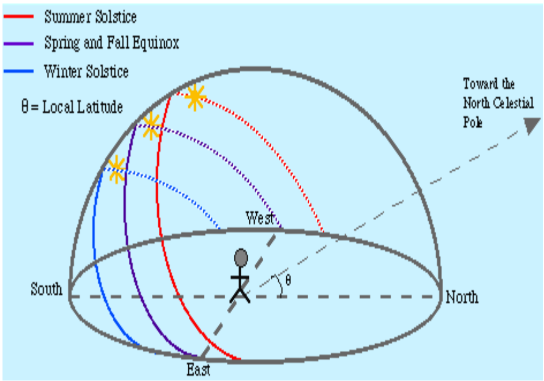


Fig.2. Sun path in the sky relative to the northern hemisphere and the seasons of the year

To capture more energy during the motion it is necessary to adjust the tilt of the panel according to the season.
Declination is the tilt of the earth's axis, results in a change in the relative position of the sun as the earth moves in its orbit. This change in the relative position of the sun is reflected in the change that occurs in the angle the sun's rays make with the equatorial plane. This angle is known as the declination angle and is shown schematically in Fig.3.The declination will vary from maximum of 23·4º at the summer, Solstice to minimum of -23·4º at the winter. Twice in the year, the declination will be zero, this occurs at spring and autumn Equinox, [10]-[12].

Mounting the solar panel declination angle to an optimized angle with respect to the horizontal axis must take into consideration the location, the time of the year and the inclined angle of the robot due to the minefield surface and nature. The panel holder mechanism of the panel can be oriented in any azimuth range between (South East) (0º) and (South West) (180º) and elevated between vertical (0º) and horizontal (90º) position in preprogrammed steps. Relevant parameters are measured continuously, acquired in the program database, and used for panel position adjustments. The mine detection robot moves in the desert through the minefield, searching the mines changing its path, direction angles and inclination angle continuously due to the nature of the ground of the field. The designed mechanism and controller is capable of rapidly locking into the sun position and follow the sun during the robot's searching operation.

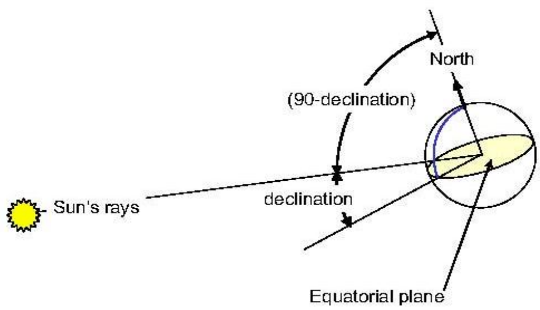


Fig.3. Declination angle

The controller of the tracking mechanism calculations requires number of variables to produce the net angels of the solar panel that have to be in specified instant like the position of the robot, the daytime, the location of the robot on the earth, and the season of the year. This system is always in synchronization with the rotation of earth, without any extra component, starts at the time of sunrise and goes on as earth rotates on its own axis until the sun set i.e., from 6 AM to 6 PM. Fig.4 illustrates the synchronization process and the movement of solar panel during any motion.

The controller is coded using an algorithm based on astronomical data to produce the final angels of the solar panel, [13]-[17]. The panel-positioning auto tracking control system is a two axes motorized rotator carrying panel holder composed of PIC18F452 MCU circuit, sensors and a monocrystalline solar panel of 90 watt.

III. Power consideration for the tracking system.

The tracker needs to respond quickly to the robot's path changes to avoid energy loss and low charging efficiency. The realized tracking system has a boost converter to raise the output voltage of the solar panel under variable insolation conditions to a fixed value; the voltage charging process is controlled using the programmed microcontroller. The combination of the voltage charging controller and the tracking positioning mechanism is implemented with the use of the algorithm coded on the PIC 18F452 which results in a two axes tracking strategy. The DC-DC boost converter used to deliver a fixed voltage to the 24V dc batteries, which is controlled using pulse width modulation technique (PWM), protecting the battery from over-charged and over discharged condition and overcome the lower output voltage of solar panel in a specified output voltage range. The converter is designed to fix the fluctuating or variable input voltage to a constant output with input range of 10-18 volts and for transferring maximum power from the solar PV module to charge the robot's deep cycle batteries then drive motors and electronic circuits.

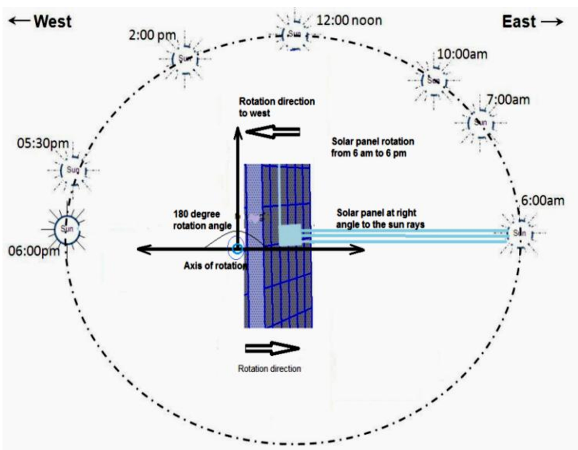


Fig.4.The synchronization process and movement of the panel during the day

To produce a constant output voltage, a feedback loop is used. The output voltage is compared with a reference voltage and a PWM wave is generated from the microcontroller to control switching actions.

IV. OPERATION OF THE PROPOSED BOOST CONVERTER

The scheme shown in Fig. 5 represents the proposed boost converter. The converter is based on the use of microcontroller to control a conventional DC -DC converter, operated in continuous conduction mode CCM, connected to photovoltaic (PV) solar panel of mono crystalline type, has following parameters:

- Maximum power (P_{max}) = 90Watt
- Voltage at P_{max} (V_{mp}) = 18V
- Current at P_{max} (I_{mp}) = 4.94A
- Open-Circuit Voltage (V_{oc}) = 22.1V
- Short-Circuit Current (I_{sc}) =5.35A

The PV rated voltage is fluctuating between 10and 18 Volt DC for variable insolation and it is required to charge 24 V battery bank. The boost regulator provides a constant output voltage (Vo) of 25 volt, which is greater than its input voltage. Referring to the proposed boost converter circuit, D2 allows current to flow into the booster but cannot flow out of the battery to a void back feed of power. The bulky capacitance bank is used to stabilize the PV voltage. Coil L1, switch power transistor BJT S1 and capacitance C2 are the boost regulator components. Diode D2 is used to disconnect the battery if the boost regulator output voltage is less than the battery bank. Two feedback resistances are used for voltage and current sensation.

During the switch closing time, the inductor gets charged and capacitor is delivering the required power to the load.

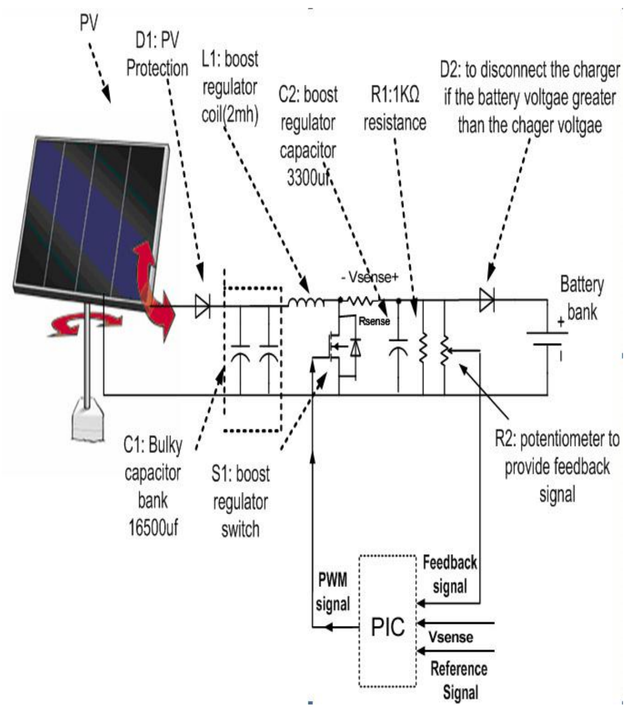


Fig.5. Battery chargers boost converter circuit that used in the tracking system.

During switch opening time, the inductor discharges supplying the full power to load and charging the capacitor simultaneously. When the converter is used in PV applications, the input power, voltage and current change continuously with the atmospheric conditions, thus the converter conduction mode changes since it depends on them. In other word, the average output voltage is controlled by switching on and off time duration. At constant switching frequency, adjusting the on and off duration of the switch is called pulse-width-modulation (PWM) switching. The switching duty cycle, D is defined as the ratio of the on duration to the switching time. In addition, the duty cycle (D) is changed continuously in order to boost the varied input value of the PV voltage to a fixed output voltage. In order to produce a constant output voltage, current and voltage feedbacks are used. The output voltage will be measured and be compared with a reference voltage; the differential value is used to produce a PWM signal. Any changes in the output voltage will lead to the changes of duty cycle in PWM signal. The converter is operated at the switching frequency of 16 KHz the higher the switching frequency, the lower the inductor core size, but the power switch losses are higher, also using a large L value, the inductance value is L= 2mH.

In the steady-state analysis we present, the output filter capacitor is assumed to be very large to ensure constant output voltage $v_o(t) = V_o$, when the input voltage to the boost converter is V_d the integral time of the inductor voltage over one period must be zero.
Thus:

$$I_OB = \frac{TsVo}{2L} D(1-D)^2 \quad (1)$$

Dividing both sides by the switching time (Ts), and rearranging terms, we obtain the equation that describes the relationship between input and output voltages, switching time, and duty cycle [13].

$$\frac{Vo}{Vd} = \frac{Ts}{Toff} = \frac{1}{1-D} \quad (2)$$

This equation confirms that the output voltage is always higher than the input voltage. Assuming a lossless circuit, $P_d = P_o$, where P_d is the boost input power and P_o is the boost output power. We have also

$$\frac{Io}{Id} = (1-D) \quad (3)$$

At the boundary between continuous and discontinuous conduction, i_L goes to zero at the end of the off interval. At this boundary, the average value of the inductor current is

$$ILB = \frac{1}{2} iL\,peak = \frac{Vd}{2L} ton = \frac{TsVo}{2L} D(1-D) \quad (4)$$

In converter design the inductor current and the input current are the same ($i_d = i_L$) [13]. Using (4) we can find that the average output current at the boundary of continuous conduction as:

$$I_OB = \frac{TsVo}{2L} D(1-D)2 \quad (5)$$

The output current reaches its maximum when the duty ratio D = 1/3 = 0.333:

$$I_{OBmax} = \frac{2}{27}\frac{T_s V_o}{L} \quad (6)$$

When operating, the average output current at the edge of continuous conduction mode is important, because for a given *D*, with constant V_o, if the average load current drops below I_{OB}, the current conduction would become discontinuous. In practice, the duty cycle, *D*, would vary with time in order to keep V_o constant. That common practice allows the tracking of the peak power point. Discontinuous conduction mode is unwanted because it occurs due to a decrease in power and results in a lower inductor current I_L since V_d is constant, it will be completely avoided. The relationship between the input voltage V_d , the output voltage V_o, and the duty cycle, *D*, is given by:

$$D = \left(\frac{4}{27}\frac{V_o}{V_d}\left(\frac{V_o}{V_d}-1\right)\frac{I_o}{I_{oB,max}}\right)^{1/2} \quad (7)$$

Since in practice V_o is held constant and *D* varies in response to the variation in V_d , it is more useful to obtain the required duty ratio as a function of load current for various values of the ratio V_o/V_d .

A. *Voltage Sensor*

Voltage divider network is used as voltage sensor feedback for the controller. The resistance values chosen are 40KΩ and 10KΩ. This gives the resistance ratio of 10KΩ/ (40KΩ+10KΩ) = 0.2 and therefore gives the maximum input voltage to the A/D conversion channel as 0.2×25=5V.

B.Current Sensor

Four resistors network with two parallel paths each having two resistors is used as current sensor for the controller. By connecting a current resistor at the inputs of the two parallel paths, the current from the PV array passing through the resistor and voltage drop across it is calculated by measuring two terminal voltage of it. If the solar panel is assumed operating at its maximum capacity, the maximum output current is 4.85 amp, and if 0.5W dissipation is allowed for the current sensing resistor, the resistance value can be determined by $(0.5=(4.94)^2\times R)$ or $(R=0.5/(4.94)^2=0.0205\ \Omega)$. As standard is 0.022 Ω.

C. Charger Controller

The microcontroller PIC18F452 will attempt to maximize the power input to converter from the solar panel by controlling the duty cycle to keep the solar panel operating at its maximum power point. This is accomplished by continuously adopting voltage and current samples from the panel and using the microcontroller to either increase or decrease the duty cycle of the converter depending on the wattage from the solar panel. Fig. 6 shows the output voltage V_o versus the input voltage V_d.

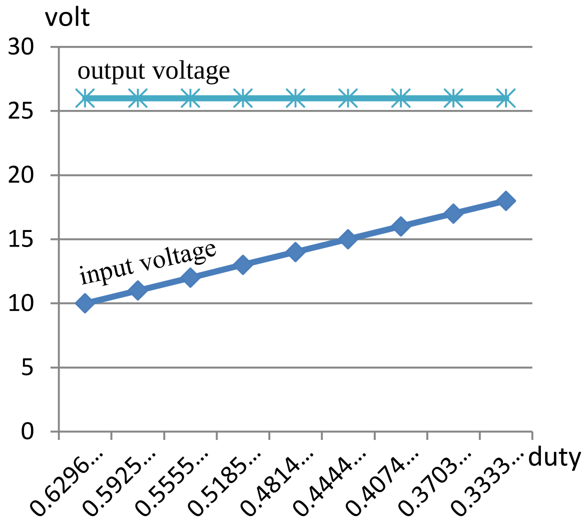


Fig.6. Boost converter output voltage (V_o) versus input voltage (V_d) from the panel and duty cycle D for 1 volt step.

The PIC program flowchart according to the following sequence, first the PIC reads the PV output voltage and if it is greater than 10 V DC the PIC calculates duty cycle D, then the PIC starts the PWM and wait for 300mSec, then, the PIC reads the output voltage and take decision depending upon:
If V_{op} > 25 volt decreases the PWM duty cycle by 1.
If V_{op} < 25 volt increases the PWM duty cycle by 1.
The controller will loop again when the system reaches its steady state operation, the output from the solar panel will oscillate at its highest output value. Charger controller measures the battery voltage and compares it with the highest and lowest threshold value so that battery is protected from being over charge and over discharge condition. Therefore, an advantage is the reduction of the cost of using separated A/D converter IC. The analog output of voltage sensor is connected to ADC pins of microcontroller and the A/D conversion is completed by using software program. ADC over the full range of mains voltage (0 ~ 25V) scaled from 0 to 5V. The resolution is 25/1024 or 0.024V. This is a high resolution.

V. Operation and Implementation of the Solar Tracking Control System and Panel Positioning Device

The main idea here is to calculate the difference angles between the robot's path in the field that affect the solar panel net angles and the path of the sun throughout the day. The calculations based on an open loop sensors, which are employed to determine the rotational azimuth, and altitude angle of the tracking axes, guarantees that the solar panel is positioned at the right angles to sunrays, The tracking system algorithm is illustrated in Fig 7.

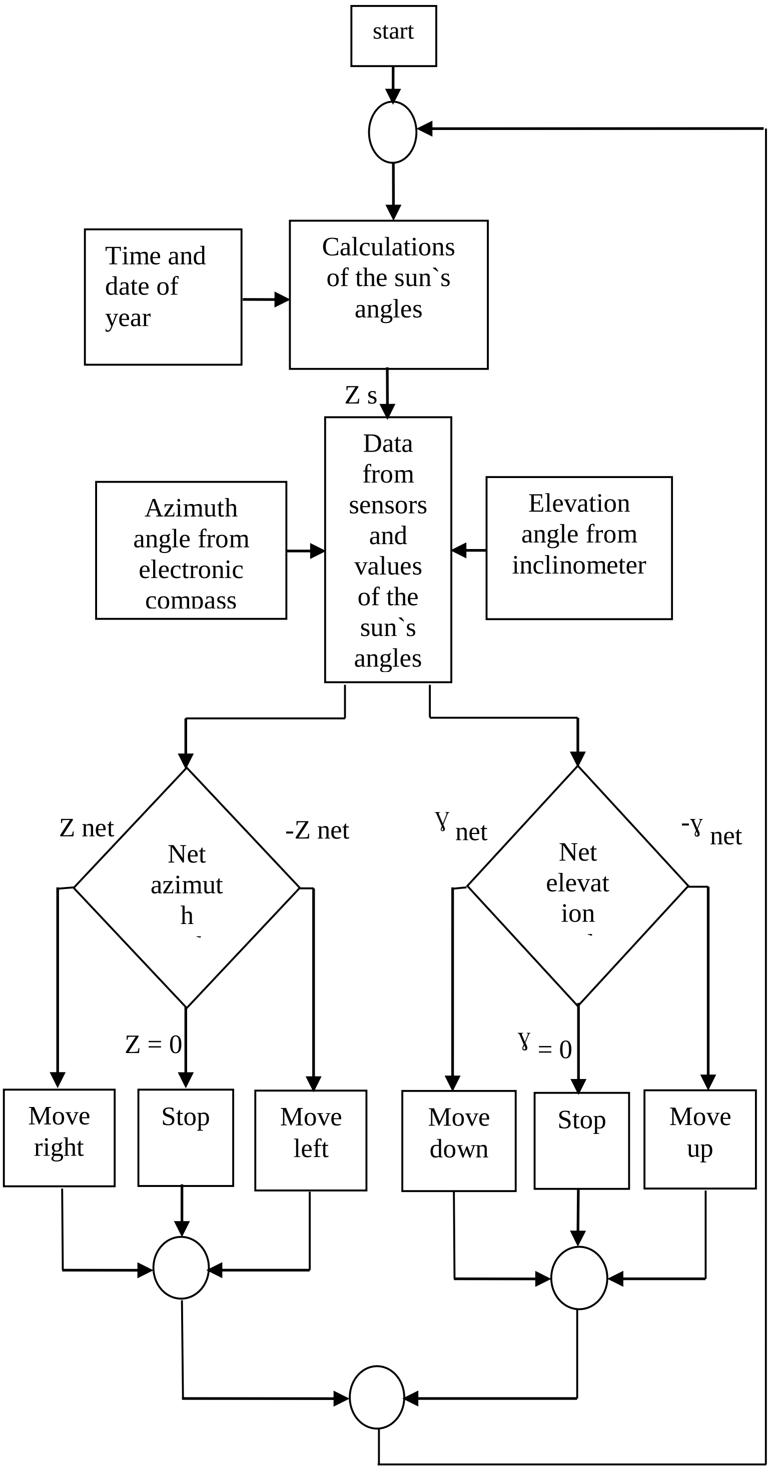


Fig.7. Flow chart algorithm of the tracking system

The tilted platform solar panel is hinged at an elevation angle = (90°- latitude angle) from the horizontal rotating plate. This plate rotates about the vertical axis of the robot.

The realized sun auto-tracking system of the solar panel consists of the 18F452 MCU, electronic compass, liquid capacitive inclinometer, LCD, 4 relays, electronic processing circuits, photovoltaic modules, two DC motors, two gearboxes of transmit ion ratio1/40 and the holder mechanism. The azimuth angle (Z) measurement sensor is electronic compass with tilt and temperature compensation.

The tilt angle (Ɣ) measuring sensor is the liquid capacitive based inclinometer used for measuring the net tilt angle of the solar panel with respect to gravity within 0 to 360° range. This inclinometer features an integrated 16-bit single chip microprocessor, which provides for linearity and temperature compensation. The embedded software virtually eliminates total errors by compensating temperature drifts and sets the sensor dynamics for the ground and the

environment at which the mine detection robot moves. The sensor inclinometer is mounted on the vertical mounting plane and connected to the RS232 adapter that is mounted on the horizontal mounting plane, The schematic diagram of the whole PV panel tracking, positioning and charging device is a schematically shown in Fig. 8.

The mechanism designed rotate from 0° to 180° angle in a day to track the sun and gives one-half rotation in 12 hours from 6am to 6 pm. It starts its rotation from vertical position at the time of sunrise facing towards southeast (perpendicular to ground) and rotates at the rate of 15° per hour. Due to robot's motion in the field and the ground terrain, the solar panel changes its azimuth direction angle becomes (Z_s) and the inclined angle on the ground ($Ɣ_s$) are continuously changed. The microcontroller calculates the difference between the instantaneous change of robot's angel values and the astronomical angel values in the code of the PIC. Microcontroller code calculates the following terms to determine the final position of the solar panel due to sun motion and applies signals to the motors to rotate to achieve the calculated angles.

The declination angle DE of the solar panel as a function of the day number is given by:

$$DE = 23.4 \cdot \text{Sin}\left(\frac{360 \cdot (284 + N)}{365}\right) \text{Degree} \qquad (8)$$

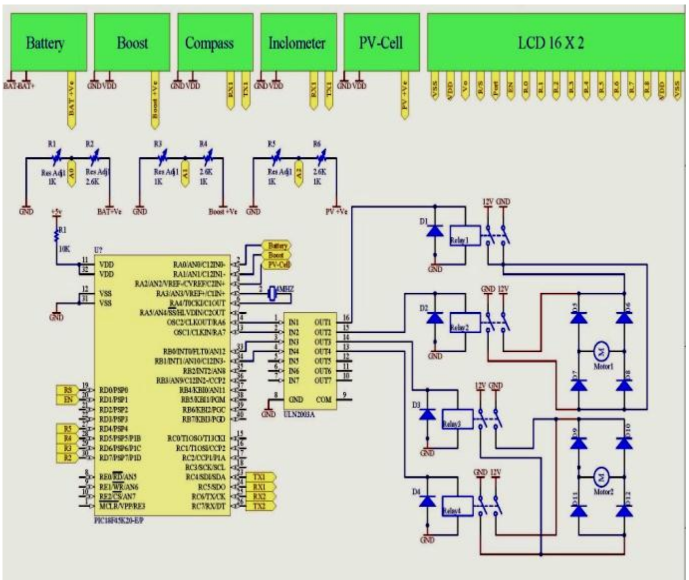


Fig.8. Schematic diagram of the solar panel tracking and positioning system with charger device

Where N is the day number of the date for which the declination calculated. January 1^{st} being day number 1 and expressed as the N = one, starting with January, thus March 11 would be $N=31+28+11=70$ and December 31 means N = 365.

$$\sin\gamma = \cos DE \times \cos L \times \cos H + (\sin DE \times \sin L) \quad (9)$$

L the latitude: is the angle from the equator to a position on Earth's surface (Egypt) [4], [5], [9].

H: is the angular hour $=15(t_s - 12)$ (degrees) (10)
It is the angle between the planes of the meridian-containing observer and meridian that touches the earth-sun line. It is zero at solar noon and increases by 15°every hour, ts is the time for rotation of earth around its own axis in 24 hours. The azimuth angle Z measured by the compass sensor, Fig. 9 shows Latitude, meridian and azimuth angle of the panel relative sun angles stand in the northern hemisphere.

$$Z = \sin^{-1}\left(\frac{\sin H \times \cos D}{\cos \gamma}\right) \quad (11)$$

The compass continuously reads the change in azimuth angle of the solar panel (Z_s) and the liquid capacitive inclinometer reads the change of the elevation angle of the solar panel (γ_s) according to robot's movement in the field.
The PIC calculates the difference of angles between the measured angles by the sensors and the desired astronomical programmed sun angles (Z) and (γ) to gives (Z_{net}) and (γ_{net}).

$$Z_{net} = Z - Z_s \quad (12)$$
$$\gamma_{net} = \gamma - \gamma_s \quad (13)$$

The signals corresponding to this difference are applied to the motors through relays to rotate in proportion to this difference, changing the angles to become (Z_{net}) and (γ_{net}), using programmed movement and measurement in duration of approximately 4 seconds between two steps.

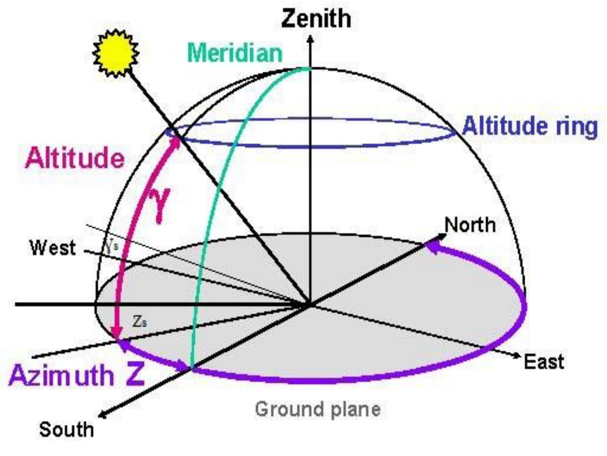
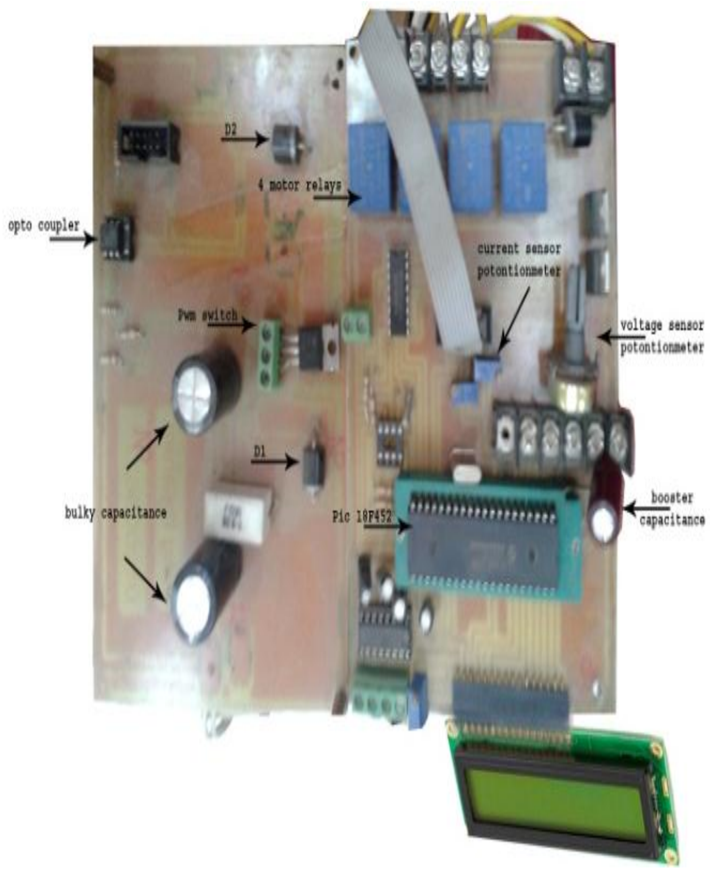


Fig.9. Latitude and azimuth angle of the panel relative sun angles stand in the northern hemisphere

VI. TEST AND RESULTS

The implementation of the system and hardware structure is shown in Fig.10. From the experimental results, it can be seen that the proposed design is able to produce a constant 25 V output voltage from input voltage range Vd 10-18 volt, with variable duty D from 0.63 to 0.28. The efficiency and the comparison of the solar panel output power with automatic tracking and without tracking during the robot's motion in the field as shown in Fig.11 and Table 1. Illustrate the effect of using the sensors for four cases of comparison, during the different movements of the robot as follows:

- Effect of adjusting fixed angles, at fixed latitude of 30° in September month and direction 180°.
- Effect of operating the compass sensor, means automatic change of the direction only with fixed tilt at 30degree.
- Effect of operating the inclinometer sensor only, automatic change in elevation angle with fixed direction.
- Effect of using the feedback of the compass and inclinometer sensors with completely automated system.



(a)

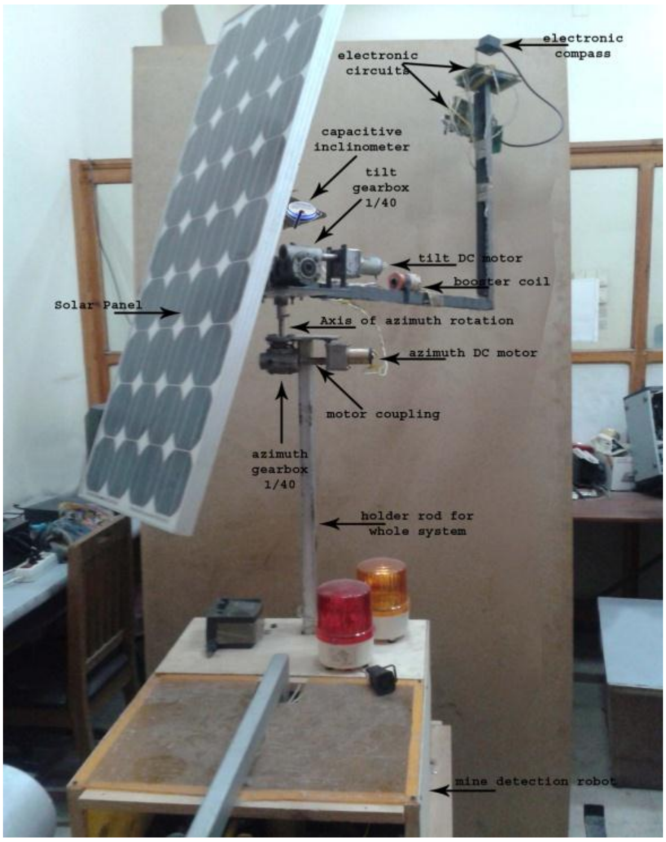


Fig.10. (a) Electronic control circuit (b) Practical tracking prototype system installed on the robot,

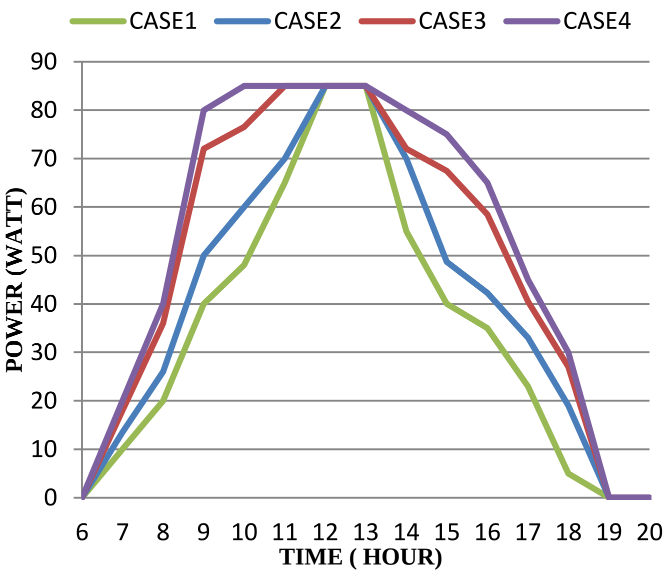


Fig. 11.The Power produced versus time of stationary solar panel (case1), using inclinometer (case2), using compass (case3) and automatic tracking panel (case4) for a fixed path of the robot

TABLE 1 COMPARISON OF THE OUTPUT POWER OF THE TRACKING SYSTEM IN FOUR CASES.

Cases	Case1 Fixed	Case2 Inclinometer sensor only	Case3 Compass sensor only	Case4 2-axis tracker
% power efficiency	52.1%	65.7%	89.2%	95%

VII. CONCLUSIONS

A novel mechanism of two axes sun tracking system installed on robot with boost converter is illustrated. A low cost high performance DC-DC closed loop boost converter has been proposed. Design of the complete system has been explained and a prototype has been built and experimentally tested for an input voltage range of 10 to18 V. For specified input variation, regulated dc output voltage of 25V has been obtained resulting in increasing of the efficiency to 95%. The combination of the voltage controller and the tracking system is implemented with the use of the algorithm coded on the PIC 18F452. The tracking system prevents the misalignment of sunrays on the azimuth axis especially because of the change of the robot's direction. The sun-tracking system is also efficient in providing reasonably high precision with much simple design and cost effective. Practically obtained results show significant improvement of the total efficiency of the photovoltaic system in comparison with the fixed one.

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