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A DUAL AXIS SOLAR TRACKER WITH A SOLAR PANEL PROTECTION FEATURE USING A FOLDABLE PANEL HOUSING-UNIT

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ABSTRACT

Solar energy is a renewable and sustainable source of energy that can be used to generate electricity, heat water, and power vehicles. Solar panels are used to convert sunlight into electricity. However, solar panels can be affected by dust, which can reduce their ability to generate power to their maximum capacity. The aim of this research is to develop a sensorless dual-axis solar tracker with a solar panel protection feature using a foldable panel housing-unit to mitigate the impact of dust. The solar tracker was modelled in Solidworks and 3D printed using polylactic acid (PLA) material. The solar positioning algorithm (SPA) was programmed to run on an Arduino Mega 2560 using a Neo-6M U-blox GPS sensor along with 2 MG966r (0°~180°) servo motors for rotating the apparatus and 1 SG 90 (0°~180°) servo motor to drive the rack and pinion set setup of the foldable housing unit. The total power percentage difference (TPPD) metric is used to compare the power generated from clean vs dusty panels and solar tracker vs static solar panels. The results of the research showed that the solar panels protected from dust by the foldable housing unit yielded an average 6.4% higher power generation compared to the panels exposed to night-time dust conditions. Additionally, the solar tracking solar panels yielded an average efficiency boost of approximately 24.27% when compared to static solar panels. The findings of this research contribute to the development of more efficient and reliable solar trackers. The use of a foldable housing unit to protect solar panels from dust is a novel approach that has the potential to significantly improve the performance of solar panels in dusty environments.

Keywords: Solar Panels, Dual axis solar tracker, Static solar panels, Foldable housing unit, SPA, GPS.

1. INTRODUCTION

With the threat of global warming rising, it is ever more important to shift our ways of energy extraction to more renewable sources [1][2]. Solar power is a promising energy technology as it extracts energy from an abundant and limitless energy source - the sun. Currently, solar technology is dominating the renewable energy market, thanks to its recent advancements, mass implementation capabilities & low costs [2][3]. To improve their efficiency, solar panels are installed with solar trackers that follow the sun throughout the day. These trackers can either be dependent on light sensitive sensors or a GPS based solar positioning algorithm that uses longitude, latitude & Unix-time inputs to determine the sun's position in the sky from the observer's position [4][5]. Solar panels also need to be cleaned frequently to prevent dust & other environmental factors from impacting its performance. To lower costs, maintenance frequencies can be decreased by covering solar panels at night which reduces dust build-up during inactive hours.

Energy extraction from the sun is inefficient as it doesn't account for the sun's daily & annual travel path. A solar panel is most efficient when the sun's rays are incident at right angles to the solar panels. Significant deviations from this greatly reduce the solar panel's energy conversion capabilities and the result is the extraction of insufficient power which isn't ideal to meet the energy demands of today.

Solar trackers based on light sensitive sensors have an increased failure rate probability because sensors can be damaged easily, rendering the tracker useless. There are several environmental factors that leads the sensor to fail. These factors are dust, humidity, chemical exposure, mechanical stress and temperature. Accumulation of dust in the solar panel reduces the sensitivity of the light sensor. Temperature also has a huge impact on the sensor when it is extremely hot and cold. Extreme temperatures can lead to thermal drift, affecting sensitivity and response. Chemical exposure also reduces the sensitivity by forming a corrosion on the electronic materials. Additionally, these sensors can be confused with shadows or potent enough light sources resulting in the tracker pointing elsewhere, following the light source instead of the sun. This is highly noticeable during sunrise/sunset hours. Similar issues were tackled in the works of [5,6].

Keeping solar panels clean is usually difficult and cumbersome as there aren't ways to prevent the buildup of dust. This is important as energy conversion rates of solar panels are substantially affected if the panels are covered with a layer of dust as indicated by the work of [7,8]. Therefore, the technology to lower dust build-up on solar panels needs to be further expanded.

1.1 Solar Tracking Concepts

Solar panel efficiencies can be increased in 3 ways: Advancing semiconductor technologies, maximum power point tracking or using solar trackers [2][9]. For solar tracking, the sun's rays should incident the solar panel plane at right angles for maximum efficiency. Solar tracking is the process of orienting solar panels in a way that maximizes the amount of sunlight incident on them throughout the day. Solar trackers are commonly classified into two main types based on their degrees of freedom: single-axis and dual-axis trackers [1]. Single axis solar trackers follow the sun in 1 direction accounting for its daily travel path while dual axis trackers follow the sun in 2 directions also accounting for its annual travel path [1][9]. Besides these, there are other classification metrics such as active/passive/time-based trackers & algorithmic classifications such as open loop/closed loop systems [1][9]. For the solar tracking aspect, this report focuses on building a time-based, open-loop, dual axis solar tracker to improve the efficiency of a pair of solar panels.

1.2 Types of Solar Tracking Technologies

A. *Solar Positioning Algorithm (SPA)*

A GPS guided SPA is a time driven, mathematical model that determines the optimal orientation for solar panels to maximize the amount of sunlight they receive [5]. It calculates the sun's azimuth and elevation angles relative to the solar tracker's location. The azimuth & elevation angles represent its daily & annual travel position, respectively, within a horizontal coordinate system [5]. The azimuth is the clockwise angle between the true north & the sun in the global-horizontal plane while the elevation angle is the angle between the global-horizontal & the sun in the global-vertical plane, relative to the tracker's location [1]. After the sun's position is known, the SPA is used to control the motors driving the solar tracker's motion to bridge the gap between its position & the sun's position. Then, this process loops after a set time interval. Table 1 shows a comparative analysis of SPA for the proposed design concept and other related works.

B. *LDR Based Solar Tracking*

The light sensitive algorithm uses sensors to control the motion of the solar panels. In the described prototype of [9], four light-dependent resistors (LDRs) are mounted on opposite ends of the solar panel to collect real-time light data, and two servo motors are used to rotate the single axis tracker. An Atmega 328 Arduino microcontroller controls the system, and an Arduino motor shield drives the movement of the servo motors based on the inputs from the microcontroller [9]. The LDRs generate a region of low and high resistance based on the sun's intensity, and the motor is driven to the region of low resistance/high intensity until the resistance balance is restored, as determined, and controlled by the microcontroller [9].

C. *Shadow-pattern based tracking:*

This is a manual method where the sun's travel path is determined by observing the shadows produced by a reference object and calculating the sun's angle of incidence. These angles are then hardcoded into the solar tracker which results in non-dynamic working apparatus as indicated by the work of [10]. [10] repeated the experiment over multiple days to account for the change in the sun's orbit with respect to tracker's position. The estimated angles were then programmed into the single axis solar tracker comprised of a motor, a speed reducer, and a real timer. The efficiency increase compared to a conventional, stationary set of panels was nearly 28.41% [10].

1.3 Impact of Soiling

"Soiling" refers to dust build-up on solar panel surfaces due to long term-exposure that causes it to underperform compared to optimal conditions [7]. Sandy geographic locations are affected by soiling, thereby emphasizing the need to clean solar panels at least once annually during peak dusty weather [7]. The opacity of the soiling particles absorbs light causing less surface area of the solar panels to be incident with light thereby becoming less effective. Water doesn't affect panel performance as it is clear and helps clean the surface of unwanted particles [7][8]. Therefore, rainwater can be beneficial provided all electric components are well insulated. Table 2 shows the comparison of the proposed design with existing methods considering the dust impact.

1.4 Tracker Body

The solar panel tracking system requires a robot arm with at least 2 degrees of freedom to mount and position the panels. It is important to consider the structural integrity of the robot arm, as it needs to be able to hold and carry loads without breaking or buckling [12]. This includes monitoring internal stresses and moments to ensure the frames can withstand induced load conditions. The shape of the arm links also affects the structural integrity and can be analysed using the concept of "section modulus," which is calculated using the second moment of area and the maximum distance from the neutral axis [12]. Generally, though, a pair of rectangular beams was found to have the highest structural strength [12].

1.5 Foldable Housing Unit Contraption

Folding solar panel systems are designed to save space, be portable, and lightweight, as well as protect the panels [9][10]. There are several different folding techniques that can be used, such as the Miura folding pattern, which allows large rigid structures to be contracted into a compact space and expand back in one motion [9]. Another technique involves using a spring-based mechanism to deploy an array of lined up solar panels and a cable to assist in folding and unfolding the array [11]. These folding solar panel systems can improve portability and protect the panels from wear and tear. Various folding contraption solar panel has analyzed and compare with the proposed designed as indicated in Table 3.

TABLE 1: COMPARATIVE ANALYSIS OF SPA

NO	RESEARCH TITLE	TYPE OF SPA	APPLICATION	ADVANTAGES	DISADVANTAGES
1	An Origami Based Portable Solar Panel System [9]	Active, Closed-Loop, LDR based SPA	Ideally used in regions with varying levels of shadows and light as it can readjust its tracking course thanks to LDR sensors	Practical applications over a large geographic location as LDRs are used to detect light intensity & control the solar panel movement.	Is expensive to produce & purchase.
				High precision of solar panel movement controls due to multiple strategically position LDRs.	Tracking system can be fooled by shining bright lights on the LDRs. No method for telling apart sunlight from other types of light.
			Interstellar use where the sun-tracking system can increase the amount of useful energy output of the system by generating electricity from unfiltered solar rays of the sun.	High accuracy & adjusts to best possible position automatically. No guesswork required.	Can also be confused with regions of intense shadows. This is noticeable when all 4 LDRs are in consistent darkness due to an obstruction that blocks the sun.
				Lower maintenance as electronic components are used for the position altering mechanism of the tracking system instead of a completely heat sensitive fluid-based mechanical tracking systems.	LDRs are fragile and can be damaged in high light load conditions.
2	Design and Development of Mechanical Solar Tracking System [10]	Active, Open-Loop, manually determined SPA	For generating energy in fixed locations with a consistence sun travel path as no chance of failure due to sensor or GPS malfunction.	Very simple design & construction.	Reduced power output when compared to a dual axis solar tracker.
				Inexpensive	Applicable over a small geographical region as the panel rotation angles have been hardwired into the system. New location = re-evaluating the sun's position manually.
				Provides relatively high-power output	Low accuracy as sun's position angles are evaluated manually. Experiment used was to determine sun's angles using shadows of a work specimen which doesn't yield accurate results.
				Uses less components	Large, bulky & heavy making it less portable.
3	Solar Tracking System Design based on GPS and Astronomical Equations [11]	Active, Open Loop, GPS guided SPA	Can be used to generate energy in harsh climate regions with rain/snow & little sunlight exposure as it doesn't rely on sensors.	Sensor-less system thereby increasing system reliability as there is no chance of sensors failing due to damage or confusion	System relies on GPS signal to function properly. If the GPS signal is weak or it fails, then the entire system is rendered useless.
			Can be implemented globally as it automatically detects the location & time of the testing ground and readjust accordingly.	Can function even during cloudy weather as the lack of sensors no longer confuses the system.	SPA should account for additional conditions such as altitude levels of the experiment, tracker's starting orientation, leap years etc. The SPA can become complex.
4	Proposed design concept	Active, Open Loop, GPS guided SPA	Can be implemented in low light & bad weather geographical regions Can be utilized worldwide due to its auto adjustment capabilities.	No chance of system failing due to sensor malfunction. Can function irrespective of weather conditions.	A smart SPA must be used to ensure it always works in all places such as different altitude, orientation levels & leap years.

TABLE 2: COMPARATIVE ANALYSIS OF DUST IMPACT

NO	RES. TITLE	RESEARCH CONCEPT	APPLICATION	ADVANTAGES	DISADVANTAGES
1	The Effect of Dust on Solar Photovoltaic Systems [7]	To test soiling on solar panels in Santa Clara, California by comparing energy efficiency rates of unclean solar panels against panels manually cleaned once a year & ones cleaned using an automated cleaning system.	Energy companies can plan, the maintenance sessions for solar panels in terms of costs, downtime, etc. as they now know that summer & drought weathers conditions are not ideal.	This paper helps indicate how much energy conversion capability is being wasted by not keeping the solar panels clean.	The experiment was only limited to 108 days, from spring to autumn. Panel efficiencies during winter weather were not analyzed and so an annual panel efficiency pattern cannot be developed.
				Develop an automated solar panel cleaning system to get more energy.	Initial R&D & manufacturing costs of the automated solar panel cleaning system is expensive.
			Implement a backup plan for energy generation during the maintenance sessions such as wind turbines or hydropower	Indicates the importance of scheduling a panel maintenance session	Manual maintenance sessions for cleaning solar panels is expensive & time
2	Influence of Dirt Accumulation on Performance of PV Panels [8]	To test the efficiency of solar panels by comparing clean solar panels against panels exposed to talcum, dust, sand, water & moss.	It can be used in countries with tropical weather conditions to account for the buildup of moss and other unwanted particles	Can boost the development of various protective coatings for solar panels that prevent the buildup of the examined particles	The experiment is limited to 5 particulate types only. Additional research is required to develop a more well-rounded, universal preventative measure.
3	Proposed design concept	To compare the efficiency of exposed solar panels to ones enclosed in a foldable housing unit.	Energy companies can implement protective housing units of various contraptions to keep their solar panels safe from the harsh environmental conditions.	Boost the development of protective solar panel housing units to prevent unwanted dust particles.	
				Reduce down time and maintenance cost	.

TABLE 3: COMPARATIVE ANALYSIS OF SOLAR PANEL FOLDING CONTRAPTION (SPFC)

NO	RESEARCH TITLE	TYPES OF SPFC	APPLICATION	ADVANTAGES	DISADVANTAGES
1	An Origami Based Portable Solar Panel System.[9]	Miura Folding Pattern (derived from origami art).	Domestic use where deployable solar panels can be installed to power for home appliances.	Effective folding technique allows for large structures to be packed into the smallest volume possible.	Lack of gradual/incremented "expanded state" makes it unsuitable to be deployed in small spaces.
			Emergency uses- backup power supply when electricity source is down or low.	Automatic deployment makes it easy to deploy where needed.	Expensive to develop & purchase.
			Interstellar use where large scale foldable solar panels can be deployed to generate electricity from unfiltered solar rays of the sun.	Highly portable & light weight, it makes easy to transport.	Lack of manual deployment system in case any of the unfolding mechanism
				Increased panel protection from dust, scratches & damage using 2 dimensions of protection.	
2	A New Mechanism for the Deployment of Modular Solar Arrays: Kinematic and Static Analysis.[13]	Deployable/Retractable foldable skeletal array structure.	Used in space faring systems to power space stations, communication devices, etc.	Can incorporate a great number of large sized solar panels into a compact volume.	Unable to track the sun for increased power conversion.
				No manual labor is required to deploy & retract the solar panels	Large, bulky & heavy so it isn't very portable.
			Can be used to power up space bases, space rover vehicles, tools/equipment used in space, etc.	High power output & stability compared to others deployable/retractable systems	Consists of multiple moving parts such the various hinge components & cable
				Box shaped housing is ideal for transportation & stacking.	
				Can be used on different planets with different gravity values.	Very expensive to develop & test.
3	Proposed design concept	Foldable solar panel housing unit that opens/closes like a book.	Domestic applications to power home appliances.	Remains open during the day to be exposed to the sun & closes back down to prevent dust collecting during off hours.	Uses more energy to power the servo motor driving the folding housing unit.
			Backup power when primary energy source is off.	Uses fewer moving parts (less hinges & actuators) to open/close	
				The housing unit provides protection to the panels from physical impacts/collisions	

1.6 Solar Panel Cleaning Technologies

Solar panel cleaning technologies can be mainly classified into manual & self-cleaning (active & passive) [14]. Manual-cleaning uses a labor force which poses cost and time challenges. Active self-cleaning employs automated equipment such as water jets, dust/windshields, & cleaning robots. Passive self-cleaning utilizes rain, clear winds, & chemical coatings like hydrophobic/hydrophilic compounds to prevent particulate adhesion [14] [15].

A. Dust shield, mechanical vibrator & hydrophilic coating combination

Eisa, K et.al.[14] developed an automated cleaning apparatus for streetlight solar panels by combining a dust shield, a mechanical vibrator, and a hydrophilic coating. Single dust shields over double proved more effective as they allow some degree of wind clearance to wipe the dust off the panel surfaces. They also measured efficiency drops due to dust accumulation over 6-weeks and chose 10% as a threshold for a mandatory manual maintenance session. The single shield and mechanical vibrator combination demonstrated the most significant performance improvement, delaying the maintenance session beyond 5 weeks. Adding a hydrophilic coating further delayed this session to nearly 2 months, however this was due to a rainfall assist around week 3 that aided in cleaning the panels.

B. Hydrophobic SiO_2 nanomaterial coating

Alamri, H.R et.al. [15] investigated the efficiency enhancement of solar panels through a hydrophobic SiO_2 nanomaterial coating. They conducted a 45-day experiment, comparing a coated panel to an uncoated, manually cleaned panel, and an uncoated, dusty panel. The hydrophobic coating improved efficiency by 5% compared to the manually cleaned panel and by 15% compared to the dusty panel. The coating exhibited anti-static properties by creating low-resistance regions, causing water and dust particles to naturally slide off. Using the Wenzel and Cassie/Baxter models, they depicted water behavior on hydrophobic surfaces. The anti-reflection effect also led to a 5% and 10% reduction in surface temperature compared to manually cleaned and dusty panels, respectively.

C. Electrostatic cleaning system

Altıntaş, M., & Arslan [16] focused on employing an Electrostatic cleaning method to remove dust from solar panels. Conducting tests in Şanlıurfa, Turkey, they designed a new electrostatic cleaning device, comparing it with a traditional model. The prototype demonstrated higher power efficiencies with the same electric loss values. In water-scarce areas like Şanlıurfa, they found electrostatic cleaning to be ideal, clearing nearly 80% of accumulated dust based on the region's dust pattern. They highlighted the importance of varying electrode voltage to compensate for dust size & density, emphasizing the significant role of electrode shape in cleaning performance and power consumption.

In general, the dust cleaning/dust prevention technologies, dust shields and hydrophobic/hydrophilic coatings are ideal as they are low cost, lack any moving parts & don't consume additional power. Dust shields can also block most particulate types as they disrupt wind flow. However, this depends on wind direction, dust shield size and its tilt angle. Therefore, airborne impurities flowing from a different direction or entering from an unprotected region can still be deposited onto solar panels. With chemical coatings, all evidence points to their effectiveness being tied to rainfall which isn't frequent in water scarce locations like the MENA region (Middle East North Africa) as reported by [14] [15].

Eisa, K etal.[14] also analyzed mechanical vibrators which provided potent cleaning capabilities that is insensitive to particulate type and depends mainly on the vibrational intensity. However, they require an external power source to function which needs to be accounted for to prevent diminishing returns. This is similar with electrostatic cleaning methods as the electrodes need to constantly maintain their charged state to generate the electric field waves to clean as detailed by [16].

Table 4 summarizes the pros and cons of each technique and compare it with existing methods. The proposed foldable housing unit combines all the good attributes of each technique as it provides an all-encompassing shielding from multiple impurities without the need for water assisted cleaning. This is because it folds the solar panels onto one another to cover them. However, the downside is that it only provides protection during the night and requires power to operate the folding mechanisms.

TABLE 4: COMPARATIVE ANALYSIS OF SOLAR PANEL CLEANING TECHNOLOGY (SPCT)

NO	RESEARCH TITLE	TYPES OF SPCT	APPLICATION	ADVANTAGES	DISADVANTAGES
1	Mitigation of dust on PV panels that operate light posts using a wind shield, mechanical vibrations and AN antistatic coating.[14]	Dust Shield + Mechanical Vibrator + Hydrophilic coating Combination.	To power streetlights in urban/suburban areas as self-cleaning can help with the pollution levels.	Increased energy efficiency as the self-cleaning mechanism combination helps the solar panels clean.	Mechanical vibrators require additional energy to operate which can lead to diminishing returns
			Can power traffic signaling systems in remote or off-grid locations.	Reduced maintenance costs as self-cleaning solar panels prolong the mandatory maintenance sessions.	The hydrophilic coating is only effective due to rain which can be less frequent in areas with low precipitation.
			To power border security surveillance systems in remote areas, benefiting from low maintenance.	Conserve water as it is designed to rely on rainwater instead of additional water sources or chemicals.	The mechanical components, like vibrators, can experience wear & tear over time, leading to maintenance requirements.
			Can give power emergency communication systems in disaster-stricken areas	Can be deployed in harsh dust/polluted environments and water scarce regions.	High initial setup costs.
2	Experimental Investigation to Improve the Energy Efficiency of Solar PV Panels Using Hydrophobic SiO2 Nanomaterial.[15]	Chemical coating made of a hydrophobic SiO2 nanomaterial.	Can be used for agricultural/farm operations as the coating prevents water accumulation on the panels.	Enhanced durability as hydrophobic coatings provide a protective layer against extreme weather conditions.	Applying nanomaterial coatings requires precision, and improper application may lead to uneven coverage or reduced effectiveness.
			Can be used in floating solar farms to protect solar panels from saltwater damage.	Increased efficiency as solar panels remain clean for more solar irradiance.	Inhalation or skin exposure to nanoparticles can pose a risk to health & safety of the workers.
			Can be used in emergency power stations, in areas prone to storms & heavy rainfall.	Increased resistance to saltwater corrosion.	Limited self-cleaning capability as it cannot repel contaminants like pollen, bird droppings, etc.
			On solar panels used at EV charging stations to reduce weather impact on charging capabilities.	Increased resistance to organic growth as less microorganisms gets embedded on the panels.	Mechanical wear or abrasion can compromise the integrity of hydrophobic coatings over time.
3	The Study of Dust Removal Using Electrostatic Cleaning System for Solar Panels.[16]	Electrostatic shielding system.	Can be used in desert power sites or mining/quarry sites where sand & other airborne particles are prevalent.	Provides an automated cleaning system, thereby reducing maintenance costs in remote locations.	Requires additional energy to operate which can lead to diminishing returns.
			Solar panels near oil and gas facilities can benefit from electrostatic cleaning to mitigate the impact of pollutants.	Can operate without water consumption making it ideal for water scarce regions.	Regular maintenance for components like electrodes, charge-emitting elements, to ensure proper operation.
			Solar panels at military outposts in diverse environments, including those with airborne particles from military activities.	Increased compatibility with various solar panel types, including photovoltaic and concentrated solar power systems.	Inadequate protection under extreme weather conditions & limited protection from different contaminants like droppings, organic residue, etc.
4	Proposed design concept.	Protective foldable housing unit that covers the solar panels by folding them.	For urban rooftop installations where the panels are folded to protect them from the city's air pollutants.	Can protect from almost all types of contaminants such as dust, mud, rain, bird droppings, organic material,	Only shields the solar panels at night as it needs to expose them during the day for power extraction.
			Remote research stations located in harsh environments like polar regions/deserts where cleaning maintenance sessions can be difficult.	Enhanced system durability as the housing unit acts as hard casing to protect the solar panels from any extreme environmental conditions.	Requires additional energy to operate which can lead to diminishing returns.
			Fore marine operations where the panels can be protected during docking or when inactive to prevent damage from saltwater corrosion.	Doesn’t require additional water for cleaning so it can be ideal for water scarce regions.	
				Doesn't obstruct any power harnessing capabilities unlike somewhat opaque coatings or shadows casted from dust shields.	

2. MATERIALS AND METHODS

2.1 DESIGN OF PROPOSED CONCEPT

Figures 1 & 2 display the CAD model of the dual axis solar tracker with foldable housing unit, in its open and closed state. The sliding motion was achieved through a rack & pinion setup operated by a servomotor. It was designed using Solid works and later 3D printed using PLA material [17].

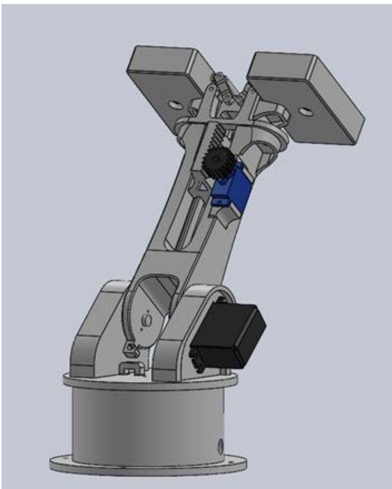

FIGURE 1: DUAL AXIS SOLAR TRACKER WITH FOLDABLE HOUSING UNIT IN ITS OPEN STATE.

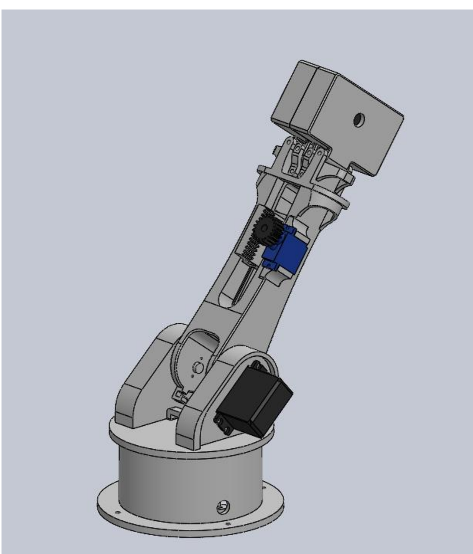

FIGURE 2: DUAL AXIS SOLAR TRACKER WITH FOLDABLE HOUSING UNIT IN ITS CLOSED STATE.

2.2 Arduino Code

The main header files used were the “SunPosition.h” & “UnixTime.h”, found within the Arduino IDE libraries. They are used to calculate the sun’s positional information and Unix time respectively [18][19]. Figure 3 showcases the Arduino connections necessary for the functioning of the dual axis solar tracker. Pin connections for this project are demonstrated in Table 5.

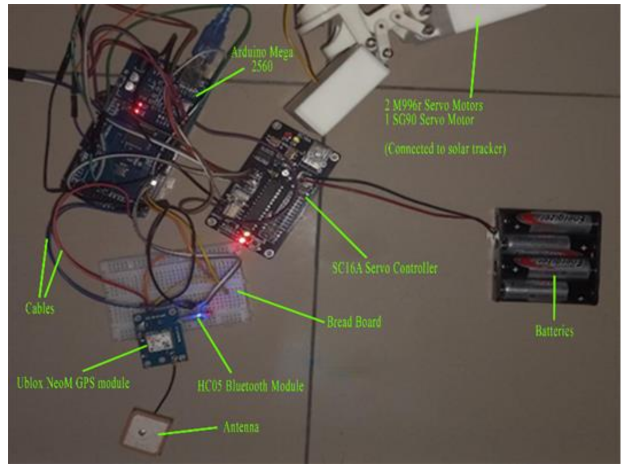

FIGURE 3: COMPONENT CONNECTIONS TO THE ARDUINO MEGA 2560 & SC16A SERVO CONTROLLER.

TABLE 5: COMPONENT CONNECTIONS

Component	Connection on Arduino Mega 2560 and/or SC16A Servo controller
Ublox NeoM GPS module (Serial 1)	TXD → TXD18, RXD → RXD19, GND → GND, VCC → 5V
HC05 Bluetooth Module (Serial 2)	TXD → RXD21, RXD → TXD22, GND → GND, VCC → 5V
SC16A Servo Controller (Serial 3)	TXD → RXD31 RXD → TXD32 GND → GND 5V → 5V
SG90 Servo Motor	PWR → “+” GND → “-” (S0 pins of SC16A) SGNL → DIGI 3 (Arduino)
M996r Servo Motor (waist)	PWR → “+” GND → “-” (S2 pins of SC16A) SGNL → DIGI 4 (Arduino)
M996r Servo Motor (base)	PWR → “+” GND → “-” (S4 pins of SC16A) SGNL → DIGI 5 (Arduino)
Battery	“+ -” Servo Power pins (SC16A)
Power Bank	USB → TTL serial cable (Arduino)

2.3 Working Principle of the solar tracker

The protective solar tracker waits for the GPS to receive a signal lock before collecting inputs about its position & time. After verifying the data's validity, the program calculates the sun's positional data and verifies if the time is within the designated operating hours. It then opens the foldable housing unit & drives the servos to track the sun's position. The sun and tracker's position are displayed to the user on his/her mobile phone. If the current time is not in the selected range, the system resets the solar tracker to its starting position while it recollects new data inputs. Figure 4 shows the working procedure of protective solar tracker.

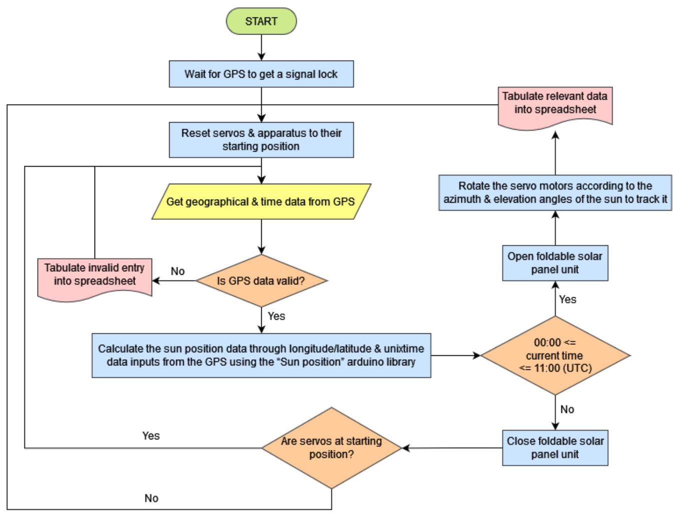

FIGURE 4: THE SOLAR TRACKER'S WORKING PROCEDURES.

2.4 Dust Testing Procedure

Two pairs of solar panels, in series connection, are mounted onto the respective housing units, i.e., foldable & static housing units. These housing units are placed in a dust prone environment (above a wardrobe) to collect a uniform dust fall pattern on the solar panel surfaces. After waiting a few days for decent dust fall, relevant readings are taken to generate comparative analysis of the dust fall to panel efficiency for both housing units. Figure 5 shows that dust exposure testing procedure.

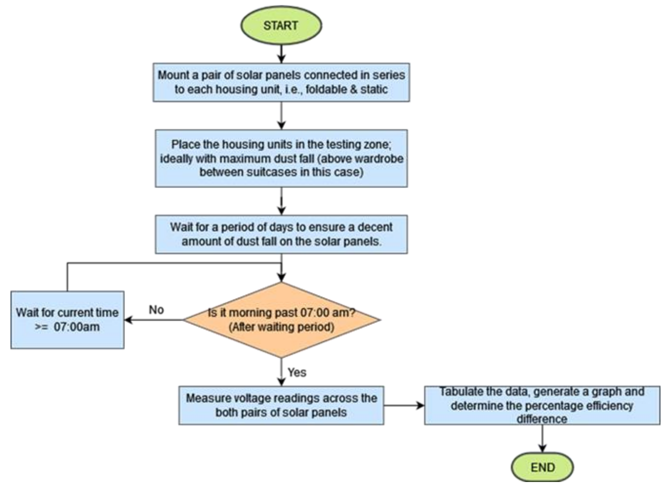

FIGURE 5 : DUST EXPOSURE TESTING PROCEDURE.

3. RESULTS AND DISCUSSION

3.1 Protected vs Exposed to Dust Comparative Analysis

The results from the experiment conducted are displayed in Table 6 which lists the solar panel housing type, the voltage drops, the induced current, power generated, the light loads, and the efficiency difference of the panels.

TABLE 6: VOLTAGE (V), CURRENT(CU) & POWER (PW) READINGS FOR CLEAN VS DUSTY SOLAR PANELS.

Light Brightness (lm)	Clean Solar Panels			Dusty Solar Panels			PW Difference	% Difference
	V	Cu (µA)	PW (µW)	V	Cu (µA)	PW		
200	2.46	16	39.36	2.40	15	36.00	3.36	9.33
925	3.30	30	99.00	3.19	28	89.32	9.68	10.84
1650	3.82	41	156.62	3.75	41	153.75	2.87	1.87
2375	4.26	54	230.04	4.20	53	222.60	7.44	3.34
3100	4.71	69	324.99	4.59	65	298.35	26.64	8.93
3825	5.03	80	402.40	4.91	78	382.98	19.42	5.07
4550	5.29	91	481.39	5.17	89	460.13	21.26	4.62
5275	5.48	101	553.48	5.36	96	514.56	38.92	7.56
							Average	**6.45**

Figure 6 shows the comparison of power output between clean and dusty solar panels under 8 different light brightness levels. The results show that clean solar panels generate more power than dusty ones due to the protection provided by foldable housing unit. The hypothesis that dust exposure during night-time affects solar panel performance is confirmed. Both clean and dusty panels show increased power generation with increased light brightness. The difference between clean and dusty panels after 5 days of exposure is 6.4%. Longer exposure periods can result in a larger difference and compromise energy generation capabilities.

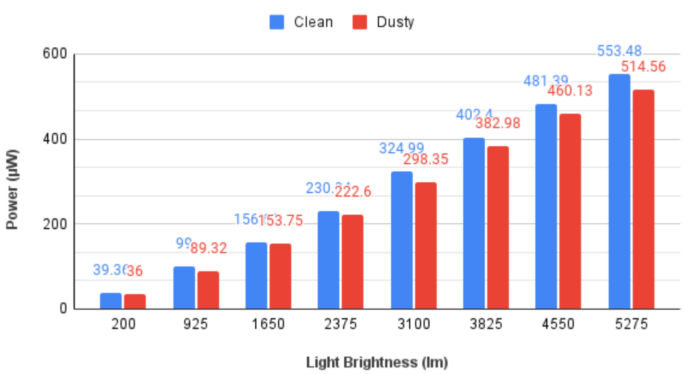

FIGURE 6: POWER OUTPUT OF CLEAN VS DUST SOLAR PANELS.

3.2 Solar Tracking Vs Stationary Solar Panel Comparative Analysis

Table 7 the voltage, current, and power data for the solar tracker and static solar panels laid outside in the sun from 9:00Am to 07:00Pm.

TABLE 7: VOLTAGE, CURRENT & POWER READINGS OF SOLAR TRACKER VS STATIC PANELS.

Time	Solar Tracker			Static Panels		
	Voltage (V)	Current (μA)	Power (μW)	Voltage (V)	Current (μA)	Power (μW)
09:00	10.97	21.60	236.95	10.91	12.00	130.92
09:30	11.13	23.70	263.78	10.99	13.90	152.76
10:00	11.18	25.30	282.85	11.03	16.60	183.10
10:30	11.33	28.50	322.91	11.10	18.30	203.13
11:00	11.17	40.10	447.92	10.96	30.80	337.57
11:30	11.14	43.80	487.93	11.00	38.80	426.80
12:00	11.12	46.70	519.30	11.08	43.70	484.20
12:30	11.60	50.30	583.48	11.31	46.40	524.78
13:00	11.22	45.20	507.14	11.15	38.80	432.62
13:30	11.16	47.80	533.45	11.10	44.50	493.95
14:00	11.09	42.30	469.11	11.02	39.80	438.60
14:30	10.98	34.70	381.01	10.92	32.30	352.72
15:00	11.06	32.50	359.45	11.00	30.90	339.90
15:30	11.00	27.10	298.10	10.96	25.40	278.38
16:00	10.97	25.70	281.93	10.85	21.40	232.19
16:30	11.02	29.10	320.68	10.91	20.30	221.47
17:00	11.12	32.00	355.84	10.81	16.00	172.96
17:30	10.95	17.80	194.91	10.70	12.30	131.61
18:00	10.66	11.10	118.33	10.41	7.05	73.39
18:30	10.14	5.52	55.97	9.86	3.99	39.34
19:00	8.46	1.56	13.20	8.22	1.23	10.11
		Total	7034.24		**Total**	5660.50

Based on Table 3 data the total power percentage difference analysed using Equation (1)

$$TPPD = \left[\frac{TPST - TPSP}{TPSP}\right] x100 \quad (1)$$

Where,
TPPD is Total power percentage difference.
TPST is Total power of solar tracker.
TPSP is total power of static panel.

$$TPPD = \left[\frac{7034.2374 - 5660.4985}{5660.4985}\right] x100 = 24.26\%$$

The power percentage difference results show that the dual-axis solar tracker outperforms the static panels, generating 7034.24 μW compared to 5660.50 μW of power, resulting in a performance boost of 24.27%.

Figure 7 compares the power outputs of a solar tracker and static solar panels from 09:00 am to 07:00 pm as the sun's position changes throughout the day. Both the solar tracker and the static panels have a similar convex shaped power output curve, with the minimum power output occurring at sunrise/sunset and the maximum power output occurring at solar noon The difference between the two starts at a minimum at sunrise, gradually increases to a noticeable difference where it is roughly maintained throughout the day before minimizing again at sunset. These results align with previous studies [5][9][10] which demonstrate that solar trackers outperform static panels. However, it is worth noting that there was an exception at the 17:00 time stamp, where there was a significant power gap which could be due to tracker misalignment or cloud interference during recording. This highlights the importance of monitoring and maintaining the proper alignment of solar trackers to ensure optimal performance.

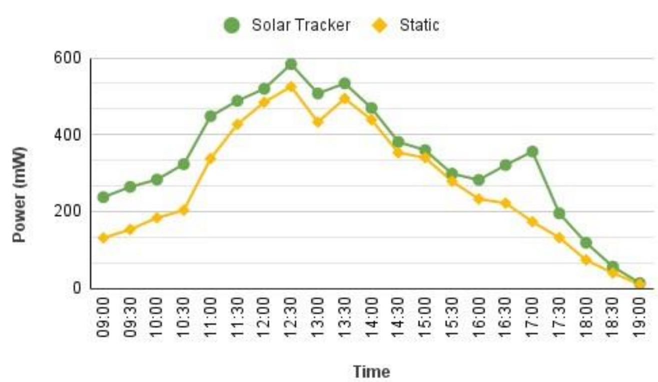

FIGURE 7: POWER OUTPUT FOR SOLAR TRACKER AND STATIC SOLAR PANELS FROM 09:00 TO 19:00

3.3 Standard error and uncertainty analysis for solar tracker and static solar panel

The standard error (SE) for solar tracker and static solar panel analysed using Equation (2).

$$SE = \frac{STDEV.S}{\sqrt{number} of\ samples} \quad (2)$$

Where,

STDEV.S is the standard deviation of the sample

Using Equation (2) and Figure 7 data, the SE of the solar tracker is 34.22 µW and on the other hand the SE for Static solar panel is 34.28. The SE difference between solar tracker and static solar panel is very minimal. The mean value for solar tracker and static panel are 334.96 and 269.55 respectively. Hence, the uncertainty of the solar tracker is 334.96 ± 34.22 and the static solar panel is 269.55 ± 34.28.

The fractional uncertainty can be expressed using Equation (3).

$$\text{Fractional Uncertainty} = \frac{\text{Uncertainty}}{\text{Average}} \quad (3)$$

Based on Equation (3), The fractional uncertainty of the solar tracker is 10.21% and for the static solar panel is 12.72%.

4. CONCLUSION

The results of this research showed that a sensorless dual-axis solar tracker with a solar panel protection feature using a foldable panel housing-unit can be developed to mitigate the impact of dust. The findings of this research have the potential to significantly improve the performance of solar panels in dusty environments.

A. *Clean vs Dusty Solar Panel Conclusions.*

- The solar panels mounted in foldable housing unit outperforms the ones mounted in the static housing unit in all 8 lighting conditions. Therefore, the foldable housing works as intended protecting the solar panels and keeping them clean.
- Five days of dust exposure led to a performance difference of 6.4%. Prolonged exposure could lead to unignorably performance difference levels. Hence panels should be cleaned often.

B. *Solar Tracking vs Static Solar Panel Conclusions*

- The solar tracker outperformed the static solar panels throughout the experiment's duration with an approximate difference of 24.27% in the total power generated throughout the day.
- The difference in power output is minimum during sunrise and sunset.
- The solar tracker doesn't alter the trend in power generation of solar panel units but merely increases the amount of power generated while following a similar trend.

In summary, the study presented the enhancement of solar panel efficiency through a dual-axis solar tracker and a foldable panel housing unit for dust protection. These approaches addressed two major efficiency-reducing factors in solar panels: misalignment with the sun's position and dust accumulation. The findings reveal that this innovative approach leads to a notable increase in efficiency, with dust protection contributing to a 6.4% efficiency gain, and the solar tracking mechanism providing an additional 24.27% increase. This combination of technologies addresses critical efficiency challenges in dusty environments, offering a significant advancement in solar energy utilization.

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