Challenges and recent developments in solar tracking strategies for concentrated solar parabolic dish

Franch Maverick A. Lorilla[1,2], Renyl Barroca[1]
[1]School of Engineering and Architecture, Ateneo de Davao University, Davao City, Philippines
[2]Energy Systems Management Department, College of Technology,
University of Science and Technology of Southern Philippines, Cagayan de Oro City, Philippines

Article Info

Article history:

Received Apr 21, 2021
Revised Mar 29, 2022
Accepted Apr 15, 2022

Keywords:

Control strategies
CSP
Parabolic solar dish
Solar tracking system

ABSTRACT

This contribution presents an overview of control strategies for parabolic dish concentrated solar power (PD-CSP) sun tracker technologies from the literature on different implementations. This paper also highlights the practical challenges in designing sun trackers for CSP applications. Solar radiation undergoes seasonal changes and transients from the cloud that is exceptionally challenging to manipulate. This paper may provide control engineers with technical information on high-precision solar dynamic tracking and optical accuracy by emphasizing the features, advantages, and limitations of different control techniques and algorithms. Implementation of efficient control strategies addresses concerns in amending dynamics and nonlinearities, thus improving the system responses and extending the operational timeline of CSP plants, which results in a reduced cost per kWh produced.

Corresponding Author:

Franch Maverick A. Lorilla
College of Technology, Energy Systems Management,
University of Science and Technology of Southern Philippines
FMM4+WM4, Cagayan de Oro, Misamis Oriental, Philippines
Email: franchmaverick.lorilla@ustp.edu.ph, franchmaverick.lorilla@ustp.edu.ph

1. INTRODUCTION

One of the fundamental inputs to economic activity is energy. Since the 20th century, fossil fuel consumption has increased proportionally on the global population and economic growth. However, this also corresponds to the continuing deterioration of natural resources as the need arises. Thus, there is an urgent need to develop initiatives on increasing economic development while conserving natural assets. To facilitate this, we need to catalyze policies and investment on innovation for sustainable growth and the rise of new economic opportunities. In this context, the energy sector presents a challenging case on reducing our dependence on fossil fuels, as it contributes to 89% of the global greenhouse gas emissions in 2018 [1].

Solar energy technology emerged as a potential global approach to deal with climate change, energy conservation, environmental enhancement, and pollution reduction. Two main technologies in solar energy are being utilized to convert it into electrical energy: i) photovoltaic (PV) and ii) concentrated solar power (CSP) technology. To date, photovoltaics technology efficiency has reached about 20% while thermal technologies are in the range of 40-60% [2]. Between the two, thermal technology showed great potential in meeting up the world's power demand and expected to provide 10% of global energy demand by 2015-2050 [3]. CSP is catching up with competitive pricing with conventional fossil fuel due to some technological development and improved operation [4].

CSP collect and concentrate sunlight to produce high-temperature heat to produce steam converting it into a mechanical action in a turbine that generates electricity. There are four (4) main technologies under CSP and these are: i) linear fresnel, ii) parabolic trough reflector, iii) central tower receiver, and iv) parabolic dish [5]. Great attention was given to parabolic trough as it deployed successful commercial applications and accounted for 90% capacity of the currently installed solar thermal power plants. Thus, minimal interest is left for other technology, particularly on the solar parabolic dish solar concentrators (PDSCs). Yet among the technologies, the PDSCs are the most efficient and has the highest concentration ratios [6] and suitable for micro-scale power production in remote areas and small communities with capacities in the range of 10-100kW [7], [8].

Commercialization of the PDSCs is yet to be proven and most of its implementation are still in prototypes and the amount of electrical energy produced should breakeven the cost of the equipment, energy consumed of the moving parts and as well cost of maintenance and operation. In recent years, attempts in improving PDSC's efficiency is considered using solar tracking systems (STS) that will dynamically point the position of the sun and flexibly adjust on the daily angular (altitude-α and azimuth- γ) changes. However, deploying this of system requires: i) complex structure with actuators, gears, and sensors ii) sophisticated installation, and iii) implementation of applicable control strategy.

To address these limitations, this paper presents list of current challenges along with some of the recommendations and insights from literatures in developing PDSCs for better design considerations and techniques. Several works in reviewing STS were done for PV and CSP technologies, but most of if it focused on the classification of different types of ST systems, their pros and cons, design methodologies and their implementation. The work presented here summarizes PDSCs technologies with their corresponding STS design based on the dish diameter, capacity, thermal efficiency, algorithms, solar sensors, control units and sun position methods and energy costs.

This paper is arranged as follows; section 2 presents different design challenges in PDSCs STS development. Section 3 resents advancement in PDSCs STS. Finally, the discussion and conclusions are also shown in section 4 respectively.

2. PRACTICAL DESIGN CHALLENGES IN SOLAR TRACKING SYSTEM (STS)

Concentrated solar power (CSP) systems generate electricity that commensurate with the amount of solar energy collected. To achieve a large amount of solar energy, scientists and engineers have investigated the CSP's efficiency. Literature reveals that there are three ways to maximize the efficacy of CSP systems: i) increasing the power efficiency, ii) applying control algorithms and power transmission strategies, and iii) using the tracking system for full solar power [9]. This section aims to explore both the second and third methods for solar parabolic dish concentrators. Along with the different control strategies and tracking systems studied and developed, CSP power generation's volatility produces erratic variations in solar irradiance and power production as factors to be discussed. This section also includes challenges in solar harvesting and its effects on CSP power generation.

2.1. Cloud disruptions

The sky and the clouds are the CSP's heel of Achilles. Cloud transients can significantly affect control systems for the solar tracker and power plant substation. During the regular period, solar radiation changes continuously with moving clouds. In their planned lifespan of more than 30 years, solar power plant central receivers experience over ten thousand start-ups and shutdowns. Also, they undergo quick metal receiver temperature changes of over 25,000 [10]. These changes are 25 to 50 times more than any traditional power station. Metal temperatures increase in start-ups and shutdowns from ambient to over 700°C on regular days [11]. Solar irradiation of intermittent clouds may be decreased by 5 percent per second, contributing to a shift in metal temperature by 600° C per minute at receptor elevated flux points [12]. These factors induce substantial thermal stress in products, reduce the plant's life, and maintenance costs.

2.2. Costs and complexity

Given the cost of tracking systems in terms of initial and energy costs, CSP STS is between 30-40 % higher than for fixed systems [13]. The tracking device is primarily responsible for 20% of the CSP plant's running and repair costs [14]. It is also important to reduce the valuation of solar trackers as much as possible to prove the economic viability of the CSP scheme. With a view to an independent off-grid low-cost infrastructure, the United Nations mechanism for climate change communicates its engagement in empowering rural populations by encouraging the development of stand-alone CSP dish technologies. However, considering many emerging countries' social contexts and technical strengths, simplicity and sustainability would be considered as critical factors. Prinsloo [15] demonstrated a stand-alone Parabolic solar dish device in some rural areas of African Villages, striving for simple implementation and compact architecture by implementing an effective automated positioner operated device to generate a potential 12 kW of solar harvesting at noon of full sunshine. The research further suggests improving the structural feature STS of the parabolic solar dish concept for its modular implementation. In the analysis performed by Alexandru and Tatu [16], higher costs will still arise in the engine and traveling joint monitoring system. This technology still proves commercial efficiency and service. High investment costs are needed for a stable support system and axis tracking mechanism [7]. The framework can be cost-effective with the advancement of computer and control system technology [17].

2.3. Environmental conditions of the Field

In addition to the complexity of mechanical structural motion and balance, a solar tracking unit's design option must live up to the area's harsh conditions. Environmental factors such as air temperatures, temperature changes, deposits of soil dust (especially mirrors), strong winds, snow, rain/raining, and lightning, create operational challenges. Considering the design robustness, these effects should be considered since some solar generation systems can be deployed where the maintenance crews are not readily available. Components of solar concentrate should be handled to corrosion, whereas components of stainless steel are selected for critical subcomponents.

To protect against humidity and dusty conditions, control electronics must be housed in a watertight and correctly-ground enclosure. When used outdoors in severe weather conditions, all modules should instead have an IP level of at least IP55 to stay secure [18]. Many manufacturers of concentrated solar collection and solar control systems do not consider on-site assembly as practical. Due to the mathematical precision required for assembling structural components, the concentration of solar housing systems is challenging to assemble in remote rural areas. Many parabolic concentrator assemblies would require technical expertise to navigate and coordinate optically.

The cable trusses may also be tensioned, and the mechanism is coordinated optically by an industrial crane or mechanical hoist in most cases. They are also inaccessible or mobile to remote rural or mountain areas. In specific mountain regions, snowfall during the winter season is often subject to extreme fluctuations in temperatures. Because of potential snow and ice deposits, the solar tracking platform's design needs to compensate for extra gravity. Materials with a wide range of working temperatures must, however, be selected.

2.4. High wind conditions

Solar trackers move the payload towards the sun throughout the day; thus, its mechanical drives should make easy and active transitions of the STS and lock its position to the sun regardless of any deviations in the environment. In design and development, understanding the wind loads can help optimize energy production per unit cost. Wind load on STS may be the most challenging design calculation in developing the product since the tracker parts simultaneously move in various directions. The current STS design supports the collector at the single axis; however, the design should support gravity and wind load. The need to consider forces acting and their moments should be observed practically in the design process [19].

3. RECENT ADVANCEMENTS IN SOLAR TRACKING CONTROL STRATEGIES IN PDSCs

In 1975, McFee [20] presented the first automatic STS, for which the author can calculate the distribution of flux density and received power in the central solar receiver systems. A few years later, Semma and Imamru [21] used a microprocessor to change the solar collector's position in the thermal collector. The rapid growth of control system technology following the advent of Industry 4.0 has opened the way for studies to improve the use of STS to increase power efficiency and reduce costs of the CSP. Improved efficiency, accuracy, and stability can be obtained through continuous surveillance of all solar energy incidents. The CSP tracking strategies are classified in various forms. In terms of their mobility, CSP STS are classified as: i) the one-axis tracked by a single rotating pivot point and ii) the dual-axis tracked by two pivot points in two separate directions, following the sun's track. These types can also be categorized in terms of their control strategies: i) open-loop, ii) closed-loop, and iii) hybrid [22]. These methods may also be categorized as active or passive trackers. The rest of this section describes recent developments, approaches, and algorithms for each category.

3.1. Open-loop control strategies

A strategy for open-loop control follows its implant instructions (i.e., algorithms and astronomical equations) faithfully to track and target solar energy. It uses information such as the sun vector and the sun's direction, measured at any time, to shift a parabola into the sun's center without reactions [23]. Figure 1 demonstrates the typical configuration of this system. This strategy is straightforward and inexpensive to implement but will need extensive configuration to match the algorithm. The passive open-loop tracking device has many error sources such as time, subscales, site latitude and longitude, varying astigmatisms, a cosine effect, processor precision, refraction atmosphere, structural and mechanical tolerances and tolerances for installation [24]. Moreover, it makes the control system more complex and less reliable, since it does not track the output data.

Several studies have been conducted that involve algorithms, regardless of the input factor, enhancing sun-tracking precision. These open-loop algorithms started when McCluney (1983) implemented an early-research guide to a solar-irradiation geometry model. In 1983, a microcontroller-based dual-axis solar tracking device for astronomical sun coordinates was implemented by Al-Naima and Yaghobian [25]. Comparative tests have shown that their approach has provided a far better tracking performance than a conventional sensor unit with a tracking error less than 1o. Several years later, Blanco-Muriel *et al.* [26] developed a new algorithm using a simple algorithm in a low-cost microprocessor that allows determining true solar vector with an accuracy of 0.5 minutes of arc for the period of 1999-2015. For azimuth and zenith, the algorithm was 15% and 22% better than those from past algorithms.

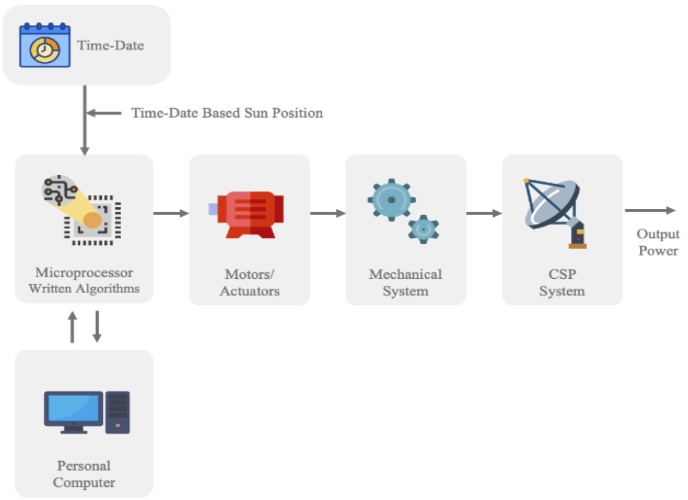

Figure 1. Generic configuration of an open-loop solar tracking system

Beshears *et al.* [27] released a successful hybrid illumination tracker in 2003. Instead of sensing the relative sun is wearing with the optical sensors by calculating the sun's celestial bearing to the earth, the sun is determined by latitude, longitude, date, and time zone. The following year, a two-axis electromechanical sun tracker programmed based on solar angle analysis and motor speed calculations through programmable logic controllers (PLC) was introduced by Abdallah and Nijmeh [28]. The said system was able to increase energy accumulation by around 41.34% over a fixed 32° surface. Similarly, Reda and Andreas [29] proposed a straightforward build of an open-loop solar algorithm using the aforementioned key input variables: ecliptic longitude, mean latitude, Date equinox, only ascending right and declining with the following correction parameters: longitude nutrition, obliquity nutrition, ecliptic obliquity, and precise geometry decline. Many of these parameters are used in algorithms to compensate for reliable errors in performance management. It achieved greater accuracy of less than 0.0003° error on its solar zenith and azimuth angles. Studies [30], [31] were then successfully conducted using the non-linear concept of analog optical compensation to show the sun sensor algorithm, where the incident sunlight illuminates a picture to signal inside the quadrants on the detector plane. The signal was proportionate with the light area and the angle of the incident. A variety of scientific equations have also been used to solve potential errors due to the non-linear shift of the projected image and shifts in the solar beam's incident angle. The proposed algorithm could have better accuracy of 0.2° over the whole view area (62° for both axes). Chong *et al.* [32] proposed an inventive general sun-tracking formula to accurately track the sun with a 2.99 mrad maximum error. The said system can effectively enhance efficiency, reducing the cost of high-concentration systems.

In 2012, Grena [33] proposed a new, simple open-loop algorithms to ensure high accuracy in the sun's direction by uniform fractions of length, time, and distance. The algorithm tests the rotational axis of the earth's ecliptic angle and inclination angle to calculate the exact location of the sun on the Elliptical Plane. Most of these algorithms indicate that the open-loop method's error are monitored between 0.0003°

and 0.0027°. In 2013, Omara and Eltawil [34] designed and installed a solar-powered open-loop PLC control system for a dual-axis solar dish concentrator. The system rotates the collector at a constant rate of 15°/h, corresponding to the earth's rotational speed, and performed well when the wind velocity remained within a range of up to 2.0 m/s. The results show that their daily efficiency is 68%. Three years later, Skouri *et al.* [35] conducted a comparative study with a commercial tracker of the three sun-tracking systems. The tracker's total price is estimated to be about 1300 euros, based on efficiency and economic criteria, and its tracking error is less than 0.2°. Yang *et al.* [36] developed a dual-axis open-looped concentrated STS without the additional power. Sunlight concentration was made possible using Fresnel lens module on Stirling Engine's heading head. The said STS uses solar PV for its power supply. During the experiment, the heating head reached a 900^{o}C. Recently, Shufat, Kurt, and Hancerlioğulları [37] designed a two-axis automatic parabolic dish tracking system that can raise the concentrated sun radiation by up to 40% compared to fixed systems. The designed tracker used direct normal irradiation (DNI) and data of sun trajectory angles (azimuth and altitude) as a basis for the PLC programming. According to the present side, operating simulations were done via MATLAB/Simulink to identify tracking features to be applied during the site implementation. In line with the results above, numerous single- and double-axis trailer algorithms are easy to see, most of which produce reasonably good results to decide the sun's location in open-loop controls. However, a lot of preconceptions and experiments will be needed during and before the design process. We also want to explore more flexible solutions. The designer wants faster systems and hence the closing control system to describe its dynamic behavior and current operating conditions.

3.2. Closed-loop control strategies

Closed-loop ST primarily uses concept of control feedback in an open-loop system. In these systems, the inputs from solar sensors, camera images, or visually imported encoders are usually employed to trigger the drive's accuracy. This improves the overall accuracy of the solar panel's rotation, showing the its precise location in the air. In a closed-loop tracking solution, any variation between measured angles via an algorithm and synchronous positioning of the CSP can be observed and corrected. STS ensures that monitoring errors caused by wind effects, mechanical reverse effects, implementation mismatches, cumulative errors, or any other disorders in the parabolic dish's positioning can be remedied or avoided with this input. Figure 2 shows the generic structure of the solar tracker configuration.

The configuration of the closed-loop to the solar tracker's control system dramatically improves the system's performance. For instance, the solar power station efficiency increased from 357 W to 500 W when a closed-looped tracker is installed [38]. At the same time, Maish [39] designed an inexpensive and straightforward STS with the aim of improving daily tracking precision below 0.1°. A neural network controller was used for the Solar tracker system developed by Brown and Stone [40] to manage the error model to retain error below 0.01°, which shows improved controller performance. To improve the parabolic concentrator's thermal performance, Khalifa and Al-Mutawalli [41] constructed a dual-axis tracker, with sun-tracking capability every 3-4 minutes the azimuthal axis and 4-5 minutes in the altitude axis. Two adjacent phototransistors are provided in each axis to create voltage difference, which drives the STS. The tracking system is expected to consume 0.5 hours of energy and increase solar energy by approximately 75% compared to a fixed collector of the same size. Yousef [42] has also demonstrated fuzzy logic on the desktop computer, interfacing card, sensor, data processing module, driving circuits, signals, and serial communication module for solar tracker deployment. His results revealed the robustness of the fuzzy logic controller.

To trace solar altitudes with CSP systems, Falbel *et al.* [43], have suggested an algorithm using an analog dual-axis module to track and obtain accurate results with an allowed error below 0.05 ° of the sun for its optical axis. Luque-Heredia et al. [44] proposed an accurate sun tracker using 1,000X micro-concentrator modules. It uses a suitable algorithm to absorb unexpected or variable time errors by automatically calibrating low-cost, sun-starter sensors running in extreme winds with direct solar radiation of 95%.

Roth, Georgiev, and Boudinov [45] introduced the solar tracker using an algorithm for tracking sunlight via a closed servo belt, with a pyrheliometer. In the 4-quadrant sensor center, a digital camera was installed on a computer to capture the projected real-time sun images by the heliostats [46]. Images are continually captured and compared with the sun's radiation perpendicular to the heliostat. Any difference will re-orientate the solar beam to 90^{o} through servo motors. Aiuchi *et al.* [47] proposed two photosensor trackers to follow sunlight's reflected direction. The two image sensors were placed side-by-side in the system, partly illuminated by the solar system, on a box's base. Photosensor output signals were generated with an electrical signal based on the light's area to indicate the direction of reflected radiation, which were then used to adjust the mirror angle. Tracking Error of under 0.0006 rad, was achieved by the system.

Similarly, Alata *et al.* [48] demonstrated the design and simulation of step sun-tracking systems, which includes i) a latitude tilt axis, ii) dual-axis equatorial, and iii) azimuth/altitude. For modeling and control architecture, Sugeno's first-order fuzzy inference method is used. The simulation results indicate that trackers and time-controlled systems with low energy consumption are capable of providing advantages. Lee *et al*. [49] investigated the development of the sun-post sensor and algorithm to use sunscreen imagery properly. However, when low irradiation occurs, either of them cannot maintain high precision. The solar position sensor based on image vision will fix the downside. The findings demonstrate that the Sun tracking device will solve cloud-based weather uncertainty and achieve a tracking precision of 0.04°.

In 2016, Patil *et al*. [50] carried out an experimental study using Arduino with its five light-dependent resistors (LDR) to detect and collect the maximum solar energy using two-axis automatic solar trackers. The two DC engine permanent motors were developed with an algorithm to detect sunbeam in 20 minutes. Rahimoon *et al.* [51], just recently prototyped a low-cost Arduino automated control system for a 1.22 m diameter parabolic Stirling engine dish following an algorithm that was demonstrated. Although it is still in a prototype stage, it proved to be powerful since 210W/m^2 at 21.6° C could be achieved.

Ruelas *et al*. [52] the following year, proposed a microcontroller-based sensor with a synchronous clock, a geo-location inertial measurement sensor, and an angle of incidence, tilt position, and sensor position. The sensor representation showed how the accuracy of 0.0426° and 0.986 percent uncertainty could be measured to achieve accuracy below 0.01° for a tracking error. The confirmation of this sensor has been identified, and the concentration error has been shown in Kipp and Zone SOLYS 2. Carballo *et al.* [53] new approach to the computer screen, low-cost hardware, and in-depth solar tracking systems training. The preliminary test performed successfully at the solar aleria platform (PSA) showed great potential. New approaches offer STS' essential controlled variables, such as cloud transient forecasting, blocking and shadow detection, air damping, or concentrated solar radiation measurement, thus enhancing system and system control strategies per system. Examining these techniques and algorithms and extensive neural network training will be part of future work to further improve the results achieved while reducing calculation costs. Wardhana, Ashari, and Suryoatmojo [54] recently developed a closed-loop system for a two-stage parabolic dish concentrator utilizing figures from gyrosensors and thermocouples. The feedback controller applied fuzzy logic based on tuning up the optimization at genetic algorithm-simple additive weighting (GA-SAW) to maintain the optimal temperature condition on the absorber receiver. Results reveal better power output and heat flux increased up to 62.49%.

One downside to closed-loop STS control is the recovery from extended periods of cloud cover will be troublesome using the PLC system. Optical observation's solar vector may be challenging to establish in the absence of guidance from an astronomical algorithm. The case is valid if the sun has passed beyond the sun sensor/imaging camera's field of view or if the sun's direction is no longer in the optical device's field of view. An optical feedback approach can be used more effectively in hybrid-loop control strategies to solve this problem. In the following section, a hybrid open/closed-loop tracking control will be discussed to overcome closed-loop control limitations.

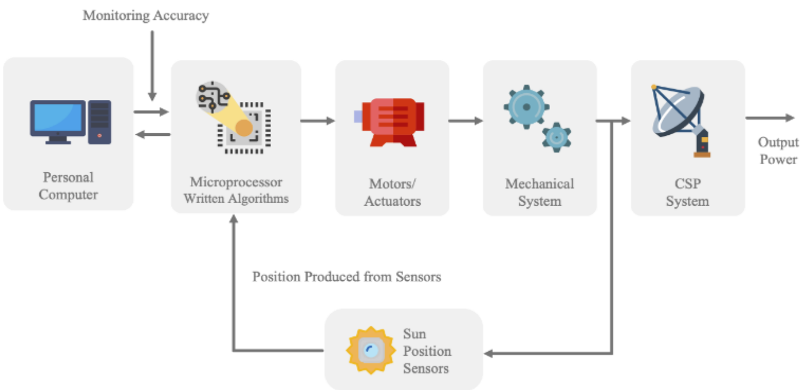

Figure 2. Generic configuration of a close-loop solar tracking system

3.3. Hybrid-loop control

Solar tracker hybrid loop refers to an open-circuit approach in tandem with a closed-loop approach, as shown in Figure 3. To overcome the disadvantages of the open-loop controller, error from tracking the sun's position is added to generate an accurate alignment, assembly, and precision scheduling. Two types of hybrid STS controllers offer calibration and prevention approaches. Model-based calibration is based on mathematical errors in the model. Multiple systematic sources of error can be identified. After an apparent day of the session, tracking errors are measured; the template parameters are calibrated-part of the calibration process to correct the accumulated error data into a best-fit model. From then on, the calibrated model will be used on a purely open-loop basis without additional feedback requirements for error-tracking. The sun position algorithm for error correction will be based on estimates based on past error tracking measurements and iterative estimates without an error-modeling process.

It is Safan, Shaaban and Abu El-Sebah [55] who implemented a multi-degree freedom-simplified universal intelligent PID (MDOF-SUI PID) sun-tracking process controller. Their study reveals that the maximum tracking error achieved was ±0.0067 °. In addition to active tracking by using an image processing algorithm and a commercial webcam as a sensing element, Chauhan *et al.* [56] proposed an innovative hybrid active-passive solar tracker System is provided using GPS tracking with the SG2 algorithm's help. Analysis of the pictures acquired by a webcam allows accurate data from the azimuth position and the sun's altitude to be collected. The system's core advantage is its high flexibility to operate under extreme conditions when the sun's position is not very clear due to weather conditions such as cloud cover. Depending on the location's spatial coordinates, the System can track the sun both in real-time, regardless of the space-time coordination, and passively. The information extracted from the cam-GPS system is used to control the two servo motors, one for the azimuth and altitude axis of the solar tracker's dual mechanism, to achieve the optimal alignment of the payloads connected to the solar tracker to increase the power generation.

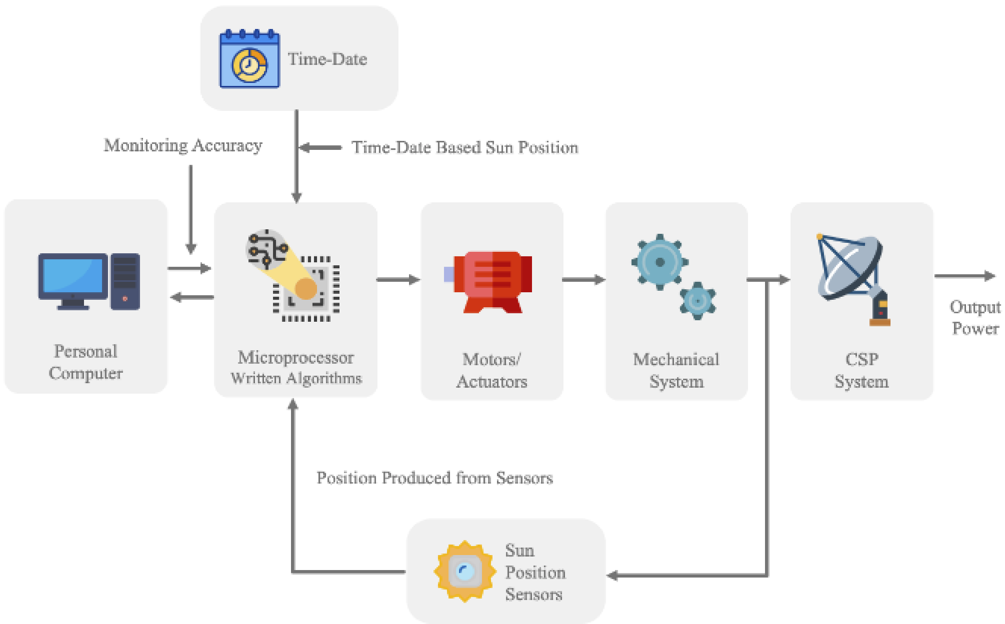

Figure 3. Generic configuration of a hybrid-loop solar tracking system

4. DISCUSSION

Upon analysis, it was realized that open-loop control with special and improved algorithm offers greater tracking accuracy and solar to energy efficiency (SEE) compared with close-loop control. This control is ideal mostly with PDSCs with large diameter. Closed-loop control through its new approaches in its sensor characterization and approaches, make it available for PDSCs with greater power capacities and arrive with greater thermal efficiency. Hybrid-loop on the other end, offer both advantages and implementations fit the need for microscale installations. Table 1 in APPENDIX summarizes recent advances in sun-tracking strategies. Also, efficiency, and comparative benefits and limits have been evaluated. Every control strategy has its own benefits, and its implementation depends on the cost, dish diameter and target capacity (KW) and modularity.

5. CONCLUSION AND FUTURE OUTLOOK

Increasing energy capacities on CSP for the past decades invites interesting development on one of its essential parts, the STS. This paper first presented practical design challenges and recent developments related to tracking strategies of PDSCs. The review leaves a call to scientists and control engineers to design improvements to the following i) to counter fluctuations in solar radiations which causes thermal stress in the cavity receiver, ii) reduce STS complexity which causes increased costs, iii) could withstand harsh environmental conditions when deployed to rural areas, and lastly iv) can make easy dish transitions against wind loads. This also paper analyzed tested algorithms, and sun sensors developed over the last 30 years for sun tracking strategies. Algorithms used for STS are categorized as open-looped, closed-looped, or hybrid in general. Each method was reviewed with control and computer principles. The study should, in the future, focus more on computer vision and artificial intelligence.

ACKNOWLEDGEMENTS

The researchers would like to thank the experts who were involved in the validation of this study. Without them, the researchers might not meet their objectives in doing this study. To Dr. Michael Abundo and Dr. Eleonor Palconit who also contributed in the success of this study.

APPENDIX

Table 1. Recent advancements in parabolic dish tracking strategies

Ref.	Degree of freedom	Control module	Description of investigated strategy	Performance and significant gains
			Open loop control strategies	
[25]	Dual-axis	µC	Improved tracking capabilities using the astronomical coordinates of the sun.	Tracking error lesser than 1º
[26]	-	µC	Determines the actual solar vector for 1999–2015 with 0.5 minutes of arc.	Azimuth and zenith is 15% and 22% better than previous Algorithms.
[27]	-	µC	The sun's position is determined by calculating the sun's celestial bearing to the earth, the sun is determined by latitude, longitude, date and time zone.	Average Error on X-Tilt, Y-Tilt and prim-to-sec distance is +0.089°, -0.209° and -1.55 mm respectively.
[28]	Dual-axis	PLC	The control programming algorithm is based on solar angle analysis and motor speed calculations through PLC	Increased energy accumulation by around 41.34% over a fixed 32° surface.
[29]	-		The solar zenith and azimuth angles measurement process from 2000 to 6000 was progressively established. The incidence angle of the surface tiled with any horizontal or vertical angle was also calculated.	Tracking error lesser than 0.0003°
[30]	-		Used a novel optical vernier measuring principle that is accurate and has large FOV.	In the whole FOV (visual field), the precision is ±64 º better than 0.02º (arc approx. 1 minute).
[31]	-		The algorithm tests the rotational axis of the Earth's ecliptic angle and inclination angle to calculate the exact location of the Sun on the Eclical Plane.	The tracking errors are between 0.0003 ° and 0.0027 °.
[32]	Dual-axis		The computer program uses the three unknown angles of orientation to be measured in practice, not precisely by the instruments, i.e., φ, λ, and ζ.	There has been a maximum point error of 2.99 mrad, which is below the 4.13 mrad encoder resolution limit.
[34]	Dual-axis	PLC	Used a special approach to the position of the sun in relation to a solar collector tracking device.	Its daily average efficiency is 68%.
[35]	-		They developed an algorithm focusing on solar tracker performance and cost-effectiveness. The algorithm uses time and geographic parameters to determine sun angles as a time angle and angle of decay. Solar information is then used in the horizontal plane to recognize diffuse and direct radiation elements.	Tracking error is inferior to 0.2°.
[36]	-		The sun was tracked by a constant angle tracking method. Photovoltaic and photothermal devices can be combined with more solar energy.	The temperature of the heating head reached around 900 °C under a cloudless environment.
[37]	-	PLC	Simulations were carried out with high efficiency using azimuth and altitude data for the DNI values of Kufra city in Libya.	The operating DNI is equivalent to 80% to 90% of the total sun DNI.
			Closed loop control strategies	
[39]	Dual-axis	Solar trak	It consists of two counter-sensors on every axis, a limit switch, and the angle reference sensor for reference to fixed hardware's internal counter location.	Accuracies of better than ± 0.1 have been achieved.
[40]	-	µC	Using a neural network controller, the error model is managed and the neural network controller performs better.	Tracking error lesser than 1º
[41]	-	-	Two identical subunits and two adjacent phototransistors with a differential voltage are used to track the sun to detect the sun's location.	The tracking system was said to have a power consumption of 0.5 Whr and increase solar energy by around 75% compared to a fixed collector of the same sizes.
[42]	-	-	Fuzzy logic was shown for implementing solar tracker on personal computers, interfaces, sensors, data acquisition modules, circuits, and signal conditioning circuits.	It achieved positive results that revealed the Fuzzy logic controller's robustness.
[43]		µC	Uses 100 deg sun FOV sensor where in-flight software program use to manage interpolation of the matrix points.	It achieved ±, 0.5 solar position accuracy.

Table 1. Recent advancements in parabolic dish tracking strategies *(continue)*

Ref.	Degree of freedom	Control module	Description of investigated strategy	Performance and significant gains
[44]	-	-	Includes a control unit that relies on an adaptive algorithm to absorb unexpected or time-variate errors by self-calibrating low-cost, sun-starter sensors.	Remained in high-wind operations accounting for 95% of the direct solar radiation available.
[45]	Dual-axis	-	Calculated direct solar radiation with a pyrheliometer. The axes' speeds are relatively low, but the system's design ensures a long time without costly maintenance.	The demonstrated tracker illustrates the practical working of a cost-effective and uncomplicated mechanism adapted for use in more effective systems such as solar cell panels.
[46]		PC	Used binary color CCD camera (4-quadrant) to correct solar position deviations and AI to control heliostat to point collected solar radiation to the receiver.	Images are continually captured and compared with the sun's radiation perpendicular to the heliostat. Any difference will re-orientate the solar beam to 90º through servo motors.
[47]	-	-	Two photosensor trackers monitored the reflected path of solar radiation. Both image sensors were mounted side by side at the base of the box, partially illuminated by the device's sunlight.	Tracking error of less than 0.0343775º
[48]	-	-	The controller was developed with a flashy logic platform, and the input and output signal were generated with a squarely less subtractive cluster algorithm.	The robust logic was demonstrated, and the results were satisfactory.
[49]	-	-	Four-quadrant sensors and bar-shadow photosensors have been used to track the location of the sun over recent years. Nevertheless, in low irradiation conditions, neither can achieve high accuracy. This downside will be addressed by the Solar position sensor based on the image.	Tracking accuracy of 0.04°.
[50]	-	µC	Experimental study using Arduino with its five light-dependent resistors (LDR) to detect and collect the maximum solar energy using two-axis automatic solar trackers.	Able to detect sunbeam in 20 minutes.
[51]	-	µC	A low-cost Arduino automated control system for a 1.22 m diameter parabolic Stirling engine.	It proved to be powerful since 210 W / m^2 at 21.6 °C could be achieved.
[52]	-	-	The proposed sensor consists of a real-time clock microcontroller, geo-location inertial measuring sensor, sunlight incident angle, tilt position, and sensor position.	The sensor characterization showed how the precision of 0.0426 ° and uncertainty of 0.986 percent could be calculated to achieve a precision under 0.01 °
[53]	-	-	A new approach to computer-screen, low-cost hardware, and profound training solar tracking systems	Provided essential variables in controlling the sun tracking system, such as the cloud movement forecasts, blocking and shadow detection, air damping, or concentrated solar radiation measurement, thus enhancing system and system control strategies per system
[54]	-	-	A new Fuzzy Logic system based on Dual Parabolic Dish Concentrator Optimization Tuning for Genetic Algorithm-simple additive weighting (DS-SAW).	In this investigation, the acquired fuzzy controller's result was 0.497 seconds on average, and the average increase was 0.277 seconds faster than the standard PID controller.
		Hybrid loop control strategies		
[55]	-	-	A hybrid control strategy has been implemented, and the sun tracking process has included the multi-degree reformed MDOF-SUI PID controller.	Achieved a maximum tracking error of ±0.0068 °.
[56]	-	-	Innovative hybrid active-passive solar tracker system with GPS tracking using SG2, the quick implementation of the popular SPA, combined with active tracking with image processing algorithms and a commercial webcam.	The system can monitor the sun both in real-time, irrespective of space-time synchronization and passively per spatial location coordinates.

REFERENCES

[1] ClientEarth, "Fossil fuels and climate change: the facts," 2022. https://www.clientearth.org/latest/latest-updates/stories/fossil-fuels-and-climate-change-the-facts/ (accessed Apr. 07, 2022).

[2] G. M. Wilson *et al.*, "The 2020 photovoltaic technologies roadmap," *Journal of Physics D: Applied Physics*, vol. 53, no. 49, 2020, doi: 10.1088/1361-6463/ab9c6a.

[3] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strategy Reviews*, vol. 24, pp. 38–50, 2019, doi: 10.1016/J.ESR.2019.01.006.

[4] REN21, "Renewables 2019 Global Status Report Collaborative," vol. 105, 2019.
[5] M. T. Islam, N. Huda, and R. Saidur, "Current energy mix and techno-economic analysis of concentrating solar power (CSP) technologies in Malaysia," *Renewable Energy*, vol. 140, pp. 789–806, 2019, doi: 10.1016/j.renene.2019.03.107.
[6] A. K. Pandey, R. K. R, and M. Samykano, "Chapter 1 - Solar energy: direct and indirect methods to harvest usable energy," A. K. Pandey, S. Shahabuddin, and M. S. B. T.-D.-S. S. C. Ahmad, Eds. Academic Press, 2022, pp. 1–24.
[7] G. Simbolotti, "Concentrating Solar Power Technology Brief," *IEA-ETSAP and IRENA*, 2013.
[8] G. Prinsloo and R. Dobson, "Combined solar heat and power with microgrid storage and layered smartgrid control toward supplying off-grid rural villages," *Energy Science & Engineering*, vol. 3, no. 2, pp. 135–144, 2015, doi: 10.1002/ese3.57.
[9] I. Stamatescu, I. Făgărăşan, G. Stamatescu, N. Arghira, and S. S. Iliescu, "Design and implementation of a solar-tracking algorithm," *Procedia Engineering*, vol. 69, pp. 500–507, 2014, doi: 10.1016/j.proeng.2014.03.018.
[10] J. Fang, C. Zhang, N. Tu, J. Wei, and Z. Wan, "Thermal characteristics and thermal stress analysis of a superheated water/steam solar cavity receiver under non-uniform concentrated solar irradiation," *Applied Thermal Engineering*, vol. 183, p. 116234, 2021, doi: 10.1016/j.applthermaleng.2020.116234.
[11] E. Sani, L. Mercatelli, P. Sansoni, L. Silvestroni, and D. Sciti, "Spectrally selective ultra-high temperature ceramic absorbers for high-temperature solar plants," *Journal of Renewable and Sustainable Energy*, vol. 4, pp. 33104, 2012, doi: 10.1063/1.4717515.
[12] G. Augsburger and D. Favrat, "Modelling of the receiver transient flux distribution due to cloud passages on a solar tower thermal power plant," *Solar Energy*, vol. 87, pp. 42–52, 2013, doi: 10.1016/j.solener.2012.10.010.
[13] M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia, "Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate," *Energy Conversion and Management*, vol. 69, pp. 163–173, 2013, doi: 10.1016/j.enconman.2013.02.005.
[14] E. W. Ramde, E. T. Tchao, Y. A. Fiagbe, J. J. Kponyo, and A. S. Atuah, "Pilot Low-Cost Concentrating Solar Power Systems Deployment in Sub-Saharan Africa: A Case Study of Implementation Challenges," *Sustainability*, vol. 12, no. 15. 2020, doi: 10.3390/su12156223.
[15] G. J. Prinsloo, "Automatic positioner and control system for a motorized parabolic solar reflector," Department of Mechanical and Mechatronic Engineering, Faculty of Engineering, Stellenbosch University 2014.
[16] M. Geyer, R. Aringhoff, S. Teske, and G. Brakmann, "Concentrated solar thermal power-now!," Greenpeace, ESTIA, SolarPACES Brochure, 2005.
[17] W. Nsengiyumva, S. G. Chen, L. Hu, and X. Chen, "Recent advancements and challenges in solar tracking systems (STS): A review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 250–279, 2018, doi: 10.1016/j.rser.2017.06.085.
[18] W. Bisenius, "Degrees of Protection Provided by Enclosures (IP Code)," Assoc. Electr. Equip. Med. Imaging, 2012.
[19] J. A. Peterka, Z. Tan, B. Bienkiewicz, and J. E. Cermak, "Wind loads on heliostats and parabolic dish collectors; final subcontractor report," United States: N. p., 1988.
[20] R. H. McFee, "Power collection reduction by mirror surface nonflatness and tracking error for a central receiver solar power system," *Applied Optics*, vol. 14, no. 7, pp. 1493–1502, 1975, doi: 10.1364/AO.14.001493.
[21] R. P. Semma and M. S. Imamura, "Sun tracking controller for multi-kW photovoltaic concentrator system," In: *Palz, W, (eds) Photovoltaic Solar Energy Conference*, Springer, Dordrecht, doi: 10.1007/978-94-009-8423-3_54.
[22] M. Shahabuddin, M. A. Alim, T. Alam, M. Mofijur, S. F. Ahmed, and G. Perkins, "A critical review on the development and challenges of concentrated solar power technologies," *Sustainable Energy Technologies and Assessments*, vol. 47, p. 101434, 2021, doi: 10.1016/j.seta.2021.101434.
[23] R. F. Fuentes-Morales *et al.*, "Control algorithms applied to active solar tracking systems: A review," *Solar Energy*, vol. 212, pp. 203–219, 2020, doi: 10.1016/j.solener.2020.10.071.
[24] S. Racharla and K. Rajan, "Solar tracking system–a review," *International Journal of Sustainable Engineering*, vol. 10, no. 2, pp. 72–81, 2017, doi: 10.1080/19397038.2016.1267816.
[25] F. M. Al-Naima and N. A. Yaghobian, "Design and construction of a solar tracking system," *Solar & Wind Technology*, vol. 7, no. 5, pp. 611–617, 1990, doi: 10.1016/0741-983X(90)90072-A.
[26] M. Blanco-Muriel, D. C. Alarcón-Padilla, T. López-Moratalla, and M. Lara-Coira, "Computing the solar vector," *Solar Energy*, vol. 70, no. 5, pp. 431–441, 2001, doi: 10.1016/S0038-092X(00)00156-0.
[27] D. Beshears *et al.*, "Tracking Systems Evaluation for the 'Hybrid Lighting System," *Proceedings of the ASME 2003 International Solar Energy Conference*, 2003, pp. 699-708, doi: 10.1115/ISEC2003-44055.
[28] S. Abdallah and S. Nijmeh, "Two axes sun tracking system with PLC control," *Energy Conversion and Management*, vol. 45, no. 11, pp. 1931–1939, 2004, doi: 10.1016/j.enconman.2003.10.007.
[29] I. Reda and A. Andreas, "Solar position algorithm for solar radiation applications," *Solar Energy*, vol. 76, no. 5, pp. 577–589, 2004, doi: 10.1016/j.solener.2003.12.003.
[30] F. Chen and J. Feng, "Analogue sun sensor based on the optical nonlinear compensation measuring principle," *Measurement Science and Technology*, vol. 18, no. 7, pp. 2111, 2007, doi: 10.1088/0957-0233/18/7/042.
[31] F. Chen, J. Feng, and Z. Hong, "Digital sun sensor based on the optical vernier measuring principle," *Measurement Science and Technology*, vol. 17, no. 9, pp. 2494, 2006, doi: 10.1088/0957-0233/17/9/017.
[32] K. K. Chong *et al.*, "Integration of an on-axis general sun-tracking formula in the algorithm of an open-loop sun-tracking system," *Sensors*, vol. 9, no. 10, pp. 7849–7865, 2009, doi: 10.3390/s91007849.
[33] R. Grena, "Five new algorithms for the computation of sun position from 2010 to 2110," *Solar Energy*, vol. 86, no. 5, pp. 1323–1337, 2012, doi: 10.1016/j.solener.2012.01.024.
[34] Z. M. Omara and M. A. Eltawil, "Hybrid of solar dish concentrator, new boiler and simple solar collector for brackish water desalination," *Desalination*, vol. 326, pp. 62–68, 2013, doi: 10.1016/j.desal.2013.07.019.
[35] S. Skouri, A. B. H. Ali, S. Bouadila, M. B. Salah, and S. B. Nasrallah, "Design and construction of sun tracking systems for solar parabolic concentrator displacement," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1419–1429, 2016, doi: 10.1016/j.rser.2016.03.006.
[36] C.-K. Yang, T.-C. Cheng, C.-H. Cheng, C.-C. Wang, and C.-C. Lee, "Open-loop altitude-azimuth concentrated solar tracking system for solar-thermal applications," *Solar Energy*, vol. 147, pp. 52–60, 2017, doi: 10.1016/j.solener.2017.03.014.
[37] S. A. A. Shufat, E. Kurt, and A. Hancerlioğulları, "Modeling and design of azimuth-altitude dual axis solar tracker for maximum solar energy generation," *International Journal of Renewable Energy Development*, vol. 8, no. 1, pp. 7–13, 2019, doi: 10.14710/ijred.8.1.7-13.
[38] K. A. Akhmedyarov, B. A. Bazarov, B. Ishankuliev, and Kh. E. Karshenas, "Economic efficiency of the FV-500 solar photoelectric station with automatic tracking of the sun," *Applied Solar Energy*, no. 22, pp. 44–47, 1986.
[39] A. B. Maish, "Performance of a self-aligning solar array tracking controller," *IEEE Conference on Photovoltaic Specialists*, 1990, pp. 864-869 vol. 2, doi: 10.1109/PVSC.1990.111744.

[40] D. Brown and K. Stone, "High accuracy/low cost tracking system for solar concentrators using a neural network," *SAE, WARRENDALE, PA(USA)*, 1993, pp. 577-584.

[41] A.-J. N. Khalifa and S. S. Al-Mutawalli, "Effect of two-axis sun tracking on the performance of compound parabolic concentrators," *Energy Conversion and Management*, vol. 39, no. 10, pp. 1073–1079, 1998, doi: 10.1016/S0196-8904(97)10020-6.

[42] A. Z. Hafez, A. M. Yousef, and N. M. Harag, "Solar tracking systems: Technologies and trackers drive types – A review," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 754–782, 2018, doi: 10.1016/j.rser.2018.03.094.

[43] G. Falbel, J. P. Suari and A. Peczalski, "Sun oriented and powered, 3 axis and spin stabilized CubeSats," *Proceedings, IEEE Aerospace Conference*, 2002, pp. 1-1, doi: 10.1109/AERO.2002.1036864.

[44] I. Luque-Heredia *et al.*, "A subdegree precision sun tracker for 1000X microconcentrator modules," *3rd World Conference onPhotovoltaic Energy Conversion, 2003. Proceedings of*, 2003, vol.1, pp. 857-860.

[45] P. Roth, A. Georgiev, and H. Boudinov, "Design and construction of a system for sun-tracking," *Renewable Energy*, vol. 29, no. 3, pp. 393–402, 2004, doi: 10.1016/S0960-1481(03)00196-4.

[46] M. Berenguel *et al.*, "An artificial vision-based control system for automatic heliostat positioning offset correction in a central receiver solar power plant," *Solar Energy*, vol. 76, no. 5, pp. 563–575, 2004, doi: 10.1016/j.solener.2003.12.006.

[47] K. Aiuchi, K. Yoshida, Y. Katayama, M. Nakamura, and K. Nakamura, "Sun tracking photo-sensor for solar thermal concentrating system." *Proceedings of the ASME 2004 International Solar Energy Conference, Solar Energy*, Portland, Oregon, USA, 2004. pp. 625-631, doi: 10.1115/ISEC2004-65025

[48] M. Alata, M. A. Al-Nimr, and Y. Qaroush, "Developing a multipurpose sun tracking system using fuzzy control," *Energy Conversion and Management*, vol. 46, no. 7, pp. 1229–1245, 2005, doi: 10.1016/j.enconman.2004.06.013.

[49] C-D. Lee, H-C. Huang, and H-Y. Yeh, "The development of sun-tracking system using image processing," *Sensors*, vol. 13, no. 5, pp. 5448–5459, 2013, doi: 10.3390/s130505448.

[50] P. N. Patil, M. A. Khandekar and S. N. Patil, "Automatic dual-axis solar tracking system for parabolic dish," *2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)*, 2016, pp. 699-703, doi: 10.1109/AEEICB.2016.7538383.

[51] A. A. Rahimoon, M. N. Abdullah, D. M. Soomro, M. Y. Nassar, Z. A. Memon, and P. H. Shaikh, "Design of parabolic solar dish tracking system using arduino," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 17, no. 2, pp. 914–921, 2020, doi: 10.11591/ijeecs.v17.i2.pp914-921.

[52] A. Ruelas, N. Velázquez, L. A. G. Uribe, C. Villa-Angulo, and O. García, "Design, implementation and evaluation of a solar tracking system based on a video processing sensor," *International Journal of Advanced Research in Computer Science and Software Engineering (IJARCSSE)*, vol. 3, pp. 172–178, 2013.

[53] J. A. Carballo, J. Bonilla, M. Berenguel, J. F. Reche, and G. García, "New approach for solar tracking systems based on computer vision, low cost hardware and deep learning," *Renewable Energy*, pp. 1158–1166, 2019, doi: 10.1016/j.renene.2018.08.101.

[54] A. S. Wardhana, M. Ashari, and H. Suryoatmojo, "Optimal control of robotic arm system to improve flux distribution on dual parabola dish concentrator," *International Journal of Intelligent Engineering and Systems*, vol. 13, no. 1, pp. 364–378, 2020, doi: 10.22266/ijies2020.0229.34.

[55] Y. M. Safan, S. Shaaban and M. I. A. El-Sebah, "Hybrid control of a solar tracking system using SUI-PID controller," *2017 Sensors Networks Smart and Emerging Technologies (SENSET)*, 2017, pp. 1-4, doi: 10.1109/SENSET.2017.8125035.

[56] I. S. Chauhan, P. Kumara, S. Ahmad, and D. Mohan, "Development of a hybrid active-passive solar tracker using GPS tracking and image processing," *Journal of Environmental Nanotechnology*, vol. 7, no. 4, pp. 9–15, 2018, doi: 10.13074/jent.2018.12.184327.

BIOGRAPHIES OF AUTHORS

Franch Maverick Lorilla is an Associate Professor at the College of Technology-Energy Management Systems of the University of Science and Technology of the Philippines (USTP) and currently designated as a Technology Business Incubation (TBI) Manager of the CDObites. He was formerly a startup founder and COO of CloudFarm Innovations from 2016-2018, for which he gained insights and experience, however with the passion to help more startups, he started his career as a startup enabler through managing incubators since 2018. To date, he was able to lead channel funds of more than 24.5 M funding for R&D and Non-R&D grants to facilitate innovation activities and established infrastructures that helped startups to reached revenue of total 45M and more than 1500 participants trained as the resource person in startup series lectures. He is currently pursuing his Doctor of Engineering in Energy Systems Management at the Ateneo de Davao University. His research interest are Internet of Things, Renewable Energy, and Computer Vision. He can be contacted at email: franchmaverick.lorilla@ustp.edu.ph and fmalorilla@addu.edu.ph.

Renyl B. Barroca is a Doctor of Engineering in Mechanical Engineering. He obtained his degree at the Mindanao State University-Iligan Institute of Technology. Dr. Barroca is currently the Assistant Dean and a faculty member of the School of Engineering and Architecture of the Ateneo de Davao University, Davao City. Dr. Barroca has been working on research and development that is meant to benefit rural communities in Mindanao in the fields of renewable energy, specifically micro-hydro turbines, wind turbines, and solar thermal technology. He can be contacted at email: rbbarroca@addu.edu.ph.