Intelligent single-axis solar tracking system for enhanced energy harvesting efficiency

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ABSTRACT

The need for efficient clean energy solutions has increased due to population growth, climate change, and the development of industries. Among these, the most valuable clean and sustainable alternative is solar energy, i.e., photovoltaic (PV) technology. However, the key challenge is represented by maximizing the PV systems' efficiency. This paper proposes an IoT-enabled single-axis solar tracking system for improving PV by constantly aligning solar panels with the trajectory of the sun. To achieve that, an Arduino microcontroller is integrated with light-dependent resistors (LDRs). LRDs perform real-time detection of solar irradiance in order to adjust along with the azimuth axis. Based on the experimental results, the IoT-enabled single-axis solar tracking system improves energy harvesting by comparing with fixed-tilt PV. The proposed system outperforms the fixed-tilt PV by 22.5% in daily energy yield and average power output. Furthermore, tracking efficiency is better than fixed-tilt PV by 96.3% and tracking error of 3.7%.

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1. INTRODUCTION

Energy is vital for the sustainable growth of industry and improving nations' lives. An increasing population, with expected increases in duration and intensity of extreme weather, increases the demand for energy. The global renewable energy production capacity was 3064 GW in 2021 and increased to 4448 GW in 2024 [1]. Therefore, the demand for energy has increased due to population growth and industrial expansion. Another reason for the demand for energy is the climate conditions change and temperature rise [2], [3]. This demand caused the world to face energy deficiency problems led to look for other energy sources. Some of these alternative sources are solar, wind, and nuclear sources. Solar energy is considered the cleanest energy source. The sun is one of the most powerful and clean energy sources available to humans. However, the energy collected by solar panels often depends on their position in relation to the sun. Static (or fixed) solar panels cannot adjust to these changes, which leads to lower efficiency. The estimated power received from the sun is about $1.8*10^{11}$ MW [4]. Solar energy from photovoltaic (PV) technologies is rapidly increasing as a vital means of renewable energy resource. Solar PV is capable of supporting diverse applications such as water desalination [5], [6]. However, to maximize the production and efficiency of the PV panels in a changing climate remains a challenge. A solar tracking system is a good alternative to increase the energy. The system improves capturing energy since it follows the sun's movement, which keeps the panels aligned for maximum sunlight exposure [7], [8].

Solar power has become one of the most prominent sources of clean energy. The energy harvested by the solar system is influenced by the changes in climate. Solar tracking technologies enhanced the photovoltaic production. There are three methods to extract energy from the sun using solar panels. These methods are: fixed (static), single-axis tracking (SAT), and dual-axis tracking (DAT) methods [9]-[12]. There are two primary methods for maximizing solar production. These methods are the single and the DAT systems. Single-axis follows the sun by rotating along one axis. The rotation takes place from east to west. It enhances energy production by keeping panels always aligned with the sun's trajectory. The DAT system has two degrees of movement. That is, it can move along two axes, both east-west and north-south; this enables the system to track the sun with more precision during the whole day. A single-axis tracker has an efficiency of approximately 30% over the fixed-tilt (static) solar panel, while the DAT can increase efficiency by about 36% [7]. Karabiber and Güneş [13] proposed a solar tracking system that increases the energy obtained using photovoltaic approximately from 25% and 38% over the static solar system. Various environmental factors can significantly degrade the production of solar panel such as dust, dirt, shadows, and bird droppings [14]. A thorough and profound review of SAT systems is presented in [15], [16].

In this paper, we propose the usage of a single-axis tracking system to improve the production of solar panels by spontaneously regulating their angle according to the movement of the sun and maintaining the best possible alignment throughout the day. The main parts of the system are the Arduino controller and the LDR sensors. The system employs the LDR sensors to find out the surrounding amount of light and allow to move the solar panels in azimuth and elevation axes directions.

2. METHOD

2.1. IoT-enabled single-axis tracking (SAT) system overview

In this paper, the IoT-enabled SAT system is proposed. The overview of the system is presented in Figure 1. It is designed to automatically align the PV unit toward the sun during the day. The system integrates hardware components with software control logic. Hardware components are represented as sensors, actuators, and a microcontroller. Software control logic interprets real-time light intensity data to optimize the solar panel's azimuthal orientation. Maximizing harvesting of solar radiation and energy output, in addition to exploiting IoT connectivity to enable remote supervision, is the key objective.

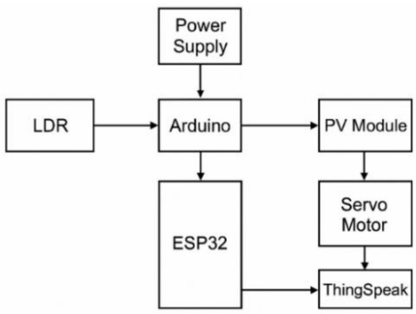

Figure 1. IoT-enabled single-axis tracking system overview

2.2. Hardware design

The hardware design of the proposed IoT-enabled SAT system consists of the following core components.

2.2.1. Panel unit

PV panel converts light energy directly into electricity. That is, it utilizes solar cell arrays to generate electric power. It consists of interconnected individual cells that generate DC current, which can be transformed to AC current. The PV absorbs the photons from the light and releases electrons in the solar panel. Most PV cells are made from crystalline silicon and produce current proportional to the solar radiation level [17]-[20]. Figure 2 displays a solar panel.

2.2.2. Sensing unit

This unit is represented by the LDR sensor. It is a photo resistor used to measure the strength of light [21]. The resistance of an LDR sensor diminishes as the light strength increases. In our case, the intensity of the sunlight. A general LDR sensor's resistance against light intensity is shown in Figure 3.

Figure 2. A typical solar panel

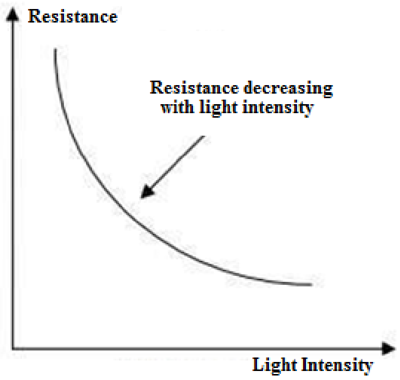

Figure 3. General LDR sensor resistance against light intensity

2.2.3. Control unit

This unit is represented by the Arduino Uno microcontroller. It processes the LDRs' analog signals. It has digital /analog I/O pins that can be interfaced with other circuits. Arduino microcontroller has the ability to read inputs from other components and make outputs to other instruments such as motors [22], [23]. Figure 4 displays an Arduino microcontroller.

2.2.4. Actuation unit

The SG90 motor is used for the rotation of the solar panel. SG90 is controlled by a PWM signal for a period of 20 ms [25], [26]. The angle of the rotation of the motor is monitored and commanded by the Arduino and can rotate from 0° to 180°. The SG90 motor is displayed in Figure 5.

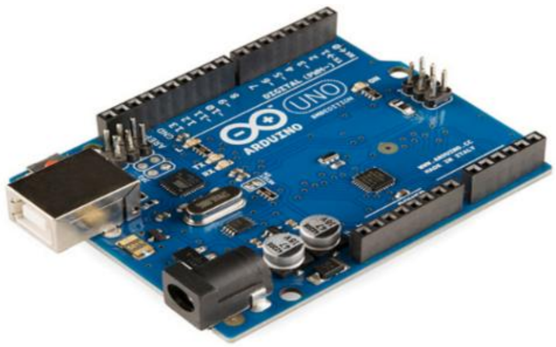

Figure 4. Arduino microcontroller board [24]

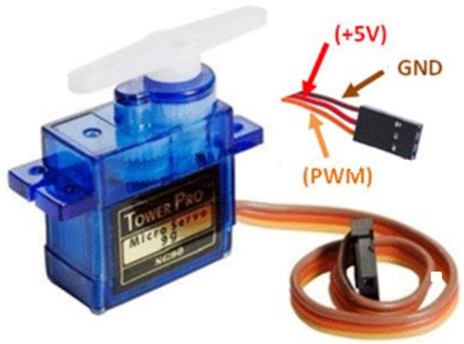

Figure 5. SG90 servo motor pinout [25]

2.2.5. IoT-based communication unit

The importance of this unit is in supporting data storage and real-time performance visualization. This is fulfilled by an ESP32 Wi-Fi module interface, which is interfaced with Arduino. This interface transfers the parameters of the system, i.e., irradiance, voltage, and the angle of the panel, to the ThingSpeak cloud server using the MQTT protocol.

2.3. The control logic and software implementation

The implementation of the software was developed by Arduino IDE. The values of the real-time analog voltage generated by LDR sensors, represented by LDR_1 and LDR_2. These values are continuously compared to predefine the threshold ΔV_{th}. The value of ΔV_{th} is predefined by calculating the difference between $| LDR_1 - LDR_2 |$. If $| LDR_1 - LDR_2 |$ value is larger than ΔV_{th}, the servo motor is activated by the control unit to rotate the PV unit towards the top lighting side. Meanwhile, the PV remains stable when the values are balanced. That is, when the $VLDR$ values are approximately equal.

The flow chart in Figure 6 represents the control logic of the proposed system. The system operates according to the following sequences: i) Initialization by activating the all system units such as sensors, motor servo, in addition to WIFI modules; ii) Read sequence that read the LDR analog values; iii) Comparing, which compares the difference of LDR values ($| LDR_1 - LDR_2 |$) and the threshold (ΔV_{th}); iv) Determining sequence which decides to rotate the panel direction left or right. Accordingly, the angle (θ) of the servo motor is gradually adjusted to reduce the light difference; and v) The uploaded sequence, which sends the data represented by the current system parameters to the ThingSpeak cloud server. The mentioned sequences are repeated every ten-second interval for continuous alignment.

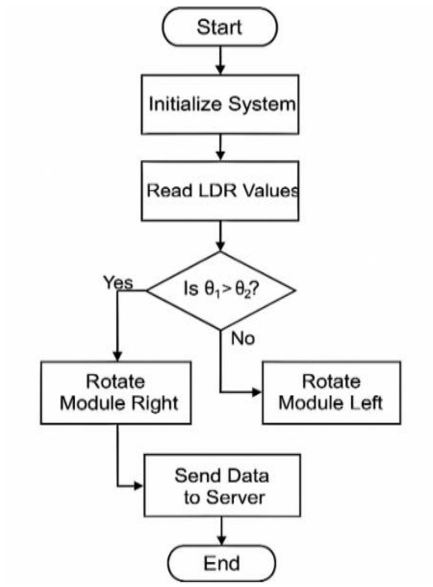

Figure 6. Control logic of the proposed system

3. RESULTS AND SIMULATION

3.1. Simulation setup

Performance evaluation of the SAT proposed system is conducted using MATLAB/Simulink and Proteus IoT Suite. The system components and technical specifications of the simulation are represented in Table 1.

Table 1. System components and technical specifications

Component	Description/function	Specification/parameter
Microcontroller	Central control unit for sensor data acquisition and IoT communication.	ESP32; supports Wi-Fi and MQTT protocol.
Sensors	Detect differential solar irradiance for tracking adjustment.	Dual LDRs positioned at ±15° from panel center axis.
Actuator	Adjusts the solar panel's orientation according to sensor feedback.	Servo motor (SG90), rotation range 0–180°.
PV module	Converts solar irradiance into electrical energy for evaluation and comparison.	100 W monocrystalline photovoltaic panel
Network interface	Enables real-time data transmission to IoT cloud monitoring platform.	Integrated Wi-Fi module (ThingSpeak connection)
Sampling interval	Frequency of data acquisition and control loop execution.	Sensor readings every 1 s; control update every 10 s.

3.2. Performance metrics

In this section, metrics used to evaluate work of the proposed SAT system are presented as follows.

3.2.1. Tracking efficiency (η_t)

Tracking efficiency is a qualitative metric that assesses how well a solar panel is aligned with the sun, as in (1).

$$\eta_t = (P_{tracked} / P_{max}) \times 100\% \quad (1)$$

Where:
$P_{tracked}$: the power captured by the tracker.
P_{max}: the extreme power at normal irradiance.

3.2.2. Average power output (W)

Average power output (W) measures the increased percentage in the output of the electrical energy. It measures the achievement of the solar tracking system compared with the PV system under the same conditions. Another definition is measuring the tracking benefits in terms of harvested power from the radiation of the sun, as in (2).

$$W = ((E_{tracked} - E_{fixed}) / E_{fixed}) \times 100\% \quad (2)$$

Where:
E_tracked: the power yields by single-axis solar tracking PV.
E_fixed: the energy yields by fixed-tilt PV.

3.2.3. Tracking accuracy error (ε)

The accuracy with which a solar tracking system aligns a solar PV panel with the locus of the sun during the day is measured by tracking accuracy error (ε). Tracking accuracy error is defined as (3).

$$\varepsilon = \frac{(|\theta_{sun} - \theta_{panel}|)}{\theta_{sun}} \times 100\% \quad (3)$$

Where:
θ_{sun}: solar azimuth angle (true sun position).
θ_{panel}: panel azimuth angle (actual panel position).

3.3. Simulation results

According to Table 2, the parameters used to evaluate the proposed system are: average power output (W), daily energy yield (Wh), tracking efficiency (η_t), and tracking accuracy error (ε). Accordingly, the proposed system achieved 22–25 % by comparing with the fixed system based on the value of average power output (W). According to the tracking accuracy error value, the mean angular error is below 4°. This value ensures precise alignment throughout daylight hours. The values are also represented in Figure 7.

Table 2. The parameters used to evaluate the proposed system

Parameter	Fixed system	IoT-based tracker	Improvement
Average power output (W)	72.4	88.7	+22.5%
Daily energy yield (Wh)	579.2	709.6	+22.5%
Tracking efficiency (η_t)	–	96.3 %	–
Tracking accuracy error (ε)	–	3.7 %	–

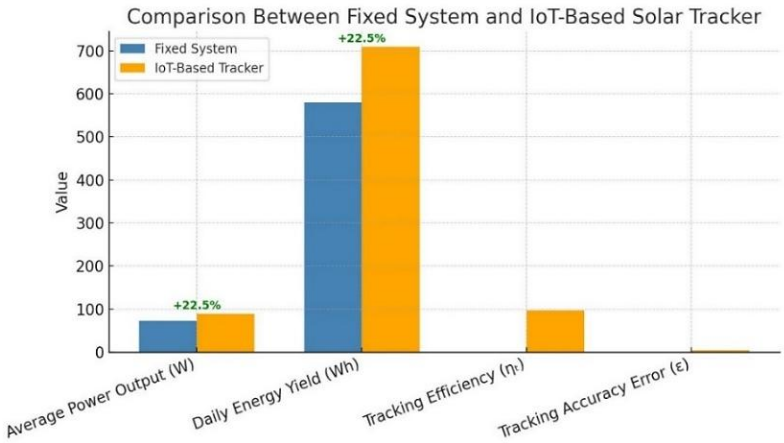

Figure 7. Comparison between fixed and IoT-based solar tracking system

3.4. IoT performance analysis

Data transmission was verified as stable through real-time monitoring via ThingSpeak with a latency of less than 180 milliseconds and a data delivery reliability of 99.4%. System status parameters (motor current, board temperature) were successfully recorded, enabling predictive maintenance. Figure 8 shows the power output over the day, from 8:00 AM to 6:00 PM. The intelligent tracker continuously aligned with solar azimuth variation, while the fixed system exhibited up to 25 % irradiance loss during morning and afternoon periods.

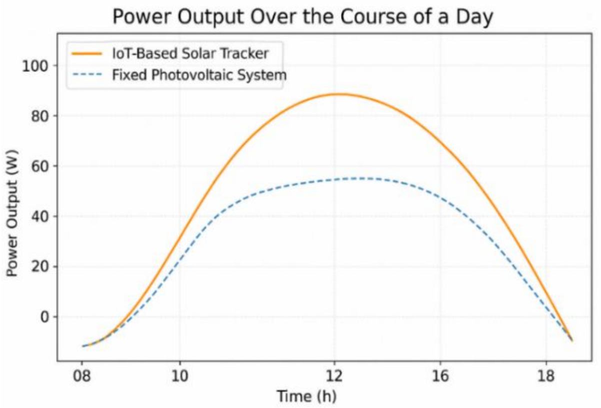

Figure 8. Power output from 8:00 AM to 6:00 PM

4. CONCLUSION

This paper proposed an IoT-enabled single-axis solar tracking system to increase PV power harvesting. It has continuous real-time adjustment with the trajectory of the sun. In addition, real-time adjustment to the proposed system simultaneously enabling remote monitoring through a cloud platform by including dual LDR sensors, Arduino-based control unit, a servo motor, and an ESP32 IoT communication module.

Based on the experimental results, IoT-enabled single-axis solar tracking system improves energy harvesting by comparing with fixed-tilt PV. The proposed system outperforms the fixed-tilt PV by 22.5% in daily energy yield and average power output. Furthermore, tracking efficiency is better than fixed-tilt PV by 96.3% and tracking error of 3.7%. As a future work, the integration of the proposed system with machine learning to mitigate the error of alignment, in addition to optimize response time. These developments will support the creation of more independent and adaptable solar power systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Deema Al-Shogran		✓	✓	✓	✓	✓		✓	✓		✓			
Hazem Jihad Badarneh		✓	✓	✓	✓	✓	✓	✓		✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Each author in this work agrees to declare that we have no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] The International Renewable Energy Agency (IRENA), "Renewable energy statistics 2025," 2025. [Online]. Available: https://www.irena.org/Publications/2025/Jul/Renewable-energy-statistics-2025

[2] R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, "A review and comparative analysis of solar tracking systems," *Energies*, vol. 18, no. 10, 2025, doi: 10.3390/en18102553.

[3] A. M. Al-Smadi and T. M. Alrjoub, "Considerations for energy saving and street lighting lamps replacement in Jordanian Roads," *Przeglad Elektrotechniczny*, vol. 2024, no. 1, pp. 134–137, 2024, doi: 10.15199/48.2024.01.28.

[4] 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.

[5] M. Goyal, M. N, An. Raj, and K. Kumar, "Smart solar tracking system," *International Journal of Engineering Research and Technology*, vol. 4, no. 2, pp. 367–369, 2015.

[6] Y. P. L. Madhushani, C. Chandrasiri, S. Jayawickrama, R. Lakmal, and M. Herath, "Smart sun tracking system for solar energy generation," 2021.

[7] S. Sahu, S. Tiwari, and R. N. Patel, "Analysis and testing of dual axis solar tracker for a standalone PV system," *2020 1st International Conference on Power, Control and Computing Technologies, ICPC2T 2020*, pp. 96–101, 2020, doi: 10.1109/ICPC2T48082.2020.9071451.

[8] D. Panimariyal J, "Sun tracking solar panel with weather monitoring system," *Interantional Journal of Scientific Research in Engineering and Management*, vol. 09, no. 02, pp. 1–9, Feb. 2025, doi: 10.55041/IJSREM41600.

[9] U. Mamodiya, I. Kishor, P. Ganguly, I. Mukherjee, and N. Naik, "A machine learning approach to assess the climate change impacts on single and dual-axis tracking photovoltaic systems," *Scientific Reports*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-10831-3.

[10] A. Zurfi, A. A. R. Altahir, and A. Ibrahim, "Investigation of optimal tilt, orientation, and tracking of a solar PV system in Iraq," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 16, no. 3, pp. 1914–1925, 2025, doi: 10.11591/ijpeds.v16.i3.pp1914-1925.

[11] K. Chenchireddy, G. B. Mulla, V. Jagan, W. Sultana, S. A. Sydu, and E. Giddalur, "Solar tracker using Arduino microcontroller and light dependent resistor," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 16, no. 1, pp. 70–75, 2025, doi: 10.11591/ijpeds.v16.i1.pp70-75.

[12] M. Talbi, N. Mensia, and H. Ezzaouia, "Modeling of a PV panel and application of maximum power point tracking command based on ANN," *The International Arab Journal of Information Technology*, vol. 18, no. 4, pp. 568–577, 2021, doi: 10.1007/978-3-031-69746-3_4.

[13] A. Karabiber and Y. Güneş, "Single-motor and dual-axis solar tracking system for micro photovoltaic power plants," *Journal of Solar Energy Engineering*, vol. 145, no. 5, Oct. 2023, doi: 10.1115/1.4056739.

[14] E. H. Sepúlveda-Oviedo, "Impact of environmental factors on photovoltaic system performance degradation," *Energy Strategy Reviews*, vol. 59, 2025, doi: 10.1016/j.esr.2025.101682.

[15] E. N. Agrawal, E. P. Agrawal, U. Agrawal, V. Meena, V. Saini, and T. Sharma, "Single axis solar tracking system," *International Journal for Research in Applied Science and Engineering Technology*, vol. 13, no. 5, pp. 2434–2439, May 2025, doi: 10.22214/ijraset.2025.70639.

[16] M. A. Ponce-Jara, I. Pazmino, Á. Moreira-Espinoza, A. Gunsha-Morales, and C. Rus-Casas, "Assessment of single-axis solar tracking system efficiency in equatorial regions: a case study of Manta, Ecuador," *Energies*, vol. 17, no. 16, 2024, doi: 10.3390/en17163946.

[17] Kenu E. Sarah, U. Roland, and O. Ephraim, "A review of solar photovoltaic technologies," *International Journal of Engineering Research and*, vol. 9, no. 7, Jul. 2020, doi: 10.17577/IJERTV9IS070244.

[18] A. Luque and S. Hegedus, *Handbook of photovoltaic science and engineering*, 1st ed. 2003. doi: 10.1002/0470014008.

[19] D. Tan and A. K. Seng, *Handbook for solar photovoltaic (PV) systems*. 2016. [Online]. Available: https://www.bca.gov.sg/publications/.../handbook_for_solar_pv_systems.pdf

[20] S. Yamuna and M. Sreedhar, "Optimization of maximum power point tracking controllers for enhanced performance in solar photovoltaic systems," *Solar Energy*, vol. 302, p. 114011, Dec. 2025, doi: 10.1016/j.solener.2025.114011.

[21] A. M. Al-Smadi, S. T. Salah, A. A. Al-Moomani, and M. S. Al-Bataineh, "Street lighting energy-saving system," in *2019 16th International Multi-Conference on Systems, Signals & Devices (SSD)*, Mar. 2019, pp. 763–766. doi: 10.1109/SSD.2019.8893160.

[22] A. Al-Smadi and M. Msallam, "Vehicle auto parking system," *2022 9th International Conference on Electrical and Electronics Engineering, ICEEE 2022*, pp. 108–111, 2022, doi: 10.1109/ICEEE55327.2022.9772583.

[23] A. Al-Smadi, M. Al-Nusairat, A. Erjoub, L. Freitekh, and M. Khouj, "Intelligent farm irrigation and safety system," in *2024 25th International Arab Conference on Information Technology (ACIT)*, Dec. 2024, pp. 1–4. doi: 10.1109/ACIT62805.2024.10876975.

[24] A. M. Al-Smadi, W. Al-Ksasbeh, M. Ababneh, and M. Al-Nsairat, "Intelligent automobile collision avoidance and safety system," in *2020 17th International Multi-Conference on Systems, Signals & Devices (SSD)*, Jul. 2020, pp. 319–322. doi: 10.1109/SSD49366.2020.9364169.

[25] M. Khamidah, "Activator token KWh meter using servo motor SG90 based on Arduino Uno microcontroller," *Journal of Energy, Material, and Instrumentation Technology*, vol. 4, no. 2, pp. 72–79, 2023, doi: 10.23960/jemit.v4i2.179.

[26] G. Di Pasquo, "SG90 servo characterization," *CERN European Organization for Nuclear Research*, 2021, [Online]. Available: https://www.researchgate.net/publication/353754375

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