Embedded system with automatic control for solar energy capture using photovoltaic panels

Frank Rojas[1], Fabrizzio Contreras[1], Juan Alvarez[1], Ricardo Yauri[1], Rafael Espino[2]
[1]Facultad de Ingeniería y Gestión, Universidad Nacional Tecnológica de Lima Sur, Lima, Perú
[2]Facultad de Ingeniería, Universidad Tecnológica del Perú, Lima, Perú

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ABSTRACT

Solar energy harvesting addresses challenges related to environmental variability and the limitations of fixed systems, which affect the energy yield obtained from photovoltaic panels. To improve efficiency, tracking systems are being developed using control algorithms or algorithmic energy management strategies. Reviewed research has explored methodologies such as software modeling, experimental testing, and integration of embedded systems with fuzzy logic and internet of things (IoT) for energy monitoring and management, using both single-axis and dual-axis technologies, demonstrating improvements in energy harvesting efficiency. This paper presents the development of a microcontroller-based system with automatic control to optimize solar energy capture in photovoltaic panels using light-dependent sensors and integrating control algorithms into low-cost hardware. The tests carried out demonstrated the operation of the tracking algorithm, confirming that the integration of light-dependent sensors, servo motors and the Arduino UNO microcontroller orient the solar panel based on the detected light, determining that with the generation of 900 mA with 6.98 V in full sunlight, the 5 V and 4400 mAh battery is charged, obtaining an autonomy of up to 3.65 days without solar recharging.

Corresponding Author:

Rafael Espino
Facultad de Ingeniería, Universidad Tecnológica del Perú
125 Natalio Sanchez Road, Santa Beatriz, Lima, Perú
Email: c22165@utp.edu.pe

1. INTRODUCTION

The growing energy demand and environmental issues have driven the use of renewable sources such as solar energy, improving its efficiency using tracking systems [1], [2]. Photovoltaic systems require maintaining a proper orientation to maximize energy capture, using solar trackers, control algorithms or machine learning techniques to improve their performance [3], [4]. Furthermore, remote parameter monitoring and the use of maximum power point tracking (MPPT) converters are important to optimize energy conversion under different conditions [5], [6], such as remote areas without access to the power grid [7]. Solar energy is also applied in applications related to heating systems, battery energy storage, internet of things (IoT) [8] and sustainable mobility [9].

In relation to the problem of solar energy capture, it faces difficulties due to the variability of environmental conditions, such as temperature, irradiance and shadow generation, which affect the performance of photovoltaic panels [10]. In addition, fixed systems do not allow the optimization of the captured radiation, while solar trackers may present limitations in their control and response [11]. Furthermore, gaps have been found in previous research because energy self-sufficiency and the balance between consumption monitoring and energy harvesting are not adequately addressed. Besides, it should be considered that the efficient use of the energy generated by the batteries must be balanced with the energy used for photovoltaic tracking systems [12], [13].

Regarding the problem of technological integration, the development of solar tracking systems is required to improve the orientation of the panels without increasing complexity, considering controller systems that use MPPT optimization algorithms and strategies to manage the charging of multiple batteries [14], [15]. Furthermore, in other situations it is necessary to integrate remote monitoring technologies to evaluate environmental parameters that influence the performance of solar panels [16]. On the other hand, technologies are considered to increase the efficiency of thermal generation systems and their integration in specific applications, such as solar air heaters [17], [18].

The reviewed research covers the development and improvement of solar energy collection systems where the use of one and two axes has been found, using structures to optimize solar energy collection and its comparison with fixed systems [19]. Some research has also focused on optimizing energy management by designing storage systems for efficient battery charging [20]. On the other hand, IoT-based solutions have been developed for remote monitoring of environmental parameters and those related to battery charging [21].

Some methodologies used in the reviewed articles include MATLAB modeling to validate solar tracking algorithms, energy optimization, and predictive control [22]. The integration of sensors and IoT platforms has enabled data analysis, applying machine learning and artificial intelligence techniques for energy performance assessment [23]. In addition, experimental comparisons have been made between tracking systems and fixed panels, measuring electrical parameters using sensors [24], [25]. Research papers describe how solar tracking systems using single and dual axes showed increases in energy collection efficiency of up to 32% per year.

The purpose of this paper is to design and validate a low-cost, energy-autonomous solar tracking prototype using open-source hardware and light dependent resistor (LDR) sensors, aimed at solving the problem of inefficient energy capture in fixed photovoltaic systems. The main contribution is to demonstrate, through a prototype, that acceptable tracking performance can be achieved using simple electronics and without advanced or expensive controllers. The following sections detail the design methodology, hardware selection, control algorithm, experimental setup, and validation results, demonstrating how the proposed system meets the requirements of efficiency and autonomy.

2. PROPOSED SYSTEM

The architecture described was selected so that the system could operate autonomously using only the energy generated by the panel, which aligns with the problems and objectives described in the introduction. The system integrates a 7-volt solar panel with automatic tracking, resistive light sensors (LDRs), a microcontroller (Arduino UNO), and SG90 servomotors (Figure 1), which are described in the scientific literature as suitable low-cost components for the system [26], [27]. Considering that the algorithm acquires light intensity signals and controls the rotation and elevation of the solar cell, which are shown to be the most important characteristics for solar energy capture [28]. For component integration, a structure is considered to perform the movement of the panel in two directions, designed and built using 3D printing techniques, which are justified in related research [29]. The solar tracking algorithm is then designed and implemented to analyze the information from the light sensors (Figure 2).

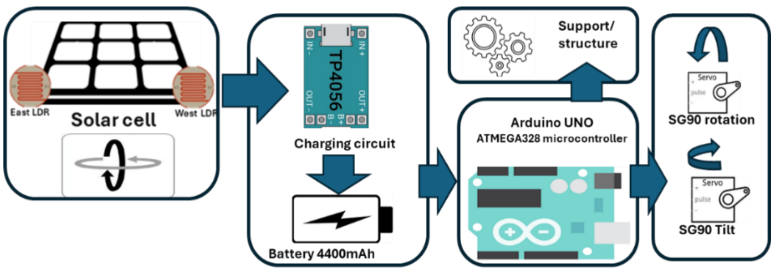


Figure 1. System component diagram

2.1. Electronic stage

The selection of Arduino UNO, LDR sensors, and SG90 servo motors was based on their effectiveness in low-cost solar tracking systems reported in the literature. Research describes a dual-axis tracker using LDRs and Arduino to achieve a low-cost solution [30], and another highlights the SG90 servo motor as a suitable option for photovoltaic modules due to its low power consumption [31].

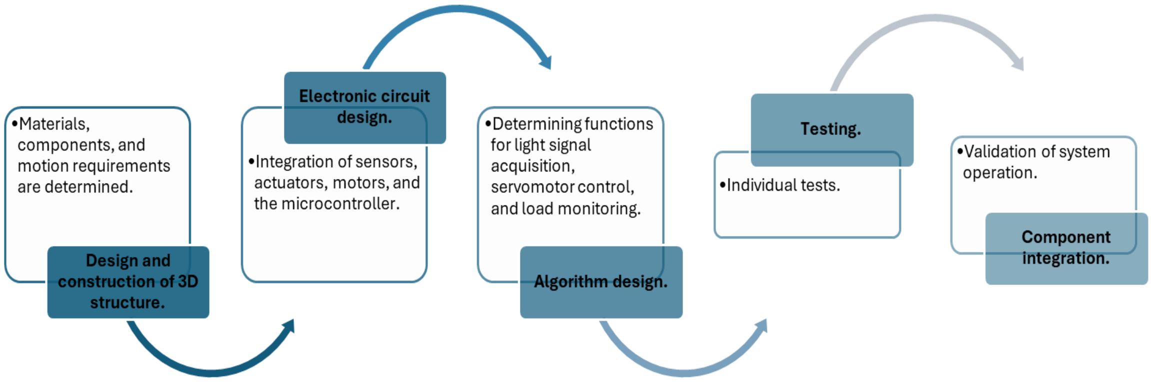


Figure 2. Development method

For experimental validation of the electronics, the system was mounted in a controlled outdoor environment, with clear skies and temperatures between 18 °C and 24 °C. The electronic stage consists of the components responsible for data processing and automatic adjustment of the solar panel position, using four LDR light sensors (Table 1). In the case of the servomotor, the SG90 model (Table 2) is used to move the solar panel on the horizontal vertical axes and is controlled by pulse-width modulation (PWM) signals. Table 3 shows the characteristics of the solar cell, which has a nominal voltage of 7 V and a short-circuit current of 1.5 A, allowing it to generate a maximum power of 10.5 W. It also has an efficiency of 18%, which corresponds to its ability to convert sunlight into electric current. This solar cell is connected to a TP4050 charge management circuit to charge the battery (Figure 3).

Table 1. Light sensor features

Feature	Value
Type	LDR
Dark resistance	Approx. 1 MΩ
Full light resistance	Approx. 100 Ω
Operating voltage	3.3-5 V
Response time	20-30 ms

Table 2. Features of the SG90 servo motor

Feature	Value
Type	Servo SG90
Turning angle	0° to 180°
Power consumption	4.8–6 V
Standby current	10 mA
Full load current	650 mA

Table 3. Solar panel features

Feature	Value
Nominal voltage	7 V
Short-circuit current	1.5 A
Nominal power	10.5 W
Dimensions	250×200 mm
Efficiency	18%
Cell code	SP-7 V-10 W
Nominal voltage	7 V

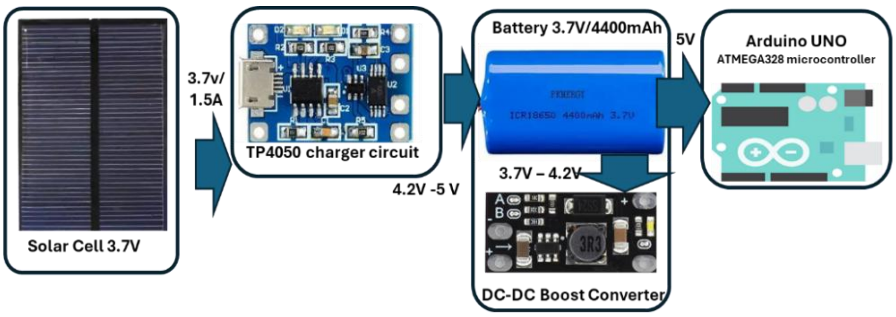


Figure 3. Energy management stage

2.2. Control algorithm

The logic employed in the control algorithm is based on direct comparisons between light intensity values captured by LDR sensors, used in low-cost dual-tracking systems. This approach has proven to be efficient and is supported by recent research using similar configurations with Arduino and SG90 servomotors [31]. Furthermore, it is also noted that the use of control algorithms based on voltage differences [32] allows achieving efficiency improvements of up to 30–40% compared to fixed systems.

During the execution of the control algorithm, data from the four LDRs and the angular position of the servomotors were recorded every 60 seconds during six-hour test intervals. Validation procedures included subjecting the system to control variations in artificial light. To improve clarity and reproducibility, the algorithm was also represented in a flowchart (Figure 4), showing the decision logic for moving the panel toward the highest light intensity. The main processes are:

a. Start; the libraries needed to control the servomotors are imported.
b. Initial setup; the servos are positioned in a starting position serial communication is initialized.
c. Main loop; the values from LDRs and servos are read.
d. Adjustment conditions; if the panel is already oriented toward the brightest light source, no changes are made, and the system remains in the loop.

The servomotors are controlled by the PWM module using pins 6 and 7 of the Arduino microcontroller and powered by 5 volts (Figure 5). The vertical servomotor adjusts the panel's angle by comparing the light intensity between the upper and lower sensors: if there is lighter below, the panel rises; if there is lighter above, it tilts downward. For horizontal movement, if the left-side sensors receive more light than those on the right, the panel rotates to the left.

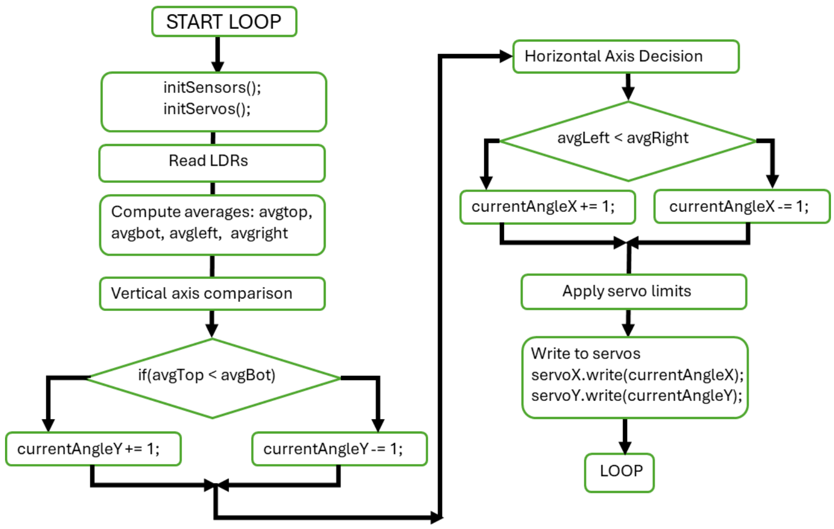


Figure 4. Algorithm flowchart

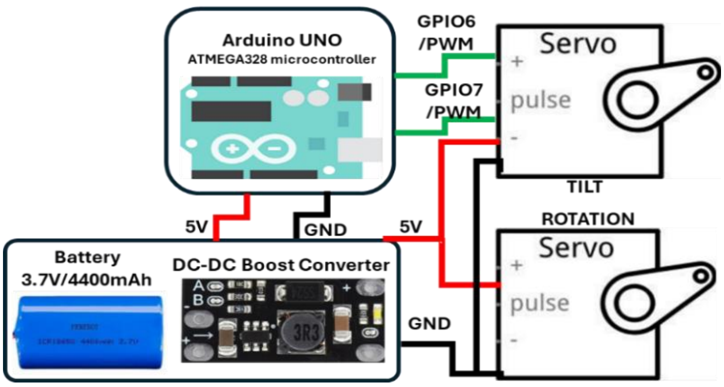
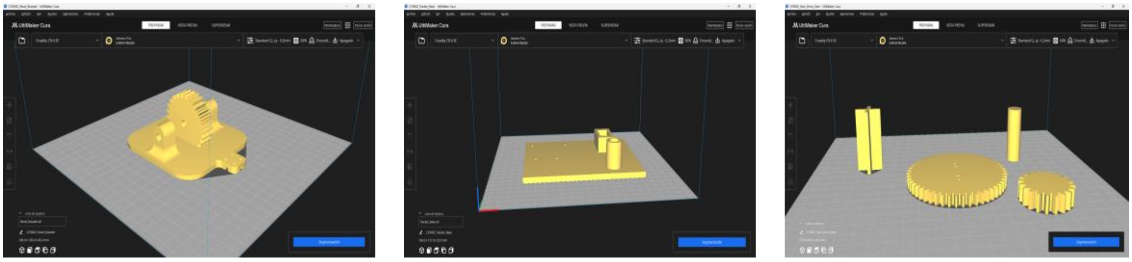


Figure 5. Servomotor control diagram

2.3. System structure

The physical structure of the system was evaluated for mechanical strength through continuous operation tests over three days, verifying that no deformations occurred. To ensure reproducibility, the 3D printing parameters (layer height 0.2 mm, infill density 30%, and extrusion temperature 200 °C) were documented, including the repetitive activation of the servomotors on both axes (500 cycles). These mechanical tests were designed to meet the objective. The design focuses on the following key aspects:

- Lightweight structure: a base structure has been created for vertical movement (Figure 6(a)).
- Motor mounts: servomotor mounts are included, allowing the panel to rotate and adjust horizontally and vertically (Figure 6(b)). Gears were also designed for movement on two axes (Figure 6(c)).



(a) (b) (c)

Figure 6. Parts of the mechanical structure; (a) vertical motion support, (b) motor support, and (c) gears for movement on two axes

3. RESULTS AND DISCUSSION

Figure 7 shows the connections made with the system components, which were assembled to meet the objective of having a functional prototype considering that the solar cells are connected to a charge management stage and a rechargeable battery (Figure 8). Compared to previous solutions reported in the literature, such as solar tracking systems based on photodiodes [33] or astronomical calculations [34], [35], the presented proposal stands out for employing LDRs as main sensors, which reduces the cost without compromising the ability to detect light variations.

The results obtained through direct measurements of current, voltage, and energy consumption are consistent with reports on solar tracking systems using LDRs and servomotors, where generation greatly exceeds demand, confirming that the proposed design is suitable for energy efficiency. A quantitative analysis revealed a current generation of 900 mA, using 6.98 volts in full sunlight. Furthermore, the current output was successfully matched by the TP4050 solar charger to power a 5 V, 4400 mAh battery. The system operates 24 hours a day with a consumption of 1204,3 mAh and the servomotors are activated at 1-hour intervals for a maximum time of 1 second. Statistical analysis was not applied in this section, because the main objective was to validate the basic operation of the system and its autonomy under controlled conditions.

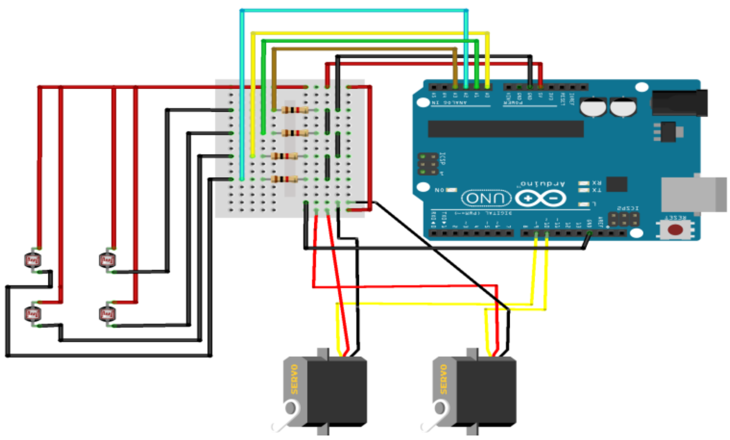


Figure 7. Interconnection diagram for validation of program operation

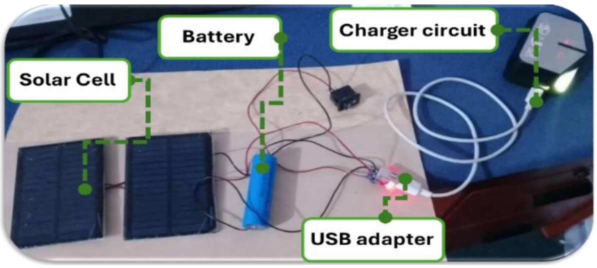


Figure 8. Test with solar cells

Comparing these results with non-tracking static solar collection systems described in [32], [34] it is confirmed that LDR-based trackers increase energy production by 20% to 35%, while servomotor consumption is relatively low. Similar improvements in efficiency have also been reported in other recent works using light sensors with low-cost microcontrollers [19], [26], [30], reinforcing the validity of the approach in this study.

In the case of this research, the estimated daily generation of 9180 mAh during 12 hours of radiation exceeds the total electrical consumption of the system, so the system consumes approximately 27% of the total battery capacity per day (1204.3 mAh out of a total capacity of 4400 mAh), which allows an autonomy of 3.65 days without recharging (Table 4). This result is consistent with prior studies where similar prototypes achieved full-day operation and multi-day autonomy using comparable low-cost architectures [9], [31], providing additional evidence that simple embedded solutions can achieve energy independence. Additionally, the observed 27% improvement is within the same range of 20–35% reported by dual-axis low-cost systems [19], supporting the consistency of the proposed design. Although the algorithm smooths the readings by averaging to reduce noise, a quantitative error analysis between the actual point of maximum irradiance was not conducted.

Table 4. Measurement of energy characteristics

Parameter	Value
Battery capacity	4400 mAh
Battery voltage	5 V
Arduino UNO power consumption	46.5 mA
Power consumption of each servomotor (moving)	230 mA
Number of servomotors	2
Servomotor activity time per day	24 s (1 s every hour, 24 hours)
Arduino power consumption per day	46.5 mA×24 h=1116 mAh
Servomotor power consumption per day	2×230 mA×(24÷3600 s)=3.07 mAh
Total power consumption per day	1116+3.07 mAh=1204.3 mAh
Battery life without recharging	4400 mAh÷1204.3 mAh/day=3.65 days

Figure 9 shows the implemented physical prototype, demonstrating the construction of the 3D structure. During testing, the system was validated to respond appropriately to changes in light direction by adjusting the panel's tilt and rotation with a response time of less than 2 seconds. Therefore, the system not only meets the objective of providing a low-cost solar tracking solution, but also demonstrates performance.

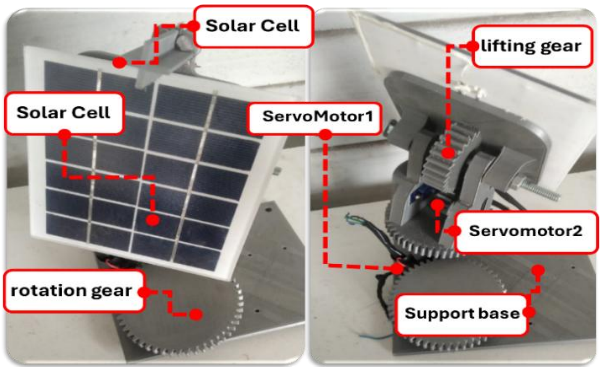


Figure 9. Integrated system

To validate the system's functionality, a preliminary error estimate was obtained from electrical measurements. During the test intervals, the current fluctuated between 850 mA and 920 mA, around an average value of 900 mA, corresponding to an estimated variation of ±3.8%. Voltage values ranged between 6.85 V and 7.02 V, representing a deviation of less than 2.5%. This initial quantification suggests that the panel remained near the point of maximum irradiance (Table 5).

Table 5. Measurement of energy characteristics

Parameter	Mean value	Min–max range	Estimated variation (%)
Current (mA)	900	850–920	±3.8
Voltage (V)	6.98	6.85–7.02	±2.5

4. CONCLUSION

The study confirmed that a low-cost dual-axis solar tracking prototype, built with LDR sensors, Arduino UNO, and SG90 servomotors, can operate autonomously for several days, validating that simple embedded electronics are sufficient for effective solar tracking. The main contribution is the demonstration that open-source hardware combined with 3D-printed structures achieves energy performance comparable to more complex systems, while remaining accessible for small-scale

Beyond validating functionality, the system showed stable current generation around 900 mA with minor fluctuations, indicating adequate alignment precision under controlled conditions. However, the absence of a detailed error quantification is an opportunity for further work. Future research should include statistical analysis of long-term measurements, systematic evaluation of alignment error, and testing in variable climatic conditions, which would strengthen the robustness and broaden the applicability of the proposed design. This contribution is important for renewable energy research, as it proves that efficient solar energy capture does not require complex or high-cost components, and can therefore be extended to off-grid scenarios and resource-limited environments. These updates will contribute to improving its applicability to different renewable energy contexts.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Frank Rojas	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Fabrizzio Contreras	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Juan Alvarez	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Ricardo Yauri		✓			✓	✓			✓	✓	✓	✓	✓	
Rafael Espino		✓			✓	✓			✓	✓	✓	✓	✓	

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

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Ricardo Yauri, upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Frank Rojas is a student of Electronic and Telecommunications Engineering with a focus on embedded systems and automation. He actively participated in the design and implementation of a project that uses a solar tracking algorithm, integrating LDR sensors with Arduino UNO microcontrollers. His work focused on the development of automatic control using sequential logic and code optimization to reduce system energy consumption. He has demonstrated interest in smart renewable energy systems, collaborating on single-axis and dual-axis solar tracking projects with low-cost servomotors. He can be contacted at email: 1921010123@untels.edu.pe.

Fabrizzio Contreras is a student of Electronic and Telecommunications Engineering with experience in structural design and 3D modeling applied to technological projects. He has knowledge of 3D modeling and printing tools to generate support for the two-axis movement of photovoltaic panels. He has experience planning mechanical integration with electronic components, ensuring stable operation. His interest lies in combining mechanical engineering with embedded electronics. He can be contacted at email: 1921010324@untels.edu.pe.

Juan Alvarez is an Electronic Engineering student focused on energy sources and energy management in IoT devices. He has experience in the management of energy generated by solar panels. He has used tools to evaluate the consumption of electronic systems and estimate energy autonomy. His interest lies in the development of energy-self-sufficient systems with applications in rural or hard-to-reach areas. He can be contacted at email: 1921010522@untels.edu.pe.

Ricardo Yauri is a Master of Science in Electronic Engineering with a Mention in Biomedical. He is associate professor at the Universidad Nacional Mayor de San Marcos (UNMSM) and Ph.D. student in Systems Engineering. He is professor at Universidad Tecnológica del Perú and Universidad Peruana del Norte. He has participated as a teacher in courses oriented to the internet of things and applications in home automation and the Cisco academy for IoT. He was a researcher at INICTEL-UNI in the Embedded Systems and Internet of Things research group. He developed research projects on the implementation of low consumption IoT devices that involve inference techniques, machine learning algorithms. He can be contacted at email: C24068@utp.edu.pe and ryaurir@unmsm.edu.pe.

Rafael Espino specialist in development of electronic systems and embedded firmware. Research professor at the Universidad Tecnológica del Perú, involved in various research projects. His interests focus mainly on renewable energies, electronic measurement systems, IoT monitoring systems, and technologies to mitigate environmental impact and climate change. He can be contacted at email: c22165@utp.edu.pe and rafalloelo@gmail.com.