

DESIGN AND EXPERIMENTAL ANALYSIS OF LOW-COST AUTOMATED SOLAR TRACKING SYSTEM

Maja Anačkova, Mario Angjelkovski, Evgenija Jovanovska, David Pejovski, Filip Rajčevski

Faculty of Mechanical Engineering, “Ss. Cyril and Methodius” University in Skopje,

P.O. Box 464, MK-1001 Skopje, Republic of North Macedonia

maja.anackova@mf.edu.mk

A b s t r a c t: This paper presents a low cost dual-axis light tracking prototype developed as a basis for future photovoltaic (PV) solar tracker systems. The device uses an Arduino microcontroller and four light resistors (LDRs) arranged in four sensing quadrants. The controller continuously samples and compares the quadrant signals to estimate the light direction and drives two SG90 servo motors to position the platform in azimuth and elevation. To improve stability and reduce unnecessary actuation, the control strategy applies averaged sensor sampling, differential error evaluation, and a tunable tolerance band (dead zone) that suppresses micro-adjustments under small intensity variations. This prototype is more energy efficient and simple to implement, making it suitable for educational demonstrations and preliminary research. Future work will integrate a photovoltaic module (solar panel) and external electrical measurements to quantify the improvements in energy yield over fixed – tilt configurations.

Key words: dual-axis tracker; Arduino; LDR sensors; closed-loop control; tolerance band

ДИЗАЈН И ЕКСПЕРИМЕНТАЛНА АНАЛИЗА НА НИСКОБУЏЕТЕН АВТОМАТИЗИРАН СИСТЕМ ЗА СЛЕДЕЊЕ НА СОНЦЕТО

А п с т р а к т: Во овој труд е претставен нискобуџетен прототип за двоосно следење на светлина, развиен како основа за идни фотоволтаични (PV) системи за следење на Сонцето. Уредот користи Arduino-микрoкoн-тролер и четири фотоотпорници (LDR), поставени во четири сензорски квадранти. Контролерот континуирано ги мери и споредува сигналите од квадрантите за да ја процени насоката на светлината и управува со два сер-вомотора SG90 за позиционирање на платформата по азимут и елевација. За подобрување на стабилноста и намалување на непотребното активирање, контролната стратегија применува просечно земање примероци од сензорите, процена на диференцијалната грешка и приспособување на опсегот на толеранција (мртва зона), со кој се потиснуваат микро-поместувањата при мали промени во интензитетот на светлината. Овој прототип е енергетски поефикасен и едноставен за имплементација, што го прави погоден за едукативни демонстрации и прелиминарни истражувања. Идната работа ќе вклучи интеграција на фотоволтаичен модул (соларен панел) и надворешни електрични мерења, со цел да се квантифицира подобрувањето на добиената енергија во споредба со конфигурации со фиксен агол на поставување.

Клучни зборови: двоосен следач; Arduino; LDR сензори; управување во затворена јамка; опсег на толеранција

INTRODUCTION

The increasing demand for electricity and the need to reduce the environmental impact of energy production have intensified interest in photovoltaic

(PV) systems for residential and small scale applications. However, many PV installations are fixed (e.g., roof-mounted arrays), which leads to significant daily output variation due to the continuous change in the Sun’s apparent position, panels

mounted on opposite roof sides may perform better at different times of the day, highlighting the limitations of static mounting [1].

Solar tracking systems reduce these losses by reorienting the PV surface toward the largest light source. Prior work ranges from simplified single-axis mechanisms to dual-axis closed-loop solutions. A dual-axis Arduino-based tracker using photodiodes with stepper and linear actuation reported approximately 18% higher energy yield compared to a static panel [2], while a low-cost dual – axis design based on LDR sensing and two servo motors achieved a reported 13.44% improvement over an immobile PV system. Despite these benefits, low – cost sensor driven trackers may exhibit oscillations and unnecessary micro movements under sensor noise and rapid illumination changes, which can reduce mechanical stability and increase wear [3].

In this paper, a low cost dual-axis light tracking prototype is developed as a foundation for future PV tracker integration. The system uses an Arduino microcontroller, four quadrant arranged LDR sensors, and two servo motors for azimuth and elevation control. Averaged sampling, differential error

evaluation, and a tunable tolerance band are implemented to suppress unnecessary movements and improve stability, providing a modular platform for educational use and future outdoor PV performance measurements.

EXPERIMENTAL

System overview and hardware components

The proposed dual-axis light tracking prototype comprises a miniature solar panel, two SG90 servo motors, four light-dependent resistors (LDRs), an Arduino Uno microcontroller, an LCD display, and a 3D-printed mechanical structure as shown in Figure 1.

The mechanical assembly provides two orthogonal degrees of freedom (horizontal/azimuth and vertical/elevation), enabling the panel to be oriented toward the dominant light direction. The device is powered from a 5V supply.

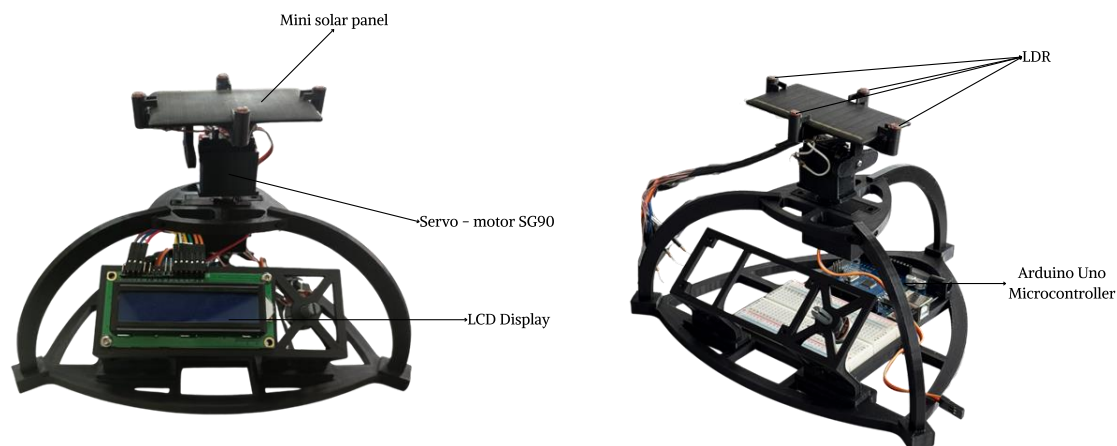


Fig. 1. Developed dual-axis solar tracking prototype with main components

Mechanical construction and fabrication

The supporting frame was 3D printed, using PLA for the main structure and PETG for the moving parts to improve wear resistance. A CAD model defined the precise assembly interfaces between the servos and the panel mount (Figure 2).

Four vertical walls separate the LDR sensors on the top mount, forming what are referred to as quadrant shadow casters. When the light source is

off-axis, these walls cast a shadow over the sensors facing away from it, while the sensors facing toward it remain fully exposed. The resulting intensity difference between opposing sensors produces the differential signal used to drive the servo motors [4].

Due to the tracker's compact geometry, the design lacks physical end-stops, risking mechanical collision at extreme elevation angles. To prevent structural damage and actuator stalling, all rotational constraints are strictly enforced through the microcontroller's software logic.

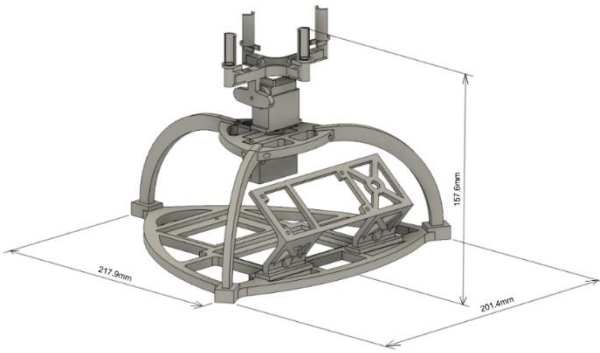


Fig. 2. CAD model of the 3D-printed mechanical structure of the dual-axis solar tracker with overall dimensions (mm)

Sensor configuration and signal acquisition

Light sensing is implemented using four LDR5 photoresistors arranged in a cross configuration (top, bottom, left, right). Each LDR forms a voltage divider with a fixed 10 k Ω resistor, producing an analog voltage proportional to incident light intensity (Figure 3).

The four divider outputs are connected to the Arduino Uno analog inputs A0 – A3. The built-in 10-bit analog-to-digital converter (ADC) converts these voltages into digital values in the range 0 – 1023. The selected LDR characteristics are suitable for dynamic tracking applications, with peak spectral sensitivity around 540 nm and response times of approximately 20 ms (rise) and 30 ms (fall). The typical resistance transitions from a high dark resistance (≤ 500 k Ω) to a lower illuminated resistance (approximately 5 – 10 k Ω), enabling reliable discrimination of light differences between quadrants within the operating temperature range of -30 °C to $+70$ °C.

To reduce the influence of sensor tolerances and short term fluctuations, the sampled readings are processed in software using averaging and calibration steps before being used by the control logic. The processed sensor values represent the relative illumination in each quadrant and serve as the system's input for determining the required orientation corrections.

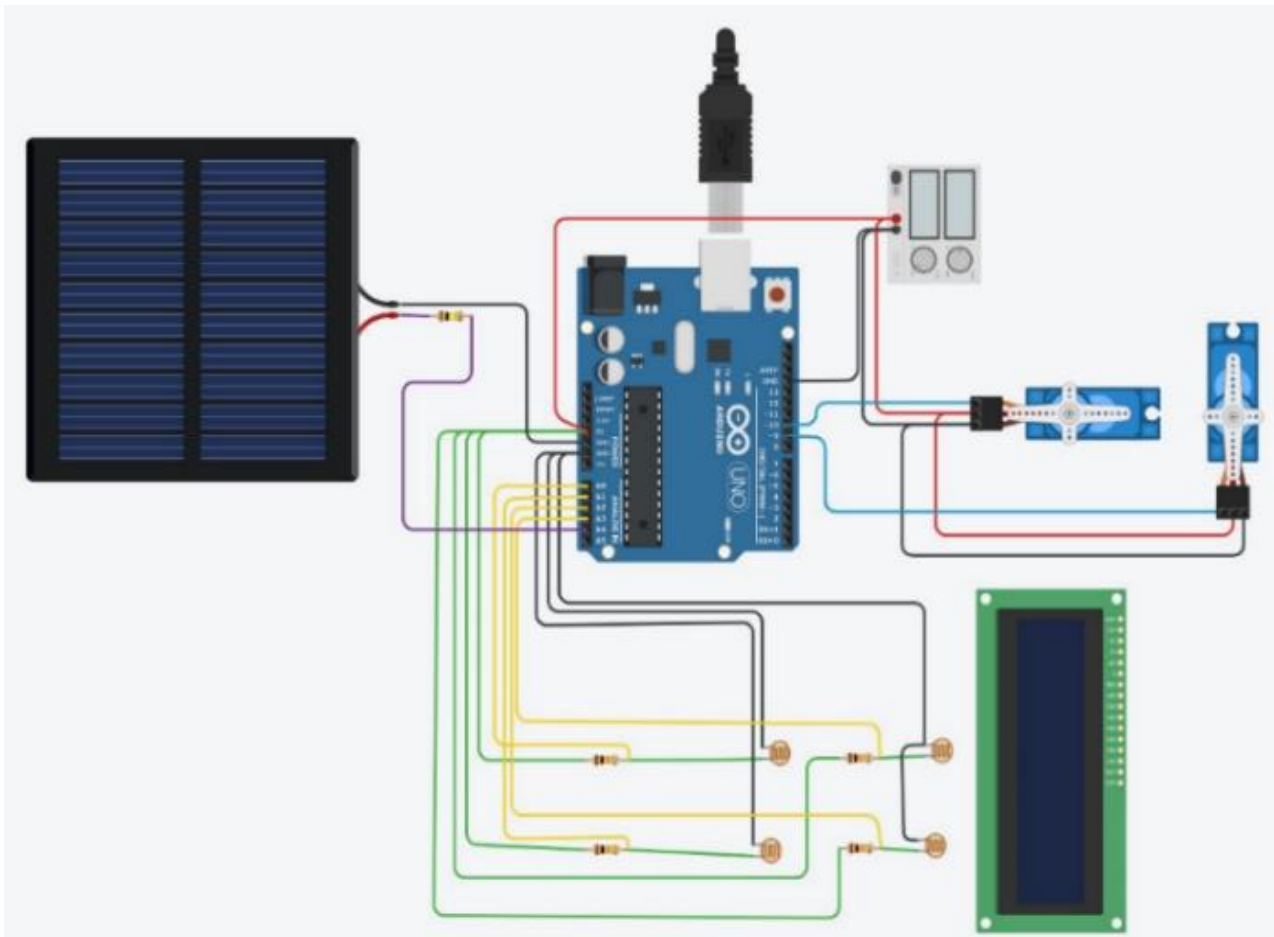


Fig. 3. Electrical wiring diagram of the dual-axis solar tracking system implemented in TinkerCad

Control algorithm

The control strategy (Figure 4) is based on pairwise comparison of quadrant sensors. Horizontal correction is determined from the difference between the left and right LDR readings, while vertical correction is determined from the difference between the top and bottom readings.

If the absolute difference between a sensor pair exceeds a predefined dead-zone (tolerance threshold), the controller commands a small angular step toward the brighter side. If the difference remains within the dead-zone, no motion is executed, which suppresses unnecessary micro-adjustments and improves stability.

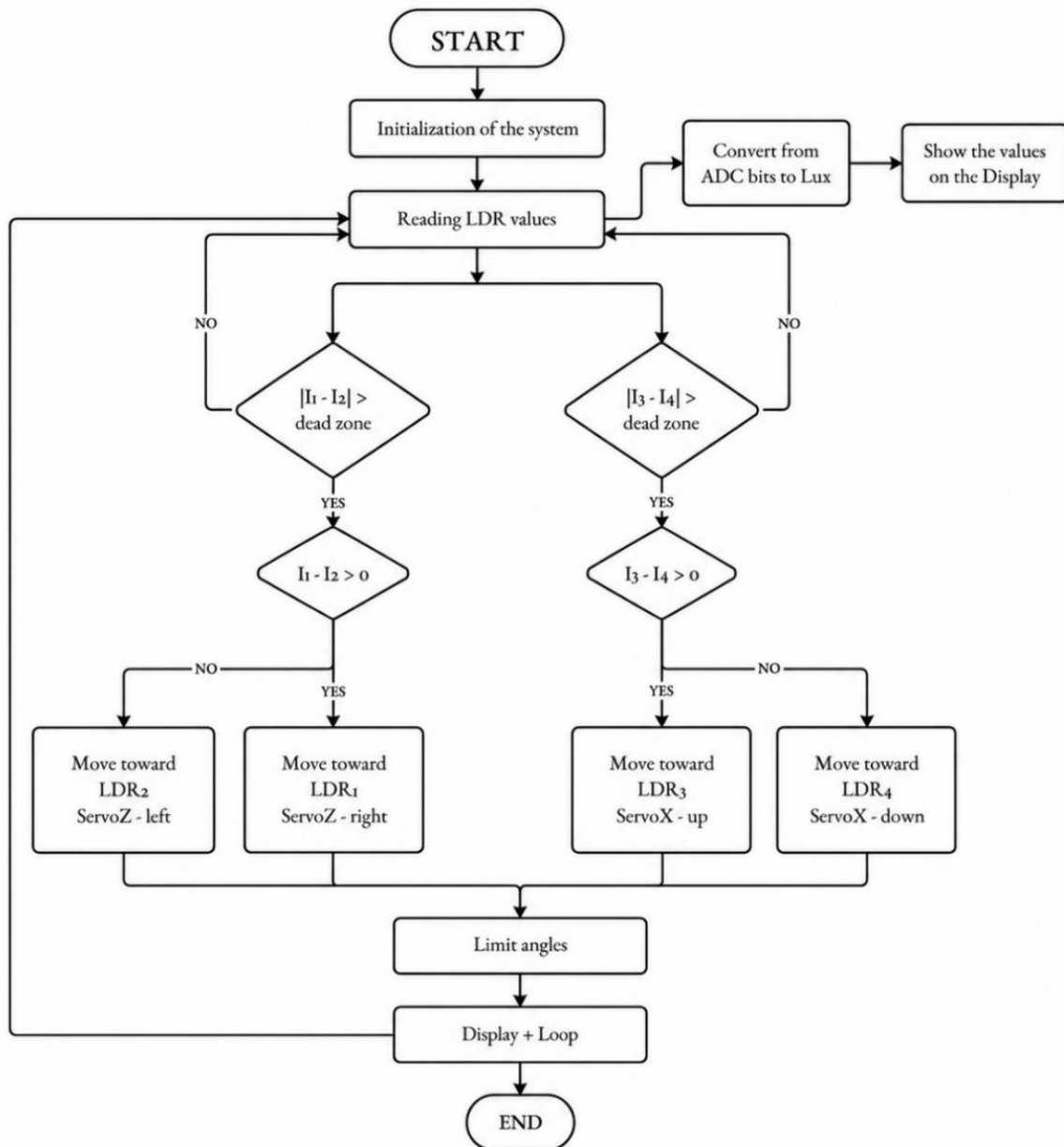


Fig. 4. Flowchart of the dual-axis solar tracking control algorithm

Safety limits are applied to constrain the minimum and maximum servo angles especially for the vertical axis to prevent mechanical interference and damage. In addition, protective transition logic is implemented when moving between extreme posi-

tions to avoid rapid back-and-forth behavior and oscillations. This ensures stable operation under varying illumination conditions and avoids continuous actuator activity caused by small sensor noise.

Actuation and motion strategy

The actuation is done by two servo motors controlled by an Arduino Uno microcontroller (Figure 5). ServoX controls the elevation using the difference between the top and bottom LDRs. While ServoZ controls the azimuth using the difference between the left and right LDRs. In case the ServoZ motor exceeds its mechanical limits, a so-called flip maneuver is activated. Where 180° is subtracted from the values of both motors.

When the flip maneuver is performed, there is a small angular limitation so that it does not return back, in order to avoid oscillation of the flip maneuver.



Fig. 5. Actuation mechanism of the proposed solar tracking prototype

RESULTS

Light intensity measurements

To determine the relative sensitivity of the photoresistors used in the system, a controlled experimental measurement was performed. An electric lamp of known characteristics was used as a light source and positioned so that the light beam fell directly and approximately perpendicularly on the surface of the photoresistors, thus minimizing the influence of the angle of illumination.

The experiment was carried out by gradually changing the distance between the light source and the LDRs. We first measured the distance from the light source, and then the distance from it to see if hysteresis would occur. The measurements were carried out at the following distances: 15, 30, 45, 60,

75, 90, 105, 120, 135, 150, 165, 180, 195, 210, 225, 240 cm. To improve accuracy and reduce random deviations, measurements were repeated three times under the same conditions. The results are presented in Figure 6.

The result from the graph shows that the increasing and decreasing measurements show no measurable hysteresis and follows an exponential curve.

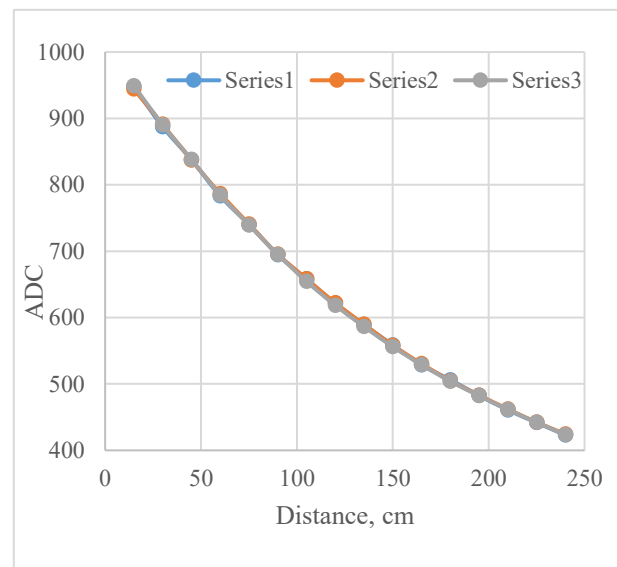


Fig. 6. LDR response during increasing and decreasing distance measurements

The second graph, Figure 7 (from the second experiment) shows a full-day outdoor test of the solar tracking system. The test was conducted to evaluate the real-time performance, stability, and reliability of the system under actual outdoor operating conditions.

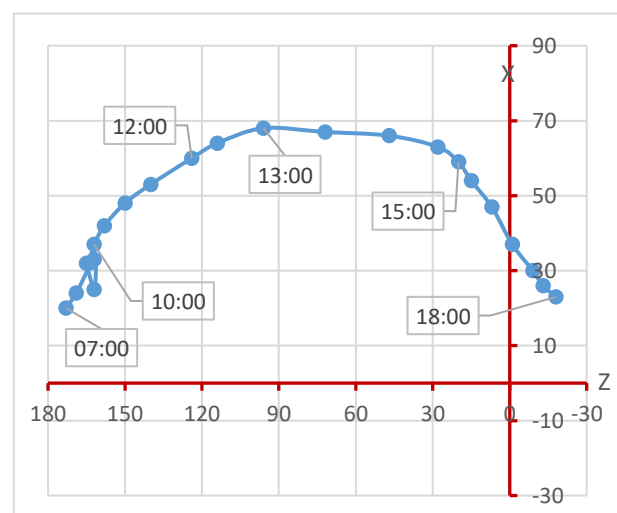


Fig. 7. Measured angular trajectory of the dual-axis solar tracking system during outdoor testing

From the graph, it can be observed that the tracker accurately followed the Sun's trajectory across the sky from 07:00 to 18:00. The gradual change of the tracking angle during the day confirms that the system continuously adjusted its position according to the movement of the Sun.

Finally, the third graph, Figure 8 demonstrates the advantage of such a system, showing how solar tracking can improve the overall efficiency of the panel compared to a fixed-position setup. The experiment was performed using two methods: a stationary setup and an active solar tracking setup.

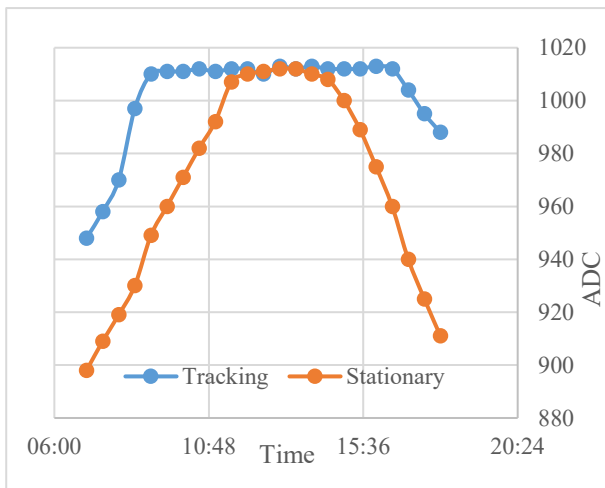


Fig. 8. Comparison of light intensity between tracking and stationary setup during the day

The measured light-intensity profile shows better performance when the device actively tracked the Sun compared to the stationary control setup. The readings are presented as ADC values, which represent the sensor output voltage.

Measurement of speed and response time

To determine the response speed, an experiment was conducted in which an angular displacement of 90 degrees resulted in an average response time of approximately 1 second, corresponding to about 11 ms per degree. Since the measurements were performed manually, involving two operators, the experiment was repeated five times in order to account for possible human error. The most repeatable measurement was selected as the representative value, as it was closest to the value defined in the program.

Overshoot

Figure 9 shows the occurrence of overshoot during a sudden change in illumination, where the signal exceeds the set dead zone (from -16 to 16 ADC bits).

The overshoot is short-lived and the system quickly stabilizes, indicating a stable but fast response of the control system.

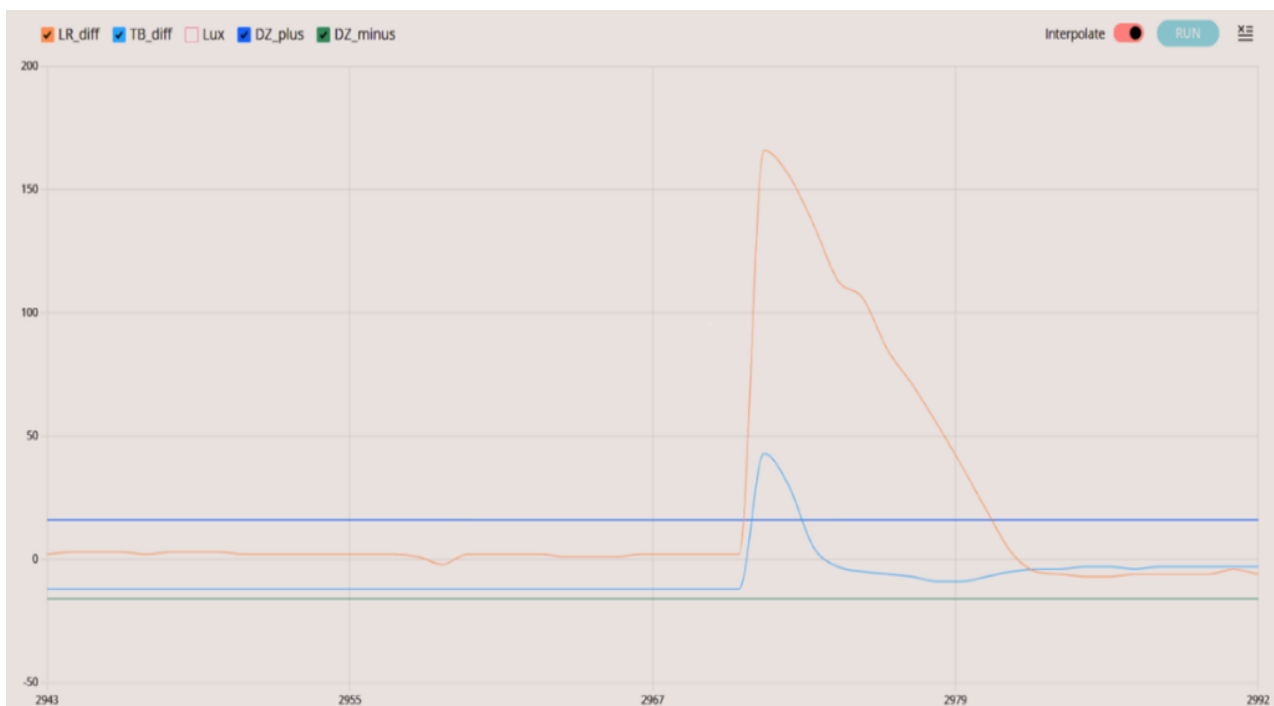


Fig. 9. Overshoot in differential control signal during rapid light variation

Display latency

In this system, latency does not refer to the control algorithm or the servo motor response, but to the update rate of the values shown on the LCD. Due to LCD module limitations and the requirement for the information to remain readable to the user, the displayed values are not updated continuously; instead, they are refreshed periodically, approximately every 480 ms.

This interval was selected as a compromise between update speed and human visual perception, since excessively fast updates make changes difficult to observe on the screen.

CONCLUSION

Within this project, a dual-axis automatic light-tracking system was designed and implemented using photoresistors and an Arduino microcontroller platform. The system processes sensor signals and controls servo motors to continuously adjust the panel orientation according to the light source.

Experimental measurements confirmed the functionality and sensitivity of the sensors, as well as the expected relationship between light intensity and distance from the source. The results indicate stable system response to illumination changes and successful position correction.

Although the system requires additional mechanical optimization and maintenance, it represents a practical solution for small-scale and educational applications. Future work will focus on improving the voltage divider design, upgrading the controller platform, enabling wireless monitoring, and comparing the real energy yield of the tracking system with a fixed reference setup.

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REFERENCES

- [1] Alijanov, D. D., Topvoldiyev, N. A. (2021): Solar tracker system using Arduino, *ISJ Theoretical & Applied Science*, Vol **101** (9), pp. 249–253, DOI: 10.15863/TAS.2021.09.101.18
- [2] Morón, C., Ferrández, D., Saiz, P., Vega, G., Díaz, J. P. (2017): New prototype of photovoltaic solar tracker based on Arduino, *Energies*, vol. **10**, No. 9, 1298. DOI: <https://doi.org/10.3390/en10091298>
- [3] Kaur, T., Mahajan, S., Verma, S., Gambhir, J. (2016): Arduino based low cost active dual axis solar tracker, *Proceedings of the 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, pp. 1–5.
- [4] Wang, J. M., Lu, C. L. (2013): Design and implementation of a sun tracker with a dual-axis single motor for an optical sensor-based photovoltaic system, *Sensors*, Vol. **13**, No. 3, pp. 3157–3168. <https://doi.org/10.3390/s130303157>

