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DESIGN AND DEVELOPMENT OF LOW-COST LDR-BASED TARGET TRACKING SYSTEM

S. Ramasubramanian[1], Sidharth J[2], Daksha Soni[3], Shanya S[3], Mikail Ahmed Shaikh[3]

[1]Associate Professor, Department of Aviation, Vels Institute of Science, Technology & Advanced Studies, Chennai, 600117, Tamil Nadu India.
[2]Assistant Professor, MH Cockpit Private Limited, 600117, Tamil Nadu, India
[3]Student, Department of Aviation, Vels Institute of Science, Technology & Advanced Studies, Chennai, 600117, Tamil Nadu, India

ABSTRACT

As we advance technologically, real-time target tracking has become a critical function in domains such as aviation, surveillance, and robotics. Conventional approaches, including radar and vision-based systems, provide high accuracy but are often associated with significant cost, computational complexity, and power consumption. All of this limits their applicability in low-cost and small-scale implementations.

This paper presents to you presents the design and development of a cost-effective, sensor-based target tracking system using Light Dependent Resistors (LDRs), an Arduino Uno microcontroller, ultrasonic sensing, and servo-based actuation. The system employs a quadrant arrangement of LDR sensors to detect directional variations in light intensity emitted or reflected by a moving target. By computing differential light intensity across sensor pairs, the system determines the relative position of the target in both horizontal and vertical axes.

The proposed system demonstrates real-time tracking capability with satisfactory response time and stability under controlled lighting conditions. Experimental evaluation points out the system achievement through reliable directional tracking with minimal latency, though the performance is influenced by ambient light variability. Despite the simplicity, the system provides a scalable foundation for developing more advanced tracking solutions through integration with vision systems, Artificial intelligence and IoT frameworks.

The study highlights the potential of low-cost sensor fusion techniques in bridging the gap between basic light-following systems and complex tracking technologies, making it suitable for educational, prototyping, and limited real-world applications.

Keywords: Target Tracking, LDR, Arduino Uno, Real-Time control system, Servo Motors

1. INTRODUCTION

The ability to detect, locate, and track moving targets in real time is fundamental to a wide range of modern technological systems, including aviation navigation, defence surveillance, autonomous robotics, and intelligent monitoring platforms. It helps in improved situational awareness, collision avoidance, and automated decision-making, proving itself to be a critical component in both civil and military operations.

Traditional target tracking systems primarily rely on radar and vision-based technologies. Radar systems, which are widely used in aviation and defence, offer long-range detection and high reliability but require substantial infrastructure, high power consumption, and significant financial investment. Vision-based systems, which utilize cameras and image processing algorithms, do provide high precision and flexibility; however, they depend heavily on computational resources and are sensitive to environmental factors such as lighting conditions, occlusions, and weather disturbances.

In contrast, sensor-based tracking offer a simpler and more economical alternative for specific applications. Among these, Light Dependent Resistors (LDRs) have been extensively used in solar tracking systems, where they detect variations in light intensity to orient solar panels toward a light source. These systems demonstrate the effectiveness of differential light sensing but are typically limited to static or slowly varying light sources.

The adaptation of LDR-based sensing for dynamic target tracking presents an unexplored yet promising approach. By leveraging differences in light intensity across multiple sensors, it is possible to infer the direction of a moving target and continuously adjust system orientation. However, existing implementations of LDR-based systems are generally restricted to basic light-following mechanisms and lack the precision, responsiveness, and integration required for real-time tracking in dynamic environments.

The primary limitation highlighted in existing work is the gap between low-cost sensor-based systems and advanced tracking technologies. Most existing solutions either achieve high performance with burdens of complexity or maintain simplicity while sacrificing functionality.

To address this gap, this study proposes a low-cost, LDR-based automated target tracking system capable of real-time operation. The system integrates a quadrant LDR sensor array for directional detection, an ultrasonic sensor for distance estimation, and a microcontroller-based control unit for processing and actuation. A closed-loop feedback mechanism enables continuous alignment with a moving target, improving responsiveness and stability compared to conventional light-following designs.

The primary contribution of this work lies in extending the application of LDR-based sensing from static solar tracking to dynamic target tracking scenarios. By combining directional light sensing with distance measurement, this system can provides a practical and scalable framework for low-cost tracking applications.

2. RELATED WORK AND RESEARCH GAP

Target tracking has been extensively studied across multiple domains, with approaches broadly categorized into radar-based systems, vision-based systems, and sensor-based tracking mechanisms.

Radar-based tracking remains the standard in aviation and defence due to its long-range detection capability and robustness under varying environmental conditions. However, these systems require complex signal processing, high energy consumption, and costly infrastructure, limiting their applicability in low-cost or small-scale deployments. Vision-based tracking systems, on the other hand, leverage cameras and image processing algorithms to achieve high accuracy and flexibility. Despite their effectiveness, such systems are computationally intensive and highly sensitive to environmental factors such as illumination changes, occlusions, and weather conditions.

In contrast, sensor-based approaches provide a simpler and more economical alternative. Among these, Light Dependent Resistor (LDR) based systems have been widely implemented in solar tracking applications. These systems utilize differential light intensity measurements to orient solar panels toward a light source, demonstrating reliable performance with minimal computational requirements. Past studies have shown that multi-sensor LDR configurations, combined with microcontroller-based control, can achieve efficient and stable tracking for static or moving light sources.

Several works have explored enhancements to LDR-based systems, including dual-axis tracking, integration with real-time clock modules, and incorporation of IoT frameworks for remote monitoring. These studies confirm the effectiveness of LDR sensors in detecting light intensity variations and enabling automated control. Additionally, research in robotic applications has demonstrated that multi-sensor arrangements improve directional accuracy and response time, reinforcing the viability of differential sensing techniques.

However, a critical limitation persists across existing literature: the majority of LDR-based systems are designed for static or quasi-static environments, such as solar tracking, where the light source changes slowly and predictably. Their application in dynamic target tracking scenarios, where the target moves unpredictably in real time, remains limited. Basic light-following robots partially address this challenge but often lack precision, stability, and integration with additional sensing modalities.

The reference project also reflects this gap, noting that while LDR systems are cost-effective and easy to implement, they are not typically designed for continuous real-time tracking of moving targets. Furthermore, there is minimal exploration of combining light-based directional sensing with distance estimation to enhance tracking performance.

This creates a clear research gap between high-performance and complex tracking systems (radar and vision-based) and simple but functionally limited sensor-based approaches. Specifically, there is a need for a system that:

- Maintains low cost and simplicity
- Supports real-time tracking of moving targets
- Integrates multiple sensing modalities for improved accuracy
- Operates with minimal computational requirements

To address this gap, the presented work proposes a hybrid sensor-based tracking system that combines LDR-based directional sensing with ultrasonic distance measurement and closed-loop servo control. This approach extends the functionality of traditional LDR systems beyond static applications, enabling dynamic tracking while preserving affordability and implementation simplicity.

3. SYSTEM DESIGN AND METHODOLOGY

The system is designed as a closed-loop, sensor-based target tracking platform that integrates directional light sensing, distance estimation, and servo-based actuation. The objective is to achieve real-time tracking of a moving light source using a computationally efficient and low-cost architecture.

3.1 System Architecture

The overall system consists of three primary modules: sensing unit, processing unit, and, actuation unit.

The sensing unit includes a quadrant arrangement of four Light Dependent Resistors (LDRs) and an ultrasonic sensor. The LDR array is responsible for detecting directional variations in light intensity, while the ultrasonic sensor provides distance measurements to improve tracking response. The processing unit uses an Arduino Uno microcontroller, which performs real-time data acquisition and control computation. The actuation unit consists of two servo motors enabling bidirectional movement along horizontal (pan) and vertical (tilt) axes.

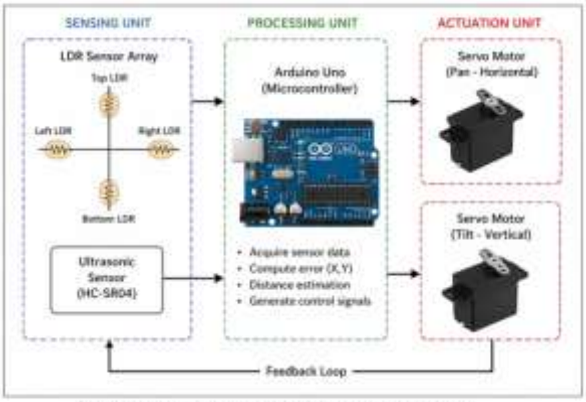

Fig. 1. Block diagram of the proposed target tracking system.

As illustrated in the system block diagram, the architecture follows a continuous feedback loop in which sensor inputs are processed and used to dynamically adjust system orientation.

3.2 Directional Light Sensing Mechanism

The main tracking mechanism is based on differential light sensing. Four LDRs are arranged in a quadrant configuration (top, bottom, left, right), allowing the system to compare light intensity across dual axes.

Each LDR forms part of a voltage divider circuit, converting light intensity variations into corresponding voltage signals. These analogue signals are read by the microcontroller through analogue input pins.

Directional estimation is achieved by computing the difference between opposing sensor pairs:

- Horizontal deviation: difference between left and right LDRs
- Vertical deviation: difference between top and bottom LDRs

A non-zero difference indicates misalignment between the system and the target. The magnitude and sign of the difference determine both the direction and extent of required correction.

This method enables the system not only to detect the presence of a light source but also to estimate its relative position in two-dimensional space.

3.3 Distance Measurement Integration

To enhance tracking accuracy, an ultrasonic sensor (HC-SR04) is incorporated into the system. The sensor measures the distance to the target by calculating the time delay between transmitted and reflected ultrasonic waves.

The distance (d) is computed as:

$$d = \frac{v.t}{2}$$

Where (v) is the speed of sound in air and (t) is the measured time interval.

Distance information is used to modulate system behaviour, such as adjusting response sensitivity or limiting unnecessary movement when the target is beyond an effective range. This additional sensing layer improves system robustness compared to purely light-based tracking.

3.4 Control Algorithm

The control logic is implemented as a continuous feedback loop within the microcontroller. The algorithm operates as follows:

1. Acquire analogue readings from all LDR sensors
2. Measure target distance using the ultrasonic sensor
3. Compute horizontal and vertical intensity differences
4. Compare differences against predefined thresholds
5. Generate control signals for servo motors
6. Adjust servo angles to minimize intensity differences
7. Repeat continuously for real-time tracking

Thresholding is applied to prevent excessive oscillations caused by minor fluctuations in light intensity, thereby improving system stability.

3.5 Actuation and Feedback Mechanism

Two servo motors are used to achieve motion along orthogonal axes. Based on computed error signals (intensity differences), the microcontroller generates Pulse Width Modulation (PWM) signals to control servo positions.

The actuation system continuously attempts to minimize the error between opposing LDR readings. When the intensity difference approaches zero, the system is considered aligned with the target.

This closed-loop feedback mechanism ensures continuous tracking by dynamically correcting positional deviations as the target moves.

3.6 Design Considerations

Several design choices were made to balance performance and simplicity:

- **Low computational overhead:** avoids complex image processing
- **Cost efficiency:** uses readily available components
- **Modular design:** allows future integration with advanced sensors
- **Real-time responsiveness:** achieved through continuous feedback control

Despite its simplicity, the system effectively demonstrates how multi-sensor integration can enable dynamic tracking in resource-constrained environments.

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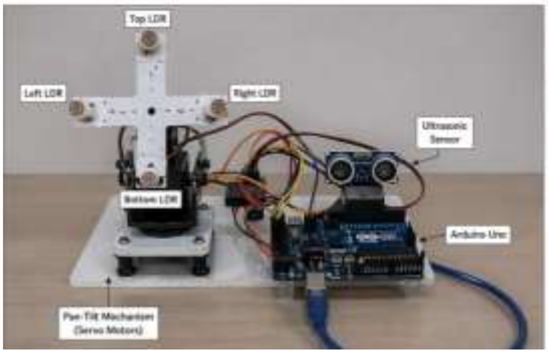
4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

4.1 Hardware Implementation

The system was implemented using readily available and cost-effective electronic components, ensuring ease of replication and scalability. The primary hardware includes four LDR sensors configured in a voltage divider arrangement, an Arduino Uno microcontroller, an HC-SR04 ultrasonic sensor, and two servo motors for actuation.

Each LDR sensor was connected in series with a fixed resistor (10 kΩ) to form a voltage divider circuit, enabling conversion of light intensity variations into measurable analogue voltages. These signals were interfaced with the analogue input pins of the microcontroller. The ultrasonic sensor was connected via digital I/O pins for trigger and echo signal processing, allowing real-time distance estimation.

Servo motors were interfaced using PWM-enabled digital pins, enabling precise angular control. A stable 5V power supply was used to ensure consistent system performance, with an external supply considered for improved servo stability under load conditions.



The circuit configuration and interconnections, as illustrated, demonstrate a compact and modular hardware layout suitable for prototype-level deployment.

4.2 Software Implementation

The control algorithm was implemented using embedded C within the Arduino development environment. The software architecture follows a continuous polling mechanism, where sensor inputs are periodically read, processed, and translated into actuation commands.

Analog readings from the LDR sensors were normalized and compared to compute directional error signals. Distance measurements from the ultrasonic sensor were incorporated to refine control behaviour. Servo angles were updated dynamically based on computed deviations, ensuring smooth and responsive tracking.

To improve stability, a threshold-based filtering mechanism was implemented. This prevents unnecessary micro-adjustments caused by minor fluctuations in ambient light, reducing oscillations and improving system reliability.

4.3 Experimental Setup

The system was evaluated in a controlled indoor environment using a movable light source to simulate a dynamic target. The LDR sensor array was mounted on a pan-tilt mechanism driven by servo motors, allowing two-axis movement.

The experimental procedure involved moving the light source across different trajectories and observing the system's ability to maintain alignment. Distance variations were also introduced to assess the contribution of ultrasonic sensing in tracking performance.

The setup ensures consistent lighting conditions while allowing controlled variation in target movement and positioning.

4.4 Performance Evaluation

Performance of the system was evaluated based on tracking accuracy, response time, and stability.

- **Tracking Accuracy:** The system successfully aligned with the moving light source with reasonable precision under stable lighting conditions. The quadrant LDR configuration enabled effective directional detection.
- **Response Time:** The system exhibited low latency in responding to target movement. Experimental observations indicate that response time increased with larger angular displacements, which is expected due to servo motion constraints.
- **Stability:** The implementation of threshold-based control significantly reduced jitter and oscillatory behaviour, resulting in smoother tracking.
- **Environmental Sensitivity:** Performance was influenced by ambient light variations. Under fluctuating lighting conditions, minor deviations were observed due to interference in sensor readings.

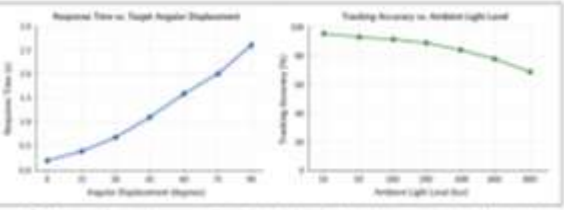


Fig. 3. Experimental results: (a) response time versus angular displacement, (b) tracking accuracy versus ambient light level.

The performance trends illustrated, including response time versus movement and accuracy versus lighting conditions, support these observations.

4.5 Discussion

The experimental results demonstrate that the proposed system achieves reliable real-time tracking using a simple and low-cost architecture. The integration of directional light sensing with distance measurement enhances overall system responsiveness compared to single-sensor approaches.

However, limitations remain. The reliance on light intensity makes the system sensitive to ambient illumination and restricts its applicability to light-emitting or reflective targets. Additionally, the absence of predictive control or filtering techniques limits performance in highly dynamic environments.

Despite these constraints, the system provides a practical proof-of-concept for extending LDR-based sensing into dynamic tracking applications, offering a strong foundation for further enhancements.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

This paper presented the design and implementation of a low-cost, LDR-based real-time target tracking system capable of dynamically following a moving light source. By integrating a quadrant LDR sensor array with an ultrasonic distance sensor, Arduino-based processing, and servo-driven actuation, the system achieves continuous alignment through a closed-loop feedback mechanism.

The results demonstrate that differential light sensing can be effectively extended beyond traditional static applications, such as solar tracking, to support dynamic target tracking. The inclusion of distance measurement improves system responsiveness and provides an additional layer of control, enhancing overall tracking performance.

Experimental evaluation confirms that the system delivers satisfactory accuracy and response time under controlled conditions, while maintaining low computational complexity and minimal hardware requirements. These characteristics make the proposed approach particularly suitable for educational applications, rapid prototyping, and low-cost automation systems.

However, the system is inherently limited by its dependence on light intensity as the primary sensing modality. Variations in ambient lighting conditions introduce noise into sensor readings, affecting tracking precision. Additionally, the system is restricted to tracking light-emitting or highly reflective targets, limiting its applicability in broader real-world scenarios.

Despite these limitations, the work successfully bridges the gap between simple sensor-based systems and more advanced tracking technologies by demonstrating a practical and scalable approach to real-time tracking.

5.2 Future Work

Several enhancements can be implemented to improve the performance and applicability of the proposed system:

- **Integration of Vision-Based Systems:** Incorporating cameras and image processing algorithms can enable tracking of non-light-based targets and improve robustness under varying environmental conditions.
- **Adaptive Filtering and Control:** Implementing advanced control techniques, such as PID control or Kalman filtering can enhance tracking stability and reduce noise-induced oscillations.
- **Sensor Fusion Expansion:** Combining additional sensors, such as infrared or motion detectors can improve detection reliability and expand operational capability.
- **IoT and Wireless Integration:** Enabling remote monitoring and control through wireless communication can extend the system's usability in real-world applications.
- **Mechanical Optimization:** Using high-precision actuators and improved structural design can enhance movement accuracy and response speed.
- **Application Scaling:** The system can be adapted for more complex applications in UAV tracking, surveillance, and autonomous robotics with appropriate modifications.

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