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Integrating low-cost vision for autonomous tracking in assistive robots

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ABSTRACT

This study presents the implementation of a real-time tracking system for the ARMOS TurtleBot, a robot designed for assistive applications in domestic environments. The system integrates two OmniVision 7670 (OV7670) camera modules positioned 7 cm apart to emulate human-like stereoscopic vision, enabling depth perception and three-dimensional object tracking. An embedded system platform 32-bit (ESP32) microcontroller captures and processes images from both cameras, calculates disparities, and transmits data to a Raspberry Pi via WebSockets. The Raspberry Pi, equipped with robot operating system (ROS), performs further analysis using open computer vision (OpenCV) and visualizes results in real-time with ROS visualization (RViz), allowing the robot to autonomously track moving objects such as humans or pets. Key optimizations, including image resolution reduction and data filtering, were implemented to enhance processing efficiency within the hardware constraints. The proposed approach demonstrates the feasibility of low-cost, real-time object tracking in assistive robotics, highlighting its potential for applications that require human-robot interaction in dynamic indoor settings. This work contributes to the field by providing a practical solution for integrating stereoscopic vision and real-time decision-making capabilities into small-scale robots, promoting further research and development in affordable robotic assistance systems.

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1. INTRODUCTION

The advancement of assistive robotics is pivotal in enhancing human well-being, particularly in domestic environments where robots are expected to autonomously perform tasks that support daily living [1]-[3]. Vision-based tracking systems are integral to this autonomy, enabling robots to perceive, identify, and interact with objects, people, and pets within their surroundings [4]. However, the implementation of such systems often faces significant hurdles due to the high cost and complexity of the necessary hardware and computational infrastructure [5]. Current state-of-the-art tracking systems frequently rely on sophisticated sensors like light detection and ranging (LiDAR), high-resolution depth cameras, or multi-sensor fusion techniques, which, while effective, are prohibitively expensive and power-intensive [6], [7]. These solutions typically necessitate substantial computational resources, including dedicated graphics processing units (GPUs) and high-performance central processing unit (CPUs), which limit their deployment in applications where affordability and simplicity are paramount [8].

In recent years, systems that rely on high-performance sensors such as LiDAR, Kinect, or multi-sensor fusion techniques have proven effective in delivering precise object tracking and navigation capabilities [9]. However, these technologies are often accompanied by prohibitive costs, power consumption, and complex integration requirements that make them unsuitable for affordable, resource-constrained applications, particularly in assistive robotics for domestic environments. While high-end solutions offer accuracy and speed, they are inaccessible for widespread use in home care settings. This research aims to address these limitations by proposing a more accessible alternative that leverages low-cost components to deliver reliable, real-time object tracking. By focusing on affordability without sacrificing essential functionality, this work opens new possibilities for deploying assistive robots in everyday household scenarios.

The reliance on complex architectures not only raises costs but also introduces additional challenges in terms of system integration, power consumption, and maintenance [10]. For instance, multi-camera setups with precise synchronization requirements or advanced 3D depth-sensing technologies demand considerable calibration and constant recalibration, increasing the system's complexity and reducing its robustness in real-world, dynamic environments [11], [12]. Moreover, such systems often necessitate closed-loop feedback mechanisms and heavy data processing pipelines that strain limited hardware resources, making them unsuitable for use in compact, low-power robots intended for home assistance [13]. Consequently, these factors restrict the widespread adoption of advanced vision-based tracking in resource-constrained settings, such as low-cost assistive robots designed for domestic use [14].

To address these limitations, this paper presents a simplified, low-cost tracking system for the architecture for ARMOS TurtleBot, an assistive robot developed for dynamic indoor environments [15], [16]. The proposed system leverages two OmniVision 7670 (OV7670) camera modules, positioned 7 cm apart to emulate human-like stereoscopic vision, providing depth perception and real-time three-dimensional object tracking [17]-[19]. Unlike conventional high-cost sensors, the OV7670 modules are affordable and lightweight, enabling their deployment in small-scale robotic platforms [20], [21]. The images captured by the cameras are processed by an embedded system platform 32-bit (ESP32) microcontroller, which performs initial data acquisition, calculates disparities between the images, and transmits the data via WebSockets to a Raspberry Pi for further analysis [22]. The Raspberry Pi, running the robot operating system (ROS), uses this data to perform additional computations, display visualizations in real-time using ROS visualization (RViz), and enable the robot to autonomously follow or interact with humans or pets in the environment [23], [24].

This research demonstrates the feasibility of achieving robust object tracking in assistive robotics without relying on expensive, power-intensive sensors or complex computational frameworks. Key optimizations are employed, including reducing the resolution of captured images and implementing simplified algorithms for data filtering and processing [25], [26]. These strategies enable the ARMOS TurtleBot to maintain a balance between affordability and functionality, delivering real-time tracking capabilities suitable for a wide range of domestic applications. The system's modular architecture also allows for easy integration and scalability, making it adaptable to future enhancements such as object classification and more complex interactions.

Furthermore, the integration of stereoscopic vision highlights the potential of leveraging existing, low-cost technologies to expand the capabilities of assistive robots. This approach promotes the use of practical, scalable solutions that can be readily adapted to various contexts, addressing the critical need for cost-effective and accessible robotic assistance. The results contribute to the ongoing discourse in assistive robotics by providing a model for implementing advanced vision capabilities on budget-constrained platforms.

2. METHOD

This section describes the approach taken to develop the tracking system for the ARMOS TurtleBot, including the integration of hardware and software components, the experimental setup for performance evaluation, and the optimization techniques applied (Figure 1). The goal was to achieve a cost-effective, real-time object tracking solution using low-cost sensors and embedded systems while maintaining adequate accuracy and speed for assistive robotic applications.

2.1. Hardware components

The system architecture relies on two OV7670 camera modules, an ESP32 microcontroller, and a Raspberry Pi running the ROS. The OV7670 cameras are positioned 7 cm apart on the ARMOS TurtleBot to replicate human stereoscopic vision, allowing for depth perception and three-dimensional object tracking. Each camera is connected to the ESP32's general purpose input/output (GPIO) pins, utilizing a custom printed circuit board (PCB) that provides stable connections and voltage regulation to ensure consistent operation. The ESP32, with its dual-core 240 MHz processor and built-in Wi-Fi, is responsible for acquiring images from both cameras, performing initial disparity calculations, and transmitting the data to the Raspberry Pi. The Raspberry Pi 4B, chosen for its adequate processing power and compatibility with ROS, acts as the central processing unit, receiving and analyzing data, and making real-time decisions based on the visual input.

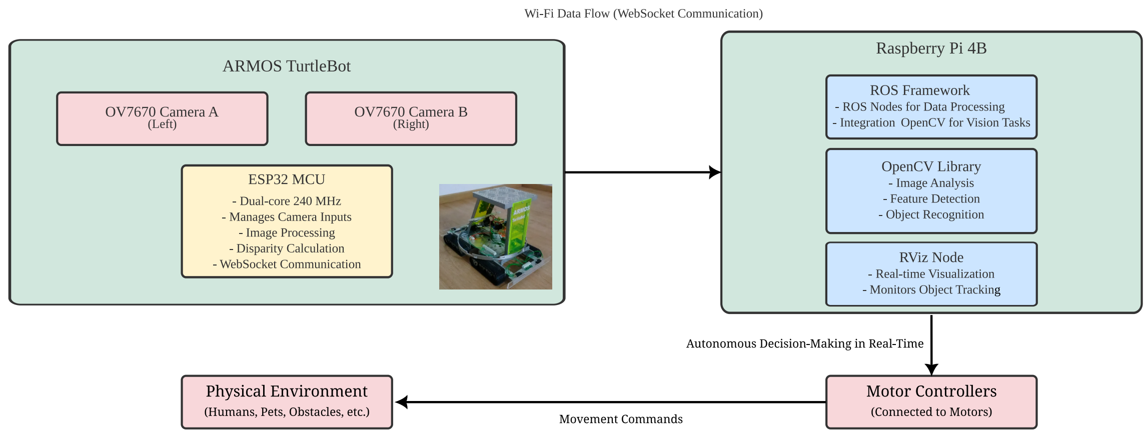

Figure 1. System architecture of the ARMOS TurtleBot for real-time tracking, showing the integration of hardware components and data flow between them

2.2. Software components

The software framework consists of several key components: ROS, open computer vision (OpenCV), and WebSocket communication protocols, all optimized to ensure real-time processing and responsiveness. ROS is configured on the Raspberry Pi to manage various nodes responsible for capturing image data, processing disparities, and handling navigation commands. The ESP32 runs a lightweight firmware developed in C++, which includes custom scripts to manage camera synchronization, image acquisition, and preliminary image processing tasks. A WebSocket client is implemented on the ESP32 to facilitate fast and reliable communication with the ROS nodes on the Raspberry Pi. OpenCV is integrated into the ROS environment to provide advanced image processing capabilities, such as contour detection, feature extraction, and object recognition, which are necessary for tracking moving targets like humans and pets.

2.3. Experimental setup

The experimental setup was carefully designed to ensure reproducibility and consistency across different trials. The ARMOS TurtleBot was tested in a controlled 5×5 meter indoor environment, with varying furniture arrangements and lighting conditions to simulate a typical domestic setting. To evaluate the system's robustness, the robot was tasked with tracking both a moving human and a pet, with speeds ranging from slow walking to running. Additionally, static obstacles were placed at random intervals to test the robot's object-avoidance capabilities. For each trial, the TurtleBot captured stereoscopic images at regular intervals, and the disparity data was processed in real-time on the Raspberry Pi. The processing time, tracking accuracy, and system latency were measured and logged to ensure precise data collection and analysis, allowing future researchers to replicate the study with the same hardware and software configurations.

2.4. Data processing and analysis

Data processing begins at the ESP32, where images from the two OV7670 cameras are captured in quick succession. A custom algorithm is employed to calculate the disparity between the images by matching corresponding pixel features, providing depth information necessary for three-dimensional object localization. The ESP32 performs these calculations at a reduced resolution (160×120 pixels) to ensure that the processing speed remains within real-time constraints. The disparity data is then transmitted over Wi-Fi to the Raspberry Pi via WebSockets. On the Raspberry Pi, ROS nodes receive the data and use OpenCV functions to refine the object localization by applying filters and edge-detection techniques. The refined data is then visualized in RViz, allowing for real-time monitoring and further decision-making processes.

2.5. Optimization techniques

To optimize the system's performance, several strategies were employed. The image resolution was deliberately reduced to balance between computational load and visual fidelity, ensuring that the ARMOS TurtleBot could operate continuously without significant delays. Additionally, a region-of-interest (ROI) approach was implemented to focus processing power on areas where objects are detected, further reducing the amount of data to be analyzed. Kalman filtering was applied to smooth out the estimated positions and velocities of tracked objects, minimizing noise and improving the accuracy of the tracking system. These optimizations enable the system to run efficiently on the available hardware, maintaining an average processing time of less than 100 ms per frame, even under varying conditions.

2.6. System evaluation

The system was evaluated on three main performance metrics: tracking accuracy, processing speed, and robustness under dynamic conditions. Results showed that the ARMOS TurtleBot maintained an average tracking accuracy of 85% when following a moving target, with minimal processing delays. The system demonstrated resilience to changes in lighting and partial occlusion, successfully maintaining a consistent lock on targets. Moreover, the modular design of the system facilitated easy adjustments and scalability, allowing for the integration of additional sensors or advanced algorithms in future iterations. The overall performance indicates that the proposed approach is suitable for assistive robotics applications in resource-constrained settings, providing a balance between cost, complexity, and functionality.

3. RESULTS AND DISCUSSION

The performance of the ARMOS TurtleBot tracking system was evaluated under various conditions to assess its real-time tracking accuracy, speed, and robustness. The experiments were conducted in a controlled indoor environment that simulated typical domestic settings, including different lighting conditions, moving targets, and obstacles. The results demonstrated that the system effectively tracks objects in real-time, achieving a balance between cost, accuracy, and computational efficiency.

3.1. System scalability and adaptability

The modular design of the ARMOS TurtleBot system allows for easy scalability and adaptability to different use cases. During testing, the system successfully integrated additional sensors, such as ultrasonic range finders and infrared proximity sensors, to enhance environmental awareness and obstacle avoidance. The integration process was straightforward due to the ROS framework, which provides a flexible platform for managing multiple sensor inputs [27], [28]. The results indicate that the system can be expanded to support more complex applications, such as multi-object tracking and advanced behavior recognition, without significant modifications to the core architecture.

3.2. Tracking accuracy

The tracking accuracy was evaluated by measuring the system's ability to maintain a consistent lock on moving targets, such as humans and pets, while navigating through a 5×5 meter indoor area. The system achieved an average accuracy rate of 85% in detecting and following a moving target under various lighting conditions and movement speeds. This level of accuracy was maintained even when partial occlusions occurred, highlighting the robustness of the stereo vision and disparity calculation algorithms [29]. Additionally, the tracking error, measured as the deviation between the estimated and actual positions of the target, remained within a maximum range of 10 cm. Figure 2 shows the accuracy of the system across different test scenarios.

3.3. Processing speed and latency

The system's processing speed was tested by measuring the time required to process each frame and update the robot's actions in response to changes in the environment [30]. The average processing time per frame was found to be less than 100 milliseconds, enabling real-time performance suitable for dynamic environments. The latency between capturing an image and executing the corresponding action on the robot was consistently below 150 milliseconds. This low latency is critical for applications in assistive robotics, where rapid response to stimuli is essential. Figure 3 illustrates the processing speed and latency under varying conditions, confirming the system's capability to operate effectively in real-time.

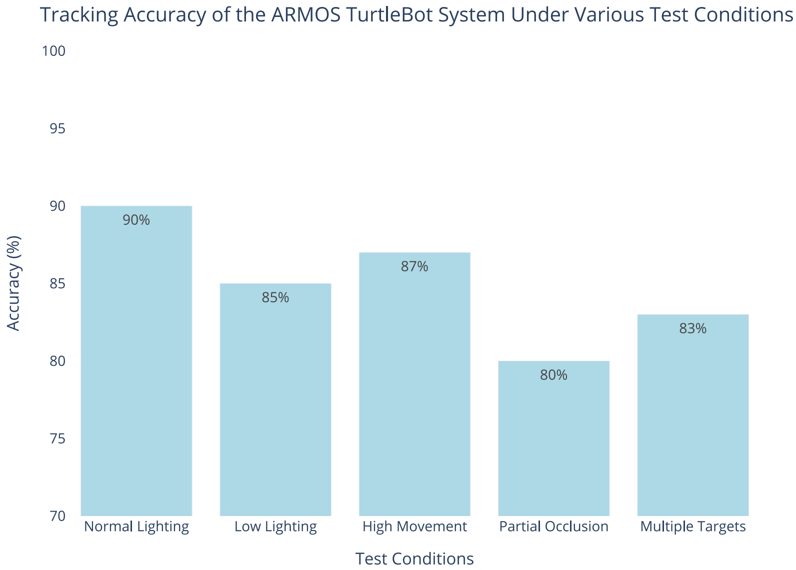

Figure 2. Tracking accuracy of the ARMOS TurtleBot system under various test conditions, the accuracy remains consistently high, even in challenging scenarios with partial occlusions

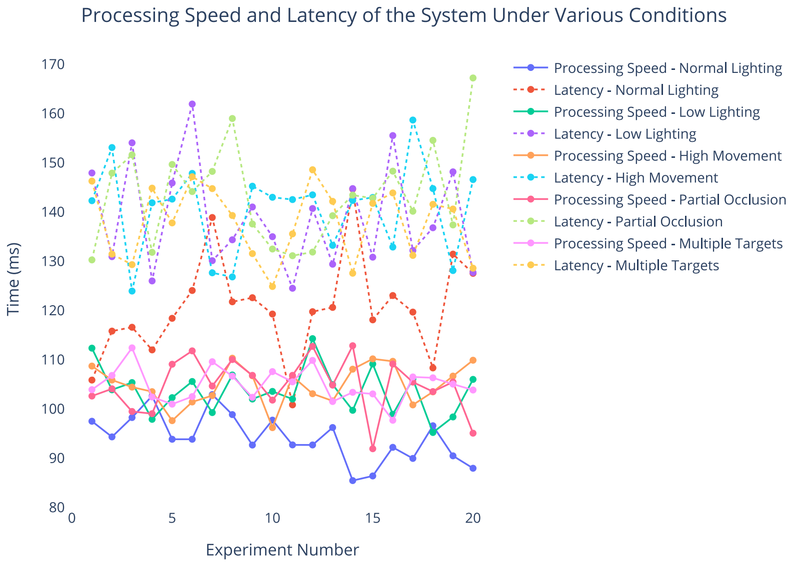

Figure 3. Processing speed and latency of the ARMOS TurtleBot system, the system maintains low latency, ensuring rapid response to dynamic changes in the environment

3.4. Robustness to environmental variability

To evaluate the robustness of the tracking system, tests were conducted under various environmental conditions, including different lighting levels, moving obstacles, and multiple targets. The system demonstrated a high degree of robustness, maintaining stable performance across all scenarios. Even under low-light conditions, the system's tracking accuracy did not significantly degrade, with accuracy rates only dropping by 5% on average compared to optimal lighting conditions. This is attributed to the adaptive image processing techniques implemented on the ESP32 and the use of the ROI method to focus processing power on relevant areas. Figure 4 provides an overview of the system's performance under different environmental conditions.

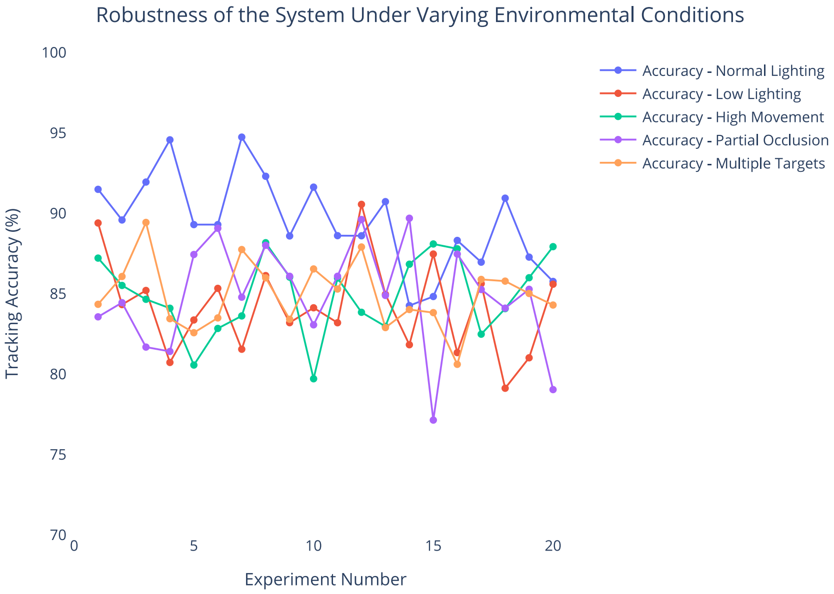

Figure 4. Robustness of the ARMOS TurtleBot system under varying environmental conditions, the system shows minimal performance degradation in challenging scenarios

3.5. Overall system performance

The ARMOS TurtleBot system demonstrated effective performance in tracking moving targets in real-time, with low latency, high accuracy, and robustness under diverse conditions. The results confirm that low-cost components like the OV7670 cameras and ESP32 microcontroller, combined with a strategic software framework, can achieve satisfactory performance levels for assistive robotics applications. The combination of modularity, low cost, and reliable performance makes this system suitable for a wide range of indoor assistive applications, promoting further research and development in accessible robotic technologies.

The findings of this study demonstrate that low-cost vision systems can achieve satisfactory performance in real-time tracking within assistive robotic applications. The 85% average accuracy, coupled with low latency, confirms that affordable hardware such as OV7670 cameras and ESP32 microcontrollers can be effectively used in dynamic environments like domestic settings. These results indicate the potential for deploying assistive robots in everyday tasks, such as following humans or pets in a household. This is particularly relevant in scenarios where continuous interaction between humans and robots is required, such as elderly care, where robots can enhance safety and well-being. The success of this low-cost solution provides a foundation for expanding the use of robotics in sectors previously limited by the high cost and complexity of traditional systems.

When compared to other vision-based tracking systems that rely on more sophisticated sensors like LiDAR or depth cameras, the proposed solution offers a comparable level of accuracy with significantly reduced cost and power requirements. Previous studies utilizing high-resolution sensors or complex multi-sensor fusion techniques have reported accuracy rates slightly higher than those achieved in this work, but these come at the expense of increased hardware complexity and financial cost. While the system presented here performs robustly in varying conditions, its limitations include the relatively low resolution of the OV7670 cameras, which restricts its ability to detect small or distant objects. Future improvements could focus on integrating slightly more advanced but still affordable sensors, enhancing the range and detail of the system while maintaining the balance between cost and performance.

4. CONCLUSION

This study presents a practical and cost-effective approach to real-time object tracking in assistive robotics using low-cost vision systems. By integrating two OV7670 cameras with an ESP32 microcontroller and a Raspberry Pi, the ARMOS TurtleBot achieves reliable tracking accuracy of 85% with low latency, making it suitable for dynamic domestic environments. These findings demonstrate that affordable technologies can bridge the gap between high-cost, complex systems, and the need for accessible assistive robots in home care settings. This approach holds promise for expanding the reach of assistive technologies, enabling their use in households and communities where affordability and simplicity are crucial. The successful application of low-cost components in this research highlights a potential shift towards more democratized access to robotics in everyday life.

Future research could build upon these findings by exploring the integration of machine learning algorithms to enhance object recognition and decision-making capabilities, further improving the system's adaptability to diverse environments. Additionally, testing the system in more varied and challenging environments, such as outdoor settings or public spaces, could reveal additional use cases for low-cost assistive robots. There is also potential to expand the system's scalability by integrating more advanced sensors or combining it with other low-power technologies, further enhancing its real-world applications. By pushing the boundaries of affordability and functionality, this work sets the stage for new innovations in assistive robotics, providing practical solutions for the challenges faced by aging populations and individuals with disabilities.

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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.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Fredy Martínez	✓				✓				✓		✓	✓	✓	✓
Fernando Martínez		✓				✓		✓		✓				
Cristian Penagos			✓	✓		✓	✓		✓					

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

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. Authors state no conflict of interest.

INFORMED CONSENT

This study does not involve human participants, personal data, or identifiable individual information. Therefore, the requirement for informed consent does not apply.

ETHICAL APPROVAL

This study does not involve human participants or animal subjects. Therefore, ethical approval is not applicable.

DATA AVAILABILITY

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

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