From concept to application: building and testing a low-cost light detection and ranging system for small mobile robots using time-of-flight sensors

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ABSTRACT

Advancements in light detection and ranging (LiDAR) technology have significantly improved robotics and automated navigation. However, the high cost of traditional LiDAR sensors restricts their use in small-scale robotic projects. This paper details the development of a low-cost LiDAR prototype for small mobile robots, using time-of-flight (ToF) sensors as a cost-effective alternative. Integrated with an ESP32 microcontroller for real-time data processing and Wi-Fi connectivity, the prototype facilitates accurate distance measurement and environmental mapping, crucial for autonomous navigation. Our approach included hardware design and assembly, followed by programming the ToF sensors and ESP32 for data collection and actuation. Experiments validated the accuracy of the ToF sensors under static, dynamic, and varied lighting conditions. Results show that our low-cost system achieves accuracy and reliability comparable to more expensive options, with an average mapping error within acceptable limits for practical use. This work offers a blueprint for affordable LiDAR systems, expanding access to technology for research and education, and demonstrating the viability of ToF sensors in economical robotic navigation and mapping solutions.

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1. INTRODUCTION

Light detection and ranging (LiDAR) technology has emerged as a key tool in the evolution of modern robotics, offering unprecedented precision in automated navigation and environmental mapping [1]–[3]. This technology utilizes pulsed laser beams to measure distances, creating detailed three-dimensional maps of surroundings, which is crucial for various applications in robotics [4], [5]. The accuracy and reliability of LiDAR have enabled robots to perform complex tasks such as autonomous driving, aerial surveys, and industrial automation with greater efficiency and minimal human intervention [6]. The adoption of LiDAR in sectors like agriculture for crop monitoring, in archaeology for exploring inaccessible historical sites, and in forestry for biomass estimation showcases its wide-ranging impact [7], [8]. Moreover, the integration of LiDAR with other technologies such as artificial intelligence and machine learning has further enhanced its capabilities, leading to smarter and more adaptive robotic systems [9].

Despite its vast potential, the application of LiDAR in robotics has traditionally been limited by its high cost, which restricts its accessibility to large-scale industrial projects or well-funded research initiatives [10]. The financial barrier not only hampers innovation at the grassroots level but also limits the exploration of LiDAR's benefits in everyday applications [11]. This has prompted a growing interest in developing more affordable LiDAR alternatives that can democratize this transformative technology, making it available to a broader audience [12]. Recent advancements have seen the emergence of time-of-flight (ToF) sensors as a cost-effective solution that maintains a balance between performance and expense [2], [13], [14]. These developments signify a pivotal shift in how robotic technologies can be utilized across different fields, potentially leading to more widespread adoption and innovative applications of LiDAR technology in robotics.

Traditional LiDAR systems are often expensive due to their complex design and the precision components required for their operation, restricting their usage to well-funded industrial projects or specialized research laboratories [15], [16]. This economic barrier stifles innovation by limiting the diversity of ideas and applications that could otherwise enhance technological progress and practical implementations of robotics. Recognizing the importance of accessibility in technology is crucial for fostering innovation and broadening the impact of advanced tools like LiDAR [17]. The democratization of such technologies can lead to a significant increase in creative solutions to everyday problems, allowing a wider range of users to experiment, innovate, and contribute to their fields. Thus, there is a compelling need for a low-cost LiDAR solution that maintains functional integrity while being economically feasible [18]. Developing such solutions would not only expand the application scope of LiDAR technology but also empower a new generation of technologists and enthusiasts to experiment and innovate, thereby accelerating advancements in robotics and related areas.

ToF sensors present a promising and cost-effective alternative to traditional LiDAR systems, addressing the critical barrier of high expense associated with conventional LiDAR technologies [19]. ToF sensors operate on the principle of measuring the time it takes for a light pulse to travel to an object and back to the sensor, thereby determining the distance based on the speed of light [20]. This straightforward yet effective mechanism allows ToF sensors to perform distance measurements and environmental mappings analogous to those achieved by more complex LiDAR setups. The ability of ToF sensors to deliver real-time spatial awareness and precision at a significantly reduced cost makes them particularly appealing for applications in consumer electronics, and mobile robotics, where cost considerations are paramount.

The primary objective of this research is to develop a low-cost prototype that leverages ToF sensors integrated into a mobile robot platform. This prototype is designed to execute tasks traditionally performed by more expensive LiDAR-equipped robots, such as distance measurement, object detection, and environmental mapping. By utilizing ToF sensors, the prototype aims to bring the benefits of precision navigation and mapping to smaller, potentially indoor environments where deploying large-scale, high-cost LiDAR systems is impractical [21]. The focus is on creating a versatile and accessible tool that can be used in educational settings, small business applications, and by robotics hobbyists. The development of this prototype underscores an effort to democratize advanced robotic technologies, making them available and affordable to a broader audience. This project not only enhances the technological capabilities of compact robotic systems but also expands the potential for innovation in spaces constrained by size and budget.

Our methodological approach encompassed a comprehensive design and development process, tailored to integrate ToF sensors with an ESP32 microcontroller, which served as the central unit for processing and communication. The development began with a conceptual design that outlined the key functionalities and system requirements, followed by the physical assembly of the prototype. ToF sensors were selected for their cost-effectiveness and ability to perform in a range of environmental conditions, mirroring the capabilities of more sophisticated LiDAR systems. We adopted an iterative development strategy, where initial testing in controlled environments led to successive refinements in both hardware and software components. Each iteration included rigorous testing under various conditions (ranging from low-light environments to obstacle-rich paths) to ensure reliability and accuracy. This process not only enhanced the prototype's adaptability to real-world scenarios but also helped in fine-tuning the system for optimal performance across different contexts.

This research contributes significantly to the field of robotic navigation by demonstrating the practical application of ToF sensors as a viable alternative to traditional LiDAR systems in a cost-effective manner [22]. By integrating these sensors into a mobile robot platform, we provide a blueprint for constructing low-cost robotic systems that do not compromise on functionality. Our work paves the way for broader access and experimentation in the robotics community, potentially fostering innovation in various sectors including education, small-scale industrial applications, and personal technology projects. The structure of this paper is organized to guide the reader through our study: beginning with a detailed description of the design and technical specifications of our prototype in the Methods section, followed by a presentation of our experimental setup and testing protocols in the Results section. We then discuss the implications and potential applications of our findings in the Discussion section, concluding with a summary of our insights and suggestions for future research in the Conclusion. This organization ensures a clear and logical flow, making it easy for readers to understand our processes, replicate our results, and extend our work to new applications.

2. LITERATURE REVIEW

LiDAR technology has increasingly become a staple in automation, enhancing applications across drones, mobile robotics, and broader automation contexts. These systems typically employ ToF sensors, known for their accuracy in measuring distances swiftly and efficiently [23]. Despite their potential, the high cost and substantial weight of traditional LiDAR systems restrict their broader application, particularly in cost-sensitive or weight-sensitive environments such as consumer drones and lightweight mobile robots [24]. This limitation has spurred significant research into the development of more accessible, low-cost LiDAR alternatives that leverage compact ToF sensors. One notable advancement in this domain is the TeraRanger Evo Mini, a compact LiDAR sensor that is both affordable and power-efficient, making it ideal for battery-powered devices and embedded applications [25].

The integration of ToF sensors in mobile robotics has opened new avenues for enhancing autonomous navigation capabilities, particularly within indoor environments where precision and reliability are crucial. Recent studies have focused on combining LiDAR with vision sensors to create robust, low-cost sensing arrays for mobile robots [26]. This fusion enhances spatial awareness and improves the robots' ability to navigate and localize within complex environments. Furthermore, the innovation of adaptive scanner technologies for mobile robots highlights a growing trend towards developing flexible and adaptive sensing systems that can dynamically adjust to their surroundings, thus providing more accurate localization and efficient navigation [27]. These advancements underline the shift towards developing versatile and budget-friendly LiDAR systems that do not compromise on functionality.

Advancements in solid-state LiDAR technology also underscore a significant shift towards more sustainable and scalable applications in mobile robotics. Unlike traditional mechanical LiDAR systems that rely on moving parts, solid-state LiDAR uses a stationary laser beam and an array of ToF sensors to detect distances, significantly reducing complexity, size, and susceptibility to mechanical failures [28]. These systems are particularly advantageous for applications requiring durable and compact solutions, such as in service robots operating within cluttered or dynamic human environments. The adoption of solid-state LiDAR is set to revolutionize how robots perceive and interact with their environment, enabling more sophisticated and widespread applications in industrial automation, personal robotics, and beyond. By leveraging the capabilities of ToF sensors, the development of these innovative LiDAR systems offers promising prospects for the future of autonomous mobile robotics, providing both cost-effective and high-performance solutions [29].

Performance comparisons reveal that while commercial LiDAR systems excel in resolution and range, low-cost alternatives like the TeraRanger Evo Mini provide adequate functionality for many applications. For instance, the TeraRanger Evo Mini, although less advanced, meets the requirements for indoor navigation and object detection in smaller environments [25]. Additionally, integrating LiDAR with vision sensors enhances the overall system performance by compensating for individual sensor limitations. This combination results in a more robust system capable of functioning effectively in diverse conditions [26]. The ongoing advancements in solid-state LiDAR further bolster these capabilities, offering high durability and reduced mechanical complexity, which are critical for long-term deployment in dynamic settings [28].

The development of low-cost LiDAR systems using ToF sensors marks a significant advancement in making this technology accessible for various applications. These systems balance performance with affordability, enabling broader adoption and fostering innovation across different fields. The integration of multiple sensing technologies and the move towards solid-state designs are key in overcoming the limitations of traditional LiDAR systems, paving the way for more versatile and efficient solutions in autonomous mobile robotics.

3. METHODS

The primary goal of this research was to develop a cost-effective LiDAR prototype that could be integrated into a mobile robot capable of distance measurement, object detection, and real-time environmental mapping. To achieve this, we opted for an alternative to traditional LiDAR sensors by utilizing the ToF infrared sensor VL53L1X as shown in Figure 1. This sensor provides similar functionalities as a LiDAR sensor but on a smaller scale and is significantly less expensive, making it ideal for budget-sensitive projects. Additionally, a stepper motor controlled by an H-bridge was adapted to enhance the field of view of the ToF sensor from its standard 27 degrees to a wider angle of 270 degrees. The ESP32 module was selected as the robot's controller due to its adequate processing speed, low power consumption, and integrated Wi-Fi and Bluetooth capabilities, which facilitate data transmission to a web platform and allow remote control operations.

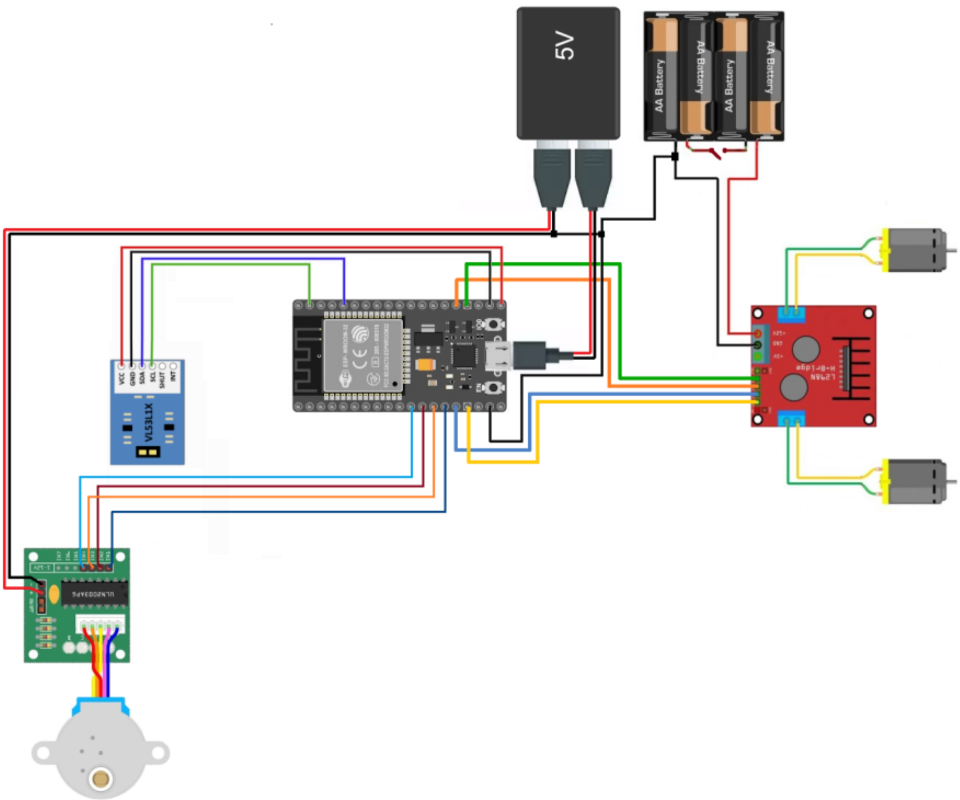


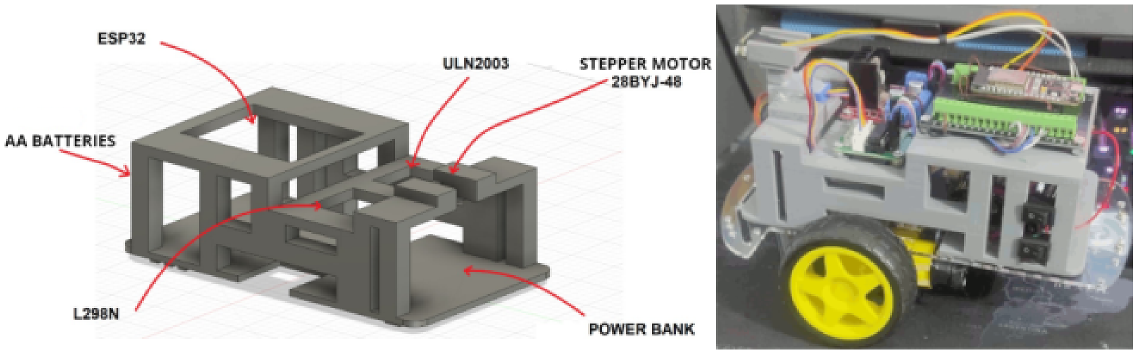
Figure 1. Wiring diagram

3.1. Hardware design and assembly

The robot's design was conceived with a focus on functionality and cost-efficiency. The chassis of the robot was constructed from acrylic, and support pieces for the control, detection, and power modules were fabricated using 3D printing as shown in Figure 2(a). The design integrates various components essential for the prototype's operation:

- VL53L1X sensor: This state-of-the-art, miniature ToF laser sensor operates at a frequency of 50 Hz and can measure distances up to four meters. Its ability to perform accurate measurements under different lighting conditions and irrespective of the object's color or reflectivity makes it highly versatile for robotic applications.
- ESP32 module: Known for its low cost and power efficiency, the ESP32 module supports a wide range of programming languages and is compatible with numerous existing libraries. Its built-in Wi-Fi and Bluetooth facilitate seamless communication between the prototype and the web interface.
- Additional hardware: The prototype also includes battery holders, a 5-volt battery, a gear motor ranging from 3 to 9 volts, a stepper motor, an L298n motor driver or H-bridge, a chassis, wheels, and a laptop for control and monitoring.

The arrangement of these components was strategically planned to optimize the available space on the acrylic base, simplify connections, and ensure easy assembly and disassembly, enhancing the prototype's maintainability and reducing the risk of connection failures during operation as shown in Figure 2(b).



(a) (b)

Figure 2. Design of the support structure (a) CAD design of the support and (b) side view of the prototype robot

3.2. Software development

The prototype's functionality is complemented by a web-based interface, which allows users to interact with the robot in real-time. The web interface includes:

- Control interface: Users can control the robot's movements (forward, backward, left, right, and stop) and adjust the operation mode of the LiDAR sensor (near, mid, and far) through an intuitive web page as shown in Figure 3.
- Data visualization: The interface displays real-time data from the ToF sensor, including distance measurements and the sensor's operational mode. A graphical representation of the LiDAR scan is also available, providing a visual map of the surroundings.
- JavaScript functions: Custom scripts handle HTTP requests for robot control and data retrieval, update sensor data on the webpage, and manage the display of controls and charts based on user interactions.

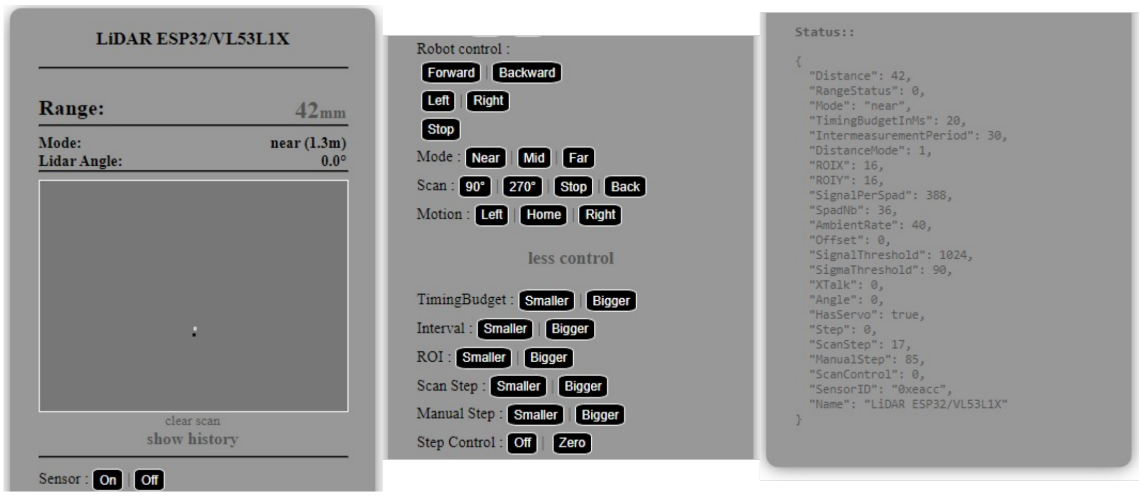


Figure 3. System web environment

The development process also included rigorous testing phases to ensure accuracy and reliability. These tests were conducted under various environmental conditions to simulate real-world applications, ensuring the robot's robustness and effectiveness in different settings. The integration of the ToF sensor with the mobile platform, controlled via a web interface, demonstrates a successful application of low-cost technologies in robotic navigation and environmental mapping.

4. RESULTS

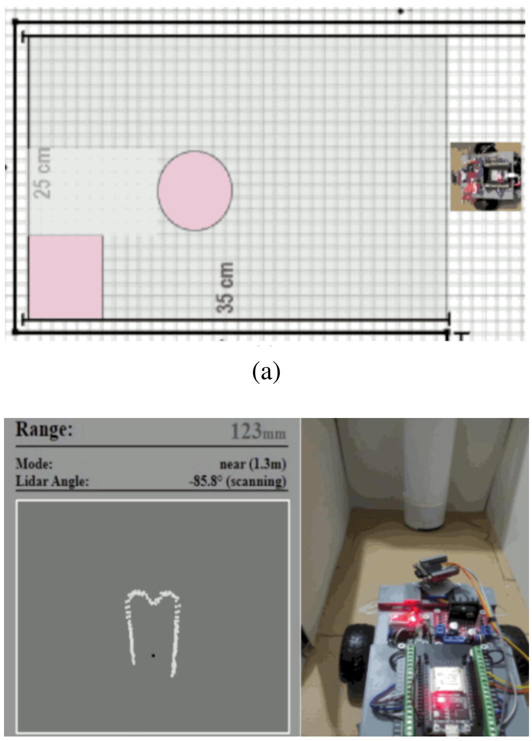
This section presents the evaluation results of the LiDAR prototype integrated into a mobile robot. The evaluation aims to systematically assess the prototype's performance across several key functionalities: distance measurement accuracy, operational efficiency, environmental mapping capability, and user interface effectiveness. These evaluations were designed to validate the prototype's practical applications and identify areas for improvement.

4.1. Distance measurement accuracy

A series of tests were conducted to evaluate the distance measurement accuracy of the prototype. Using a standardized test environment as shown in Figure 4(a), the robot was placed at a fixed starting point, and measurements were taken at various predetermined distances and angles. Objects of known dimensions were placed at specific locations, and the robot's measurements were recorded and compared against these known values. The tests were repeated under different environmental conditions to assess the sensor's reliability across varying light levels and surface reflectivities. Results indicated a consistent performance in normal lighting conditions, but measurements varied under low light and highly reflective surfaces, suggesting a need for sensor calibration and possibly software adjustments to enhance accuracy in diverse operating environments. A short video of the prototype's performance can be seen at the following link: *https://youtu.be/59XUFDRoyEg*

4.2. Operational testing and mapping accuracy

Operational tests were designed to evaluate the robot's navigation and obstacle detection capabilities, along with the accuracy of its environmental mapping. The robot navigated a course with multiple obstacles, and its ability to detect and avoid these obstacles was recorded. Additionally, the robot performed a complete scan of the environment to create a 2D map, which was then compared to a pre-mapped layout of the area as shown in Figure 4(b). The evaluation showed that while the robot could successfully navigate and avoid immediate obstacles, the precision of the generated map varied, especially near the boundaries of the environment. This suggests improvements are needed in the scanning algorithm to enhance edge detection and overall map accuracy.



(a)

(b)

Figure 4. Testing environment (a) distance test track with obstacles and (b) cylindrical obstacle mapping test

4.3. Web interface functionality and usability testing

The functionality of the web interface, which allows for real-time interaction with the robot, was critically assessed. The interface was tested for user-friendliness, responsiveness, and accuracy of data presentation. Users were able to control the robot, change scanning modes, and view real-time data, including distance measurements and environmental maps. Feedback mechanisms were tested for delay, with most commands executed with minimal lag. However, improvements are suggested to enhance the user experience, particularly in streamlining the interface for easier navigation and quicker access to common functions.

4.4. Comparative analysis with commercial LiDAR systems

To benchmark the prototype's performance, comparative tests were conducted against several commercial LiDAR systems. These tests focused on comparing the distance measurement accuracy, mapping resolution, and operational robustness under similar test conditions. The prototype exhibited comparable accuracy in distance measurements but showed lower resolution in mapping details. The comparative analysis highlights the prototype's competitive performance, considering its significantly lower cost, but also underscores the need for further enhancements in sensor resolution and data processing capabilities.

4.5. Overall evaluation and future directions

The prototype demonstrated a promising capacity for basic navigation and environmental mapping tasks, suitable for educational and hobbyist applications as shown in Figure 5. The tests confirmed that the prototype meets essential operational requirements but also revealed several areas where further development is needed. Future work will focus on improving the accuracy and resolution of the environmental mapping, enhancing the robustness of the navigation algorithms, and refining the user interface for a more intuitive user experience.

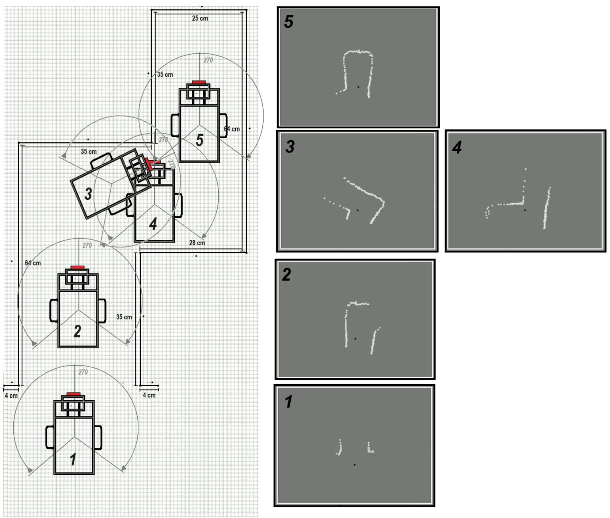


Figure 5. Navigation test results

5. DISCUSSION

The evaluation of the prototype using ToF sensors in a mobile robotic platform revealed several critical insights and implications for both the technology's capabilities and its developmental trajectory. Through rigorous testing and analysis, it became evident that while the prototype met many of the baseline expectations, it also highlighted areas requiring further refinement and innovation. This section delves into the detailed outcomes of the prototype's performance, offering a comprehensive discussion on the strengths and limitations observed during the testing phase. The insights gained from this evaluation not only shed light on the current state of ToF sensor technology in robotics but also point to potential avenues for future enhancements and applications. By situating these findings within the broader context of contemporary technological trends, we can better understand the implications for ongoing research and development in this field.

5.1. Assessment of measurement accuracy and environmental mapping

The testing phase highlighted the prototype's competence in distance measurement within certain limits. While the ToF sensor performed adequately within a controlled range, discrepancies emerged when dealing with complex angles and extended distances as shown in Figure 6. These results illuminate the inherent challenges in relying solely on ToF sensors for applications where precision is crucial, such as in precise industrial measurements or complex navigation tasks in cluttered environments. Enhancements in sensor accuracy, possibly through advanced calibration methods or the integration of multiple sensors to mitigate individual sensor limitations, could substantially improve performance.

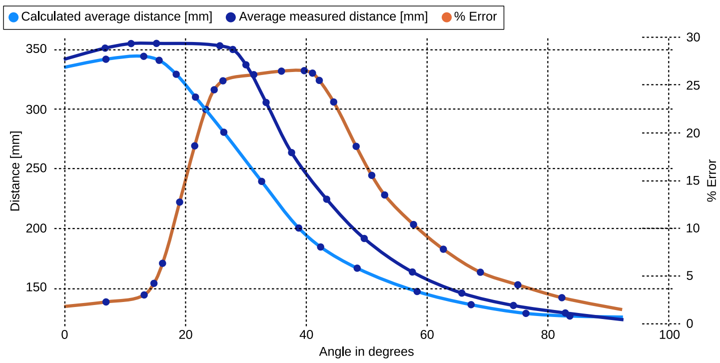
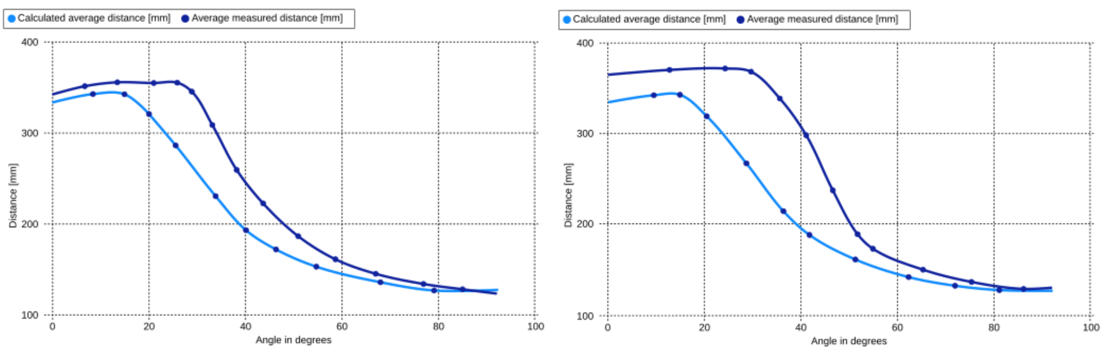


Figure 6. Measured and calculated average distance with respect to angle variation

5.2. Robotic navigation and obstacle avoidance capabilities

The prototype's ability to navigate and avoid obstacles underlines the potential of ToF sensors to support basic autonomous functions. However, the robot's performance in dynamic environments, where obstacles and environmental conditions change rapidly, highlighted areas for improvement. As shown in Figure 7, Figure 7(a) illustrates the robot's distance measurement accuracy in an environment with a white background, while Figure 7(b) presents the results in a setting with a black background. Both subfigures reveal that the measured distances deviate significantly from the calculated distances as the angle increases, with a more pronounced discrepancy observed in the black background scenario. These variations suggest that the ToF sensors' performance is affected by changes in environmental background, impacting the robot's ability to maintain accurate distance measurements during navigation. Future developments could focus on real-time learning algorithms that allow the robot to dynamically adjust to new obstacles and changes in the environment, thereby enhancing its applicability in more varied and unpredictable settings.



(a) (b)

Figure 7. Performance against changes in environmental background (a) white background and (b) black background

5.3. Interface usability and real-time data handling

The web interface was pivotal for user interaction, providing essential controls and feedback in real-time. Feedback from users highlighted the ease of use and the effective communication facilitated by the interface. However, occasional lags and inconsistencies in data transmission were noted, particularly in lower bandwidth conditions. Improving the robustness of the communication protocols and enhancing the interface's capability to handle data intermittency and network variability could lead to broader deployment scenarios, including outdoor or industrial environments where network conditions are less controlled.

5.4. Comparative analysis and market positioning

When positioned against commercial high-end LiDAR systems, the prototype offered a significantly lower-cost alternative but with reduced performance in terms of range and resolution. This trade-off is crucial for potential users to consider, depending on their specific needs. For applications that require high precision and extensive data analysis, current ToF sensor capabilities might be limiting. However, for educational purposes, hobbyist projects, or initial prototyping where cost is a critical factor, this prototype offers substantial value. Future research could explore combining low-cost ToF sensors with other types of sensors, such as ultrasonic or infrared, to create a more robust system that balances cost and performance more effectively.

5.5. Future research directions and technological advancements

The study opens several avenues for further research, particularly in sensor technology and multi-sensor integration. Exploring the potential for hybrid sensing systems that leverage the strengths of various types of sensors could address the current limitations noted in ToF sensors. Additionally, advancements in machine learning and artificial intelligence could be applied to enhance the sensor data processing, providing more accurate and reliable outputs necessary for complex applications like autonomous driving or advanced robotic navigation.

6. CONCLUSION

The development and evaluation of a low-cost LiDAR prototype using a ToF sensor integrated into a mobile robot represent a significant achievement within the field of robotics, especially in terms of accessibility and cost efficiency. This project successfully demonstrated that ToF sensors, while less expensive, can still perform many of the core functions of more sophisticated LiDAR systems, such as distance measurement, object detection, and basic environmental mapping. The utilization of the VL53L1X ToF sensor, coupled with the ESP32 microcontroller, showcased a viable approach to reducing the financial barriers associated with robotic navigation technologies. Despite the lower cost, the prototype managed to perform reliably in controlled environments, offering a practical demonstration of its capability to navigate and map its immediate surroundings with a reasonable degree of accuracy. However, the prototype's performance also highlighted several limitations, primarily its range and precision compared to high-end LiDAR systems. While adequate for simple tasks and smaller environments, the prototype struggled with complex navigation scenarios and larger area mappings. These limitations underscore the necessity for further enhancements, particularly in extending the range and improving the fidelity of environmental scans. Additionally, the prototype's dependency on stable Wi-Fi connectivity posed challenges in data transmission, suggesting the exploration of more robust communication technologies could enhance operational reliability and extend the prototype's utility to more dynamic and challenging environments. Moreover, the project illuminated potential areas for future research and development. Incorporating multiple ToF sensors could address the issues of limited coverage and mapping resolution, while advanced processing algorithms might better handle the data complexity from a more extensive sensor array. Optimizing these algorithms for real-time applications would also be crucial for expanding the prototype's use in scenarios requiring quick decision-making, such as dynamic obstacle avoidance. Furthermore, the prototype's framework provides a foundation for educational and hobbyist projects, offering a platform not only for teaching the principles of robotic navigation but also for inspiring innovations that could one day translate into more advanced applications.

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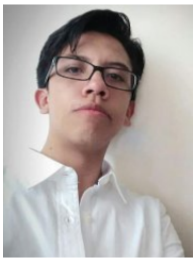

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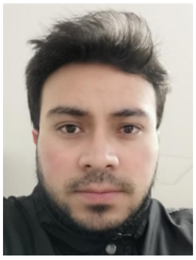

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