

Evaluation of the GPS Neo Ublox M8N and Four-Sided Ultrasonic Sensor for Smart Navigation: A Case Study of a Miniature Unmanned Ground Vehicle

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ABSTRACT

The rapid advancement of autonomous systems has driven the development of intelligent navigation technologies across various fields, including transportation, robotics, and environmental monitoring. However, many autonomous ground vehicle platforms rely on high-cost sensors and complex system architectures, limiting their accessibility for research and education purposes. To address this challenge, this study proposes a cost-effective miniature Unmanned Ground Vehicle (UGV) integrating a Neo Ublox M8N GPS module with a four-sided ultrasonic sensing system to support real-time navigation and local obstacle awareness. The proposed system combines global positioning data with multi-directional short-range distance detection, processed through a Raspberry Pi and visualized via a web-based platform for real-time monitoring. Experimental testing was conducted under controlled outdoor and indoor conditions to evaluate GPS positioning accuracy, ultrasonic detection performance, and overall system responsiveness. The Neo Ublox M8N module achieved an average positional error of 4.35 m, corresponding to an accuracy of 97.4%, representing an improvement over previous studies using low-cost GPS receivers without algorithmic enhancement. Meanwhile, the ultrasonic sensors demonstrated reliable obstacle detection within a range of 5–70 cm, with an error of less than 1% and stable readings across all four sides of the UGV. The integration of these two sensing modalities demonstrated effective coordination between global and local navigation tasks, enabling real-time path visualization and obstacle awareness. Overall, the findings indicate that the proposed miniature UGV provides a scalable, low-cost platform suitable for research, prototyping, and education applications in autonomous navigation. This work also contributes practical insights for developing intelligent sensing architectures in small-scale robotic systems and highlights opportunities for further enhancements through sensor fusion and autonomous control strategies.

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I. INTRODUCTION

In the current era, research and innovation in autonomous systems have been encouraged by the Fourth Industrial Revolution's (4IR) rapid improvement in technology [1], [2]. The development of smarter systems is driven by the integration of artificial intelligence (AI) [3], [4], robotics [5], the Internet of Things (IoT) [6], and cyber-physical systems [7], [8] which together support autonomous production methods powered by intelligent machines. Autonomous systems encourage the development of more intelligent, self-operating production and service systems by emphasizing safety, adaptability, variety, and coordination. Autonomous driving, an application of the

autonomous system, has gained significant attention in recent years [9].

Unmanned Ground Vehicles (UGVs), which are related to autonomous driving technologies, have received growing attention due to their potential applications in transportation, logistics, defense, agriculture, and urban mobility [10], [11]. The global UGV market was projected to exceed USD 2.9 billion in 2024, with an anticipated robust compound yearly growth rate (CAGR) of 14.0%, reaching over USD 10.8 billion by 2034 [12]. UGVs are expected to perform intelligent navigation tasks, driven by rapid advancements in control strategies,

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path planning, and safety, requiring precise mapping, localization, trajectory planning, and control implementation.

conceptual and descriptive, though, and lacks experimental validation. Unmanned Ground Vehicles (UGVs) are frequently investigated in these studies as adaptable platforms with sensor fusion and autonomous

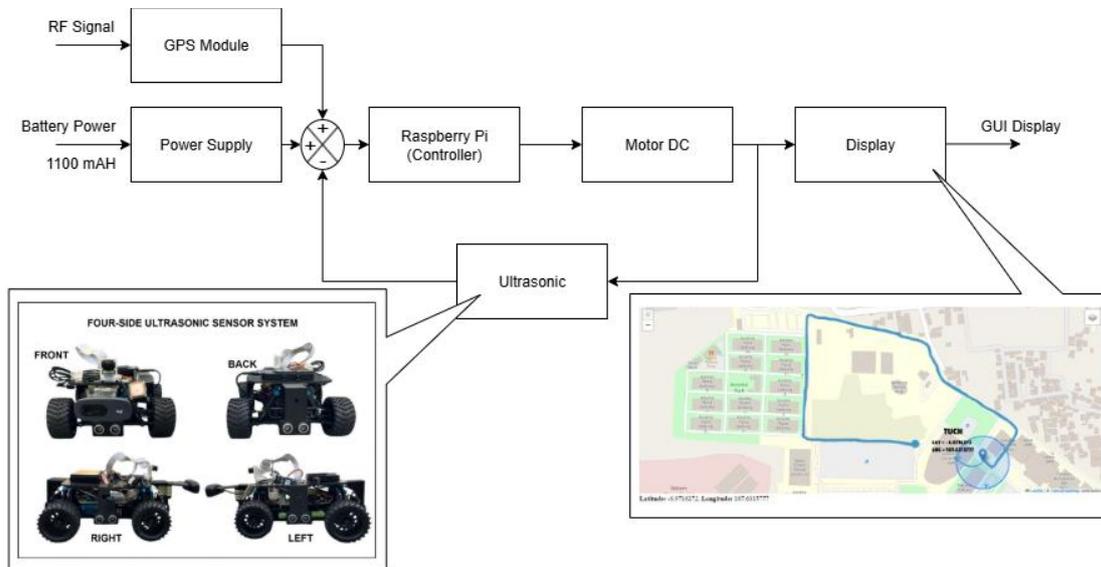


Fig. 1. The block layout of the integrated GPS and ultrasonic sensor system in a miniature unmanned ground vehicle.

Despite the increasing demand and potential of UGVs, there are still many challenges in the way of full-scale autonomous vehicle development, such as safety validation, public acceptance, regulatory gaps, AI driving algorithm integration, sensor fusion, and developing modular control platforms for diverse applications like defense, agriculture, and industrial automation [13]. Furthermore, there are frequently no open platforms accessible for students and early-stage researchers to explore autonomous navigation rules in real-world contexts [14]. These limitations delay both academic contributions and real-world uses of autonomous ground vehicle technologies.

Nevertheless, several researchers have studied the features of UGVs in different methods. An updated study [15] proposes a robust control strategy for UGV navigation and obstacle avoidance using a simplified second-order sliding mode controller, integrating GPS, LiDAR, and inertial sensors. Its stability is proven with Lyapunov theory and validated through both simulations and outdoor experiments. However, the study's limitations include high computational requirements and reliance on costly sensor suites such as LiDAR, which limit its practicality for miniature or low-cost UGV applications.

Another updated study [16] provides a comprehensive review of UGVs for photovoltaic plant inspection, highlighting their benefits for improving inspection efficiency and reliability. The reviewed systems still have issues, such as high implementation costs and reliance on GPS and vision sensors that may not be reliable in certain environmental conditions. It is still primarily

navigation algorithms to support applications such as logistics [17], search and rescue [18], indoor environmental monitoring [19], and agricultural disease diagnosis [20]. Enhancing situational awareness, spatial coverage, and obstacle avoidance using LiDAR, environmental sensors, and intelligent control techniques is the shared objective [21], [22], [23], [24]. Even with these developments, common issues persist across all the work. For example, navigating complex environments like cluttered indoor spaces, dense vegetation, or uneven terrain frequently results in lower sensing resolution and localization accuracy, and scalability is limited by computational load, sensor costs, and generalizability issues, especially for small or inexpensive UGV applications.

A cost-effective and adaptable unmanned ground vehicle (UGV) platform for educational applications was developed in [25], where the authors evaluated GPS precision, inclination-based navigation, and the structural durability of a 3D-printed chassis. Although their work effectively showcased affordability and adaptability, it failed to investigate the integration of advanced sensing systems (e.g., ultrasonic sensors for obstacle detection) or advanced navigation strategies beyond fundamental waypoint following. As a result, a research gap remains in the development of cost-effective, yet intelligent UGV systems that combine GPS-based global tracking with local sensing for obstacle detection, enabling reliable operation in more complex and realistic environments.

To bridge the gap, this study aims to develop a miniature UGV platform integrating two key features,

including GPS-based live tracking using the integration across multiple platforms for real-time navigation monitoring, and ultrasonic-based distance detection on multiple sides to enable obstacle awareness.

To provide an educational platform and a basis for further autonomous vehicle research, this study aims to create, build, and evaluate an integrated miniature UGV system that demonstrates accurate real-time navigation, precise obstacle detection, and robust structural modeling.

This study contributes by developing a miniature UGV platform that integrates ultrasonic distance detection and GPS-based real-time monitoring for autonomous navigation. A web-based interface is used to set up the system for live monitoring, and its general dependability, obstacle awareness, and tracking accuracy are assessed. The results establish a scalable framework for further UGV research and offer useful insights into the functionality of integrated navigation systems.

This study evaluates the integration of GPS and ultrasonic sensors for smart navigation in a miniature UGV. The research uses a case study to evaluate the performance of the integrated system and its benefits and drawbacks. The results should provide information on the feasibility of low-cost navigation solutions, which could impact smart mobility technology.

II. MATERIALS AND METHOD

A. System Overview

In this research, the integration of two main subsystems, GPS-based live tracking and ultrasonic distance detection, was involved with the miniature UGV, utilizing Raspberry Pi as the processing unit. The main objective is to enable the UGV to perform basic smart navigation tasks, such as live path monitoring and obstacle awareness, within a scaled-down environment that simulates real conditions.

The proposed smart navigation system integrates GPS and ultrasonic sensors to enhance the UGV's capability in both positioning and local obstacle detection. The system is designed as a modular architecture consisting of three main subsystems such as sensing, processing, and actuation. The system architecture, as illustrated in Fig. 1, consists of integrated hardware components that enable autonomous navigation. A power supply unit provides a consistent power supply to all modules, ensuring continuous operation. During the sensing process, the GPS module provides positioning data, while the ultrasonic sensor provides real-time distance readings to obstacles. Both inputs are processed by the Raspberry Pi controller as the processing subsystem, which serves as the primary processing unit for data fusion and the controller. Based on the collected data, the controller generates control

signals for the DC motor as the actuation subsystem, enabling the vehicle to move and change its path.

Additionally, the system is combined with the display module, which displays navigation status and sensor information, enabling users to monitor the UGV's operation. This architecture creates an integrated system in which the GPS provides global course tracking, the ultrasonic sensor improves local obstacle detection, and the Raspberry Pi controller effectively coordinates them.

To implement the proposed smart navigation system, a set of hardware components was assembled and integrated into the miniature UGV platform based on compatibility, availability, and suitability for small-scale autonomous navigation experiments. The Neo-M8N GPS module [26], which is utilized in this work, is well known for its excellent tracking sensitivity, multi-GNSS compatibility, and high positioning accuracy, making it dependable for autonomous navigation across a variety of settings. It performs better than previous modules, such as the Neo-6M [27], according to comparative tests, providing enhanced precision, reliable signal acquisition, and sophisticated features like spoofing detection and geofencing. Because of these features, the Neo-M8N is especially well-suited for autonomous ground vehicle applications that demand stable waypoint navigation with low error [28], [29].

A Raspberry Pi 4B [30] is used to control the navigation core, processing positional data from the GPS module, and transmitting it to a Firebase [31] database for synchronization and real-time storage. Leaflet.js [32], an open-source JavaScript library for developing interactive maps, is then used to display the stored data, offering a dynamic map interface for tracking the UGV's path.

The system uses an HC-SR04 ultrasonic sensor [33] to measure short-range distances and detect obstacles. This sensor offers notable advantages over other ultrasonic sensors in terms of accuracy, precision, and usefulness. With detection ranges of up to 430 cm, accuracy levels of 98–99%, and enhanced performance through optimization approaches, it provides a reliable, cost-effective, and small solution for both general and precision robotic applications [34], [35]. As shown in Fig. 1, four ultrasonic sensors are installed on each side of the miniature UGV to demonstrate their capabilities, which are less expensive than LiDAR.

All components are integrated into a miniature UGV to evaluate its autonomous navigation performance in detecting positions and measuring objects during operation.

B. Data Collection

In this study, the Raspberry Pi acts as the central controller for a smart navigation system, which integrates several sensors and modules to collect data. In Fig. 1, the data collection process is started on the GPS module,

which receives low-power radio signals from GPS satellites. These radio signals are converted into real-time positioning data, including latitude, longitude, and time, which are essential for waypoint navigation and path tracking using Leaflet.js on the Raspberry Pi. This positional data is stored in Firebase, enabling continuous monitoring and analysis of the vehicle's movement. The recorded position also serves as the basis for the controller to determine the DC motor's action, allowing the vehicle to travel along the predetermined path.

Table 1. The threshold levels of distance detection on a miniature UGV

Threshold	Level Information
≥ 50 cm	Safe
≤ 50 cm	Obstacle detected
≤ 30 cm	Near obstacle
≤ 10 cm	Danger

Furthermore, when the HC-SR04 ultrasonic sensor detects an object at a very near range, the system sends a warning signal to the observer. On the other hand, depending on the GPS data, the car keeps going forward in a straight line if no obstacles are detected. Based on the speed of sound, the ultrasonic sensor measures distance, enabling precise estimates of item proximity within certain limits. Therefore, 50 cm is established as the safe detection distance, and the UGV's implementation is planned to use the present layout scale. An object is considered an obstacle if it is spotted at a distance of less than 50 cm. As a result, Table 1 summarizes the four threshold levels for distance detection on the UGV.

C. Data Processing

The data processing stage is crucial because it converts raw sensor data into useful information that enables the miniature UGV to navigate effectively. This study uses two main data sources: a GPS module and four-sided ultrasonic sensors.

During the positioning process, the Raspberry Pi continuously processes raw GPS data to derive accurate real-time coordinates using the Haversine equation Eq. (1), which mathematically transforms latitude and longitude into precise distance measurements. The equation is expressed as [36], [37], [38]:

$$d = R \cdot 2 \cdot \tan^{-1} \left(\frac{\sqrt{\sin^2 \frac{\Delta\theta}{2} + \cos(\theta_1) \cdot \cos(\theta_2) \cdot \sin^2 \frac{\Delta\lambda}{2}}}{\sqrt{1 - \sin^2 \frac{\Delta\theta}{2} + \cos(\theta_1) \cdot \cos(\theta_2) \cdot \sin^2 \frac{\Delta\lambda}{2}}} \right) \quad (1)$$

where $\Delta\theta$ is latitude, $\Delta\lambda$ is longitude, R is the Earth's radius (approximately 6,371 km) [39], and d is the distance between two points on the Earth's surface. For distance detection using ultrasonic sensors, the Raspberry Pi computes the elapsed time (Δt) between the

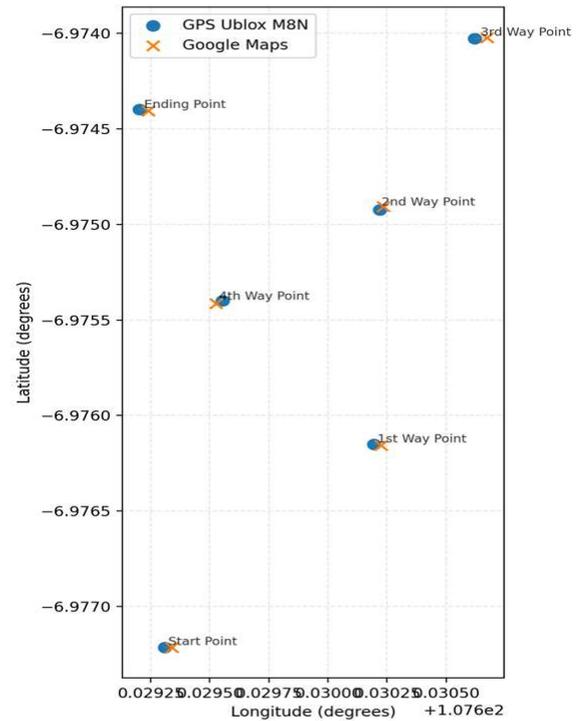


Fig. 2. The comparison graph of recorded points between the GPS and Google Maps

emission (start time, t_i) and reception (stop time, t_f) of the ultrasonic pulse [40], as shown in Eq. (2). This elapsed time is then converted into the raw distance (d_r) using the known speed of sound (c), as expressed in Eq. (3).

$$\Delta t = t_f - t_i \quad (2)$$

$$d_r = \frac{\Delta t \cdot c}{2} \quad (3)$$

The speed of sound in air is 34,300 cm/s [41]. The raw distance is corrected using the offset value (OS) defined in Eq. (4), and the final corrected distance (d_c) is obtained using Eq. (5).

$$OS = \left(\frac{OS_{i+1} - OS_i}{d_{i+1} - d_i} \right) \times (d_r - d_i) + OS_i \quad (4)$$

$$d_c = d_r + OS \quad (5)$$

where d_{i+1} and d_i are the two nearest calibrated distances, which are based on the raw distance in Eq.(2) and Eq.(3), while OS_{i+1} and OS_i are the offset values between the two nearest calibrated distances. Finally, the processed GPS and ultrasonic data streams are combined to make a complete navigation dataset. These datasets are used together to determine the actions to be performed by the UGV, according to the rules shown in Table 1.

III. RESULTS

A. Accuracy

The accuracy of the UGV's localization and obstacle detection process was evaluated by comparing sensor

data with the UGV's true position and the actual distances to detected obstacles. The accuracy evaluation focuses on two keys subsystems, including GPS-based position tracking and ultrasonic distance detection.

Table 2. The total average of the standard deviation and error from the UGV ultrasonic sensors

Sensor	Average	
	Standard Deviation (cm)	Error (%)
Front-side	0.016	0,21
Back-side	0.024	0,59
Right-side	0.014	0,92
Left-side	0.049	0,45

The GPS module was tested across six predefined waypoints when the UGV was moving. For each waypoint, the recorded latitude and longitude were compared to the Google Maps reference coordinates [41]. The deviation between the GPS-measured coordinates and the Google Maps reference points was quantified to assess the UGV's localization precision. Based on the comparison, the average GPS localization error was approximately 4.35 m. As shown in Fig. 2, the miniature UGV applications are within the acceptable range of 2 to 5 m.

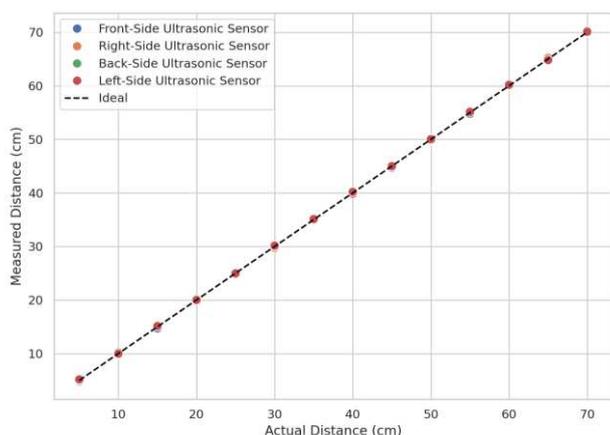


Fig. 3. The comparison graph of recorded points between the Four-Sided Distance and the Ideal

The ultrasonic sensors' performance was evaluated by placing obstacles at distances ranging from 5 to 70 cm. In this study, multiple readings were taken for each distance and compared to the actual measured distance. Figure 3 shows that every-sided sensors achieved accurate detection within the range, with an average standard deviation of under 0.05 cm, and an error of under 1% from the actual measurement, as shown in Table 2.

B. Performance

The system's performance was assessed by evaluating the GPS and ultrasonic devices integrated into the miniature UGV. The test involved placing nine obstacles

of varying sizes and positions on the test track, which the UGV drove. The data in Table 3 represent the system's detection performance in identifying obstacles from different sensor positions on a moving UGV.

The front-side system columns show the earliest possible distance at which the obstacle was first detected as the UGV approaches from the front, whereas the back-side system columns show the maximum distance at which the obstacle remains detectable after the UGV has passed it, as viewed from the rear of the UGV, respectively. Meanwhile, the Right-or-Left-side system column shows the closest detectable distance while the UGV navigated alongside the obstacle, representing the shortest range at which the side sensors could still identify the object. In this test, the GPS-enabled tracking of the vehicle's trajectory.

This information offers an overview of the UGV's performance in detecting objects at different orientations. Larger values at the front and rear indicate the system's ability to detect obstacles farther away, ensuring an earlier response time. In contrast, the smaller side values indicate the system's detection threshold during lateral movement, which is important when maneuvering through confined spaces or preventing collisions during sideways navigation.

Table 3. The system's performance in detecting obstacles both in front of, behind, and beside the UGV

Obstacle	Distance of UGV to obstacle (cm)		
	Front-side system	Back-side system	Right-or-Left-side system
1	63.59	31.84	9.65
2	55.82	10.56	10.84
3	70.31	71.17	12.22
4	100.1	90.48	9.65
5	105.2	95.42	11.25
6	73.07	52.77	10.52
7	50.67	33.29	12.33
8	51.69	56.40	12.17
9	53.97	50.66	11.36

The integration of GPS and ultrasonic data enabled the system to deliver effective global positioning and local obstacle detection. The precision of integration was verified by observing the UGV's movement on the web-based map interface while simultaneously validating real-time obstacle recognition.

IV. DISCUSSION

This study aims to evaluate the performance of the Neo Ublox M8N module and the four-sided ultrasonic system

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in the miniature UGV. The results of the miniature UGV showed that integrating GPS and ultrasonic sensors effectively supports intelligent navigation in a small-scale autonomous system. Based on the accuracy of the GPS, the live tracking using the Neo Ublox M8N module in the UGV system achieved an average positional error of around 4.35 m with an accuracy 97,4%, which is better than the previous study, with the same module showing a location accuracy of approximately 6 m with an accuracy of 95%, without any algorithmic advancements [42]. Although the additional algorithm in this previous study achieved around 1,5 m, its accuracy was only 66%, so it couldn't be used in complex systems like autonomous navigation.

As shown in Table 3, the four-sided ultrasonic system using HC-SR04 reliably detected obstacles on a moving UGV. In the test, the sensors provided reliable obstacle detection within a range of 5 to around 70 cm, with a deviation of less than 10% from actual measurements. This result confirms the performance of ultrasonic sensing as a cost-effective approach for short-range detection, confirming the results of previous studies [40], [43].

Additionally, the four-sided ultrasonic system offered valuable information regarding directional sensitivity. For this study, the UGV system can detect an object from around 70 cm in front and behind, with a minimum threshold that can be detected during lateral navigation is around 10 cm. This orientation-dependent performance highlights the need to include multi-directional sensing in UGV design.

In contrast, there is a constraint on UGV prototypes designed to improve the efficacy of low-cost components, such as GPS modules or ultrasonic sensors. The integrated approach presented in this study addresses this gap by combining the two subsystems into a single platform. This integration not only improves reliability but also provides a closer approximation to real-world navigation scenarios, where vehicles must balance global positioning with local environmental awareness simultaneously.

Overall, the results suggest that the proposed miniature UGV serves as an effective and scalable platform for studying autonomous navigation. It provides a balance between affordability, ease of implementation, and functional reliability, making it particularly suitable for academic research and as a learning medium for students. However, further improvements, such as advanced filtering techniques for GPS signals, the fusion of multiple sensing modalities, and the development of autonomous decision-making algorithms, could enhance system robustness and scalability for larger-scale applications.

V. CONCLUSION

With the objective of improving intelligent navigation on a

miniature unmanned ground vehicle (UGV), this study evaluates the performance of an integrated system that uses a GPS Neo Ublox M8N module as the GPS and a Four-Sided Ultrasonic Sensor for direction detection. This research successfully developed a miniature UGV system that serves as both a learning and research platform for autonomous navigation studies.

The ultrasonic sensors on all four sides enabled detection of obstacles up to 5–70 cm away. The GPS-based live tracking system, which used the Neo Ublox M8N module with Raspberry Pi, Leaflet.js, and Firebase, had an average positional error of about 4,35 m with an accuracy of more than 95%, which is in line with what is typical for low-cost GPS modules. These results show that the proposed system improves real-time navigation and awareness of the surroundings in small UGVs. Furthermore, it provides a scalable framework for future research and educational activities while improving the real-time navigation and environmental awareness of small UGVs, thereby offering valuable insights for future applications in smart vehicle technology.

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