International Journal of Advanced Engineering and Technology

Journal homepage: https://ijaetech.org/index.php/ijaetech

Development of a GIS-Based Embedded Vehicle Navigation Prototype Using GPS and Digital Compass Integration

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ABSTRACT

The increasing demand for efficient transportation has accelerated the development of intelligent vehicle navigation systems capable of providing accurate positioning and route guidance. This study aims to develop a prototype Geographic Information System (GIS) for vehicle navigation by integrating a Global Positioning System (GPS) receiver, a digital compass, an AVR microcontroller, and a computer-based visualization interface. The results demonstrated that the prototype successfully acquired and transmitted real-time positioning, speed, and heading information while maintaining reliable communication with the computer. The GPS receiver remained operational at vehicle speeds of up to approximately 100 km/h, and the measured speed showed good agreement with the vehicle speedometer. Although slight positioning deviations and map display inaccuracies were observed due to standalone GPS positioning and raster-based mapping, the prototype successfully fulfilled its intended navigation functions. The developed prototype demonstrates that integrating GPS, a digital compass, and GIS provides a practical and cost-effective solution for embedded vehicle navigation systems and offers a useful foundation for future research involving advanced sensor fusion and intelligent transportation technologies.

ARTICLE INFO

Article History:

Submitted/Received 24 Jul 2026
First Revised 02 Aug 2026
Accepted 8 Aug 2026
First Available Online 12 Aug 2026
Publication Date 12 xxx 2026

Keyword:

Geographic Information System, Global Positioning System, Vehicle Navigation, Digital Compass, Embedded System

1. INTRODUCTION

The rapid development of transportation technology and intelligent mobility systems has significantly increased the demand for accurate and reliable vehicle navigation. The growth of urban populations and the increasing number of vehicles have created more complex traffic conditions, requiring navigation systems capable of providing real-time positioning and route guidance. Modern navigation systems not only determine the geographic location of a vehicle but also integrate spatial information, traffic conditions, and destination guidance to improve travel efficiency and driving safety. Geographic Information Systems (GIS) have become one of the primary technologies supporting intelligent transportation systems because they can process, analyze, and visualize spatial information dynamically (Goodchild, 2020; Li et al., 2021; Wang & Xu, 2023).

The Global Positioning System (GPS) remains the most widely adopted positioning technology in vehicle navigation due to its global coverage, relatively high positioning accuracy, and continuous operation under various environmental conditions. Recent developments in Global Navigation Satellite Systems (GNSS), combined with Geographic Information Systems, have enabled various applications such as autonomous vehicles, fleet management, logistics monitoring, emergency response, and smart city transportation. In addition, digital compass sensors provide heading information that complements GPS positioning by determining the orientation of vehicle movement, particularly during low-speed conditions where GPS heading accuracy decreases. The integration of GPS and digital compass technologies has therefore become increasingly important for developing reliable navigation systems (Kaplan & Hegarty, 2021; Groves, 2022; Quddus et al., 2022; Teunissen & Montenbruck, 2023).

Several previous studies have investigated GPS-based navigation systems using various hardware platforms, including microcontrollers and embedded systems. Research has demonstrated that integrating GPS receivers with embedded controllers enables real-time acquisition of latitude, longitude, speed, and navigation information. Other studies have combined inertial sensors, digital compasses, and GIS platforms to improve navigation performance in mobile applications. Nevertheless, many low-cost navigation systems still experience several limitations, including GPS positioning errors, communication latency, sensor integration challenges, and limited visualization capabilities for route guidance. Furthermore, most commercial navigation devices employ proprietary software and expensive hardware, making them less suitable for educational and prototype development purposes (Farrell, 2020; Gao et al., 2021; Zhang et al., 2022; Ahmed et al., 2023; Kim & Park, 2024).

Based on these challenges, this research proposes the design of a Geographic Information System prototype for vehicle navigation by integrating a GPS receiver, a digital compass module, an AVR microcontroller, and a personal computer-based visualization interface. The proposed prototype aims to provide real-time information regarding vehicle position, heading direction, travel speed, and navigation guidance toward a specified destination. The contribution of this study lies in developing a low-cost integrated navigation prototype that combines spatial information processing, GPS positioning, and digital compass orientation into a single system capable of supporting vehicle navigation applications. The experimental evaluation focuses on measuring positioning accuracy, speed accuracy, heading information, and real-time communication performance between hardware and software components. This concept aligns with the research objective of the thesis: to design a vehicle navigation

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

prototype that integrates GPS, a digital compass, a microcontroller, and a GIS application to provide information on the vehicle's position, speed, and direction.

2. METHODS

This study employed an engineering design and experimental testing approach to develop a prototype Geographic Information System for vehicle navigation. The prototype was designed to acquire the vehicle's geographic position, movement speed, and heading direction, transmit the data to a computer, and display the movement of the vehicle relative to a predetermined destination. The development process consisted of system requirement identification, hardware integration, microcontroller programming, GIS interface development, and prototype performance testing. The research focused on the functional integration of a GPS receiver, a digital compass, an AVR microcontroller, serial communication, and a computer-based navigation interface.

The prototype used the first valid GPS coordinate received by the system as the initial position. The user then entered the geographic coordinates of the destination. Based on these two coordinates, the software calculated the distance and direction from the initial position to the destination. During vehicle movement, the prototype continuously acquired latitude, longitude, speed, time, and heading information to track the vehicle and provide navigation information.

The system consisted of a GPS receiver module, a CMPS03 digital compass, a DT-AVR low-cost microcontroller system, an RS-232 communication module, and a personal computer running the navigation application. The GPS antenna received signals from navigation satellites and transferred the positioning data to the GPS receiver. The GPS receiver and digital compass were connected to the microcontroller, which selected, processed, and transmitted the required information to the computer.

The GPS module provided geographic coordinates and vehicle speed, while the CMPS03 digital compass supplied the vehicle heading relative to geographic north. The microcontroller combined these data and transmitted them through serial communication to the computer. The computer application then processed the input data, calculated the distance and direction to the destination, and displayed the vehicle movement on a digital map.

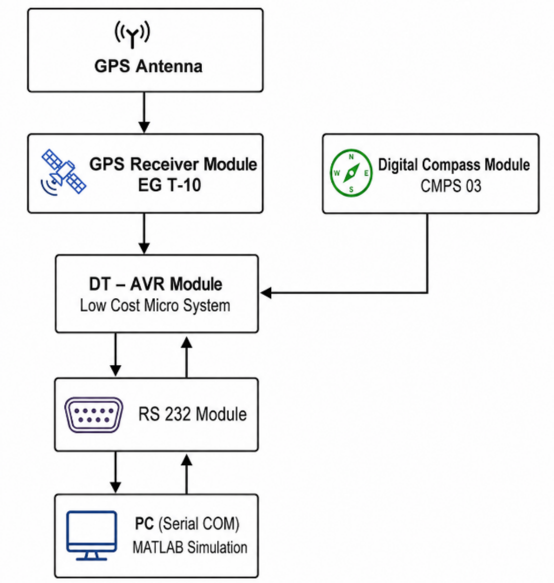

Figure 1. Overall architecture of the proposed vehicle navigation prototype.

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

3. RESULTS

3.1 Prototype Implementation

The proposed vehicle navigation prototype was successfully developed by integrating a GPS receiver module, a CMPS03 digital compass, a DT–AVR microcontroller, an RS-232 communication interface, and a computer-based Geographic Information System application. The GPS module continuously acquired vehicle position and speed information from navigation satellites, whereas the digital compass measured the heading angle relative to geographic north. The microcontroller processed both sensor outputs and transmitted the combined information to the computer through serial communication. The developed software subsequently visualized the vehicle movement and navigation information in real time.

The developed prototype operated according to the architecture presented in Figure 1. During operation, GPS data were validated before transmission, while heading information from the digital compass was continuously updated. The communication between the embedded hardware and the computer required approximately one second for each data transmission cycle.

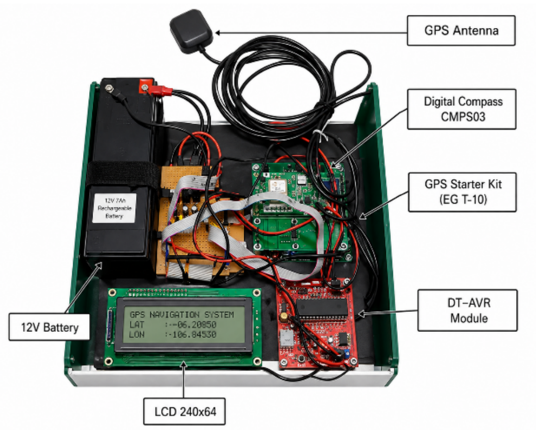

Figure 2. Physical configuration of the developed navigation prototype

3.2 GPS Position Acquisition

The GPS receiver successfully acquired latitude and longitude information under both stationary and moving conditions. During stationary testing, repeated measurements showed small coordinate variations caused by satellite geometry, atmospheric effects, and receiver uncertainty. The prototype successfully filtered invalid GPS messages before processing the navigation data.

When installed on the vehicle, the GPS receiver continuously transmitted geographic coordinates together with speed and time information. These data were received and processed correctly by the microcontroller before being forwarded to the computer.

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e-ISSN: 3089-767X; p-ISSN:3089-8439

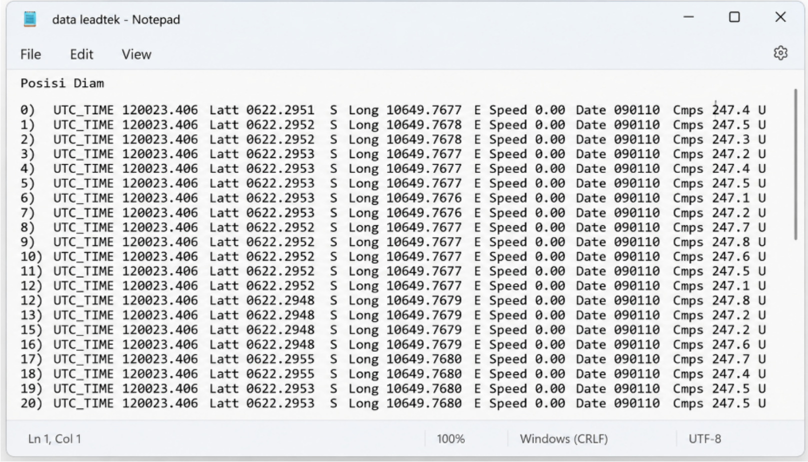

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Figure 3. GPS data received during stationary positioning.

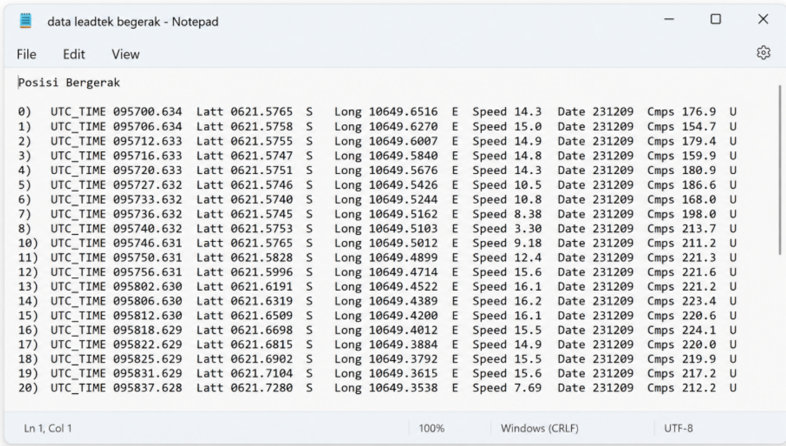

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Figure 4. GPS data received during vehicle movement

3.3 Position Accuracy Evaluation

Position stability was evaluated by repeatedly recording latitude and longitude measurements while the prototype remained stationary. The first coordinate measurement was selected as the reference position, whereas subsequent measurements were compared with the reference coordinate using the navigation equations described in the methodology section.

The coordinate differences were relatively small, indicating that the GPS receiver was capable of maintaining stable positioning. Nevertheless, fluctuations remained unavoidable because the prototype used absolute GPS positioning without differential correction. Multipath propagation, atmospheric conditions, and satellite visibility also contributed to positioning uncertainty.

The original prototype reported an average positioning deviation of approximately 6.378 m, which is acceptable for low-cost navigation applications. The observed positioning performance indicates that the prototype can provide sufficient location information for educational navigation systems and prototype development.

Table 1. Position error obtained during stationary testing

No	Latitude (degree minutes second)		Longitude (degree minutes second)		Spare Latt (degree minutes)	Spare Long (degree minutes)	Error Distance (m)
0	6°22’17.706”	S	106°49’46.062”	E	-	-	-
1	6°22’17.712”	S	106°49’46.080”	E	0,0001	0,0003	7564.006627
2	6°22’17.712”	S	106°49’46.080”	E	0,0001	0,0003	7564.006627

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

Volume 2 Nomor 1 May 2026 Page 114-127

No	Latitude (degree minutes second)		Longitude (degree minutes second)		Spare Latt (degree minutes)	Spare Long (degree minutes)	Error Distance (m)
3	6°22’17.718”	S	106°49’46.080”	E	0,0002	0,0003	7564.008597
4	6°22’17.718”	S	106°49’46.068”	E	0,0002	0,0001	7564.007142
5	6°22’17.718”	S	106°49’46.068”	E	0,0002	0,0001	7564.007142
6	6°22’17.718”	S	106°49’46.086”	E	0,0002	0,0004	7564.009324
7	6°22’17.718”	S	106°49’46.086”	E	0,0002	0,0004	7564.009324
8	6°22’17.712”	S	106°49’46.086”	E	0,0001	0,0004	7564.007355
9	6°22’17.712”	S	106°49’46.062”	E	0,0001	0,0000	7564.004445
10	6°22’17.712”	S	106°49’46.062”	E	0,0001	0,0000	7564.004445
11	6°22’17.712”	S	106°49’46.062”	E	0,0001	0,0000	7564.004445
Rate	**6°22’17.712”**	**S**	**106°49’46.062”**	**E**	**0,0005**	**0,0004**	**7564.004445**
Max	**6°22’17.718”**	**S**	**106°49’46.086”**	**E**	**0,0002**	**0,0004**	**7564.009324**
Min	**6°22’17.706”**	**S**	**106°49’46.062”**	**E**	**0,0001**	**0,0000**	**7564.006627**

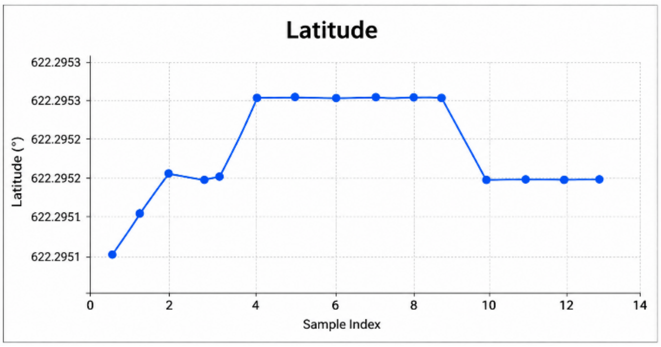

Figure 5. Latitude variation

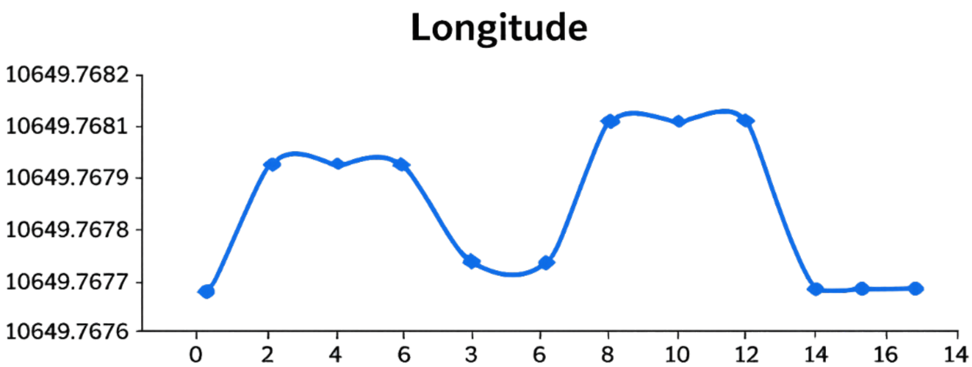

Figure 6. Longitude variation

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e-ISSN: 3089-767X; p-ISSN:3089-8439

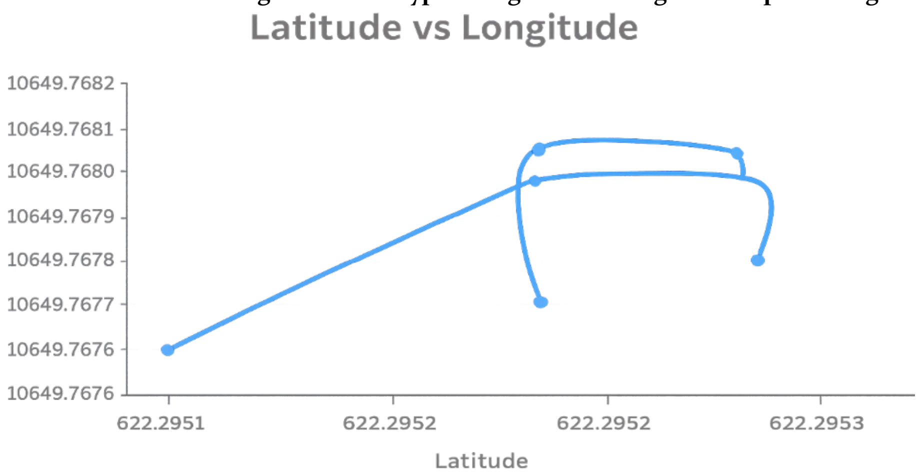

Figure 7. Combined latitude–longitude trajectory

3.4 Speed Measurement Performance

Vehicle speed obtained from the GPS receiver was compared with the vehicle speedometer under different driving speeds. The experimental results demonstrated a strong agreement between both measurements throughout the entire testing range.

The GPS receiver successfully measured vehicle speed from approximately 10 km/h to 100 km/h. The smallest difference between GPS speed and the reference speedometer occurred at approximately 90 km/h, whereas the largest deviation occurred near 60 km/h. Overall, the GPS receiver maintained good consistency with the vehicle speedometer, demonstrating its suitability for navigation purposes.

Table 2. Comparison between GPS speed and vehicle speedometer."

Speedometer Speed (km/h)	GPS Starter Kit Speed (km/h)	Error (%)
10	9.33408	0.66592
20	20.14976	0.14976
30	29.94684	0.05316
40	40.1884	0.1884
50	49.74472	0.25528
60	58.65284	1.34716
70	70.13524	0.13524
80	80.0848	0.0848
90	90.04424	0.04424
100	99.9154	0.0846

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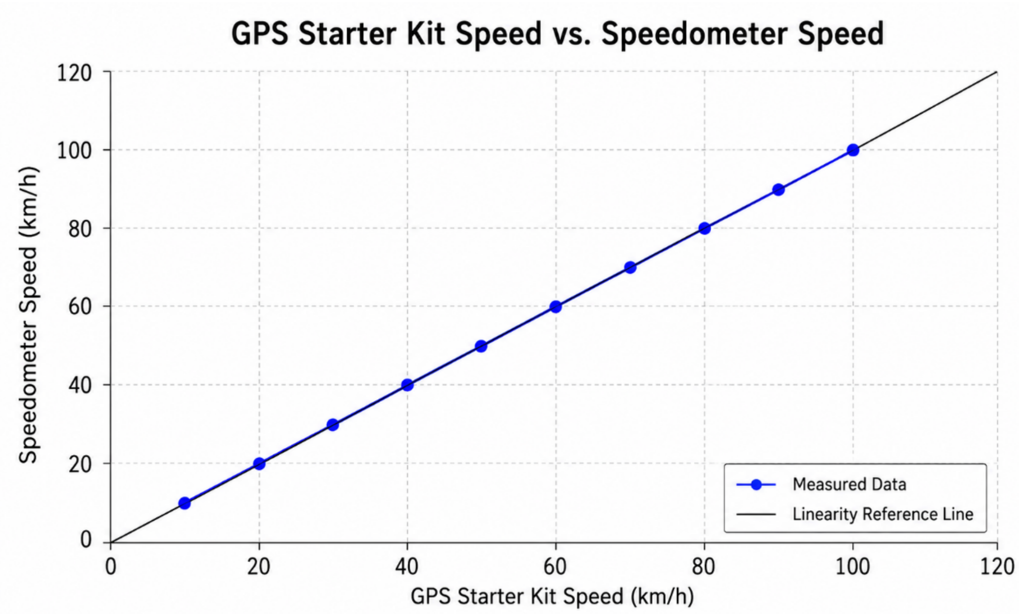

Figure 8. Comparison between GPS speed and vehicle speedometer

Latitude	Longitude	Direction	Altitude (m)	Speed (km/h)	Top Speed (km/h)
Lat 8.6118	10641.6473	S Long	861.64	51.87	51.87
Lat 8.6118	10641.0333	S Long	861.66	52.86	52.86
Lat 8.6118	10641.0194	S Long	861.67	52.92	52.92
Lat 8.6118	10641.0056	S Long	861.69	53.60	53.60
Lat 8.6118	10640.9913	S Long	861.69	52.80	53.60
Lat 8.6118	10640.9772	S Long	861.70	53.00	53.60
Lat 8.6118	10640.9631	S Long	861.71	53.17	53.60
Lat 8.6118	10640.9489	E	861.73	54.46	54.46
Lat 8.6118	10640.9347	E	861.74	53.11	53.60
Lat 8.6118	10640.9203	E	861.75	53.41	54.46
Lat 8.6118	10640.9068	E	861.76	54.46	54.46
Lat 8.6118	10640.8937	E	861.77	53.92	54.46
Lat 8.6118	10640.8807	E	861.78	54.14	54.46
Lat 8.6118	10640.8669	E	861.79	52.10	54.46
Lat 8.6118	10640.8536	E	861.80	51.55	54.46
Lat 8.6118	10640.8406	E	861.81	51.98	54.46
Lat 8.6118	10640.8274	E	861.82	51.67	54.46
Lat 8.6118	10640.8147	E	861.83	50.76	54.46
Lat 8.6118	10640.8014	E	861.84	49.86	54.46
Lat 8.6118	10640.7861	E	861.85	47.29	54.46
Lat 8.6118	10640.7746	E	861.86	44.68	54.46

Top Speed
54.46 km/h

Figure 9. GPS response during high-speed testing

3.5 Navigation Interface Performance

The developed Geographic Information System successfully received serial communication from the embedded navigation hardware and displayed the vehicle position in real time. The software first acquired the initial GPS coordinate before allowing the user to enter the destination coordinates. After both positions had been determined, the application calculated the navigation distance and continuously updated the vehicle position while displaying heading direction and speed.

The software also displayed Coordinated Universal Time (UTC), latitude, longitude, compass heading, and vehicle speed simultaneously. Throughout the experimental evaluation, the interface successfully updated the vehicle trajectory using continuously transmitted GPS data.

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

Although the prototype demonstrated reliable functionality, slight deviations between the displayed vehicle position and the map were observed. These discrepancies were mainly caused by the use of raster-based mapping and coordinate transformation limitations rather than failures of the positioning hardware itself.

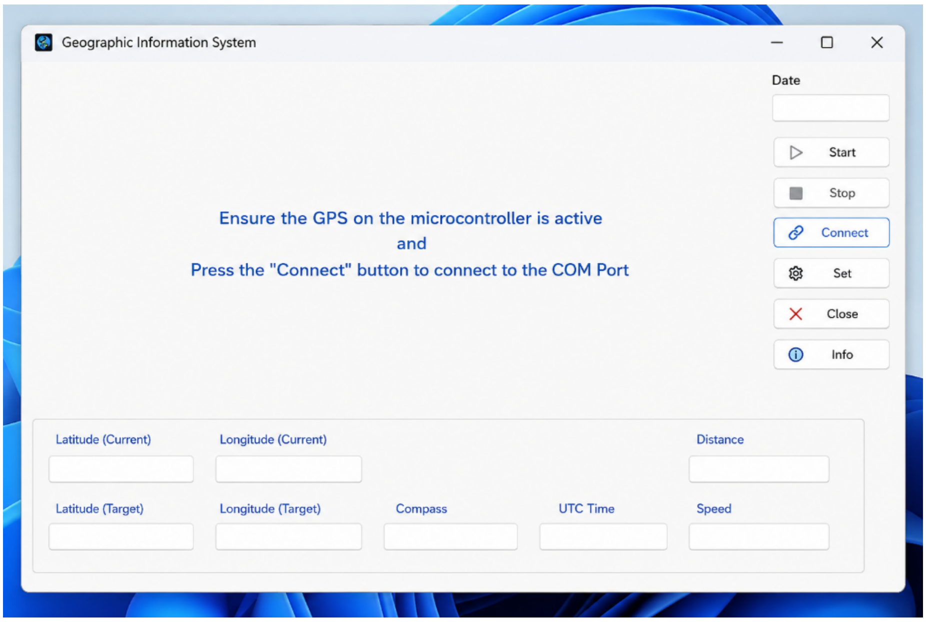

Figure 10. Initial interface

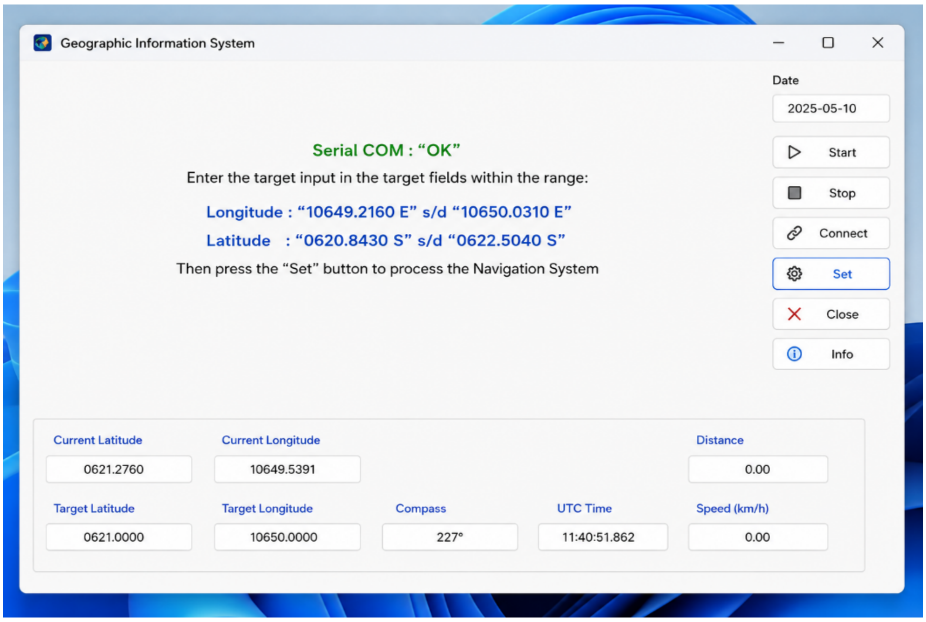

Figure 11. Connection established

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

Volume 2 Nomor 1 May 2026 Page 114-127

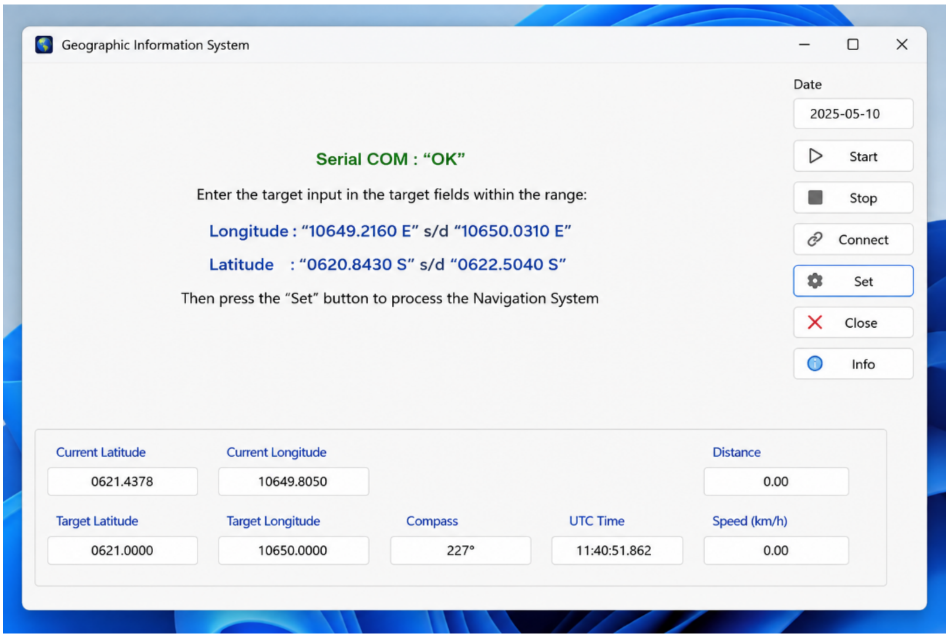

Figure 12. Destination input interface

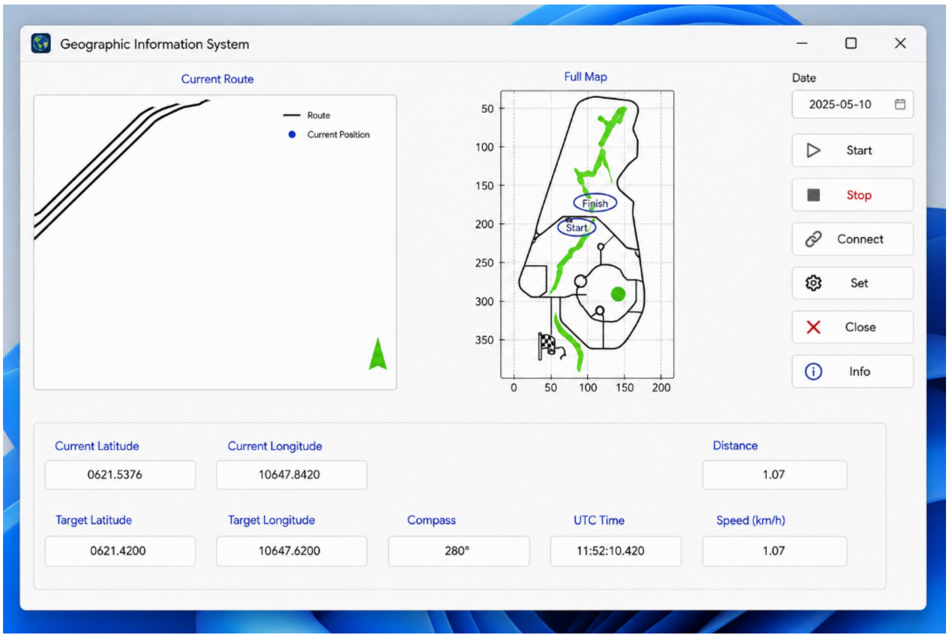

Figure 13. Navigation map

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

Figure 14. Vehicle movement visualization

4. DISCUSSION

The proposed vehicle navigation prototype successfully demonstrated the integration of a GPS receiver, a digital compass, an AVR microcontroller, and a Geographic Information System into a functional navigation platform. The experimental results indicate that the prototype was capable of continuously acquiring geographical coordinates, vehicle speed, and heading information while transmitting these data to a computer-based visualization interface. This finding confirms that low-cost embedded hardware can be effectively integrated to provide real-time navigation functionality for educational and research purposes. The successful communication between hardware and software components also demonstrates that serial-based data transmission remains a practical solution for prototype-scale navigation systems.

The positioning results showed that the GPS receiver produced relatively stable latitude and longitude measurements under stationary conditions, although slight coordinate variations were still observed. These fluctuations are consistent with the inherent characteristics of standalone GPS positioning, where measurement accuracy is influenced by satellite geometry, atmospheric delay, receiver noise, and multipath propagation. Since the developed prototype employed absolute positioning without differential correction, the observed positioning deviations are expected and remain within the typical performance range of low-cost GPS receivers. Previous studies on GNSS-based navigation have similarly reported that positioning accuracy in standalone receivers is strongly affected by environmental conditions and satellite visibility, particularly in urban areas where signal obstruction frequently occurs.

Vehicle speed measurements obtained from the GPS receiver exhibited good agreement with the vehicle speedometer throughout the experimental tests. The prototype successfully measured speeds up to approximately 100 km/h with only minor differences compared with the reference instrument. These results indicate that GPS-derived velocity estimation provides reliable performance for general vehicle navigation applications. Unlike coordinate positioning, GPS speed estimation is calculated from Doppler frequency measurements, making it generally more stable than position estimation under favorable satellite reception conditions. Consequently, the speed measurement capability of the proposed prototype represents one of its strongest functional characteristics.

The integration of the CMPS03 digital compass significantly improved the navigation capability of the prototype by providing heading information independent of vehicle displacement. GPS receivers generally estimate heading accurately only while the vehicle is moving. In contrast, the digital compass supplies orientation information even at very low speeds or when the vehicle is stationary. This complementary relationship between GPS positioning and compass heading enhances the overall navigation process because the software continuously determines both vehicle position and movement direction. The implemented sensor combination therefore represents an effective approach for low-cost navigation systems that do not employ inertial measurement units.

The software implementation successfully received serial data from the embedded hardware and displayed vehicle movement in real time on a Geographic Information System interface. The application correctly acquired the initial GPS position, accepted destination coordinates from the user, calculated navigation distance, and updated vehicle movement during operation. Nevertheless, slight discrepancies between the plotted vehicle position and the background map were observed during testing. These deviations were mainly caused by the use of a raster-based map instead of a georeferenced vector map, together with the absence of coordinate transformation and map-matching algorithms. As acknowledged in the prototype implementation, raster mapping limits spatial accuracy because vehicle coordinates are represented relative to image pixels rather than accurately referenced geographic coordinates.

Although the developed prototype achieved its primary objectives, several limitations should be considered. First, the navigation system relied solely on GPS and a digital compass without integrating inertial sensors such as accelerometers or gyroscopes. Consequently, navigation performance may degrade during temporary satellite signal loss. Second, communication between the embedded system and the computer employed an RS-232 serial interface, which is appropriate for prototype development but less suitable for modern embedded applications requiring wireless communication or Internet of Things connectivity. Third, the prototype did not incorporate differential GNSS correction techniques, real-time kinematic positioning, or sensor fusion algorithms that have become increasingly common in recent intelligent transportation systems. These technologies can substantially improve positioning accuracy and navigation reliability.

Future research should therefore focus on integrating multi-sensor navigation approaches, including GNSS, inertial measurement units, wheel odometry, LiDAR, or computer vision, to improve positioning robustness under GNSS-challenged environments. In addition, replacing raster-based mapping with georeferenced digital maps and implementing map-matching algorithms would significantly improve spatial accuracy. The integration of wireless communication technologies, cloud-based Geographic Information Systems, and real-time traffic information could further extend the applicability of the proposed prototype toward modern intelligent transportation and smart mobility systems.

5. CONCLUSION

This study successfully developed a prototype Geographic Information System for vehicle navigation by integrating an EG T-10 GPS receiver, a CMPS03 digital compass, a DT–AVR microcontroller, an RS-232 communication interface, and a MATLAB-based visualization

DOI: https://doi.org/10.63956/ijaetech.v2i1.72
e-ISSN: 3089-767X; p-ISSN:3089-8439

application. The developed prototype was capable of acquiring vehicle position, speed, and heading information in real time, transmitting the data to a computer, and displaying the vehicle movement toward a specified destination. Experimental evaluation demonstrated that the system functioned reliably during both stationary and moving conditions, while GPS speed measurements showed good agreement with the vehicle speedometer. Although slight positioning deviations and map display inaccuracies were observed, the prototype achieved its primary objective as a functional low-cost navigation system.

The findings indicate that integrating GPS positioning, digital compass measurements, and Geographic Information System visualization provides an effective approach for developing embedded vehicle navigation systems. However, the current prototype is limited by the use of standalone GPS positioning, raster-based mapping, and wired serial communication, which affect positioning accuracy and system flexibility. Future work should therefore focus on incorporating georeferenced digital maps, wireless communication technologies, inertial sensors, and advanced GNSS sensor-fusion techniques to improve positioning accuracy, navigation reliability, and applicability in modern intelligent transportation systems..

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DOI: https://doi.org/10.63956/ijaetech.v2i1.72
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Volume 2 Nomor 1 May 2026 Page 114-127

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e-ISSN: 3089-767X; p-ISSN:3089-8439