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IMU Aided GPS Based Navigation of Ackermann Steered Rover

Original Article

Muhammad Sufyan Arshad[1], Ijlal Hussain[2], Abdur Rahman Maud[2], Moazam Maqsood[2]
[1]School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad, Pakistan.
[2]Department of Electrical Engineering, Institute of Space Technology, Islamabad, Pakistan.
* **Correspondence:** Muhammad Sufyan Arshad **Email: msufyanarsh@gmail.com**

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GPS signal loss is a major issue when the navigation system of rovers is based solely on GPS for outdoor navigation rendering the rover stuck in the mid of the road in case of signal loss. In this study, a low-cost IMU aided GPS-based navigation system for Ackermann Steered mobile robots is presented and tested to cater to the issue of GPS signal loss along. GPS path is selected and fed using the android application which provides real-time location tracking of the rover on the map embedded into the application. System utilizes Arduino along with the node MCU, compass, IMU, Rotary encoders, and an Ackermann steered rover. Contorller processes the path file, compares its current position with the path coordinates and navigates using inertial sensor aided navigation algorithm, avoiding obstacles to reach its destination. IMU measures the distance traveled from each path point, and in case of signal loss, it makes the rover move for the remaining distance in the direction of destination point. Rover faced a sinusoidal motion due to the steering, so PID was implemented. The system was successfully tested in the IST premises and finds its application in the delivery trolley, institutional delivery carts, and related applications.

Keywords: Autonomous navigation of Rover; GPS, IMU; User interactive Navigation, Location tracking and monitoring.

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Author's Contribution. First author conceptualized the idea and devised the proposed system. Second author wrote the initial draft, which was edited to bring its language to the Journal level by the third and fourth authors who provided supervision for the hardware implementation as well.

Introduction

With every passing day, owing to low or no human intervention and its capability to maneuver and work independently, automation has received great attention. All the businesses going from tooth paste making to the mechanical production system of vehicles, each industry has been utilizing automation in one manner because of their capacity to accomplish greater work rapidly and productively[1]. From these, Autonomous Navigation of robots/vehicles is the most intriguing. Exploring the path by regulating the velocity and heading of motion and avoiding all the hindrances in the way is called Autonomous Navigation[2].

Autonomous navigation has developed so much over time that it has formed applications in self-driving vehicles for delivery, hospitals, agriculture, helping farmers cultivate fields, harvesting crops and assisting companies in delivery of daily use items to the consumers[3]–[5]. These algorithms for navigation were developed to make human life easier as autonomous navigation helps the individual in moving the vehicles in restricted spaces for parking, driving, and lane assist[6], [7]. Besides vehicles, autonomous navigation frameworks are utilized in exploratory robots used for exploring remote areas[8].

Navigation frameworks find their application in autonomous delivery carts, rovers, and daily use household gadgets such as vacuum bots [3], [9]–[11]. Depending on the application, different navigation systems have been used in robotics [12]–[17]. Navigation systems used for rovers are mainly of the following types

- Navigation using IMU
- GPS-based system of navigation
- GPS and inertial sensors system

Navigation systems are utilized for robots according to the requirement and purposes such as remote exploration and delivery of products using small carts ranging from indoor to outdoor navigation. For indoor purposes, inertial sensors are used in navigation and for outdoor purposes, GPS based navigation system is used along with other sensors(Compass, accelerometer) [12], [18]. Depending upon these indoor/outdoor navigation requirements and environment, rover chassis and sensors are developed to make the robot more autonomous and robust. Some systems use camera for tracking the road edges using image/video processing, while other use IR, ultrasonic sensors, or laser sensors for obstacle avoidance[5], [19], [20]. Each of these systems used for navigation has some drawbacks, as road edges and marks are not available everywhere. IR sensors cannot be used for outdoor navigation due to their low range and incapability to work properly outdoor[21]. Ultrasonic sensor has shortcoming of field of view and atmospheric conditions affecting its range. Rovers with IMU-based navigation were assisted with these sensors to navigate through indoor environment. These are limited to moving for a precise distance (mostly indoor) [22]. While navigation using GPS is more robust for outdoor navigation due to continuous localizied information, making them beneficial for long-distance navigation but GPS based navigation systems have issue of compromised accuracy in cases[23], [24]. While navigating through areas, signal loss can be faced, which renders the GPS navigation system useless till it locks with the satellites[25].

This study presents a solution for the GPS signal loss issue during navigation which renders the rover or device stranded midway. The contribution of this study is

- IMU-aided GPS-based navigation System is proposed, which caters to plight of GPS signal loss by moving the Ackermann-steered rover to the next known location based on the IMU and Rotary Encoders. This makes retrieving the robot easier, and the navigation base switching from GPS to IMU allows the rover to move for a certain distance, which may allow the GPS signal locking.

- Developed system provides a user interactive path feeding mechanism using the android application
- System provides real time location tracking on the maps embedded in the application.
- Developed system has been rigorously tested in different paths.

Paper is set in way that the related work is reviewed and hypothesis is devised. Based on that, system is proposed along with the attributes. Next section discusses the materials and methods followed by the testing and results. In discussion section, comparison is made with already implemented systems, followed by conclusion.

Related Works.

Different outdoor navigation systems have been developed and applied over years to achieve the target/goal. In the study [12], system was developed which uses GPS to navigate through the path. Still, the algorithm corrects the direction of motion using the distance, which leaves many uncertainties unaddressed as the PID controller will need some time and will have to move in all directions to understand the direction in which distance to the target will decrease. Path feeding is also not addressed as the system uses the path already stored in the code to change which robot is required to bring to dock station, which limits the idea of autonomy in robot. In study [26], developed system uses compass with GPS and application to use navigate along with a differential drive rover. System is more autonomous in nature as it uses the application, but for tracking, different websites are used, which adds delay to the tracking. System developed in study [27] utilized GPS based navigation with EKF and utilized IMU for the EKF rather than catering for the GPS signal loss. Robot used was a small Ackermann steered robot for farming applications. System developed in the study [28] utilized Ackermann steered rover for the navigation and control of steering but did not utilize GPS for outdoor navigation rendering long distance autonomous navigation handicapped. Similarly, systems developed in [29], [30] utilize odometery and BBNAs for the navigation of four wheel steering rovers. System proposed in [31] utilizes IMU along with the visuals for the navigation of the Ackermann steered rover with the help of Lidar. System depends on the vision based navigation requiring high computation. Study [32] proposed Lidar and Thermal camera based navigation for steered robots in GPS denied environments with dark environment. System only targets navigation without the GPS and light requiring high computation and does not incorporate a hybrid approach. Study [33] provides a similar conceptual system. Study utilized speed reduction instead of PID implementation to attain minimal divergence while following the path. System developed in the study [34] uses Dead reckoning and GPS for sensor fusion to navigate. Error accumulation was an issue as for outdoor navigation rover was moved for longer distances increasing the uncertainties. So, for a complete autonomous outdoor navigation of Ackermann steered rover, a system is required that addresses the problem of path feeding, location tracking, GPS signal loss during navigation, leaving the robot stranded in mid-journey, and obstacle avoidance.

Hypothesis.

Rover will reach the destination ,using GPS and in case of signal loss/satellite lock issue, IMU will assist the system to reach the calculated distance towards the next way point, until the GPS locks with the satellite. System developed in [26] caters to the problem of feeding the path manually, while [35] uses navigation system based on IMU (representing the case of GPS signal loss). So a system can be developed using both methods to cater to the

GPS signal loss and stated issues. Android application can be infused as well, easing up the user interactivity with the rover.

Proposed System.

Proposed system for the navigation consists of the following sets

- A rover
- Communication link
- User end Application

Rover

Rover is the movable unit that navigates along the path with navigation system comprising of Arduino, motor drivers, a camera for taking pictures, GPS, accelerometer, Wi-Fi module along with ultrasonic sensor to go through the path.

The Ackermann steered rover was used for navigation with LM298 motor driver to power the motors.

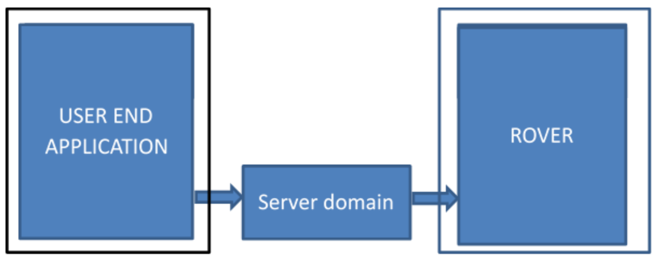

Figure 1 Proposed model

User end application

User end application is developed to save the user from hassle of manually feeding the path. To gain access to the app, user has to input the login details to secure the activity over the Wi-Fi link, as shown in Figure 2. Both the user end device and the Wi-Fi module at rover end are connected to the same network. Connection is established b/w rover and user end application by inputting the IP address of the module deployed on rover. As shown in Figure 2, real time location of rover is achieved by clicking the current location button on application which shows the location on map by placing a marker. After that, desired multiple waypoints are selected by tapping on the map, which also marks a cursor on the map showing the path. After selection of each waypoint, save location button is pressed to add the way point coordinates to the CSV path file. Process is repeated ,until the desired way points are selected, and the path file is transferred to the rover by pressing the send path button via communication link.

Communication link

Wi-Fi is used as the communication medium b/w user end, and rover for transfer of the record of the path followed, current location, and other features of system.

Figure 2 Application layout

System Attributes.

Following are the system attributes

- Path file generation
- Accelerometer-aided GPS navigation
- Obstacle avoidance
- Real-time location monitoring

Path file generation:

In user application, path file is generated which comprises latitude and longitude of path waypoints in csv format and is transmitted to the rover end for further processing. This path file generation provides autonomy in terms of path feeding.

Obstacle avoidance:

System consists of set of ultrasonic sensors that make the rover tackle the obstacles and aid it in navigation through narrow paths by keeping it in the center of the road avoiding the road edges.

Real time location tracking:

Real time location of the rover is monitored using the application. Data from the GPS module deployed on the rover is sent to the application using the communication link which is used on the map integrated in the android application.

IMU aided GPS navigation:

Conventional GPS navigation systems consist of only GPS modules. GPS requires 4 satellites to lock its position successfully, but in some areas, signal might be weak, so GPS might not be able to lock its position, so to cater with that problem accelerometer is used. Distance is calculated from the current known GPS location to 1st destination point of path file. As soon as rover moves, with every update of the GPS coordinates, IMU also calculates the distance from starting point to next destination point, so if GPS loses its signal during navigation, IMU makes the rover move for that specific distance calculated using GPS and destination point and stops rover after travelling that distance. Rotary Encoders attached with the wheel are used to estimate the distance travelled to cater to the error accumulation during integration of IMU after every 5 sec. This system is better than simple GPS navigation system[26] as the rover doesn't stop in the middle of the road but continues to move towards the first known point.

Materials and Methods.

SLR Methodology

The process of collecting and reviewing articles comprised downloading the papers based on the search keywords and according to the criteria. After the selection of the papers based on the inclusion and exclusion criteria, Authors classified these articles based on the implemented method of study, objectives of the article, recommendation technique, and results. Figure 3 shows the procedure. Details of the methods can be found as follows.

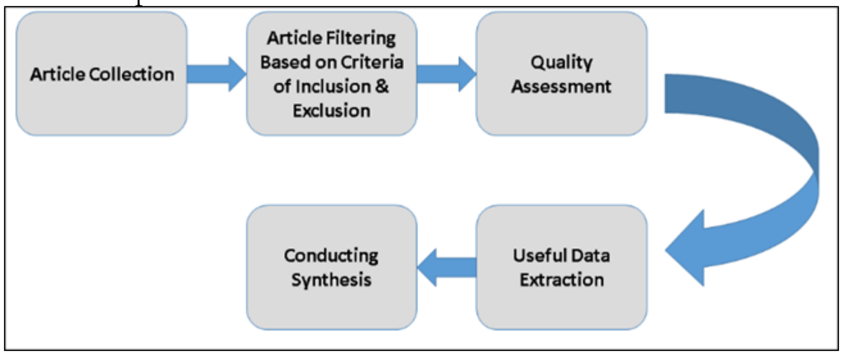

Figure 3 Methodology Flow

Database and search keyword Used.

Research articles were downloaded from different database repositories to be used in the study. Key terms such as 'GPS Navigation of Rovers' OR 'Ackermann steered rover navigation') AND ('Robot Navigation IMU and GPS' OR 'IMU and GPS Navigation of Rover) were used to find the research articles. Database Repositories are listed below.

Table 1: Databases

DATABASE	URL
IEEEXPLORE	http://ieeexplore.ieee.org/
GOOGLE SCHOLAR	http://scholar.google.com/
WEB OF KNOWLEDGE	http://www.webofknowledge.com/
CITESEERX LIBRARY	http://dl.acm.org/

Study Selection Criteria

Inclusion and exclusion of the research work for study is covered. Criteria is defined and research work is filtered based on that by studying the content of the papers, title and keywords. Criteria are discussed as follows

Inclusion Criteria:

- Must be an article published in High IF Peer Reviewed Journal.
- Full length papers from the proceedings of international conferences.
- Approach implemented in formal hardware.
- Work should be executed from 2018 till April 2022.

Exclusion Criteria:

- Any chapters from books.
- Studies with no implementation in formal hardware
- Articles having no empirical evidence.

Studies Selection procedure:

The study selection was performed by coordinating all the authors, and work was done in different phases. In first phase, keywords string was applied to the scholarly databases, which resulted in 263 articles. In second phase, documents were filtered concerning the inclusion and exclusion criteria. Articles relevant to the research were included in the next phase, and all others were excluded from consideration. A total number of 61 articles were included from 263 articles. In third phase, abstracts along with introduction and conclusion of the paper were studied, and the papers were included in the study based on their relevance and potential with respect to our study. A total number of 46 papers were found to be the duplicates which were downloaded from repositories of different databases. Duplicates of these papers were excluded from the shortlisted papers resulting in 37 shortlisted final research papers for first study.

Study Quality Assessment:

Papers included in the study were thoroughly examined for their quality and relevance to address and answer the objectives of our study. They had to meet following checklist

- Was there any implementation of the framework?
- The navigation system must be based on DD or steered rover and should have GPS, IMU or supplementary navigation source.

Based on the study quality assessment, 28 Papers were selected.

Useful data extraction:

The authors used non statistical methods for useful data extraction such as drawbacks, framework type, and navigation system primary source. Based on that, authors conducted the synthesis of study.

Hardware Setup

Ublox NEO-6m was used for the current location, having a built-in battery which showed an accuracy of 1m-2m when tested in outdoors, while in datasheet mentioned, accuracy was 3m. GY-80 multi sensor module was used for compass (HMC5883L) and accelerometer (ADXL345) purposes. These modules were selected due to the availability in the market. Arduino mega (ATmega2560) was opted for controller purpose due to its I/O pin peripherals. HC-SR04 ultra sonic sensor was used for collision avoidance with 10ft tested accuracy. Node MCU was used because of the available Wi-Fi network.

Ultrasonic sensors are placed (three in the front and one in the back of the rover) to avoid obstacles[36] from hitting the rover while moving forward or reversing. Rover is a 4 wheel, 2 motor RC rover base with front two wheels having axial turning (Ackermann Steered Rover). The front motor tilts the axle to left or right, which controls the rover's direction. Due to this feature, to change the direction, rover needs to move some distance to set its heading towards the required destination point. Second motor controls the rover's movement and speed, i.e. moving in forward or backward direction. Wi-Fi module communicates the data between rover and application and delivers path file, real time location, as well as pictures taken from camera. IMU is placed in the back to separate it from magnetic fields of wires so that compass output is not affected. Figure 4 shows the setup.

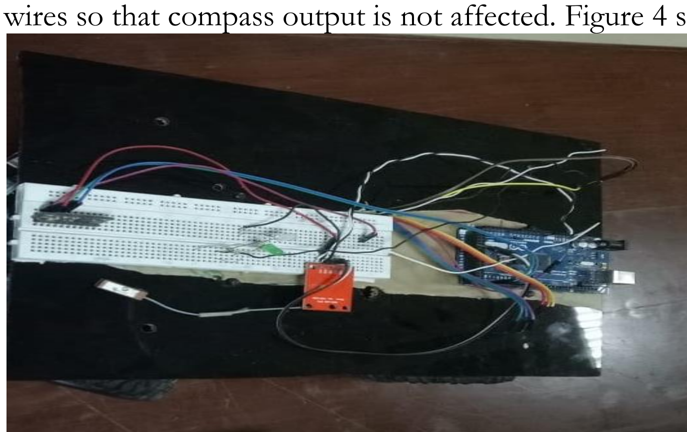

Figure 4 Rover with cast acrylic sheet

Navigation Algorithm

At start up, ,the system waits for the GPS to set its location and then for user input. After path file communication, at rover side, data from the file is extracted. The current location of the rover and coordinates of first way point from path file is used to calculate the distance that needs to be covered and direction towards which the rover has to move. The difference in the rover's current heading and the desired direction is calculated and the difference is compensated by direction correction using the rover's front wheels. Direction/heading it needs to move is also calculated using formulas and compared with the direction received from compass. With each update of the GPS data, distance and direction is recalculated, giving a better path following. Distance is monitored, and rover stops when distance is zero b/w current location and destination point. After that,, the controller updates the 2nd waypoint of path file as the destination point, and the whole procedure is repeated until the last waypoint is reached. As soon as rover starts moving, rotary encoders also start measuring the distance travelled, which is used for compensation of accumulated error for IMU. In case of GPS signal loss(marked by flag using NMEA format), IMU makes the rover move for the specific distance, which is remaining b/w the last know GPS value and the targeted way point. Rover stops at the known waypoint till the GPS module locks with the satellites. This system is better in terms that the rover doesn't stop midway of the path but moves till the next known waypoint. Data from the front three ultrasonic sensors is used to detect objects and avoid from collision. If the distance is more than 2m, then rover tries to avoid it while moving by steering in the direction of the Ultrasonic sensor, which has no object in front of it. After avoiding the obstacle, it sets its direction towards the destination point and continues to move forward. If the distance is less than 1m (sudden moving object is placed in front of it), then rover brakes reverses and sets towards the destination after avoiding the obstacle. Figure 5 shows the algorithm.

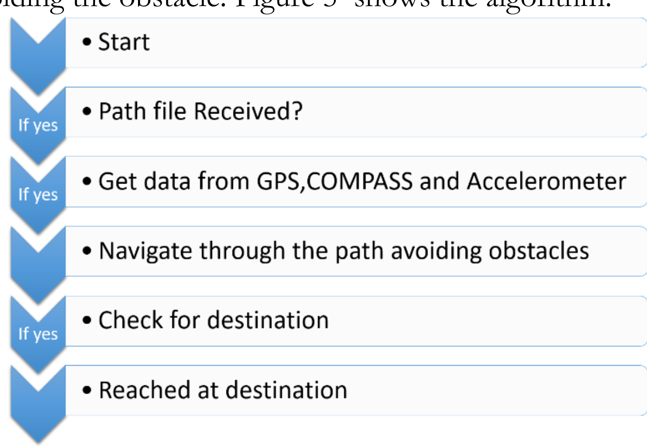

Figure 5 Navigation algorithm

Testing and Results.

In the initial phase, the rover was tested on the field with one destination point, as shown in figure 6. One point was selected on the user end application, and path was communicated to the rover. Multiple repetitive tests with the same single point destination were performed. The problem of stopping distance was faced due to the rover's inertial speed which, even after reaching the destination,didn't stop. So proportional speed controller was introduced in the algorithm, which pretty much solved the problem as the speed would decrease with decreasing distance from the destination.

After that, a path comprising of coordinates along a straight road was fed via the user. Rover started from its initial position, and while moving towards the destination point, it followed the sinusoidal path as shown in figure 7 as the rover base consisted of Ackermann steered rover, and it needed some distance to correct the heading. To cater that PID controller was designed to remove sinusoidal implementation. Desired angle (heading to the destination point) and current angle were given as input to the controller, with output being the PWM for actuators ranging from +125 to -125, as shown in figure 8 PID controller was tuned for kp=1.6 and kd=0.8, and desired response was achieved, as shown in figure 9.

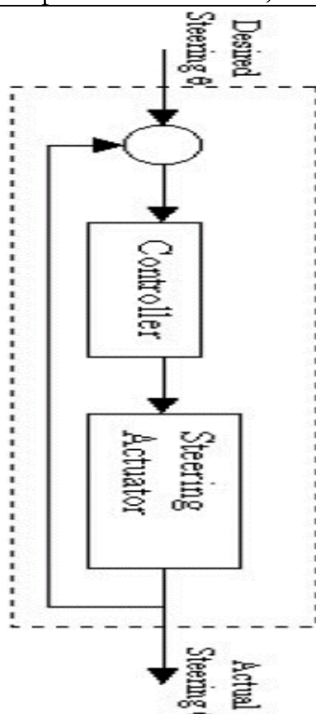

Figure 6 Steering PID controller for Direction of Ackermann Rover[37]

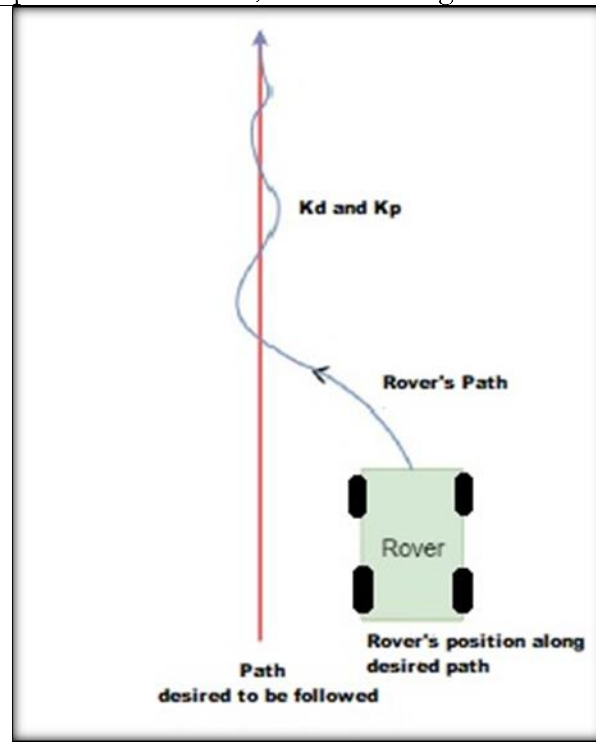

Figure 7 Desired Output (Path needed to be followed by rover)

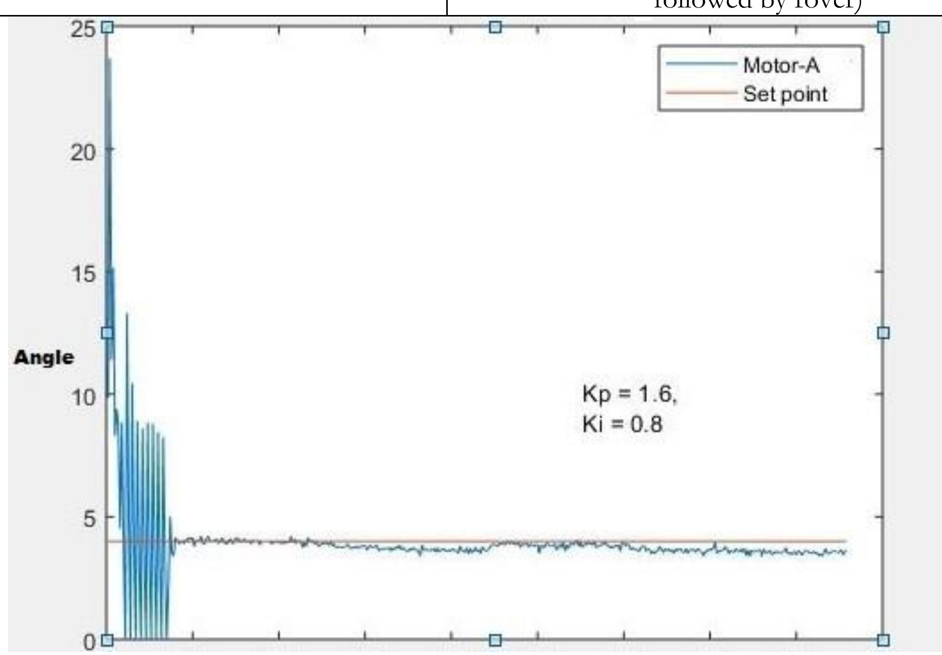

Figure 8 PID controller output of Steering for the desired direction angle

Finally the rover was tested along with the modules, a short path was selected and fed to the rover with turns in the path, as sown in figure 9. Rover started from its current position and followed the path with minimal deviations across both sides of the straight line path and made it to the first turn, and after taking the turn, followed the path. Upon reaching the second turn, collision avoidance system aided the rover to take a turn by reversing and setting the direction to the destination point as the road edge was grasped while turning, as shown in figure 10 with red markers. ,The line shown in the figure represents the path that needs to be followed, and points show logged GPS points saved in SD card attached with the Arduino along with the calculated distance.

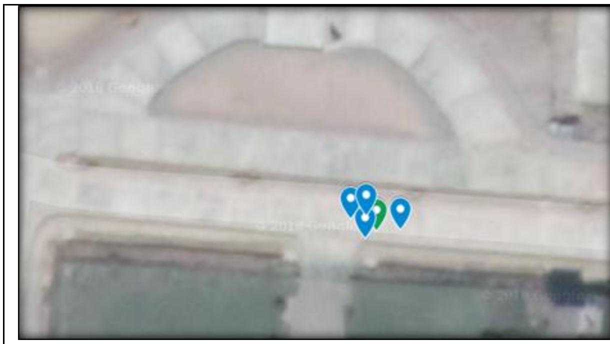

Figure 9 Testing of stopping distance from the destination point

Figure 10 Path followed in initial testing of path in a straight line

Figure 11 Final testing on a complete path with points representing followed path and line representing path to be followed.

Figure 12 Position tracking on app while following the path: Rover moving on the road (left), making a turn (right)

A path comprising of the path waypoints was designated along the road and entrance to the university gate. Path was communicated to the rover, as shown in figure 11 Rover made a turn towards the university road (right). While making a turn, rover faced the entrance barrier as obstacle and avoided it by steering towards the sensor with no obstacle in front of it, as shown in figure 12. Rover followed the path and reached in front of university gate (Figure 13).

IMU based navigation was tested by interrupting to switch the navigation function to IMU based navigation (imitating the lack of GPS with last updated distance and direction to the point). Error accumulated during the integration process was emitted by the moved distance received from rotary encoders. Rover travelled the desired distance in the required direction with acceptable tolerance. Results for different tests are mentioned in Table 2.

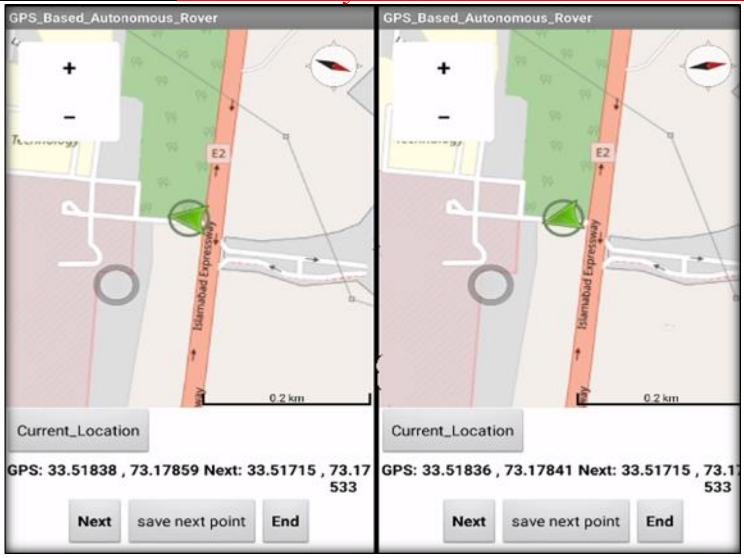

Figure 13 Navigation through the path tested on road, rover entering the road (left), rover avoiding the obstacle by changing heading (right)

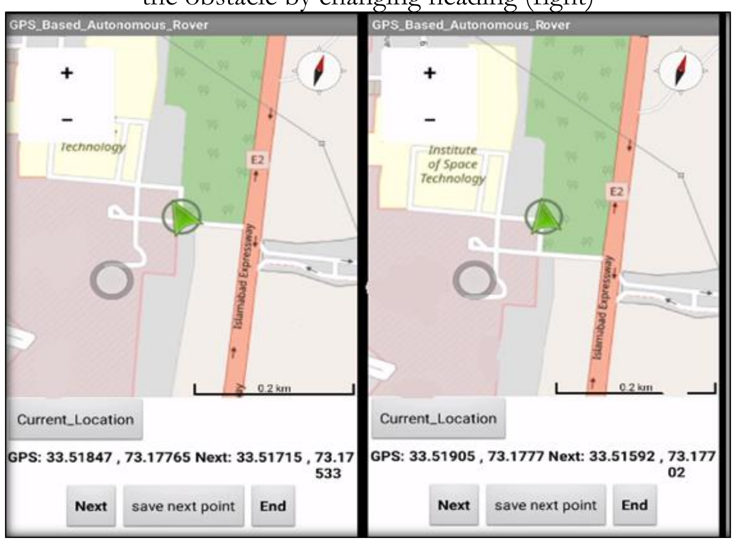

Figure 12 Path followed in initial testing of path in a straight line

TABLE 2 IMU BASED NAVIGATION TESTING USING INTERRUPT FUNCTION TO MIMIC SIGNAL LOSS STATE

Waypoint (LAT,LONG)	Destination Point (LAT, LONG)	Distance needs to be travelled(m)	Distance Travelled using IMU(m)
33.520510, 73.176587	33.520517, 73.176435	14	13.1
33.520641, 73.174768	33.520518, 73.175396	60	58.3
33.520652, 73.174724	33.520703, 73.174059	62	59.7

Discussions.

This study developed and tested IMU aided GPS-based navigation of the Ackermann steered rover. Individual modules were tested during the development before fully autonomous testing was performed and different observations were made. In navigation based on GPS, It was observed that robot did not stop at the destination point and crossed it due to the inertia before stopping. So proportional speed control was implemented, that slowed the rover with the decreasing distance to stop the rover at the destination point with the accuracy of approximately 1 ft (0.30 meter).

Different tests were performed for both GPS based navigation for whole path and IMU based navigation imitating absence of GPS signal,. Acceptable results were achieved with maximum distance error of 3.7 percent.

Our proposed IMU-aided GPS navigation provides the ability to the rover for indoor navigation by minor changes in the algorithm that would give rise to a completely autonomous rover capable of indoor and outdoor navigation that also caters for signal loss. Table 3 compares our system with already implemented systems and enlists the variables.

TABLE 3 IMU BASED NAVIGATION TESTING USING INTERRUPT FUNCTION TO MIMIC SIGNAL LOSS STATE

Study	Rover/Robot Steering Type	Navigation	Real Time location Tracking	Signal Loss catering (Standalone IMU Navigation)
[38]	Ackermann Steered ATV	GPS Remote Control	No	No
[39]	Ackermann Steered Rover	GPS	No	No
[40]	Ackermann Steered Rover	IMU RF Based Control	No	No GPS
Our System	Ackermann Steered Rover	IMU Aided GPS Based Navigation	Yes	Yes (No need for Landmarks)
[41]	Articulate Steered Rover	GPS IMU (utilized only for heading)	No	No
[42]	Differential Driver Rover with caster wheel	GPS IMU (EKF) Land Mark Based	No	Yes (Utilizes Landmarks)
[43]	Differential Driver Rover (Four Wheel)	GPS and Curb Detection	No	No

Conclusion.

IMU-aided GPS-based navigation system for Ackermann steered rover was presented. Proposed system was completed and verified. Different paths inside the institute were tested for algorithm verification along with the turning, collision avoidance, and navigation System. Rover followed a sinusoidal path at some point along the original path due to Ackermann rover's steering as it needed some distance to correct its heading, so PID was implemented. Future work will be carried out by testing GPS spoofing on the rover. A home location will also be introduced in the application by which the rover irrespective of its current location, will come to that location. Work can be extended for institutional delivery cart using hybrid navigation system (IMU and GPS can function individually) which will be able to collect mails and documents from one department and navigate towards the other using GPS-based navigation for outdoor and for indoor department delivery, navigation can be switched to IMU-based navigation.

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