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Design of an Autonomous Controlled and GPS-guided: Experimental Small-Scale Prototype

[1]Farhan Aizuddin and[2]* Wan Rahiman
School of Electrical and Electronics Engineering
UniversitiSains Malaysia, Engineering Campus,
14300, NibongTebal, Pulau Pinang
[1]michael3a10@gmail.com,[2]wanrahiman@usm.my
**Corresponding Author: Wan Rahiman, Senior Lecturer, School of Electrical and Electronic Engineering, UniversitiSains Malaysia, Engineering Campus, 14300 NibongTebal, Penang, Malaysia.* *This research was supported by UniversitiSains Malaysia Research University Grant (RU) (grant number: 304/PELECT/6316121.*

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Abstract:
Research work on autonomous ground vehicle are commonly used small-scale vehicles as a proof of concept for autonomous navigation system. This paper describes the design development process of developing a navigation system based on COTS (commercially-off-the-shelf) components for small-scale autonomous car prototype for waypoints via GPS and magnetometer as navigational inputs. Field experiments were conducted at a selected test site to validate the navigational algorithm developed and the small-scale prototype. The experiments were successful where the small-scale prototype has successfully managed to navigate to all waypoints within the designated turning and stopping criteria. However, the prototype is found to have looping behaviour when traveling from Waypoint 2 to Waypoint 3 which is attributed to the GPS receiver obtained a different current GPS position while travelling and the maneuvering of the prototype based on the differences between the heading angles of the two sensors.

Keywords: *Autonomous control navigation, Small-scale prototype, GPS, magnetometer.*

I. INTRODUCTION

An autonomous ground vehicle is a ground vehiclethat can maneuver itself towards the intended destination with minimal human input[1]. In order to maneuver the vehicle, the implementation of a good navigation system is an important aspect which would allow the autonomous vehicle to be efficient when travelling towards the designated destination.

One of the current technologies that is able to provide positioning information at any point of the Earth information is the Global Positioning System (GPS)[2]. The technological advancement has made the GPS receiver to be smaller in size, which made the technology to be popular among different field applications[3].

However, the main drawback of the GPS technology is that the positional accuracy given by the GPS is reliant on the weather, terrain, urban environment and satellite availability[4]. To overcome this problem, several researchers designed systems which has a GPS module as the primary input and another sensor as the secondary input for the vehicle to make better decision in maneuvering as shown in[5]–[8].

In using GPS systems, research work was conducted on small autonomous ground vehicles (AGVs) to demonstrate the maneuvering capabilities. However, the AGVs are often ready made with the vehicle chassis, microprocessors, control systems and sensors are not low cost and commercially of the shelf components [9]–[11].

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Furthermore, as research work are always proof of concepts, limitation of costs and the use of COTS are often the main criteria.

This paper addresses this research gap where the development and design process of a small-scale experimental car prototype using GPS and magnetometer for navigation purposes. A navigation software is also developed for steering a small-scale experimental car prototype autonomously.

II. DESIGN AND DEVELOPMENT

A. Design of the autonomous small-scale experimental prototype.

The designed small-scale experimental car prototype is able to steer point to point autonomously. It involves four main sections:

- Mechanical design: A small-scale vehicle is developed by considering the chassis, mass, and power for autonomous steering and navigation.
- Microcontroller and Sensors: The Arduino microcontroller is selected as the main microcontroller with the relevant driver boards. For sensors the GPS and Magnetometer are used for navigation purposes.
- Steering mechanism: The steering mechanism is controlled by high torque servo which steers the steering wheels based on the navigation algorithm inputs derived from GPS and Magnetometer sensors.

Autonomous guidance control algorithm: The software is developed based on C++ language on an Arduino based microcontroller boards and associated libraries.

III. MECHANICAL HARDWARE DEVELOPMENT

A small-scale prototype is chosen to be tested for autonomous navigation by having a GPS receiver and a magnetometer as inputs to the navigation algorithm.

A. Mass budget

A small-scale car is defined as a miniaturized version of a real car, usually found in the form of a Radio-Controlled (RC) car. For this project, the prototype must be within 2.0 ± 0.1 kg maximum when all of the components are assembled and the approximated mass budget for the project is given in Table I.

Table I The approximate mass budget for the project

No.	Components	Estimated Weight (g)
1	Microcontroller	40
2	Sensor boards	50
3	Relevant driver boards	80
4	Servo	50
5	DC Motor	80
6	Batteries	700
7	Platforms and chassis	900
11	Miscellaneous	100
	Total	2000

Since the weight of the electronics components are less than 100 gram, the bulk of the mass budget lies upon the type of material for the platform on which the components will be placed, the chassis for the prototype and the DC motor to drive the small-scale car.

The platform that is used for this project is a 15 mm thick acrylic sheet with the dimension of 18 cm by 17 cm that has the mass of 0.185 gram. The power budget refers to the rated power consumption that are calculated from the specifications of the electronics components that are chosen for the project and the accompanying batteries. Table II provides the rated voltage input and current consumption for the electronics component that are selected for this project. Two step-down power modules are chosen to monitor allow a uniform voltage is distributed among the DC motor, microcontroller and the selected sensors.

Hence, there is a need to provide two independent batteries for power supplies for each component. A battery rated at 7.4 V and 6000mAH capacity is used to supply 8 V to the sensors and related boards while a 12 V with the capacity of 5200mAh is used to provide power to the microcontroller and the DC motor. The wiring diagram for the system is shown in Fig 1 and drawn via Fritzing and the description is given in Table II.

Table II Description of the wiring diagram.

No.	Description
1	Arduino Mega 2560
2	Adafruit GPS Ultimate Logger Shield
3	Adafruit 16-Channel 12-bit PWM/Servo Driver
4	Tower Pro MG995 servo
5	Adafruit 10 DOF IMU Breakout Board
6	LM2596 Step Down Power Module
7	Adafruit Motor/Stepper/Servo Shield for Arduino v2.3 Kit
8	DC Motor
9	7.4 V 6000mAh
10	11.1 V 5200mAh
11	12 V Terminal
12	Ground Terminal
13	5 V Terminal
14	SCL Terminal
15	SDA Terminal

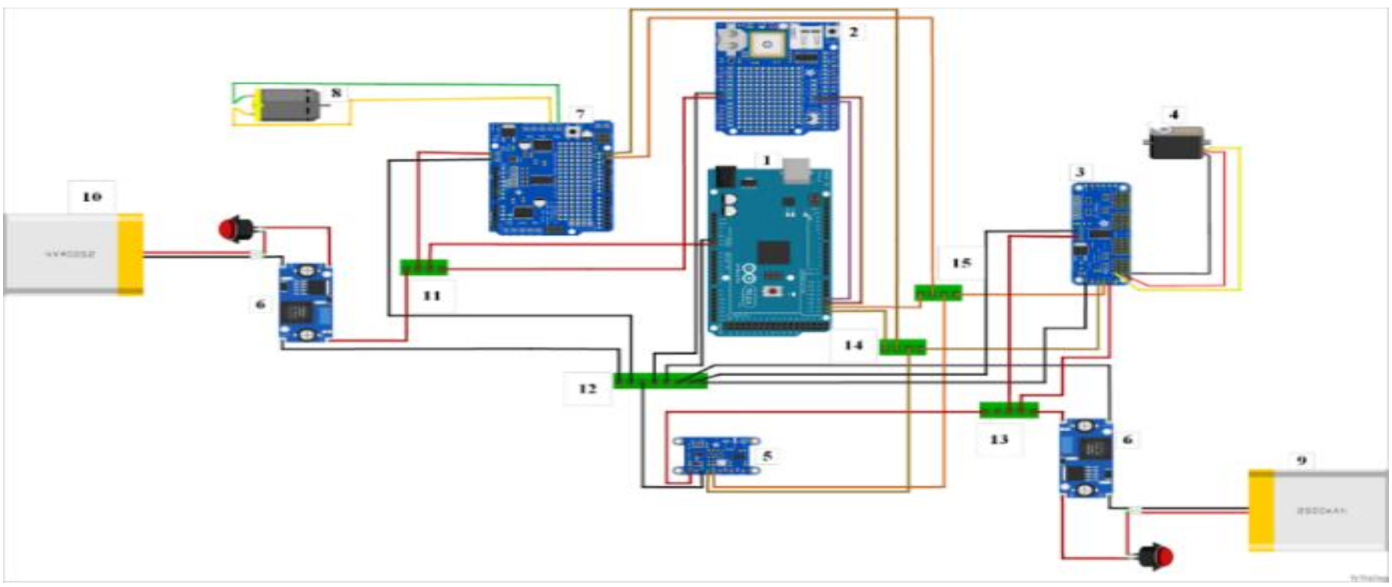

Figure 1 Wiring diagram for the system

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IV. MICROCONTROLLERS AND SENSORS

A. Microcontroller

The diversity of microcontrollers in the market allows the researchers to choose any microcontroller that suits their interest. For low powered applications, Arduino is a popular choice due to the cost, user-friendly and wide access for support in various projects. The prototype used Arduino Mega 2560 Rev.3 as the microcontroller for the prototype.

There are many GPS modules available in the market. This project requires the module to be small to be fitted onto the prototype vehicle, readily available and compatible with the Arduino Mega 2560. Furthermore, the data storage has also to be considered as to whether to have the data transmitted wirelessly or having it stored in a traditional method such as microSD card.

The selected GPS module for the project is the Adafruit GPS Ultimate Logger Shield which has a GPS module and microSD card facility combined into an Arduino-compatible board to be stacked on the Arduino Mega 2560 as displayed in Fig. 2. The Adafruit GPS Ultimate Logger Shield specifications are listed in Table III.

Figure 2 Adafruit GPS Ultimate Logger Shield stacked onto an Arduino Uno

Table III Adafruit GPS Ultimate Logger Shield specifications

Parameter		MTK3339
No. of satellites tracked		22
Update rate		1–10 Hz
Baud rate		9600
Position accuracy		3 meters
V_{in}		3–5 V
Current draw	Acquisition	25mA
	Navigation	20mA
Output		NMEA 0183
Channels		66
Sensitivity		-165dBm
Accuracy		1 PPS
Serial interface		UART
Jitter		10 ns
Storage		microSD
Weight (kg)		0.028
L (mm) x W (mm)		68.6 x 53.4

As for the compass, the chosen board for the project is the Adafruit 10 DOF IMU breakout board which consist of three axis accelerometer and magnetometer, three axis gyroscope and a barometer as shown in Fig. 3. For this project, only magnetometer is used to compare the heading angle faced by the vehicle to the calculated GPS heading angle.The other sensors are planned to be used for further improvement of this project.The placement of the magnetometer is 25 cm above the platform to avoid any distortion of the output.

Figure 3 Adafruit 10 DOF IMU breakout board

B. Global Positioning System (GPS)

Global Positioning System (GPS) is a network consist of a constellation of satellites that are orbiting

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around the Earth and are divided into three segments as shown in Fig. 4

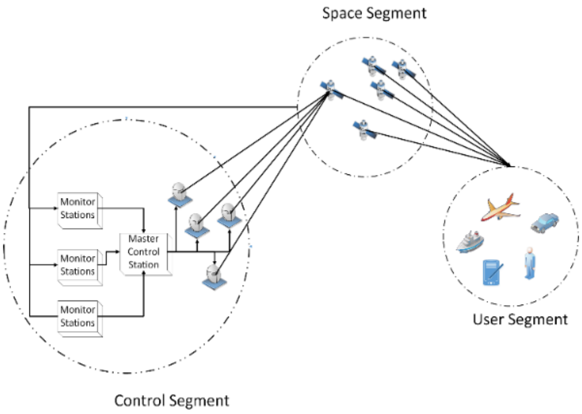

Figure 4 GPS segments (adapted from [12])

The transmitted radio signals from the satellites are received by the receiver on the Earth which is a part of the user segment. The protocols that dictates the settings and format of the sent signals are named NMEA0183 [12].

If a vehicle, or the receiver in particular, changes position when the signal is being received, the extrapolated measurement could produce an error in the estimated and true position [13]. Fig. 5 shows the concept of accuracy and precision given by Gomez-Gil et al. (2013) where the estimated position given by the GPS is considered to be accurate and precise if the measurement is clustered near the actual position whereas the least accurate and precise scenario occurred when the readings obtained from GPS receiver is spread away from the actual position. For civilian purpose, the accuracy of GPS accuracy is 3 to 10 meters[14].

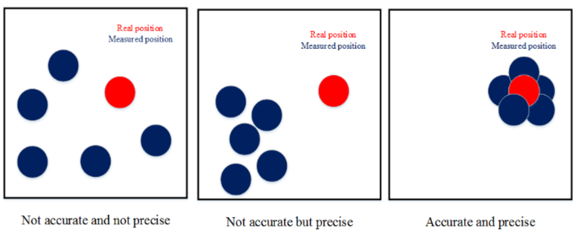

Figure 5 GPS accuracy and precision

C. *Magnetometer*

A magnetometer is a device that measures the magnetic field strength the device is subjected to. Mainly used as a compass, it can provide a heading angle that is related to the magnetic North. To align the compass towards the True North, (1) is used when the sensor detected a negative value in the measured axes.

$$\theta = \theta + 360° \tag{1}$$

whereθ is the heading angle.

V. STEERING AND DRIVE MECHANISM

A. *Steering*

The wheels that are to be manipulated for steering is set to be the front wheels while the rear wheels are set to moved only in forward direction. The selection criteria of the servo to handle the steering is based on (2).

$$\tau = Fd \; . \tag{2}$$

where τ is torque, F is Newton force and d is the perpendicular distance between the wheels and the shaft of the servo.

Given that the perpendicular distance is 5 cm and the Newton force is the 20 N, the calculated torque, τ is 100 N.cm or 10 kg cm. Further consideration that should be taken into account is the power source that is needed to be supplied to the servo for operational applications. Since Arduino boards only permits of maximum DC current (A_{DC}) of 20 mA per I/O pins, the servo might drained more current should the 5V pin of the servo is directly connected to the 5V output of the Arduino which would have reset the operation of microcontroller.

A solution is to have two separate LiPo batteries to provide power supply to the microcontroller and DC motor on one part and the servo and sensors on the other part. Furthermore, the servo is connected to a servo driver where the current drain is handled by the driver which ensures the Arduino does not reset. Thus, the servo that fits the criteria is TowerPro MG995, a continuous-type servo which has 11kg/cm torque when the supplied voltage is 6.0 V.

The DC motor that drives prototype is JGA25-370 DC gearmotor which has four different modes of operation to drive different payloads. Since the prototype vehicle is weighed at 2.04 kg when fully assembled, the motor is then supplied with 12 V input voltage in order to deliver 0.23 kg cm torque to move. A motor driver from Adafruit as shown in Fig. 7 is used to convert the decimal values used to set the appropriate speed into motor speed where the conversion is given in (3) where v_{motor} is the measured motor speed in revolution per minute (rpm) and V_{in} is the voltage supplied to the motor driver.

Figure 6Adafruit Motor Shield ver 2.3

$$v_{motor} = \frac{Decimal\ \ number}{255} * V_{in} \quad (3)$$

Since the chosen microcontroller used an 8-bit microchip, the value of the decimal is chosen within the range of 0 to 255. The communication between the motor driver and the Arduino Mega 2560 is done via I^2C protocol. The advantage of the driver is that it is stackable over Arduino Mega 2560, thus saving space on the platform. The resulted motor speed corresponding to respective decimal values based on (3) are given in Table IV.

Table IV Decimal number and voltage inputs and the corresponding measured no-load DC motor speed

Decimal Number	v_{motor} (rpm)	V_{in} (V)
10	51	0.49
20	59	0.99
30	61	1.48
40	95	1.98
50	122	2.47
60	152	2.96
70	179	3.46
80	207	3.95
90	236	4.45
100	263	4.94
110	293	5.44
120	321	5.93
130	350	6.42
140	377	6.92
150	407	7.41
160	434	7.91
170	462	8.40
180	490	8.89
190	518	9.39
200	544	9.88
210	571	10.38
220	599	10.87
230	627	11.36
240	652	11.86
250	683	12.35

VI. NAVIGATION ALGORITHM

To guide the vehicle moving from one waypoint to the other, readings from the compass is then compared with heading angle calculated from current latitude and longitude with respect to the intended destination as shown in Fig. 7.

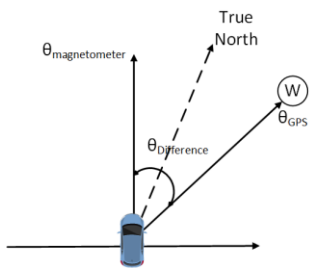

Figure 7 The difference between the normalized heading angle from the two sensors

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Equation (4) is used to calculate the heading angle from the magnetometer where the heading angle is defined as the angle between the magnetic field of the y-axis (M_y) and magnetic field of the x-axis (M_x).

$$\theta_{magnetometer} = atan2\left(\frac{M_y}{M_x}\right) \quad (4)$$

The GPS heading (7) is calculated from the current positional data which is fetch every 250 milliseconds and is represented in (5) and (6) for individual components.

$$y_{GPS} = \sin(\Delta\lambda)\, cos\,(\phi_2) \quad (5)$$

$$x_{GPS} = \cos(\phi_1)\, sin(\phi_2) - \sin(\phi_1)\, cos\,(\phi_2)\, cos\,(\Delta\lambda) \quad (6)$$

$$\theta_{GPS} = atan2\left(\frac{y_{GPS}}{x_{GPS}}\right) \quad (7)$$

where$\Delta\lambda$ is the difference between the longitude of the destination and the current position in radians, ϕ_2 is the destination latitude and ϕ_1 is the current latitude.

Depending on the differences between the heading angles from the two sensors, the servo will steer the vehicle as shown in Fig. 9. The servo angle, δ is obtained by testing the decimal values into the Arduino to gauge the minimum and maximum values for the servo to rotate.

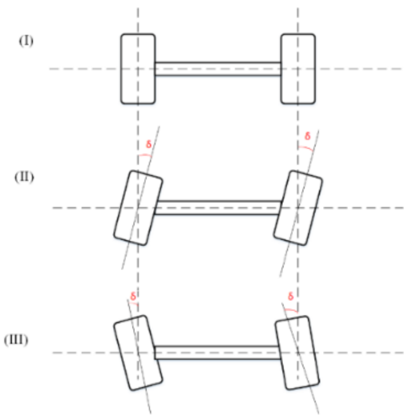

Figure 8 Servo steering angle

The values that were selected to be used for the maneuvering procedures are tabulated in Table V.

Table V Steering conditions and related decimal values for servo angles

Steering conditions	Servo Angle, δ (°)
Hard Left	60
Middle Left	70
Soft Left	80
Neutral	90
Soft Right	100
Middle Right	110
Hard Right	120

The navigation algorithm is designed to reach within 1.5 meters of the destination waypoint before switching to another waypoint through calculating the distance traveled by vehicle from the GPS data as shown in (8)-(10).

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \sin^2\left(\frac{\Delta\lambda}{2}\right)\cos\left(\frac{\lambda_1}{2}\right)\cos\left(\frac{\lambda_2}{2}\right) \quad (8)$$

$$c = atan2\left(\sqrt{a}, \sqrt{1-a}\right) \quad (9)$$

$$d = R * c \quad (10)$$

where $\Delta\phi$ is the difference between the current latitude and destination latitude, λ_1 is the current longitude, λ_2 is the destination latitude and d is the calculated through the GPS data and R is the radius of the Earth which is 6371 km.

15 experimental runs are conducted on the basketball court in PusatSukanUniversitiSains Malaysia, KampusKejuruteraan as shown in Fig. 9. The goal of these experiments is to validate whether the prototype is able navigate itself towards the 6 selected waypoints starting from the chosen starting point (SP) which are shown in Fig. 9 and their recorded GPS location is in Table VI. The results to be discussed are 4 selected runs of the 15 runs.

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Figure 9 Experimental test site

Table VI Selected waypoints for the experimental runs

Waypoint No.	Latitude (D°)	Longitude (D°)	Reference Heading Angle (°)
SP	5.147994	100.497500	68.25
W1	5.148050	100.497643	85.50
W2	5.148056	100.497719	180.15
W3	5.147936	100.497719	270.05
W4	5.147936	100.497566	355.76
W5	5.148039	100.497559	82.50
W6	5.148050	100.497643	68.25

VII. RESULTS AND DISCUSSIONS

Experimental runs were conducted and graphically represented in Fig.10. It can be seen that the prototype vehicle is able to navigate through each selected waypoint before stopping a distance away from the last waypoint. It is however noted that the initial starting position recorded does not correspond to the chosen starting point.

It is however noted that the initial starting position recorded does not correspond to the chosen starting point. The differences between the two position is tabulated in TableVII. Based on (7) - (9), the distance between the initial starting position and the selected starting position were manually calculated and tabulated in Fig. 10 where Fig.10 (A) represents the first experimental run and the GPS position of the prototype is 5.72 meters away from SP while the other runs registered the initial starting point closer towards SP. This would indicate that the GPS receiver is able to approximately pinpoints the current position of the prototype within the limits of the accuracy of the GPS receiver.

The prototype is observed to perform loops as shown in Fig.10 where the vehicle looped thrice before heading towards W3 as shown in Fig. 10 (C) when compared to the other runs in which the prototype exhibits only one or two looping patterns.

A probable reason for this behaviour is that the prototype registered a new position which is further away from the path. As noted in [13], the GPS receiver might have received a wrong position data when it is moving from W2 to W3. As the vehicle continues to maneuver based on the calculated heading, new sentences continued to be received by the receiver as shown in Fig. 11. However, the GPS receiver is then shown to be able to provide latitude and longitude that are closer to the travel path.

Table VIIDistance between the chosen starting point and the experimental starting point for each run

Run No.	Reference Starting Point Latitude (D°)	Reference Starting Point Longitude (D°)	Recorded Starting Point Latitude (D°)	Recorded Starting Point Latitude (D°)	Calculated Distance (m)
1	5.147994	100.497500	5.147957	100.497536	5.72
4	5.147994	100.497500	5.147965	100.497513	3.53
9	5.147994	100.497500	5.148012	100.497513	2.42
13	5.147994	100.497500	5.147990	100.497520	2.30

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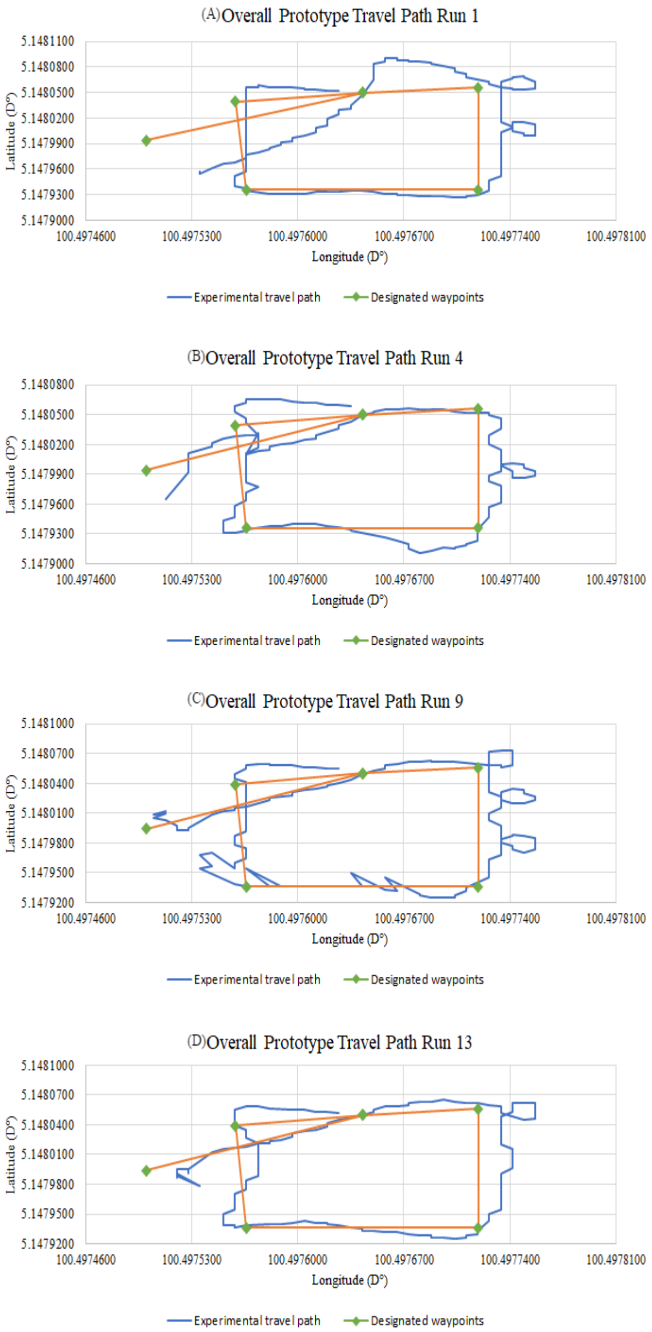

Figure 10 Results of experimental runs

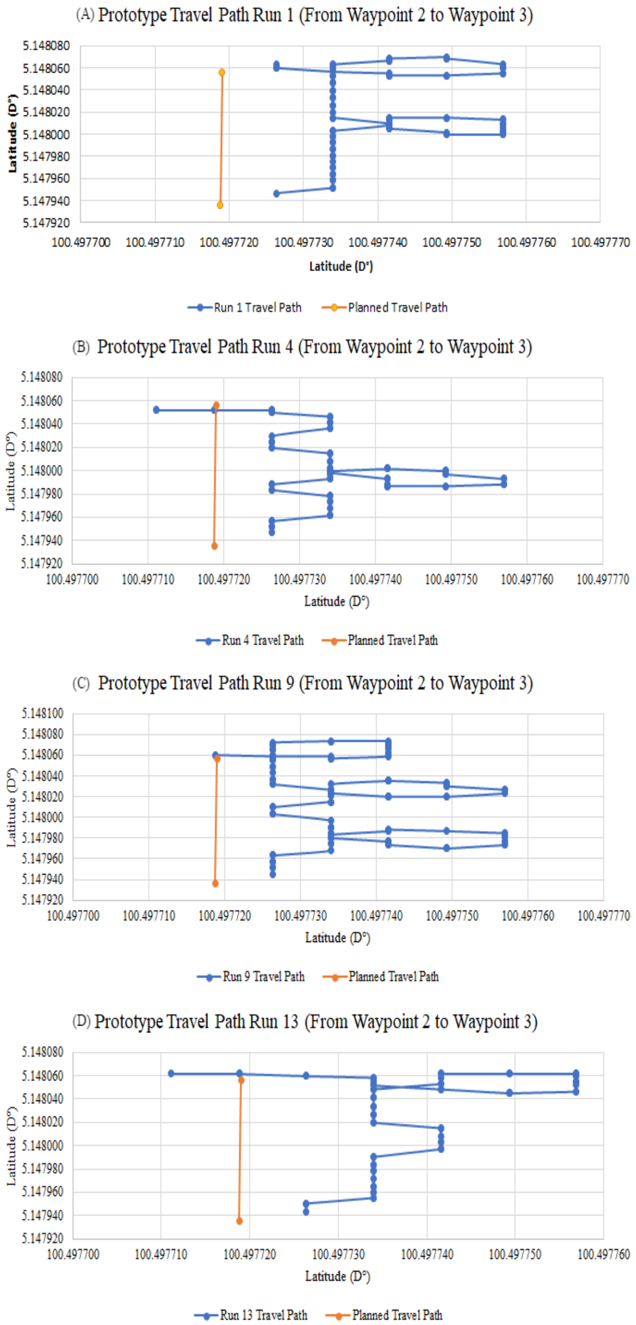

Figure 11 Prototype recorded position during traveling from W2 to W3

The values for the heading angles from magnetometer and GPS that are obtained from (4) and (7) respectively are illustrated in Fig. 12. The maneuvering of the prototype that might also cause the looping behavior since the differences of the heading angle between the two sensors determined the type of maneuvering the vehicle would undertake. Each of the looping behaviour is detected when the magnetometer heading angle is found to jump towards 350° from a lower heading angle value in the previous reading. This would cause the prototype to maneuver to the left and continues to do so until the magnetometer heading angle is aligned with the GPS heading angle.

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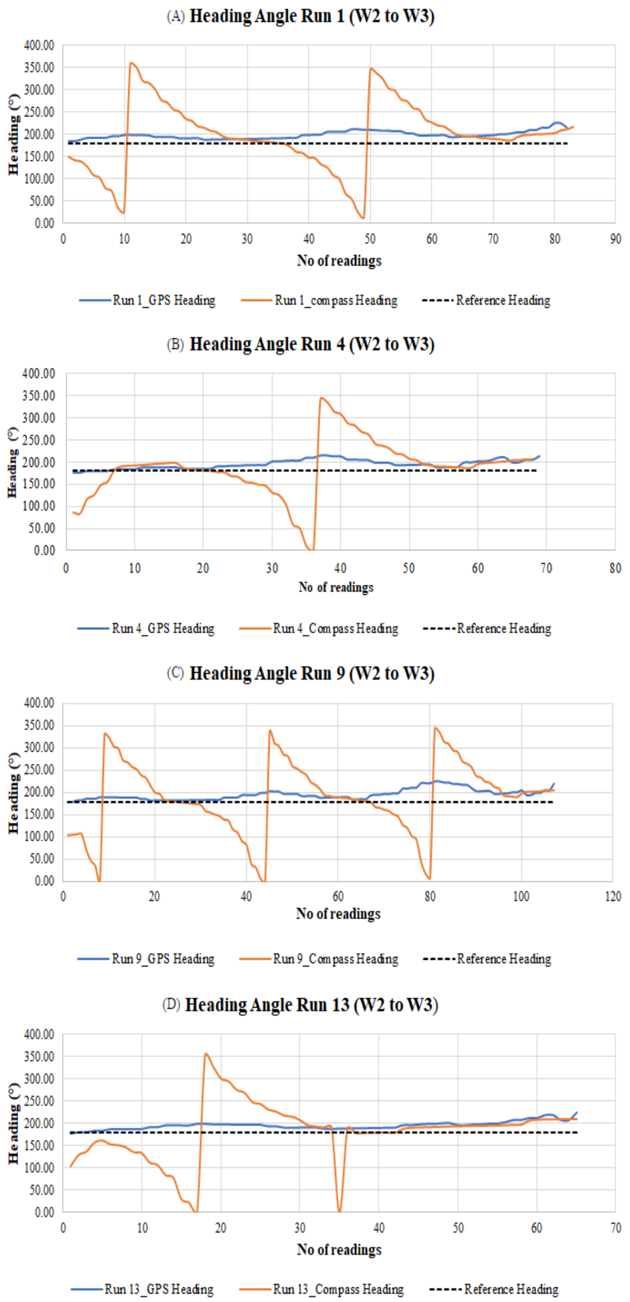

Figure 12 Heading angle for different runs from W2 to W3

Overall, the prototype vehicle is able to close the loop by travelling to all waypoints and managed to stop 1.5 meters away from the final waypoint W6 as shown in Table VIII. At average, the distance that is calculated by the Arduino to stop the vehicle is 1.135 meters away from W6.

Table VIII Distance of the prototype from the final waypoints at selected runs

Experimental Run No.	Distance from final waypoint (m)
1	1.105
4	1.098
9	1.232
13	1.105

CONCLUSION

In conclusion, an overview of the hardware development for a GPS-based small-scale prototype vehicle is presented. The goal of the vehicle is to move towards selected waypoints without any human interference and the navigation algorithm is presented in order for the vehicle to navigate based on the inputs obtained from the GPS module and the magnetometer. Furthermore, the selection criteria for the sensors, microcontrollers and the power and mass budgets are also presented in order to make a better planning for the prototype development. The vehicle is tested and found that the designed algorithm has managed to guide the vehicle towards the selected waypoints and stopped when the distance is less than 1.5 meters away from the final waypoint. However, the prototype vehicle is found to perform looping when travelling from W2 to W3 which assumed to be attributed to the GPS registered a new position while moving and the type of maneuvering the prototype would undertake when the differences between the heading angles from the two sensors are more than 100°.

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