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ORIGINAL ARTICLE

GPS tracking system for autonomous vehicles

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Tracking system

Abstract This paper presents a proposed design of a mechatronics system for autonomous vehicles. The proposed design is able to memorize a route based on Global Positioning System (GPS) rather than using pre-saved maps that are infrequently updated and do not include all roads of all countries. Moreover, it can autonomously avoid obstacles and detect bumps. Experimental tests are conducted using a small-scale car equipped with the proposed mechatronics system. The results show that the proposed system operates with minor errors and slips. The proposed autonomous vehicle can serve normal, disabled, and elderly people. It can be used on roads and even inside facilities like campuses, airports, and factories to transport passengers or loads thus reducing workmanship and costs.

1. Introduction

For the past fifty years, engineers went on searching for keys to further minimize the human input in driving vehicles. Jansson [1] stated that 93% of car accidents are caused by human errors and a study conducted by the Lebanese Red Cross [2] revealed that car accidents in 2014 yielded 14,516 casualties. These shocking statistics are due to the constantly increasing traffic density on the slow developing existing infrastructure as stated by Zlocki et al. [3]. This resulted in more complex and difficult driving situations, which upsurge the possibility of a human error and thus increasing accident rates. The need to develop driverless vehicles arouse in order to eliminate this error and most importantly to spare human lives. Another statistical study conducted by the Lebanese Ministry of Social Affairs [4] revealed that 10% of the Lebanese population suffer from a disability. So people who face difficulties with driving, such as disabled people and elderly people would be able to experience the freedom of car travel using autonomous vehicles. On the luxury side, cars could become mini-leisure rooms where passengers will have no need to be facing forwards at all times and can sleep, enjoy entertainment features, and even work on the go without the concern of driving. This technology is accompanied with disadvantages, as driverless cars would likely be very expensive when first introduced. Also truck drivers and taxi drivers would lose their jobs. On the other hand, crash repair shops and automobile insurance firms might suffer as the technology makes certain aspects of these occupations obsolete.

After surveying the advantages and disadvantages of this technology, researchers realized that the benefits of it would likely outweigh its disadvantages, as the economic concerns that might arise are like any economic problem a new technology brings. This issue has long been present and people found

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other fields of experience to cope with new technologies. So why haven't we seen autonomous vehicles on the roads yet? The numerous scenarios these vehicles will face in the real world and the conditions they have to operate in are the main reasons of holding back manufacturers from releasing them in the market.

Multiple automation systems for vehicles were developed to address these numerous scenarios. One of these systems is the tracking system that sets the location of the vehicle. A system developed by Quddus and Noland [5], uses a digital road map, which is a machine vision of the road that detects the road boundaries and curb using a Light Image Detecting and Ranging (LIDAR) sensor, to keep the vehicle centered between road limits by using the by-wire controls according to Davis [6]. In the work done by Kojima et al. [7], a tracking system uses GPS positional data to roughly estimate the vehicle's location and a laser scanner to monitor the vehicles surroundings to roughly estimate the vehicle's location by coordinates and enhance it by the relative positional changes of surrounding objects. In addition, marker tracking systems position the vehicle by adhering to special markers or lines according to Zhu and Chen [8]. Other automation systems include collision avoidance systems. When facing a possible collision, a driver may have two options, either brake or steer. Labayrade et al. [9,10] applied a longitudinal collision avoidance system to control the braking of the vehicle to either stop the vehicle before reaching the obstacle or maintain safe distances from other vehicles. A lateral collision avoidance system steers the vehicle away from an accident based on the situation of the collision event similar to the work of Glaser et al. [11], or as a system devised by Scacchiolia et al. [12] that applies intentional instability by controlling the vehicle's brakes to drift it away from potential danger when neither steering nor slowing down is sufficient for avoiding a collision. Additional existing systems are self-parking systems discussed by Paromtchik et al. [13] and lane departure systems presented by Enache et al. [14].

Driverless cars often provide the user with digital pre-saved maps of roads where he can choose his preferred route via a touch screen as stated by Kaller [15]. This method has a drawback, as digital maps are not updated frequently by manufacturers and do not include all roads. The method of setting the route in this paper addresses this problem. Indeed, the user has to drive his car manually over his desired route only for once while the GPS tracking system memorizes the road. This gives the freedom of choosing any path, does not bound to specific pre-saved routes, and enables updating the roads instantly when they change. This paper focuses on this method only. However, to get the best of both worlds, the typical and the proposed method can be used together where the driver sets the route using digital maps, then update these maps if needed.

This paper presents a mechatronics system for autonomous vehicles. The proposed system is able to memorize a route based on a GPS tracking system. For more practical applications, it also includes the following features: collision avoidance, bump detection. The proposed design commits to a tight budget by building model of the autonomous vehicle using cheap microcontrollers and sensors. It can be used to transport passengers inside campuses, airports and even on roads. Moreover, it can be used to carry loads and transport them in a certain facility or factory reducing workmanship and costs.

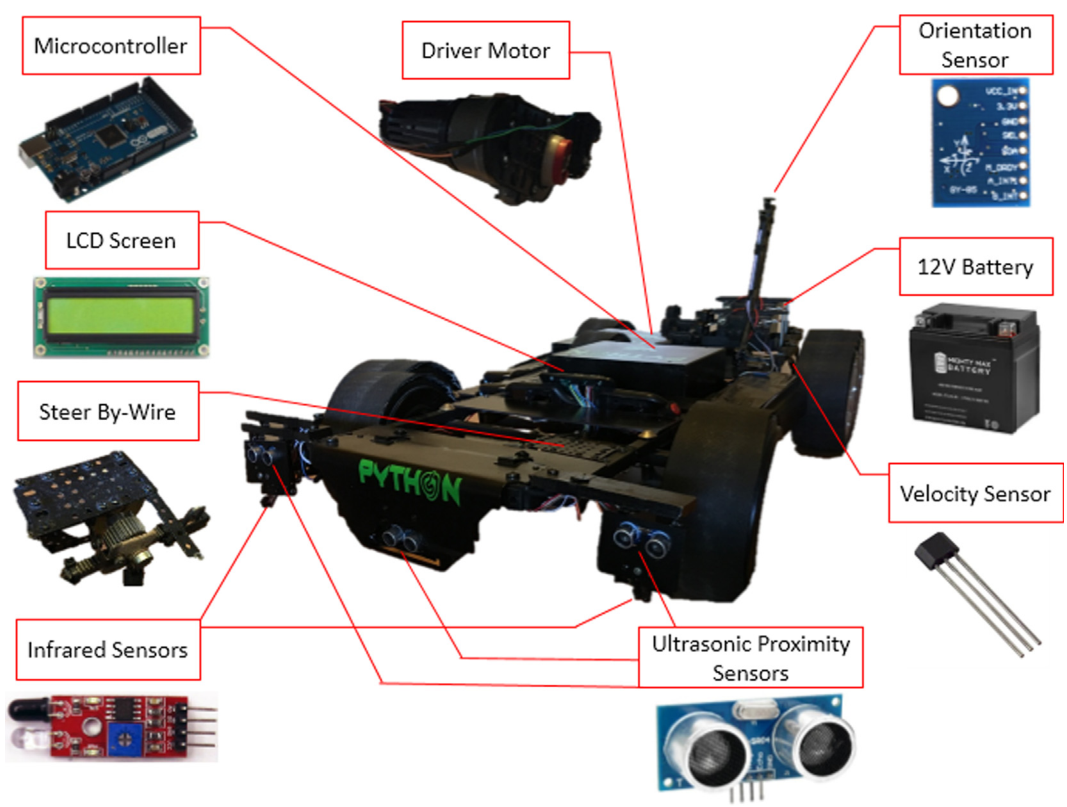

Fig. 1 Prototype of the proposed autonomous vehicle.

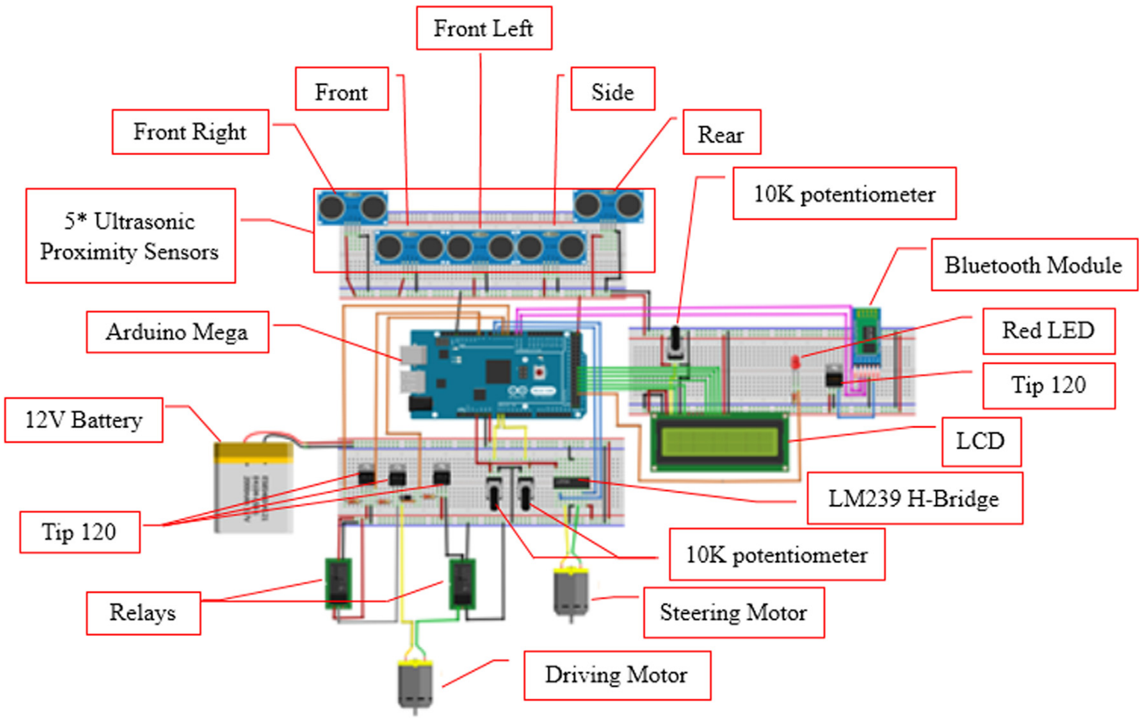

Fig. 2 Proposed mechatronics system.

2. Proposed design

2.1. Mechatronics system

The systems proposed in this paper were implemented on a prototype based on a small scale vehicle that was modified to have by-wire controls and to accommodate all sensors and electronic hardware. It features a metal chassis on which a motor-gearbox drivetrain and a by-wire rack and pinion steering assembly are installed. It also holds in the center the Arduino Mega microcontroller programmed using C++ language which accommodates multiple sensors distributed among different locations in the vehicle as shown in Fig. 1.

The connections of the different sensors and actuators relative to their position on the prototype are presented in Fig. 2.

The various electronic components and their usages are represented in Table 1.

2.2. Tracking of the path

In order to navigate a certain path autonomously, the driver has to drive the vehicle on the desired path only for once while a GPS tracking system memorizes the path by saving GPS waypoints received from the GPS sensor of an onboard Android phone and distances calculated from the velocity sensor according to a control sequence as shown in Fig. 3.

Fig. 4 illustrates how a forward path that does not include any left or right bends is saved by the tracking system. The starting point is the datum from which the distance covered, D, is calculated from the velocity provided by the velocity sensor while moving forward.

This distance ends when the vehicle encounters a turn as shown in Fig. 5.

The final distance is then saved in an array to be called next in the autonomous trip. As the steering occurs, the current coordinates of the vehicle are saved as shown in Fig. 6.

When a turn ends, a forward path starts again where a new starting point is taken and the distance covered is measured as explained previously. This phase is illustrated in Fig. 7. If the vehicle encounters another turn, the same procedure is performed as shown in Fig. 8.

The same procedure repeats until the final destination is reached as shown in Fig. 9. This way of tracking the path enables the vehicle to calculate the turning angles of every bend and the instants a bend is encountered as explained in Section 2.3.

2.3. Autonomous navigation

After the path has been memorized during the tracking trip, the vehicle can now navigate this path with no driver interference. The same path illustrated in Fig. 9 will be considered in this section. The procedure of navigating autonomously is explained in the flowchart presented in Fig. 10.

The driving motor of the vehicle is switched on automatically after selecting the autonomous mode. For the forward path, the saved distance, D, is compared with distance D_c which is the current distance covered by the vehicle. If D_c is less than D, the vehicle will continue moving straightforward as shown in Fig. 11(a), until the two distances are equal as depicted in Fig. 11(b).

The end of the forward path indicates the beginning of a turn. So the first and second waypoints are called in order to calculate the turning direction and angle θ as shown in Fig. 12.

In order to calculate the turn angle θ, the coordinates, latitude (LAT) and longitude (LON) values, of the first waypoint

Table 1 Electronics list.

Electronic Components	Usage	Error range
Arduino mega	Microcontroller	N/A
5* HC-SR04 ultrasonic sensors	Reads distances up to 3 m	5% error rises in longer distances
Android phone	Includes the GPS sensor	0.5–1 m reading variations
HC-06 bluetooth module	Receives GPS coordinates from phone	Exact readings
3* 10 K potentiometers	Steering servo, LCD contrast, set PWM	Exact readings
GY-85 magnetometer	Provides the yaw angle of the vehicle	Has a ±2° variation
2* infrared modules	Detects obstacles up to 30 cm	5% error
Remote control module	Remote control signal receiver	Exact readings
Hall effect sensor	Drive shaft RPM counter	20% error
2*12 V DC motors	Steer-by wire motor, driver motor	N/A
Red LED	Indicates faults	N/A
16 × 02 LCD screen	Displays readings and modes	N/A
4*Tip 120 transistors	Controls driver motor relays	N/A
LM293 H-bridge	Controls steering motor direction	N/A
Relay motor driver	Controls driver motor direction	N/A

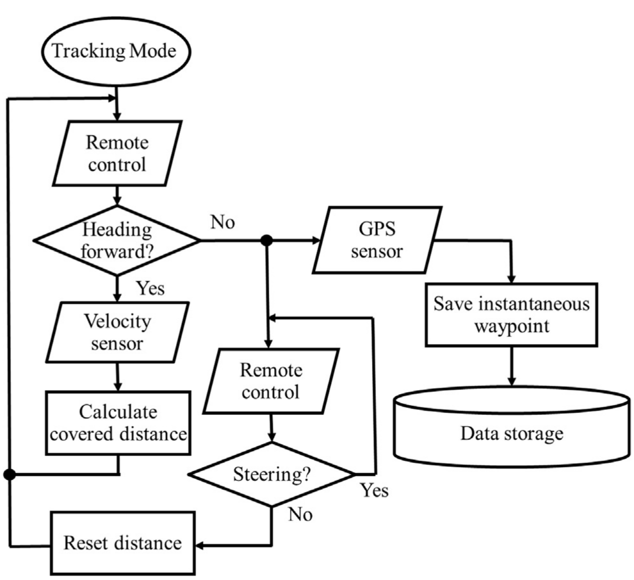

Fig. 3 Flowchart of control sequence of the tracking mode.

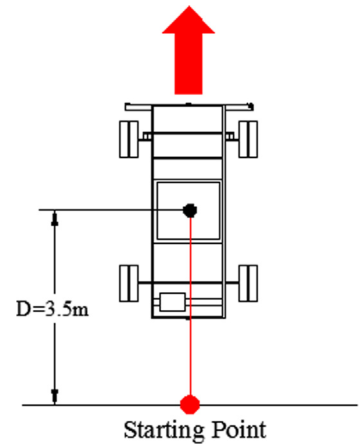

Fig. 4 Heading forward tracking criterion.

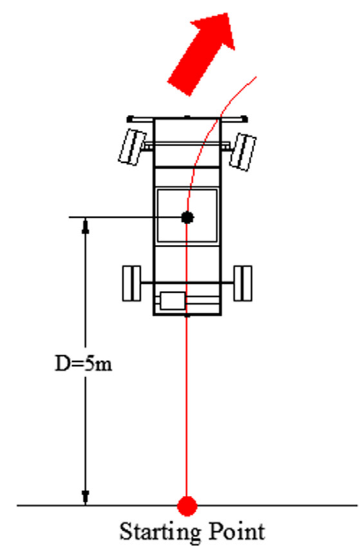

Fig. 5 Saved distance.

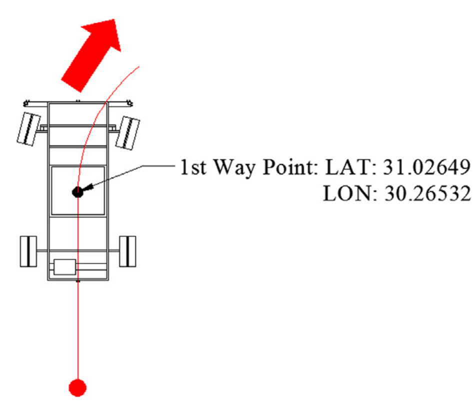

Fig. 6 Saved way point.

are subtracted from the coordinates of the next waypoint. The longitude and latitude differences are Δλ and Δφ, respectively, as expressed in Eqs. (1) and (2).

$$\Delta\lambda = LON_2 - LON_1 \tag{1}$$

$$\Delta\varphi = LAT_2 - LAT_1 \tag{2}$$

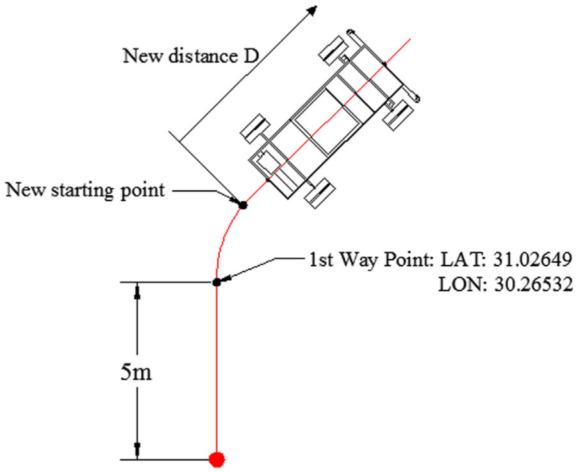

Fig. 7 New forward path.

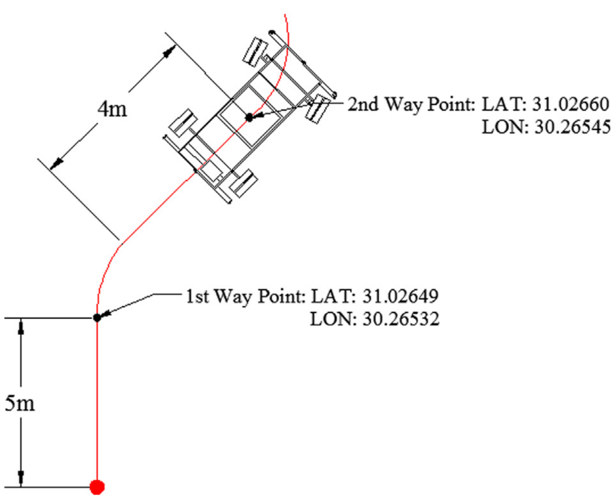

Fig. 8 New way point.

Using the characteristics of a right triangle, the angle θ can be calculated as shown in Fig. 13 and Eq. (3).

$$\theta = \tan^{-1}\frac{\Delta\lambda}{\Delta\varphi} \tag{3}$$

This case is only applicable if the vehicle approaches the start of the turn in the same direction of the $\Delta\varphi$ line as shown in Fig. 14(a). If the vehicle approaches the turn at an angle as shown in Fig. 14(b), the previous calculation is false and a new turn angle, θ', should be calculated.

To calculate θ', Eq. (3) should be modified to compensate for the heading of the vehicle at the entry point. This compensation depends on the heading angle ζ of the vehicle measured from the absolute north by the orientation sensor as illustrated in Fig. 15.

After acquiring this angle at the entry point of the turn, the angle θ' can be calculated depending on quadrant conditions and the sign of $\Delta\varphi$ as illustrated in Table 2.

The equations presented in Table 2 will be used to calculate the turn angle of the second turn in the considered path shown previously in Fig. 9 since the vehicle is approaching the turn at an angle and not along the vertical line $\Delta\varphi$ as shown in Fig. 16.

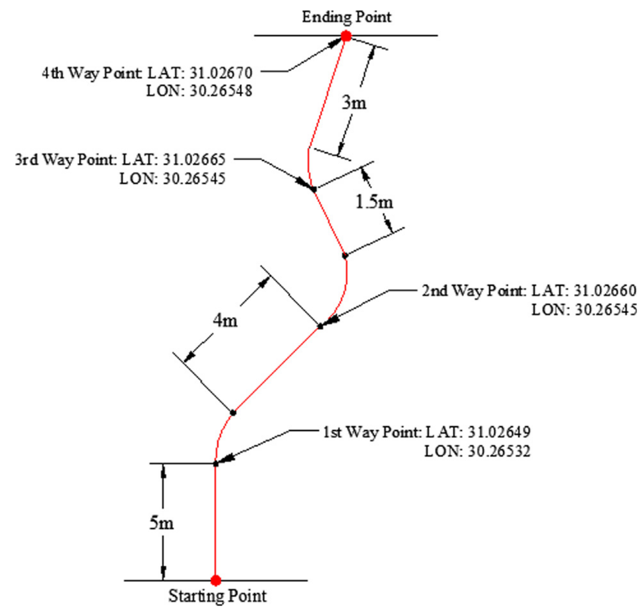

Fig. 9 Saved full path example.

If the calculated turn angle θ' is positive, then the vehicle should turn right and if it is negative, the vehicle should turn left. The vehicle will keep turning until the orientation sensor reads a rotational displacement equal to the calculated turn angle. After this angle is reached, the vehicle heads forward and the same procedure explained in this section is repeated.

2.4. Collision avoidance

In order to avoid crashing into other vehicles and any obstacles that come near the autonomous vehicle, a collision avoidance system is a must in an autonomous automobile. The system installed in this version of the autonomous vehicle consists of three ultrasonic proximity sensors mounted on the vehicle's nose and facing forward as shown in Fig. 17. They serve to detect any obstacle that comes within the width of the vehicle. These sensors can read up to a distance of 3 m with high accuracy and return the exact position of the obstacle relative to the vehicle.

The collision avoidance operation consists of two phases. The first phase is triggered if an obstacle falls within 1 m in front of the vehicle. The car is then ordered to stop until the road is clear again. It is noteworthy that the first phase is triggered if at least one sensor reads an obstacle within 1 m, as illustrated in Fig. 18.

The second phase is triggered when an obstacle suddenly falls in front of the vehicle at a distance less than 0.5 m. The vehicle is then ordered to perform an evasion maneuver since it cannot completely stop within 0.5 m and will inevitably collide with the obstacle. Instead, the vehicle steers away from the obstacle. If the left sensor detects the obstacle, the vehicle steers right and vice versa as shown in Fig. 19.

The evasion maneuver explained hereafter has two sequences; the first is shown in Fig. 20 while the second is shown in Fig. 21. When an obstacle suddenly falls within 0.5 m, the vehicle steers immediately dodging the obstacle. The vehicle stops steering when the obstacle is no longer

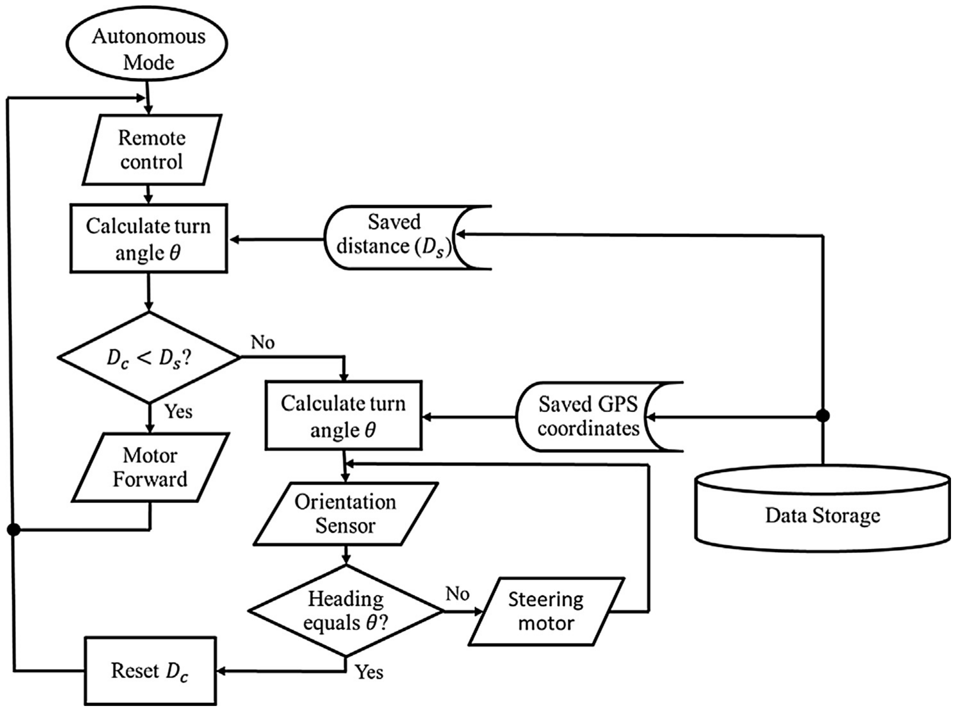

Fig. 10 Flowchart of control sequence of the autonomous navigation.

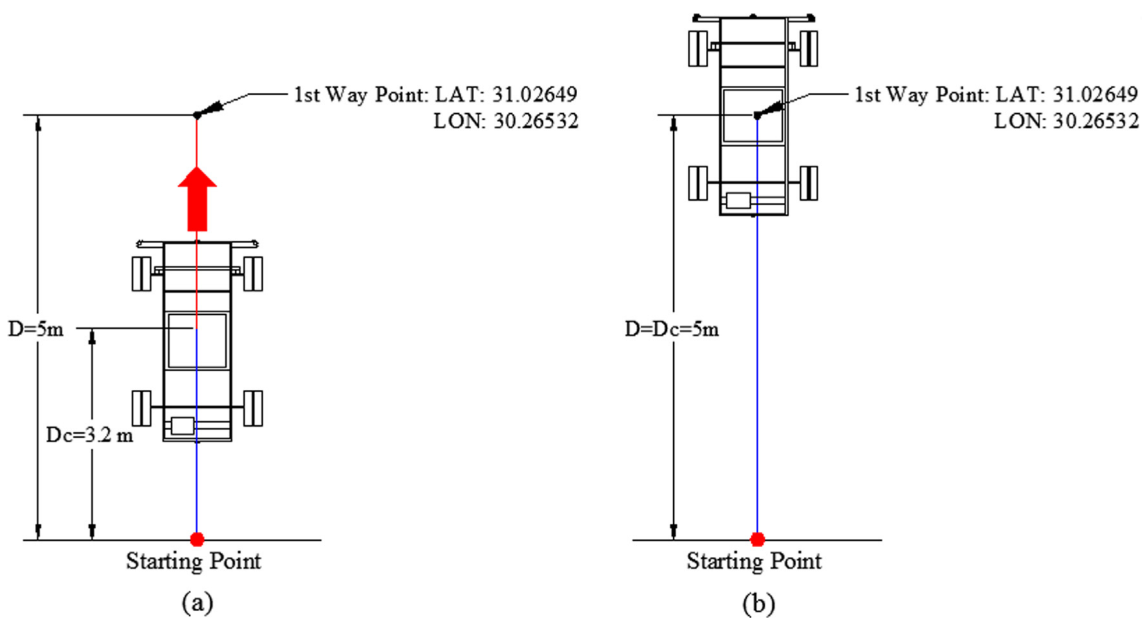

Fig. 11 Forward path in autonomous mode; (a) the covered distance is less than the saved distance, (b) the covered distance is equal to the saved distance.

observable. During the dodging sequence, the deviation angle is noted in order to retain the original heading. If the vehicle steered by an angle ψ to the right, it steers again to the left by the same angle. The vehicle now is parallel to the original track as shown in Fig. 20. It is noted that the solid line represents the normal path and the dashed line represents the evasion path.

The second sequence is the opposite of the first where the vehicle steers back towards the original path by the same deviation angle. The vehicle then steers back to the right to take back the original path as shown in Fig. 21.

2.5. Bump detection

In order to cope with changing road conditions, the proposed vehicle is equipped with a bump detection system that spots any speed bumps on the road and slows the vehicle's speed

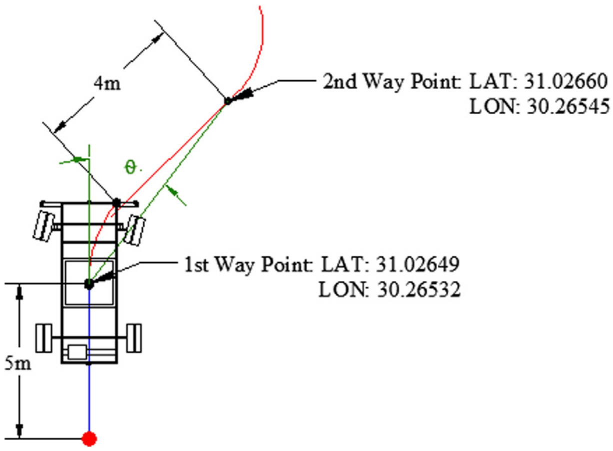

Fig. 12 Turn angle illustration.

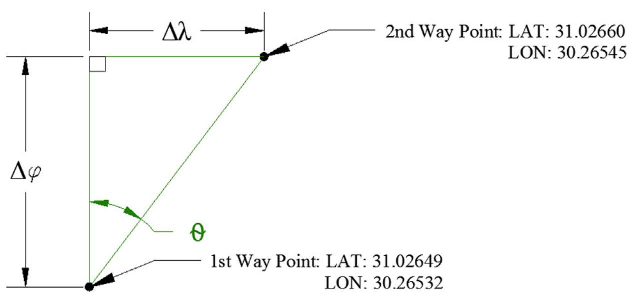

Fig. 13 Turn angle calculation.

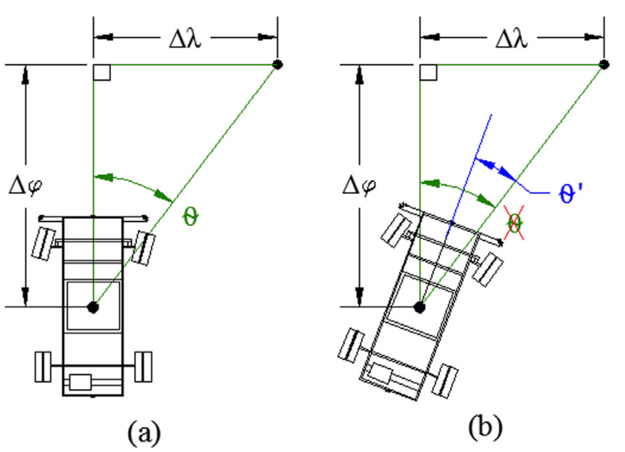

Fig. 14 Turn angle conditions; (a) direction of vehicle along Δφ line, (b) vehicle approaching the turn at an angle.

in order to prevent damage and compromise passenger discomfort. This system consists of two infrared emitter detectors mounted in front of the front wheels and pointing on the road. As long as the sensors read a constant distance to the ground, this means that the road is flat as shown in Fig. 22(a). If the distance read by one of the sensors decreases, it refers to a bump encounter in front of the respective wheel as shown in Fig. 22(b). Then, the vehicle is ordered to slow down until the vehicle covers a distance of 0.7 m so that the rear wheels pass the bump as presented in Fig. 22(c).

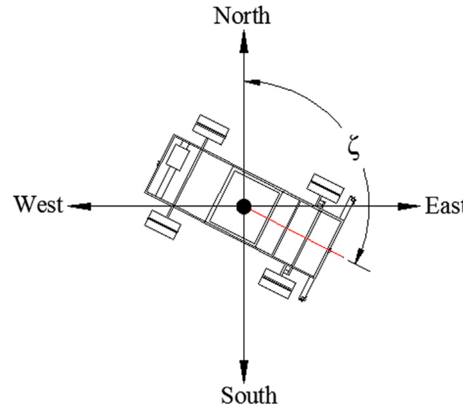

Fig. 15 Presentation of heading angle ζ.

Table 2 Equations of turning angles.

	$0 \leqslant \zeta \leqslant 180$	$180 \leqslant \zeta \leqslant 360$
$\Delta\varphi \geqslant 0$	$\theta' = arctan\left(\frac{\Delta\lambda}{\Delta\varphi}\right) - \zeta$	$\theta' = arctan\left(\frac{\Delta\lambda}{\Delta\varphi}\right) - \zeta + 360$
$\Delta\varphi < 0$	$\theta' = arctan\left(\frac{\Delta\lambda}{\Delta\varphi}\right) - \zeta - 180$	

3. Test results and discussion

3.1. Autonomous navigation results

The data obtained by testing the tracking system was analyzed to approve the proposed design. The realistic dimensions of the saved track presented in Fig. 23 were measured using a measuring tape and a protractor. The saved GPS coordinates and distances obtained from the tracking trip are presented in Fig. 24.

Now the turn angles of every curve can be calculated using the equations of turning angles presented in Table 2. Taking the first curve as an example, yields:

$$\Delta\lambda = LON_2 - LON_1 = 35.60220 - 35.60235 = -0.00015 \quad (4)$$

$$\Delta\varphi = LAT_2 - LAT_1 = 33.82160 - 33.82152 = 0.00008 \quad (5)$$

Since $\Delta\varphi > 0$ and $\zeta = 231°$, then from Table 2, it follows that:

$$\theta' = arctan\left(\frac{\Delta\lambda}{\Delta\varphi}\right) - \zeta + 360 \quad (6)$$

$$\theta' = arctan\left(\frac{-0.00015}{0.00008}\right) - 231 + 360 = 67° \quad (7)$$

Realistically the angle of the first curve is 69° while the calculated angle is 67°. This is due to some error in the GPS readings and this error can relatively be accepted. In the autonomous trip, the realistic dimensions of the path are shown in Fig. 25 where the red[1] line represents the saved track and the blue line represents the autonomous track. On the

[1] For interpretation of color in Figs. 25 and 26, the reader is referred to the web version of this article.

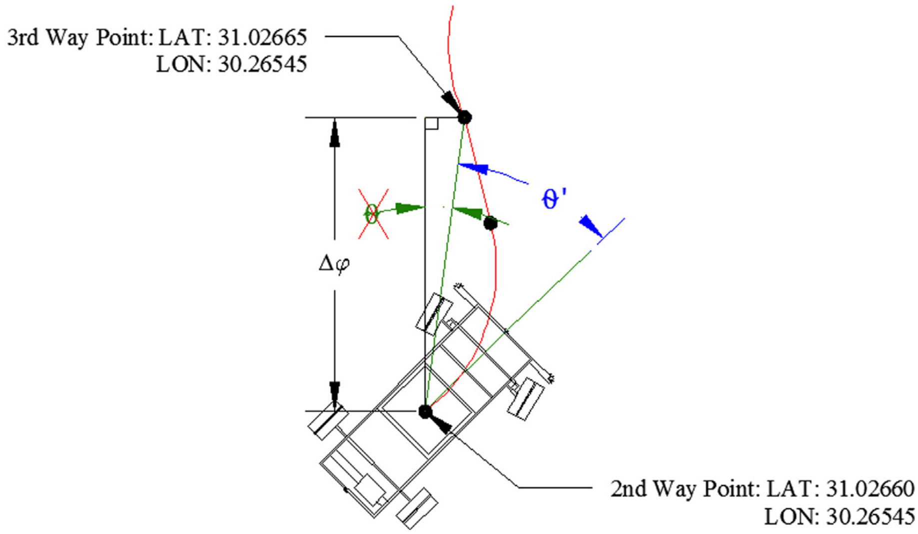

Fig. 16 Second bend turn angle.

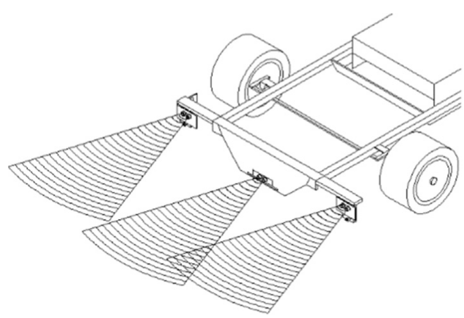

Fig. 17 Ultrasonic proximity sensors.

other hand, the dimensions measured by the velocity sensor and the angles calculated based on the equations given in Table 2 are shown in Fig. 26.

It is observed that the errors obtained with the measured distance and calculated turn angles are in reasonable proportions. As illustrated in Fig. 26, the blue line is very close to the red line which refers to an error range from 0.5 to 1 m from the saved track. These errors may be reduced further by using more precise but expensive GPS modules, more accurate odometers, and additional localization systems.

3.2. Bump detection results

The monitored parameters were the velocity and the Pulse Width Modulation (PWM) value. The PWM is a technique used to control the rotational velocity of the driver motor by reducing or increasing the current flow to the DC motor. Once the sensors detect the bump, the PWM value is dropped down to zero in order to instantly reduce the vehicle's speed drastically before climbing the bump. Then after 1 s, the PWM increases to 150 until the rear wheels pass the bump. Next, the PWM is restored to the original value of 255 which corresponds to the original velocity as shown in Fig. 27. Fig. 28 shows the time history of the velocity of the vehicle.

It is observed that the velocity dropped drastically as the PWM went from 255 to 0 then became approximately constant when the PWM value increased to 150. After the vehicle's rear

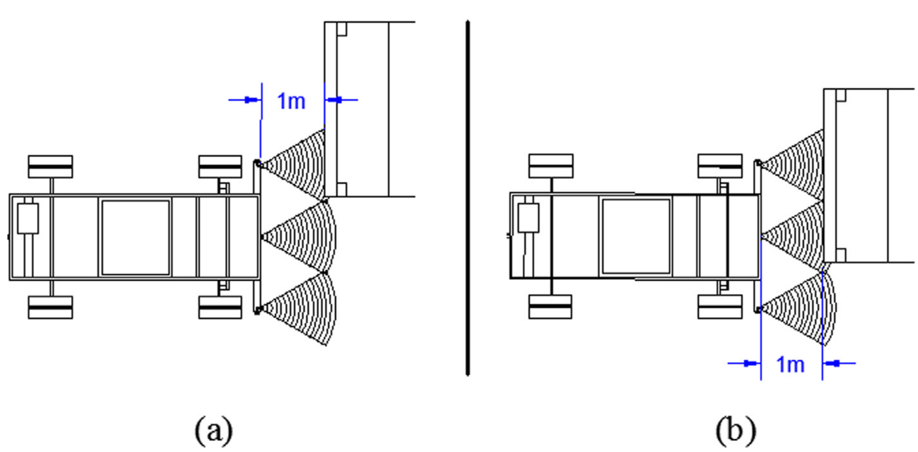

Fig. 18 First phase collision avoidance; (a) one sensor detects an obstacle, (b) two sensors detect the obstacle.

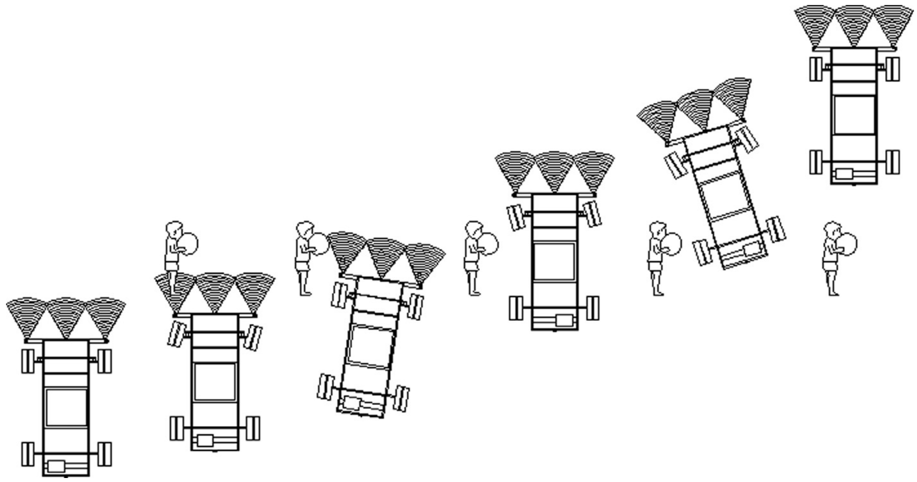

Fig. 19 Second phase collision avoidance.

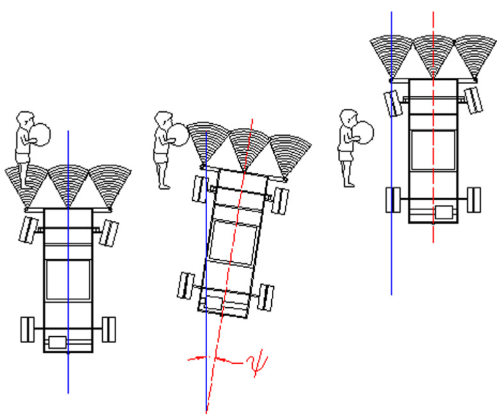

Fig. 20 First evasion sequence.

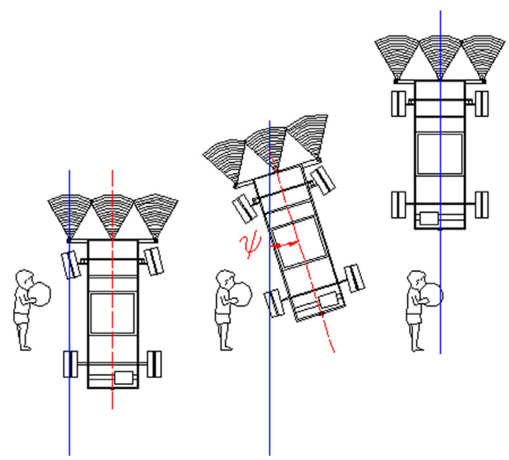

Fig. 21 Second evasion sequence.

wheels passed the bump, the PWM was restored to 255 and the velocity increased back to its original value. The time intervals and the change in PWM value were set after experiment in order to reach the suitable velocity to pass over the bump safely. It was observed that the suitable velocity was between 3 and 3.5 km/h and the PWM values were set accordingly.

4. Conclusions

In this paper, a mechatronics system for autonomous vehicles was proposed. It addresses the issue of pre-saved digital maps that are not frequently updated and do not contain all roads and shortcuts. This proposal uses a tracking system to introduce unknown roads to the traditional digital maps. The methods of tracking were discussed in details. In order to build a

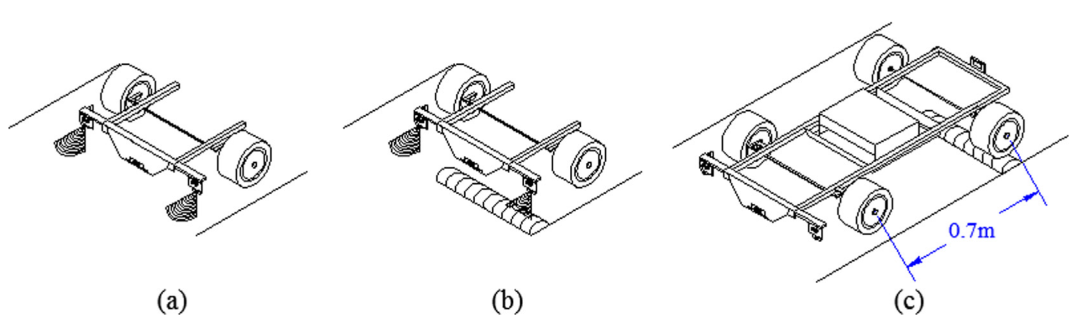

Fig. 22 Bump detection; (a) no bump detected, (b) bump detected by one of the sensors, (c) speed is reduced until the rear wheels pass the bump.

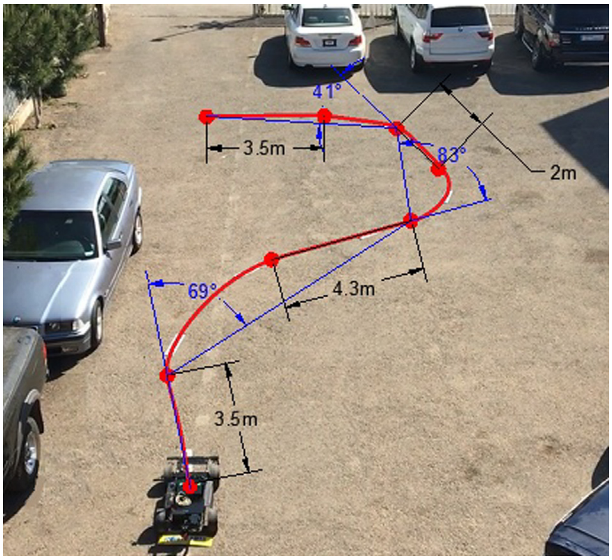

Fig. 23 Path realistic dimensions.

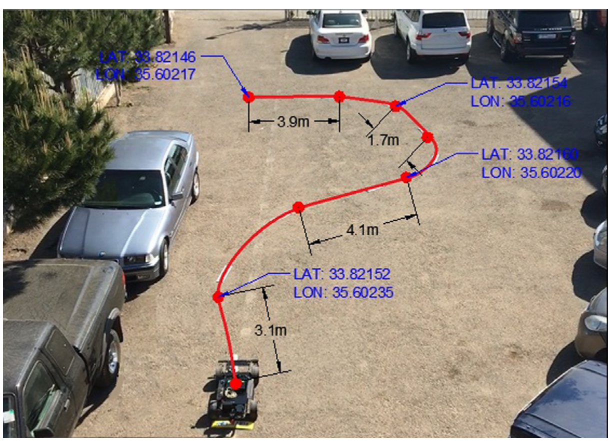

Fig. 24 Saved parameters of the path.

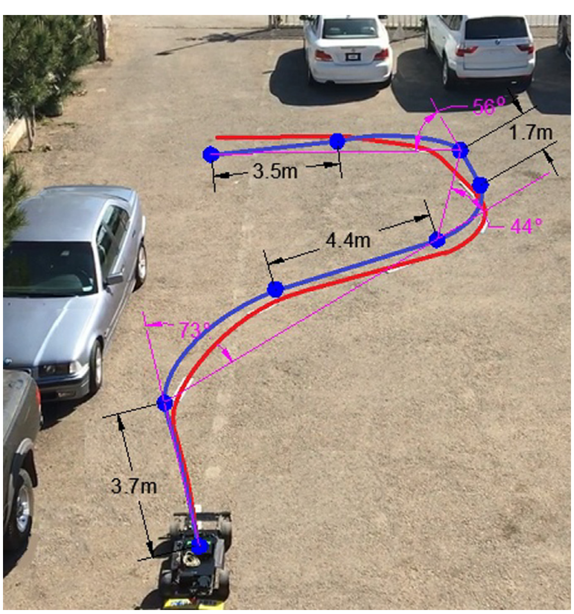

Fig. 25 Autonomous trip realistic results.

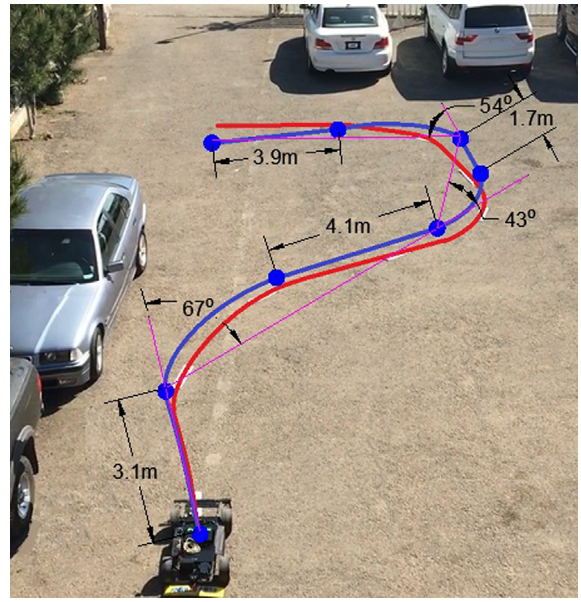

Fig. 26 Calculated parameters.

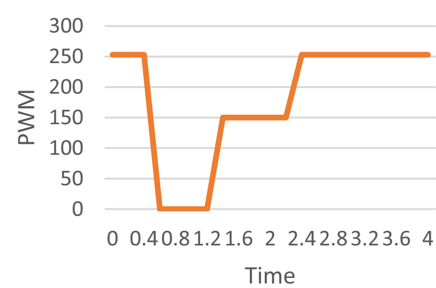

Fig. 27 Pulse Width Modulation time history.

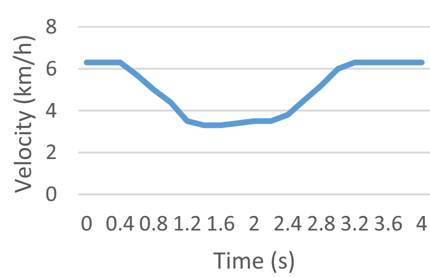

Fig. 28 Velocity time history.

safe autonomous vehicle, a set of systems for collision avoidance and bump detection were integrated as well. Several tests and experiments were conducted on a small-scale car in order to prove that the proposed systems are practical and feasible. It turned out that the system operated with acceptable errors. The proposed autonomous vehicle can serve normal, disabled, and elderly people. It can be used on roads and even inside facilities like campuses, airports, and factories to transport passengers or loads thus reducing workmanship and costs.

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