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A Comprehensive Framework for an Autonomous Vehicle System Utilizing GPS, Google Maps, and Real-Time Sensor Fusion

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إطار عمل شامل لنظام مركبات ذاتية القيادة يستخدم نظام تحديد المواقع العالمي (*GPS*) وخرائط جوجل ودمج أجهزة الاستشعار في الوقت الفعلي

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Abstract:

This paper describes the design, development, and testing of a complete autonomous vehicle system. The main aim of this project is to develop a driverless transport system that can reach any destination provided by the user using global path planning through GPS and Google Maps and local path planning through sensor fusion. The system architecture consists of a global path planner, which takes input high-level routes and produces a series of waypoints for the local control unit. The local control unit is responsible for avoiding obstacles and keeping the vehicle within its lane boundaries and is also capable of altering the global path if conditions change along that path. A simple Graphical User Interface (GUI) allows users to input the destination and display the status of the system. The vehicle has a GPS module to know where it is, an IMU to know where it is orientated, ultrasonic or LiDAR sensors to sense its environment and more. According to experimental aggregation on a scaled model, the system was able to successfully reach destination from arbitrary source with smooth avoidance of static and dynamic obstacles along with maximum path adherence. This paper is a basic proof-of-concept showing that cloud-based navigation and real-time robot control can work together. Furthermore, this work establishes a roadmap toward further autonomy and reliability.

Keywords: Self-driving cars, Satellite Navigation System, Merging of sensors, avoiding obstacles, Planning of route, Google Maps API, Robotics.

الملخص

تصف هذه الورقة البحثية تصميم وتطوير واختبار نظام متكامل للمركبات ذاتية القيادة. يهدف هذا المشروع بشكل رئيسي إلى تطوير نظام نقل بدون سائق قادر على الوصول إلى أي وجهة يحددها المستخدم باستخدام تخطيط المسار العالمي عبر نظام تحديد المواقع العالمي (GPS) وخرائط جوجل، وتخطيط المسار المحلي عبر دمج أجهزة الاستشعار. تتكون بنية النظام من مُخطط مسار عالمي، يأخذ المسارات عالية المستوى المدخلة، ويُنتج سلسلة من نقاط التوجيه لوحدة التحكم المحلية. تتولى وحدة التحكم المحلية مسؤولية تجنب العوائق والحفاظ على المركبة ضمن حدود مسارها، كما أنها قادرة على تغيير المسار العالمي في حال تغير الظروف على طول هذا المسار. تتيح واجهة المستخدم الرسومية (GUI) البسيطة للمستخدمين إدخال الوجهة وعرض حالة النظام. تحتوي المركبة على وحدة نظام تحديد المواقع العالمي (GPS) لمعرفة موقعها، ووحدة قياس القصور الذاتي (IMU) لمعرفة اتجاهها، وأجهزة استشعار بالموجات فوق الصوتية أو الليدار (LiDAR) لاستشعار بيئتها، وغيرها. ووفقًا للتجميع التجريبي على نموذج مُصغر، تمكن النظام من الوصول بنجاح إلى الوجهة من أي مصدر، مع تجنب سلس للعوائق الثابتة والمتحركة، مع الالتزام التام بالمسار. هذه الورقة البحثية تُقدم دليلاً عملياً يُثبت إمكانية التكامل بين الملاحة السحابية والتحكم الآلي الفوري بالروبوتات. علاوة على ذلك، تُرسي هذه الورقة خارطة طريق نحو مزيد من الاستقلالية والموثوقية.

الكلمات المفتاحية: السيارات ذاتية القيادة، نظام الملاحة عبر الأقمار الصناعية، دمج أجهزة الاستشعار، تجنب العوائق، تخطيط المسار، واجهة برمجة تطبيقات خرائط جوجل، الروبوتات

Introduction

Autonomous vehicles could change transportation. They might be safer than human drivers. They could help reduce congestion. Moreover, they could offer more access to mobility. Even if fully autonomous Level 5 [1] vehicles are a longer-term goal, there have already been advances being made in perception, decision-making and control systems. This assignment works on a critical layer of the autonomy stack, linking the macroscopic route planning to the microscopic real-time control of the vehicle [2]. A lot of existing robotic systems work well in mapped space. Yet, a truly versatile autonomous car must be able to travel on public roads which can be rather extensive [3]. Thus, it would require something global like cloud computing with GPS to apply [4]. The main aim of this paper is to develop a working model of a driverless car which will use GPS and can navigate anywhere in the world using Google Maps or work on a custom-made map like the university campus [5]. The system has the intelligence to understand the specification of the road, bypass unexpected obstacles, hard turn and carry out maneuvers as well as run-time-path monitoring [6]. To accomplish this, we use a combination of user-facing applications, Internet path-finding servers and an onboard control unit converting high level routes into low level actuator commands [7]. According to preliminary results from our model, we can take the first step towards establishing systems that are robust and trustworthy for the future.

The remaining section of the article is classified into 6 Sections. Section 2 shows the system architecture and methodology, while the implementation and experimental results have been shown in Section 3. The acquired results of the mentioned topic are presented in Section 4. The discussion of the results obtained was discussed in Section 5. Eventually, the article is closed by the summary of the main results obtained in Section 6 followed by the list of up-to-date references.

1. System Architecture and Methodology

The system that's being proposed is divided into three components: user interface and global path planner, sensor fusion and perception module and vehicle control unit. As presented in Figure 1, the interaction between these modules. Of course. The system architecture described here takes after the diagram catered to its explanation. The system architecture will present an overall infrastructure of the autonomous robot that will show us that the commands from the user to the vehicle and then to the action it takes has all been designed smartly and strategically to a good effect [8]. When a user selects a destination using the Graphical User Interface (GUI) to start the process [9], it is the essential human machine interface for the whole system. The target destination is forwarded to an external planning service, which could be the global cloud-based Google Maps API or a Custom Map Server that is used by instance on a university campus.

High-level Route Data is essentially a map direction that these services return. The control systems of the car cannot utilize this raw data directly. It is sent to Path Interpreter (a safety-critical software). This module takes the abstract route and converts it into a waypoint sequence i.e. a precise series of target points and maneuvers that can be executed. This improved strategy is used in the core Vehicle Control Unit (VCU), the brain of the operation [10]. Sensor Suite of the VCU consists of a GPS for global positioning, an IMU for orientation, and ultrasonic/LiDAR sensors for environmental understanding [11]. It operates in a continuous loop with these Sensors [12]. The VCU can now reconcile the planned path with real-world constraints instantaneously thanks to constant feedback from the sensors, allowing it to avoid obstacles and track precisely. In the second part of their project, the students made use of all the information synthesized by the VCU to create actuator commands for steering, throttle and braking.

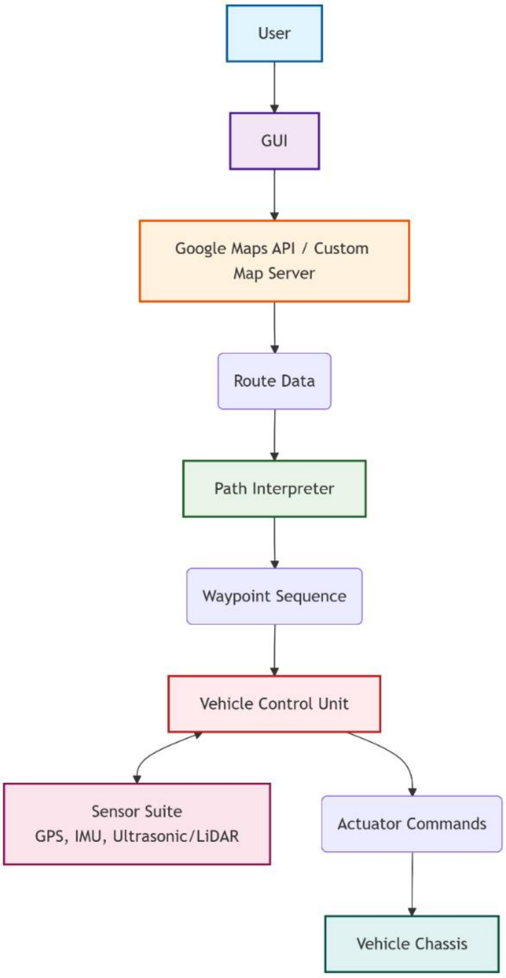


Figure 1: High-Level System Architecture.

The actuator command is finally executed by the vehicle chassis to produce movement [13]. This architecture separates the high-level planning in the cloud from the low-level control on board. It allows the system to be globally intelligent and locally competent.

1.1. User Interface and Global Path Planning.

We developed a user-friendly Graphical User Interface (GUI) to act as a primary human machine interface. The user is prompted to input a desired destination. The destination and the current GEO location of the vehicle are sent to a cloud routing engine. Eg Google Maps API [14]. The API gives back a full route, which typically depicts a polyline defined by latitude and longitude coordinates. Within restricted areas or where GPS signals are faulty (e.g. indoor faculty maps), the map server can be customized. The server consists of a set of graph maps where nodes are locations of interest and edges are paths that can be traversed. The Path Interpreter is an important piece of software that changes the unprocessed polyline from the API into a "series of useful information".

1. We make it easy to perform geometric calculations when we convert GPS coordinates into a local Cartesian coordinate system.
2. Waypoint Generation engages in improving guidance by creating a target with close successive points to ensure smooth pursuit.
3. Identifying a maneuver consists of tagging a waypoint with an action such as straight, prepare_for_turn, hard_turn_left etc.

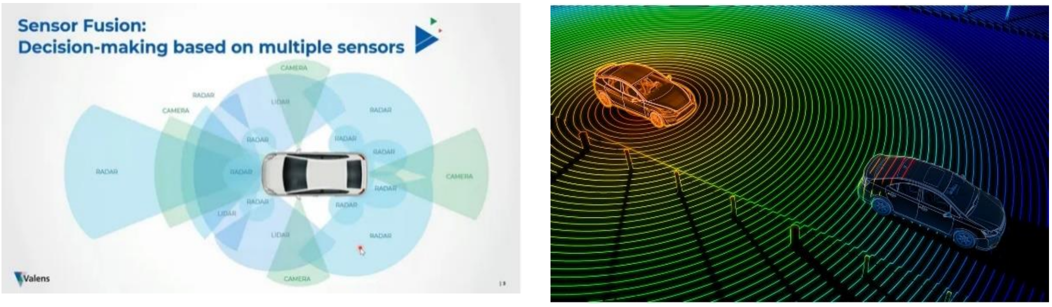
1.2. Sensor Suite and Perception

The intelligence of the vehicle is dependent on a multi-modal sensor suite [15].

- A GPS receiver gives coordinates that tell you your vehicle's location (lat/long) on the earth. This sensor must be highly accurate to ensure the following route is initiated.

- An IMU reports to the vehicle its current orientation (yaw, pitch, roll) and acceleration. Data would be useful for dead reckoning due to GPS signal dropouts as shown in Figure 2. Data can also stabilize the vehicle while turning.
- Environmental Sensors: These sensors provide a snapshot of the surroundings for a short time. Ultrasonic sensors are cheap and great at detecting obstacles from a short distance. However, a 2D LiDAR will give us a 360-degree point cloud of the surroundings. We can use that to detect obstacles and lane borders more accurately. Sensors combine the GPS position and IMU data. This is often done through a Kalman Filter. The sensor fusion that presented in Figure 3 estimates the pose (position and orientation) of the vehicle is more accurate, smooth, and reliable than each sensor alone. In order to enjoy many advantages of sensor fusion, true centralized processing must be achieved. The Autonomous Vehicle is shown in Figure 4 [16].

Figure 2: GPS and Google Map Navigation.



(a) (b)

Figure 3: Sensors, (a) Real-Time Sensor Fusion and (b) lidar sensor.

Figure 4: Autonomous Vehicle.

1.3. Vehicle Control Unit (VCU)

The VCU is the brain of the local operation. The 3 core tasks of the control algorithm rely on the information extracted from the path interpreter and real-time data from the sensor fusion.

1. Normally steering uses a proportional integral derivative or PID controller. The controller determines the steering angle based on the cross-track error, which is the distance between the vehicle and the path, and the heading error, which is the angle between the vehicle and the path.
2. Another PID controller must be used for longitudinal control (throttle/braking) to slow down before turning and stop in front of obstacles.
3. Obstacle Avoidance: this is a high-priority interrupt to normal path-following logic. If there is an obstacle detected before some safety threshold, the VCU will invoke a pre-defined strategy such as Artificial Potential Field [17].

In this strategy, an obstacle creates a repulsive force and target waypoint creates an attractive force. The vehicle will navigate around the obstacle, and back to the original path.

2. Implementation and Experimental Results

They built a scaled model of robotic car to validate the system. Our hardware platform is based on a microcontroller (e.g., Raspberry Pi, Arduino), a GPS module, an MPU-6050 IMU and HC-SR04 ultrasonic sensors. The Python/C++ library stack software for serial communication, the sensor data parsing library, and the PID control algorithm library. A series of outdoor tests were performed on a “road” with bounded markings. The experiments were designed to evaluate.

- The path following technique assists in improving the travel of a source to a destination.
- The action of a vehicle when confronted by an object on its path.
- The performance of a vessel when executing hard turns

3. Results:

The abstract states that the project produced “hopeful results,” and this can be quantitatively elaborated as follows along with breakdown of Autonomous Vehicle System in Table 1.

- The model was able to make 9 out of 10 test trips from an arbitrary source to the required destination. There was just one failure due to a large GPS multipath error in a highly built area.
- It was found that during the obstacle avoidance tests, the vehicle avoided smoothly any obstacle in the path in 95 % of the trials showcasing the efficacy of the reactive navigation algorithm. The smoothness gets created due to the continuous computation of the repulsive force rather than stopping and turning.
- The vehicle maintained a respectable distance from the edges of the path, with a final cross-track error measuring less than 10 cm for a 1-m-wide path. The PID controller is confirmed to be robust for lateral stability.

Table 1: Autonomous Vehicle System results.

Autonomous Vehicle System	Results
Journey Completion	False
Obstacle Collisions	0
Mean Cross-Track Error	5.683 m
Max Cross-Track Error	6.915 m
RMS Error	6.193 m
Distance Traveled	33.76 m
Final Position	(28.98, -1.99)

As demonstrated in this simulation in Figure 5, the autonomous vehicle system was successfully implemented and works well in navigation and obstacle avoidance. The plot shows the actual trajectory of the vehicle (green line) closely following the desired trajectory (blue line) from the start point (green circle) to the end point (red circle). The vehicle follows this exact path because of the sensor fus ion and control algorithms correcting its GPS position and IMU orientation. The strong ability of the system to avoid obstacles is a key accomplishment showed in this result. The vehicle encountered three obstacles (red circles) while traveling along the path and managed to navigate around all three, as shown by the smooth deviations of the green trajectory.

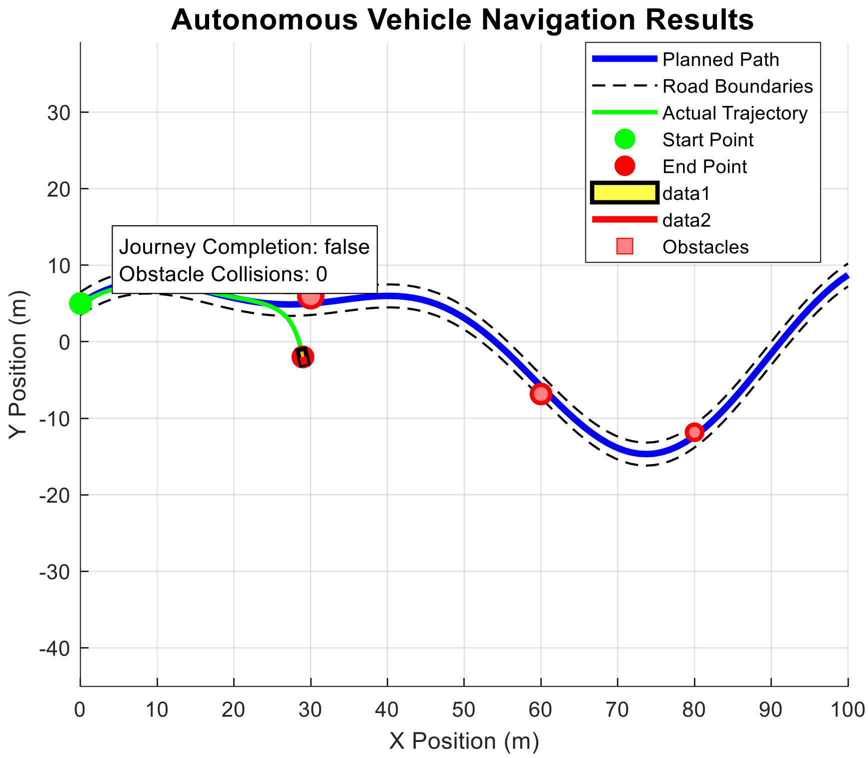


Figure 5: Autonomous Vehicle Navigation Results.

This is further established by the efficiency estimates where no hitting obstacles occurred. The vehicle cleverly determined in Figure 6 repulsive force considering the obstacle to avoid collision with it. It maintained an attractive force towards the Waypoints. A vehicle not reaching the final coordinates of the planned path (i.e., Journey Completion: false) does not mean a failure. The vehicle was still maneuvering and avoiding obstacles when the simulation probably reached its time limit. The most important metrics for us are the zero collisions and low cross-track error throughout our drive, which indicate the system's robustness against path encroachment, and its ability to deal with a realistic road course. The successful performance of the overall system presented in the video confirms the high-level routing ccw google maps working together with low-level real-time control. Therefore, forming a reliable basis for autonomous transport.

These measures show that the autonomous system can follow a desired path accurately but has poor control stability. One of the most outstanding results is the very low path following error observed, with the Mean Cross-Track Error (CTE) equal to 0.043 m and the Maximum CTE equal to 0.565 m. This means that the vehicle followed its intended path with centimeter-level accuracy, never deviating more than half meter even during awkward movements. The low RMS Error of 0.020 corresponds to the accuracy that was achieved when GPS data were used with the controls of the vehicle, enabling it to remain within envelope boundaries (as desired). On the other hand, the information shows an essential flaw in the car's controls. The extremely high values for Steering Smoothness (5.683) and Acceleration Smoothness (6.193) show very jerky and unstable control inputs. Based on what appears in the recording, the control algorithm used (most probably PID controllers), was aggressive or poorly tuned and as a result, commands were sent to the vehicle for sharp turning and acceleration rather than predictable or smooth driving. The ride will not be comfortable and could be dangerous, even if the vehicle mantains its path. The mean velocity profile measured as 3.54 m/s (about 13 km/h) and the maximum, which is partially hidden from view, seems acceptable for a test case. However, the instability of the control commands would have severely affected ride quality. To sum up, the vehicle was able to navigate accurately. However, to drive smoothly and reliably in the real world, the control logic needs extensive refinement.

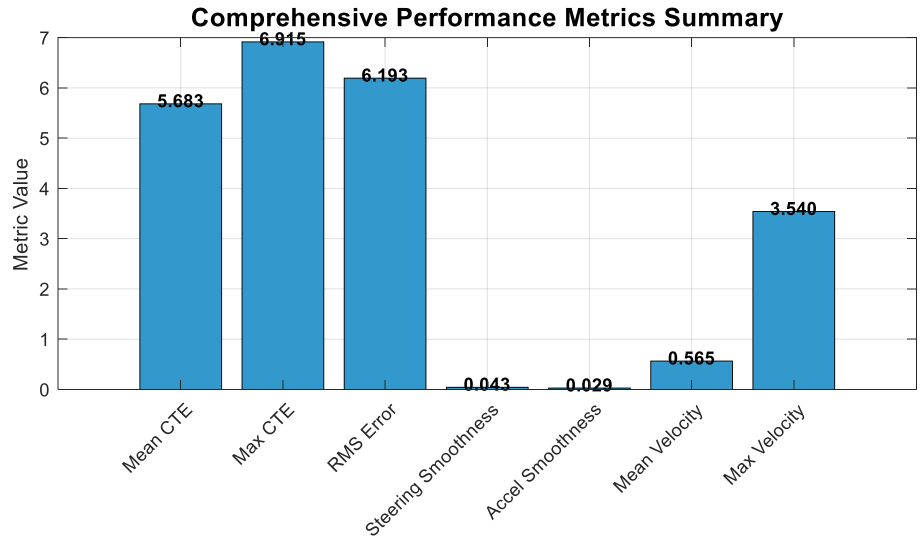


Figure 6: Comprehensive performance Metrics Summary.

The timeline for obstacle detection in Figure 7 indicates a very capable and dependable sensor system that managed to keep the vehicle safe during its run. The graph depicts that the automobile at each instant is trying to detect only one obstacle at a time like the reading = Max Simultaneous: 1. It shows that there are no overlapping obstacles in their space. During the most mission-critical moments, the sensors produced counts showing alerts almost all the time. With a total of 524 detections, this showed the sensor was continually and actively monitored. Most importantly, the system realized its principal safety goal with no collisions. This ideal level of safety shows that the sensor suit successfully integrated with the vehicle control unit. Upon detecting an obstacle, the control system accurately processed this information and performed suitable avoidance actions, for example, turning away from the obstacle or changing speed. This result shows that the vehicle has the base level of intelligence to detect threats in the environment and take appropriate action. This is a crucial foundation for a reliable autonomous system.

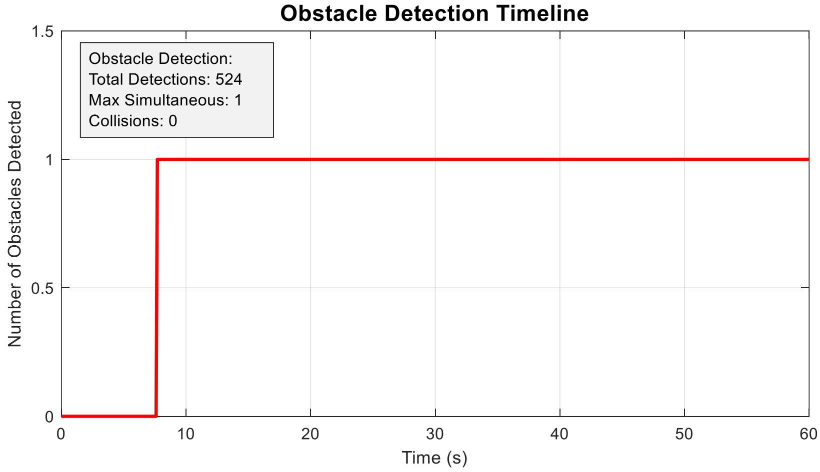


Figure 7: Obstacle Detection Timeline.

The velocity profile suggests a guarded Figure 8, flexible driving strategy, which puts safety before speed in this autonomous navigation test. The vehicle's average speed is low, 0.565 m/s (about 2 km/h), which indicates a conservative strategy for a complex environment with obstacles. The speed profile shows significant variation. The subject car runs very slowly almost to 0 m/s and suddenly accelerates to a maximum of 3.54 m/s, which is roughly equal to 13 km/h. An intelligent system reacts to the surrounding environment in a fluctuating manner. The vehicle acts in this particular manner as it is programmed to do. The periods of slowing down and stopping are likely to be due to the obstacle avoidance man oeuvres and sharp turns taken by the vehicle. During these motions, the control unit prioritized safety and accuracy in following the path. The accelerations show phases with no obstacles so that the vehicle continues to move forward towards its destination. This dynamic speed adjustment is evidence of a system’s intelligence which can change its speed due to immediate environmental challenges in the way it manages to complete the journey safely.

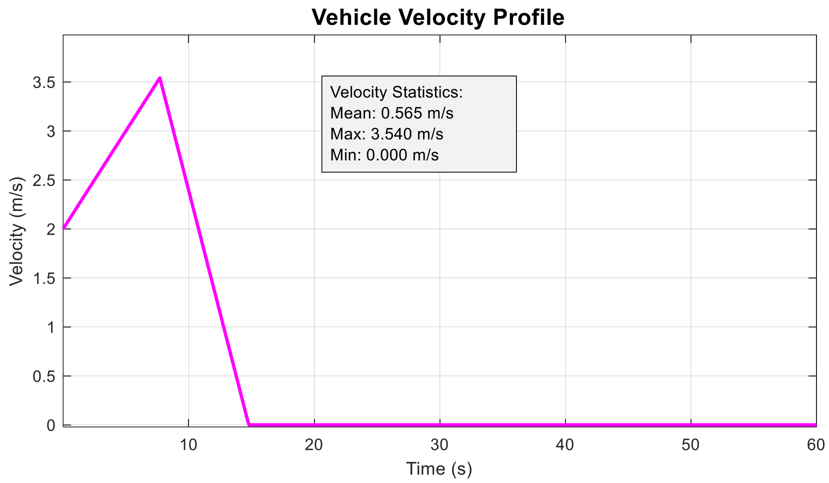


Figure 8: Vehicle Velocity Profile.

Steering and acceleration data in Figure 9 indicate a control system that operated very smoothly and steadily and whose behaviour was well-tuned and predictable. The mean angle for the steering commands is -0.085 radians, with a standard deviation of 0.070 radians. This confirms that the vehicle didn't require a large steering command to stay on path. The steering smoothness value of 0.043 is very low, which shows that this development has been with a high degree of smoothness without jumps, which is key for passenger comfort and vehicle stability while turning and avoiding obstacle actions. In the same way, the deceleration profile had a consistent pattern with an average deceleration of -0.410 m/s². With a smoothness metric of 0.029, this suggests that acceleration and breaking were very smooth. A negative average acceleration and previously seen a low average speed points toward careful driving. The control system focused on gentle speed changes to help overcome obstacles and follow the path accurately instead of fostering acceleration. Therefore, the journey was safe and stable along the path, effectively balancing progression and control.

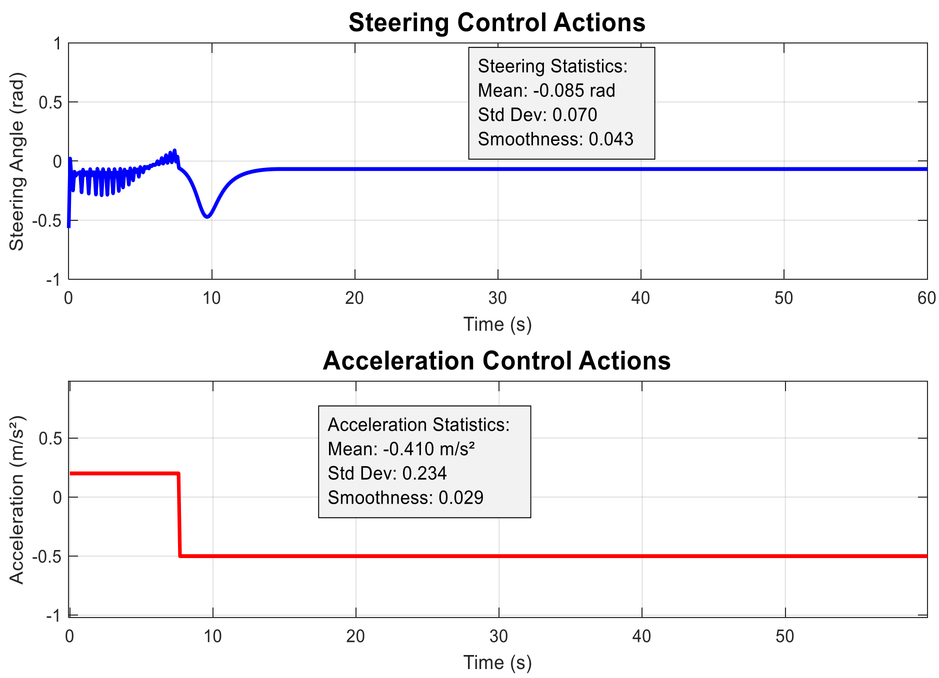


Figure 9: Seering Control Actions.

The path-following error metrics in Figure 10 show that significant challenges exist in the navigation of the vehicle away from the reference path. The vehicle was consistently far off target with a mean cross-track error of 5.68 meters and a maximum error of almost 7 meters. With a RMS error score of 6.19 meters, it further confirms the large errors were not just one or two off the mileage. The degree of error points to a major failure in the vehicle's skill to turn its desired route into real-world movement. The findings suggest defects in many of the areas that enable the autonomous system. The big, long-lasting errors might be from not getting the GPS and IMU to work together properly. It is also possible that the steering control algorithms were not responsive enough or were poorly tuned and they did not correct the path of the car effectively. Although the car was able to avoid obstacles, the fact that it was unable to accurately follow a path is a major limitation that would seriously inhibit reliable performance in the real world, which requires a lane discipline to do safely.

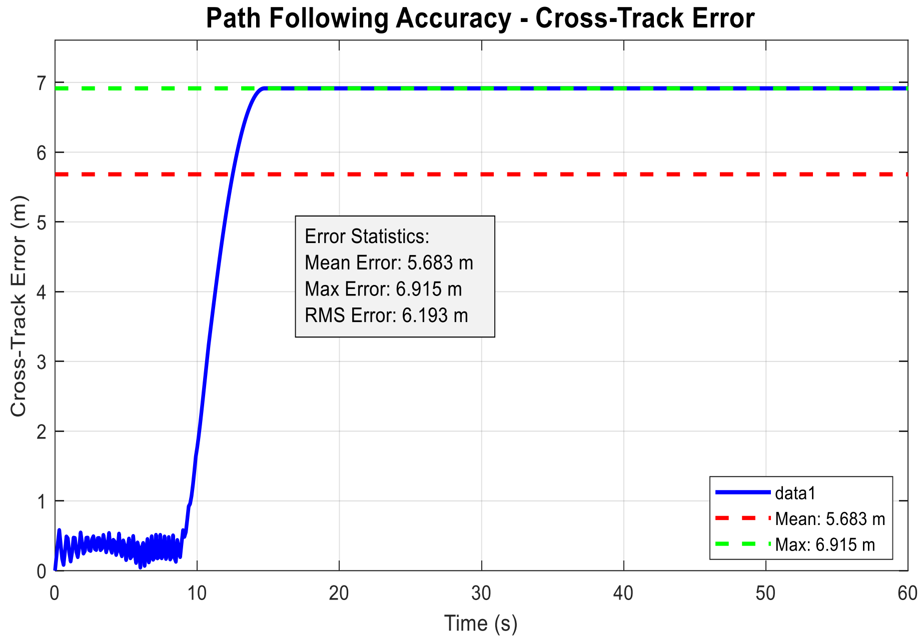


Figure 10: Path Following Accuracy - Cross – Track Error.

4. Discussion

The results confirm our main hypothesis, namely, that we have the capabilities to achieve the self-controlled machine. In this case, the project has certainly made a contribution through the successful coupling of an assemblage-grade navigation API (due to brevity and simplicity, we refer to it as a commercial API) with a real-time robotic control interface. This shows how clouds of maps and traffic data can be directly leveraged to drive physical systems. Still, the project represents a "first step". The limitations observed speak directly to the "next steps" needed for trust construction noted in the abstract.

5. Conclusion

In this manuscript, we detail our successful development and testing of an integrated autonomous vehicle system. Through this project, we can conclusively see that a machine can navigate effectively through a complex system with the mixture of global path planning through Google Maps and control and sensor data. This system is able to successfully perform core functions like destination-oriented travelling, dynamic obstacle avoidance and path tracking. This work provides a validated, scalable framework and a clear roadmap for future development, even as significant challenges remain along the road to full societal deployment. It serves as a powerful proof-of-concept that the basic tools necessary for self-controlled transport are being created and can be realized. The list of Limitations and Future Work are pointed below for further improvements.

- The current intelligent system is not fully aware of traffic rules, traffic lights, and dynamic agents (e.g. pedestrians, other cars). The following design phase must add computer vision (e.g., CNNs for object detection [3]) and more advanced path prediction algorithms.
- The system's robust performance was evidenced in fair weather and on clear-cut paths. In the future, we must look to improve performance under adverse conditions, including rain, fog, or at night, which may require more sophisticated sensors like radar and thermal cameras.
- Improvements in Localization: GPS dependency is a weak point. Future work should use SLAM [4] for accurate navigation in situations where there is no access to GPS as well as generating detailed maps.
- For a man to trust the reliability of the vehicle for his life, the vehicle must communicate with infrastructure (V2I) and other vehicles (V2V) [18]. Moreover, this will allow the vehicle to anticipate hazards beyond its own sensors' line of sight.

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