

Path Planning for Autonomous Vehicles with Dynamic Lane Mapping and Obstacle Avoidance

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Abstract: Path planning is at the core of autonomous driving capabilities, and obstacle avoidance is a fundamental part of autonomous vehicles as it has a great effect on passenger safety. One of the challenges of path planning is building an accurate map that responds to changes in the drivable area. In this paper, we present a novel path planning model with static and moving obstacle avoidance capabilities, LiDAR-based localization, and dynamic lane mapping according to road width. We describe our cost-based map building approach and show the vehicle trajectory model. Then, we evaluate our model by performing a simulation test as well as a real life demo, in which the proposed model proves to be effective at maneuvering around static road obstacles, as well as avoiding collisions with moving obstacles such as in pedestrian crossing scenarios.

1 INTRODUCTION

Road traffic injuries kill approximately 1.35 million people each year (WHO, 2020). Among the primary risk factors for road traffic deaths are speeding, distracted driving and driving under the influence, all preventable human errors (WHO, 2020). Autonomous driving features have the power to alert the driver of surrounding dangers and potentially fatal errors. Fully autonomous driving systems have to be aware of the vehicle's surroundings with high accuracy, and need to be able to plan ahead the motion of the vehicle in a way that does not impose any danger on surrounding pedestrians or traffic, while maintaining some level of driving comfort inside the vehicle by reducing sudden acceleration or changes of direction of the vehicle.

Path planning is the means by which autonomous vehicles plan ahead their movements and navigate through the environment. There are multiple challenges in planning an autonomous vehicle's path through a dynamic environment:

1. Building an offline coordinate-based map that will provide a basis for the vehicle's real-world position and its planned trajectory.
2. Localizing the vehicle's current position on the map, and planning a short-term path through these points. There can be multiple candidate points for the vehicle's next step. The best candidate must

be decided based on the positions of the obstacles (e.g. traffic and pedestrians) detected by the vehicle's sensing modules.

3. Finding the best heading and acceleration for the vehicle to ensure a safe path possibly also taking comfortability into account (favouring smoother paths with less sudden acceleration).

Grid-based approaches are commonly used for the offline map, representing the drivable environment as a set of grid cells (called waypoints) with fixed positions.

Acquiring accurate information about the vehicle's position is essential for path generation. GPS-based approaches may not provide the needed accuracy for autonomous navigation. Another approach is to use a pre-generated point cloud map stored on the vehicle. A point cloud map is a set of 3D points mapping the environment, usually recorded from live LiDAR data.

In the path finding step, given that a map of the environment exists and we know the current position of the vehicle on the map, we are interested in generating a plan of the ideal path for vehicle over the next few seconds. This plan should be in the same domain as the environment map (meaning that we are not concerned with the vehicle's exact trajectory yet, only its next positions on the map).

A cost function provides a way to numerically represent the likeliness that any given selection in the ve-

hicle's path is the most ideal one. In the case of grid-based maps they can be used to assign a cost value to each node in the grid. A shortest path algorithm can then take into account these costs in order to find a path of least cumulative cost. Cost functions must take into account the chance of collision that is introduced by taking a given path. A cost function should never favor a path that puts the vehicle into a collision trajectory. Cost functions may also consider the comfortability of a given path based on factors such as the frequency of lane switches (Boroujeni et al., 2017), or the acceleration or jerk in the generated path (Elbanihawi et al., 2015).

The vehicle trajectory step involves transforming the motion plan from the environment map domain into real-world physical coordinates, and creating a trajectory plan that steers the vehicle along the nodes of the generated path. In some grid-based approaches, cubic spline interpolation is used to convert the grid path into an continuous curve that can be traced by the vehicle (Francis et al., 2018) (Lemos et al., 2016). Other approaches aim to model specific maneuvers such as lane changes using polynomial curves (Zhang et al., 2013).

In this paper, we propose a novel path planning system for autonomous vehicles. The proposed system takes into consideration the position of surrounding static obstacles (such as road irregularities) and the position and trajectory of moving obstacles (such as road traffic and pedestrians), and generates a path and trajectory plan for the vehicle valid for the next few seconds that safely maneuvers the vehicle around the surrounding obstacles. The system should be able to accurately localize the vehicle within a pre-mapped environment and follow a mapped path. Waypoints will be dynamically expanded into a set of lane waypoints by acquiring information about the road width at each waypoint from drivable area information.

The remaining sections of the paper are organized as follows. In Section 2 we review the most pertaining research in literature. In Section 3, we discuss the implementation details of our path planning architecture, and in Section 4 we discuss the performance evaluation. Finally, Section 5 offers concluding remarks.

2 RELATED WORK

Grid-based map building approaches have been extensively researched and applied. In grid-based approaches, the environment is approximated by a set of 2D or 3D points. This allows each point to be assigned a cost based on the surrounding obstacles. A shortest path finding algorithm can be applied to de-

termine the best route through these points. (Francis et al., 2018) (Boroujeni et al., 2017) This allows lanes in the road to be each represented by a grid point, where moving from one point to another on the lateral axis represents a lane change. However, in this approach, lane positions are fixed and have to be determined when building the map. This is non-ideal in environments that do not have defined lanes (such as in a university campus), since the vehicle will be bound to fixed positions regardless of the available drivable area and the vehicle dimensions.

Non-grid based approaches for path planning have also been investigated. One such approach is discrete optimization, where finite set paths are generated and the best path is selected at each planning step (Hu et al., 2018) (Montemerlo et al., 2008). In the paper by Hu et al. (Hu et al., 2018), the center line of the road is constructed by interpolating the waypoint map, and in each planning step, a set of paths are constructed by varying the amount of deviation from the center position of the road. Paths which intersect static and moving obstacles are eliminated. These approaches may be more computationally expensive as the candidate paths have to be generated at each computation step.

The use of potential fields has been researched as a non-grid based approach for path planning in vehicles and ground robots (Ahmed et al., 2015) (Daily and Bevlly, 2008). In this approach, the environment is modeled as a vector field where the planning goal is modeled as an attraction force, and obstacles are modeled as repulsion forces. The selected path for the vehicle is the path following the gradient of the field. This provides a flexible and dynamic model for the environment since the vehicle is not bound to any set of discrete paths. However, this approach may fail to correctly determine the best path in some cases, due to encountering local minima in the vector field.

3 SYSTEM ARCHITECTURE

In this paper, we present our waypoint-based path planning architecture with LiDAR-based localization, dynamic lane mapping and static and moving obstacle avoidance. We utilize road width information at each waypoint from real-time drivable area data to dynamically map the positions of lanes according to a defined lane width. Information about the position of static obstacles and the position and velocity of moving obstacles are integrated to provide a cost for each lane waypoint. Finally, we use the pure pursuit algorithm (Coulter, 1992) for trajectory planning.

The project implementation is built on ROS

(Robot Operating System), a framework designed to assist the development of robot software. It provides a communication protocol that the modules of a robot platform can use to establish communication channels between each other. These channels are based on a publisher/subscriber model.

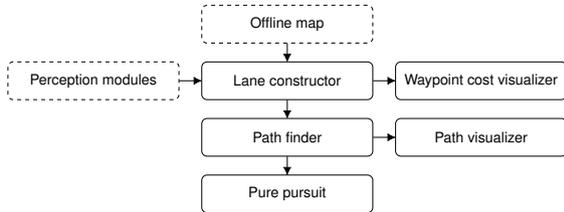


Figure 1: Overview of system architecture.

Our proposed system is made of three main components as shown in Figure 1: the lane constructor, path finder, and pure pursuit modules, which will be explained in this section. The offline map component represents the list of waypoints. The perception modules use raw sensor data to sense parameters such as drivable area and the positions and measured velocities of obstacles. These modules are outside the scope of this paper, but we assume that we can obtain these parameters.

3.1 Offline Map

The offline map is a directed graph of GPS coordinates called waypoints. Since the waypoints are connected, they imply a heading. Waypoints are used to mark a section of the road. Since the lateral position of the vehicle does not depend on the lateral position of the waypoint on the road, they should not be used to mark lanes. Each waypoint is also associated with the maximum driving speed value for this section of the road.

Waypoints are loaded from the offline map progressively with a set look-ahead distance starting from the current vehicle position.

A point cloud map of the environment is saved locally, and Normal Distributions Transform (NDT) matching (Biber and Strasser, 2003) is used to determine the vehicle's position and velocity within the map from live LiDAR data.

3.2 Lane Construction

Since waypoints do not carry information about the road width or lane positions (and not all roads have clearly defined lanes), we need to be able to construct our own lane positions for the vehicle.

From drivable area data, we can know the width of the road at any waypoint position. Since waypoints have a heading, we can construct a line at the waypoint position normal to the waypoint heading. This line will intersect with the boundaries of the drivable area of the road. The road width is then calculated as the distance between the leftmost and rightmost points of intersection along the constructed line, shown in Figure 2 as W_L and W_R respectively.

The road width is used to determine a reasonable number of lanes at the position of each waypoint. Given the left and right distances from the waypoint to the road boundaries W_L and W_R respectively, and the desired lane width L , we can calculate the number of lanes N as:

$$N = \left\lceil \frac{W_L + W_R}{L} \right\rceil \quad (1)$$

Lanes are centered within the drivable area of the road, and are not separated by any distance. The new waypoints are positioned at the center of each constructed lane, as shown in Figure 3. These waypoints are passed to the next step, the path finder module.

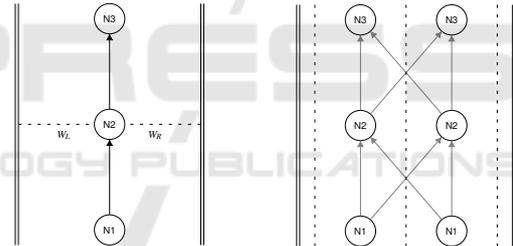


Figure 2: Calculation of road width W at the waypoint N_2 .

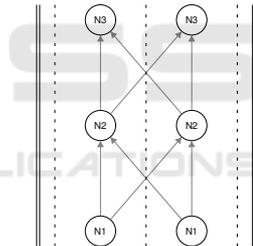


Figure 3: Constructed lane waypoints.

3.3 Assigning Costs

A cost value in the interval $[0, 1]$ is assigned to each lane waypoint. These values are primarily assigned according to the proximity of nearby obstacles. A waypoint having a cost of 1 is considered to be impassable.

The cost of a waypoint can be interpreted as the measured risk of driving through it. A waypoint having a cost closer to 1 is likely to be in close vicinity of one or more obstacles. As a safety measure, the speed of the vehicle is linked to the waypoint cost: as the cost approaches 1, the driving speed approaches 0. Thus, if V_T is the target driving speed, V_W is the maximum speed set to the current waypoint, and C is the waypoint cost, the target speed can be expressed as:

$$V_T = V_W * (1 - C) \quad (2)$$

3.3.1 Static Obstacles

Static obstacles are modeled as circular regions having a position and a radius. Lane waypoints are also assigned a circular region having a diameter equal to the lane width, as shown in Figure 4. If the obstacle region intersects the waypoint region, the waypoint is assigned a cost of 1.

Since the waypoint region covers the width of the lane, and practically the distance between consecutive waypoints will be very small, a lane that intersects an obstacle will always be blocked.

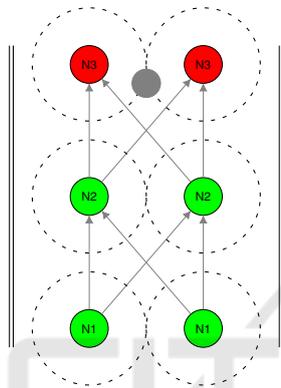


Figure 4: A static obstacle, shown as a solid gray circle, intersects the regions of the $N2$ lane waypoints.

3.3.2 Moving Obstacles

Moving obstacles are modeled as a single point in space having a velocity vector. Obstacles are expected to follow this vector at constant velocity. Changes in the velocity of an obstacle can only be accounted for at the next planning interval, after the velocity vector is updated.

To find the possibility of collision with a moving obstacle at a given waypoint, a velocity vector for each waypoint is defined to be a vector pointing in the same heading as the waypoint and having a magnitude equal to the current vehicle speed.

To determine for a given waypoint whether the chance of collision with a moving obstacle exists within a defined time frame, we obtain the parametric equations for the moving obstacle and the vehicle driving along the waypoint velocity vector. We are interested in finding two parameters t_{ob} and t_{wp} , the time parameters for the obstacle and waypoint equations respectively, that result in the equality of the position vectors of the vehicle and waypoint. A solvable system indicates that the two constructed straight lines intersect. Furthermore, if the magnitude in difference

between the two parameters t_{ob} and t_{wp} is within a defined range, this indicates that the obstacle and the vehicle will pass through the same point in space at nearly the same time. This range can depend on the physical size of the vehicle and the separation distance required.

This process is repeated for each waypoint and moving obstacle pair. A waypoint whose check fails with any of the detected moving obstacles (i.e. the difference in the parameters t_{ob} and t_{wp} is too small) is assigned a cost of 1.

3.3.3 Cost Smoothing

The techniques described so far can detect whether a waypoint is in direct contact with an obstacle, or in the path of a moving obstacle. In both cases, the waypoint should be completely blocked. Thus, we can only assign waypoints a cost of 0 or 1 depending on whether the waypoint intersects with an obstacle.

This can result in paths that are in very close contact to an obstacle when safer alternatives exist. For example, in Figure 5, the vehicle is initially driving in the leftmost lane, so it continues to drive in that lane until the last waypoint that is not in contact with the obstacle, and then makes a lane switch to the middle lane right before encountering the obstacle. All waypoints in the path have a cost of 0, so the vehicle moves at the maximum allowed speed. In this scenario, the selected path is unfavorable as it moves the vehicle dangerously close to an obstacle at possibly high speeds.

We can represent the costs in the grid of waypoints in Figure 5 by the following 2D matrix:

$$W = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \end{bmatrix} \quad (3)$$

In order to achieve a cost gradient, a discrete 2D convolution is used. This kernel is used in the simulation:

$$K = \begin{bmatrix} 0.1 & 0.5 & 0.1 \\ 0.2 & 1.0 & 0.2 \\ 0.2 & 0.5 & 0.2 \\ 0.1 & 0.3 & 0.1 \\ 0.0 & 0.2 & 0.0 \\ 0.0 & 0.1 & 0.0 \\ 0.0 & 0.1 & 0.0 \end{bmatrix} \quad (4)$$

K_{22} is the center of the kernel. For edge cells, zero padding is used. All values of the output matrix are

bound to $[0, 1]$. The kernel values are selected to introduce a cost to the waypoints leading to the obstacle, the first waypoint ahead of the obstacle, and the lanes adjacent to the blocked lane. Changing these values effectively changes the obstacle avoidance profile of the vehicle. For example, increasing the values will cause the vehicle to decelerate more sharply when approaching an obstacle, favoring safety versus comfortability. The matrix size determines the distance from the obstacle at which the vehicle starts the avoidance maneuver.

Figure 6 shows the generated path after using the costs from the $W * K$ matrix on the waypoint grid.

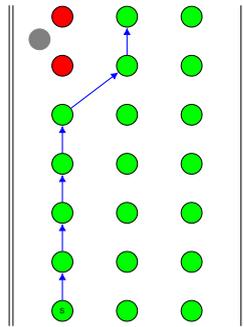


Figure 5: Generated path in a 3-lane road with a static obstacle, without cost smoothing.

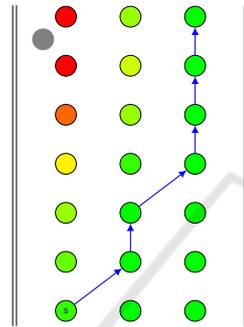


Figure 6: Generated path after cost smoothing.

3.4 Path Finding

The best path in a lane waypoint grid is modeled as a shortest path problem. As shown in Figure 3, lane waypoints can be modeled as a directed graph where each node connects to the next node in the same lane, and the next nodes in the left and right lanes signifying a lane change.

The D* lite algorithm (Koenig and Likhachev, 2002) is used to find the shortest path between the current waypoint and any of the goal waypoints. Goal waypoints are the final set of lane waypoints in the loaded section of the offline map.

To decrease the number of lane changes, a constant value is added to the traversal cost when making a lane change. As a result, the planner will not make a lane change unless the difference between the cost of the current lane waypoint and the target lane waypoint is greater than a certain constant value.

3.5 Vehicle Trajectory

An implementation of the pure pursuit algorithm (Coulter, 1992) is used to steer the vehicle along the

generated path. Pure pursuit finds a curvature that moves the vehicle from its current position to a goal position. The goal position is calculated by constructing a circle with a defined search radius centered around the vehicle position. Then, a straight line is constructed between each two consecutive waypoints. The intersection point between the search circle and the first line that intersects it is set to be the goal waypoint.

The search radius is typically a function of the current vehicle speed. The changes in vehicle heading become steeper as the search radius decreases. For purposes of the simulation, it is set to the vehicle speed multiplied by 2.5, as this value was found in testing to result in smooth steering curves while not deviating too far away from the waypoint plan during turns.

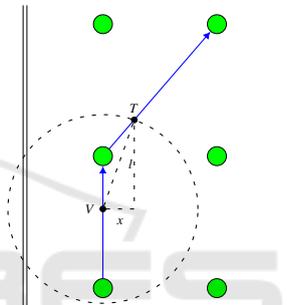


Figure 7: Pure pursuit target construction.

The goal is to find the radius of the circle that joins the vehicle position V with the target point T , such that the chord length from V to T is equal to the search radius l . The radius can be expressed as: (Coulter, 1992)

$$r = \frac{l^2}{2x} \tag{5}$$

The arc joining V and T with radius r is the final intended trajectory of the vehicle.

4 PERFORMANCE EVALUATION

4.1 Simulation Experiments

The LGSVL Simulator provides an environment for testing autonomous driving functionalities in a 3D environment. The simulator integrates with the ROS platform, providing a vehicle model which can be controlled using ROS commands, and simulates sensors typically used in autonomous driving such as camera, LiDAR and GPS.

The simulator was used to test the static and moving obstacle avoidance capabilities of the proposed system by two means: Simulating a static obstacle ahead of the vehicle position in the same driving lane, and simulating a moving obstacle moving laterally in front of the vehicle (i.e. a person crossing the road). The distance from the obstacle to the vehicle and the deceleration of the vehicle are evaluated.

The test route is a straight 4-lane road section 556 meters long, with a single turn. The target speed for the test was set to 25 km/h. Higher speeds were not tested due to technical constraints of the simulation environment.

4.1.1 Results of the Simulation Test

During the test, the vehicle managed to stay within a safe distance from all introduced obstacles.

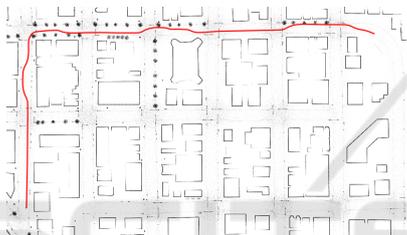


Figure 8: Vehicle path within a point cloud map of the environment.

In the static obstacle tests, the vehicle initiated a lane change approximately 14 meters away from the obstacle. Figure 9 shows the maneuver made by the vehicle as the obstacle comes into the look-ahead distance of the planner. The vehicle changes to the first lane from the third lane, and continues driving in the third lane until encountering the next obstacle. The reason for the double lane change is due to the configuration of the convolution matrix described in Section 3.3.3, which assigns a cost to the lanes adjacent to the obstacle. Since the vehicle does not drive into the higher cost region (shown as the yellow and orange waypoints in Figure 9), the vehicle's driving speed stays constant at 25 km/h for the duration of the lane change.



Figure 9: Vehicle trajectory at different frames during static obstacle avoidance, showing the waypoint plan (blue line) and the pure pursuit trajectory (white arc).

The forward and lateral acceleration (shown in Figure 10) of the vehicle was recorded during the maneuver. The lateral acceleration reaches a peak value of 2.88 m/s^2 ($0.29g$) when initiating the lane change, and then reaches 1.84 m/s^2 ($0.19g$) in the opposite direction as the vehicle returns to its forward position. To ensure the lateral stability of the vehicle in lane changes the lateral acceleration should not be above $0.4g$ (Sun and Wang, 2020), which the proposed model does not exceed.

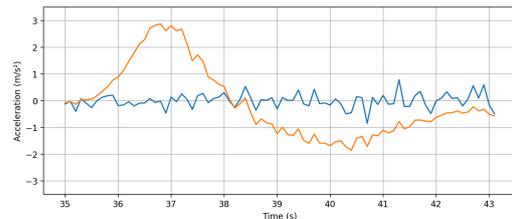


Figure 10: Graph of the forward (blue) and lateral (orange) acceleration of the vehicle during static obstacle avoidance.

In the moving obstacle tests, a moving obstacle models a pedestrian crossing the road. Since the direction of movement of the obstacle is lateral to the road, all lanes are blocked (shown in Figure 11), and the vehicle needs to stop completely. The vehicle reaches a full stop 10 meters away from the obstacle's line of motion, and then begins to accelerate after the obstacle passes the vehicle's lane.

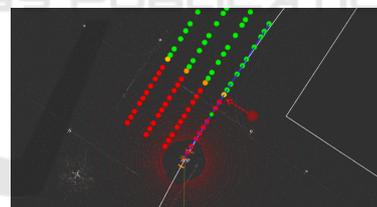


Figure 11: Waypoint map during a moving obstacle test.

Figure 12 shows the acceleration of the vehicle as it encounters the moving obstacle, while the vehicle is stopped, and as it continues its route.

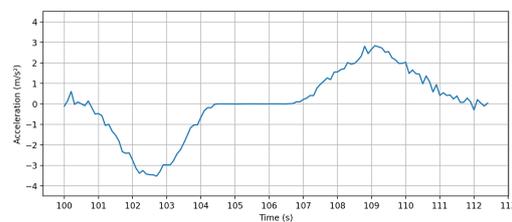


Figure 12: Graph of the forward acceleration of the vehicle during moving obstacle avoidance.

4.2 Field Test

A live demo of the path planning modules was performed using a modified electric golf cart. Data processing and vehicle control is done locally on a computer running the ROS platform. The steering column and throttle actuators of the vehicle are electrically connected to an Arduino controller, which receives commands from a ROS node running on the vehicle computer through a serial connection.

The steering angle is set to the curvature of the pure pursuit arc described in Section 3.5. The throttle value is initially set to 0, and a change to the throttle value is calculated every interval which is proportional to the difference between the target and current velocities. A full stop of the vehicle is performed by setting the throttle value to 0. Engine braking assists in stopping the vehicle in a distance that is sufficiently short for purposes of the demo.

4.2.1 Mapping

A point cloud map of the testing area was created using LiDAR mapping, and waypoints were mapped tracing the testing route. The waypoints were placed 1 meter apart. The route is approximately 175 meters in length. The route includes a straight section, then a short slightly uphill climb, followed by a series of sharp turns. The target speed for the route was set to 7 km/h as a safety precaution, due to the multiple turns in the path and to minimize the risk of collision. The route has a single lane due to space constraints of the testing area.

4.2.2 Results of the Field Test

Two trials were performed: A first trial where the vehicle makes a full route with no obstacles, and a second trial with a simulated pedestrian crossing event once the vehicle reaches the target speed. The vehicle's position, heading and velocity data was recorded for the duration of the two runs.

In the first run, the vehicle managed to maneuver around the sharp corners, however it had problems maintaining its heading in the straight sections, as shown in Figure 13. This was found to be due to inaccuracies related to the steering controller of the vehicle for small steering angles (up to 10 degrees).

Figure 14 shows the vehicle speed for the duration of the first trial. The vehicle takes 10 seconds to accelerate to the target speed of 7 km/h. The speed slightly fluctuates between 6 and 8 km/h (1 km/h deviation) for several seconds following accelerating. This can be resolved by further tuning of the throttle

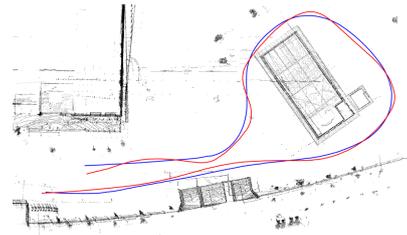
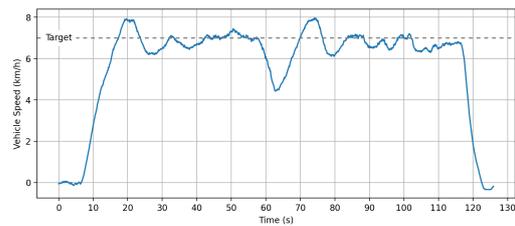
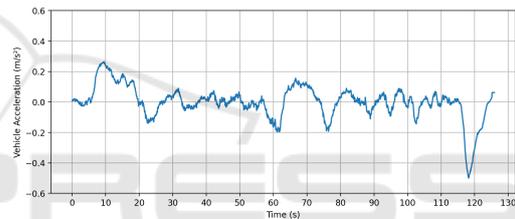


Figure 13: Actual vehicle path of the test route (red line) versus the waypoint map (blue line) within a point cloud map of the first trial.



(a) Vehicle speed



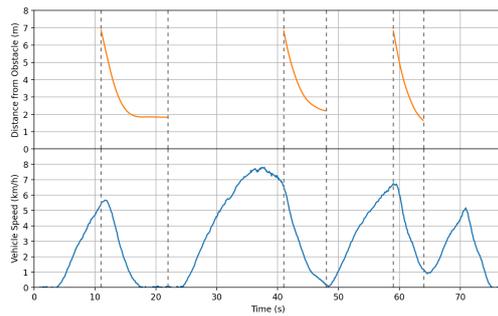
(b) Vehicle acceleration

Figure 14: Vehicle speed and acceleration graphs for the first trial (no obstacles).

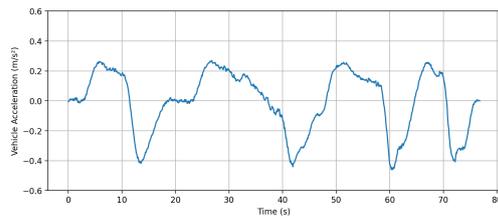
controller of the vehicle. The speed drops at approximately $t = 58$ s when the vehicle reaches the uphill part of the route, then the vehicle slowly accelerates back to its target speed.

The acceleration of the vehicle reaches a maximum of 0.25 m/s^2 when accelerating from a stopping position to the target speed, and a minimum of -0.5 m/s^2 when stopping at the end of the route.

For the second trial, three pedestrian crossing events were initiated at $t = 11$ s, 41 s, and 59 s during the test. The speed and acceleration of the vehicle (shown in Figure 15) were recorded for the duration of the trial. In each event, a simulated obstacle was placed 7 meters ahead of the current position in the path of the vehicle and removed several seconds later. The distance between the vehicle and the obstacle position was recorded, shown in Figure 15 (b). The vehicle starts to decelerate as soon as the obstacle is detected and manages to stop an average of about 3 meters away of the obstacle in the three events.



(a) Distance between vehicle and obstacle in meters plotted against the current vehicle speed in km/h



(b) Vehicle acceleration

Figure 15: Vehicle speed and acceleration graphs for the second trial (obstacle testing).

5 CONCLUSIONS

In this paper, we present a novel path planning approach with static and moving obstacle avoidance, and dynamic lane mapping from road width calculated from real-time drivable area data. We evaluate our approach by means of a simulation test, as well as a real world demo by implementing and running the model on a vehicle modified to allow autonomous driving functionalities.

The proposed model was tested on speeds of up to 25 km/h. Thus, further testing needs to be performed in order to verify the validity of the model with higher speeds. A limitation in the approach is that the convolution matrix described in Section 3.3.3 is static, so the separation distance between the vehicle and surrounding obstacles does not change depending on the driving speed. Such limitation would pose safety risks when driving at high speeds. Therefore, the convolution approach needs to be adjusted with high speed driving taken into consideration. Moreover, the proposed approach needs to be improved to find the intersection between obstacles and waypoints, as it may not cover cases where an obstacle is positioned in certain positions of the road outside the waypoint region but still posing a risk to the vehicle. Finally, a confirmation window for the drivable area needs to be implemented in order to account for short variations in drivable area width and the number of lane waypoints.

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