Research on the Path Following Control of Intelligent Vehicle with Method of Added Planning Layer

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Abstract. Aimed at intelligent vehicles operating in complex driving environment, the paper is described on the basis that the reference trajectory has been determined. According to the vehicle running state and obstacle information, the vehicle's running track can be adjusted in real time to solve the path planning problem and according to the re-planned reference track, the following control is carried out in the paper to avoid obstacles. Firstly, a point mass model is established which ignores the car body size. Secondly, on the premise that the size of obstacles is smaller than the car body size, according to the obstacle information obtained by the sensor and the established point mass model, the obstacle avoidance penalty function is established, then the objective function of the path planner is established. Finally, two working conditions: single obstacle and two obstacles, are set up to simulate and verify the designed obstacle avoidance trajectory following system. By observing the distance between the actual track and obstacles under different simulated speeds, varied range of front wheel angle and centre of mass side deflection angle, different range of angular velocity of lateral swing and lateral acceleration to verify whether the vehicles can successfully avoid obstacles with different speed and numbers of obstacles in order to maintain good driving stability in the process. Simulation results show that, under the control of the path following system added to the planning layer, intelligent vehicles in a complex driving environment can autonomously plan their paths, avoid obstacles, follow the path, and ensure good driving stability meanwhile.

1. Introduction
The key technologies of intelligent vehicle \cite{1-5} mainly include the following three parts: (1) Technology of environmental awareness: Intelligent vehicles identify the surroundings through on-board cameras, radars and other electronic devices and obtain such information. Environmental awareness technology is a very important research topic in the field of intelligent vehicle research. Nowadays, sensors and electronic devices commonly used in cars are mainly included as: on-board cameras, GPS positioning system, million-meter-wave radar and so on. (2) Technology of decision-making: In the driving process of intelligent vehicles, the driving operation behaviour of intelligent vehicles can be completed by processing the road and surrounding environment information obtained by the system. At present, the commonly used decision-making technologies mainly include PID control, optimal control, fuzzy control, robust control and so on. (3) Technology of path planning: When the intelligent vehicle encounters obstacles or moves laterally, it needs to plan an optimal feasible path for it by using pre-designed rules or strategies. Path planning plays an important role in motion control technology. (4) Technology of motion control: The planned driving path is used to
determine the driving behaviour of the car through effective control strategies or methods. It plays a
decisive role in judging the performance of the driving system of intelligent vehicles.

When the intelligent car driving on the road, due to the complexity and changeability of the driving
environment, the following control of a given reference trajectory has some limitations. For example,
when there are obstacles in the given reference path, intelligent vehicles cannot well follow the path,
therefore, the trajectory needs to be re-planned to avoid obstacles and then the reference trajectory
needs to be followed again. According to the principle of model predictive control, a new control
system combining path planning and path following is formed by combining the vehicle's current
driving state and obstacle information. Among them, path planning belongs to the upper controller, its
main function is to adjust the trajectory of intelligent vehicles in real time according to the vehicle
running state, obstacles and reference track information, and solve the problem of path planning. Path
following belongs to the lower controller, its main function is to follow and control the path according
to the planned path, so as to avoid obstacles. The work of this part of the path planning is based on the
reference trajectory has been determined, belongs to the local planning.

2. Path Following Control System with Added Planning Layer

The path following control system added to the planning layer is shown in figure 1. According to the
model predictive control principle, the path planner processes the received obstacle information,
reference track information and vehicle status information, then output the new trajectory information.
The path following controller receives the path information generated by the path planner, combined
with the current vehicle status, the front wheel Angle can be output, so as to avoid obstacles and
continue to go back to the original reference track.

![Path following control system with added planning layer](image)

**Figure 1.** Path following control system with the added planning layer

3. Design of the Path Planning Controller

The path planner is designed in the part. The main task of the path planner is to solve the trajectory
that can meet constraints and avoid obstacles according to the obtained obstacle information, track
information and the current vehicle state, the planned local trajectory should be as close as possible to
the reference trajectory. Therefore, the objective function should include the deviation between the
planned trajectory and the reference trajectory, the control quantity and the obstacle avoidance
function.

3.1. Model of Point Mass

Due to the large computation amount of path planning algorithm itself, therefore, a lower precision
model is needed to reduce the computational burden. The lower precision model is adopted in the path
planning layer and the higher model is adopted in the path following control layer, not only the control
performance is good, but also the calculation speed has been greatly improved. Therefore, the point
mass model that ignores the body size is adopted in the path planning layer, as shown in figure 2.

The model is represented as follows:
The vehicle's dynamic constraints are:
\[ |a_y| \leq \mu g \tag{2} \]

Equation (1) can be written as follows:
\[ \dot{\xi}(t) = f(\xi(t), u(t)) \tag{3} \]

The state amount is defined as: \( \xi = [y \ x \ \phi \ y \ x]^T \), the control amount is defined as \( u = \delta \).

3.2. Objective Function of Path Planner

In the process of path following, intelligent vehicles acquire and process obstacle information through sensors, the information from the sensors is scattered, this chapter focuses on obstacle avoidance trajectory planning and path following control, think less about the size of the obstacles. Therefore, in order to prevent the vehicle from passing through the obstacles, it is assumed that the size of the obstacles is smaller than the body size, as is shown in figure 3.

**Figure 2.** Model of point mass  
**Figure 3.** Penalty function for obstacle avoidance

The obstacle avoidance penalty function mainly depends on the distance between the front of the vehicle and the obstacle, at time \( t \), sensors on intelligent vehicles can obtain information about obstacles, the centre of mass coordinates of the vehicle are \( (X_k, Y_k) \), the position of the obstacle can be represented by \( n \) discrete points, where the position coordinate of the point \( j \) is: \( p_{x,j} = (P_{X,j}, P_{Y,j}) \), \( j = 1, 2, 3 \ldots n \), convert these points to the body coordinate system, the conversion relationship is:

\[
P_{x,k,t} = (P_{X,j} - X_{k,j})\cos\phi_{k,j} + (P_{Y,j} - Y_{k,j})\sin\phi_{k,j}
\]
\[
P_{y,k,t} = (P_{Y,j} - Y_{k,j})\cos\phi_{k,j} - (P_{X,j} - X_{k,j})\sin\phi_{k,j}
\]

At time \( t \), the obstacle avoidance penalty function can be expressed as:
\[
J_{\text{obs}} = K_{\text{obs}}V_{k,j}d_{\min,k,t} + \varepsilon
\]

Among them, \( K_{\text{obs}} \) is collision weight function. When the weight coefficient increases, the result of path planning becomes conservative and the deviation between the planned trajectory and the reference trajectory also increases, \( V_{k,t} = u_{k,t}^2 + v_{k,t}^2 \), \( d_{\min,k,t} \) represents the minimum distance from the vehicle to all obstacle points, among them, the \( d_{k,t,j} \) is:
In conclusion, the objective function of the path planner can be expressed as:

\[
\min \sum_{i=1}^{N_u} \| y(k+i) - y_r(k+i) \|^2 Q + \sum_{i=0}^{N_c-1} \| u(k+i) \|^2 R + J_{\text{obr}}
\]

Among them, the first term represents the deviation between the planned trajectory and the reference trajectory, reflecting the control requirements for the deviation; the second item reflects the control requirements of the input quantity; the third item represents the function of obstacle avoidance.

4. Simulation Verification to Path Following System with Added Planning Layer

By designing two working conditions -- single obstacle and two obstacles to simulate and verify the designed obstacle avoidance trajectory following system, the reference path selection is shown in figure 4. The simulation speed is set as \( v=10 \text{m/s} \), \( v=15 \text{m/s} \), \( v=20 \text{m/s} \), road adhesion coefficient is \( \mu=0.8 \), the parameters of the controller are shown in table 1.

![Figure 4. The Reference track](image)

| name of parameter | Path planning controller | Path following controller |
|-------------------|--------------------------|---------------------------|
| Predicted time domain \( N_p \) | 15 | 20 |
| Controlled time domain \( N_c \) | 2 | 10 |
| Sampling time \( T/s \) | 0.05 | 0.01 |

4.1. Single Obstacle Condition

The position of the obstacle is (-2.5, 15), the size is 4m*1m, the simulation results of intelligent vehicles with different speeds is shown from figure 5 to figure 7. The red rectangles represent obstacles, figure 5 shows the trajectory of intelligent vehicles when they avoid obstacles at the speed of 10m/s, figure 6 is the track diagram of the intelligent vehicle when it avoids obstacles at the speed of 15m/s, figure 7 is the trajectory map of intelligent vehicle when it avoids obstacles at a speed of 20m/s.
The distance between the actual track and the obstacle also increases, as seen from the figure 5 to figure 7, with the increase of speed. Vehicles began to avoid obstacles and ensure safety. And the curvature of the vehicle's trajectory becomes smaller, the higher the speed the earlier the vehicle to avoid obstacles, which is consistent with practical driving habits. Finally, the vehicle can return to the reference track after completing the obstacle avoidance. The intelligent vehicle with the controller can successfully complete autonomous path planning, avoid obstacles and follow the path with different speeds.

The overall variation range of the front wheel angle is from -5deg to 5deg, which is always within the constraint range, and the variation is stable, which can ensure the smooth implementation of the actuator, according to figure 8. The lateral deviation angle of the centre of mass and the lateral angular velocity of swing are both important parameters to measure the stability of a vehicle. From figure 9 and figure 10, the centroid side-slip Angle under different speed of the overall change in the range of -1.4 deg ~ 1.4 deg, far below the scope of centre of mass of side-slip Angle constraint set, and stable, the change of the transverse swing angular velocity amplitude as the speed increases, but the overall
range for -14 deg/s ~ 17 deg/s, it indicates that the vehicle has no dangerous situation such as side-slip
or rollover in the process of driving. As can be seen from figure 11, the range of lateral acceleration is
0.4 m/s² ~ 0.5 m/s², which is far below the constraint range, it indicates that the vehicle has good driving
stability.

4.2. Condition with Two Obstacle
The positions of the two obstacles with different sizes are (-2.5, 15), (0, 140), the dimensions are
4m*1m and 4m*0.5m respectively. The simulation results of intelligent vehicles with different speeds
is shown from figure 12 to figure 14. The red rectangles representing obstacles, among them, figure
10.1 shows the trajectory of intelligent vehicles when they avoid obstacles at the speed of 10 m/s,
figure 10.2 is the track diagram of the intelligent vehicle when it avoids obstacles at the speed of
15 m/s, figure 10.3 is the trajectory map of intelligent vehicle when it avoids obstacles at a speed of
20 m/s.

![Figure 12. Simulation result of a single obstacle with speed v=10m/s](image1)

![Figure 13. Simulation result of a single obstacle with speed v=15m/s](image2)

![Figure 14. Simulation result of a single obstacle with speed v=20m/s](image3)

The distance between the actual track and the obstacle also increases, as seen from the figure 12 to
figure 14, with the increase of speed. Vehicles began to avoid obstacles and ensure safety. And the
curvature of the vehicle's trajectory becomes smaller, this is because the higher the speed, the earlier
the vehicle to avoid obstacles, which is consistent with practical driving habits, finally, the vehicle can
return to the reference track after completing the obstacle avoidance. Therefore, at different speeds,
intelligent vehicles can successfully complete autonomous path planning, avoid obstacles and follow
the path.

![Figure 15. Simulation results of the front wheel steer angle at different speeds](image4)

![Figure 16. Simulation results of side slip angle at different speeds](image5)
The overall variation range of the front wheel angle is from -4deg to 4deg, which is always within the constraint range, and the variation is stable, which can ensure the smooth implementation of the actuator, according to figure 15. The lateral deviation Angle of the centre of mass and the lateral angular velocity of swing are both important parameters to measure the stability of a vehicle. From figure 16 and figure 17, the centroid side-slip Angle under different speed of the overall change in the range of -1.7 deg ~ 1.5 deg, far below the scope of centre of mass of side-slip Angle constraint set, and stable, the change of the transverse swing angular velocity amplitude as the speed increases, but the overall range for - 20 deg/s ~ 16 deg/s, it indicates that the vehicle has no dangerous situation such as side-slip or rollover in the process of driving. As can be seen from figure 18, the range of lateral acceleration is -0.4m/s²~0.5m/s², which is far below the constraint range, it indicates that the vehicle has good driving stability.

5. Conclusion
When the intelligent car driving on the road, due to the complexity and changeability of the driving environment, the following control of a given reference trajectory has some limitations. According to the vehicle running state and obstacle information, the vehicle's running track can be adjusted in real time, to solve the path planning problem, and according to the re-planned reference track, the following control is carried out to avoid obstacles in the paper. Firstly, a point mass model is established which ignores the car body size. Secondly, on the premise that the size of obstacles is smaller than the car body size, according to the obstacle information obtained by the sensor and the established point mass model, the obstacle avoidance penalty function is established, then the objective function of the path planner is established. Finally, two working conditions -- single obstacle and two obstacles -- are set up to simulate and verify the designed obstacle avoidance trajectory following system.

6. Acknowledgments
Thanks for the found of NSFC (51505071) and the support of Northeastern University.

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