Leader Following and Multiple Obstacle Avoidance of Autonomous Vehicle with Steering-Wheel and Driving-Wheel Torques Using Path Planning and Model Predictive Control

Hamed Kouhi[a*], Esmaeil Salahshoor[b],

[1] Faculty of Mechanical Engineering, University of Guilan, Rasht, Iran (Corresponding author to provide)
[2] Department of Mechanical Engineering, Islamic Azad University of Izeh, Izeh, Iran,

ABSTRACT

This paper studies the autonomous vehicle leader following and collision avoidance problem. In this paper, like as a real vehicle, geometric dimensions, mass and moment of inertia are considered for the vehicle; steering-wheel and driving-wheel torques are the two control inputs. The nonlinear dynamics equation of the vehicle is derived. At first, an algorithm is proposed for changing the direction of the vehicle to follow the leader, then the suitable path for multiple obstacle avoidance and leader following is proposed, and then a nonlinear model predictive controller (MPC) is used to follow the reference trajectory. The desired trajectory is designed according to the elastic band method which is a powerful method for obstacle avoidance and leader following. The performances of the closed-loop system are illustrated through simulations. During the simulation the vehicle first changes its direction and then follows the leader without colliding with obstacles. Although the vehicle is inertial and non-holonomic in behavior, the simulations show that the two path planning methods with MPC scheme works well. For the future works the authors aim to solve the problem with moving obstacles.

KEYWORDS

Autonomous vehicle, Multiple Obstacle Avoidance, Nonholonomic Constraint, Trajectory Planning, Nonlinear Model Predictive Control.

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[*] Corresponding Author: Email: hamed.koohi@guilan.ac.ir

1. Introduction

In recent years control of autonomous vehicles has gained extra attention [1, 2]. Leader following is an important task in robot control. To prevent the vehicle from colliding with an obstacle, a collision avoidance algorithm must be proposed.

Currently, because of the high potential of MPC, it is used in the automotive industry. A survey of MPC development in automotive applications was carried out [3]. In [4], a new trajectory planning based on elastic band is proposed, which is combined with driving intention for vehicle obstacle avoidance. In [5, 6] methods have been proposed to pass two-wheeled robots through obstacles, but four-wheeled vehicles are far more difficult to control than two-wheeled robots. The issue of autonomous vehicles passing a single obstacle has been discussed a lot (as in [7, 8]), but investigating the movement of autonomous vehicles through several obstacles requires more research. limited data about multiple obstacles avoidance and leader following is available in the literature. But in this paper, the issue of following a leader in a two-dimensional environment that requires more general maneuvers by the vehicle is investigated.

The most important contributions of this paper are:

- Two algorithms will be proposed, depending on the environmental conditions, the vehicle will use these two algorithms so that it can even move backwards if necessary.
- In addition to path planning, a new trajectory planning technique will be proposed.
- The goal is to reduce the number of optimization decision variables in the trajectory planning to make optimization easier.
- The proposed trajectory planning, and control methods are flexible against the number of obstacles.

2. Control problem statement

The autonomous vehicle is shown in figure 1, and its mass and moment of inertia are considered. By determining state variables:

$$x_1 = x_c, x_2 = \dot{x}_c, x_3 = y_c, x_4 = \dot{y}_c, \\ x_5 = \theta, x_6 = \dot{\theta}, x_7 = v, x_8 = \Phi. \tag{1}$$

the state space equations are [1]

$$\dot{\mathbf{X}} = \mathbf{f}\left(\mathbf{X}, \boldsymbol{\tau}\right) \\ \mathbf{X} = \begin{bmatrix} x_1 & x_2 & \cdots & x_8 \end{bmatrix}^T, \ \boldsymbol{\tau} = \begin{bmatrix} \tau_1 & \tau_2 \end{bmatrix}^T \tag{2}$$

where, θ is the body yaw angle, Φ is steering angle, v is the front wheel speed, F_1 is robot driving force, and control inputs are chosen as $\dot{\Phi} = \tau_1$ and $F_1 = \tau_2$.

In figure 1, a leader is shown with a position x_L, y_L to be followed by a vehicle despite some obstacles. The desired trajectory is shown as small points. x_d, y_d shows the position of each point on the trajectory. The desired trajectory will be achieved by an optimization problem.

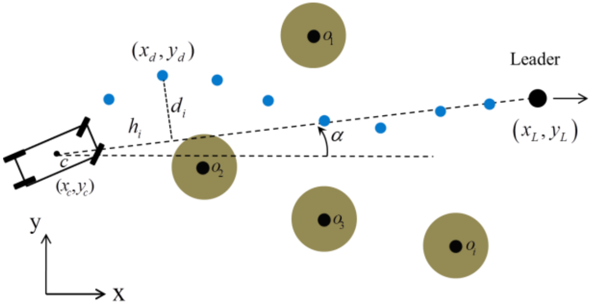

Figure 1. Optimal trajectory for leader following and obstacle avoidance.

First, $\mathbf{D} = \left[d_1, d_2, \ldots, d_{n_d} \right]$ is defined as decision variables in the optimization problem. The aim is to find the best vector $\mathbf{D}$ for leader following and obstacle avoidance. The proposed cost function that should be minimized to give the optimal trajectory is

$$J_{Traj} = \sum_{i=1}^{n_d} \sum_{j=1}^{n_o} J_{i,j} + w_1 \sum_{k=2}^{n_d} (d_k - d_{k-1})^2 \\ + w_2 \left((x_{d,1} - x_{c,1})^2 + (y_{d,1} - y_{c,1})^2 \right) \\ + w_3 \left((x_{d,n_d} - x_L)^2 + (y_{d,n_d} - y_L)^2 \right) \tag{3}$$

where, the penalty function $J_{i,j}$ is for obstacles collision avoidance. Finally, the following optimization problem gives us the optimal trajectory

$$\mathbf{D}_{optimal} = \min_{\mathbf{D}} J_{Traj} \tag{4}$$

Figure 2 shows the robot direction $\mathbf{e}_{car}$ relative to the direction of the leader relative position $\mathbf{e}_L$. And we have

$$\gamma = \cos^{-1}(\mathbf{e}_{car}.\mathbf{e}_L). \tag{5}$$

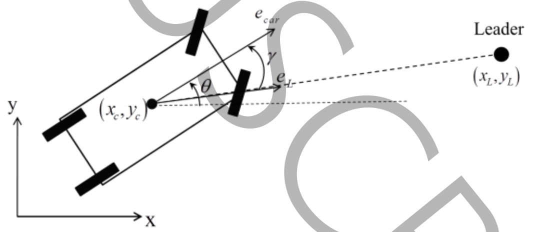

Figure 2. The vehicle direction relative to the direction of leader's relative position.

According to the value of γ, two special control algorithms are employed which are described here. Control logic for $\gamma > \gamma_0$: In this case (e.g., $\gamma_0 = 80^0$), before following the leader, the robot's direction should be placed in a suitable direction to follow the leader easily. The cost function to be minimized is as follows

$$J_c=\sum_{i=1}^{N_p}\left[\left(\gamma_{cd,i}^2\right)+w_4\left(\dot{x}_{c,i}^2+\dot{y}_{c,i}^2\right)\right]+\sum_{i=1}^{N_c}\left[w_5\tau_{1,i}^2+w_6\tau_{2,i}^2\right] \tag{6}$$

Control logic for $\gamma\le\gamma_0$: In this case, the direction of the robot is suitable for following the leader. The proposed cost function for this case is as follows

$$\begin{aligned}J_c=\sum_{i=1}^{N_p}\Bigg[\left(\left(x_{d,i}-x_{c,i}\right)^2+\left(y_{d,i}-y_{c,i}\right)^2\right)\\ w_7\left(\left(V_{d,i}(1)-\dot{x}_{c,i}\right)^2+\left(V_{d,i}(2)-\dot{y}_{c,i}\right)^2\right)\Bigg]+\sum_{i=1}^{N_c}\left[w_8\tau_{1,i}^2+w_9\tau_{2,i}^2\right]\end{aligned} \tag{7}$$

where, $\mathbf{V}_{d,i}$ is the desired velocity vector obtained from the trajectory planning.

Finally, the following optimization problem must be solved to obtain optimal control inputs:

$$\boldsymbol{\tau}_{optimal}=\min_{\tau} J_c \tag{8}$$

Subject to

$$\begin{aligned}&\mathbf{X}(i+1)=\mathbf{f}(\mathbf{X}(i),\boldsymbol{\tau})dt+\mathbf{X}(i)\\ &\left|\tau_1\right|\le\tau_{1,\max},\ \left|\tau_2\right|\le\tau_{2,\max},\ \left|\Phi\right|\le\Phi_{\max}.\end{aligned} \tag{9}$$

where, $\tau_{1,\max}$ and $\tau_{2,\max}$ are the maximum torques and $\Phi_{\max}$ is the maximum steering angle.

3. Results and Discussion

In this section, a leader with initial position [0 0] and velocity [3,0]m/s are considered. In Figure 3, the trajectory of the autonomous vehicle, which is moving among the three obstacles, is shown. The vehicle tracks the virtual leader by using the proposed trajectory planning and NMPC scheme. In the beginning, the first control logic is activated to change the direction of the vehicle in the suitable direction. After changing the vehicle direction, the second control law is activated for leader following and obstacle avoidance.

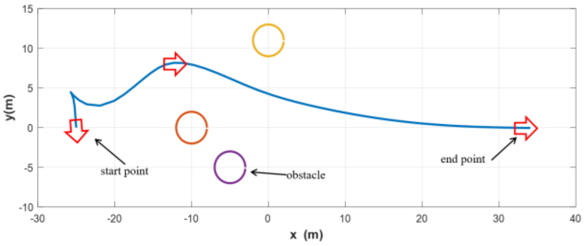

Figure 3. The trajectory of the autonomous vehicle moving among the multiple obstacles.

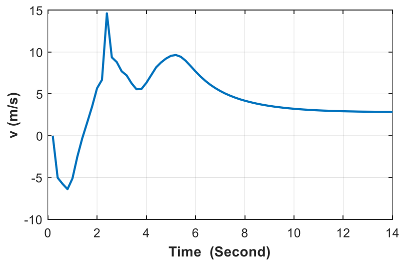

Figure 4. The vehicle's velocity time response.

4. Conclusions

In addition to the dynamics model, steering limitation, actuator saturation and nonholonomic constraints make the control problem difficult. For changing the direction of the robot to follow the leader, an MPC-based control algorithm is proposed. The simulation results show that the direction-changing algorithm can be used in practice. A new trajectory planning method is proposed for leader following and to make sure that the collision is avoided. The proposed method first used trajectory planning and then used an MPC controller to follow the reference trajectory. Although physical constraints such as actuator saturation exist, the closed-loop system has suitable performance and leader following with obstacles avoidance is well done.

5. References

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