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Obstacle Avoidance Path Planning Algorithm Based on Model Predictive Control

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Abstract: In recent years, as image processing and control technology have been studied extensively, autonomous vehicle becomes an active research area. For autonomous driving, it is essential to generate a safe obstacle avoidance path considering the surrounding environments. In this paper, an algorithm based on real-time output constraints model predictive control (RCMPC) is devised for obstacle avoidance path planning in the high-speed driving situations. Four simulations were conducted to compare with the normal model predictive control (NMPC) algorithm. The MPC computation times were also compared to verify robustness of the algorithm in the high-speed driving situations. The ISO 2631-1 comfort level standard was used to quantify driver's comfort and to compare with the results. The results of the RCMPC resulted in faster computation times than that of the NMPC and showed a high comfort level scores.

Keywords: Model Predictive Control, Obstacle Avoidance, Path Planning, Comfort Level

1. INTRODUCTION

Recently, autonomous vehicle based on various technologies such as image processing, electronics, V2X communication, and control theory has been studied. Autonomous vehicle must avoid the obstacles on the global path and generate an optimal path so that vehicle can travel to the target point. Representative path planning algorithms include A* algorithm [1] and 3D-Potential field algorithm [2]. The A* algorithm has a disadvantage that it requires the whole path regeneration when host vehicle avoids the dynamic obstacle. On the other hand, the 3D-Potential field algorithm may not generate a path because of the local minima problem.

An algorithm of steering and braking control is essential in an obstacle avoidance system that is part of an active safety system. Recently, an algorithm for obstacle avoidance path planning using model predictive control (MPC) has been studied [3]. MPC is a control system that predicts outputs using vehicle model and optimizes the cost function. In this paper, the vehicle model is designed as a state space equation. A modified algorithm is devised to reduce the amount of computation times and to optimize the cost function by adjusting time varying constraints on the output values of the MPC [4]. The proposed algorithm can construct an active safety system that avoids the obstacle in real-time by using MPC under high-speed driving situations.

In Section 2, described the vehicle modeling and the proposed real-time output constraints model predictive control (RCMPC) algorithm. In Section 3, MATLAB simulations are implemented and compared both the normal model predictive control (NMPC) algorithm and the proposed RCMPC algorithm. Finally, Section 4 was consisted of conclusion.

2. MODEL PREDICTIVE CONTROL ALGORITHM

The purpose of the proposed algorithm is to move the vehicle quickly to the target point without collision. This section describes the vehicle model which is a state space equation and the model predictive control to construct an obstacle avoidance path planning algorithm. Also, real-time output constraints model predictive control is devised to improve the computation times and to generate a comfortable path.

2.1 Vehicle Model

The 2 degrees of freedom (DOF) bicycle model shown in Fig.1 is used for the model prediction in the MPC algorithm. To ensure the real-time performance, a linearized vehicle model is applied. The lateral velocity of the vehicle is constant and the slip angle is zero degree to simplified the tire model.

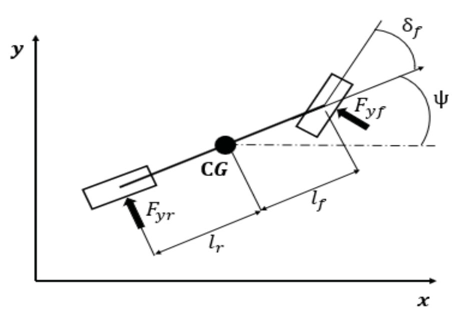


Fig. 1 2-DOF Bicycle Model.

In this paper, the model of the vehicle is represented by the state space equation (1)~(2) and equations are consisted of the velocities and positions. The state space equation's constant matrices are given in (3)~(4).

$$\dot{x} = Ax + Bu \tag{1}$$
$$y = Cx + Du \tag{2}$$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ T_s & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & T_s & 1 \end{bmatrix}, B = \begin{bmatrix} T_s & 0 \\ 0.5{T_s}^2 & 0 \\ 0 & T_s \\ 0 & 0.5{T_s}^2 \end{bmatrix} \tag{3}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

2.2 Model Predictive Control

After the state space equation of the vehicle is defined, the outputs which generate the driving path are derived through the model predictive controller as shown in the Fig 2. The reason for choosing MPC is that it is robust against time delays and has the advantage of being able to process multiple variables simultaneously. The purpose of the MPC is to solve the cost function and minimize the equation (5) when the current state is given. Also, it is possible to constraints on the inputs and outputs. Using the MPC, the predicted vehicle state information can be obtained. The predicted vehicle state information is combined with the control inputs to derive the accurate outputs.

$$\min_{u_0,\dots,u_{N-1}} \sum_{k=0}^{N-1}\left(\left\|y_{a,k} - y_{a,ref,k}\right\|_{Q_y}^2 + \left\|u_{a,k} - u_{a,ref,k}\right\|_{Q_u}^2\right) \tag{5}$$

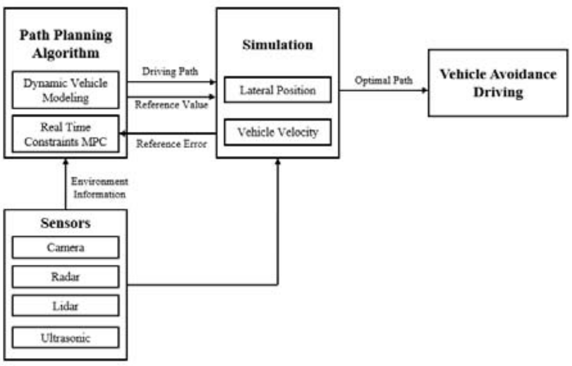


Fig. 2 Structure of path planning based on MPC.

In this paper, the value of the environmental sensors is assumed that accurately obtained and there is no error or disturbance. The outputs which are derived from the cost function generate a path and the outputs are returned to the model predictive controller via feedback control.

2.3 Real-Time Output Constraints MPC

A time varying output constraints box is proposed to generate an obstacle avoidance path in the high-speed driving situations. The output constraints box is achieved by measuring the direction of x and y distances between the host vehicle and the obstacle vehicle at each step. When the output constraints box is constructed, the size of the vehicle and the safety margin are considered as shown in Fig 3. Through this process, the non-convex problem is replaced with the convex problem by excluding the path that does not satisfy the constraints among the two paths. By excluding the one path, the calculation amount of MPC can be reduced in the process of solving the cost function. To construct the output constraints box, additional small preprocessing time is required. However, preprocessing time is considerably smaller than time to solve the non-convex problem. By applying the output constraints box, it is possible to real-time obstacle avoidance of the MPC. It can be said that proposed algorithm can operate more accurate in the high-speed driving situations.

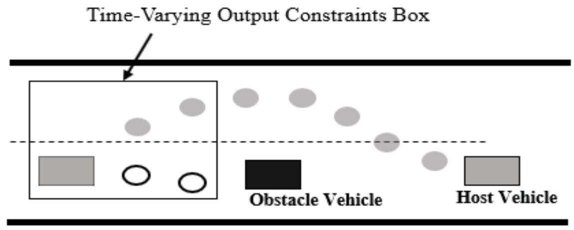


Fig. 3 Real-time output constraints MPC.

3. SIMULATION RESULTS

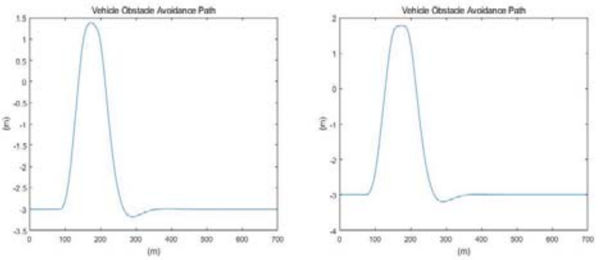
This section presents the simulation results of the proposed model predictive control algorithm. In order to evaluate and compare with the both algorithms, four cases of scenarios were considered. The first scenario was about a stationary obstacle vehicle. The remaining scenarios were about dynamic obstacle vehicles. Also, the ISO 2631-1 standard was considered for measuring the driver's comfortable level [5].

3.1 Simulation Environment

In our experimental environment, MATLAB simulation was performed with Intel® Core™ i7-4770 CPU @ 3.40GHz, 4 GB RAM. The environment of the road was straight 1km long and 6m width two-lane. The host vehicle model was European Van, and various size models were used for obstacle vehicles. Model predictive control's prediction horizon was fixed 15 steps, control horizon was 2 steps and sampling time was 0.25s.

3.2 The computation time of MPC

The NMPC algorithm and RCMPC are compared. The RCMPC algorithm finds the optimal solution of the cost function by adjusting real-time output constraints in every simulation step. Experiments were conducted to compare with the computation times of MPC in four scenarios and to evaluate the obstacle avoidance path of the proposed algorithm. As shown in the Fig 4, there was no significant difference in the avoidance path between the two algorithms. However, the performance of the proposed algorithm was superior in computation times. The following Table 1 shows each scenario result.



(a) (b)

Fig. 4 Obstacle avoidance path.
(a) Normal MPC (b) Real-time output constraints MPC

Table 1 The comparison of MPC operation time.
(1) stationary obstacle scenario and (2)~(4) dynamic obstacle scenarios.

	Scenario	NMPC	RCMPC
(1)	Stationary	0.01619s	0.01087s
(2)	Straight	0.01624s	0.01014s
(3)	Cut in	0.01931s	0.01251s
(4)	Cut out	0.01933s	0.01266s

3.3 Comfort Level

It is also important to generate a comfortable path when planning an obstacle vehicle avoidance path. When avoiding an obstacle vehicle, the host vehicle should follow the path which is close to the center line of the road. Also, the driver should avoid an obstacle in the most comfortable path. To evaluate the comfort level, the normal MPC algorithm and the proposed algorithm were compared and analyzed based on ISO 2631-1 standard, which details are given Table 2.

$$a_w = \sqrt{k_x^2 * a_{wx}^2 + k_y^2 * a_{wy}^2 + k_z^2 * a_{wz}^2} \qquad (6)$$

In this equation, a_{wx}, a_{wy}, a_{wz} are the acceleration on x, y, z direction respectively. k_x, k_y, k_z are multiplying factors and $k_x = 1.4, k_y = 1.4, k_z = 1$.

Table 2 Comfort level based on ISO 2631-1 standard.

Acceleration section	Consequence
$a_w < 0.315$	Comfortable
$0.315 < a_w < 0.63$	A little uncomfortable
$0.5 < a_w < 1$	Fairly uncomfortable
$0.8 < a_w < 1.6$	Uncomfortable
$1.25 < a_w < 2.5$	Very Uncomfortable
$a_w > 2.5$	Extremely uncomfortable

In the MATLAB simulation environment, comfort levels were obtained and scored. To evaluate quantitatively, the score of "Comfortable" was 10 points and "Extremely uncomfortable" was 0 point. The score was lowered by 2 points each section and the scores of all the simulation steps were averaged. The simulation results are shown in Table 3.

Table 3 The comparison of comfort level score.
(1) stationary obstacle and (2)~(4) dynamic obstacle situations.

	Scenario	NMPC	RCMPC
(1)	Stationary	6.67	7.22
(2)	Straight	7.28	8.13
(3)	Cut in	7.19	8.00
(4)	Cut out	8.05	9.19

4. CONCLUSION

In this paper, an algorithm to avoid the obstacle by using the MPC is proposed. In order to utilize the model predictive control algorithm in the high-speed driving situations, it is suggested to real-time output constraints MPC which is considering distance and velocity between host vehicle and obstacle vehicle. To evaluate the proposed algorithm, MATLAB simulations were conducted in four scenarios. In four scenarios, MPC computation times and driver's comfort level were compared which are indispensable indicators for future high-speed autonomous driving situations. The proposed algorithm resulted in comfortable obstacle avoidance path and demonstrated a 30 percent faster at the computation times. To represent the comfort level of the obstacle avoidance path, ISO 2631-1 standard was applied to proposed path planning algorithm. The simulation results showed that proposed algorithm can avoid the static and dynamic vehicles in the future high-speed autonomous driving situations.

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