Improvement of Trajectory Tracking Performance in Autonomous Collision Avoidance by Steering

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Abstract: This study discusses the autonomous obstacle avoidance system by combined control of braking and steering as an active safety technology to prevent accidents, focusing on how to consider the limitation of steering angular velocity of the automatic steering system in order to improve its effectiveness. A modification method of the desired steering angle profile is proposed and the validity of the proposed method is verified by numerical simulations and real car experiments. The results indicate that the proposed method improves the effectiveness of the autonomous collision avoidance system.

1. INTRODUCTION

In recent years, many kinds of active safety technologies have been developed to prevent accidents. Based on the fact that about 40 per cent of the drivers who caused accidents did not take any avoidance manoeuvre because of their recognition delay or judgment error (ITARDA, 2005, Shimizu et al., 2007), autonomous collision avoidance is an effective way to prevent accidents. In fact, several collision avoidance systems have already been commercialized. They recognize a frontal obstacle and make the vehicle stop automatically by braking if necessary. However, braking is not the only way to avoid collision. Steering can be the alternative way. Reportedly, avoidance by braking is effective if the vehicle speed is low, whereas steering is effective when running at high speed, in general (Horiuchi et al., 2006). Time-to-collision, which is the distance between the obstacle and the vehicle divided by their relative velocity, is an important index to judge which avoidance method is suitable. Therefore, an active safety technology which can avoid a frontal obstacle by steering autonomously can reduce the number of traffic accidents furthermore.

Based on these backgrounds, other researchers have proposed some obstacle avoidance methods using potential field (Noto et al., 2011), optimal control (Fujioka et al., 2008) and random tree algorithm (Cheng et al., 2001). Meanwhile, the authors proposed an autonomous collision avoidance system in the previous studies (Isogai et al., 2009, Hayashi et al., 2012) using geometrically-optimized avoidance trajectories. It realizes successful autonomous frontal obstacle avoidance by combined control of braking and steering to make the vehicle follow the target trajectory. The advantages of the proposed system include the very low computational cost and the optimality of the vehicle attitude when it makes its closest approach to an obstacle. However, a challenge remains in the accuracy of judgement whether the vehicle can surely avoid the obstacle without collision or not. A stepwise rapid steering is necessary to follow the geometrically-optimized avoidance trajectory, but the steering system of the actual vehicle cannot realize it because of the limitation of steering angular velocity. This caused large trajectory errors between the target and actual trajectories.

This leads to a new research objective to develop a method to improve the trajectory tracking performance of the autonomous avoidance system by considering the limitation of steering angular velocity. This study proposes a method to transform the shape of the desired steering angle profile from a step-shaped one into a trapezoidal one in order to improve the trajectory tracking performance because a trapezoidal-shaped desired steering angle profile with limited steering angular velocity is easier to be realised by the automatic steering system. Then two kinds of real car experiments are carried out. One is to show that the proposed method reduce the trajectory errors and improve the trajectory tracking performance. The other is to show that the proposed method expands the range of application of the autonomous collision avoidance since the improved tracking performance enables more appropriate judgement of the availability of safe avoidance by steering.

1.1 Target Driving Scenario

This paper focuses on a scenario where an obstacle suddenly appears in front of the vehicle while it is driving in a straight road with boundaries such as walls on both sides, the same scenario as the previous paper. The scenario is illustrated in Fig. 1. The conditions are as follows:

1) Only a single obstacle appears in front of the vehicle, and it does not move after the appearance.

Fig. 1. Obstacle avoidance situation
2) Due to a small clearance between the obstacle and the left-side road boundary for the vehicle to pass through, it is impossible to avoid the obstacle by evading leftward.

3) There is an enough space between the obstacle and right road boundary for the vehicle to pass.

1.2 Experimental Vehicle

Fig. 2 shows the experimental vehicle used in this research. This vehicle is equipped with a laser range finder at its front end to obtain the relative distance to objects in wide range. Additionally, other sensors are mounted to measure the vehicle speed, longitudinal and lateral accelerations, and yaw rate. The digital signal processor, which is installed in the vehicle, can control the vehicle speed and steering angle by means of in-wheel motors and an AC-servo motor.

2. AUTONOMOUS FORWARD OBSTACLE AVOIDANCE SYSTEM (Isogai et al., 2009)

2.1 Outline of the System

The outline of the autonomous obstacle avoidance system proposed in the previous study is shown in Fig. 3. The surroundings recognition subsystem obtains the coordinate of the right edge of the obstacle \((x_{pr}, y_{pr})\) and the lateral distance from the vehicle to the right road boundary \(L_{wr}\) by using the laser range finder. These data are sent to the avoidance path generation subsystem where two kinds of avoidance trajectories by steering are calculated. One appropriate avoidance method is selected among three kinds of avoidance method and the turning radius \(R\) and turning angle \(\theta\) is sent to the desired velocity and steering angle generation subsystem.

It generates a profile of the desired steering angle and vehicle speed which enable the vehicle to follow the avoidance trajectory. As a result of automatic control of the in-wheel motors and the steering servo motor, autonomous collision avoidance is executed.

In this paper, the authors focus on the derivation of the avoidance trajectory and the calculation of the desired steering angle to profile to make the vehicle follow the trajectory. Therefore, explanation about the surroundings recognition and automatic control of the vehicle is omitted. Avoidance path generation, decision of avoidance method, and desired steering angle generation are described in detail in the following sections. In this study, the influence of the dynamics of the vehicle is neglected in calculating the desired steering angle profile because the target area of the system is an urban area where the speed limit is less than 30 km/h.

2.2 Avoidance Path Generation

The evasive avoidance trajectory is calculated geometrically with connected two identical arcs as shown in Fig. 4. Avoidance starts at point \(O\). First, the vehicle is made to turn right to evade the obstacle, and then turn left after reaching the steering changeover point \(S\). Avoidance finishes at finishing point \(F\). The avoidance trajectory is derived so that the turning radius is as large as possible.

Two kinds of avoidance trajectories have to be considered depending mainly on the distance to the right road boundary \(L_{wr}\). They are termed as “Steering A” and “Steering B.” They are defined and calculated as follows.

**Steering A** (Fig. 4(a))

This avoidance trajectory is for the cases in which the position of a right road boundary does not need to be taken into account because it is far enough from the vehicle.

The turning radius \(R_A\) and the turning angle \(\theta_A\) are derived from the condition that the circle \(C_R\) is circumscribed to the circle \(C_P\) as follows:

\[
R_A = \frac{x_{pr}^2 + y_{pr}^2 - r^2}{2(r - y_{pr})}, \quad \theta_A = \cos^{-1}\left(\frac{R_A + y_{pr}}{R_A + r}\right). \tag{1}
\]

**Steering B** (Fig. 4(b))

This avoidance trajectory is for the cases where the presence of the right road boundary must be taken into account.

![Fig. 5. Decision flow of avoidance method](image-url)
The turning radius \( R_B \) and the turning angle \( \theta_B \) are derived from the condition that the circle \( C_P \) is inscribed in the circle \( C_R \), as follows:

\[
R_B = \frac{-a_1}{2a_1^2 - 4a_1a_2}, \quad \theta_B = \cos^{-1} \left( \frac{R_A + y_p}{R_A + r} \right),
\]

where \( a_1, a_2, a_3, \) and \( a_4 \) are expressed as:

\[
\begin{align*}
    a_1 &= \frac{L_{W_0} - y_p}{2x_p}, \\
    a_2 &= \frac{x_p^2 + y_p^2 - r^2 + 2(L_{W_0} - r)y_p}{4x_p}, \\
    a_3 &= 2a_2a_4 - L_{W_0} + r, \\
    a_4 &= a_2^2 + (L_{W_0} - r)^2/4.
\end{align*}
\]

2.3 Decision of Avoidance Method

Fig. 5 shows the decision flow to select an appropriate avoidance method. In the proposed system, the priority is given to avoidance by braking rather than avoidance by steering because avoidance by braking has less influence on other vehicles in traffic. Thus, the availability of each avoidance method is assessed in sequence by avoidance by braking. This decision is made just once at the time when a frontal obstacle is detected.

The system executes an autonomous avoidance if TTC (Time to Collision) with the obstacle is less than 2s. This condition is expressed as follows:

\[
x_p \leq 2V_0,
\]

where \( V_0 \) is the vehicle speed when the obstacle is detected.

If an evasive action is decided to be conducted, the system first assesses the availability of avoidance only by braking, which makes the vehicle stop before the obstacle. Avoidance is available if the distance between the obstacle and the front end of the vehicle is more than the stopping distance of the vehicle as shown by the following inequality:

\[
x_p \geq \frac{-V_0^2}{2a_s},
\]

where \( a_s \) is the acceleration of the vehicle. In this study, \( a_s \) is set to \(-2m/s^2\), the maximum deceleration which the experimental vehicle can generate by the in-wheel motors.

If avoidance by braking is not available, the system then assesses the availability of Steering A. The turning radius \( R_A \) and angle \( \theta_A \) calculated by (1) are used to assess the availability. Steering A is available if turning with radius \( R_A \) does not make the vehicle collide with the right road boundary. Moreover, the radius \( R_A \) must not be smaller than the minimum turning radius of the vehicle \( R_{\text{min}} \). These conditions are expressed mathematically as follows:

\[
L_{W_0} \geq 2R_A \left( 1 - \cos \theta_A \right) + r, \quad R_A \geq R_{\text{min}}.
\]

If Steering A is not available, the system lastly assesses the availability of Steering B. Similarly to the assessment of Steering A, turning radius \( R_B \) and angle \( \theta_B \) calculated by (2) are used to assess the availability. Steering B is available if only the gap between the obstacle and the right road boundary is larger than the vehicle’s width. However, the radius \( R_B \) must not be smaller than the minimum turning radius of the vehicle \( R_{\text{min}} \). These conditions are expressed mathematically as below:

\[
L_{W_0} \geq 2r - y_p, \quad R_B \geq R_{\text{min}}.
\]

If all of the avoidance methods are judged to be unavailable, it means that collision with the obstacle is unavoidable. Then the system executes a collision mitigation brake.

2.4 Generation of Desired Velocity and Steering Angle

In this study, for any avoidance method, the system commands the maximum deceleration because the supposed scenes are emergency avoidance scenes. Therefore, in any case, the desired velocity \( V^* (t) \) is expressed as follows:

\[
V^* (t) = \begin{cases} 
V_0 + a_s t & \text{if } 0 \leq t < t_5, \\
0 & \text{if } t \geq t_5. 
\end{cases}
\]

\[
\delta^* (t) = \begin{cases} 
-\delta_0 & \text{if } 0 \leq t < t_5, \\
\delta_0 & \text{if } t_5 \leq t < t_6. 
\end{cases}
\]

where \( \delta_0 \) is expressed as:

\[
\delta_0 = \left( 1 + K (V^* (t))^2 \right) \eta \frac{J}{R}.
\]

\[
t_5 = \frac{V_0 - a_s r}{-a_s}, \quad t_6 = \frac{V_0 + 4a_s R_A}{-a_s}. 
\]

Thus, the desired velocity and steering angle are calculated as shown in Fig.6 (b).

3. IMPROVEMENT OF TRAJECTORY TRACKING PERFORMANCE

2.1 Problem in the Previously Proposed System

Since the desired steering angle profile generated in the previous system has stepwise changes, it is difficult for the actual automatic steering system to follow the desired value. It is mainly because of the limitation of steering angular velocity. Therefore, taking the trajectory tracking error into account prospectively, the system puts extra margins beside the vehicle by assuming the vehicle’s width wider than it is. (in (1) and (2) correspond to the half of the vehicle width.) These margins are estimated uniformly regardless of the position of the obstacle or the distance from road boundary. Therefore, the system has a possibility to judge some situations as unavoidable although they are avoidable ones. The improvement of the judgement accuracy of availability of avoidance is one of the remaining challenges for the previous system.
2.2 Solution Approach

This paper proposes a conversion method of the desired steering angle profile generated by the previous system. The trapezoidal steering profile should be transformed into a trapezoidal shape by limiting the change rate to 500 deg/s, which is the limit of the steering angular velocity of the automatic steering system of the experimental vehicle. Instead, the maximum value of the desired steering angle is raised in order to compensate the deficiency of steering. Therefore, the vehicle is supposed to decelerate in the autonomous avoidance. Therefore, the time scale of the transformed steering profile must be converted again in order to adapt to the condition that the vehicle is decelerated. The conceptual image of the time scale conversion is shown in Fig. 9. The time scale is elongated with the decreasing vehicle speed so that the travel distance of the vehicle in each instant of time coincide with that in the constant speed condition. The time scale conversion is expressed as:

\[
\hat{t} = \frac{T}{a_\delta} \left( \frac{V_0}{a_\delta} - \frac{V}{a_\delta} \right) t \times 500 \quad (20)
\]

where \( \hat{t} \) and \( T \) indicate time before and after the conversion, respectively.
Thus, the desired steering angle is modified by the trapezoid transformation and the time scale conversion before conducting automatic steering.

4. VERIFICATION OF THE TRAJECTORY TRACKING PERFORMANCE BY REAL CAR EXPERIMENTS

To evaluate the improvement of the trajectory tracking performance, virtual avoidance manoeuvres are conducted by using the experimental vehicle. Surroundings recognitions using laser range finder are not executed in order to reproduce the same conditions. The vehicle is made to follow the same avoidance trajectory as if the system detects the same condition of the obstacle and road boundary. The initial vehicle speed is set to 5 m/s. In these experiments, the system does not set any extra space margins in the vehicle width to compensate the trajectory error, since these experiments are to evaluate the trajectory errors.

The conditions of obstacles and the results of the experiments are shown in Table 1. The trajectory error is defined as the difference between the lateral displacement of the steering changeover point in the desired trajectory and the actual lateral displacement at the time t5. These results indicate that the proposed system reduces the trajectory errors by half.

5 EXPANSION OF RANGE OF APPLICATION

5.1 Reduction of the Space Margin

Since the trajectory error is reduced by the proposed method, the space margin to compensate the trajectory error can be reduced. Hence, the radius of the circle r is reduced to 0.65 m from 0.8m of the previous system.

To discuss the effect of reduction of the extra margin, numerical simulations are carried exhaustively. The results are shown in Fig. 10. In these simulations, the initial vehicle speed and the initial distance to the right road boundary are set to be \( V_0 = 7 \text{ m/s} \) and \( L_{W_0} = 2 \text{ m} \), respectively. The coloured areas mean that the system judges that the avoidance is available if the right edge of an obstacle is in the area. Black circles mean the positions of the edges of the obstacles which are successfully avoided by the system in the simulations. Fig. 10 (a) indicates that there is a wide area in which the previous system misjudges the availability of safe avoidance and fails in collision avoidance by steering, whereas Fig. 10 (b) indicates that the system with the proposed method makes safe avoidances almost perfectly if it judges the condition as avoidable.

This leads to a conclusion that the system with the proposed method has higher accuracy in judgement of availability of safe avoidance. In addition, the system with the proposed method judges many conditions of obstacles whose y-coordinates \( y_{pr} \) are smaller than \(-0.5\) m as avoidable and succeeds in collision avoidance actually, whereas the previous system judges all of the obstacle as unavoidable if its y-coordinate is smaller than \(-0.5\) m. This indicates that the system has a larger range of application than the previous system.

From these results, it is concluded that the proposed method is effective in improving the accuracy of availability of collision avoidance and expanding the range of application of the autonomous collision avoidance system.

5.2 Demonstration of the System with the Proposed Method by Real Car Experiments

Two conditions shown in Table 2 are selected for demonstration experiments to show the improvement of accuracy of judgement and expansion of range of application. Fig. 11 and Fig. 12 show the result of no. 201 by the previous system and the system with the proposed method, respectively. Fig. 11 indicates that the previous system judges that the obstacle is avoidable but fails in collision avoidance because of the limitation of the steering angular velocity, whereas Fig. 12 indicates that the system with the proposed method judges that the collision is unavoidable. These results indicate that the system with the proposed method makes a right judgement in this condition.

Fig. 13 and Fig. 14 show the result of no. 202 by the previous system and the system with the proposed method, respectively. Fig. 13 indicates that the previous system judges that the obstacle is avoidable and has a collision with it, whereas Fig. 14 indicates that the system with the proposed method judges that the collision is avoidable and realizes a safe avoidance. These results indicate that the system with the proposed method has an advantage in collision avoidance under conditions that the gap between the obstacle and the right road boundary is not large enough compared to the vehicle width.

6. CONCLUSIONS

The study proposed the modification method of the desired steering angle profile for the autonomous obstacle avoidance system by considering the limitation of the steering system of the vehicle speed.

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<th>Table 1. Comparison of trajectory errors</th>
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Fig. 10. Simulation results


