Collision Avoidance Control with Steering using Velocity Potential Field*

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Abstract—It is expected that a collision avoidance system based on steering control could help avoid collisions even in cases where a collision cannot be avoided by braking only. For realizing steering-based collision avoidance, accurate environmental recognition and rapid motion planning in a highly dynamic environment are needed. The velocity potential field control method, which was proposed for mobile robot motion planning, has the advantages of a very low computation cost, even in dynamic environments with moving obstacles without any deadlock. In addition, the method generates the desired velocity vector to be followed but vehicle trajectory. With this feature, avoidance velocity vector is generated in realtime even in the case that the obstacles are moving and their movements cannot be anticipated. Thus, the present study proposes a collision avoidance method with steering control by generating a trajectory for obstacle avoidance using local environmental recognition based on application of the velocity potential field approach. In addition, a parameter determination method for the velocity potential function is derived. A preview steering control method for following the derived velocity vector is proposed. The simulation results obtained using vehicle dynamics software demonstrate that the proposed method can generate appropriate obstacle avoidance trajectories, even for moving obstacles, and the derived velocity vector can be tracked by an automobile.

I. INTRODUCTION

Active safety technologies that prevent collisions, including warning systems and advanced driver assistance systems, have been developed. Among such technologies, it is expected that collision avoidance systems would dramatically improve road traffic safety. Consequently, such systems are already available in the market. In fact, braking-based collision avoidance systems such as the Advanced Emergency Braking System (AEBS) have contributed to reducing the number of collisions[1][2][3][4].

Recently, collision avoidance systems that use steering control for avoiding collisions have drawn attention because such systems have the potential to further reduce the number of collisions[5],[6]. Several studies on collision avoidance using steering control have been conducted. Trajectory-generation methods for specific and simple situations have been proposed. For example, Hayashi et al. proposed a rigorous path-generation method for avoiding a single lead vehicle by connecting circular arcs based on obstacle motion prediction [7] [8]. In addition, a few studies have attempted to derive a methodology for generating a collision avoidance path in complex situations through iterative calculation for obtaining rigorous solutions. For example, a method that chooses to avoid a collision using either braking or steering was investigated based on detailed calculations of multiple vehicles’ collision courses [9]. Literature [10] proposes a control method to prove safety for various scenarios by reachability analysis. Most of these approaches require long calculation time. More recently, fully automated vehicles have been studied based on environmental recognition methods using external sensors such as LIDARs and cameras [11] [12] [13]. These studies focus on environment recognition under highly complex and dynamic situations. A study [14] proposed an automated lateral control method for vehicle passage through a curve using C2C communication for reducing the environment recognition load. Currently, it is thought that these methods focus on stationary driving rather than on crash-imminent situations. Thus, a fast path-generation method for collision avoidance in a crash-imminent situation that can be applied to dynamic and complex environments such as one with multiple vehicles is required.

The potential field approach was proposed for path planning to a target position for mobile robots[15]. This approach is suitable for navigating a robot to a target position even in complex environments. Recently, a few studies applied the potential field approach to automobile control[16],[17]. However, there is a concern that in complex situations, it is difficult to guarantee no deadlock using the potential field approach. In contrast, the velocity potential field approach is capable of fast trajectory generation even in dynamic environments with moving obstacles without any deadlock[18], [19]. In addition, the method generates the desired velocity directly by differentiating the potential function, which is an advantage from the automotive application viewpoint.

Thus, the present study proposes a collision avoidance method with steering control by the velocity potential approach for generating an obstacle-avoidance velocity vector with local environmental recognition. This method does not generate any trajectory to be followed but generates a velocity vector of the host vehicle at every moment of the driving for avoiding collision. With this feature, avoidance velocity vector is generated in realtime even in the case that the obstacles are moving and their movements cannot be anticipated. A parameter determination method for the velocity potential function is derived as well. In addition, a preview steering control method for following the derived velocity vector is proposed. Numerical simulations are conducted with vehicle dynamics software considering both static and
moving obstacles for validating the proposed control method.

II. COLLISION AVOIDANCE CONTROL USING VELOCITY POTENTIAL FIELD

A. Scenario

As the first step in this study, we assume a scenario in which the host vehicle (HV) is driven on a two-lane road in a single direction and the HV encounters a lead vehicle (LV) that is either driving slowly or stationary, as shown in Fig. 1. The present study aims to propose a collision avoidance control system that avoids collisions with a LV using steering control as well as braking when the driver does not react to an imminent crash with the LV.

It is assumed that the HV’s coarse lateral position within the lane markers is known based at least on the distances from the lane markers, which are determined using HV-mounted sensors such as a laser range finder (LRF) and cameras. In addition, it is assumed that the relative position to the LV and the LV’s approximate size are determined by the car-mounted sensors. It should be noted that only local information such as LV width was available in the first stage of avoidance because the car-mounted sensors are capable of measuring local information only.

B. System Overview

In this study, COMS, a micro electric vehicle (Toyota Auto Body Co., Ltd.) (Fig. 2), is assumed as the HV. In addition, it is assumed that the HV status and the relative distance between the HV and obstacles on the road boundary can be obtained by the HV-mounted sensors.

An overview of the proposed collision avoidance system is shown in Fig. 3. A velocity potential function is constructed based on the sensor information, and it is used to calculate the desired velocity vector for collision avoidance. The desired vehicle sideslip angle $\beta_d$ and the desired vehicle velocity $V_d$ are determined using the velocity vector and its norm, respectively (see Section II-G for the detail).

The desired vehicle sideslip angle is converted to the steering wheel angle using a bicycle model. Finally, an appropriate feedback controller for steering wheel angle and vehicle velocity realizes collision avoidance using the abovementioned variables’ calculated values.

C. Velocity Potential

It is known that the velocity of an incompressible inviscid fluid can be described by $v = \nabla \phi$ and the following equation is satisfied[20].

$$ \text{div } v = \nabla^2 \phi = 0 $$  \hspace{1cm} (1)

where $\phi$ is referred to as the velocity potential function. The function $\phi$ is a harmonic function and is continuous in all regions except for singularity points such as a source and a sink. This means that there is no deadlock in the region. In the case of a flow on a two-dimensional plane, the velocity potential can be expressed as the complex velocity potential, eq. (2), by introducing the complex plane.

$$ f(z) = \phi(x, y) + i \psi(x, y) $$  \hspace{1cm} (2)

where $x, y$ denote Cartesian coordinates of the position in the plane, $i$ denotes the imaginary unit, and $z = x + iy$. $\psi(x, y)$ and $\phi(x, y)$ are the stream function and the velocity potential, respectively.

The conjugate complex velocity is obtained by differentiating the velocity potential with respect to $z$ (Eq. (3)).

$$ \tilde{v}(z) = \frac{df(z)}{dz} = u(z) - iv(z) $$  \hspace{1cm} (3)

where $u(z)$ and $v(z)$ represent the velocity in $x$ and $y$ directions, respectively. An object can move along a flowline if this velocity is achieved. It should be noted that the principle of superposition can be employed in the case of multiple elements. Thus, a complex potential field can be constructed by superimposing multiple basic flow elements, as shown in Fig. 4 [20].

The flow of a fluid whose potential function is given by harmonic function is suitable for vehicle motion generation because it guarantees no collisions with obstacles and no deadlock. In addition, the desired velocity is generated in real time by differentiating the potential function. This is highly advantageous for vehicle control. Therefore, the harmonic velocity potential field of an incompressible inviscid fluid is used for automobile collision avoidance. Please note again that the proposed method does not generate any vehicle trajectory but does generate velocity vector at every moment.
for realizing collision avoidance. Thus, the proposed method is robust to changes in environment.

D. Potential Field Design

In this section, we propose a method for designing the velocity potential $f(z)$ of the scenario described in Fig. 1. The potential function elements are set to six points on the obstacle and the road, as shown in Fig. 5. The velocity potential function at point $j$ is defined by eq.(4).

$$f_j(z) = G_j(z) + C_j(z) + D_j(z)$$

where $z (= x + iy)$ is the position of interest on the plane, and the functions $G_j(z)$, $C_j(z)$, and $D_j(z)$ denote the velocity potential functions describing flow around a cylinder, vortex, and source, respectively, and are given by eqs.(5), (6), and (7) (Fig.4).

$$G_j(z) = \frac{a_j^2}{z - z_j}$$

(5)

$$C_j(z) = ik_j \log(z - z_j)$$

(6)

$$D_j(z) = m_j \log(z - z_j)$$

(7)

where $z_j (= x_j + iy_j)$ denotes the position of point $j$ or cylinder, vortex, and source. Scalars $a_j$, $k_j$, and $m_j$ represent the radius of the cylinder, intensity of the vortex, and intensity of the source, respectively. Please note that the flowline described in Fig.4-(b) is generated by the potential function $G_j(z)$ in eq.(5) with the uniform flow given in eq.(8).

The locations and numbers of points at which the potential functions were located, were determined by trial and error.

In addition, the uniform flow shown in Fig.4-(a) is used for describing the travel direction or road direction. The potential function of the uniform flow is given by eq.(8).

$$P(z) = U e^{-i\alpha z}$$

(8)

where $\alpha$ denotes the angle of flow from $x$ axis, and $U$ denotes the uniform flow velocity.

Finally, the velocity potential field of the scenario is given by eq.(9)

$$f(z) = P(z) + \sum_{j=1}^{6} \{ G_j(z) + C_j(z) + D_j(z) \}$$

(9)

E. Parameter Determination Method

In this section, a method for determining the potential functions’ parameters is derived. A set of parameters was determined so that it reproduces the driving pattern corresponding to a given driving data as closely as possible. A fixed-base driving simulator (DS) was used to measure the collision avoidance trajectories of a driver. The subject drove the DS from the different three initial positions after getting used to the simulator.

Please note that the cylinder parameters were fixed as $a_i = 0.01$ for $i = 1, 2, 3, 4$ and $a_i = 0.55$ for $i = 5$ and $6$ by trial and error. In addition, magnitude of the uniform flow, $U$, is determined as the initial HV value. Thus, the parameters of the potential functions of the vortex and the source are determined by solving the following optimization problem. Please note that parameter optimization of the potential functions’ parameters is derived. A set of parameters was determined so that it reproduces the driving pattern corresponding to a given driving data as closely as possible. A fixed-base driving simulator (DS) was used to measure the collision avoidance trajectories of a driver. The subject drove the DS from the different three initial positions after getting used to the simulator.

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$$J = -\sum_{l=1}^{L} \sum_{j=1}^{n} \frac{\mathbf{v}(x_j, y_j)^T \hat{\mathbf{v}}(x_j, y_j)}{||\mathbf{v}(x_j, y_j)||^2 ||\hat{\mathbf{v}}(x_j, y_j)||^2}$$

(11)

s.t. $m_6 = m_2$ and $k_6 = -k_2$

(12)

where $\mathbf{v}(x_j, y_j)$ denotes the observed velocity vector at position $(x_j, y_j)$ and $\hat{\mathbf{v}}(x_j, y_j)$ denotes the velocity vector calculated using the velocity potential function. Scalars $L$ and $n$ denote the number of driving trials and the number of observed points during each driving trial, respectively; $L = 3$ and $n = 20$ were selected in our experiments. Fig.6 shows the measured three driving trajectories. The twenty observed points for each trial were determined by dividing its trajectory into x-direction. A quasi-Newton method was used for determining the optimal parameter values.

Points 1 and 2 are set to both the road boundary points that are closest to the HV and move along with the HV.

Points 3, 4, and 5 are fixed to both ends and center of the LV’s back.

Point 6 is set on the right side of the LV, which is the closest from the HV, and this point moves along with the HV.
**F. Parameter Identification Results**

Table I lists the parameters identified from the driving data. Fig.7 shows the flowlines calculated using the potential function with the identified parameters, as well as one of the three observed vehicle trajectory for comparison. This figure indicates that the potential function with the identified parameters can generate a smooth trajectory within the road boundaries while avoiding any collision with the LV. In addition, it is found that the flowline generated by the model agrees well with the observed driving data.

<table>
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<th>parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>203.31</td>
<td>10.00</td>
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</table>

Fig. 6. Observed vehicle trajectory

**G. Preview Steering Control for Following Desired Direction**

The desired sideslip angle of the vehicle $\beta_d(t)$ is determined using the velocity vector.

$$\beta_d(t) = \arg \hat{\nu} (z(t + \tau))$$  \hspace{1cm} (13)

where $\tau$ denotes the preview time, $\tau = 0.15s$ in the present paper, and $z(t + \tau) = x(t + \tau) + iy(t + \tau)$ is defined in eq.(14).

$$z(t + \tau) = z(t) + V r e^{i(\theta(t) + \beta(t))}$$  \hspace{1cm} (14)

where $\theta(t)$ denotes the vehicle’s yaw angle at time $t$.

The desired steering angle of a vehicle that realizes the desired sideslip angle $\beta_d$ is calculated using eq.15 under the assumption that the vehicle has a steady turning circle[21].

$$\delta_d(t) = \frac{1 + AV^2}{(1 - \frac{M f r}{2V} \frac{l_r}{l_f})^2} \beta_d(t)$$  \hspace{1cm} (15)

where $A$ is the stability factor. Scalars $l_r$ and $l_f$ represent the distances of the rear and front wheel axles from the vehicle’s center of gravity, respectively, and $f$ denotes vehicle wheelbase. Scalars $K_r$, $M$, $V$ denote the cornering power, vehicle weight, and vehicle velocity, respectively.

The desired steering angle given by eq.(15) is realized with a simple position feedback scheme such as PD feedback of the steering angle $\delta$.

**III. COLLISION AVOIDANCE SIMULATION**

**A. Simulation condition**

The validity of the proposed collision avoidance method is examined by computer simulations. The proposed control method was implemented in CarSim, a vehicle motion simulation software (MSC Co., Ltd.). The scenario described in section II was used for the simulation. The vehicle parameter of the micro electric vehicle COMS were used. The test course was a two-lane road with 4 m wide for each lane. The vehicle was driven on the center of the left lane at about 20 [km/h], approaching the LV.

The activation timing of the collision avoidance function was determined as time-to-collision TTC = 1.4 s. The LV location was changed in four manners as follows for examining the robustness of the method to changes in obstacle location:

**Condition 1**: The LV is parked throughout the simulation. The LV’s center of mass (COM) in the lateral direction is 1 m left of the HV’s lateral position.

**Condition 2**: The LV is parked throughout the simulation. The LV’s COM in the lateral direction is 1 m right of the HV’s lateral position.

**Condition 3**: The LV is parked throughout the simulation. The LV’s COM in the lateral direction is 1 m left of the HV’s lateral position.

**Condition 4**: First, the LV is parked in the same location as in condition 1. Then, the LV is moved in the −45 deg direction at a speed of 3.6 km/h.
The HV’s velocity was controlled to the velocity calculated from the velocity potential function, while the upper limit of velocity was set to the HV’s initial velocity. The parameters of the potential functions identified in the previous section were used here.

**B. Simulation Results**

Figs. 9–12 show the simulation results under all conditions. The blue lines, which are written as desired trajectory in Figs. 9–12(c) denotes the trajectories calculating by integrating the desired velocity from the current position to 0.5s later. Overall, the resultant trajectories under all these conditions successfully avoided collision with the LV, while driving a smooth trajectory and not departing from the road. In addition, it is confirmed that the resultant vehicle trajectories are similar to the generated trajectory by integrating the desired velocity vector. As can be seen in Figs. 9–11, the proposed method yields similar collision avoidance results regardless of the difference in LV position, even with the same control parameters. A resultant collision avoidance trajectory with a larger inclination toward the right was automatically generated for condition 3 than for conditions 1 and 2. Figure 12 shows that the proposed control scheme avoids collisions even if the LV moves by changing the desired path in real time.
From Figs.9–11-(c), it is found that the vehicle drives almost along the calculated desired flowline even existence of the vehicle dynamics. It is thought that the preview control leads the results. In contrast, some delay is found in the case with a moving obstacle (Fig.12). However, it should be noted again that even in this case, no collision with the LV occurred in the simulation. Moreover, Fig. 13 shows that a larger lateral acceleration was required for avoidance action in tighter situations, i.e. condition 4.

These results indicate that the proposed method automatically generates collision avoidance trajectories corresponding to the LV’s position without changing the velocity potential function parameters. In addition, stable collision avoidance can be achieved even in the case that the HV cannot realize the desired velocity vector because another velocity vector is generated at the next moment using the measured environmental information at the moment.

IV. CONCLUSION

A steering-based collision avoidance method for automobiles was proposed using a velocity potential approach. Desired velocity vectors at each moment were generated in real-time. A driving data-based parameter determination method was proposed. In addition, a preview steering control method was proposed using the desired velocity vector. The results of a simulation that considered vehicle dynamics showed that collision avoidance was successfully realized using the proposed method. Furthermore, it was shown that the parameters of the same velocity potential can be used in different vehicle locations for collision avoidance even with the moving obstacle. The results indicate the robustness of the velocity potential approach against spatial errors because the proposed method can automatically generate desired velocity vectors that realizes similar flowlines near the original trajectory for collision avoidance. This feature can realize smooth changes of the desired trajectory in the case of a delay in the vehicle’s or the obstacle’s motion.

Simulation conditions should be added to prove the collision avoidance ability of the proposed method. Experimental verification of the proposed method using a vehicle is a future work. Furthermore, expansion of the proposed method to situations with multiple vehicles is important as a future study. Finally, a method to prove safety is necessary like [10]. It is expected that proof of the collision free is easily realized because the resultant trajectory can be calculated by integrating the desired velocity.

Fig. 13. Lateral acceleration

REFERENCES