A Safe-Distance Based Threat Assessment with Geometrical Based Steering Control for Vehicle Collision Avoidance

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***Abstract*— This work proposes a vehicle collision avoidance strategy based on the usage of Geometrical Based Steering Controller. The algorithm is composed of these features : 1) Collision Detection strategy using safe distance threshold, 2) predicts the future trajectory of the vehicle in the occurrence of obstacle, 3) decision making prior to avoiding collision, 4) avoiding obstacles while ensuring the vehicle to return to its original path. The strategy used a nonlinear vehicle model with steering and braking input as the actuators that will react and avoid collisions. Simulation results depict the ability of the methods to avoid the potential collision while returning to its original path. The inclusion of the Threat Assessment Strategy ensures the hindrance of the vehicle from colliding with the obstacle's edge.**

***Index Terms*— Geometrical method; Threat assessment; Vehicle collision avoidance.**

I. INTRODUCTION

Real life implementations of autonomous vehicles have been the dream of many automobile manufacturers today. Advanced Driver Assistance Systems (ADAS) is an important aspect of safety for the autonomous vehicles where it helps the automation of the driving experience. ADAS comprised of several features, one among them is the development of the Vehicle Collision Avoidance (VCA) system. Throughout the years, there have been many works done in the field of VCA, with the main aim to enable a vehicle to move autonomously without any collisions. Among the well-known methods are Artificial Potential Method (APF), Global Dynamic Window Approach (GDWA), Visibility Graph Method (VGM) and Genetic Algorithms (GA) like Rapidly-Exploring Random Trees and Particle Swarm Optimization.

However, there are significant flaws with these aforementioned methods. For example, APF faces the local minima problem [1] and GDWA is not suitable for a VCA usage as it tends to continue the calculations despite having no obstacle, thus providing an always-changing vehicle heading [2]. GA on the other hand does not ensure a global optimum solution in the occurrence of emergency collision avoidance [3].

As mobile robot obstacle avoidance is different compared to VCA due to the like of nonholonomic constraint of the vehicle dynamics, thus for a successful VCA maneuver, several features need to be put into considerations, i.e. the threat assessment (strategies to determine the seriousness of a potential threat), prediction of future trajectory of the vehicle while avoiding obstacles, decision making strategy for the lower level control (actuators such as steering, braking and throttle) as well as path following strategy of the original path after a successful VCA. These will be discussed in the later sections.

Among the earliest works of VCA is presented by Lozano-Perez et al. [4], and the idea utilized the concept of Geometrical-Based Method Controller (GMC), where its aim is to enable a collision-free move from the start point until target point. Lozano-Perez then expanded the idea with Configuration Space Approach; where the algorithm represents the robot in a configuration space, and each of its position in the space symbolize its degree of freedom in the position and its orientation, while the obstacles are represented as a configuration forbidden to the robots [5].

The main theory behind GMC like the Road-Mapping path planning method is it consists of a graph of various positions of the robot and obstacles, and these nodes are connected between each other, creating a path that allow features like trajectory tracking. One of the advantages of GMC is its low computation time and simple algorithms. Though can be considered as one of the pioneer methods in the field of VCA, it is still studied by researchers until very recently. For example, in [6], GMC is combined with RRT* to lower the computation time of RRT and in [7], it is combined with APF to enable a dynamic environment collision avoidance.

However, the drawback of GMC is it does not ensure a totally free-obstacles path as in the case of visibility graph method where the robot might still be in contact with the obstacles edges. This can be hindered by having a threat assessment (TA) strategy into the full control architecture. TA is a preventive measure to avoid any unintended accidents and to prevent the robot from colliding with the obstacles, thus enabling a total collision-free path. It is a part of the Collision Warning System.

The main aim of this work is to propose a VCA strategy using GMC which includes the application of threat assessment to enable a free-collision path. GMC is expected to manipulate the input of the vehicle model (steering) to help the vehicle from colliding with obstacle. The paper is written as follows: in following section, the mathematical models of the vehicle which include its kinematic and dynamic models is discussed; then in the next sections, the proposed controller and the threat assessment strategy is presented; then the authors includes the validation results of the proposed method. In the final section, the authors ascribed the conclusions of this work and the brief idea on the potential future works.

In this work, the authors proposed a non-linear GMC-based steering control for an emergency VCA in a straight path. This paper's main contribution is it developed a successful VCA algorithm using GMC by including TA strategy. The GMC Method is known for its computational advantages and the inclusion of TA will ensure a successful free-collision VCA maneuver in real life.

II. MATHEMATICAL MODELING

This section encompasses of the mathematical models of the vehicle model, which is based on the work of [8] [9] and have an input of steering and braking to the plant. The vehicle possesses a 3-DOF system as shown in Figure 1 below. It considers the vehicle's lateral and longitudinal motions as well as its yaw motion. It is assumed that the longitudinal velocity is constant and the vehicle is moving in a straight line. The initial acceleration is neglected. Figure 1 depicts the vehicle model used in this work.

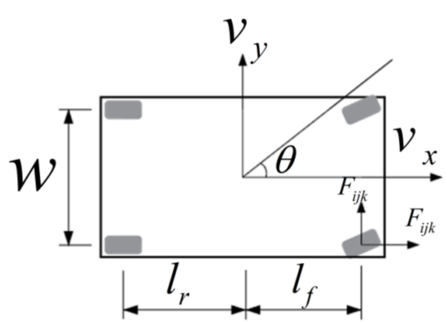

Figure 1: The illustration of 3-DOF vehicle model used in this work.

A. Vehicle Dynamics

The following equations are used for the vehicle dynamics model within a lane:

$$\dot{v}_x = a_x + v_y \cdot \dot{r} \tag{1}$$

$$a_x = \frac{F_{xfl} \cdot cos\delta - F_{yfl} \cdot sin\delta + F_{xfr} \cdot cos\delta - F_{yfr} \cdot sin\delta + F_{xrl} + F_{xrr}}{m_t} \tag{2}$$

$$\dot{v}_y = a_y - v_x \cdot \dot{r} \tag{3}$$

$$a_y = \frac{F_{yfl} \cdot cos\delta + F_{xfl} \cdot sin\delta + F_{yfr} \cdot cos\delta + F_{xfr} \cdot sin\delta + F_{yrl} + F_{yrr}}{m_t} \tag{4}$$

Equation (1) and (3) each refers to the longitudinal and lateral acceleration of the vehicle, while Equation (2) and (4) described them in details, where a_x and a_y is the summation of the forces in longitudinal and lateral directions respectively divided by the vehicle mass, m_t. v_x and v_y, each denotes the longitudinal and lateral vehicle velocities. F_{ijk} represents the forces at each tire, where *i* represents the force direction and *jk* represents the positions of the tire (*j* denotes front or rear tires, while *k* denotes left or right tires) and δ denotes the front steering angle of the vehicle. It is important to note that in this work the authors consider only the front wheels steering angles of the vehicle can be controlled, while the rear steering angle is assumed to be constantly zero. For the lateral forces of the tire, F_{ijk} Pacejka Magic Tire formula is utilized [10].

For the braking input to the vehicle in this work, the authors assumed the vehicle to be moving in a straight line with constant speed without any braking maneuver. So, the GMC controller will only output the steering actuation for VCA.

From Equations (1) and (3), $\dot{r}$ refers to the yaw rate of the vehicle, where $\ddot{r}$ its yaw motion as is described below:

$$\ddot{r} = \frac{1}{J_z}\Big(\frac{w}{2}\big(F_{xfl} \cdot cos\delta + F_{xfr} \cdot cos\delta + F_{xrl} - F_{xrr}\big) + \frac{w}{2}\big(F_{yfl} \cdot sin\delta - F_{yfr} \cdot sin\delta\big) - l_r\big(F_{yrl} - F_{yrr}\big) + l_f\big(F_{yfl} \cdot cos\delta + F_{yfr} \cdot cos\delta - F_{xfl} \cdot sin\delta - F_{xfr} \cdot sin\delta\big)\Big) \tag{5}$$

where J_z denotes the yaw inertia of the vehicle, l_f and l_r each denotes the length from the vehicle center of gravity to the front and rear tracks. w is the vehicle track width. Equation (5) is adapted from the works of [8].

B. Kinematics Model

Kinematics model refers to the current position and coordinate of the vehicle in a certain instant. Consider a vehicle located at (x, y) coordinate with vehicle orientation, θ. For a successful VCA, the vehicle current and future positions must be projected along the lane center line relative to the obstacle positions (which is obtained from the exogenous signals using sensing devices). Figure 2 represents the brief illustration of the kinematics of the vehicle.

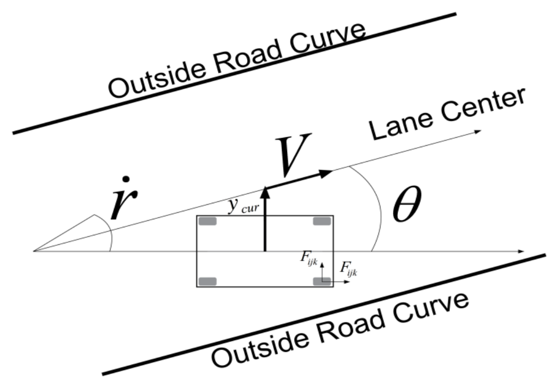

Figure 2: The illustration of kinematics model for the vehicle.

The longitudinal and lateral velocities of the vehicle along the path trajectory, *V* and *U* respectively, are described below,

$$V = \left(\frac{R}{R - y_{cur}}\right) \cdot (v_x \cdot cos\theta - v_y \cdot sin\theta) \tag{6}$$

$$U = v_y \cdot cos\theta + v_x \cdot sin\theta \tag{7}$$

$$\dot{x}_{cur} = V \tag{8}$$

$$\dot{y}_{cur} = U \tag{9}$$

$$\rho = \frac{1}{R} \tag{10}$$

$$\dot{\theta} = \dot{r} \tag{11}$$

where R is the radius of the curvature, ρ is the road curvature and (x_{cur}, y_{cur}) is the current (x, y) position of the vehicle. Equations (6) to (11) are taken from [11] and [12].

C. Threat Assessment

For a real-time VCA to be successfully implemented, a decisive threat assessment strategy (TAS) must be included into the VCA architecture to determine the potential threat. There are many types of TAS, among them are Time-To-Collision and Time-Headway [13, 14].

In this paper, the authors are using the safe-distance threshold as the threat assessment, based on the work of [15] and [16].

The idea is to have an invisible rectangular region around an obstacle, regardless of its size. Distances from each of the vehicle corner to the center of gravity (COG) of the obstacle is considered as the threshold and must be below certain value for the VCA maneuver to be activated. The calculation for the safe-distance is:

$$d_{xov} = \frac{(2 \cdot d_{xvjk})}{l_o} \tag{12}$$

$$d_{yov} = \frac{(2 \cdot d_{yvjk})}{w_o} \tag{13}$$

$$S_{djk} = \begin{bmatrix} d_{xov} \\ d_{yov} \end{bmatrix} \tag{14}$$

$$T_{tjk} = \left\| S_{djk} \right\|_{\infty} \tag{15}$$

d_{xov} and d_{yov} is the longitudinal and lateral distance respectively of each of the vehicle tire to the COG of vehicle, relative to the obstacle length and width, l_o and w_o respectively. This is important to create a safe region constraint around the obstacle in order for the vehicle to avoid it. d_{xvjk} and d_{yvjk} is the longitudinal and lateral distances of each of vehicle tires from the COG of obstacle. The full equations can be obtained in the work of [15].

In Equation (15), the authors calculate the infinity norm of matrix S_{djk} to return the T_{tjk}, the safe-distance threshold of each of the vehicle tires towards the obstacle's COG. This ensures that the vehicle will always stay in a safe distance from the potential object of collisions.

Figure 3 shows the safe-distance threshold of the full architecture. Once the vehicle surpasses the threshold, GMC-VCA algorithm will be activated.

D. Trajectory Replanner

For trajectory replanning in the case of obstacle's presence, the authors use the conditioning related to the threat assessment.

If the vehicle surpasses certain safe-distance threshold value, consider 2 meter near the obstacle, the VCA Control architecture will be activated. For the obstacle avoidance maneuver, this paper proposed the yawing rate of the vehicle to be manipulated during the collision avoidance. This is to create a Replanned VCA Trajectory. Refer to Equation (16) for details. And for the manipulations of the yawing rate, the formulation is in Equation (17).

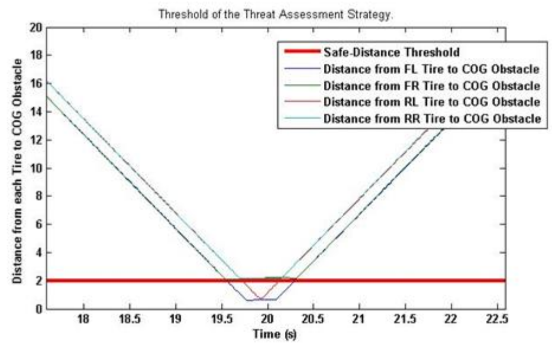

Figure 3: Once the safe-distance threshold has been violated, GMC-VCA block will be activated.

$$VCA_{activated} = \begin{cases} 1, & if\ T_{tjk} \leq 2\ meter \\ 0, & otherwise \end{cases} \tag{16}$$
$$\forall jk = fl, fr, rl, rr$$

$$\dot{r} = \begin{cases} +0.05\ rad, & if\ T_{tjk} \leq 2\ meter \\ 0, & if\ T_{tjk} \geq 2\ meter \\ -0.05\ rad, & if\ T_{tjk} \leq 1\ meter \end{cases} \tag{17}$$
$$\forall jk = fl, fr, rl, rr$$

If the vehicle is going further from the obstacle, then the yawing rate will turn to its original value, which is zero for this work, and thus will lead the vehicle to its original trajectory. The 2 meter safe distance is used in accordance with the informal ‘two-seconds-rule’ that is being used worldwide [17], while the ISO 2631-1 standard was utilized as the benchmark to ensure a suitable comfort level while avoiding the obstacles [12].

E. Vehicle Collision Avoidance Control

The authors are proposing a GMC-based controller for the work in this paper. It is derived after the work of [12]. The controller is used with intention as a path following controller, to follow the reference path that have been created in previous block of Trajectory Replanner. The whole architecture of the VCA system is displayed in Figure 4.

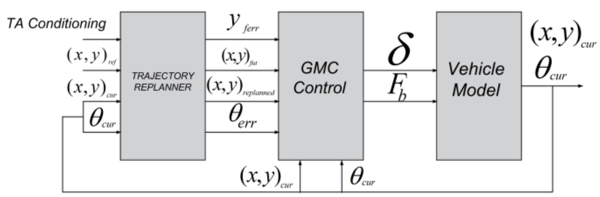

Figure 4: Overall architecture of VCA system. The GMC will be activated once the TA-threshold is violated.

F. VCA using Geometrical Method Control (GMC)

The GMC method used the calculations of the vehicle kinematics in order to output the desired steering angle that can follow the reference trajectory, in the case of obstacle's occurrence. The calculation for the coordinate errors is shown below:

$$x_{err} = cos\theta_{cur} \cdot (x_{ref} - x_{cur}) + sin\theta_{cur} \cdot (x_{ref} - x_{cur}) \quad (18)$$

$$y_{err} = -sin\theta_{cur} \cdot (x_{ref} - x_{cur}) + cos\theta_{cur} \cdot (x_{ref} - x_{cur}) \quad (19)$$

$$\theta_{err} = \theta_{ref} - \theta_{cur} \quad (20)$$

where x_{err} and y_{err} are both the (x, y) coordinate error respectively and θ_{err} is the vehicle heading error. $(x, y)_{ref}$ is the reference vehicle coordinates and θ_{cur} is the vehicle current heading.

The GMC acts based upon the idea of yaw rate tracking. This means the controller will generate a collision-avoidance steering angle when the lateral error (difference between replanned path and current path) is increased. This will then turn the vehicle towards the reference path, thus avoiding the obstacle. The formulations are described below:

$$x_{fut} = l \cdot \cos\theta_{cur} + x_{cur} \quad (21)$$

$$y_{fut} = l \cdot sin\theta_{cur} + y_{cur} \quad (22)$$

$$y_{ferr} = -sin\theta_{cur} \cdot (x_{ref} - x_{fut}) + cos\theta_{cur} \cdot (y_{ref} - y_{fut}) \quad (23)$$

where y_{ferr} is the vehicle's future trajectory deviations error, x_{fut} and y_{fut} are the future predictions of the vehicle's (x, y) coordinate and l is the distance from the vehicle and its future position.

The nonlinear controller formulation for the VCA using GMC is denoted below:

$$\delta_{GMC} = sin\theta_{err} + \frac{K \cdot y_{ferr}}{V} \quad (24)$$

where δ_{GMC} denotes the evasive VCA steering action using GMC method and K is the gain of the controller. Results from the simulations using this controller are shown in following section. Figure 5 depicts the formulations of future trajectory error tracking.

G. Constraints

To allow the vehicle to return to its original path after VCA maneuver happened, several constraints need to be put into considerations. These include the constraints on the lateral positions, y_{cur}, the tire slip angles, α and the steering input to the plant:

$$-y_{max} \leq y_{cur} \leq y_{max} \quad (25)$$

$$-\alpha_{max} \leq \alpha_{cur} \leq \alpha_{max} \quad (26)$$

$$-\delta_{max} \leq \delta_{GMC} \leq \delta_{max} \quad (27)$$

Tire slip angles, α need to be constrained to avoid the vehicle from sliding out of the lane. This section is based on the work of [11].

III. Simulation And Results

A. Simulation Descriptions

To verify that the GMC method can work as a VCA algorithm controllers, the authors have done computer simulations, where the aim is for the vehicle to avoid the obstacle by following the replanned path from the path replanner. GMC acts as the path following controller. The simulation only covers the static obstacle avoidance, and the vehicle is assumed to be moving in a straight line with a constant velocity. Simulation is done using MATLAB Simulink platform and the parameter that is used in the simulations is presented in the Table 1.

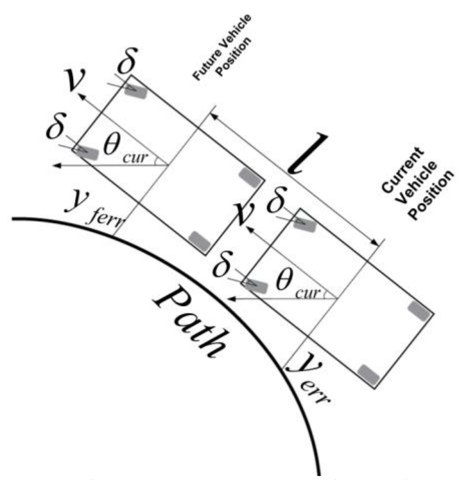

Figure 5: Coordinate of host and current vehicle to find the future lateral error.

Table 1
Parameters used in the simulations.

Mass (g)	
Vehicle Mass, m_t (kg)	1529.98
Vehicle Track Width, w (m)	1.55
Distance of Vehicle COG from front axle, l_f (m)	1.14
Distance of Vehicle COG from rear axle, l_r (m)	1.64
Coefficient of Friction, μ (N)	0.85

B. Results and Discussions

The results show that the controller demonstrated the ability of avoiding the collisions, and return to its original path. The GMC-based controller is able to manipulate the steering input to the vehicle model and smoothly avoiding the collisions while slowing down the velocity (Figure 8).

The black square in Figure 6 represents the invisible rectangle region around the obstacle that the TA Strategy calculated. The simulation results proved that the vehicle managed to avoid any collision with the obstacle's edges, even for a circular obstacle. This shows that the inclusion of TA is profoundly helpful for a good VCA algorithm. However, due to the inability of the GMC to include multivariable conditions into its calculations, the braking force input into the vehicle model is neglected.

Vehicle Velocity is shown in Figure 8, where the vehicle can be identified as slowing down while avoiding the obstacle although there is no braking maneuver happening. This is due to the dynamic features of the vehicle. To further study about the integrations of low-level controller (braking, steering and throttle), GMC can be combined with other methods such as Model Predictive Controller (MPC), which is known for its ability to handle multivariable dynamic process of a vehicle active dynamics model.

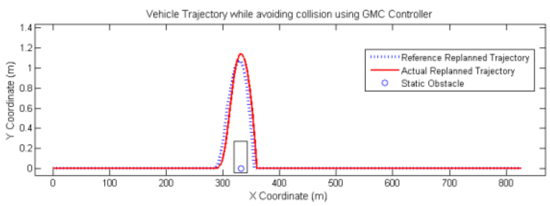

Figure 6: VCA using GMC method.

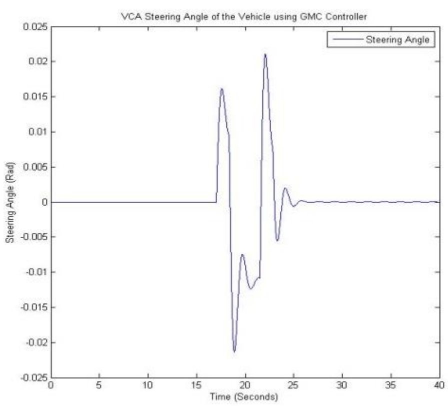

Figure 7: Steering angle using GMC Method.

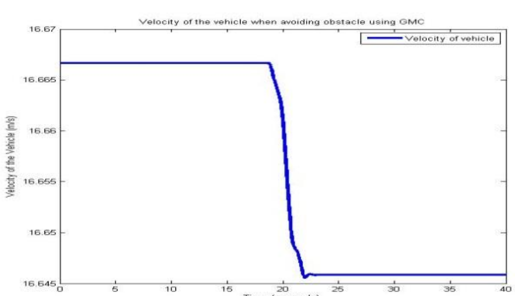

Figure 8: Vehicle Velocity while avoiding obstacle using GMC Method.

IV. Conclusion And Future Works

In this work, GMC is proposed for the Vehicle Collision Avoidance algorithm. It acts as the replanned trajectory follower controller and the maneuver is done by manipulating the model variables, i.e. the steering input to allow the vehicle to avoid the potential collisions and eventually return to its original path, which in the work is the straight line path. Also shown is the inclusion of safe-distance Threat Assessment strategy for VCA. By having simulations done, it is proven that GMC and TA are both in needs of each other to perform a successful VCA. GMC can be better improved in the future by having a trajectory replanner which includes the full vehicle dynamics such as its lateral and longitudinal forces, the inertia and its body slip. In the occurrence of a failed VCA maneuver in an emergency high speed scenario (which has very little percentage to happen), a full deceleration maneuver with considerations of the vehicle stability can be developed and included into the VCA architecture. Further works include the implementation of the algorithm on a real-vehicle and the expansion of the algorithm into dynamic VCA.

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