An Autonomous Navigation Algorithm for UGV and its 3D Graphical Simulation

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Abstract: This paper proposed an algorithm and 3D graphical simulation approaches for autonomous navigation of UGV(Unmanned Ground Vehicle). The autonomous navigation algorithm is proposed for the environment where the vehicle is navigating on a multi-lane road with other multiple vehicles. The algorithm for autonomous navigation is mainly focused on seeking the optimal trajectory to avoid collisions with adjacent multiple vehicles navigating on multi-lane road environment. The 3D graphical simulation model is constructed to visualize the autonomous navigation control and verify the proposed algorithm and the control system.

Key-Words: UGV(unmanned ground vehicle), autonomous navigation, 3D graphic simulation, collision avoidance

1 Introduction
In recent decades, there have been growing interests in control for application to automated highway systems and driver assistance systems. As the driver is limited in recognizing, judging and operating in hazardous situations, accidents are practically inevitable. It has also been known that many of the car accidents are due to human errors. If the human driver limits can be overcome by automating some parts of the driving tasks, many of the accidents can be avoided. Based on the belief that vehicle automation can reduce the risk of accidents, improve safety, increase capacity and enhance overall comfort and performance of drivers, many researches on automating some or all aspects of driving task has been presented [1][2].

Early researches in the late 1980s and beginning of 1990s were initiated to improve highway capacity and safety with automation in highway and vehicle level. Researches[3] on advanced highway systems were based on the idea of substitution human driving decisions and actions with more automated tasks to achieve regulated traffic flow and safe driving. Later the research interests switched from advanced highway systems to intelligent vehicle systems. Many researches have been presented to introduce adaptive cruise control and other advanced features like collision warning and avoidance systems into products.[4]

Recently, the higher level control schemes[5][6] have been studied to determine the desired motion of the vehicle for autonomously controlling the vehicle itself under the condition that sufficient information about the vehicle environment such as the state of vehicle with respect to other vehicles and the road, onboard sensors are given. Moreover, studies on the vehicle to vehicle communication are recently presented to provide the information.

This paper focuses on the 3 dimensional graphic simulation of the higher level control schemes to determine the desired motion for autonomous navigation and collision avoidance, under the condition that position and velocity information of neighbor vehicles is available from vehicle to vehicle communication. The autonomous navigation algorithm is proposed for the environment where the vehicle is navigating on a multi-lane road with other multiple vehicles. The algorithm for autonomous navigation is mainly focused on seeking the optimal way to avoid collisions with adjacent multiple vehicles navigating on multi-lane road environment. The trajectory for the controlled autonomous vehicle to track is assumed to be given from road map and global positioning in this paper.

In order to visualize the autonomous navigation control and verify the proposed algorithm, a 3D graphical simulation model is constructed. The 3D graphical model of multiple vehicles and road environment is constructed on Matlab Simulink with VRML(Virtual Reality Modeling Language) description and combined with the dynamic control model of the autonomous navigation. In this paper, the controlled vehicle is simulated with 7 other vehicles on 3-lane road environment under various navigation situations.

2 Trajectory tracking of car-like vehicle
Since the autonomous navigation of UGV in this paper is based on the optimal navigation road lane selection and
trajectory tracking control, we shall first describe the trajectory tracking control of car-like vehicle. The kinematic model of car-like vehicle shown in fig.1 is given in [7] as follows.

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} = 
\begin{bmatrix}
\alpha \dot{\theta} & \dot{\alpha} \\
\dot{\alpha} & \rho
\end{bmatrix}
\begin{bmatrix}
v_1 \\
v_2
\end{bmatrix} + 
\begin{bmatrix}
0 \\
0
\end{bmatrix}
\]

where \(v_1\) and \(v_2\) are the driving and the steering velocity input.

The generalized coordinates are \(q = (x, y, \theta, \phi)\), where \(x, y\) are the Cartesian coordinates of the real wheel, \(\theta\) measures the orientation of the car body with respect to the \(x\) axis, and \(\phi\) is the steering angle. Using the change of coordinates

\[
x_1 = x \\
x_2 = k\tan\phi / l\cos^3 \theta \\
x_3 = k\tan\theta \\
x_4 = y
\]

together with the input transformation

\[
v_1 = u_1 / \alpha \theta \\
v_2 = -3k\phi \sin^2 \phi u_1 / l\alpha \sec^2 \theta + l\alpha \cos^3 \theta \alpha \sec^2 \phi u_2
\]

the kinematic model (1) can be converted into chained form

\[
\begin{align*}
\dot{x}_1 &= u_1 \\
\dot{x}_2 &= u_2 \\
\dot{x}_3 &= x_2 u_1 \\
\dot{x}_4 &= x_3 u_1
\end{align*}
\]

For the chained form model, the nonlinear dynamic feedback controller is derived as follows.[7]

\[
\begin{align*}
u_1 &= \xi_1 \\
u_2 &= (r_2 - x_3 r_1 - 3 x_2 \xi_1 \xi_2) / \xi_1^2 \\
\xi_1 &= \xi_2 \\
\xi_2 &= r_1
\end{align*}
\]

The control inputs \(r_1\) and \(r_2\) for obtaining globally stabilizing feedback for the desired trajectory are

\[
r_1 = \dot{z}_d + k_{al}(\dot{z}_d - z_i) + k_{al}(\dot{z}_d - z_i)
\]

where the feedback gains are such that the polynomials

\[
\lambda^3 + k_{al}\lambda^2 + k_{al}\lambda + k_{pi}, \quad i = 1, 2
\]

are Hurwitz.

Figure 2 shows the trajectory tracking of the nonlinear dynamic feedback control when the controlled vehicle is changing the navigating road lane. As we can see from figure 2, the controlled vehicle tracks the desired navigation trajectory with fairly good performance. Thus, choosing the proper navigation road lane and generating the associated lane changing trajectory can make the controlled vehicle to navigate safely with avoiding collision with neighboring vehicles.

3 Autonomous navigation algorithm

In the advanced navigation control systems, certain types of vehicle to vehicle communications are required to provide data for other vehicle driving information such as position and velocity. In this paper, we simulate a safe lane choosing algorithm and the trajectory tracking for an automated vehicle that plans its navigation trajectory.

The simulation includes lateral and longitudinal control, maintenance of collision avoidance with neighboring vehicles. In order to generate a proper trajectory for autonomous vehicle navigating on predefined track, it should be determined whether the driving lane is changed or not, and the desired driving and steering velocity to track the predefined driving path should be determined. An algorithm for generating appropriate trajectory for autonomous vehicle is presented by determining the safer lane and appropriate acceleration.

In this paper, it is assumed that current position and velocity of the nearest neighbors in front and behind of controlled vehicles are given by information from vehicle to vehicle communication. We shall use the symbols \(x^f(t), x^b(t), x^o(t), \) and \(x^p(t)\) to denote the
longitudinal position of vehicles in front and behind of the controlled vehicle on the current lane and other lane, respectively. Under the situation that vehicles are navigating on a track, the path for vehicles to navigate is predetermined and the trajectory generation problem is to determine the lane to follow and the acceleration value to obtain the safer navigation. The procedures to determine the better driving lane and acceleration value is as follows.

Step 1: calculate the scope ranges $R_s^f, R_s^b$.

$$R_s^f = \alpha_{raw} \cdot v_c$$
$$R_s^b = \alpha_{raw} \cdot v_{max}$$

where $v_c$ denotes the driving velocity of the controlled vehicle and $R_s^f, R_s^b$ denote the forward and backward scope range.

Step 2: calculate the safety criterion $T_f^i, T_b^i, T_f^b, T_b^b$ of vehicles in nearest front and behind of the controlled vehicle within the scope range on the current lane and other adjacent lane. The safety criterion $T_f^i$ and $T_b^i$ means the estimated time to collision with the prior vehicle on the current lane and other lane, respectively, when the prior vehicle decelerate maximally whereas the controlled vehicle maintains the driving velocity as constant value. The criterion is calculated as follows.

If $\frac{v(0) - v(0) - v_c(0)}{a_{max}} - 2(x(0) - x_c(0)) > 0$, then $T_f^i = \frac{\sqrt{\left(v(0) - v_c(0)\right)^2 + 2a_{max}(x(0) - x_c(0))}}{\alpha_{max}}$.

else $T_f^i = \frac{1}{v_c(0)} \left(\frac{1}{x(0) - x_c(0)} + \frac{v(0)^2}{2a_{max}}\right)$ $i = c, o$.

The safety criterion $T_b^c$ and $T_b^o$ means the estimated time to collision of the maximally accelerating rear vehicle on the current lane and other lane, respectively, to the controlled vehicle with constant velocity.

If $\frac{(v_{max} - v(0))v_{max}v(0) - 2(v_c(0) - v(0))}{a_{max}} - 2(x(0) - x_c(0)) > 0$, then $T_b^i = \frac{\sqrt{(v_c(0) - v(0))^2 + 2a_{max}(x_c(0) - x(0))}}{\alpha_{max}}$.

else $T_b^i = \frac{\left(x(0) - x_c(0)\right)v_{max}v(0)}{v_c(0)v_{max}}$ $i = c, o$.

Step 3: determine the driving lane and acceleration

If $\max \left(T_f^i, T_b^i, T_f^b, T_b^b\right) = T_f^i$ or $T_b^i$, then change the lane, else keep the current lane.

The appropriate acceleration value is determined as

$$a_c^i = \alpha_{raw} \cdot \left(T_f^i - T_b^i\right)$$
$$a_c^c = \alpha_{raw} \cdot \left(T_f^c - T_b^c\right)$$

where $a_c^i$ and $a_c^c$ denote the acceleration of the controlled vehicle on the current lane and other changed lane, respectively. The selected lane and acceleration value are provided to create the reference desired trajectory. Fig. 3 shows the overall flow to determine the proper driving lane and acceleration value of the controlled vehicle in the simulation where the controlled vehicle is navigating together with 7 other vehicles.

4 Simulation and results

Visual simulation is an affordable way to test the automated navigation control scheme because the real experiment is dangerous and time consuming, and various environment and driving situation should be tested for enhancing the reliability of the devised control scheme.

In this paper, the control scheme is simulated in Matlab Simulink and Virtual Reality (VR) toolbox under the 3D modeled driving environment described with Virtual Reality Modeling Language (VRML). The VR is a solution for interacting with virtual reality models of dynamic systems over time. The simulated driving
environment is modeled by 3D virtual reality model with VRML using Cosmo Worlds which is shown in fig. 4. The controlled vehicle is simulated under the environment where non-controlled vehicles are navigating with predetermined velocities and paths. We simulate and visualize the driving trajectories of the controlled vehicle together with non-controlled ones under 3D modeled virtual driving environment.

The simulated road has 3 lane track constituted with linear and circular path as shown in fig. 4. Initially, two non-controlled vehicles are positioned in front and behind of the controlled vehicle on a lane and two other non-controlled vehicles are placed on the each other lane. By varying the navigation trajectories of the neighboring vehicles, we could simulate the autonomous navigation algorithm under various driving situations.

The desired trajectory \( (x_d(t), y_d(t)) \) for the controlled vehicle to track is generated using the selected lane and path information together with the desired acceleration of the vehicle. With the desired trajectory \( (x_d(t), y_d(t)) \) and the nonlinear dynamic feedback controller (2)-(4), tracking control is accomplished and the simulation results of two cases are shown in figure 5 and figure 6.

Figure 5 shows the simulation results of the case when a neighboring vehicle cuts in the front of the controlled vehicle. The controlled vehicle is navigating on the lane 1 in the scene no. 1. The scene no. 2 shows that the controlled vehicle changes the navigation lane from lane 1 to lane 2 because the neighboring vehicle with no.1 cuts in the front of the controlled vehicle. The figure of scene no. 3 shows that the controlled vehicle changes its lane from lane 2 to lane 1 due to the vehicle no. 2 cutting in the front of the controlled vehicle. The scene no. 6 shows the scene that the controlled vehicle escapes to the lane 1 due...
to the vehicle no. 3. We can understand the scenes from lateral and longitudinal positions of the navigating vehicles in the figure (b). Figure (c) shows the variations of distance from controlled vehicle to each neighboring vehicles and the estimated time to collision which are used to determine the safe lane and acceleration of the controlled vehicle.

Figure 6 shows the simulation results of the case when a vehicle is approaching the controlled vehicle from behind with accelerated speed. In this case, similarly, we can understand the scenes in figure (a) from the lateral and longitudinal positions of controlled and neighboring vehicles shown in figure (b).

5 Conclusion

In this paper, an algorithm and 3D graphical simulation approaches have been presented for autonomous driving of unmanned ground vehicle. The trajectory planning scheme is based on the utilization of position and velocity information of neighbor vehicles which can be obtained by vehicle to vehicle communication in real situation.

The safety criterion has been proposed to evaluate which lane is safer from the point of time to collision. The acceleration value has been also determined to provide the desired driving velocity of the controlled vehicle based on the safety criterion. The proposed navigation control system has been investigated on the 3D graphical simulation model where the controlled vehicle has been simulated on multi-lane road and multiple vehicles environment. We have simulated various navigation situations by generating various trajectories of the neighboring vehicles. In this paper, simulation results are presented for two cases of navigating situation that can be frequently occurred in real world.

From the simulation results, we can mention that the presented autonomous navigation control and simulation model are well suited for simulation study of the autonomous navigation control.

References:

Fig. 6 Simulation of the case when a rear vehicle is approaching the controlled vehicle


