Tracking Control for Intelligent Tracing Car based on Novel Path Tracking Strategy

Lie Yu, Lei Ding and Yukang Tian

Abstract—**The intelligent tracing car is a complex system with high linearity, and the design of path tracking strategy is one of the most important technologies in intelligent tracing car field. This paper proposed a novel path tracking strategy based on control dynamic model of the intelligent tracing car. The vehicle dynamic models are established separately according to the vehicle parameters and kinetic equation. The traditional path tracking strategy used the distance between the desired and actual displacements to compute the error for position control. However, the paper utilized the past and current states of the desired displacement to figure out a motion vector. The error was acquired through calculating the difference between the desired and current displacements along this motion vector. Simulation results showed excellent performance in position control and speed control for the intelligent tracing car.**

Index Terms—**Intelligent tracing car; path tracking strategy; vehicle dynamic; position control; speed control**

I. Introduction

Recently, the intelligent vehicles have gained considerable attention from the research community and industry due to their suitability for carrying airport luggage, sightseeing vehicles, or taking multiple trailer [1]-[2]. The intelligent vehicles are complex systems in theory and technique, which consists of circuit design, sensing and control, embedded system and implementation, mechanical manufacture, and software programming [3]. The main goal of the intelligent vehicle technologies is to realize automatic driving robustly with high accuracy and efficiency.

Automatic driving is a complex and nonlinear problem which includes terrain identification, real-time localization and motion control [1]. Terrain identification is usually implemented through charge-coupled device (CCD) cameras to picture the terrains and convert the photograph into binary text images. Real-time localization is realized by decoupling the binary text images into the position and orientation of intelligent vehicles against the path. Meanwhile, motion control requires intelligent vehicles to track the desired path following the path tracking algorithm.

The aim of path tracking algorithm is to make the vehicles follow the track stably and response quickly by manipulating the tractor's velocity and steering direction [2]. One of the primary tasks in the path tracking algorithm is to explore the dynamic capabilities and improve its tracking strategy in order to drive faster on a given track [4]. Many researchers in the literature had presented their studies of path tracking algorithms. Sasiadek and Lu presented a path tracking method for autonomous load haul dump articulated vehicle, which developed a fuzzy logic control system for this intelligent vehicle to control the lateral and longitudinal motion [5]. Specifically, the lateral control would keep the vehicle along the planned path, while the longitudinal control could make the vehicle run at the designed speed. Olofssona and Nielsen proposed a high-performance path tracking algorithm for manipulators with actuator constraints [6]. The path to be tracked is assumed given, while the nominal trajectories are computed using time-optimal path tracking algorithm [7-8]. Path velocity control was developed to keep the speed along the tangent of the path, and handled the deviations along the transversal directions of the path. Nizard et al presented a nonlinear tracking algorithm for autonomous bi-steerable vehicles [9]. In this design, the reference path for manipulating the rear wheel was converted into two synchronized paths, which introduced a new approach to compute the desired yaw rate for this vehicle without numerical derivatives. In order to design the proposed control law, accurate equations were used to describe the motion of the vehicle with respect to this "dual-path".

When the path tracking algorithm is determined, the control law should be built. Li et al. utilized the fuzzy logic control (FLC) to realize the human-like driving skills for an autonomous car-like mobile robot [10]. Four kinds of FLCs were selected to achieve the autonomous fuzzy control. The specific four types of FLC are listed as fuzzy garage-parking control, fuzzy wall-following control, fuzzy parallel parking control and fuzzy corner control. Low and Wang proposed a GPS-based tracking controller for a car-like wheeled mobile robot [11]. This controller used the GPS and aiding sensors to monitor the posture, speed, and perturbations to compensate the control strategy. Indiveri presented a closed loop control law to implement the time-invariant and stable control for a bicycle-like kinematic model [12]. The linear speed remained arbitrary small to avoid the relatively large accelerations and the problem of actuator saturation. As a result, the proposed law could adopt to the planar control of automatic vehicles which was required to run in one specified direction. Meanwhile, this solution was to avoid the cusps in the paths and meed the need of a major requirement.

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In this paper, a novel path tracking strategy was presented based on the dynamic and kinetic model of the intelligent tracing car. The dynamic models had been established according to the system parameters and kinetic equation. The past and current states of the desired displacement were utilized to figure out a motion vector. The error was acquired through calculating the difference between the desired and current displacements along this motion vector. Position control and speed control had been conducted to ensure the stable control for the intelligent vehicle.

II. Simulation Modelling of Intelligent Tracing Car

As shown in Figure 1, intelligent tracing car could be introduced as a multiple rigid body system which is composed of mechanical components, embedded sensors, electrical actuator, and mechanical elements. Specifically, mechanical components consist of a car body, power source, two front wheels, two rear wheels and one steering engine. The front wheels are parallel, while could simultaneously turn to the desired orientation and position. The rear wheels are fastened parallel to the car chassis, while allowed the car to roll or spin but not slip. The steering engine is used to control the motion orientation of the front wheels. Embedded sensors include an encoder and a charge coupled device (CCD). Encoder is mounted with the wheel shaft of the front wheel to measure the rotational speed for the front wheel, and the linear speed can be deduced based on this rotational velocity. CCD is located above the car body to photograph the traffic situations which could be transferred into binary text images. The binary text images can be analyzed to acquire the desired displacements (i.e., orientation and position) where the car would arrive in the future period. Electrical actuator is a DC motor which is used to drive the front wheels to move to the desired position.

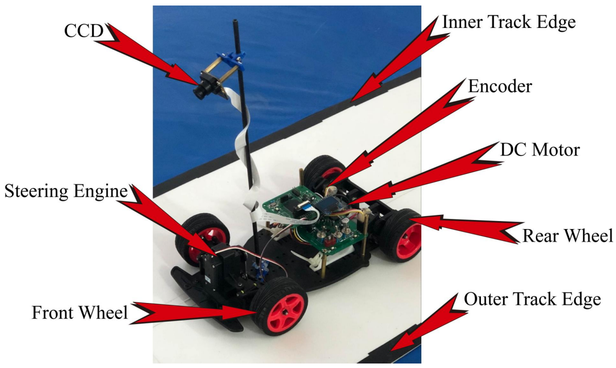

Fig. 1. Description of intelligent tracing car.

A. Kinematic Model of Intelligent Tracing Car

The intelligent tracing car under consideration is drafted in Figure 2. As the car is driven by the DC motor and steering engine, the total machine dynamics of intelligent tracing car is considered as follows:

$$\begin{cases} m\ddot{v} = F_M - F_f \\ J\ddot{\phi} = T_S \end{cases} \tag{1}$$

where m and v are severally the mass and moving speed of the car. F_M is the driving force generated by the DC motor, while F_f is the frictional force which hinders the car to move. J is the rotational inertia of the parallel front wheels, ϕ is the steering angle for the front wheel turning to, and T_S is the driving torque generated by the steering engine.

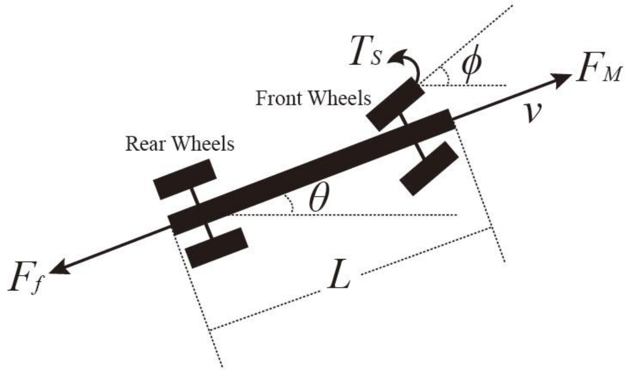

Fig. 2. Schematic diagram of intelligent tracing car.

In theory, the driving speed v is expected to be "the faster, the better". However, in fact, the traffic situations collected by the CCD are limited such that the car would run out of the pathway on a sharp bend at a super fast speed. As a result, the intelligent tracing car is set to move at an appropriate and constant speed. Therefore, the DC motor generates the driving force which overcomes the frictional force and accelerates the car to move. When the moving speed exactly arrives at the setting speed, the driving force only counteracts the frictional force (i.e., F_M=F_f). In the motion process, on one hand, when the moving speed is smaller than the setting speed after a sharp bend, the driving force would be enhanced to accelerate the car. On the other hand, when the fictional force suddenly reduces at a relatively smooth pathway, the driving force would attenuate to decelerate the car.

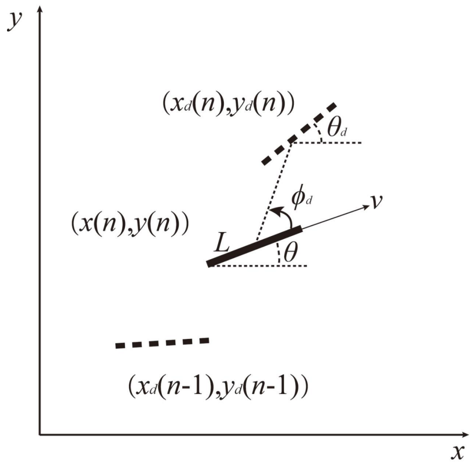

Fig. 3. Modeling of tracking pathway for intelligent tracing car.

As to the modeling of the intelligent tracing car, the moving speed v is constant. Consider the intelligent tracing car placed at a non-zero distance with respect to the desired displacement, the car should move from the actual displacement ($x(n)$, $y(n)$) to the desired displacement ($x_d(n)$, $y_d(n)$), as pictured in Figure 3. In fact, the desired position ($x_d(n)$, $y_d(n)$) is figured out through analyzing the binary text images photographed from the CCD. Then, the total dynamic of the intelligent tracing car can be described as

$$\begin{cases} \dot{x} = v \cdot \cos(\theta) \\ \dot{y} = v \cdot \sin(\theta) \end{cases} \quad (2)$$

where x and y are the Cartesian positions of the car with respect to the earth, θ is the angle between the car body orientation and the x-axis. The car should turn the current orientation θ to the orientation of θ_d. The car moves well when the error between θ and θ_d the is closed to be zero. With the knowledge of the current displacement ($x(n)$, $y(n)$) and desired displacement ($x_d(n)$, $y_d(n)$), the θ_d can be computed in the following.

$$\phi_d(n) = \arctan \frac{y_d(n) - y(n)}{x_d(n) - x(n)} - \theta(n) \quad (3)$$

For simulation, the desired displacement is given in advance, and the desired orientation is computed based on Equation (3). In fact, both the desired displacement and orientation are figured out through analyzing the binary text images photographed from the CCD. Then, the path tracking strategy should be presented to control the car.

B. Traditional path tracking strategy

Published studies presented their path tracking strategy that the car moved from the actual displacement ($x(n)$, $y(n)$) to the desired displacement ($x_d(n)$, $y_d(n)$), which is pictured in Figure 3. The tracking goal is to narrow down the error between the actual and desired displacements. Under ideal conditions, this error should be controlled to be zero. The error can be described as:

$$\Delta d(n) = \sqrt{(x_d(n) - x(n))^2 + (y_d(n) - y(n))^2} \quad (4)$$

Obviously, the exists a square-root function in Equation (4) such that it is difficult to minimize this error. To solve this problem, Aicardi transferred the formula in Cartesian coordinate into the equivalent formula in polar coordinate [13-15]. However, it is complicated to build a valid controller to make the whole system robust. As presented in [15], Indiveri stated that the controllers described in [13-14] couldn't be ensured to actuate the car along with a desired trajectory. Therefore, Indiveri used a modified method for the trajectory tracking controller in order to be compliant with the Ackermann steering kinematics. On the other side, Bascetta established a natural coordinates to modify the kinematic model to parametrise the desired trajectory with the result that acceptable performance was acquired after experiment validity.

C. Proposed path tracking strategy

It was first hypothesized that there would exist one kind of alternative method to figure out the error between the current and desired displacements without square-root function [16]. From the Equation (2), if the steering angle θ and the position y are known, the position x could be figured out. Based on this, the error between the desired and actual position could be simplified as:

$$\Delta\tilde{d}(n) = [y_d(n) - y(n)] + \hat{d} \quad (5)$$

where $\hat{d}$ is the estimated disturbance of this simplified model.

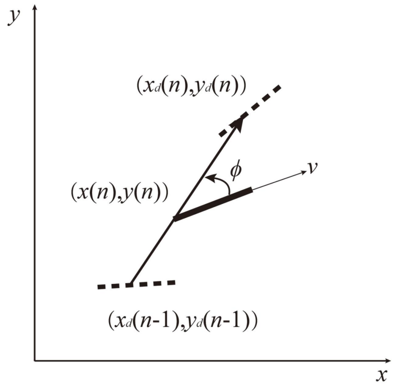

Fig. 4. The proposed path tracking strategy.

In this paper, we presented a new path tracking strategy that the desired displacement in the last period ($x_d(n\text{-}1)$, $y_d(n\text{-}1)$) is considered such that the current displacement should be controlled to follow the direction from ($x_d(n\text{-}1)$, $y_d(n\text{-}1)$) to ($x_d(n)$, $y_d(n)$), which is depicted in Figure 4. Therefore, the error of the displacement and angle could be rewritten as:

$$\begin{cases} \Delta\tilde{d}(n) = [y_d(n) - y(n)] + \hat{d} \\ \phi_d(n) = \arctan \dfrac{y_d(n) - y_d(n-1)}{x_d(n) - x_d(n-1)} \text{-} \theta(n-1) \end{cases} \quad (6)$$

As the car is expected to follow the direction from ($x_d(n\text{-}1)$, $y_d(n\text{-}1)$) to ($x_d(n)$, $y_d(n)$), there must exist the disturbance in this direction. As a result, the disturbance $\hat{d}$ could be designed as follow.

$$\hat{d} = k \cdot \frac{y_d(n) - y_d(n-1)}{x_d(n) - x_d(n-1)} \cdot [x_d(n) - x(n)] \quad (7)$$

where k is the gain. To simplify the Equation (7), it can be extracted as the following formulas.

$$\begin{cases} \Delta\bar{x}_d = x_d(n) - x_d(n-1) \\ \Delta\bar{y}_d = y_d(n) - y_d(n-1) \end{cases} \quad (8)$$

Then, the Equation (6) could be described as:

$$\Delta\tilde{d}(n) = [y_d(n) - y(n)] + k \cdot \frac{\Delta\bar{y}_d}{\Delta\bar{x}_d} \cdot [x_d(n) - x(n)] \quad (9)$$

However, if the car moves at a straight line which is parallel to the x-axis, the value of $\Delta\bar{x}_d$ would happen to be zero such that the Equation (9) would lead to being towards infinity. Therefore, in order to make the whole system robust, the square-root function only involving $\Delta\bar{x}$ and $\Delta\bar{y}$ is used to substitute the $\Delta\bar{x}$, which can be described as:

$$\Delta\tilde{d}(n) = [y_d(n) - y(n)] + k \cdot \frac{\Delta\bar{y}_d}{\sqrt{\Delta\bar{x}_d^2 + \Delta\bar{y}_d^2}} \cdot [x_d(n) - x(n)] \tag{10}$$

As a result, the controller could be deduced to make the car follow the designed trajectory.

D. Controller design

In fact, the car was manipulated by two controllers. Specifically, the first controller was used to activate the DC motor driving the car to move, while the other one was to initiate the steering engine rotating the car to turn. The aim of the first controller was to make the car follow the track and minimize the position error to be zero [17]. Meanwhile, the output was figured out based on the error between the desired (i.e., θ_d) and actual (i.e., θ) turning orientation, while the aim of the proposed controller was to turn the car as expected and minimize the orientation error to be zero. As the steering angle ϕ and orientation angle θ are both affected by the driving torque, their differential values would be similar. Moreover, the steering angle would decrease, while the orientation angle would increase. Therefore, the following result would be gained.

$$\dot{\phi}_d(n) \approx -\dot{\theta}(n) \tag{11}$$

From Equation (2-3), the actual positions (i.e., x and y) of the car both correlate with the actual turning orientation (i.e., θ), while the desired turning orientation (i.e., θ_d) is related to the actual positions (i.e., x and y). Meanwhile, the steering angle (i.e., ϕ) is related to the turning velocity (i.e., w) which is the differential form of θ. Therefore, for simulation, neglecting the dynamics of rotor and steering engine, only one controller could be built with the output of w, as pictured in Figure 5. As a result, the control law could be expressed as:

$$\dot{\phi}(n) = \alpha \cdot \Delta\tilde{d}(n) + \beta \cdot \phi_d(n) \tag{12}$$

where a and β are the controller gains. The selections of a and β in this controller are expected to realize the aims for the two controllers.

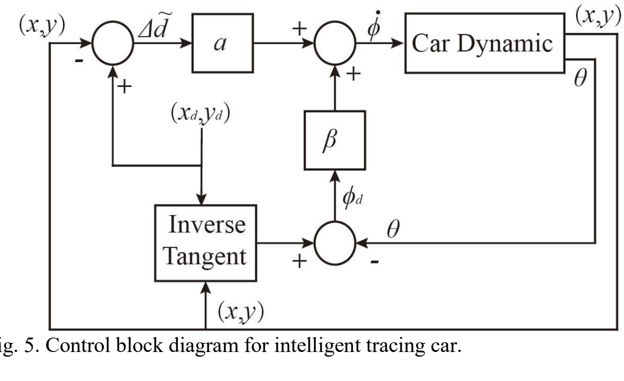

Fig. 5. Control block diagram for intelligent tracing car.

III. Results

A. Selection of System Parameters

Actually, the intelligent tracing car was set to move at a constant speed, as the CCD could only photograph the traffic situations at a short distance. If variable speeds and high speeds were severally used to manipulate the car, stable and robust control couldn't be ensured at the sharp bending of round track with a short radius. As a result, these situations would lead to the car running out of track frequently, because effective adjustments couldn't be achieved at a short distance. Therefore, the car speed was set to be 0.5 m/s. According to Equation (1), at the beginning, the driving force (i.e., F_M) is larger than the frictional (i.e., F_f) force, which could accelerate the car. If the car speed reaches 2 m/s, F_M equals F_f, and the acceleration $\ddot{v}$ was zero. In order to demonstrate the control effect, the intelligent tracing car is simulated with the following nominal parameters: m=2.64 kg and L=0.3 m.

As to the controller gains, a and β are chosen using the method of exhaustion with the range from 0 to 10. As a result, optimum gains are obtained that a=4.93 and β=5.26.

B. Simulation results

For simulation, the track were set to be a circular track. As depicted in Figure 6, the car was expected to move in the middle of the track. The desired positions (i.e., x_d and y_d) were given in the form of mathematical functions, and the car exactly followed the desired position as expected. The traditional and proposed path tracking strategies are both conducted under the given track. Figure 7 shows the control results of the two path tracking strategies. On the half way, the two path tracking strategies have the similar control effect. However, on the other half way, the traditional method is slightly off track at the beginning, and follow the track closely at the rest of the way as depicted in the enlarged part of Figure 7. The proposed method keeps up with the track closely at the whole way.

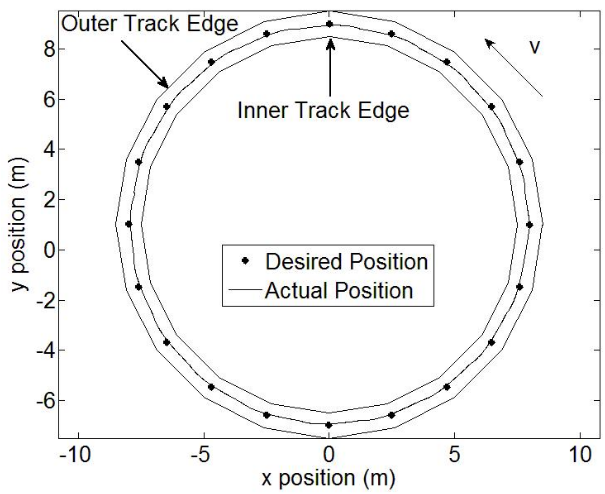

Fig. 6. Configuration of the circular track.

To obtain a more clear comparison, the orientation angle is chosen. As depicted in Figure 8, the actual angle from the traditional method followed the reference angle closely at the beginning, vibrated around the reference angle, and deviated the reference angle finally.

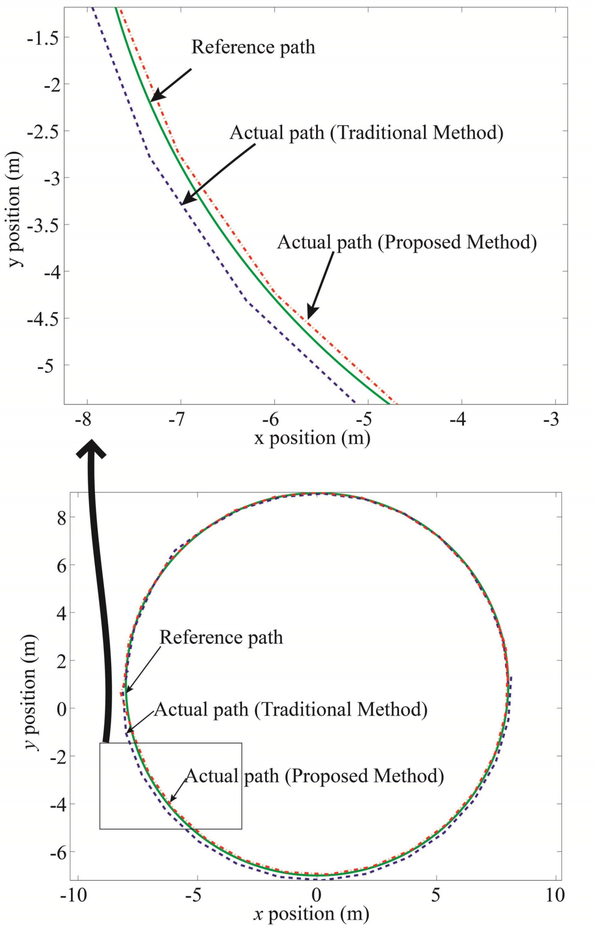

Fig. 7. Control effects of two path tracking strategies.

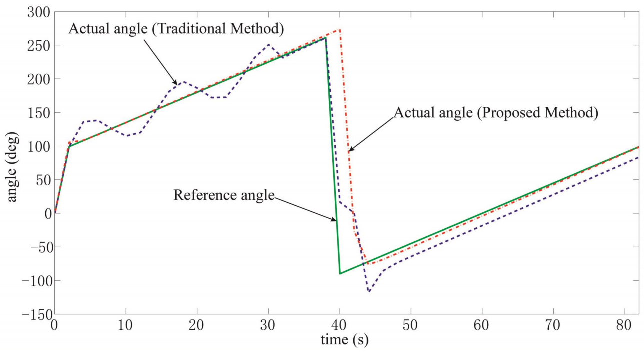

Fig. 8. Angle track of two path tracking strategies.

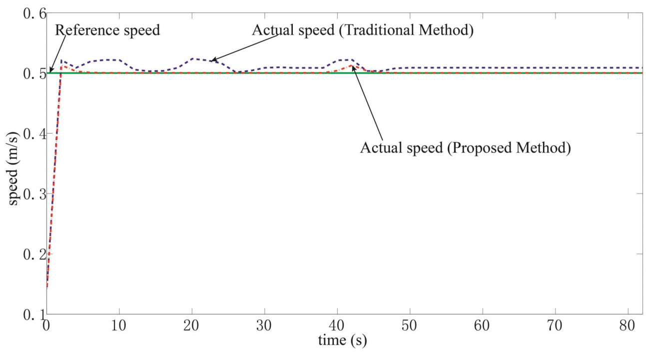

Fig. 9. Speed change under two path tracking strategies.

However, the actual angle from the proposed method kept up with the reference angle closely at the most way, and only deviated the reference angle for a short time in the middle way. As the car was set to run at a fixed speed, the speed change was pictured in Figure 9. Under the two path tracking strategies, the rise time of speed is almost the same. However, the proposed method possessed less overshoot and tracking error with the result that the car ran more smooth and steady under the control of the proposed path tracking strategy.

IV. Conclusion

This paper built the dynamic modeling of intelligent tracing car according to the vehicle parameters and kinetic equation. Position control and speed control had been conducted to ensure the stable control for the intelligent tracing vehicle, while the speed was set to be constant. A new path tracking strategy is proposed to utilized the past and current states of the desired displacement to figure out a motion vector. Based on the path tracking strategy, the controller is designed to minimize the displacement and angle errors. Simulation results showed the proposed path tracking strategy gains better performance than the traditional one in terms of displacement tracking, angle tracking and speed stability.

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