An Adaptive-PID Path Tracking Algorithm Based on High Accuracy Driving Map for an Autonomous Vehicle

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Abstract — **Trajectory tracking has been an important part of Autonomous vehicles, it is a reflection of the ability of vehicle with zero steady-state error tracking predetermined trajectory, and the error of lateral control depends mainly on nonlinear characteristics and trajectory in vehicle dynamics model of uncertainty. Therefore, this paper proposes an adaptive-PID control algorithm based on high accuracy driving maps, by using a preview factor which depends on the real-time speed and driving map curvature. The algorithm get the vehicle lateral error and heading error as input and output real-time steering angle in combination with the vehicle kinematics model and driving map model, it shows the better performance in high speed and large curvature on the road. This algorithm has been used in completely open road "Zheng-Kai road" first national test and won third position in 2014 Future Challenge of China.**

Keywords - Autonomous vehicle, trajectory tracking, high accuracy driving map, adaptive-PID control

I. INTRODUCTION

In recent years,the swift development of the technology of computer and Internet enterprise the automotive industry to make a revolutionary change happen. the intelligent vehicle technology which makes vehicle operation more simple and the driving safety better has been widely used in the meantime. The most popular future application of autonomous vehicle has been brought into focus in robotics field. The autonomous vehicle which is equipped with the intelligent software and a variety of sensors, including radar, GPS and camera is capable of decision-making and navigating by itself.

Path tracking problem is an important issues of autonomous vehicle. The problem of path tracking reflect the ability of the vehicle to driving with a predetermined trajectory with Minimum error. Path tracking problem of autonomous vehicle mainly include the following two problems, one is the deviation between the real-time trajectory and the predetermined trajectory. Another problem is the system characteristics of hysteretic feedback signal and how to ensure requirements of the real-time and stability of intelligent vehicle system.

A competitions named “Future Challenge of Intelligent Vehicles” is organized by the National Nature Science Foundation every year in China.Our autonomous vehicle named Jinglong One and Jinglong Two won the third and fourth position in the sixth competition of 2014 Future Challenge of Intelligent Vehicles which was held in Changshu city on Nov. 15, 2014 [1].

II. RELATED WORK

In recent years the research on the path-tracking control problem of autonomous vehicle has been paying more and more attention by many research institutions of domestic and international because of the motion state of vehicles has the characteristics of nonlinearity, time variation, uncertainty and so on. In the previous studies, Many theories have been put forward, a simple fuzzy PID controller is designed by Chen Huiyan which is established by two degree of freedom model of the vehicle and the control method has completed the lane keeping and improved the response speed of the system [2]. Another fuzzy PID control method with a combined compensation is proposed [3]. The method get location information of the vehicle by GPS senor, and set the yaw and lateral acceleration which is computed by comparing with the target path as the input signals to decide the steering wheel steering and speed according to the deviation and deviation change rate, the method correct the output by compensation control of fuzzy controller to achieve accurate tracking path of autonomous vehicle.These two methods also have the disadvantage of low precision and bad real time performance without considering the dynamic characteristics of the vehicle.

The method of trajectory tracking control include the traditional PID control theory [4,5], the control method of neural-network [6,7], the predictive control method [8], the fuzzy control method [9,10], the model reference adaptive method [11,12], the fractional-order control method [13].

There are also some improved algorithms based on the

PID control algorithm is discussed as below, adaptive PID control [14], adaptive PID control based on genetic algorithm [15,16] ,neural network adaptive PID control [17,18]and so on.

The control method introduced above do not consider the real-time environment of the driving, we put forward a model of driving map in this paper to appropriate for the control algorithm by the deviation of map and it is better than PID control.

In this paper we describe the adaptive PID control algorithm based on high accuracy driving map for the control system of vehicle, the paper is organized as follow: a driving map model is introduced in section 2;in section 3,the two degree of freedom bicycle model and the control system with feedforward PID control algorithm is introduced; and in section 4 the experimental results of multi-scene with different velocity are given.

III. DRIVING MAP MODEL

Digital map database, trajectory planning and trajectory guidance are three important modules in intelligent vehicle navigation system. A digital map database is necessary for the trajectory planning and trajectory guidance. Not only the common road and the roadside environment information from the digital map is necessary for the intelligent vehicle, but also the path planning of macro level and precise route guidance of micro.

There are several difference of the working environment between vehicles and robotic applications,the environmental information are mainly from real-time message of vehicle senor.The trajectory planning system will face the dynamic environment information even if the environment is static.moreover,The dynamic obstacles in the environment will also get the planning impracticable.The high speed vehicle is planed by not allowed to parking at the ending of planning. So The high accuracy driving map of intelligent vehicle is necessary to solve the problem of the higher requirements of real-time for the planning system.

This paper proposed a high accuracy driving map model which is a data mixture of image, radar and navigation sensor,and the driving map contains ten vehicle surrounding environment factors to assist the vehicle driving,The model as shown in Fig.1.

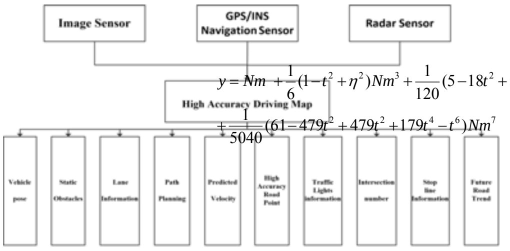

Figure 1. The framework of driving map

The geometric coordinate information from of the high accuracy of map road network provides positioning and trajectory guidance for autonomous vehicle, using high precision of the road network information, GPS or other sensor positioning results are used to match the high accuracy driving map to correct the position of vehicles.The vehicle position will be located an absolute position on the map while it is direct at one position from calculating.The the accumulated error will be eliminated after map-matching and the vehicle position will be more Accurately in every Continual periodic of system.A multiplex network of high precision map which is based on Beijing 54 Coordinate System is shown in Fig.2.

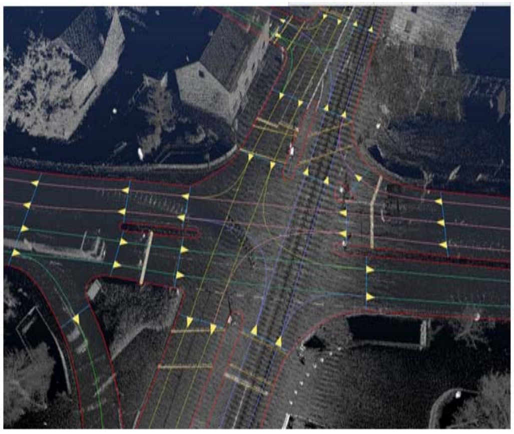

Figure 2. High accuracy driving map

The driving map based on geodetic coordinates can not satisfy the demand of trajectory planning for vehicle. So convert the geodetic coordinates to the plane coordinates by Gauss projection model, as is shown in Fig.3.

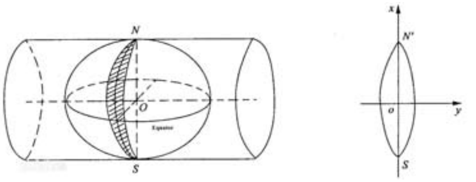

Figure 3. Gauss projection model

$$x = X + \frac{1}{2}Ntm^2 + \frac{1}{24}(5 - t^2 + 9\eta^2 + 4\eta^4)Ntm^4 + \frac{1}{720}(61 - 58t^2 + t^4)Ntm^6 + \frac{1}{40320}(1385 - 3111t^2 + 543t^4 - t^6)Ntm^8 \tag{1}$$

$$y = Nm + \frac{1}{6}(1 - t^2 + \eta^2)Nm^3 + \frac{1}{120}(5 - 18t^2 + t^4 + 14\eta^2 - 58\eta^2 t^2)Nm^5 + \frac{1}{5040}(61 - 479t^2 + 479t^2 + 179t^4 - t^6)Nm^7 \tag{2}$$

where X, m, l, t, η and N are defined as:

$$X = C_0 B - \cos B(C_1 \sin B + C_2 \sin^3 B + C_3 \sin^5 B) \tag{3}$$

$$m = l \cos B \tag{4}$$

$$l = L - L_0 \tag{5}$$

$$t = tgB \tag{6}$$

$$\eta = e'^2 \cos^2 B \tag{7}$$

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 B}} \tag{8}$$

Then get the plane coordinates into the grid map which is coordinates of the vehicle.

$$x_T = 50 + \sqrt{(x - x_1)^2 + (y - y_1)^2} * \sin(\theta - \theta_1) / 0.2 \tag{9}$$

$$y_T = 500 - \sqrt{(x - x_1)^2 + (y - y_1)^2} * \cos(\theta - \theta_1) / 0.2 \tag{10}$$

Here, (x_T,y_T) is the position of vehicle in the plane coordinates,(x,y) is the road point from the plane coordinates.

IV. MODEL OF CONTROL SYSTEM AND VEHICLE MODEL

The curvature of future road tendency is known according to the global map features of driving map road.this paper proposed a feedforward PID control algorithm based on the curvature of road.as shown in Fig.4, set lateral deviation error Δl , heading deviation $\Delta\theta$ and curvature ρ as input, the final output of PID control is the steering angle with the preview of driving map.

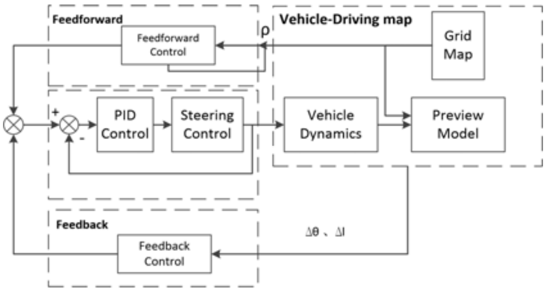

Figure 4. Control system model

In this paper, the state space of the vehicle model of two degree of freedom bicycle model is shown as Equation 11,12,And the bicycle model consists of both lateral and yaw acceleration with the neglected initial acceleration[19][20][21],we assumed the velocity is computed as constant:

$$\dot{x} = Ax + Bu \tag{11}$$

$$y = Cx + Du \tag{12}$$

Where：

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{13}$$

$$B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{14}$$

$$C = \begin{bmatrix} 1 & 0 \\ c_1 & c_2 \end{bmatrix} \tag{15}$$

$$D = \begin{bmatrix} 1 \\ d_1 \end{bmatrix} \tag{16}$$

with：

$$a_{11} = -\frac{c_f + c_r}{\mathrm{m}v_c} \quad a_{12} = -v_c - \frac{l_f c_f - l_r c_r}{m v_c}$$

$$a_{21} = -\frac{l_f c_f - l_r c_r}{I_z v_c} \quad a_{22} = -\frac{l_f{}^2 c_f + l_r{}^2 c_r}{I_z v_c}$$

$$b_1 = \frac{c_f}{\mathrm{m}} \quad b_2 = \frac{l_f c_f}{I_z}$$

$$c_1 = \frac{-l_f c_f + l_r c_r}{m v} \quad c2 = \frac{-(c_f + c_r)}{m}$$

$$d_1 = \frac{c_f}{m}$$

Table 1 Vehicle Parameters

Vehicle Parameter	Value
vehicle mass m/kg	1690
vehicle yaw inertia I_z/kg*m2	3201
wheelbase/m	2.755
distance COG-front axle l_f/m	1.524
distance COG-rear axle l_r/m	1.530
cornering stiffness of front tire C_f/N*rad-1	88000
cornering stiffness of rear tire C_r/N*rad-1	104000

We assumed the velocity of vehicle is 20m/s,it means v_c=20m/s,get the vehicle parameters which is given in Table 1 into Equation11,12we have:

$$\begin{bmatrix}\dot{v}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}-5.68 & -20.740\\ 0.391 & 0.025\end{bmatrix}\begin{bmatrix}v\\ r\end{bmatrix}+\begin{bmatrix}52.071\\ 41.897\end{bmatrix}\delta_f(t) \tag{17}$$

The controller in this paper is closely related to lateral deviation error Δl ,heading deviation $\Delta\theta$ and curvature ρ ,the final Steering Angle α is show in equation18.

$$\dot{\alpha}=m\Delta l+n\Delta\theta+k\rho \tag{18}$$

The model is shown in equation19.

$$\begin{bmatrix}\dot{v}\\ \dot{r}\\ \dot{\alpha}\end{bmatrix}=\begin{bmatrix}-5.68 & -20.74 & 0 & 0 & 0\\ 0.391 & 0.025 & 0 & 0 & 0\\ 0 & 0 & m & n & k\end{bmatrix}\begin{bmatrix}v\\ r\\ \Delta l\\ \Delta\theta\\ \rho\end{bmatrix}+\begin{bmatrix}52.071\\ 41.897\\ 0\end{bmatrix}\delta_f(t) \tag{19}$$

The transfer function of the controller is:

$$\begin{aligned}\mathrm{G}(s)&=C(sI-A)^{-1}B+D\\ &=\frac{47.23s^2-12.31s+2318}{s^4+3.098s^3+5.108s^2}\end{aligned} \tag{20}$$

Fig.5 shows the response time of PID control without feedforward.

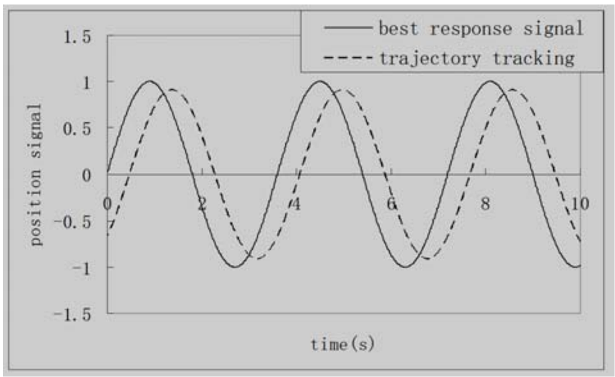

Figure 5. Position signal of Future Prediction PID

The controller system shows better performance with the Adaptive-PID algorithm,as is shown in Fig.6.

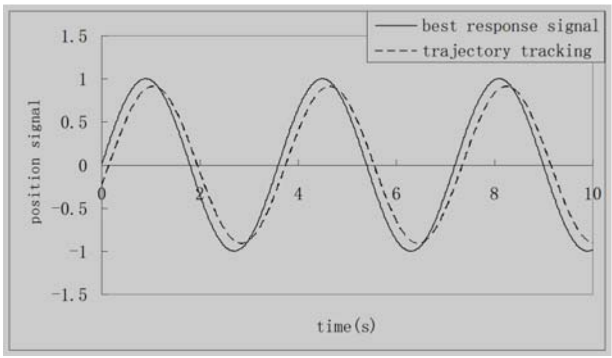

Figure 6. Position signal of Adaptive-PID

The PID controller is:

$$u(t)=K_p[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}] \tag{21}$$

Than:

$$u(k)=K_p[e_k+\frac{T}{T_i}\sum_{j=0}^{k}e_j+T_d\frac{e_k-e_{k-1}}{T}] \tag{22}$$

The adaptive-PID controller can be described as:

$$\begin{aligned}\Delta u_k&=u_k-u_{k-1}=K_p(e_k-e_{k-1}+\frac{T}{T_i}e_k+T_d\frac{e_k-2e_{k-1}+e_{k-2}}{T})\\ &=K_p(1+\frac{T}{T_i}+\frac{T_d}{T})e_k-K_p(1+\frac{2T_d}{T})e_{k-1}+K_p\frac{T_d}{T}e_{k-2})\\ &=Ae_k+Be_{k-1}+Ce_{k-2}\end{aligned} \tag{23}$$

The parameters of controller is shown below:

$$Kp=-k(e(k-1)+2e(k-2)) \tag{24}$$

$$Ti=-\frac{-(e(k-1)+2e(k-2))T}{e(k)+e(k-1)+e(k-2)} \tag{25}$$

$$Td=-\frac{e(k-2)T}{e(k-1)+2e(k-2)} \tag{26}$$

V. EXPERIMENTAL RESULTS AND DISCUSSION

The adaptive PID control system described in this paper have been used on Jinglong One autonomous vehicle. It is tested with different kinds of trajectories and different speed. The real-time road point is recorded by GPS/INS navigation equipment, update rate is 50Hz and the precision of position is 0.01-0.05m.Fig.7 shows the test of Beijing Union University playground, Future prediction PID control algorithm is left and adaptive-PID control algorithm is right(red trace is driving map, purple is real-time trajectory),The test is driven at a top speed of approximately 20km/h. The radius of curvature is 23m. Fig.8 shows Track error of the trajectory about two different algorithm and the adaptive-PID control algorithm is obviously superior to the future prediction control algorithm.

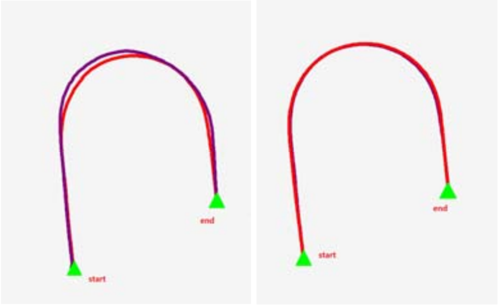

Figure 7. Actual trajectory and map trajectory

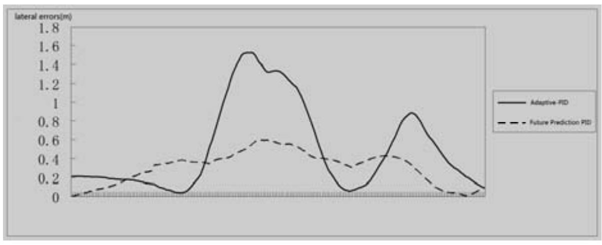

Figure 8. Track error of the trajectory

Fig.9 is a screenshot from Google Map which shows an example of a trajectory of YuanBoyuan Test Place. The 3-kilometre course driving of YuanBoyuan include four right-turn crossroads and two straight-turn crossroads, The vehicle drive in a clockwise with the maximum speed for 35km/s. The lateral error is shown in Fig.10 and Fig.11.

Figure 9. Yuanboyuan of test from Google Map

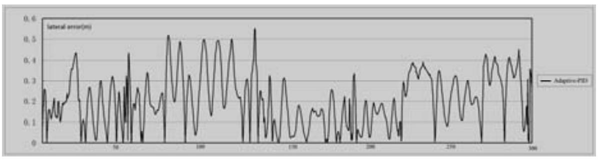

Figure 10. Track error of Yuanboyuan Test

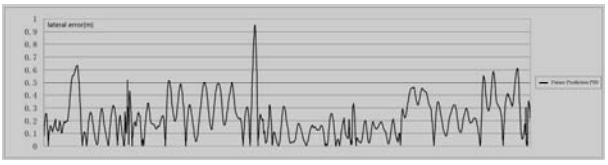

Figure 11. Track error of Yuanboyuan Test

Our intelligent vehicle Jinglong Two have participated in completely open road "Zheng-Kai road" first national test with the control system. The 32.6-kilometre course driving of Zheng-kai Road include 22 crossroads and beginning of test is The Jialu river subway station of ZhengZhou, ending is Dingyuan gate of KaiFeng, maximum speed is 35km/s.The lateral error is shown in Fig.12 and Fig.13.

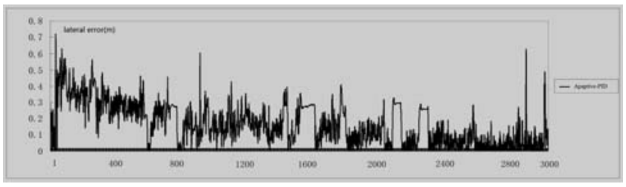

Figure 12. Track error of Zheng-Kai Road

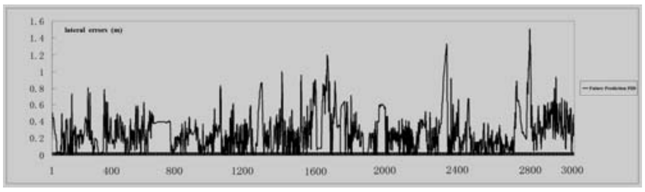

Figure 13. Track error of Zheng-Kai Road

Test Place	Algorithms	Max Speed	Max Errors	Average Errors	Variance
Yuan Boyuan	Adaptive-PID	35km/h	0.552m	0.207m	0.158
	Future Prediction PID	35km/h	0.95m	0.221m	0.341
Zheng-Kai Road	Adaptive-PID	50km/h	1.51m	0.418m	0.438
	Future Prediction PID	50km/h	0.718m	0.433m	0.122

TABLE 2 STATISTICS OF TRACK ERROR

The statistical data of Yuanboyuan and Zheng-kai Road test is shown in Table 2.The maximum lateral error of adaptive-PID algorithm is better than Future Prediction PID algorithm. But average error has hardly decreased at all. The adaptive-PID algorithm is applicable to larger lateral error.

VI. CONCLUSIONS

This paper proposed a high precision driving map model and a adaptive-PID algorithm of the feedforward control with the curvature of map which is applied to the steering control of the autonomous vehicles. This paper infers the relationship between steering wheel angle and the curvature of driving map by analysis of the vehicle dynamics model. The adaptive-PID control algorithm designed process of steering control of the autonomous vehicle which get the expected steering angle as the input of the control system. The experimental results Based on Multi-scenes prove the accuracy of path tracking with the adaptive-PID algorithm. The algorithm also has a disadvantage that we have only considered the lateral accuracy and ignored the stability of control system. We will improve the stability of the control system to make it better.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGMENTS

This research is fully supported by intelligent vehicle team of Beijing Union University. This project was supported by the Project of Construction of Innovative Teams and Teacher Career Development for Universities and Colleges under Beijing Municipality (IDHT20140508), and the major program is funded by National Nature Science Foundation of China (Grant No. 91420202). We thank Beijing Key Laboratory of Information Service Engineering for the vehicular. We also would like to thank Professor Qing Yang for his guidance and help in the process of writing our paper.

We would also like to acknowledge intelligent vehicle team of Beijing Union University for the contributions to developing the research.

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