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Design of Path Tracking Control System for UAV Based on Adaptive Preview Method

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Abstract

Because the simple preview tracking method cannot meet the requirements of UAV dynamic path tracking, a path tracking control system based on adaptive preview is designed. Firstly, the image information collected by the camera is sent through the monitoring module of the system, and the road information, such as obstacles is judged according to the TCP network communication protocol. Then, the corresponding operation instructions are sent to the bottom control module according to the monitoring information, and the image information collected by the camera is sent to the sensor through the monitoring module to build the line to judge the UAV kinematics Sex tracking error model. Finally, the future driving behavior of UAV is analyzed, and the adaptive preview time model is constructed to complete the trajectory tracking of UAV. Experiments show that the system is correct, adaptive preview has obvious advantages, and can accurately control the vehicle tracking the preset path.

Keywords: Adaptive preview; Unmanned vehicle; Path; Tracking control; Monitoring; Vehicle kinematics model;

1. Introduction

With the rapid development of China's economy, the scale of automobile production and marketing has shown an explosive growth, which has brought many practical problems: the number of deaths caused by traffic accidents in China is close to 200,000 every year, ranking the first in the world, while causing casualties, but also causing great social and economic losses, most of which are caused by the driver's misjudgment and uncivilized driving. As a result, serious traffic congestion has occurred in major cities in China, and major cities such as Beijing, Shanghai and Hangzhou have begun to limit the total number of cars. In addition, the long-term idling condition of the automobile engine severely reduces the engine's emission performance and causes serious pollution to the atmosphere (Zhang et al. 2017). These problems are not only caused by the lagging construction of traffic facilities, but also related to the unreasonable path planning and immature driving technology of drivers. The increasingly severe traffic problems force the government to strengthen the enforcement of traffic regulations, and at the same time promote the development of unmanned vehicles (Islam et al. 2017).

Unmanned vehicles were first born in the United States. In the early 1980s, the experimental prototype of the Autonomous Land Vehicle, which was funded by the U.S. Department of Defense, was born (Maeng et al. 2017). Limited to the backward sensor technology and control technology at that time, its driving speed was only 4.8 km/h, and it could not run in complex environment. As a technical verification vehicle, it demonstrated the autonomous environment recognition and obstacle avoidance of unmanned vehicle, and achieved the results of stage research (Dan et al. 2016). China's first unmanned vehicle was born in the early 1990s, limited to the technical level at that time, the vehicle still needs human intervention in the process of driving, cannot achieve full autonomous driving, and cannot drive in complex traffic environment (Guo et al. 2017). In 2000, the fourth generation of unmanned vehicle was born in Changsha, which adopted the latest electronic sensor technology at that time. The speed of the new car reached 76 km/h, and the performance of the unmanned vehicle was greatly improved (Ofodile et al. 2016). In 2011, based on the Red Flag car HQ3 of The Chinese FAW group, a new experimental prototype car with unmanned driving system developed by National Defense University of Science and Technology was assembled. The vehicle was tested at Changsha-Wuhan section of Beijing-Zhuhai Expressway. Along the road, it passed through the complicated sections of uphill and downhill, tunnel, wet and slippery road. The vehicle achieved complete autonomous driving in more than 96% of the time. It shows that China has entered the ranks of advanced countries in driverless technology (Tong 2016).

As the name implies, the unmanned vehicle is the vehicle that can perceive the driving environment and perform automatic acceleration, braking, steering, parking and tracking operations, while reaching its destination safely. These operations are based on a variety of on-board sensors and control algorithms (Fresk et al. 2016). In this

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paper, a path tracking control system for unmanned vehicle based on adaptive preview is designed to achieve high-precision path tracking control for unmanned vehicle.

2. Module description of system design

2.1. Design of system hardware

Unmanned vehicle can drive independently. The core of its system structure is "intelligence". It not only has conventional vehicle functions, such as acceleration, deceleration and steering, but also integrates intelligent monitoring (environment perception), behavior decision-making and path planning, vehicle control and other system functions. It can synthesize environment and self-driving information to achieve similar human driving behavior (Liu et al. 2016). This paper designs the structure of the path tracking control system for unmanned vehicle based on adaptive preview as shown in Figure 1, which is divided into three parts: monitoring module, planning decision module and bottom control module.

The monitoring module transmits the image information collected by the camera and the information of the sensor judging obstacles, roadsides and batteries to the monitoring terminal and the planning decision module through the TCP network communication protocol. The planning decision module transmits the corresponding operation instructions to the bottom control module according to the monitoring information (Xie et al. 2016).

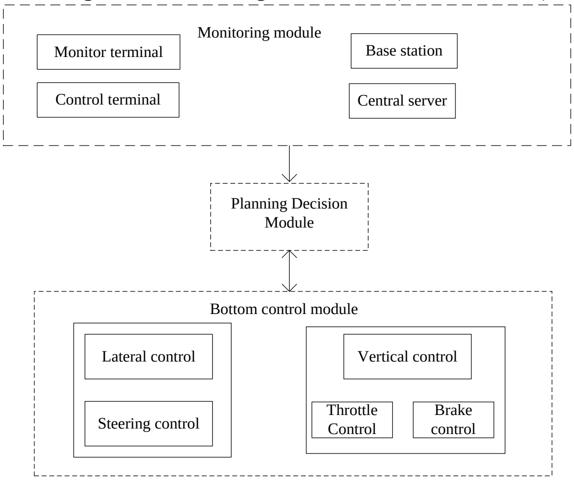


Figure 1. The overall structure of an unmanned vehicle path tracking control system based on adaptive preview

(1) Monitoring module

The module is mainly composed of an unmanned intelligent vehicle (data terminal), a server, a control terminal and a monitoring terminal, using the server and a client mode (Wen 2016). The working principle is that the unmanned vehicle transmits the information of the vehicle to the server through TCP network communication protocol. At the same time, the server transmits the information of the unmanned vehicle through TCP network communication protocol to the monitoring end and the planning decision module. The planning decision module transmits the corresponding operation instructions to the bottom control module according to the information. Figure 2 shows the principle and structure of remote monitoring system.

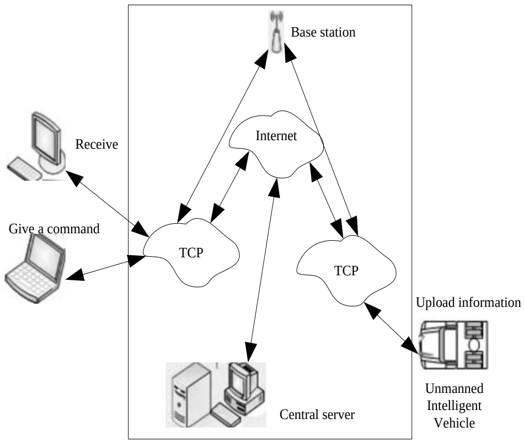


Figure 2. Principle and structure of remote monitoring system

In the remote monitoring module, the information of the unmanned vehicle is mainly positioned by the inertial navigation system (GPS). The encoder on the steering wheel collects the deflection angle of the direction of the vehicle. The camera of the unmanned vehicle collects image information and the information of sensor judging obstacles, road edges and battery (Gang et al. 2018).

(2) Planning decision module

The decision-making and planning module integrates the environment and self-driving information to produce safe and reasonable driving behavior and guide the motion control system to control the vehicle. The sub-module of behavior decision-making is a narrow decision-making module. It reasonably decides the current vehicle behavior according to the information output from the monitoring module, and determines the constraints of trajectory planning according to different behaviors. It guides the trajectory planning module to plan the appropriate path, speed and other information, and sends it to the bottom control module for tracking control. Figure 3 shows the structure of the planning decision module.

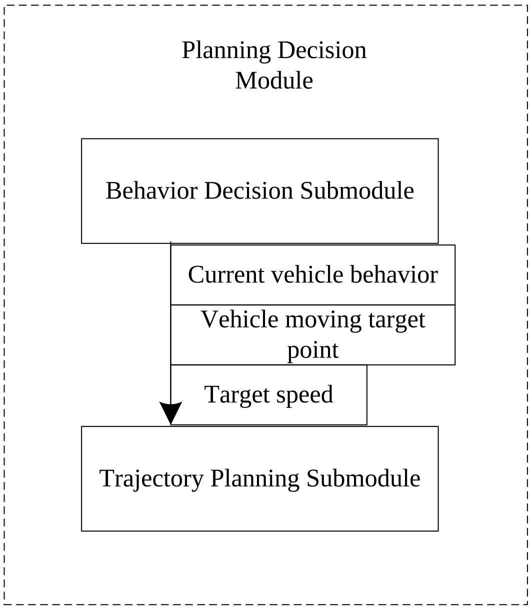


Figure 3. Structural diagram of planning and decision module

(3) Bottom control module

The structure of the underlying control module is shown in Figure 4. The core processor consists of two DSP boards. Control board 1 is responsible for vehicle steering motor control and steering lane change control (Guo 2017). Control board 2 is responsible for driving motor control, relay control, lamp and horn control (Asl & Yoon 2016). The bottom control module receives the instructions of the planning decision module and controls the vehicle response to ensure the control accuracy and track the target speed and path (Yu et al. 2016).

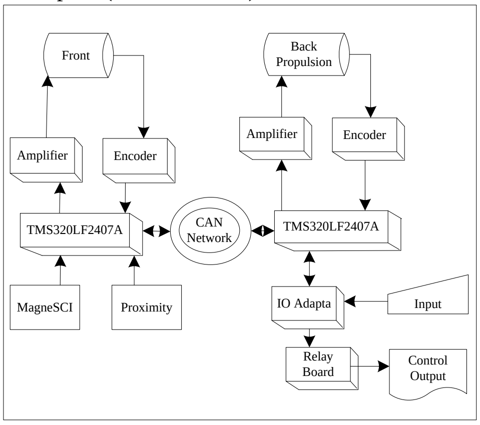


Figure 4. The overall structure of the bottom control module

2.2. Design of system software

2.2.1. Vehicle kinematics model

Firstly, the system software constructs the vehicle kinematics model, and then linearizes the vehicle kinematics model to obtain the linear tracking error model of vehicle kinematics, which can be used to predict the future behavior of the vehicle (Klinger et al. 2017).

(1) Vehicle kinematics model

A vehicle model is defined on the two-dimensional plane of Cartesian world coordinate system. As shown in Figure 5, in order to simplify the design of the controller, this paper assumes that the wheel is in point contact with the ground, and that the contact point is pure rolling without relative sliding. This ideal constraint is essentially a non-holonomic constraint (Baizid et al. 2017).

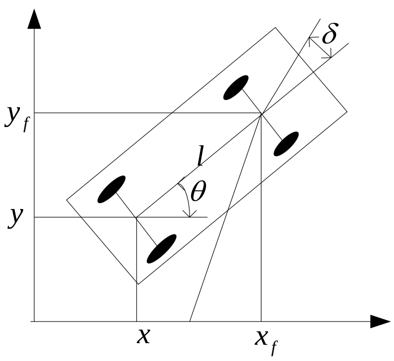


Figure 5. Generalized coordinates of vehicle

Assuming that the vehicle moves only on the plane, the nonholonomic constraint equation of the front and rear wheels is as follows:

$$\dot{x}_f \sin(\theta+\delta) - \dot{y}_f \cos(\theta+\delta) = 0 \tag{1}$$

$$\dot{x}\sin\theta - \dot{y}\cos\theta = 0 \tag{2}$$

where, $\dot{x}$ represents the abscissa of vehicle's rear wheel center in nonholonomic constraint equation; $\dot{y}$ represents the center coordinate of vehicle's rear wheel in nonholonomic constraint equation; x_f represents the center abscissa of the front wheel of a vehicle; y_f represents the longitudinal coordinate of the center of the front wheel of a vehicle; θ represents the yaw angle of the vehicle; δ represents the steering angle of the front wheel of the vehicle.

Many types of kinematics models for wheeled mobile robot can be transformed into Unicycle models. Unmanned vehicle is a typical wheeled mobile robot. The vehicle kinematics model can be written as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ \dfrac{\tan\delta}{l} \end{bmatrix} v \tag{3}$$

where: l represents the distance between the front wheel center and the rear wheel center; v represents the speed of the rear wheel center of a vehicle.

Vehicle's input variables are defined as $u = \begin{bmatrix} v & \delta \end{bmatrix}^T$, and vehicle's current coordinates are defined as $x = \begin{bmatrix} x & y & \theta \end{bmatrix}^T$.

Formula (3) can also be written as follows:

$$\dot{x} = f(x,u) \tag{4}$$

(2) Error model of vehicle kinematics

Generally speaking, in the problem of trajectory tracking, the method of tracking reference vehicle is generally adopted. The reference trajectory is assumed to be generated by a virtual reference vehicle, and the reference value is expressed by r. Therefore, the reference trajectory of a vehicle can be written as follows:

$$\dot{x}_r = f(x_r, u_r) \tag{5}$$

where, $x_r = \begin{bmatrix} x_r & y_r & \theta_r \end{bmatrix}^T$, $u_r = \begin{bmatrix} v_r & \delta_r \end{bmatrix}^T$.

The right side of Formula (5) is expanded by Taylor around point (x_r, u_r), and the higher order part is removed to obtain.

$$\dot{x} = f(x_r, u_r) + \left.\frac{\partial f(x,u)}{\partial x}\right|_{\substack{x=x_r \\ u=u_r}} \leq (x - x_r) + \left.\frac{\partial f(x,u)}{\partial u}\right|_{\substack{x=x_r \\ u=u_r}} \leq (u - u_r) \tag{6}$$

It can also be written as follows:

$$\dot{x} = f\left(x_r, u_r\right) + f_{x,r}\left(x - x_r\right) + f_{u,r}\left(u - u_r\right) \tag{7}$$

where: $f_{x,r} - f$ is the Jacobian matrix relative to x; $f_{u,r} - f$ is the Jacobian matrix relative to u.

Combining Formula (6) and Formula (7), the error model of vehicle kinematics can be obtained.

$$\dot{\tilde{x}} = f_{x,r}\tilde{x} + f_{u,r}\tilde{u} \tag{8}$$

$$\tilde{x} = x - x_r, \tilde{u} = u - u_r \tag{9}$$

where: $\tilde{x}$ represents the deviation between the current position and the reference position of the vehicle; $\tilde{u}$ represents the deviation of the control variables.

The discrete linear time-varying model of vehicle kinematics is obtained by using Euler method to make discretization of Formula (7):

$$\tilde{x}(k+1) = A(k)\tilde{x}(k) + B(k)\tilde{u}(k) \tag{10}$$

Among them,

$$A(k) = \begin{bmatrix} 1 & 0 & -v_r(k)\sin\theta_r(k)T \\ 0 & 1 & v_r(k)\cos\theta_r(k)T \\ 0 & 0 & v_r(k)\cos\theta_r(k)T \end{bmatrix},$$

$$B(k) = \begin{bmatrix} \cos\theta_r(k)T & 0 \\ \sin\theta_r(k)T & 0 \\ \dfrac{\tan\delta_r(k)T}{l} & \dfrac{v_r(k)T}{l\cos^2\delta_r(k)} \end{bmatrix}.$$

k represents the sampling time, T represents the sampling period and A and B are the discrete linear function.

2.2.2. Adaptive preview time model

After linearizing the vehicle kinematics model in the preceding section and obtaining the linear tracking error model of vehicle kinematics to predict the future behavior of vehicle, this paper establishes an adaptive preview time model to realize the path tracking control of unmanned vehicle (Okumus et al. 2017).

(1) Primary planning path

The "taboo double line shifting" experiment stipulated in ISO standard was used for analysis (Bi et al. 2017). At present, the experimental road refers to the ISO/3888 technical report of the double lane-changing driving test procedure and considers the adaptability design when the speed changes (Saska et al. 2017). The schematic diagram of the test route is shown in Figure 6.

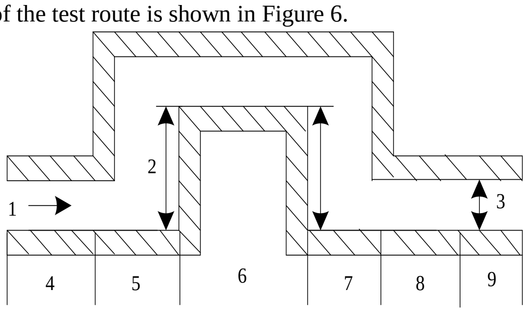


Figure 6. Test Route Diagram

In Figure 6, 1 represents the direction of the vehicle, 2 represents the drift of the lane, 3 represents the width of the road, 4 represents the section 1, 5 represents the section 2, 6 represents the section 3, 7 represents the section 4, 8 represents the section 5, and 9 represents the section 6.The sizes of roads in ISO/3888-1:2016 are shown in Table 1.

Table 1. ISO/3888-1:2016 Path Dimensions

Road section	Length	Lane departure	Road width
1	15	-	1.1 * Vehicle width + 0.25
2	30	-	-
3	25	3.5	1.2 * Vehicle width + 0.25
4	25	-	-
5	15	-	1.3 * Vehicle width + 0.25
6	15	-	1.3 * Vehicle width + 0.25

In this paper, 6-power polynomial is used to design section 2 and section 4. The formula is as follows:

$$f(x) = p_1x^6 + p_2x^5 + p_3x^4 + p_4x^3 + p_5x^2 + p_6x + p_7 \tag{11}$$

This ensures that the curve part and the straight line part are continuously differentiable (Jin et al. 2017).

The schematic diagram of the target path is shown in Figure 7.

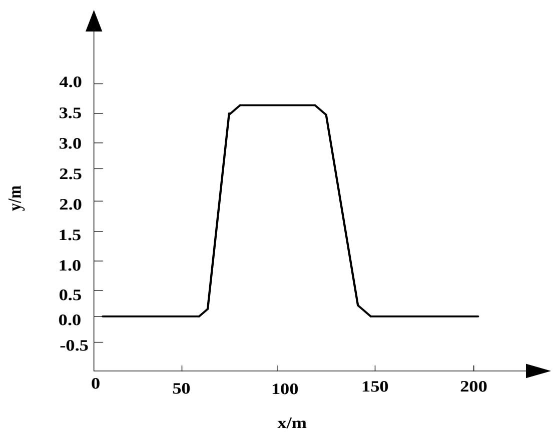


Figure 7. Target path diagram

(2) Optimal model design of fixed preview time

Generally, select a certain preview time value, or manually collect data at different road curves and speeds. This will result in a great waste of time, and there is the possibility of lateral deviation divergence when there is no data collected (Pei et al. 2017). Fixed preview time generally ranges from 0.3 s to 1.5 s. At low speeds, such preview time can meet the requirement of lateral deviation (Ding et al. 2017). When the speed is fast, the same preview time may not meet the boundary conditions of lane width. As shown in Figure 8, the vehicle track effect is better in straight road, the error is larger in bend road, and the maximum lateral deviation can reach 50 m.

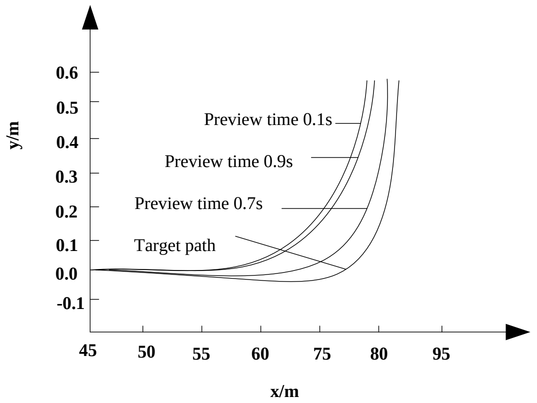


Figure 8. Corresponding trajectories of different preview times

In order to improve the adaptive ability of preview model, the model needs to adopt adaptive preview time.

(3) Adaptive preview time

In the current position of the vehicle, the lateral deviation, heading angle deviation and lateral acceleration of the actual trajectory and the primary planned path within the current traveling time t are calculated according to different preview time t_p. According to these three factors and the estimated preview time t_p, the corresponding optimization function is designed, and the steering control is carried out according to the preview time in time t (Aboudonia et al. 2017). The optimization function J_1 of lateral deviation is designed as follows:

$$J_1 = \int_0^t \left(Y_L - Y_p\right)^2 dt \tag{12}$$

where, Y_L is a primary planning path, Y_p is a preview path, dt is a derivative function and $\int_0^t$ is a steering control vector. The formula for deviation J_2 of vehicle heading angle is as follows:

$$J_2 = \left(\psi_L - \psi_p\right)^2 \tag{13}$$

where, ψ_L is the heading angle of the corresponding points on a primary planning path and ψ_p is the heading angle when it reaches the preview point.

The effect of lateral acceleration on vehicle speed is obvious and widely accepted. From the rollover hazard index, the effect of longitudinal acceleration should also be fully considered in longitudinal control (Chen et al. 2016).

$$J_3 = \int_0^t \left(\frac{a_t}{a_s}\right)^2 dt \tag{14}$$

where, J_3 is the optimization function of vehicle lateral acceleration, a_t is the lateral acceleration vector of unmanned vehicle, and a_s is the standard threshold of the lateral acceleration of unmanned vehicle.

The comprehensive optimization function is as follows:

$$J = \min\left(w_1 J_1 + w_2 J_2 + w_3 J_3\right) \tag{15}$$

where, the weight coefficients of each sub-optimal function are w_1, w_2 and w_3. The choice of the three factors determines the different driving styles. If the value of w_1 is increased, it means to reduce the lateral deviation; if the value of w_2 is increased, it means to emphasize the consistency of the heading angle of the vehicle and increase the stability of the vehicle; if the value of w_3 is increased, it represents to emphasize the consistency of vehicle heading angles. The appropriate preview time t can be obtained by iterative optimization method. The schematic diagram of adaptive preview time acquisition is shown in Figure 9.

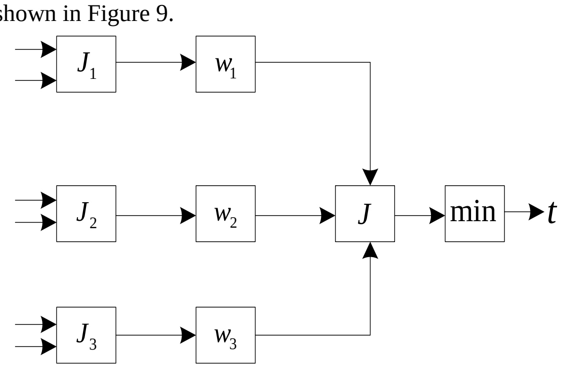
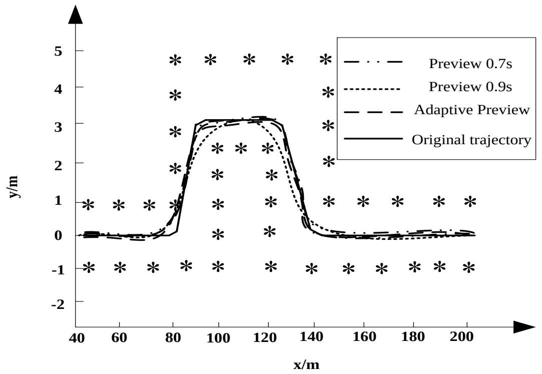


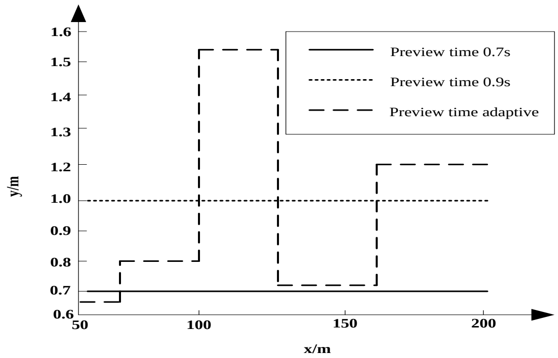
Figure 9. A schematic diagram of adaptive preview time acquisition

3. RESULTS

According to ISO3888-1:2016, double line-shifting experiment is carried out.With no brake and automatic lifting, the peak adhesion coefficient of road surface is 0.8. The simulation experiments at different speeds are carried out with this system. Figure 10 shows the trajectory at 80 km/h. Fixed preview time of 0.9 s, 0.7 s and adaptive preview are adopted respectively.



(a) 80 km/h trajectory

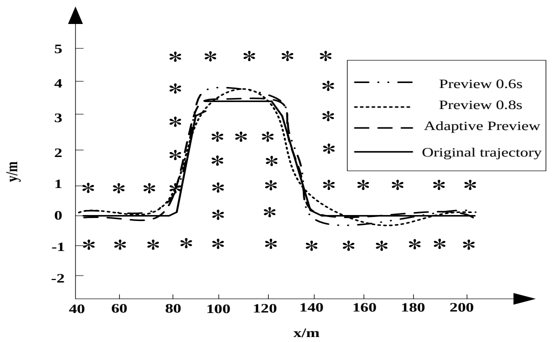


(b) Preview time at 80 km/h

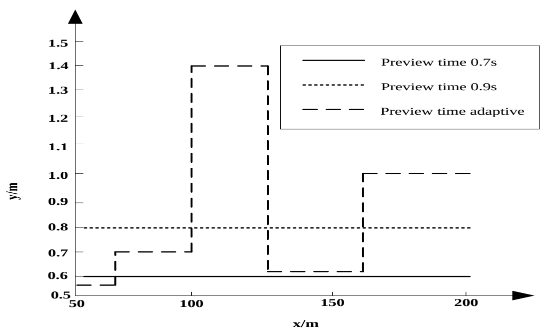
Figure 10. Simulation at 80 km/h

Figure 10 shows that the trajectory deviation is the largest when the preview time is 0.9 s, followed by 0.7 s, and the adaptive preview time is the best when the preview speed is 80 km/h.

Figure 11 is the simulation result at 90 km/h:



(a) Trajectory at 90 km/h

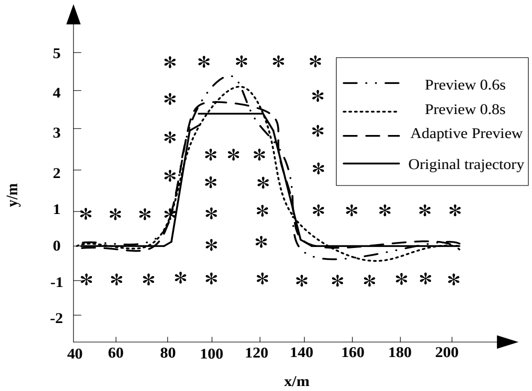


(b) Preview time at 90 km/h

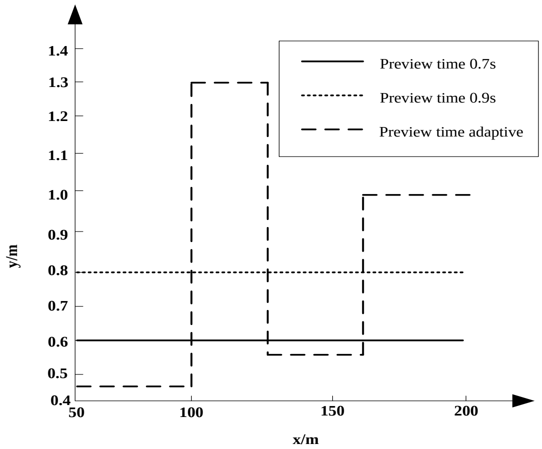
Figure 11. Simulation at 90 km/h

In Figure 11, when using fixed time of 0.6 s to preview, a large lateral deviation occurs at 100 m and a peak value of 0.5 m at 154 m; when using 0.8 s preview time, the error is 0.24 m at 110 m and the peak value of the whole trajectory occurs at 160 m. At this time, the error is 0.5 m. With the prolongation of preview time, the adjustment time after the end of the bend is prolonged correspondingly.When adapting to preview time, the lateral error can be guaranteed within 0.2 m, and the adjustment time is the shortest. The lateral error has been controlled within 0.1 m at 146 m.

Figure 12 shows the simulation results at 100 km/h:



(a) Trajectory at 100 km/h



(b) Preview time at 100 km/h

Figure 12. Simulation at 100 km/h

In Figure 12, it is obvious that the closer the speed is to the limit condition, the more obvious the advantage of adaptive preview is. The maximum error of 0.6 s preview time is 1.0 m. If the width of the vehicle is taken into account at this time, the vehicle has deviated from the road in Section 3 of double-shift line, and is close to the road edge in 0.8 s preview time, and the performance of adaptive preview time is the best. This is because the fixed preview time is equivalent to not considering the current speed and road attribute characteristics in front, and it always keeps a fixed visual angle in front, which obviously cannot adapt to the changing road conditions. Adaptive preview can make corresponding judgments according to the current vehicle speed and road characteristics ahead, and accurately track the preset path. Therefore, it can achieve better results than fixed preview time.

Figure 13 shows the path tracking using the designed system in this paper:

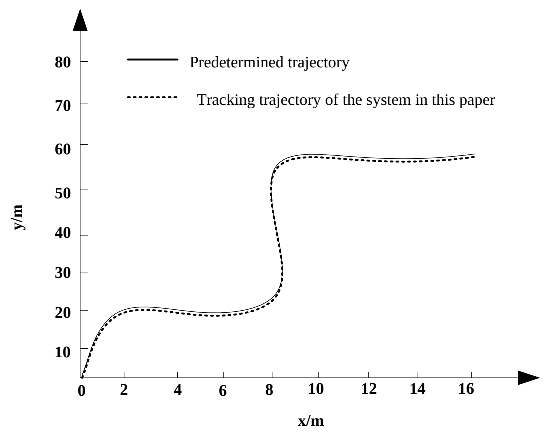


Figure 13. Path tracking of the system in this paper

The analysis of Figure 13 shows that the tracking trajectory of the unmanned vehicle is almost the same as the experimental predetermined trajectory, and the deviation is not greater than 1 m when the system is used to control the unmanned vehicle to track under the setting of adaptive preview. It shows that the tracking control accuracy of the system in this paper is high.

4. DISCUSSION

Based on the research content of this paper, the challenges faced by the future development of unmanned vehicles are discussed. Unmanned vehicle is a new thing which integrates multi-disciplines organically. Its development is a process of continuous exploration and gradual progress. There are still many challenges for real batch road operation. It is not only the maturity of technology, but also the social problems such as license, liability determination, insurance and so on. The first step to solve the problem is to acknowledge the existence of the problem, rather than to hide one's troubles and take no remedial measures. The difficulties and challenges faced by unmanned vehicles mainly include the following aspects.

(1) Safety and reliability. Safety and reliability are always the barriers that cannot be bypassed in the promotion of unmanned vehicles. The self-safety of unmanned vehicle mainly includes hardware security, software security and network security. If we recognize the concept of active safety and passive safety, the safety of unmanned vehicles is more related to active safety. Firstly, there is a risk of failure of the environmental sensor of the unmanned vehicle. Vehicle-borne high-definition camera based on the principle of visible light reflection is vulnerable to strong light interference, which makes it impossible to obtain real and clear images; ultrasonic probe based on the principle of ultrasonic reflection is vulnerable to noise and the influence of ultrasonic adsorbent material, which makes it impossible to accurately measure the distance of obstacles; millimeter-wave radar based on the principle of electromagnetic reflection may also suffer noise and deception attack under the support of specific equipment; 64-line laser rangefinder with the highest accuracy attenuates sharply in severe weather such as heavy rain and fog, which seriously affects the accuracy of three-dimensional map generation. Secondly, unmanned algorithms do not allow security vulnerabilities, which requires a lot of test data. At present, only Google has conducted seven years of closed testing, while the testing time of other manufacturers is much shorter. It is irresponsible to promote the application of unmanned driving algorithm without long-term practical verification. Finally, the access of unmanned vehicles to the Internet is bound to face network security problems. In the absence of reliable firewall strategies, network hackers can invade the core brain of unmanned vehicles through the Internet, tamper with code to remotely control unmanned vehicles, maliciously manipulate steering or braking systems, and create targeted safety incidents.

(2) The imperfection of technical evaluation standard system. How to evaluate the technical indicators of Intelligent Network Unified Vehicle needs to formulate corresponding technical standards to measure. The technical standards must be based on a large number of experimental data. China clearly divides the development stage of Intelligent Network Unified Vehicle into five stages. The technical requirements of different stages are different, and the technical parameters are different. At present, the technical standard system of Intelligent Network Unified Vehicle in China is not perfect, which cannot provide evaluation basis for different stages of Intelligent Network Unified Vehicle, especially the maturity of high-level unmanned driving technology cannot be defined and judged.

5. CONCLUSIONS

This paper designs a path tracking control system for unmanned vehicle based on adaptive preview. The system consists of monitoring module, planning decision module and bottom control module, which can realize the three functions of monitoring, decision-making and control of unmanned vehicle. The system software linearizes the vehicle kinematics model, obtains the linear tracking error model of vehicle kinematics to predict the future behavior of the vehicle, and constructs the adaptive preview time model to complete the trajectory tracking of the unmanned vehicle. After applying this system to actual operation, the tracking deviation is less than 1 m, and the effect is ideal. The adaptive preview system in this paper can make corresponding judgment according to the current vehicle speed and road characteristics in front, and accurately track the preset path, which can meet the requirements of trajectory tracking control of unmanned vehicles.

Based on the research content of this paper, the following suggestions are put forward for the future development challenges of unmanned vehicles:

(1) To reduce the application cost on the basis of guaranteeing performance. Unmanned vehicle is a sunrise industry, which will drive the development of a large number of related industries, such as sensors, cameras, vehicle-borne radar, high-precision positioning and navigation system, wireless communication network system, vehicle-borne processors, and man-machine interactive system, etc. At the same time, it will also bring many conveniences to the development of human and society, such as greatly reducing traffic accidents caused by human factors, carbon emissions, and road congestion, sharing traffic resources and improving travel efficiency. The economic and social benefits brought by the unmanned vehicle industry are considerable, but the application cost at this stage is unacceptable, and it has become a roadblock to promote the road. n view of this problem, it is suggested to draw lessons from the mature experience of the promotion of new energy vehicles:

firstly, a demonstration park is established to gradually radiate the promotion point-to-area, and reduce costs by increasing the number of applications; secondly, targeted financial subsidies, etc. are carried out, and after the technology matures, the industry is stimulated to actively reduce manufacturing costs by subsidizing the mechanism of slope reduction.

(2) To strengthen the research of networking technology among people, vehicles, roads and backgrounds. Network is a platform for integrating social information and resources. The development of unmanned vehicles in the future cannot be separated from the progress of network technology. Many real-time information related to unmanned driving needs to be obtained from Internet platform, such as the accuracy of GPS positioning system, the smooth condition of roads and bridges, the weather condition, the change of driving destination, etc. The quality of the network and the real-time nature of the network information determine whether the unmanned vehicle can advance according to the set destination. In addition, OTA (Over-the-air, air download) is the future trend of the development of the upgraded vehicle program for unmanned vehicles. Owners need not go to 4S stores to complete the upgrade of the unmanned system, so as to obtain the latest driving experience. The upgrade of OTA system also needs the support of high-speed network. Improving the download speed, coverage and signal stability of the network is another important precondition for the promotion of unmanned vehicles. At the same time, it is necessary to strengthen the research of network security technology to reduce the risk of hackers intruding into the network of unmanned vehicles.

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