# A triple closed-loop control strategy for intelligent two-car chasing system based on particle swarm optimization

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ABSTRACT. *This paper aims to acheive the optimal control of the safe distance and speed for the intelligent two-car chasing system in China's National University Students Intelligent Car Race. For this puprose, a triple closed-loop control strategy was designed based on particle swarm optimization (PSO), and verified through simulation and experiment. The results show that, when the two cars were kept apart by a safe distance, the fastest speed was 2.04m/s, close to that (2m/s) of the champion team. This means the proposed control strategy can effectively control the distance and speed of intelligent car chase, and enjoys strong self-learning ability and adaptability. The findings provide a technical reference for future Intelligent Car Races and lay the basis for the development of intelligent autopilot technology.*

RÉSUMÉ. *Cet article vise à réaliser le contrôle optimal au niveau de la distance et de la vitesse de sécurité du système régulateur pendant la poursuite à deux voitures intelligentes dans la Compétition Nationale de Voitures Intelligentes pour les étudiants universitaires en Chine. Afin d'y arriver, une stratégie de contrôle en circuit triple fermé a été conçue sur la base de l'optimisation par essaims particulaires (OEP), et vérifiée par simulation et expérimentation. Les résultats montrent que, lorsque les deux voitures marchent en gardant la distance de sécurité, la vitesse la plus rapide était de 2,04 m/s qui est proche de celle (2 m/s) de l'équipe championne. Cela signifie que la stratégie de contrôle proposée peut contrôler efficacement la distance et la vitesse pendant la poursuite de voiture intelligente en présentant d'une forte capacité d'autoapprentissage et d'adaptation. Les résultats fournissent une référence technique pour les futures compétitions de voitures intelligentes ainsi que des arguments pour la technologie intelligente de pilote automatique.*

KEYWORDS: *three closed -loop control, two-car chasing, particle swarm optimization (PSO), PID.*

MOTS-CLÉS: *contrôle en circuit triple fermé, poursuite à deux voitures intelligentes, optimisation par essaims particulaires (OEP), régulateur PID.*

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## 1. Introduction

Highly intelligent driverless technology has been a research focus. In order to promote the development of driverless technologies, the two-car chasing system has been proposed in the latest National University Students Intelligent Car Race. In the two-car chasing system, cars driving too close or too far fail to meet the best requirement for race. There are many kinds of the track types for smart cars, among them, the straight and the curve are used commonly. In straight track, the control strategy is simple and easy to achieve. Due to the complex conditions of the curve track, the control problems is most likely to happen. For this reason, the optimal control between safe distance and speed is very important significance for safe driving, and it is necessary to enhance the control performance of the intelligent car under different road conditions.

No matter what kind of traffic, there will always exist a curve, then control the car safely, smoothly and efficiently in the curve will precisely reflect the control performance of the intelligent car. At the beginning of the 20th century, the international community has developed some collision avoidance systems. Among others, Japan and Germany conducted tests on inter-vehicular safety distances. Mazda used laser scanning radar and ultrasonic sensors to detect whether there are pedestrians ahead or whether there are vehicles coming from the opposite (Merdrignac *et al*., 2015). Based on vision sensors, Israel and other countries used CCD cameras to detect obstacles in front of the vehicle. When the vehicle reaches a certain speed, the system establishes a frontal collision warning algorithm (Bensrhair *et al*., 2001; Wang *et al*., 2014). However, the above detection methods cannot always adapt to various environments.

In past decades, to establish a model for safety following distance, Nissan introduced an emergency brake advisory system that uses a brake light to alert the driver. If necessary, the automatic braking system will work (Gietelink *et al*., 2006; Wang *et al*., 2004). A security model based on vehicle distance was propose by selecting vehicle distance parameter from large volumes of experimental statistics (Ayres *et al*., 2001). However, the model failed to fully consider the car operating conditions and employ car distance warning system. In paper (Maclachlan and Mertz, 2006) and (Thorpe *et al*., 2007), the presented model involved parameters of safe distance between vehicles, such as the driving speed and the reaction time of the driver, and so on. Besides, divides the safety distance was divided into three levels to facilitate drivers to use different warning methods.

Many researchers pay more attention to control models of smart car, the research contents can be summarized as: Firstly, from the viewpoint of braking distance, both front and behind cars are in the free-running travelling state, and so emergency braking is performed only when the distance between the two vehicles is too short (Yao and Zhang, 2011; Ahmad and Ahmadian, 2011). The problem is that nonetheless, the distance between two cars is a follow-up state and, emergency braking is only an auxiliary function, and itwhich cannot satisfy the requirements of future unmanned cars. Secondly, is to determine the current safety models are developed from based on the linear relationship between distance and speed (Wang *et al*., 2011; Zhang and Bian, 2015). However, but in the actual vehicle drivingin practical, the state of the preceding car ahead is in a state of free runningtravelling, and while the behind car is adjusted in time according to the driving state of the front car ahead. Owing to a lack of communication between the two cars, which have poor adaptive capacity.Thirdly, in terms of methods for safety distance detection vary, each among country countries and every automobile manufacturers has its own way (Chen and Wang, 2007; Lin *et al*., 2012), but, the commonly used sensors equipment is are costly and difficult to maintain, and it cannot making it unable to adapt to the two-car following real time tracing in various environments in real time (Kim *et al*., 2013).

At present, the speed control of two cars still remains a challenge (Hoshino *et al*., 2018). On the one hand, in reality, the controlling safe distance, especially in different paths, cannot be measured accurately. On the other hand, the control object is a nonlinear system which cannot be accurately simulated. PSO starts from the random solution and finds the optimal solution by iteration. In nonlinear system, particle swarm optimization (PSO) is often used to tune the three control parameters of the PID based on its simple principle and high efficiency (Al-Mayyahi *et al.*, 2015). In light of features of intelligent cars, the aim of this paper was to achieve the optimal control between safe distance and speed in intelligent two-car chasing.In terms of hardware design, electromagnetic navigation (Yue *et al*., 2015) was utilized to integrate the speed of the front car and send the integral value to the behind car via wireless transmission after filtering. Then, the single chip microcomputer is employed to calculate the distance between the two cars. Finally, in combination with the PSO control algorithm and the incremental PID algorithm, the behind car speed was controlled by the three closed-loop to make the two cars realize the optimal state for speed and distace.

The rest of this paper is organized as follows. In Section2, the overall design of intelligent car control system are introduced in detail, mainly including hardware design, software design and control strategy design. A three closed-loop control model was designed in this section. In Section3, we explain some related theories and methods in detail, the control algorithm is presented based on PSO and the incremental PID. In Section 4, the control algorithm is validated by simulation and experiment, at the same time, the results are analyzed and contrasted in detail. Finally, a summary and conclusions are given in Section 5.

## 2. Overall design of the system

### *2.1. Hardware design*

In this paper, the research object is B model which designated by NXP in the National University Students Intelligent Car Race. Parameters in the B model are: length-74cm, width-25cm, height-18cm, vehicle weight 963g and the steering response range (left 45°, right 45°). Inductance was used to detect copper current in the track. The current is 100mA, the frequency is 20 kHz, and the waveform is the current change of square wave.

The 32-bit microprocessor MK60DN512ZVLQ10 produced by NXP is used in the system hardware. The circuit design mainly includes Multi-channel DC stabilized DC powervoltage supply, the minimum system of single-chip microcomputer minimum system, the unit of electromagnetic signal acquisition, the unit of speed measurement unit, motor unit, wireless communication unit, ultrasonic distance measurement unit, the steering control unit, and human-computer interaction unit. The schematic diagram of the system hardware is shown in Figure 1.

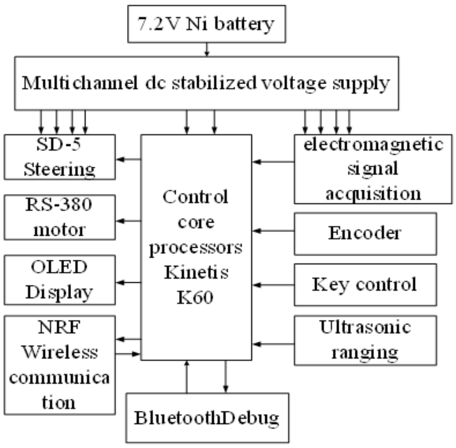


*Figure 1. Schematic diagram of the system hardware*

The functions of the main hardware circuit are as follows:

(1) As the key unit, Multi-channel DC stabilized DC powervoltage supply is key unit, which can provides power for the whole system;

(2) The unit of electromagnetic signal acquisition is mainly composed of a detection circuit and an amplification circuit. The task of this unit is to collect current changes on the track so that the smart car can identify track information;

(3) The motor unit provides driving force for the whole system;

(4) The unit of speed measurement unit can feedback theis a gauge of current real-time speed in real time and realize the speed closed loop;

(5) The wireless communication unit is an interface for data exchange and communication interaction between two cars, and the NRF communication mode is adopted in this unit;

(6) The ultrasonic distance measurement unit can measure the distance between two cars;

(7) The steering control unit enables the two cars to turn automatically. The material object of two-car are shown in Figure 2.

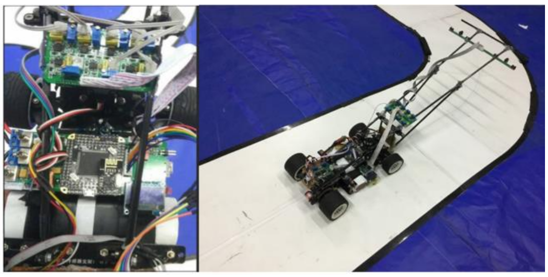

*Figure 2. The material object of two-car*

### *2.2. Software design*

While keeping at an appropriate distance based on ultrasonic distance measurement, two cars can successfully complete the real-time dynamic chasing and overtaking.The two-car chasing is shown in Figure 3.

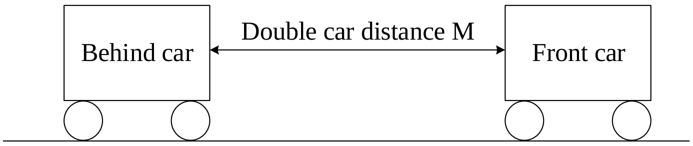


*Figure 3. Schematic diagram of two-car chasing*

In the two-cars races, the track types are is diverse and complex, as shown in Figure 4. At present, the two cars range has been widely studied. Generally, range method is divided into camera range, ultrasonic range, satellite range, laser range, etc., which are not accurate in practical application due to environmental influences. For example, during the overtaking process, especially when the two cars are on the curve, the measurement always gives rise to errors, due to the limitation of the ultrasonic measurement angle. If there is a green belt or other hinders at the curve, there are more limitations for two-car distance measurement. Therefore, this paper adopts the method of real-time speed combined with ultrasonic range, and describes it as:

(1) Before the two cars departure (straight way), the initial distance between two cars is determined by ultrasonic wave (denoted as Q);

(2) In the two-car driving, the speed of the two cars is integrated (the distance of the front car and the behind car is represented as L1,L2 respectively), and the integral speed value of the front car is given to the behind car by wireless transmission.

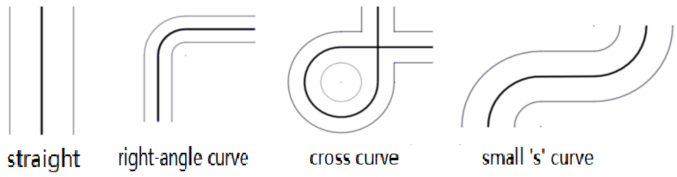


*Figure 4. Race circuit diagram*

Distance control of two cars in this system is based on the selected appropriate vehicles speed (such as medium, high and ultra-high speed) by the car front. Then, the car behind chases after the car front. While sending velocity integral value to the car behind, the vehicle ahead goes on PID closed-loop adjustment automatically, to benefit from the selected target speed. Program flow chart for the front car is shown in Figure 5.

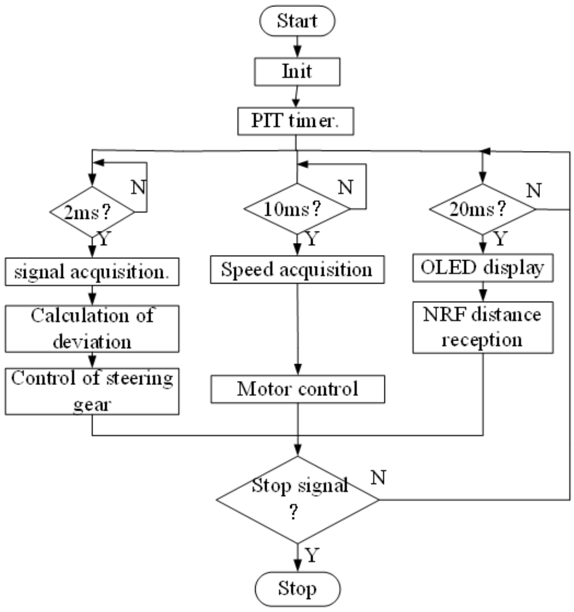


*Figure 5. Program flow chart of the front car*

Upon the initial success of the behind car, The design objective is achieved according to distance difference at a set speed and to speed changes with closed-loop adjustment. Program flow chart of the behind car is shown in Figure 6.

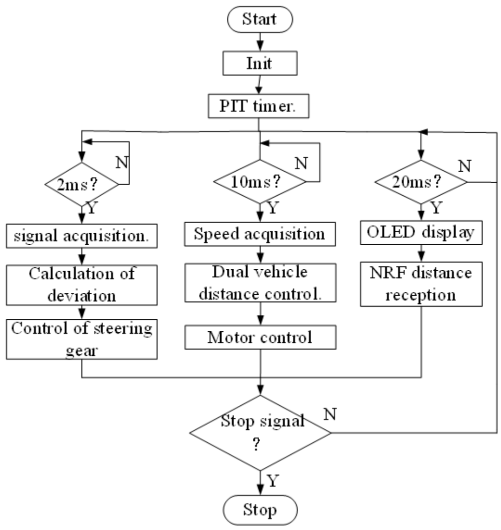


*Figure 6. Program flow chart of the behind car*

### *2.3. The design of control strategy*

In this paper, a three closed-loop method was proposed to for vehicle distance control to ensure both cars keep at an appropriate distance and cross the finish line in the shortest time. The specific strategies are as follows:

(1) The ultrasonic ranging, combining with real-time integration, was used to measure the distance. The distance between the initial distance of the two cars is defined as distance Q (Initial value of M, as shown in Figure 3).

(2) For the front car, a safe and reliable target speed needs to be set before starting. The incremental PID control algorithm was adopted to adjust the speed, integrate the velocity after filtering and calculated the distance (Represented as L1) from the strating lime . In order to simplify the program, the current speed is added and then divide N that is determined by the motor gear and coder gear. The front car control diagram is shown in Figure 7.

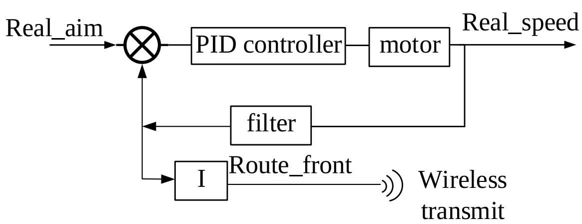


*Figure 7. Control flow chart of front car*

(3) For the behind car, it's necessary to set a target distance S, which is measured by adding the difference value between the integral speed value L2 and L1 of the front car to the initial distance Q measured with ultrasonic wave. Then, the actual distance can be calculated as M=Q+L1-L2. Figure 8 shows the control flow chart of the behind car. In this paper, the current setting value Vi is obtained by designing a PID controller based on the PSO and adjusted by the PID controller1, The setting value of current is generated by PID controller 2. The value generated by the PID controller 3 will directly act on the drive circuit by controlling the PWM, ensuring the twos cars are travelling at a proper distance.

(4) In case of overtaking under the influence of the circuit, the initial distance needs to be remarked with ultrasonic . When two cars are on the straight line or the requirements are met for ultrasonic ranging, the behind car uses ultrasound to measure the distance between two cars. At this time, under the same control strategy, the original behind car becomes the front car, while the original front car becomes the behind car.

## 3. The control algorithm based on PSO

Particle swarm optimization (PSO) is a heuristic optimization algorithm based on swarm intelligence theory, and it has the advantages of evolutionary algorithm as well (Kennedy and Mendes, 2002; Clerc and Kennedy, 2002). In the process of particle movement, decision-making is mainly based on two factors, one is the individual extremum, the other is the global extreme value. The whole particle population moves while updating the replacement individual extreme point and the global extreme point, cycling back and forth, and ultimately searching for the optimal solution (Kennedy, 2011).

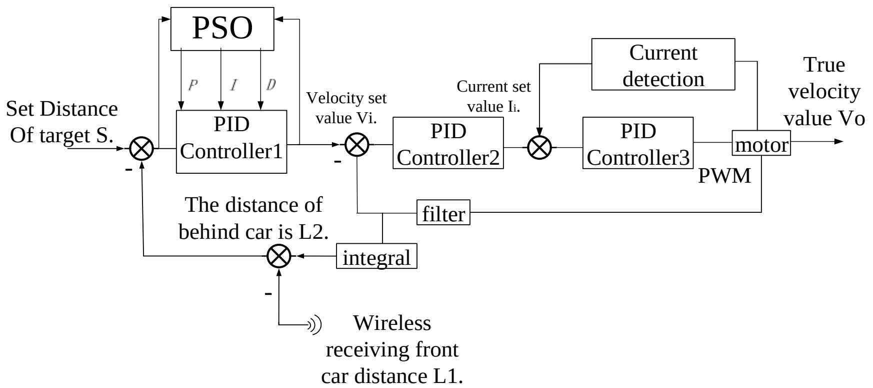


*Figure 8. Control flow chart of the behind car*

The PSO is described as follows:

(1) Suppose that in a D-dimensional search space(in this paper, D=3, it is used to generate the PID parameter of controller 1 in Figure 8), a particle population is composed of $n$ particles, in which the position of the $i$ th particle is represented by the D-dimensional vector, such as $X_i(t)=\{X_{i1}, X_{i2}, ..., X_{iD}\}, i=1, 2, ..., N$;

(2) The velocity and direction of the i th particle are expressed as $V_i=\{V_{i1}, V_{i2}, ..., V_{iD}\}, i=1, 2, ..., N$;

(3) The best searched location of the $i$ th to now is called individual extremum, which can be expressed as $P_{ibest}(t)=\{P_{i1}, P_{i2}, ..., P_{iD}\}, i=1, 2, ..., N$;

(4) The optimal location of the whole particle swarm up to now is called global extreme value,which can be expressed as $P_{gbest}(t)=\{P_{g1}, P_{g2}, ..., P_{gD}\}$.

When the two optimum extreme values are found, the particle updates its velocity and position according to the following formulas (1) and (2).

$$\begin{aligned} V_{id}(t+1) = w \bullet V_{id}(t) + c1 \bullet r1 \bullet (P_{id} - X_{id}(t)) \\ + c2 \bullet r2 \bullet (P_{gd} - X_{id}(t)) \end{aligned} \tag{1}$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \tag{2}$$

Among them, *c1* and *c2* are called learning factors or acceleration constants, and generally take 0-2 positive real numbers; *r1* and *r2* are random number with a range of [0-1]; *w* is inertia weight, and it iterated according to the following formula (3).

$$w(\mathrm{t}) = w_{start} - (w_{start} - w_{end}) \frac{t}{t_{\max}} \tag{3}$$

In formula (3), $w_{start}$ is the inertia weight at the beginning, $w_{end}$ is the inertia weight at the end. It iterates from large to small, so that the algorithm can change from a wide range of global search to a small range of precise search. At the same time, the maximum speed and maximum position are set up to prevent the particle velocity from overrunning and the position exceeding the boundary (Sun and Fang, 2016). In this papser,the main process of the algorithm is described in Figure 9.

In this paper, $J = ITAE = \int_0^\infty t|e(\mathrm{t})|$ is used as fitness function (*e(t)* is the deviation of PID controller 1), the model is shown in Figure 10. The total number of particles is 20, the maximum number of iterations is 1000, c1 is 0.8, c2 is 1.2 (Kou *et al*., 2009).

As can be seen from Figure 8, the three closed-loop PID control algorithm based on PSO is described as follow.

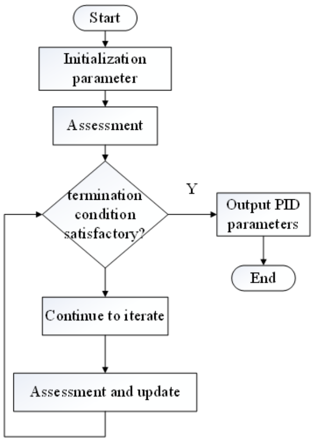


*Figure 9. The flow chart of PSO algorithm*

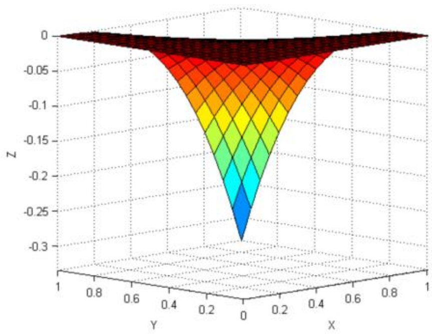


*Figure 10. The flow chart of PSO algorithm*

The first closed-loop control of distance:

$$e_{PID1} = S - M = S - (Q + L1 - L2) \tag{4}$$

$$\begin{aligned} \Delta V_i[k] = {} & K_{P\text{-}PID1}(e_{PID1}[k] - e_{PID1}[k-1]) \\ & + K_{I-PID1}(e_{PID1}[k]) + K_{D-PID1}(e_{PID1}[k] \\ & - 2 * e_{PID1}[k-1] + e_{PID1}[k-2]) \end{aligned} \tag{5}$$

The second closed-loop control of current:

$$\Delta I_i[k] = K_{P\text{-PID2}}(e_{PID2}[k] - e_{PID2}[k-1]) + K_{I-PID2}(e_{PID2}[k]) + K_{D-PID2}(e_{PID2}[k] - 2*e_{PID2}[k-1] + e_{PID2}[k-2]) \quad (6)$$

The third closed-loop control of velocity:

$$\Delta PWM_{out}(k) = K_{P\text{-PID3}}(e_{PID3}[k] - e_{PID3}[k-1]) + K_{I-PID3}(e_{PID3}[k]) + K_{D-PID3}(e_{PID3}[k] - 2*e_{PID3}[k-1] + e_{PID3}[k-2]) \quad (7)$$

In formula (7), $e_{PID2}$ is deviation between speed setting value $V_i$ and encoder return value, $e_{PID3}$ is deviation between the current setting value $I_i$ and return value of the current sensor.

## 4. Simulation and actual tests

### *4.1. Simulation*

The intelligent two-car system achieves the control speed by controlling the DC motor (Fang *et al*., 2010). The system with DC motor control can formulated as:

$$G(s) = \frac{\Omega(s)}{U(s)} = \frac{K_T}{LJs^2 + (LB+RJ)s + RB + K_T K_e} \quad (8)$$

As we know, step signals input to the control system can seriously impactthe system, Take the front car as a reference, the step value indicates the change in distance when the system has just been electrocuted. The three closed loop strategy based on PSO algorithm (called PSO-PID) is used for simulation, compared with the traditional PID algorithm (called PID), the results are shown in Figure 11 (a, b, c, d).

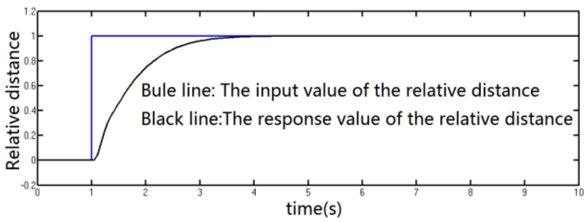


*Figure 11. (a) Simulation diagram of distance with PSO-PID*

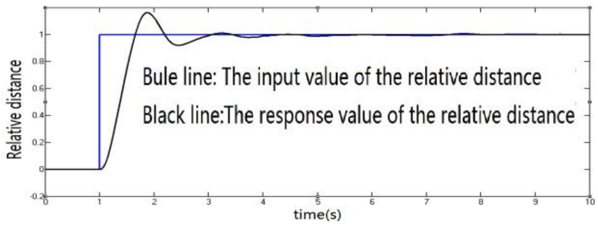


*Figure 11. (b) Simulation diagram of distance with PID*

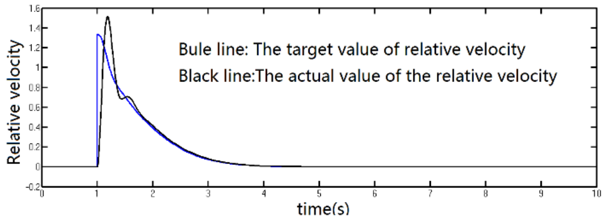


*Figure 11. (c) Simulation diagram of relative velocity with PSO-PID*

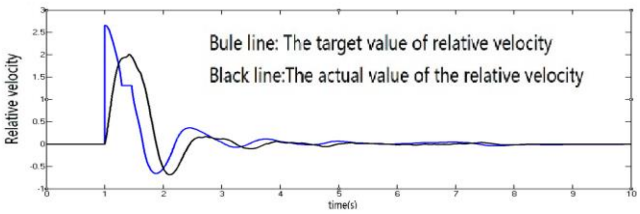


*Figure 11. (d) Simulation diagram of relative velocity with PID*

By comparing with traditional PID,the simulation results show that the three closed-loop control algorithm based on PSO has the characteristics of smaller overshoot, faster response speed and faster stability. It is evident that this algorithm featuring highly stable and applicable can meet the design requirements of two-car chasing system.

### *4.2. Actual tests*

Figure 12 (a, b) show the actual test condition. The track is 34.5m in length. Two tests were conducted respectively based on the traditional control model (PID) and the control model based on PSO (PSO-PID). With 100 sets of data, the tests have produced contrast results, as shown in Table 1 and Table 2.

*Figure 12. (a) Actual track for testing; (b) The case of two cars chasing*

*Table 1. Test results based on PID and PSO-PID*

| Parameter / Model | Collision frequency | Speed (m/s) | Time interval (s) |
|---|---|---|---|
| PID | 0.8 | 1.92 | 1.02 |
| PSO PID | 0 | 2.04 | 0.56 |

*Table 2. Test results based on the track*

| Time interval / Track type | PID | PSO- PID |
|---|---|---|
| straight | 0.38s | 0.3s |
| Right-angle curve | 0.29s | 0.22s |
| Cross curve | 0.64s | 0.41s |
| Small ‘S’curve | 0.34s | 0.24s |

The results demonstrate that the proposed model featuring shorter operation time, safety and reliability and better adaptability can improve the control of intelligent cars using the three closed-loop control strategy.

## 5. Conclusions

In this paper, substantive tests have found that the three closed-loop control strategy is practical in the chasing between two cars. As a result, the author reaches the following conclusions:

(1) The presented three closed-loop control strategy can minimize the effects of surroundings on distance measurement of curve (u-shaped) bending, cross track, slope, and ring.

(2) The two-car distance control has differences in straight and small curves. Intelligent two- cars can independently adjust speed and steering according to road conditions and cross the finish line in the shortest time. Meantime, the best state is the shortest time difference that intelligent cars cross the finish line .

(3) A race model was established based on PSO and the three closed-loop control strategy. In this model, time=the time when two cars cross the finish line+time difference that two cars cross the finish line * 5, and the fastest speed at 2.04 m/s (average speed in 2017 national intelligent car competition is 2 m/s), greatly improving the competition results.

(4) PSO-PID model is very effective in the control of the distance between the two cars, and the ability of self-learning and self-adaptive are very good, it can the actual requirements well.

(5) This proposed algorithm can contribute to speed and distance control of two-car chasing or even intelligent driverless technology in the future.

*Acknowledgements*

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