Int. J. Metrol. Qual. Eng. **12**, 1 (2021)

https://doi.org/10.1051/ijmqe/2020018

International Journal of Metrology and Quality Engineering

Available online at:
www.metrology-journal.org

RESEARCH ARTICLE OPEN ACCESS

Research on steering control performance of electric forklift with steer by wire

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Received: 22 October 2020 / Accepted: 26 December 2020

Abstract. Forklift plays an important role in cargo handling in the warehouse; therefore, it is necessary to ensure the stability of the forklift when turning to guarantee the safety of transportation. In this study, the particle swarm optimization (PSO) algorithm was improved by a genetic algorithm (GA), and the parameters of the proportion, integration, and differentiation (PID) controller were calculated using the improved algorithm for forklift steering control. Then simulation experiments were carried out using MATLAB. The results showed that the convergence speed of the improved PSO algorithm was faster than that of GA, and its adaptive value after convergence stability was significantly lower than that of the PSO algorithm; whether it was low-speed or high-speed steering, the three algorithms responded to the steering signal quickly; the yaw velocity and sideslip angle of the forklift steering under the improved PSO algorithm were more suitable for stable steering, and the increase of the steering speed would increase the yaw velocity. The novelty of this paper is that the traditional PSO algorithm is improved by GA and the particle swarm jumps out of the locally optimal solution through the crossover and mutation operations.

Keywords: Forklift / four-wheel steering / particle swarm optimization algorithm / genetic algorithm

1 Introduction

With the progress of science and technology, the power source of vehicles has gradually changed from human and animal power to steam power, fuel power, and electric power [1]. Every time the power source improves, the speed and load of vehicles greatly improve. Vehicles with higher speed make people travel more conveniently, and the larger load makes them competent for the transportation of goods [2]. A forklift is a kind of vehicle for cargo handling. The front of the forklift can move up and down. When the fork is inserted into the chassis loaded with goods, the goods can be transported horizontally and vertically. The forklift can be driven by fuel oil and electric power. The output power of an electrically driven forklift truck may be less than that of a fuel forklift, but it has the advantages of no emission, stable operation, and small noise; therefore, it is more suitable for working in a relatively closed environment (represented by warehouse later). The electric forklift must have frequent steering operations when handling goods in the warehouse. Due to the cooperation of the front and rear wheels of the electric forklift with four-wheel steering, the track radius during turning is smaller, and the turning is more flexible, but it also challenges the steering control technology [3]. Steer-by-wire technology controls the steering of tires through electronic signals. There is no direct mechanical connection in the steering wheel, which makes the four-wheel steering more flexible. However, due to the loss of mechanical connection, steer-by-wire technology needs to control the steering of four tires more accurately to ensure the coordination of front and rear wheels and further improve the stability of forklift steering. Wang et al. [4] proposed a μ integrated robust controller based on the steer-by-wire system to effectively suppress the disturbance and improve steering stability. The controller considered the influence of model uncertainty and external interference on the system dynamics. The simulation results showed that the controller could not only guarantee the robustness and robust stability of the system but also improved the vehicle handling stability effectively. Sun et al. [5] proposed an adaptive sliding mode control method. In this method, the steer-by-wire system was constructed as a second-order system from the input voltage of the steering motor to the steering angle of the front wheels, and the self-aligning torque and friction force generated by the contact between the tire and the ground were regarded as external disturbances on the steering system. Finally, the steering control experiments were carried out, that is, the forklift moved along the rotary and

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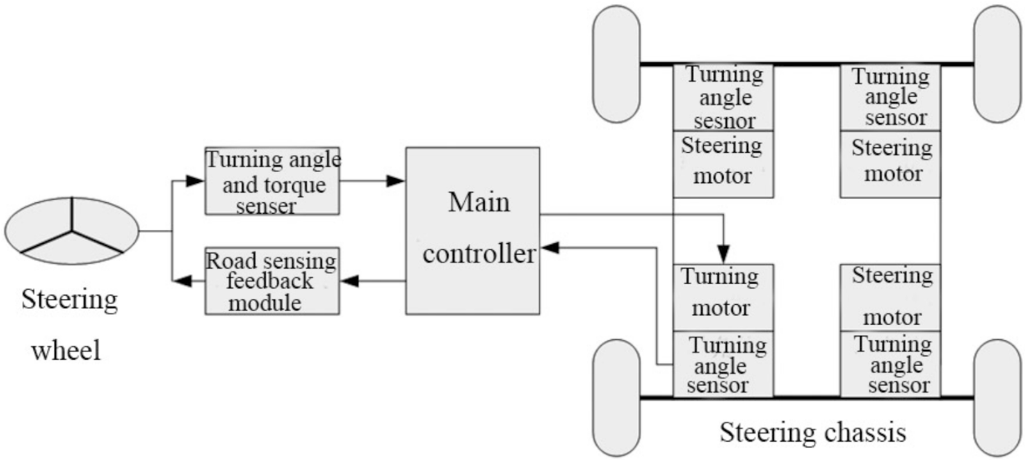

Fig. 1. Structure of the active steering system.

circular paths under different road conditions. The results verified that the method had stronger robustness and smaller tracking error. Daher et al. [6] designed a yaw stability controller for articulated frame steering. In this method, the vehicle dynamics model was derived while keeping the yaw rate decoupled from the lateral acceleration to separate the primary path-following task (driver) from the secondary disturbance-attenuation task (controller). The effectiveness of the controller was verified by simulation and prototype experiments. Electric forklift not only has a large load capacity but also can save manpower when transporting goods. However, the forklift truck often needs to turn frequently in the relatively narrow channel. No matter whether the forklift is loaded or not, its center of gravity will deviate when turning. Once the deviation exceeds some range, it will lose stability. Although the traditional mechanical control has good road feedback, it will test the driver's operation experience when turning. Therefore, in order to further ensure the forklift's operation efficiency, the drive-by-wire mode was applied, and it was given the function of automatic adjustment. In this study, the PSO algorithm was improved by GA, and the parameters of the proportion, integration, and differentiation (PID) controller were calculated by the improved algorithm for forklift steering control. Then the simulation experiment was carried out by MATLAB. The improved algorithm was compared with the GA and PSO algorithm.

2 Forklift steer-by-wire system

2.1 Introduction of forklift steering control system

As shown in Figure 1, there is a mechanical connection between various components in the steering wheel module. When the driver turns the steering wheel, the rotation shaft connected with it will rotate. The angle torque sensor installed on the steering wheel detects the rotation angle and transmits the rotation angle signal to the main controller. The road sensing feedback module [7] installed at the rotating shaft will apply resistance on the rotating shaft after receiving the signal from the main controller to replace the inherent limitation of the traditional mechanical control and provide the driver with road feel feedback.

After receiving the steering wheel steering signal from the angle torque sensor [10], the main controller in the control module calculates the steering angle of the steering wheel according to the set transmission ratio and transmits the signal to the steering motor to complete the tire steering. After that, the main controller also receives the actual steering wheel angle signal from the angle sensor, converts it into the road sensing feedback signal, and transmits it to the road sensing feedback module. In addition to the above functions, the control module will collect the real-time movement status of the forklift through the sensors installed on the vehicle body, including the travel speed, sideslip angle, yaw velocity, etc. When the forklift deviates from the normal motion state too much due to a sudden situation, the steering control algorithm in the main controller will perform a compensation control on the steering motor to make the forklift body stable.

2.2 Dynamic model of forklift truck

Compared with the traditional mechanical steering system, the steer-by-wire system greatly reduces the driver's operation difficulty. The traditional mechanical control system can not adjust spontaneously when the car body is unstable but completely depends on the driver's experience and technology, and the limitation of mechanical structure also makes the available adjustment technology limited. The steer-by-wire system can adjust the steering more freely after the mechanical connection is canceled; moreover, under the action of the controller, the vehicle body does not have to completely rely on the driver's skills when turning. The driver only needs to input the corresponding steering signal through the steering wheel, and the main controller will adjust the steering motor by using the appropriate transmission ratio and perform a compensation control for the unstable state during steering. After adopting the steer-by-wire system, the four wheels of the forklift can achieve their independent steering and finally achieve the running track shown in Figure 2. For the traditional mechanical steering control system, the rod connection between the front wheel and the rear wheel makes it unable to rotate in place.

In the active steering control algorithm, it is necessary to compare the actual and expected vehicle motion states before compensating control according to the difference. Therefore, the first step is to establish a dynamic model of forklift.

As mentioned above, the active steering control algorithm needs the expected vehicle motion state as a reference to adjust the actual vehicle motion state; therefore, it is necessary to establish a suitable forklift power model. The four-wheel steering forklift studied in this paper mostly works in a flat warehouse, and the main factors affecting its steering stability are yaw rate, lateral acceleration, etc. The two-degree-of-freedom forklift model with four-wheel steering shown in Figure 3 can include the above factors, and the two-degree-of-freedom [8] model makes enough simplification for the forklift movement. The kinematic differential equation of the motion model in Figure 3 is:

$$\begin{cases} \dfrac{mu(\beta' + \omega)}{2} = (k_1 + k_2)\beta + \dfrac{ak_1 - bk_2}{u}\omega - k_1\delta_1 - k_2\delta_2 \\ \dfrac{J_z\omega'}{2} = (ak_1 - bk_2)\beta + \dfrac{a^2k_1 - b^2k_2}{u}\omega - ak_1\delta_1 - bk_2\delta_2 \end{cases}, \quad (1)$$

where m is the mass of a forklift, u is the component of the forklift speed on the y axis, β is the side slip angle, β' is the side slip angular velocity, ω stands for the yaw velocity of a forklift along the x axis, ω' stands for the yaw angular acceleration, k_1 stands for the cornering stiffness of the front wheel, k_2 stands for the cornering stiffness of the rear wheel, a and b are the distance from the center of mass to the front axis and the distance from the center of mass to the rear axis respectively, δ_1 is the turning angle of the rear wheel, δ_2 is the turning angle of the rear wheel, and J_z is the rotational inertia of forklift around the z axis (z axis is the center of the circle pointed by the angular velocity when the forklift steers, not the centroid of the forklift).

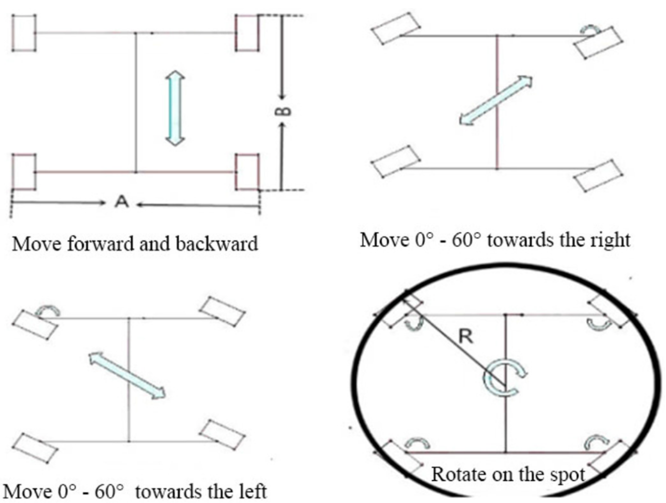

Fig. 2. The track of four-wheel steering forklift.

3 Steer-by-wire control strategy

3.1 Steer-by-wire PID control based on the traditional particle swarm optimization algorithm

In the steer-by-wire control system, the steering wheel of the forklift will rotate after the turning angle of the steering wheel is calculated based on the transmission ratio. During the operation, the sensor will collect the actual motion state of the vehicle body, including the rotation angle of the tire. After that, the active steering control algorithm in the system will adjust according to the difference between the actual motion state and the expected motion state. The active steering control strategy adopted in this study is the

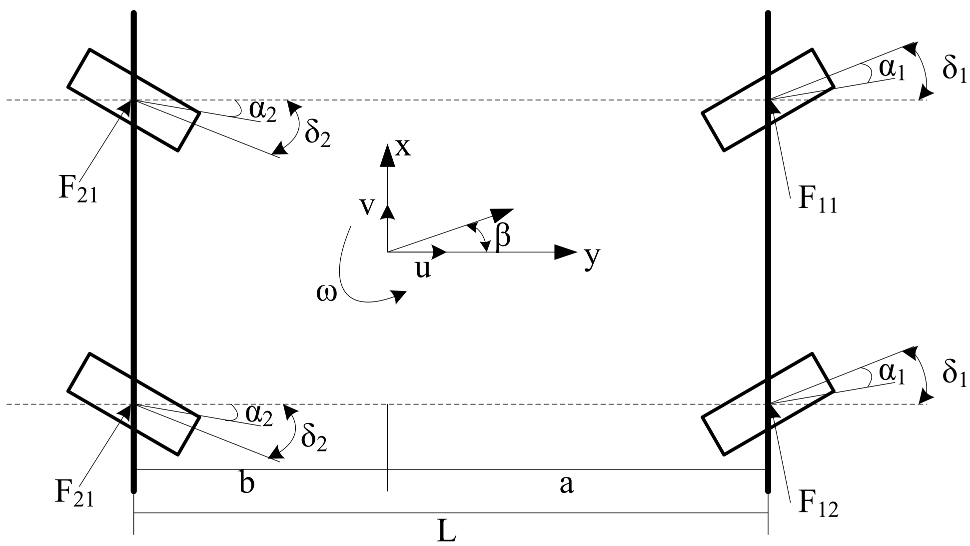

Fig. 3. The motion model of the two-degree-of-freedom forklift with four-wheel steering.

common PID control strategy [9]:

$$K(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{d}{dt} e(t), \quad (2)$$

where $K(t)$ refers to the result calculated by the PID control according to yaw velocity error $e(t)$ at time t, which is taken as the ratio of the turning angles of the front and rear wheels in this study, and K_P, K_I, and K_D are three parameters in the PID controller, that is, the proportion, integration, and differentiation parameters.

The control effect of the PID controller on forklift steering depends on K_P, K_I, and K_D. The traditional K_P, K_I, and K_D are fixed, and their values are obtained according to experience. In practical application, forklift faces with various unstable conditions when steering. Although the PID controller uses proportional, integral, and differential parameters to make the error adjustment as close to nonlinear changes as possible, the fixed adjustment parameters make the fitting range limited. If the error that needs to be adjusted beyond this range, the error adjustment effect will greatly reduce. To optimize the error adjustment effect of the PID controller, three adjustment parameters are set as variable, and the value setting is optimized by the particle swarm optimization (PSO) algorithm [10]. Parameters K_P, K_I, and K_D to be optimized are regarded as the coordinates of particles in the search space, and the three coordinate axes in the search space correspond to the candidate ranges of the three optimization parameters, respectively. The basic iterative formula of the PSO algorithm is as follows:

$$\begin{cases} v_i(t+1) = \varpi v_i(t) + c_1 r_1 (P_i(t) - x_i(t)) + c_2 r_2 (G_g(t) - x_i(t)) \\ x_i(t+1) = x_i(t) + v_i(t+1) \end{cases}, \quad (3)$$

where $v_i(t+1)$ and $x_i(t+1)$ are the speed and position of particle i after one time of iteration, $v_i(t)$ and $x_i(t)$ are the speed and position of particle i before iteration, ϖ is the inertia weight of a particle, c_1 and c_2 are learning factors, r_1 and r_2 are random numbers between 0 and 1, $P_i(t)$ is the optimal position that particle i experiences, and $G_g(t)$ is the best position that the particle swarm experiences.

3.2 Steer-by-wire PID control based on improved particle swarm optimization algorithm

To solve the premature problem of the PSO algorithm, this study used a genetic algorithm (GA) [11] for the improvement of the PSO algorithm. As a matter of fact, the optimization of K_P, K_I, and K_D can be independently performed by GA. The three parameters are taken as the gene segments of chromosome, and the optimal chromosome, that is, the optimal solution, gradually evolves from the chromosome population under the genetic operation of crossover and mutation. However, due to the existence of crossover and mutation genetic operators, it is not easy to fall into the local optimal solution. Therefore, this study combines the advantages of them and introduces the genetic operator in GA into the PSO algorithm to avoid falling into the local optimal solution. The iterative formula

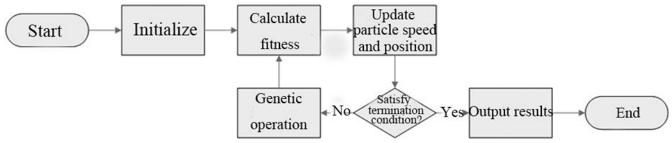

Fig. 4. The calculation flow of the improved PSO algorithm.

of the improved PSO algorithm is:

$$\begin{cases} v_i(t+1) = \varpi v_i(t) + c_1 r_1 (f_i(t) - x_i(t)) + c_2 r_2 (f_g(t) - x_i(t)) \\ x_i(t+1) = x_i(t) + v_i(t+1) \end{cases}, \quad (4)$$

The change of the improved iterative formula lies in replacing $P_i(t)$ and $G_g(t)$ in the original PSO algorithm withthe individual optimal particle $f_i(t)$ and globally optimal particle $f_g(t)$ obtained in the process of genetic operation.

The flow of optimizing K_P, K_I, and K_D with the improved PSO algorithm is shown in Figure 4.

(1) The parameters of the algorithm are initialized.

(2) The fitness value of the particles in the population is calculated:

$$f(t) = \int_0^t t|e(t)|dt, \quad (5)$$

where $e(t)$ is the difference between the expected and actual yaw velocity of the forklift under the adjustment of K_P, K_I, and K_D represented by the corresponding particles and $f(t)$ is the absolute deviation integral of the selection time. The ultimate goal of the algorithm is to search for the particles that make equation (5) reach the minimum value.

(3) The velocity and position of the particle swarm are updated according to equation (4).

(4) Whether the algorithm reaches the termination condition is determined: the fitness value converges to stable, or the iteration reaches the maximum value.

(5) If the algorithm does not meet the termination conditions, the genetic operation is performed on the particles in the particle swarm, including crossover and mutation. The coordinates of particles in the search space are regarded as three gene segments of chromosomes in genetic operation. Crossover operation is the exchange of gene segments with the same gene site between any two particles, and the probability of gene site exchange is the crossover probability [12]; mutation operation is that the gene segment of a gene site in a single particle changes randomly, that is, the corresponding PID parameters change randomly in an allowable range in this study, and the probability of random change of gene site is the mutation probability.

(6) After the genetic operation of the particle swarm, the fitness value is calculated again, and the individual optimal particle and globally optimal particle are selected for the iteration and updating of the speed and position.

(7) Steps (3)–(6) are repeated until the algorithm satisfies the termination condition.

Table 1. Basic simulation parameters of the forklift model.

Parameter name	Numerical value	Parameter name	Numerical value
Mass of forklift (m)	8500 kg	Distance from the centroid to the front axle (a)	1.2 m
Distance from the centroid to the rear axle (b)	0.5 m	Cornering stiffness of the front wheel (k_1)	6.5×10^4 N/rad
Cornering stiffness of the rear wheel (k_2)	5.5×10^4 N/rad	Maximum driving speed (v_{max})	15 km/h
Rotational inertia of the forklift body around the z axis (J_z)	3.65×10^3 kg·m^2	Gravity constant (g)	9.8m/s^2

Table 2. The comparison of the steering data between the simulation forklift and actual forklift.

	Low speed (the driving speed is 1.5 m/s and the acceleration speed is −0.5 m/s^2)		High speed (the driving speed is 4.5 m/s and the acceleration speed is −5 m/s^2)	
	Yaw velocity	Side slip angle	Yaw velocity	Side slip angle
The simulation forklift	0.251 rad/s	0.0220 rad	0.300 rad/s	0.0301 rad
The actual forklift	0.250 rad/s	0.0221 rad	0.299 rad/s	0.0297 rad
Error	0.1%	0.1%	0.09%	0.1%

4 Simulation experiment

4.1 Experimental environment

In this study, simulation experiments were carried out on the four-wheel steering forklift and the improved PSO algorithm using MATLAB software [13]. The experiment was carried out in a laboratory server. The server was equipped with Windows 7 operating system, Core i7 processor, and memory 32 G.

4.2 Experimental data

The basic simulation parameters of the forklift model are shown in Table 1.

The simulation experiment was carried out to verify the adjustment effect of the PID strategy under the improved PSO algorithm. To ensure that the simulation results were close to the actual forklift steering effect as far as possible, the modeling of the forklift simulation model referred to the actual forklift steering effect, and the final model parameters are shown in Table 1. The forklift for reference had a mass of 8500 kg, and the distances from the centroid to the front axle and the rear axle were 1.2 and 0.5 m respectively; the cornering stiffness of the front wheel and rear wheel was 6.5×10^4 and 5.5×10^4 N/rad respectively; the rotational inertia of the vehicle body rotating around the z axis was 3.65×10^4 kg · m^2; the gravity constant of the forklift during driving in the simulation experiment was set as 9.8 m/s^2.

The parameters of the improved PSO algorithm are as follows. The population size was 50, the dimension of the search space was 3, two learning factors were both set as 1.5, the maximum iteration times was 100, the inertia weight was 0.8, the crossover probability was 0.5, and the mutation probability was 0.05.

Moreover, to verify the parameter optimization effect of the improved PSO algorithm, it was compared with the standard PSO algorithm and GA. The parameters of the standard PSO algorithm were consistent with the PSO algorithm in the improved PSO algorithm, while the parameters of GA were consistent with the GA in the improved algorithm.

To ensure that the conclusion obtained from the test on the simulation model was accurate, steering tests were carried out on the simulation forklift and actual forklift before the formal test. The yaw velocity and side slip angle during the high-speed and low-speed steering were compared between the two forklifts, and the results are shown in Table 2. The comparison error in Table 2 indicated that the low-speed and high-speed steering data of the simulation model could give a relatively realistic picture of the actual steering change.

4.3 Experimental design

– The steering experiment of the simulation forklift atlow speed: the driving speed and accelerated speed of the forklift were set as 1.5 m/s and −0.5 m/s^2. As this study mainly analyzed the stability of forklift active steering control, the steering wheel transmission ratio was not considered in the simulation experiment of forklift steering, but the turning angle amplitude signal of front and rear wheels were input directly, which was regarded as the signal that has been processed by the transmission ratio. One second after the beginning of the experiment, the wheel steering signal was input: the amplitude of the turning angle of the front wheel was 0.3 rad, and that of the rear wheel was −0.2 rad. The PID controllers optimized by the above three algorithms were used for the active steering control, and the variation curves of the yaw velocity and sideslip angle were obtained by the forklift model. The simulation experiment lasted for 10 s.

– The steering experiment of the simulation forklift at high speed: the driving speed and accelerated speed of the forklift were set as 4.5 m/s and $-5\,m/s^2$, and the experimental setup was consistent with the low-speed experimental item.

4.4 Experimental results

In this study, the GA, PSO algorithm, and improved PSO algorithm realized the PID control strategy of active steering in the simulation experiment of the forklift. The three algorithms aimed at searching for the most appropriate proportion, integral, and differential factor in the PID controller. In the simulation experiment, the three algorithms needed some iterations before they obtained the optimal solution, then the fitness change of the algorithms in this process is shown in Figure 5. It was seen from Figure 5 that the fitness values of the three algorithms decreased with the increase of the number of iterations, indicating that the three algorithms gradually approached the optimal solution in the iterative process. Among the three algorithms, the standard PSO algorithm converged to stability after about 25 times of iterations, which was the fastest, but its fitness after stability was significantly higher than that of the other two algorithms. The GA convergedto stability after 50 times of iterations, which was the slowest. The improved PSO algorithm converged to stability after 40 times of iterations, and the fitness after stability was the lowest; the fitness value of the GA was close to that of the improved PSO algorithm but slightly higher.

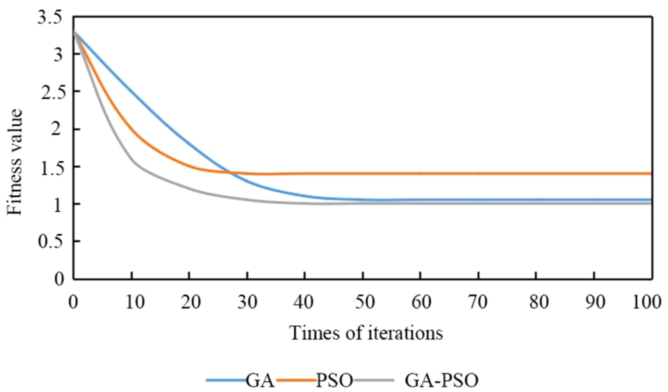

Fig. 5. Convergence curves of three parameter-optimization algorithms.

As shown in Figure 6, the yaw velocity of the three algorithms all increased rapidly one second after the convey of the steering command; the GA stabilized at 0.10 rad/s after 2.2 s, the PSO algorithm stabilized at 0.24 rad/s after 1.3 s, and the improved PSO algorithm stabilized at 0.176 rad/s after 1.4 s; the response of the improved PSO algorithm was slightly slower than that of the PSO algorithm, and the yaw velocity of the improved PSO algorithm was between the GA and PSO algorithm, which was more conducive to stable steering.

Then it was the side slip angle of the forklift. The side slip angle of the GA was 0 under the three algorithms before inputting the steering command. After inputting the steering command, the three algorithms all made responses. The side slip angle of the GA decreased to −0.075 rad within 1 s, and then it was almost stable; the side slip angle of the PSO algorithm increased suddenly first and then decreased to 0 rad within 1 s, and then it remained stable; the side slip angle of the improved PSO algorithm firstly dropped suddenly and then rose to −0.018 rad. It was seen that the side slip angle of the forklift steering was too large under the GA, which was not conducive to stable steering. Although the PSO algorithm could quickly stabilize the sideslip angle of the forklift at 0, the fluctuation at the moment of steering was greater than that of the improved PSO algorithm, which was easy to cause instability at the moment of steering and was also not conducive to stable steering.

Figure 7 shows the change of the yaw velocity and side slip angle of the forklift in the high-speed simulation experiment. The yaw velocity increased rapidly one second

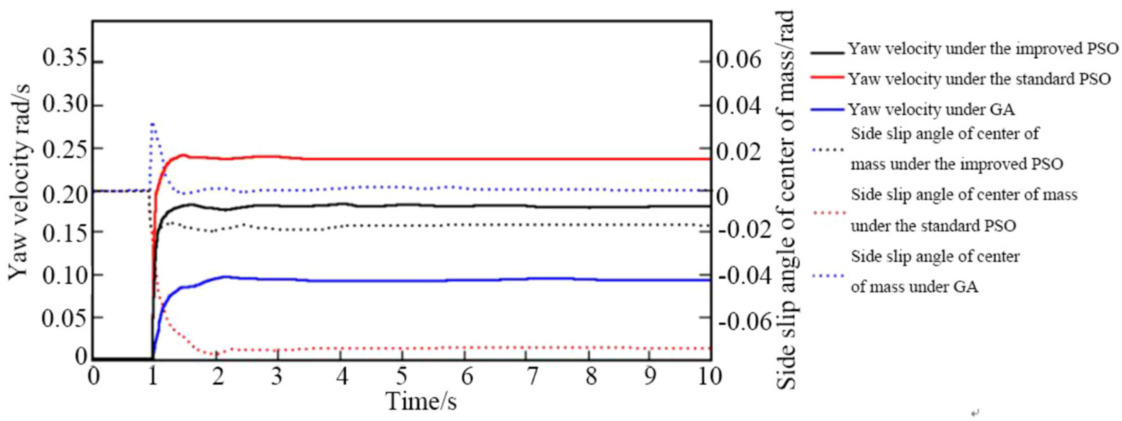

Fig. 6. The yaw velocity and sideslip angle of the center of mass of the forklift at a low driving speed under three algorithms.

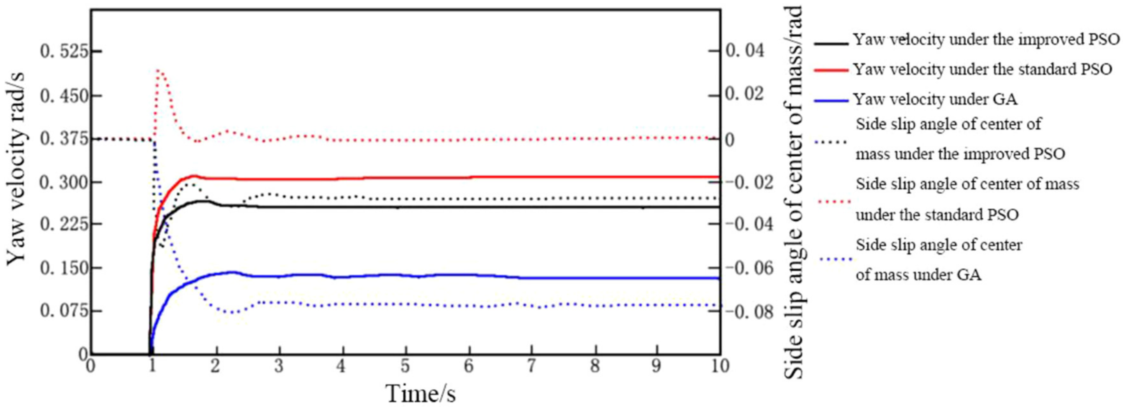

Fig. 7. Changes of the yaw velocity and side slip angle of the center of mass of the forklift in the high-speed driving.

after the convey of the steering command under the three algorithms. The GA was stable at 0.15 rad/s after 2.1 s, the PSO algorithm stabilized at 0.30 rad/s after 1.3 s, and the improved PSO algorithm stabilized at 0.23 rad/s after 1.4 s. The overall change trend was similar to that at the low speed, but it was found that the yaw velocity under the high-speed steering was higher in the same algorithm.

For the side slip angle, after the steering command was input, all the three algorithms responded quickly. The side slip angle of the GA algorithm decreased to −0.076 rad within 1 s, and then it was almost stable; the side slip angle of the PSO algorithm increased suddenly first and then decreased to 0 rad within 1 s, and then it remained stable; the side slip angle of the improved PSO algorithm firstly dropped suddenly and then rose to −0.029 rad.

5 Discussion

As a common handling tool in the warehouse, an electric forklift has the advantages of low noise and no exhaust gas. The forklift truck often turns frequently in a narrow channel when transporting goods in the warehouse. The center of gravity of the vehicle body will inevitably shift in the process of turning. Once the shift exceeds the range, the forklift will rollover. Therefore, the stability of the center of gravity should be ensured when the forklift turns. The traditional steering system is a mechanical steering system based on mechanical connection. This kind of steering system has the advantages of a relatively simple structure and more real road feedback when steering. However, the real road feedback will also increase the difficulty of steering control. To reduce the difficulty, the steer-by-wire system without a mechanical connection is adopted. In the steer-by-wire system, the steering operation of the steering wheel is transformed into an electrical signal, which controls the steering motor through the wire to realize steering. In this process, there is no direct mechanical connection between the steering structure and the steering wheel. The road feedback transmitted by the steering wheel is simulated by the steering wheel motor, which is not completely real road feedback, that is, the steering structure has room for self-regulation. One of the advantages of the steer-by-wire system is that its steering structure has a self-regulation ability under the control of the steering signal of the steering wheel, which makes the vehicle return to the stable state as soon as possible in the process of steering and reduces the difficulty of steering operation.

When the steering-by-wire system adjusts the steering stability independently, the sensor installed on the car body will collect the stability parameters of the car body and then compared it with the established dynamic model of the car body to calculate the steering angle to be adjusted. The traditional steering angle adjustment method is a PID control strategy based on the gap between the actual car body dynamics and the ideal car body dynamics. However, the road conditions are diverse, and the simple PID control strategy has the adjustment limit for the fixed adjustment parameters. Therefore, the adjustment parameters in the PID strategy were optimized by the PSO algorithm to make it self-adapt to different conditions; moreover, the PSO algorithm was improved in this study; the population was adjusted by crossover and mutation in GA to avoid "premature" as far as possible. Then the PID strategy under the control of the GA and the PID strategy under the control of the traditional and improved PSO algorithms were tested. The final results showed that the PID control strategy under the improved PSO algorithm had a better guarantee for the stability of forklift steering, whether in low-speed steering or high-speed steering. The reason was as follows. The improved PSO algorithm used the crossover and mutation operations in GA, which made up for the "premature" defect on the basis of maintaining the original simple operation. Therefore, the calculation of the optimal steering adjustment angle was more rapid and accurate, which made the forklift steering more stable.

6 Conclusion

This study mainly introduced the steer-by-wire system and active steering control strategy of the forklift. The PSO algorithm was optimized by GA, and the parameters of the PID controller were optimized. Then the low-speed and high-speed steering of the four-wheel steering forklift was simulated in MATLAB, and the improved algorithm was compared with the GA and PSO algorithm. The results are as follows. (1) The PSO algorithm converged faster, but the fitness value after stability was slightly larger; the convergence of the GA was the slowest, but the fitness value after stability was significantly smaller than that of the PSO algorithm and close to that of the improved PSO algorithm; the convergence speed of the improved PSO algorithm was close to the PSO algorithm, and the fitness value after stability was the smallest. (2) In the low-speed and high-speed steering, the three algorithms responded to the steering signal quickly; the yaw velocity of the GA was smaller, that of the PSO algorithm was larger, and that of the improved PSO algorithm was between them; moreover, the increase of steering speed increased the yaw velocity. (3) In the low-speed and high-speed steering, the absolute value of the side slip angle under the GA was the largest after convergence to stability, the absolute value of the side slip angle under the PSO algorithm was stable at 0, and the absolute value of the side slip angle under the improved PSO algorithm was between the GA and PSO algorithm.

References

1. A. Munir, F. Koushanfar, IEEE Trans. Dependable Secure, **PP**, 1–1 (2018)
2. F.S.M. Hafiz, Z. Hairi, M.S. Amri, Int. J. Veh. Tech. **2015**, 1–17 (2015)
3. H. Zhang, W. Zhao, Sci. China Technol. Sci. **6**, 1–10 (2017)
4. C.Y. Wang, K. Deng, W.Z. Zhao, G. Zhou, D. Zhou, Sci. China Technol. Sci. **1**, 16 (2017)
5. Z. Sun, J. Zheng, Z. Man, H. Wang, IEEE Trans. Ind. Electron. **63**, 2251–2262 (2016)
6. N. Daher, M. Ivantysynova, Control Eng. Pract. **45**, 46–53 (2015)
7. T. van der Sande, P. Zegelaar, I. Besselink, H. Nijmeijer, Vehicle Syst. Dyn. **54**, 1247–1268 (2016)
8. A. Munir, F. Koushanfar, *Consumer Communications & Networking Conference*, 2016, (IEEE, Las Vegas, NV, USA), p. 1066–1073
9. F.X. Xu, X.H. Liu, W. Chen, C. Zhou, Math. Probl. Eng. **2018**, 1–12 (2018)
10. C. Huang, F. Naghdy, H. Du, IEEE Trans. Cybern. **49**, 261–272 (2019)
11. D. Petranovi, A. Marui, J. Havelka, Teh. Vjesn. **26**, 156–162 (2019)
12. F. Hunaini, I. Robandi, N. Sutantra, Iran. J. Electr. Electron. Eng. **11**, 25–35 (2015)
13. F. Hunaini, Turk. J. Electr. Eng. Co. **24**, 541–557 (2016)

Cite this article as: Chuan Feng, Research on steering control performance of electric forklift with steer by wire, Int. J. Metrol. Qual. Eng. **12**, 1 (2021)