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A study of using fuzzy logic and artificial intelligence algorithms to improve the safety of oil and gas loading and unloading operations in enterprises

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Abstract There are multiple safety risk factors in corporate oil and gas loading and unloading operations, including vessel, environment, operational safety, equipment, people and management. These factors are intersecting and interrelated, forming a complex system. In this study, the explanatory structural model and fuzzy PID control algorithm based on particle swarm optimization are used to improve the safety of enterprise oil and gas loading and unloading operations. Firstly, 25 main risk factors are screened out through questionnaire survey and expert interviews, and ISM is established to analyze the risk hierarchy structure and reveal its intrinsic relationship; then, a fuzzy PID control system based on PSO optimization is designed to realize the intelligent control of oil and gas loading and unloading robotic arm. The results show that: the ISM model divides the risk factors into five layers, in which the safety of oil transfer arm, pipeline safety and reliability of anti-static device are the key risk factors in layer 2; compared with the traditional PID controller, the fuzzy PID controller based on PSO optimization shortens the rise and convergence time during startup from 2.11s to 0.54s, which is a reduction of 74.4%; and the convergence time during stopping process is reduced from 3.95s to 1.01s, a reduction of 74.4%, eliminating the system oscillation and overshooting problems. In addition, through the fuzzy rule design and parameter optimization, the nonlinear and time-varying characteristics of the system are effectively solved, and the control accuracy and system response speed are improved. Enterprises should pay attention to the regular inspection and maintenance of loading and unloading equipments, establish a perfect emergency management system, and improve the professional quality of operators, so as to comprehensively improve the safety of oil and gas loading and unloading operations.

Index Terms oil and gas loading and unloading operation, safety risk, explanatory structure model, fuzzy PID control, particle swarm optimization, intelligent control system

I. Introduction

Oil and gas chemical terminal is a key location for crude oil loading and unloading, with the recent continuous rise of crude oil loading and unloading workload, it brings more safety risks for oil and gas loading and unloading operation process and increases the possibility of accidents [1]-[3]. Due to the port dangerous goods loading and unloading operation process involves many steps and wide range of specialties, it needs the crew, pilot, marine management personnel, terminal loading and unloading operators, depot operators and other multi-party synergistic cooperation in order to be successfully completed [4]. The involvement of multiple operators may lead to negligence and errors due to increased pressure [5]. If there is improper synergy or personnel error during the operation, it may lead to serious casualties and property damage [6], [7]. More seriously, the possible fire, explosion or leakage events may cause great impacts and hazards to the neighboring communities and ecological environment [8], [9]. Therefore, safeguarding the safety of crude oil loading and unloading operations in chemical terminals is not only to protect the lives of the staff, but also to maintain the safety of the neighboring communities and protect the sustainable development of the ecological environment [10]-[12]. Based on this, the introduction of artificial intelligence algorithms to construct a scientific safety risk identification and assessment model helps to formulate targeted preventive and countermeasures to reduce the possible losses and risks.

As a pillar industry of national economy, oil and gas industry, its safety production problem is always the focus of attention of all countries. Oil and gas loading and unloading operation is the key link in the process of oil and gas transportation and storage, and is also a high accident area. According to statistics, more than 40% of the major accidents in the oil and gas industry in recent years occurred in the loading and unloading link, causing serious casualties and property losses. Oil and gas loading and unloading operations are characterized by high risk, high hazard and high pressure, and once collision, cable breakage, leakage and other accidents occur, it is very easy to cause fire, explosion and environmental pollution, resulting in chain reactions and secondary disasters. Therefore, in-depth study of oil and gas loading and unloading operation safety risk factors and their control methods has important theoretical value and practical significance. Traditional oil and gas loading and unloading safety management mainly relies on artificial experience and simple mechanical control, which is difficult to cope with the complex and changeable operating environment and unexpected conditions. In recent years, with the development of artificial intelligence and intelligent control technology, it has become possible to apply advanced control algorithms to the field of oil and gas handling safety. Fuzzy logic control has received widespread attention because of its good adaptability to nonlinear systems and effective integration of expert experience. Meanwhile, particle swarm optimization algorithm, as a new type of intelligent optimization method, performs well in parameter optimization. However, most of the existing researches focus on the application of a single technology, lack of systematic risk identification and analysis, as well as the integrated application of intelligent algorithms, which makes it difficult to comprehensively improve the safety performance of oil and gas loading and unloading operations.

Based on the idea of system engineering, this study combines the complex system analysis method with intelligent control technology to construct a framework for analyzing and controlling the safety risk of oil and gas loading and unloading operations. First, the Interpretive Structure Model (ISM) is used to systematically analyze the safety risk factors of oil and gas loading and unloading operations, to identify the key risk factors and their hierarchical structure, and to provide a decision-making basis for safety management. Secondly, for the oil and gas loading and unloading robotic arm, which is a key equipment, an intelligent control system based on fuzzy logic is designed, and the particle swarm optimization algorithm is introduced to optimize the parameters of the fuzzy PID controller, so as to improve the control accuracy and system response speed. Finally, the effectiveness of the proposed method is verified through system simulation and comparative analysis. This study combines theoretical analysis and practical application, which not only deepens the understanding of the safety risk of oil and gas loading and unloading operations, but also provides a feasible solution for the intelligent control of loading and unloading equipment, which is of great significance to improve the safety and efficiency of oil and gas loading and unloading operations.

II. Fuzzy Logic and Artificial Intelligence Algorithms Based on Enterprise Oil and Gas Loading and Unloading Operations

II. A. Safety risk factors for oil and gas handling operations in enterprises

Safety risk management of oil and gas loading and unloading operations of enterprises refers to controlling the possible dangers that may occur in the process of oil tanker port call operation, oil loading and unloading operation, and auxiliary production operation below the acceptable level through risk management, and reducing the possibilities of accidents such as collision, cable breakage, leakage, pollution, electrostatic discharge, fire, and explosion. The oil and gas loading and unloading operation system of an enterprise is affected by four types of risk factors, such as operation safety, equipment, people and management, and these risk factors are intertwined and related to each other, which makes the oil and gas loading and unloading operation system of an enterprise complex, and a single or a few factors cannot fully reflect its safety status.

In this paper, based on relevant literature, field research and interviews, 45 enterprise oil and gas handling operation safety risk influencing factors are initially screened out from 6 aspects, such as ships, environment, operation safety, equipment, people and management. Based on this, a questionnaire was designed, and the respondents were asked to score each safety risk factor (1~5 points), and the higher the score, the greater the influence of the factor on the oil and gas handling operation of the enterprise. The respondents of the questionnaire survey consisted of 50 oil port operators, 25 oil port department managers, 25 shipping company marine supervisors, and 20 professors engaged in port and shipping management research. A total of 120 questionnaires were sent out and 118 were returned, of which 115 were valid. The average score of each risk factor was obtained by counting the questionnaires, and by consulting again with professors engaged in port and shipping management research, the boundary values of the risk factors were eliminated and some of the intersecting risk factors were combined. This paper adopts the average value of all risk factor scores as the boundary value, and finally determines 25 major risk factors existing in the process of corporate oil and gas handling operations, and the safety risk factors of corporate oil and gas handling operations are shown in Table 1.

Table 1: Safety risk factors for cargo loading and unloading operation

Factor set	Risk factor	Number
Ship	Ship element	F1
	Tanker technical state	F2
Environment	Channel condition	F3
	Navigation AIDS	F4
	Ship traffic flow	F5
	Just to communicate	F6
	Port location	F7
	Meteorological hydrological conditions	F8
	Laws and regulations and standards	F9
Job safety	Docking safety	F10
	Handling safety	F11
	Safety of pipeline transport	F12
	Discharge safety	F13
Equipment	Arm safety	F14
	Pipeline safety	F15
	The reliability of antistatic devices	F16
	Effective emergency rescue equipment	F17
People	Psychological factor	F18
	Skill experience	F19
	Command violation	F20
	Operation violation	F21
	Performance of ship's drivers	F22
Management	Management safety	F23
	Emergency management	F24
	Competent authority	F25

II. B.Establishment of ISM for safety risk factors of oil and gas handling operations in enterprises

ISM [13] is used to analyze the problems related to complex socio-economic systems.ISM uses directed graphs, matrices, computer technology, and people's empirical knowledge to analyze the structure of complex systems.Firstly, it establishes adjacency and reachability matrices, and then decomposes reachability matrices to decompose the complex system into the structural form of multilevel ladder. ISM is able to identify direct and indirect risk factors from a wide range of risk factors, thus helping decision makers to focus on the most important key points and improve decision-making efficiency.

II. B. 1) Creating an adjacency matrix

The adjacency matrix is a matrix that indicates whether there is a direct relationship between factors. Combining the results of the questionnaire survey and the research interviews, the relationships between the 25 factors were determined and the adjacency matrix A was established, the elements of which a_{ij} denote the relationship of direct influence between the factors F_i and F_j, that is:

$$a_{ij} = \begin{cases} 1, \text{ When } F_i \text{ has a direct effect on } F_j \\ 0, \text{ When } F_i \text{ has no direct effect on } F_j \end{cases} \tag{1}$$

The adjacency matrix between the safety risk factors for oil and gas handling operations in the enterprise is A.

II. B. 2) Establishment of a Reachability Matrix

The reachability matrix [14] describes the degree to which a path of a certain length can be reached between two factors and indicates the existence of a direct or indirect relationship between the two factors. The element m_{ij} of the reachability matrix R is defined as:

$$m_{ij} = \begin{cases} 1, \text{Existence of a path from } F_i \text{ to } F_j \\ 0, \text{Path from } F_i \text{ to } F_j \text{ does not exist} \end{cases} \tag{2}$$

Order:

$$A_i = (A+I)^i, 1 \le i \le n-1 \tag{3}$$

where I is the unit matrix of the same order as A. It is obtained after applying the Boolean operation rules ($0+0=0$, $0+1=1$, $1+0=1$, $1+1=1$, $0\times 0=0$, $0\times 1=0$, $1\times 0=0$, $1\times 1=1$) in turn:

$$A_1 \ne A_2 \ne \cdots \ne A_{r-1} = A_r, r \le n-1 \tag{4}$$

where n is the matrix order, then:

$$A_{r-1} = \left(A+I\right)^{r-1} = R \tag{5}$$

The risk factor reachability matrix obtained with the help of MATLAB is R.

II. C.Mechanism analysis of safety of oil and gas loading and unloading operations in enterprises based on ISM

According to the grading results to establish the enterprise oil and gas loading and unloading operation safety risk factors ISM, level 1 up to the set and antecedent set as shown in Table 2; ship port call and loading and unloading operation safety ISM as shown in Figure 1. The safety risk factors at the surface level are mainly equipment factors and ship factors; the safety risks at the middle level are mainly management and environmental factors; and the risks at the deep level are mainly human and legal factors.

Tanker technical condition, navigation aids, vessel traffic flow, vessel driver behavior level, oil transfer arm safety, pipeline safety, reliability of anti-static devices, effective emergency rescue equipment and emergency management to affect the main risk factors of each operation process. Among them, ship technical conditions, navigational aids, ship traffic flow conditions and pilotage operation level directly affect berthing. Regular maintenance of ship can keep good technical condition, perfect navigation equipment and high pilotage level can improve berthing safety, and reasonable traffic control can divert ships and also improve berthing safety. The safety of oil transfer arms, process pipelines, safety accessories, the efficiency of rescue equipment and the timeliness of emergency management all have a certain impact on operational safety. Regular inspection, maintenance and improvement of emergency management systems and rescue equipment can improve operational safety.

Vessel elements, supervision by competent authorities, channel conditions, port siting, meteorological and hydrological conditions, command violations, operation violations, and just go communication conditions are the third level of risk. The age, strength and tonnage of the vessel will affect its condition. The level of supervision by the competent authority, the condition of the waterway, the siting of the port and the hydro-meteorological conditions directly affect the ship flow. Unauthorized command and operation have a direct impact on the safety of equipment, the reliability of guards and the effectiveness of rescue equipment. Communication will affect the timeliness and effectiveness of emergency response. Psychological factors, skills and experience and management safety are the fourth level of risk. It has a direct impact on the emergence of unauthorized operation. Laws, regulations and standards are the bottom risk factors, affected by changes in laws and regulations, which have a direct impact on the management of terminal safety operations, terminal location, government regulation.

Table 2: The first level can be set and the previous set

Factor number	Risk factor (F)	Adjacent matrix(A)	S ∩ A	First level
1	1,3,4,7	1	1	—
2	3,6,8	1,3	2	—
3	3,4,7,9	2,3	3	—
4	3,4,5	3,5-7,16	4	—
5	2,5,7	4,8-15,19	5	—
6	6	5-13,18	6	√
7	5,6,8-11,18	7,9-14,15-22	7	—
8	4,5,7,9	7,11,12-19	8	—
9	5,7	7,10,14-17,19,21	9	—
10	5,9	8,12,15-21,23	10	—
11	7,11	8,11,14,17	11	—
12	5,12	8,10-14,18,22	12	—
13	5,10-14,15,17	8,13,15-24	13	—
14	5,8-13,15-17	8,15,17-23	14	—
15	6,8-12,15	8,10-16,22,25	15	—
16	6,8-13,15	16	16	—
17	5,8,16	17	17	—
18	6,8-13,14,15,17	8,12-14,19	18	—
19	7,10-13,20	8,14,15,17,19	19	—
20	4,5,10,18	20	20	—
21	6,9,11-17,23	8,21	21	—
22	8,11,16,21	8,22	22	—
23	10,13-15,19	23	23	—
24	8,18-23,25	9,18-22	24	—
25	5,12-17,19	9,14-18,25	25	—

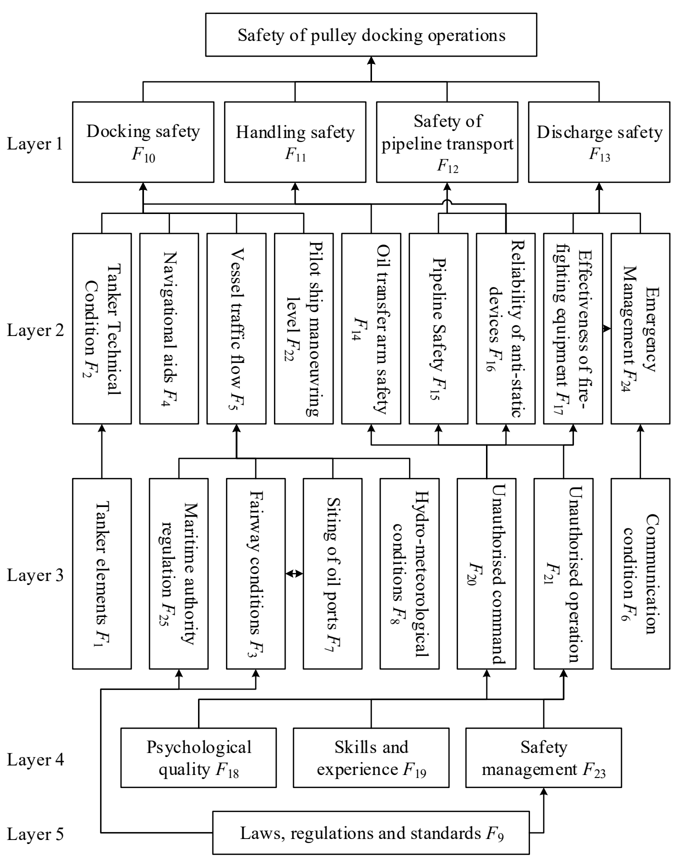

Figure 1: The ISM of the safety of port and loading and unloading

The following recommendations are made based on the results of the ISM analysis of the safety of ship berthing and production operations:

(1) Ship's berthing operation directly affects the safety of ship berthing operation and the safety management of ship's berthing and loading/unloading operation should be strengthened. Spare equipment should be checked before the ship arrives at the harbor. When the ship is moored, the tugboat should assist the ship to control the direction and speed to ensure safe mooring. Before loading and unloading, ensure that the technical condition of the oil transfer arm meets the requirements, the fire-fighting facilities are available, the electrostatic grounding is reliable, and check the sealing condition of the oil transfer arm and the composite hose. Monitor and record the temperature, pressure and flow rate of the oil. If there is any abnormality, report it in time and take emergency measures. During the venting process, it should be ensured that there is no residual oil and no air.

(2) Since the safety risk factors in the second layer of the ISM model mainly include the loading and unloading facilities of ships and oil terminals, it is recommended to inspect the loading and unloading equipment of ships and oil terminals. The safety of oil transfer arms, pipelines, valves and fittings, safety devices, fire fighting facilities, etc. should be regularly inspected and troubleshooting should be carried out in time to ensure safety and availability.

(3) Emergency response is an important safety risk factor in the second layer of the ISM model, and a comprehensive management system should be in place. Set up emergency response center and participating rescue team, formulate emergency management system, establish emergency plan for ship loading and unloading at sea, equip with enough rescue equipment, carry out regular emergency drills, and further improve the emergency management system.

(4) According to the potential factors of ISM model, it is recommended to improve the professional quality of operating personnel. Conduct emergency safety and related operation training to reduce the possibility of safety risks caused by subjectivity.

III. Analysis of safety results of oil and gas loading and unloading operations of enterprises

III. A. Control system design

III. A. 1) Control system program design

The oil and gas loading and unloading robotic arm control system takes PLC as the control core and relies on the data provided by angle, inclination, displacement and liquid level sensors. The actuator adopts a three-position four-way proportional solenoid valve. During the working process, the controller collects the position information of the robotic arm in real time through the sensors, compares it with the set value, and calculates the deviation amount, which is used as the input quantity of the system. The control parameters are corrected by the PSO-based fuzzy PID control algorithm [15], and the opening direction and size of the proportional valve are adjusted according to the calculated current changes, thus adjusting the displacement and direction of the hydraulic cylinder, as well as the speed and steering of the hydraulic motor. The input data from the vibration and pressure sensors are used to determine the current working status of the robotic arm.

III. A. 2) Fuzzy PID control principle

The traditional PID control algorithm consists of proportional (P), integral (I) and differential (D). The algorithm calculates the control quantity according to the system deviation and carries out the control, which has the characteristics of simple control structure and algorithm, good stability and wide range of application, etc. The PID control equation is:

$$u(k) = K_p e(k) + K_i \sum_{n=0}^{k} e(n) + K_d (e(k) - e(k-1)) \tag{6}$$

where, $u(k)$ is the controller output; $e(k)$ is the controller input; K_p, K_i, K_d are the proportional, integral, and differential gains, respectively.

The error $e = r(k) - y(k)$ and the rate of change of the error $e_c = de/dt$ of the piston rod of the hydraulic cylinder are used as inputs to make decisions based on fuzzy control rules. After the fuzzy controller uses the area center method to solve the fuzzy, it gets the online adjustments of PID parameters ΔK_p, ΔK_i and ΔK_d, which are summed up with the initial values of the PID parameters to realize the adaptive adjustment of the PID parameters in order to meet the needs of different different controlled objects under different working conditions, so as to maintain the stability and dynamic response effect of the system. The parameter self-tuning formula is as follows:

$$K_p = \Delta K_p + K_{p0} \tag{7}$$

$$K_i = \Delta K_i + K_{i0} \tag{8}$$

$$K_d = \Delta K_d + K_{d0} \tag{9}$$

where, K_{p0}, K_{i0}, K_{d0} are the values of PID initial parameters.

The control algorithm of fuzzy PID control for the intelligent control system of oil and gas loading and unloading robotic arm is denoted as:

$$\begin{aligned} u(k) = {} & (K_p + \Delta K_p)e(k) + (K_i + \Delta K_i)\sum_{n=0}^{k} e(n) \\ & +(K_d + \Delta K_d)(e(k) - e(k-1)) \end{aligned} \tag{10}$$

III. A. 3) Establishment of fuzzy variables and fuzzy rules

Set the set of input-output variable theories to be $\{\mathrm{NB}、\mathrm{NM}、\mathrm{NS}、\mathrm{ZO}、\mathrm{PS}、\mathrm{PM}、\mathrm{PB}\}$, where NB is negative large, NM is negative medium, NS is negative small, ZO is 0, PS is positive small, PM is positive medium, and PB is positive large. The range of the fuzzy domain is $\{-8,-6,-4,-2,0,2,4,6,8\}$. The output variables are in incremental form with the range $[-8,8]$, where the affiliation functions of e, e_c output variables are set to four, and the parameters are all trigonometric functions. According to these affiliation functions, the corresponding affiliation values can be calculated. Finally, the fuzzy control rule table for the output variables is obtained by fuzzy integrated reasoning. The fuzzy rules are designed as follows:

(1) When the error e is large, it is necessary to increase the proportional parameter K_p to increase the speed of the hydraulic cylinder movement, and at the same time reduce the integral parameter K_i appropriately to avoid the problem of integral saturation.

(2) When the error e is small, in order to prevent overshooting, the appropriate proportional parameter K_p and integral parameter K_i should be taken to ensure the stability of the system.

(3) When the error change rate e_c is small, the differential parameter K_d is appropriately increased to improve the response speed and stability of the system.

(4) When the error change rate e_c is large, the differential parameter K_d is appropriately reduced to minimize the system oscillation.

According to the above fuzzy rules, the modified parameters are obtained and calculated using the parameter self-tuning equations (7)-(9) to realize the fuzzy PID control.

The quantization factors K_e, K_{ec} and proportionality factors K_p, K_i, and K_d of the fuzzy PID controller are usually selected empirically, but both the electro-hydraulic control system of the oil and gas loading and unloading robotic arm and the robotic arm model both have the characteristics of large time-varying and nonlinearity, which makes it difficult to realize the real-time adjustment of the system and establish an accurate mathematical model. Therefore, the particle swarm optimization algorithm is used in this paper to optimize the solution.

III. A. 4) Particle swarm based fuzzy PID controller

(1) Principle of particle swarm optimization algorithm

Particle swarm optimization algorithm is a heuristic algorithm, which is widely used because it has the advantages of simple theory, fewer parameter settings, applicability to multidimensional problems and small dependency. Assuming that there are n particles in the population, denote the coordinate position of particle i in the N-dimensional solution space by $x_i = (x_{i1}, x_{i2}, \cdots, x_{i,m})$, and the corresponding velocity is $v_i = (v_{i1}, v_{i2}, \cdots, v_{i,m})$. The optimal position obtained by searching the i th particle is denoted as $P_i = (P_{i1}, P_{i2}, \cdots, P_{i,m})$, i.e., P_{best}. The particle swarm velocity and position are calculated as follows:

$$v_{i+1} = \omega \cdot v_i + c_1 \cdot r_1 \cdot (P_i - x_i) + c_2 \cdot r_2 \cdot (G_i - x_i) \tag{11}$$

$$x_{i+1} = x_i + v_{i+1} \tag{12}$$

where, ω is the inertia weight; c_1 and c_2 are the learning factors; r_1 and r_2 are the random numbers located in the interval $[0,1]$; P_i is the optimal position of an individual obtained by the search of the i th particle, and G_i is the optimal position of the global obtained by the search of the i th particle.

(2) Improved PSO algorithm to optimize fuzzy PID parameters

Similar to the case of other swarm algorithms, the PSO algorithm also suffers from the problem of local optimal solution. To ensure the balance between global and local search performance, PSO algorithm with nonlinearly decreasing inertia weights is introduced. Its inertia weights ω are:

$$\omega(t) = \omega_{\min} \left(\frac{\omega_{\max}}{\omega_{\min}} \right)^{1-t/T} \tag{13}$$

where, $\omega(t)$ is the inertia weight in t iterations; t is the current number of iterations; T is the total number of iterations; $\omega_{\max}$, $\omega_{\min}$ are the initial and final inertia weights, respectively.

The ITAE evaluation index is adopted as the adaptation function, and the individual adaptation value J_{ITAE} is obtained by calculating the absolute value of time and error with the following formula:

$$J_{ITAE} = \int_0^{\infty} t \left| e(t) \right| dt \tag{14}$$

where, t is the time; $e(t)$ is the error.

In order to measure the rapidity and accuracy of the control algorithm, three evaluation indexes are used: rise time, maximum overshoot and average error. The absolute value of the average error is:

$$\eta = \frac{1}{n} \sum_{i}^{n} \left| x_i - \overline{x} \right| \tag{15}$$

where, η is the average error; x_i and $\overline{x}$ are the expected and actual displacements, respectively; n is the total number of computed points, and n is taken as 1100 in the simulation analysis.

III. B. System Simulation and Analysis

In order to verify the effectiveness of the fuzzy PID control system of the enterprise oil and gas loading and unloading machine using the improved genetic algorithm, the optimization effect of the improved genetic algorithm and the standard genetic algorithm is investigated and the fuzzy PID controller optimized by the improved genetic algorithm is compared with the PID controller, fuzzy PID controller adjusted by experience. The control system of the corporate oil and gas handling machine is modeled and simulated in MATLAB module.

The standard genetic algorithm uses a hybridization probability $P_c = 0.95$ and a mutation probability $P_m = 0.05$; The improved genetic algorithm uses variable hybridization probabilities $P_{c1} = 0.95$, $P_{c2} = 0.05$ and variable mutation probabilities $P_{m1} = 0.05$, $P_{m2} = 0.005$; The weight coefficients of the fitness function $\omega_1 = 0.999$, $\omega_2 = 0.1$, $\omega_3 = 1$; the number of individuals in the population is 40, the number of hereditary generations is 100, and the scaling factor $k = 1$.

The optimization effect of the standard genetic algorithm and the improved genetic algorithm is shown in Figure 2. The comparison shows that the improved genetic algorithm converges to the global optimal parameter combination faster than the standard genetic algorithm, which reduces the adjustment time of parameters. The fuzzy quantization factor $K_e = 0.2103$, $K_{ec} = 0.2912$, $K_{kp} = 0.4402$, $K_{ki} = 0.8626$, $K_{kd} = 0.0014$ after optimization by the improved genetic algorithm.

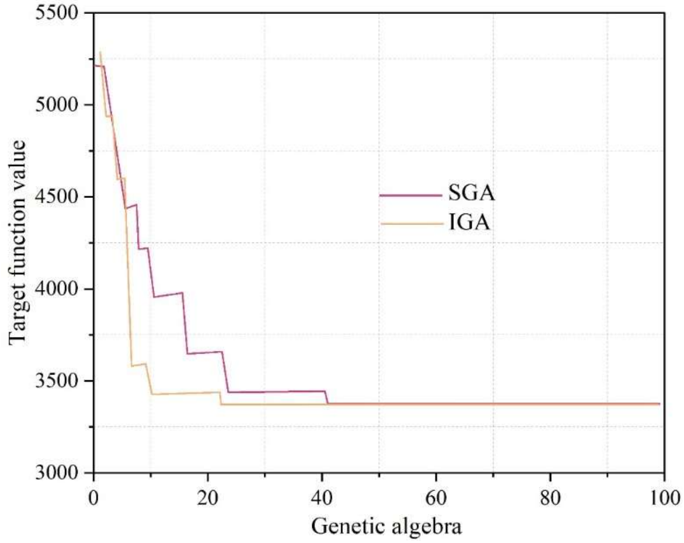

Figure 2: Genetic evolution ability comparison

According to the actual working conditions of the enterprise oil and gas loading and unloading machine, the traveling speed is set to 1.1 m/s. Under different control strategies, the speed change curve at the time of startup is shown in Fig. 3. When the enterprise oil and gas loading and unloading machine starts, the rise time of the PID control system is 2.11s, and the convergence time is 2.81s, the response speed is slow and there is overshooting; the rise time of the fuzzy PID control system is 1.60s, and it reaches the target speed at 2.49s, which improves the response speed of the system compared with that of the PID control system but there is the problem of speed fluctuation; the rise time and convergence time of the fuzzy PID control system optimized with particle swarm optimization are 1.60s. PID controller with particle swarm optimization has a rise and convergence time of 0.54s, which solves the problem of system overshooting and oscillation, and reaches the target speed quickly and keeps it stable, reducing the acceleration time of oil and gas loading and unloading machine of the enterprise.

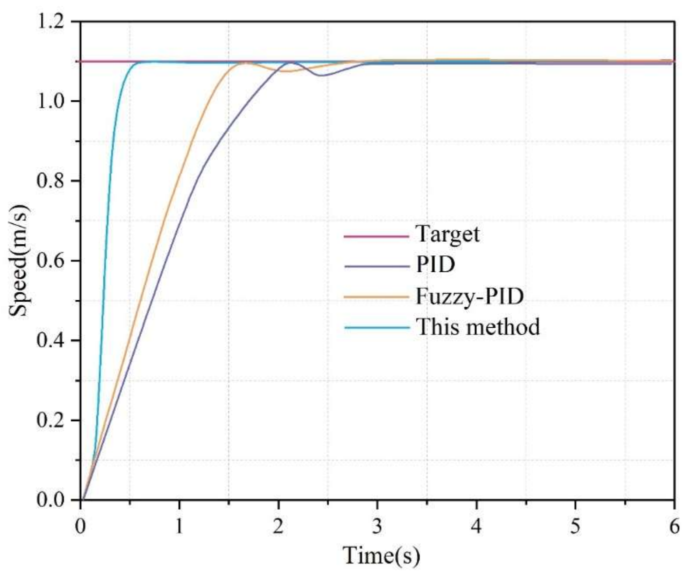

Figure 3: The change curve of the speed of speed

The velocity change curve when stopping is shown in Fig. 4. When the enterprise oil and gas loading and unloading machine stops, the speed gradually decreases from 1.1 m/s to 0. The convergence speed of the PID control system is slow, and the enterprise oil and gas loading and unloading machine needs to travel in the reverse direction in order to stop when no brakes are applied; when the fuzzy PID controller is used, the convergence time is 3.95 s, and there are fluctuations in the speed; when the fuzzy PID controller optimized by particle swarm is used, the enterprise oil and gas loading and unloading machine stays stationary after a With the particle swarm optimized fuzzy PID controller, the enterprise oil and gas loading and unloading machine stays stationary after a stable deceleration of 1.01s, which effectively improves the response speed of the system and maintains the stability of the speed, and prevents the enterprise oil and gas loading and unloading machine from generating vibration when it stops.

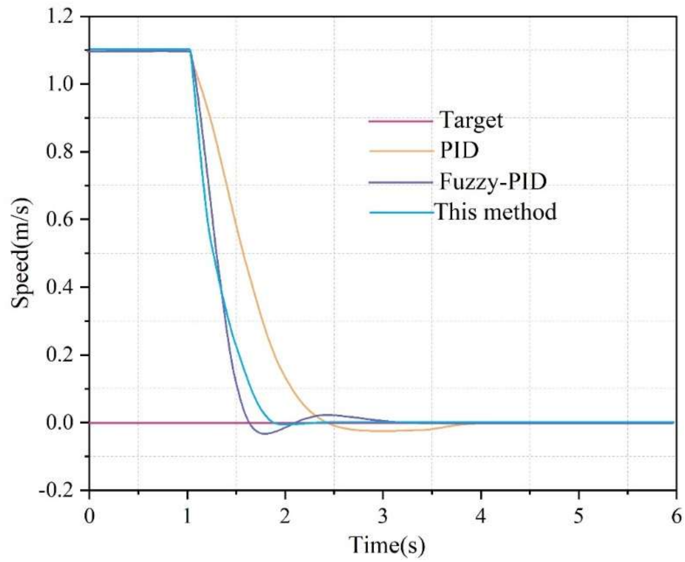

Figure 4: Stop the change curve of the speed

IV. Conclusion

The study significantly improves the safety of oil and gas loading and unloading operations in the enterprise by interpreting the structural model analysis and the fuzzy PID controller design based on particle swarm optimization.The ISM model divides the 25 main risk factors into five tiers, and identifies the key risk factors of tier 2 such as the safety of the oil transfer arm, the safety of the pipeline, and the reliability of the antistatic device, which provides a clear direction for the safety management of the enterprise. The simulation results prove that the fuzzy PID controller optimized with particle swarm has better performance compared with the traditional control method: the rise and convergence time at startup is 0.54s, eliminating the overshooting problem; the convergence time during stopping is only 1.01s, effectively reducing the vibration of loading and unloading machine. The optimized quantization factor parameters of the fuzzy controller are k1=1.72, k2=2.45, kp=4.06, ki=3.28, and kd=1.96, which greatly improves the system response speed and stability. Enterprises should strengthen the safety management of ship berthing operations, regularly check and maintain loading and unloading equipment, improve the emergency management system, and improve the professional quality of operating personnel. The combined application of intelligent control technology and risk management methods provides new ideas for the safety of oil and gas loading and unloading operations, and also provides a reference for the safety management of other high-risk operations.

References

[1] Narayanan, D. K., Ravoof, A. A., Jayapriya, J., Revathi, G., & Murugan, M. (2023). Hazards in oil, gas, and petrochemical industries. In Crises in Oil, Gas and Petrochemical Industries (pp. 71-99). Elsevier.

[2] Narayanasamy, S., Yang, F., Islam, R., Sardar, A., Garaniya, V., Kooshandehfar, P., & Nikolova, N. (2018). Safety during oil and gas transfer and transport. In Methods in Chemical Process Safety (Vol. 2, pp. 169-205). Elsevier.

[3] Devianto, H., Eviani, M., Widiatmoko, P., & Nurdin, I. (2018). Hazard assessment of LNG loading-unloading process in Cirebon Port. Reaktor, 18(2), 117-121.

[4] Wang, C., Fan, S., Yao, Y., Wu, J., Wang, B., & Zheng, L. (2021). Operational safety evaluation of tanker cargo oil system fusing multiple task information. Ocean Engineering, 239, 109856.

[5] Aneziris, O., Gerbec, M., Koromila, I., Nivolianitou, Z., Pilo, F., & Salzano, E. (2021). Safety guidelines and a training framework for LNG storage and bunkering at ports. Safety Science, 138, 105212.

[6] Bariha, N., Ojha, D. K., Srivastava, V. C., & Mishra, I. M. (2023). Fire and risk analysis during loading and unloading operation in liquefied petroleum gas (LPG) bottling plant. Journal of Loss Prevention in the process industries, 81, 104928.

[7] Maljković, M., Vukša, S., Vidan, P., & Pavić, I. (2022). Review of cargo operations on crude oil tankers and methods/models used for optimisation and improvement of safety. Časopis Pomorskog fakulteta Kotor-Journal of Maritime Sciences, 23(1/2022), 153-164.
[8] Chen, J., Zhang, W., Wan, Z., Li, S., Huang, T., & Fei, Y. (2019). Oil spills from global tankers: Status review and future governance. Journal of cleaner production, 227, 20-32.
[9] Yang, X., Haugen, S., & Paltrinieri, N. (2018). Clarifying the concept of operational risk assessment in the oil and gas industry. Safety science, 108, 259-268.
[10] Arslan, Ö., Zorba, Y., & Svetak, J. (2018). Fault tree analysis of tanker accidents during loading and unloading operations at the tanker terminals. Journal of ETA maritime science, 6(1).
[11] James, S., & Renjith, V. R. (2022). Design of Safety Zone and Optimal Risk Identification of Undesired Events During Loading and Unloading of LNG Terminal Using TSA-GEO: A Hybrid Strategy. Process Integration and Optimization for Sustainability, 6(3), 791-807.
[12] Blokus, A., Kwiatuszewska-Sarnecka, B., Wilczyński, P., & Wolny, P. (2019). Crude oil transfer safety analysis and oil spills prevention in port oil terminal. Journal of Polish Safety and Reliability Association, 10(1).
[13] Gupta Sanjay,Raj Sahil,Garg Aashish & Gupta Swati. (2025). Analyzing shopping cart abandonment enablers: an ISM and MICMAC approach. International Journal of Quality & Reliability Management,42(1),61-85.
[14] Kim Sung Soo,Kim Young Kuk & Kang Young Min. (2021). AORM: Fast Incremental Arbitrary-Order Reachability Matrix Computation for Massive Graphs. IEEE ACCESS,9,69539-69558.
[15] Mingtao Cui,Min Pan,Jie Wang & Pengjie Li. (2022). A parameterized level set method for structural topology optimization based on reaction diffusion equation and fuzzy PID control algorithm. Electronic Research Archive,30(7),2568-2599.