Research Article

Application of PID Control and Improved Ant Colony Algorithm in Path Planning of Substation Inspection Robot

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The purpose is to improve the effect of substation inspection and ensure the safety of power consumption in human society. First, this work discusses the current substation inspection-oriented robot path planning situation. Then, the proportional integration differentiation (PID) control algorithm is introduced and optimized. Ant colony algorithm (ACA) is improved. The substation inspection-oriented RPP model is designed based on the PID algorithm and optimized ACA (the proposed model is denoted as the Ant-PID algorithm). Afterward, the Ant-PID algorithm is compared with the PID control algorithm and ACA. The results show that the longest robot path of the proposed Ant-PID algorithm in different data sets is about 28 m. The shortest is about 26 m, and the number of optimal solutions is maintained at about 45–49. By comparison, the average response time of the PID algorithm is about 25 s to 28 s. The shortest response time of ACA is about 24 s, the shortest average response time is about 27 s, and the longest is about 30 s. The average response time of the proposed ant PID model is about 17 s to 20 s. Therefore, the Ant-PID algorithm can improve the substation inspection robots’ path planning effect. The research results provide technical support for improving the effect of substation inspection and contribute to social power transmission.

1. Introduction

With science and technological progress, power transmission engineering is expanding. As the intermediate medium of power transmission, substation plays an important role. The substation has a tricky structure, with heavy maintenance costs and complex detection flow. Therefore, real-time substation monitoring in power transmission is critical and challenging [1]. As a technological product to mimic and replace human intelligence, robot technologies have found applications in substation inspection, only far from mature. In particular, the inspection task-oriented robot path planning (RPP) is worthy of in-depth exploration, and the robot response time cannot meet the needs of current substation inspection to improve the working efficiency of the robot in substation inspection [2].

Although the current research on applying robots in substation inspection is not perfect, many studies have provided technical support. Tao et al. proposed a base robot to replace real-time manual inspection of substations. The optimal RPP and two-way walking were realized following the magnetic trajectory to inspect the primary equipment in the station. The designed robot could make an autonomous decision or be remotely controlled to find the thermal defects and equipment abnormalities in time. Image processing and pattern recognition distinguished the opening and closing states of switches and knife switches. When under remote control or sequential control of the intelligent substation, the robot could replace manual inspection in positioning and controlling the equipment [3]. Li et al. observed that the power grid security maintenance was becoming more intelligent with the development of information and intelligence. Major power grid companies and enterprises loved the substation inspection robot, upgrading every day as a key component in intelligent power grid development. Therefore, the research on substation inspection-oriented RPP was a hot research spot. However, the current research was challenged by real-time RPP [4]. Melo et al. implemented the substation maintenance-oriented RPP through an ant colony algorithm (ACA) and achieved an effective outcome by
continuously optimizing the robot paths. ACA provided a more comprehensive and effective RPP reference through the distributed node calculation. Besides, ACA analyzed the system error through positive feedback to encourage the system’s self-optimization through iterative training. However, ACA was still in its infancy and must be further explored to provide better technical support for RPP [5].

Ekinci et al. divided the mobile robot’s path tracking, control, and planning into two modules according to the kinematic model and using the hierarchical control theory: trajectory tracking controller and proportion integration differentiation (PID)-based robot speed controller. Based on the backstepping time-varying state feedback method and Lyapunov theory, a mobile robot-oriented global trajectory tracking algorithm was designed by introducing a virtual feedback quantity with hyperbolic tangent characteristics. PID controller was adopted to meet the real-time speed regulation requirements of the robot drive motor. Regarding the dynamic constraints of the robot, a strategy was introduced to ensure its smooth motion. The real-time trajectory tracking experiment of the algorithm was carried out on a two-wheel drive mobile robot, obtaining satisfactory results. It was found that the PID algorithm must integrate other algorithms in RPP, and more research was needed to support its development [6]. To sum up, the current research has provided a theoretical reference for applying robot technologies in substation inspection. Nevertheless, the current technical means are not perfect. For example, the system response time is long, and the intelligent RPP is not reasonable. To this end, more research is needed to support RPP’s technical improvement.

Based on the above problems of substation inspection robots and the specific research directions, this work summarizes the substation inspection-oriented RPP and the inspection robot’s specific design concept. Then, the PID algorithm is optimized. Finally, the ACA is improved, and the substation inspection-oriented RPP model is designed by integrating PID and ACA. The finding provides an essential guarantee for the regular operation of the substation and contributes to the normal power consumption of human society.

2. Research Theories and Methods

2.1. Comprehensive Design Concept of Substation Inspection Robot. Artificial intelligence (AI) equipment has become the first choice to replace humans. For example, intelligent robots have been widely used in various fields and have become the main productivity of human society [7]. As the main supporting point of human use of electricity, substation inspection plays a vital role in ensuring its normal work and the normal operation of human life. The substation inspection is a critical but boring task. Traditionally, the manual inspection often overlooks many faults and failures because the result is subjective, and individual experience and human vision are unsuitable for such missions. Therefore, the AI robot has become an essential technology for substation inspection [8]. The main task of the substation inspection robot is to reduce the labor intensity of inspection workers. During the daily inspection, the inspection robot mainly obtains the power equipment video through the camera. It transmits the data to the background for processing to repair the power equipment with potential safety hazards in time [9]. In order to complete the daily inspection work, the robot needs to integrate vision technology and path planning technology, additionally, to process the inspection results, and to transmit the information obtained by the robot to the background processing end in real time. The inspection robot should also combine multisensor information fusion technology, wireless communication, and wireless transmission technology. Last but not least, the substation inspection robot has special requirements in the overall structural design and functional hardware selection [10].

The substation has many characteristics as the main supporting point of electric power transmission (EPT). First, the overall environment is static. Substation equipment is divided into outdoor open type and indoor integrated type. Currently, the conventional outdoor open type is more used in the substation. Different equipment is assembled according to the functional objectives of the substation. The equipment is arranged in turn according to the functions, and the wiring between the equipment is safe and beautiful [11]. The building structure of the substation is reasonable, and the appearance is neat. After using robots to replace manual inspection, few people are active in the substation, so the overall environment of the substation is an overall static environment for the substation inspection robot. Thus, the substation topology can be stored in the database for the convenience of robots [12]. Second, the environment is full of high electromagnetic interference (EMI). There are transformers, high-voltage, or ultrahigh voltage (UHV) equipment in the substation, producing all kinds of corona phenomena. The high-voltage line of the substation will produce a strong electromagnetic field. Transient UHV occurs during operation [13]. Thus, complex EMI makes the electromagnetic environment of substations particularly complex. There is a clear distinction between environmentally feasible areas and obstacle areas. The overall design of the substation is relatively clean, with clear obstacle areas and feasible areas. The robot must keep a safe distance from the obstacle areas during the inspection process. Some feasible areas of the substation are relatively narrow, so the robot foothold should be minimum [14]. Finally, the feasible area is generally flat, but some potholes, slopes, and steps will be. In the substation design, the roads in feasible areas are mostly flat. However, the substation roads in mountainous areas might have potholes, and there will be slopes or steps in places with large drops [15].

The inspection robot needs to regularly conduct comprehensive and detailed inspections on the power equipment in the substation, greatly improving the efficiency and accuracy of inspection. In order to realize all-weather and no dead corner inspection, the inspection robot needs to have some functions [16]. First, the substation inspection robot can perceive the information of the environment and determine when to stop or bypass [17]. At the same time, the substation inspection robot must be timely aware of its self-
position through relevant technologies. Second, the substation inspection robot can carry out path planning. It can plan a path that traverses all stops and has the shortest distance suitable for the substation inspection [18]. Then, the substation inspection robot can feedback a clear image of the detected power equipment in real time through the communication module for expert observation and analysis [19]. Finally, the substation inspection robot can be remotely controlled. During the inspection process, the robot can receive the command from the background, change to the manual remote-control state, and monitor the abnormal power equipment at a specific position in the substation [20]. Figure 1 shows the substation’s basic characteristics and the inspection robot’s main working conditions.

As shown in Figure 1, as a substitute for substation patrol workers, the robot undertakes the main responsibility of substation inspection. Doing so prevents human injury to substation equipment and improves inspection efficiency. However, the robot inspection path needs to be designed to provide better technical support for improving the efficiency of substation inspection.

2.2. PID Control Algorithm. PID control algorithm plays a vital role in the industrial control process. With the support of the PID control algorithm, various industrial production processes have been refined. PID algorithm refers to proportional, integral, and differential linear control algorithms [21]. Figure 2 draws the main flow of the PID control algorithm.

As shown in Figure 2, in the PID control algorithm, the proportional, integral, and differential linear calculations shall be carried out, respectively. Then, the calculation results of the three shall be integrated to strengthen the control effect of the system [22]. The calculation of differential equation and transfer function of PID controller read

\[
    u(t) = K_P \left( e(t) + \frac{1}{T_I} \int_0^t e(t) \, dt + T_D \frac{de(t)}{dt} \right),
\]

(1)

\[
    D(S) = \frac{U(S)}{E(S)} = K_P \left( 1 + \frac{1}{T_I S} + T_D S \right),
\]

(2)

\[
    e(t) = r(t) - c(t).
\]

(3)

In (1)–(3), \( K_P \) is the scale factor. \( T_I \) denotes the integral time constant. \( T_D \) represents the differential time constant. \( d \) stands for the calculated bias, and \( t \) signifies the time [23]. The functions of the three modes are different. The proportional function is to map the deviation signal in the control process through a certain proportion. In other words, the proportional function will react when the system has a control deviation to reduce the control deviation of the system [24]. The integration function mainly removes the static error so that the control result of the system is the same as the final setting result. The relationship between the action effect of the integration link and the integration time constant is inversely proportional. The integration time constant is the main factor determining the action of the integration link [25]. The function of the differential link is mainly to map the changing state of the deviation signal of the slice. Suppose the changing state of the deviation signal is stronger. In that case, the system will modify the control quantity faster to effectively reduce the delay of system error.
Feedback Effect Calculation reads above equations. If discretization reads the PID algorithm is approximately discretized [27]. The discretization reads

\[ t \approx kT (k = 0, 1, 2, \ldots), \quad (4) \]

\[ e(t) \approx e(kT), \quad (5) \]

\[ \int e(t)dt \approx \sum_{j=0}^{k} e(jT)T = T \sum_{j=0}^{k} e(jT), \quad (6) \]

\[ \frac{de(t)}{dt} \approx \frac{e(kT) - e[(k-1)T]}{T}. \quad (7) \]

In (4)–(7), each element shares the same meaning as the above equations. If \( kT \) is represented by \( k \), the specific calculation reads

\[ K_I = K_P \frac{T}{T_I}, K_D \frac{T_D}{T_D}, \quad (8) \]

\[ u(k) = K_P e(k) + K_I \sum_{j=0}^{k-1} e(j) + K_D [e(k) - e(k-1)]. \quad (9) \]

This work optimizes the PID algorithm through position and increment. The first is the position PID control algorithm. In this algorithm, the system controls the control unit through \( u(k) \), and the calculated value of \( u(k) \) is the position output of the controlled unit. The second is the incremental control algorithm [28]. In this algorithm, \( u(k) \) represents the change in the position of the control unit. This algorithm is widely used because it is safer and does not need cumulative calculation. Thereby, it shortens the system calculation time and improves work efficiency [29]. Fusing position control algorithms (8) and (9) can obtain the calculation of the incremental control algorithm:

\[ u(k-1) = K_P e(k-1) + K_I \sum_{j=0}^{k-1} e(j) + K_D [e(k-1) - e(k-2)], \quad (9) \]

\[ \Delta u(k) = K_P [e(k) - e(k-1)] + K_I e(k) + K_D [e(k) - 2e(k-1) + e(k-2)]. \quad (10) \]

In (10) and (11), the result of \( \Delta u(k) \) represents the position change of the controlled unit in the control process of the PID algorithm. Only the recent errors are sampled [30]. Figure 3 presents the design concept of optimizing the PID control algorithm through position and incremental algorithms.

As shown in Figure 3, an incremental algorithm is extended based on the positional algorithm. In simple terms, the positional algorithm provides a basic concept for the incremental algorithm, and the incremental algorithm is the optimization result of the positional algorithm [31]. Therefore, in the PID optimization algorithm, the control accuracy of the incremental control algorithm is higher, and the calculation result of the algorithm is more reliable.

2.3. Optimizing ACA. ACA is designed according to the ant colony foraging process. Its main connotation is to seek simpler results in the calculation process. The robot path control calculation selects a shorter route with a high algorithm accuracy to make a more efficient substation inspection. ACA features distributed computing, self-organization, and positive feedback [32]. Distributed computing means the ant colony algorithm distributes the global computing tasks to each node in the computing process. That is, the ant individuals in the ant colony calculate independently. When the node-independent computing task is completed, the system integrates all the calculation results. Then, it compares and analyzes the integration results.
and finally outputs the optimal solution of the system calculation. Therefore, in ACA, the feasibility of the system results will not be affected by the individual calculation error. The self-organization characteristic means that the ant colony is not affected by external factors in the calculation process. The ant colony individuals independently seek the optimal solution in the calculation process. The system selects the path with the most individuals after specific iterations, namely, the result with the most individual calculation frequency [33]. The positive feedback characteristic means that when the ant colony selects a path, the individual ants generate pheromones on the shortest path. Then, the ant colony will feedback the shortest path selected most according to the pheromone concentration (PC). Thereby, it helps the ant colony chooses more shortest paths [34]. The calculation of the transition probability of ant colony selection reads

\[
P_{ij}^k = \frac{(\tau_{ij}^* (\eta_{ij}^*))}{\sum_{z \in {\text{allowed}}} (\tau_{ij}^z (\eta_{ij}^z))},
\]

(11)

In (11), \(i\) and \(j\) are the selected location nodes of the ant colony. \(z\) is the specific location. allowe represents the location set, and \(dx\) denotes the location deviation. \(\tau\) refers to the PC. The specific calculation reads

\[
\tau_{ij}(t + 1) = \rho \times \tau_{ij}(t) + \Delta \tau
\]

(12)

\[
\Delta \tau_{ij} = \sum_{k=1}^{m} \Delta \tau_{ij}^k
\]

(13)

In (12) and (13), \(\rho\) is the volatilization coefficient. \(k\) denotes the calculation position point. The PC calculation of the heuristic function reads

\[
\eta_{ij} = \frac{1}{d_{ij}}
\]

(14)

In (14), \(d\) is the Euclidean distance (ED) between location nodes. In this work, the pheromone updating mechanism is used to improve ACA. That is, in the
In (16) and (17), $\eta$ is the increased range coefficient of pheromone. $\rho$ is of utmost importance. The volatilization coefficient can adjust the pheromone distribution to find the optimal solution. Therefore, the selection of the volatilization coefficient is crucial. The adjustment of the volatilization coefficient reads

$$
\rho(t + 1) = \begin{cases} 
\gamma \cdot \rho(t), & \gamma \cdot \rho(t) \geq \rho_{\text{min}}, \\
\rho_{\text{min}}, & \text{others}.
\end{cases}
$$

In (18), $\rho_{\text{min}}$ is the minimum volatilization coefficient. $\gamma$ represents the attenuation coefficient, which is less than 1. This work designs the twice-path planning method to improve the calculation results of the ACA. Then, Figure 4 demonstrates the calculation process of the PID control algorithm combined with the proposed twice-path planning ACA.

As shown in Figure 4, based on the calculation of ACA, the twice path planning mechanism is added to increase the calculation frequency of ACA. This can effectively improve the accumulation effect of pheromone to help the substation inspection robot find a better inspection route. Integrating the PID control algorithm can effectively provide a better inspection path for the substation inspection robot. Therefore, the proposed Ant-PID control algorithm fusing the PID algorithm and ACA can improve the efficiency of the substation inspection robot.

2.4. Research Data Settings. The data set is mainly used to evaluate the comprehensive performance of the model. The data sets include (1) supersizing self-supervision (SS) dataset, containing 50 K data points and 700 hours of robot experiment and error experiment. At the same time, the data set collects more than 150 objects with different grasping ability. (2) Learning hand-eye coordination (LH) dataset describes two large-scale experiments on two independent robot platforms. The first experiment collects about 800,000 grasp attempts over two months. In the second experiment, different robot platforms and eight robots collect data sets containing more than 900,000 grab attempts. (3) Scene understanding (SUN) dataset contains 10,335 robot detection results of different scenes, 146,617 2D polygon annotations (which should refer to 2D segmentation), and 58,657 3D frames. (4) The RoboTurk Real Robot (RTRR) dataset contains 2,144 different presentations from 54 users. This includes 111 hours of robot operation data for three challenging operation tasks. This work comprehensively evaluates the performance optimization of substation robots through robot path selection simulation. The comparison algorithms used in the evaluation process include the PID algorithm and ACA.

3. Performance Optimization Evaluation of Substation Inspection Robot

3.1. Path Selection Performance Evaluation. This section uses the proposed Ant-PID control algorithm to design the substation inspection-oriented RPP model. Then, it evaluates the displacement of the robot through the PID control algorithm and carries out twice path planning through ACA to
strengthen the path planning performance of the model. Specifically, a simulation scenario with the shortest length of 25 m is designed to evaluate the model. Figure 5 demonstrates robot path selection’s optimization performance evaluation results under the proposed Ant-PID algorithm.

As shown in Figure 5, the proposed Ant-PID algorithm integrates the performance of the PID algorithm for robot displacement optimization control and the comprehensive optimization performance of ACA for robot path selection. Therefore, the path selection of the proposed Ant-PID algorithm is optimal. According to Figure 5, the longest robot path taken by the proposed Ant-PID algorithm in different data sets is about 28 m, and the shortest is about 26 m. The longest path selection of the PID control algorithm is about 50 m, and the shortest is about 28 m. The longest path selection of ACA is about 47 m, and the shortest is about 27 m. Thus, the evaluation curve convergence effect of the proposed Ant-PID algorithm is better, and the path design result is better.

3.2. Effect Evaluation of RPP. In evaluating the RPP effect of the proposed Ant-PID algorithm, this work uses the simulation scene with the shortest length of 25 m. It evaluates the path planning results of the model on different data sets.
50 times under different iterations. Figure 6 portrays the RPP evaluation results of the proposed Ant-PID algorithm. As shown in Figure 6, the proposed Ant-PID algorithm still performs well in the RPP effect. On various data sets, the optimal solution times of the proposed Ant-PID algorithm are maintained at about 45–49 times. By comparison, the performance of the other two models is poor. For example, the optimal solution times of the PID algorithm are about 15–48 times. The minimum number of optimal solutions of ACA is about 17, and the maximum number is about 49. Therefore, the proposed Ant-PID algorithm has a good RPP effect. The comprehensive RPP effect of the model also needs to evaluate the path planning efficiency of the model by factoring in the response time. Figure 7 compares the response time of the proposed Ant-PID algorithm and the other two algorithms.

Obviously, the average response time of the PID algorithm is about 25 s at the shortest and about 28 s at the longest. The shortest response time of ACA is about 24 s. The shortest average response time of ACA is about 27 s, and the longest is about 30 s. The average response time of the proposed Ant-PID algorithm is about 17 s to 20 s. Hence, the proposed Ant-PID algorithm has a quicker response in robot inspection path planning.
4. Conclusion

With science and technological development, human beings use electricity more and more. The substation plays a vital part in transmitting power and power grids. Based on this, to improve the comprehensive efficiency of substation inspection, this work first discusses the status of substation inspection. Then, the PID control algorithm is introduced and optimized. Finally, the ACA is comprehensively improved. The Ant-PID algorithm is designed by fusing the PID algorithm and ACA, and the effect of the model in the substation inspection RPP is comprehensively evaluated.

The results show that the longest robot path taken by the proposed Ant-PID algorithm in different data sets is about 28 m, and the shortest is about 26 m. The longest path selection of the PID control algorithm is about 50 m, and the shortest is about 28 m. The longest path selection of ACA is about 47 m, and the shortest is about 27 m. Second, the optimal solution times of the proposed Ant-PID algorithm are maintained at about 45–49 times, while the performance of the other two models is poor. Specifically, the optimal solution times of the PID algorithm are at least about 15 times and at most about 48 times. The minimum number of optimal solutions of ACA is about 17, and the maximum number is about 49. Finally, the average response time of the PID algorithm is about 25 s and 28 s; the shortest average response time of ACA is about 27 s, and the longest is about 30 s. The average response time of the proposed Ant-PID algorithm is about 17 s to 20 s. Although this work optimizes and designs a relatively perfect RPP model, there is less research on its practical application. Therefore, the research finding will be strengthened and generalized in future work.

Data Availability

The data used to support the findings of this study have been deposited in the Baidu Netdisk repository (https://pan.baidu.com/s/1hqstBmcaX7rFRWAYznMxNA; password: suep).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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