Design of insulator automated cleaning end-effector based on current feedback control

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Abstract. As the mileage of electrified railroads continues to expand, insulators, as a key component of the power transmission system, are crucial to the cleaning and maintenance of insulators to ensure the safety of railroad power supply. However, the dirt deposit-ed in daily use leads to the frequent occurrence of dirt flash accidents, and the traditional manual cleaning method can no longer meet the safety requirements of modern railroad operation due to its low efficiency, high operational risk and difficulty in adapting to the needs of large-scale maintenance. In view of the above problems, this paper proposes a servo control system design method based on current feedback, and designs an insulator wiping end-effector based on current feedback control. Firstly, the mechanical structure and control module design are proposed, and the three-dimensional parametric model is constructed through SolidWorks to optimize the actuator kinematic characteristics. Secondly, a high-precision servo control system is developed based on the STM32F407 master control platform, which innovatively integrates the PID regulation technology, the high-sensitivity current acquisition module and the sliding average filtering algorithm to realize the real-time dynamic and precise control of the contact pressure between the brush and insulator. Then, the model is constructed, and the actuator prototype is completed through electromechanical coupling, and simulation experiments are conducted to verify the feasibility of the project. Finally, the operation verification is carried out by building experimental platform to simulate the railway environment, and the results show that the actuator can intelligently adapt to a variety of installation postures, such as horizontal, vertical and tilted, and the accuracy of contact pressure control reaches ±0.2kg, and the efficiency of a single cleaning is improved compared with the traditional manual method. This study effectively solves the technical problem of unmanned cleaning and maintenance of railroad insulators, and provides a generalizable technical solution for the research and development of intelligent unmanned operation and maintenance equipment for contact networks.

Keywords: Sliding Average Filtering Algorithm, Insulator, Current Feedback.

1. Introduction

Insulators are critical components in contact network systems, ensuring railway safety and operational stability. However, long-term exposure to outdoor pollutants (e.g., haze, sand, industrial dust) leads to contaminant accumulation, significantly increasing the risk of fouling flashovers. In China, such flashovers rank as the second-most frequent cause of power grid accidents but result in over 10 times the economic losses, disrupting power supply, damaging equipment, and endangering personnel. Despite global efforts to automate insulator cleaning, challenges persist in achieving precise force control, environmental adaptability, and robustness under harsh conditions.

Existing solutions focus on mechanical design, control strategies, and sensor-based force regulation. For instance, Japan’s Kyushu Electric Power developed detection robots without cleaning capabilities, while Inner Mongolia University of Technology proposed a dry-ice cleaning robot lacking dynamic force control [1]. Guangdong Power Grid’s PID-based robot suffered from ±0.5 kg force errors due to unfiltered current signals [2], and North China Electric Power University’s direct force measurements failed under vibrations [3]. Harbin Institute of Technology used motor current-torque mapping for force estimation, robust in industrial robots but error-prone on multi-curved insulator surfaces [4]. Vision-guided systems (e.g., Hong Kong Polytechnic University) faced >30% accuracy drops in rain/fog [5], and Park et al.'s PID control ignored brush wear impacts [6]. Common bottlenecks include poor force precision, limited posture adaptability, and unreliable sensor performance in harsh environments.

To address these gaps, we propose an end-effector integrating industrial robot current feedback with moving average filtering and adaptive PID tuning [7]. A high-precision sensor array enables real-time brush-insulator force calculation, while a deployable mechanical structure accommodates diverse insulator postures. The STM32F407-based platform resolves prior precision issues by fusing multi-sensor data, and our servo system combines PID control with sliding average filtering for robust force regulation. Experiments demonstrate improved safety (reduced manual intervention), reliable force control, and enhanced cleaning efficiency, effectively mitigating fouling flashover risks.

2. End-effector structural design

The end-effector section focuses on the innovative design of a special-purpose execution mechanism for insulator cleaning, with its overall architecture composed of three synergistic components: the claw-type front-end assembly, the transmission and buffer assembly, and the auxiliary function assembly.

Fig. 1, Fig. 2 is the structural schematic diagram of the present structural design. In the figure, the end-effector in general consists of 1. servo electric cylinder, 2. motor bracket, 3. aluminum square tube, 4. claw end, 5. bearing, 6. claw front-end plate (left), 7. claw front-end plate (bottom), 8. brush, 9. belt pulley, 10. spacer, 11. thrust ball, 12. push-pull block, 13. L-type plate, and 14. claw front-end plate (the lowest), etc., which is further divided into three parts, which are claw front end assembly, transmission and buffer assembly and auxiliary function assembly.

The claw's front-end assembly consists of the left front plate (6), lower front plate (7), and bottommost front plate (14), which are interconnected and secured by bearings (5) and a brush mechanism (8). The claw tip (4) is pivotally connected to the front-end assembly via an aluminum square tube (3) and spacers (10), forming an openable/closable hinge structure.

The drive and cushioning assembly includes 1.servo electric cylinder, 8.brush, 9.pulley, 10.spacer, 11.thrust ball, and 13.L-plate.9.pulley is connected to the external drive mechanism to rotate the 8.brush for cleaning insulators.11.thrust ball is embedded inside the 8.brush to bear axial load and reduce friction.13.L-plate is mounted between 12.push-pull block and 3.aluminum square tube for movement. 1.servo electric cylinder is fixed on 2. motor bracket, and its output shaft is linked through 13. L-plate and 12. push-pull block and 3. aluminum square tube for movement, driving the claw. The 1. servo electric cylinder is fixed on the 2. motor bracket, and its output shaft is linked with the 3. aluminum square tube through the 13.L-shaped plate and 12. push-pull block to drive the front-end assembly of the claw to complete the clamping action.

In the auxiliary function assembly, the 5. bearing is fixedly connected to the 4. claw end to form a movement frame. 8. brushes are fixed in the preset holes of the claw front end assembly. When the 1. servo electric cylinder telescopes, the 12. push-pull block slides along the central axis of the two 3. aluminum square tubes, driving the 4. claw end to open and close in synchronization with the claw front end assembly to achieve high-precision gripping.

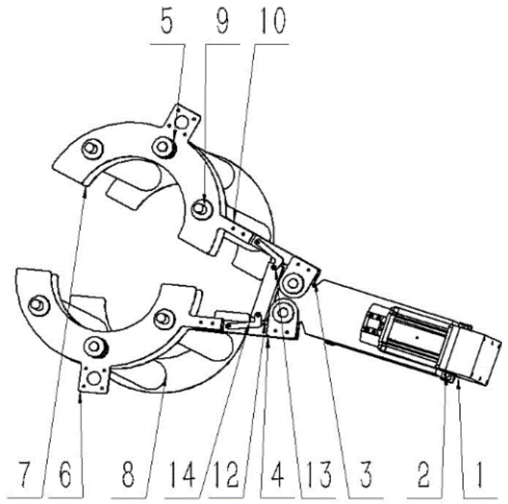

Figure 1. Structural three-dimensional schematic1

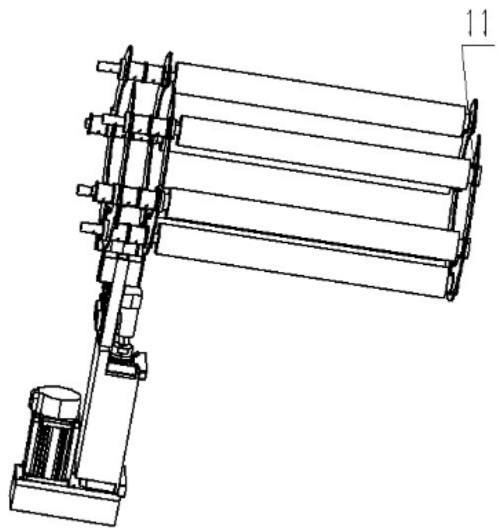

Figure 2. Structural three-dimensional schematic 2

3. Design of PID servo control system based on current feedback technology

The PID servo control system design based on current feedback technology builds a high-precision control core on the basis of the above mechanical structure, achieving dynamic and precise control of the contact pressure between the brush and the insulator by integrating current feedback mechanisms, PID control technology, and sliding average filtering algorithms. The system uses a high-precision current sensor to real-time capture the motor current signal, which is processed and filtered by the STM32F407 main control board, and then drives the servo cylinder for adaptive adjustment via a PLC. By establishing mathematical models of PID in both continuous and discrete domains and combining them with the servo motor speed control algorithm, it forms a complete control chain of "current acquisition-signal processing-closed-loop adjustment". Experimental verification shows that this system improves the contact pressure control accuracy to ±0.2 kg, effectively solving the problems of incomplete cleaning or surface damage caused by unstable contact force under complex working conditions, and providing core technical support for the intelligent operation of the end-effector.

The working principle of the PID servo control system based on current feedback technology is shown in Fig. 3, while the control system schematic is presented in Fig. 4. The complete servo system consists of a servo motor, servo cylinder, servo motor driver, and PLC [8].

The control system principle is mainly divided into two parts: the current feedback system and the servo control system. The current feedback system employs a high-precision current sensor to monitor the current at the positive load terminal of the brush stepper motor driver in real time. The main control board (STM32F407) sends a command to the current acquisition module [9] to initiate current sampling. Upon receiving the instruction, the current acquisition module transmits the measured current to the main control board. After verifying the current signal, the main control board filters and stores the current value, then sends the data to the PC for real-time monitoring and simultaneously forwards it to the PLC.

The servo control section utilizes the PLC to implement feedback control of the servo cylinder. Upon receiving the current signal from the main control board, the PLC performs algorithmic analysis and outputs a PWM signal. It then evaluates the control mode and, in conjunction with the PID controller, regulates the extension/retraction of the servo cylinder [10–11]. This adjusts the opening/closing angle of the actuating motor, ultimately achieving the dual objectives of protecting the insulator while maintaining cleaning efficiency.

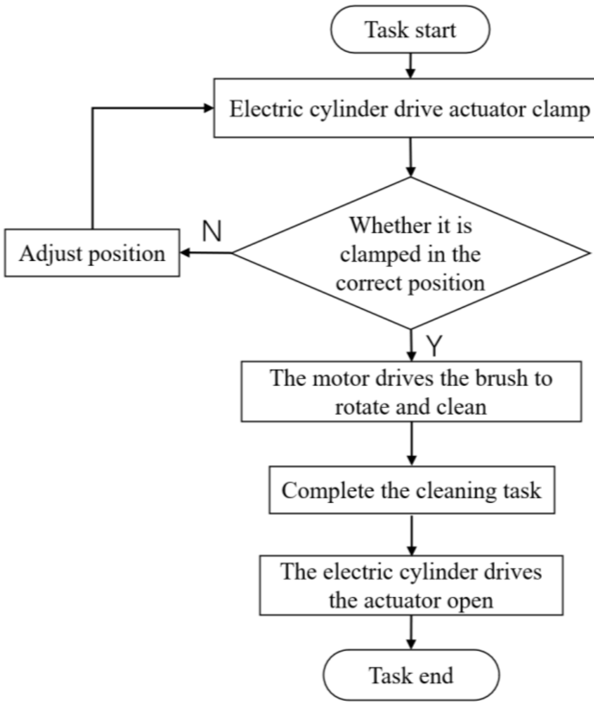

Figure 3. Actuator workflow diagram

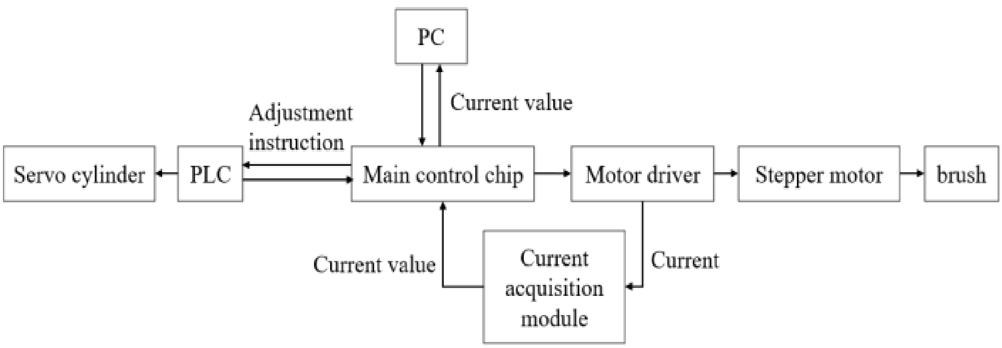

Figure 4. Control system block diagram

The servo control system adopts the proportional-integral-derivative (PID) closed-loop control architecture, and the deviation of the system output from the target setpoint is collected in real time through the acquisition module, and dynamic adjustment is carried out based on the PID control algorithm. The mathematical model of the continuous domain PID controller is:

$$u(t) = K_p e(t) + \frac{1}{T_i}\int e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

Where, $u(t)$ is the controller output, $e(t)$ is the system deviation, K_p is the proportional gain, T_i is the integral time constant and K_d is the differential gain. The controller responds quickly to the deviation through the proportional link, the integral link eliminates the steady state error, and the differential link suppresses the system overshoot.

For digital control, the PID algorithm is discretized by introducing the sampling period T , and the mathematical model is:

$$u(t) = K_p e(t) + \frac{T}{T_i}\sum_{j=0}^{k} e(jT) + K_d \frac{e_{n+1} - e_n}{T} \tag{2}$$

In the servo control system, the drive is configured in position control mode, and precise control of the motor speed is achieved by adjusting the pulse frequency f_{pulse}. The servo motor speed (unit: r/min) is calculated by the formula:

$$n = \frac{60 \cdot f_{pulse}}{1600} \tag{3}$$

Where, 1600 denotes the number of pulses required per revolution of the servo motor. The control architecture realizes closed-loop control from algorithm design to actuator, providing the system with high-precision motion control capability.

4. Experiments and analysis of results

The first experiment was designed to explore the relationship between end-effector clamping force and brush rotation motor current values. By gradually increasing the load, the change of motor current was monitored by using a current sensor and the data was recorded. The experimental results after applying moving average filtering [12] are shown in Fig. 5, demonstrating a positive correlation between motor current value and load - that is, the greater the clamping force, the higher the current value. Based on this, the opening and closing angle of the motor can be adjusted by real-time current monitoring value to realize the precise control of clamping strength. This study provides experimental basis and theoretical support for current feedback technology.

In terms of PID control parameters, for the complex working conditions of time-varying system, after system simulation verification and through multiple rounds of parameter iterative testing and optimization analysis, the parameter combinations of PID control are finally determined, as shown in Fig. 6, which has significant ad-vantages in dynamic performance, steady state accuracy and robustness, and meets the operational requirements of the actuator wiping end.

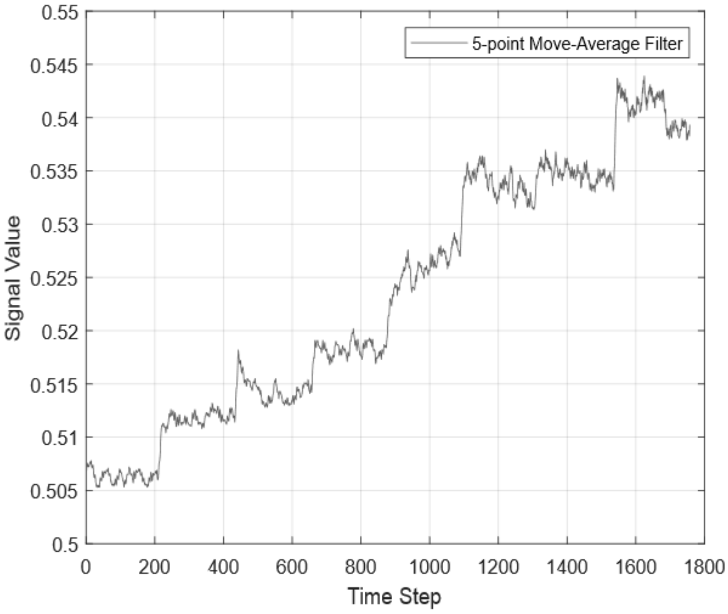

Figure 5. Current load correlation validation plot

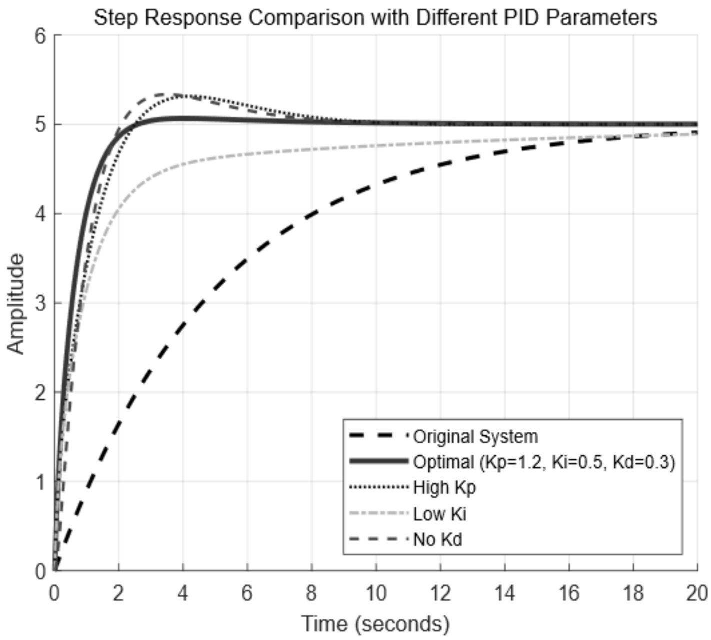

Figure 6. Validation plot of PID gain optimization under multiple parameters sets

Finally, in order to verify the performance of the cleaning robot, we built an experimental platform and carried out cleaning experiments in the laboratory environment. In this experiment, the main controller of the actuator is STM32F407 series microcontroller, so as to realize the insulator wiping and closed-loop automatic control and other functions. The insulator surface cleaning standard mainly contains two indicators: salt density and gray density, the experiment through the measurement of these two indicators as the basis for measuring the cleaning effect.

The experimental operation is as follows: evenly apply dirt on the insulator sur-face, and then use the actuator with water spray to clean it. After cleaning, it was first obvious that the dirt dust was effectively removed from the insulator surface. The Equivalent Salt Deposition Density (ESDD) measured at the beginning of this experiment was about 0.3 mg/cm², which is extremely heavy fouling in the national standard [13]. After about 1 minute of cleaning with the actuator, we re-measured the insulator ESDD, which was less than 0.03 mg/cm², the lowest level of fouling. This is a good indication that the developed end-effector can meet the cleaning requirements.

The main equipment parameters of the experimental platform are as follows:

Servo motor: Ichikawa STM2430 (750W, 1600 pulses/revolution), configure the motor for position mode, default power-on enable.

Servo Cylinder: Folding type 60 flange measuring cylinder of KOKUO servo series (100mm lead)

Driver: using the upper computer for control, configured to weld cn2 port, using terminal 14 to receive pulse signals, terminal 5 to receive directional signals, terminal 2 to connect 24V, terminal 10 link com end.

PLC: Mitsubishi FX3U-16MT/ES-A (GXWorks2 programming, ST language to realize PID)

Main control board: STM32F407 (EtherCAT bus synchronization, 1ms control cycle)

Sensor: Zero reset sensor (Omron EE-SX671), logic programming using GXWorks2 environment.

In GXWorks2 platform, ST language is used to realize the control logic, set the proportional coefficient K_p =1.2, the integral coefficient K_i =0.5, the differential coefficient K_d =0.3, synchronously obtain the feedback position of the servo encoder through the EtherCAT bus, execute the PID algorithm every 1ms cycle, dynamically adjust the pulse output frequency, apply the trapezoidal acceleration and deceleration curves on the output pulse to suppress the Mechanical shock, through the zero sensor trigger position reset, to ensure that the repetitive positioning accuracy of the electric cylinder ≤ ± 0.02mm.

The servo system outputs control commands through the STM32F4 main control board, and the optocoupler isolation conversion module converts the 5V/3.3V level signals of the microcontroller into PLC-compatible leakage-type control signals (NPN-type), which drive the start-stop control terminal of the servo system. The application of optocoupler devices to achieve electrical isolation, effectively inhibit electromagnetic interference on the control signal perturbation, through the NPN-type signal interface adapted to the input characteristics of the PLC, and ultimately ensure that the servo actuator can accurately respond to the instructions, and stably control the end of the jaws of the closure action, to complete the insulator surface dirt cleaning operations.

5. Conclusion

Aiming at the technical difficulties in railroad insulator cleaning and maintenance, this paper proposes a servo control system design method based on current feedback, and designs an end-effector specifically for insulator cleaning. The study firstly constructs a three-dimensional parametric model through SolidWorks to optimize the kinematic characteristics of the actuator; secondly, a high-precision servo control system is developed based on the STM32F407 master control platform, which innovatively integrates the PID regulation technology, the high-sensitivity current acquisition module, and the sliding average filtering algorithm to realize the real-time dynamic and precise control of the contact pressure between the brush and the insulator. control. Experimental results show that the actuator can intelligently adapt to a variety of installation postures (horizontal, vertical and tilting), and the contact pressure control accuracy reaches ±0.2kg, which significantly improves the cleaning efficiency and reduces the operational risks and costs.

The core advantage of this paper's work lies in the introduction of PID regulation, current feedback and filtering algorithms into the servo control system, which solves the problem that the contact pressure is difficult to be accurately controlled by the traditional cleaning method in a dynamic environment. Compared with the existing technology, the design not only improves the cleaning efficiency, but also significantly improves the safety and stability of the operation, providing a reliable technical solution for unmanned cleaning and maintenance of railroad insulators.

Future research can further expand the application scope of this technology, such as combining model predictive control and reinforcement learning methods to further optimize the control strategy to adapt to more complex working conditions and dynamic environments. In addition, the technical solution of this research has good promotion value and can be applied to other industrial scenarios that require high-precision contact control, such as robot grasping and precision assembly, to provide technical support for the realization of intelligent unmanned operation.

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