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The Design of Intelligent Gripper and Holding Algorithm Suitable for High Voltage Combined Electrical Appliances Docking

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Abstract: To address the issues of low efficiency, poor accuracy, and safety hazards associated with manual connections of high-voltage gas-insulated switchgear (GIS), this paper introduces a specialized intelligent gripper system and control algorithm. In terms of hardware, an innovative three-finger radial synchronous gripper is developed, featuring a carbon fiber composite finger tip and a parallel disc spring-rail dual-level adaptive mechanism, which compensates for ±3.5mm pose deviation. The perception system integrates six-axis force sensors and laser rangefinders, with dynamic gravity compensation and Kalman filtering, achieving a force resolution of 0.1N and a pose estimation error less than or equal to 0.03 mm. At the algorithm level, a hierarchical control architecture is proposed. Gain-scheduled adaptive gripping control enhances robustness through gain scheduling strategies. Directionally decoupled force-position hybrid compliant control constructs a stiffness matrix to achieve coordinated tangential low stiffness and normal adaptive stiffness. The force-position deviation mapping algorithm achieves angle error convergence at the 0.04° level. After 50 full-process tests on GIS simulation pieces, the system has a 98% connection success rate, 93.2% seal compression uniformity, a 38.7% reduction in contact force peak, and a single operation time of 4.1 minutes, significantly enhancing assembly automation.

Keywords: high voltage combined electrical appliances; intelligent gripper; force position hybrid control; compliant assembly; impedance control; adaptive clamping

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1. Introduction

Gas insulated metal-enclosed switchgear (GIS) is the core equipment of modern substations. The precision of its modular flange docking directly affects the airtightness and insulation performance [1-3]. The current manual assembly mode faces three challenges [4-7]:

1) Precision bottleneck: the compression tolerance of the sealing ring should be controlled within ±0.1mm, and the lifting of heavy parts is easy to cause millimeter-level position deviation;
2) Efficiency limit: the average time of a single docking is 6-8 hours, accounting for more than 35% of the total assembly cycle of the equipment;
3) Safety hazard: The risk of sulfur hexafluoride leakage and metal collision damage rate is as high as 5.2%.

Although industrial robots are widely used in the automotive and electronics industries, standard grippers struggle to meet the specific requirements of GIS docking, such as the structure of irregular flanges, non-rigid contact, and high damage resistance. Current research primarily focuses on general force control assembly, with models like the impedance control model proposed by Sun et al. (2020) making progress in the assembly of small parts. However, these models have limitations in the heavy power equipment sector, including insufficient force sensing accuracy and weak disturbance resistance. This paper addresses these issues by proposing a dedicated intelligent gripper system design, with core innovations including [8-12]:

1) The integration of mechanical, sensing and control architecture realizes the closed loop of environment interaction.
2) The variable gain clamping algorithm solves the grasping stability under unknown posture.
3) The direction decoupling compliant control model ensures uniform compression of the sealing ring. Through technological breakthroughs, the docking success rate is expected to be increased to more than 95%, providing technical support for smart grid equipment manufacturing.

2. Overall System Design and Key Requirements

2.1. In-Depth Analysis of GIS Docking Process

The typical docking process of 500kV GIS module includes five stages: workpiece picking, space transfer, precision alignment of flange, axial flexible insertion and bolt tightening. According to the field test, the core difficulties are as follows:

1) Geometric constraint: the flange bolt hole must maintain a centering tolerance of ±0.2 mm, with an equivalent angular deviation of less than 0.05°.
2) Mechanical constraint: the EPDM seal ring should be uniformly subjected to 1.5–2.0 MPa of compressive stress, corresponding to a normal force of 150 ± 15 N.
3) Dynamic constraint: the amplitude of vibration at the end of the robot is ±0.3 mm, primarily influenced by environmental disturbances, with the main frequency identified by spectrum analysis being 2–5 Hz.

2.2. Requirements and Specifications of Intelligent Gripper System

Based on process analysis, define key system indicators (Table 1):

Table 1. Key Indicators.

Function	Qualification	Proof technique
Clamping ability	Load is more than 1.5t, and the clamping force is adjustable from 0 to 2000N	Static load test + force sensor
Position compensation	Translation ±5mm/rotation ±1°	Laser tracker
Force control accuracy	Steady-state error is less than or equal to 5%FS	Step response test
safe guarding	Overload response time is less than or equal to 300ms	Sudden load test

2.3. System Architecture Design

Adopt modular hierarchical architecture:

1) Execution layer: three-finger adaptive gripper, with the fingertip integrating a curvature matching mechanism.
2) Perception layer: six-dimensional force sensor, laser rangefinder.
3) Control layer: a real-time industrial control computer runs the core algorithm.
4) Drive layer: EtherCAT bus servo system.

Among them, the soft controller $C(s), x_{traj}$ is used to plan the trajectory. The architecture significantly improves the robustness of the system through the collaboration of hardware specialization and intelligent control software.

3. Mechanical Structure and Perceptual System Design

3.1. Dual-Level Adaptive Gripper Design

In view of the deformation characteristics of GIS flange thin wall, a three-finger radial synchronous mechanism is developed. The core innovations include:

1) Tip optimization: V-shaped clamping block is made of carbon fiber matrix + polyurethane coating. The simulation of contact stress distribution shows that the maximum pressure drops by 42% compared to traditional flat-tip clamps.
2) Flexibility unit: The parallel disc spring-rail system provides ±3.5mm floating travel, mechanical model:

$$\begin{bmatrix} F_{n1} \\ F_{n2} \\ F_{n3} \end{bmatrix} = \mathrm{K} \cdot \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{bmatrix}, \qquad \mathrm{K} = k_s \begin{bmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{bmatrix}$$

The structure is optimized through topology optimization, and static simulation shows a maximum deformation of 0.08 mm under a 2000 N load.

3.2. Multimodal Perception System

Force sensing: a six-dimensional sensor is installed at the gripper-robot interface, and a gravity compensation algorithm is applied:

$$\mathrm{F}_{ext} = \mathrm{R}_b^w \left(\mathrm{F}_{raw} \begin{bmatrix} 0 \\ 0 \\ G_{tool} \end{bmatrix} \right), G_{tool} = 185\mathrm{N}$$

After Kalman filtering, the standard deviation of noise is reduced to 0.3N. Position perception: fusion of joint encoder and laser ranging to establish the position estimation model:

$$\Delta \mathrm{T} = \mathrm{J}\Delta \mathrm{q} + \mathrm{Kd}_{lidar} + \mathrm{B}\dot{\mathrm{F}}_{ext}$$

The calibration experiment verifies the position estimation error RMSE = 0.03mm.

3.3. Security Protection Mechanism

Three layers of protection include a mechanical hard limit with a travel margin of ±2 mm, an electronic torque threshold at 120% of the rated value, and a slip detection algorithm.

Slip criterion:

$$SlipFlag = \begin{cases} 1 & \backslash|\mathrm{F}_t\backslash| > \mu_s F_n + 10\mathrm{N} \\ 0 & \text{otherwise} \end{cases}, \mu_s = 0.25$$

The test shows that the system can respond within 250ms after the slip occurs.

4. Intelligent Clamping Algorithm Design

4.1. Hierarchical Control Architecture

The algorithm is divided into: task layer: parsing the docking process as a finite state machine; decision layer: switching control mode based on sensor data; execution layer: implementing three core algorithms.

4.2. Adaptive Clamping Control

Design of variable gain impedance-force hybrid controller:

$$\mathrm{F}_{cmd} = \mathrm{K}_p(\alpha)\mathrm{e}_p + \mathrm{K}_d\dot{\mathrm{e}}_p + \mathrm{K}_f\mathrm{e}_F$$

Gain scheduling strategy:

$$K_p(\alpha) = K_{p0} + (K_{p1}K_{p0})e^{-\beta\alpha}, \beta = 0.5$$

Among α them, contact stability is realized to realize the adaptive switching between impact prevention in the initial stage of grasping and disturbance resistance in the stable period.

4.3. Force Position Hybrid Soft Control

Improved impedance model:

$$M_d\ddot{x}_e + B_d\dot{x}_e + K_d(t)x_e = F_{ext}F_d$$

Directionally decoupled stiffness matrix:

$$K_d(t) = \begin{bmatrix} k_{xy} & 0 & 0 \\ 0 & k_{xy} & 0 \\ 0 & 0 & k_z(t) \end{bmatrix}, k_z(t) = 200 + 0.8\frac{\partial F_z}{\partial z}$$

The tangential stiffness is fixed at a low level to reduce friction, while the normal stiffness is adaptively adjusted based on the compression stiffness of the sealing ring.

4.4. Online Pose Fine-Tuning Algorithm

Force-position deviation mapping:

$$\Delta x = J^{-T}(K_f\Delta F + K_\tau\Delta\tau)$$

The experimental results show that the convergence rate of the algorithm $K_f = diag(0.02, 0.02, 0.05), K_\tau = diag(0.005, 0.005, 0.01)$ can be increased by 60%.

5. Experimental Verification and Result Analysis

5.1. Experimental Platform

The KUKA KR500 robot is equipped with an intelligent gripper system. The GIS simulation piece weighs 800kg. The measurement is carried out using a laser tracker and a dynamic signal acquisition system.

5.2. Core Performance Test

Clamping stability: when the initial bias is ±3mm, the variance of clamping force after adaptive compensation is less than or equal to 3.8N, n = 30.

Smooth control: in the compression stage of the sealing ring, the peak force of the traditional position control is 212N, while the algorithm in this paper is reduced to 148N.

Pose fine-tuning: 0.5° The initial offset Angle converges to 0.04° within 6.8s.

5.3. Full Process Docking Test

The automated tests are shown in Table 2:

Table 2. Results of 50 Automated Tests.

Metric	Bear fruit	The extent of the increase
Connection success rate	98% (49/50)	+12%
Average time taken	4.1 ± 0.3 min	-67%
Maximum contact force	156 ± 11 N	-38.70%
Uniformity of seal ring compression	93.2 ± 2.1%	22.50%

The failure case is attributed to laser ranging lock loss caused by sudden mechanical vibration during high-speed movement. The advantages of the system are highlighted as follows:

1) Accuracy: Flange coaxiality error 0.07 ± 0.03mm, meet the standard of ±0.2mm;
2) Reliability: the damage rate of parts is 0%, while the traditional method is more than 5%;

3) Robustness: the success rate is 96% under ±1mm random disturbance.

The system has addressed key technical challenges in GIS automation docking and provides strong equipment support for smart grid construction.

6. Summary and Prospect

This paper solves the technical bottleneck of high voltage combined electrical automation docking, and the main achievements include:

1) Mechanical integration innovation: the three-finger dual-level adaptive gripper is developed by designing carbon fiber finger end and parallel compliant unit to achieve 2000N load capacity and ±3.5mm position compensation under the premise of lightweight (18.5kg), and the maximum deformation is verified by static simulation <0.1mm.
2) Intelligent Perception Breakthrough: Constructing a multimodal sensing system, the six-dimensional force sensor, after gravity compensation ($\mathbf{F}{ext} = \mathbf{R}b^w (raw)-[0, 0, G{tool}]^T$) and Kalman filtering, reduces noise to a standard deviation of 0.3N. The pose fusion algorithm ($\Delta \mathbf{T} = \mathbf{J} \Delta \mathbf{q} + \mathbf{K} \mathbf{d}_{lidar}$) further reduces the estimation error to ±0.03 mm.
3) Advantages of core algorithm: Under the hierarchical control framework, the variable gain clamping strategy reduces the adjustment time by 40%, the direction decoupling compliant control reduces the compression force fluctuation of the sealing ring to ±8N (a decrease of 68%), and the position micro-adjustment algorithm realizes the rapid convergence of 0.5° deviation (6.8s).
4) Reliable engineering verification: the full-process test shows a docking success rate of 98%, and the operation time is reduced by 67%. Key indicators outperform manual operation (0.07 mm vs. 0.25 mm for coaxiality error; 0% vs. 5.2% for damage rate).

Future research can be deepened from three aspects:

1) Environmental adaptability improvement: develop vibration active suppression algorithm to deal with on-site sudden wind disturbance (such as introducing IMU sensor fusion control), enhance the sensing stability under strong electromagnetic interference.
2) Deep expansion of intelligence: construct a virtual debugging platform by combining digital twin technology, and optimize the self-integration efficiency of impedance parameters ($\mathbf{K}_d, \mathbf{B}_d)$ by using reinforcement learning.
3) Standardization and Generalization: Establish modular interface standards for grippers, expanding to similar power equipment assembly scenarios such as GIL pipe racks and transformer bushings. Human-Machine Collaboration Safety: Conduct research on a hybrid assembly model based on tactile feedback and develop collision prediction algorithms (such as potential field methods) to ensure the safety of human operations. The industrialization of this technology requires collaboration with equipment manufacturers to formulate the "Technical Specifications for High-Voltage Electrical Automation Assembly," promoting the upgrade of the smart grid equipment manufacturing system.

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