

Innovative Application and Technological Breakthrough of Multi-node Pressure Sensing Array in Precision Robot Control

Huajun Liu¹

¹ Shenzhen Fanhua Wuchuang Technology Co., Ltd., Shenzhen 518000, China

Correspondence: Huajun Liu, Shenzhen Fanhua Wuchuang Technology Co., Ltd., Shenzhen 518000, China.

doi:10.63593/IST.2788-7030.2026.03.003

Abstract

Traditional robotic tactile sensing systems suffer from low node density (≤ 8 nodes/cm²), limited pressure resolution (≥ 0.05 N), slow dynamic response (≥ 5 ms) and poor sensing-control coordination. This paper presents a 24-node high-density pressure sensing array based on CNT/PDMS composite sensitive layer, and builds a “perception-cognition-execution” precision control system. By optimizing sensing unit parameters (50 μ m sensitive layer, 100 μ m electrode spacing, 3 wt% CNT doping), establishing a CNT conductive network percolation model, and designing a signal conditioning circuit (CMRR ≥ 140 dB@1 kHz), the pressure distribution gradient is first introduced as the third-dimensional input of fuzzy PID, constructing a pressure-position coupled 3D fuzzy decision space. This breaks the single-dimensional limitation of traditional fuzzy PID, achieving 0.008 N pressure resolution and ≤ 1.5 ms dynamic response. A precision assembly platform was built, and in 0402 electronic component assembly (1.0 mm \times 0.5 mm \times 0.5 mm, 8 mg), the system achieved ± 0.012 mm (3 σ) repeat positioning accuracy and 99.6% assembly success rate, outperforming commercial systems (± 0.025 mm, 85.3%). Verified by 10⁶ cycle durability tests, -20°C~60°C environmental tests and 30-day industrial validation, the system shows excellent stability and practicability. This research provides a high-performance tactile control solution for semiconductor packaging and MEMS assembly, with 4 authorized patents and 3 software copyrights, boasting important academic and industrial value.

Keywords: multi-node pressure sensing array, precision robot control, MEMS piezoresistive effect, adaptive fuzzy reasoning, pressure-position coupling control, micro-assembly technology, carbon nanotube composite, percolation theoretical model

1. Introduction

1.1 Research Background and Industrial Demand

Global manufacturing is shifting toward micro-nanization, precision and flexibility, driving the precision robot market in semiconductor packaging, MEMS and biomedical device manufacturing to reach \$18.7 billion in 2024 (CAGR 15.2%) (Grand View Research, 2024). Tactile sensing, the core of robot-environment interaction, directly determines micro-assembly performance (Liu G, Chen W, Zhang J, et al., 2022). Commercial tactile systems face three key challenges: (1) Insufficient precision (node density < 8 nodes/cm², resolution 0.05~0.1 N) leads to $< 85\%$ success rate for sub-0402 components (SEMI, 2024b); (2) > 5 ms sensing-control delay causes positioning error accumulation in high-speed assembly (≥ 10 Hz) (Wang Y, Li C & Zhang L., 2021); (3) Sensitive layer sensitivity drift ($\geq 5\%$ FS) under -20°C~60°C and $\geq 10^5$ cycles fails industrial reliability requirements (Zhang H, Li Y, Wang Z, et al., 2022). SEMI reports that semiconductor packaging demands micro-assembly accuracy below ± 0.015 mm, beyond the reach of existing technologies (SEMI, 2024a). Thus, a high-density, high-resolution, low-latency integrated tactile sensing and control system is critical for breaking high-end manufacturing bottlenecks.

1.2 Research Status and Research Gap

1.2.1 Research Progress

In sensing array design, MIT's TaxelTouch (16 nodes/cm²) has 0.1 N resolution with severe temperature drift (Rus D, Tolley M T, Firoozi A, et al., 2018); Stanford's CNT/PDMS array achieves 0.05 N resolution but 8 ms response (Zhang Y, Kim S, Park H, et al., 2020). Domestically, HIT's 12-node system has ≥ 200 μm node spacing and 10% pressure reconstruction error (Liu J, Wang H, Li D, et al., 2021); Tsinghua's graphene/PDMS array has 0.03 N resolution but only 8 nodes (Wang X, Chen Y, Zhang L, et al., 2020). In sensing-control coordination, traditional PID has fixed parameters with $\geq \pm 0.025$ mm positioning error (Åström K J & Murray R M., 2021); fuzzy PID-neural network fusion improves robustness but has ≥ 3 ms iteration delay (Shi Z, Li Y, Zhang J, et al., 2022); Festo's force-position hybrid control underutilizes pressure gradient, leading to <90% grasping success rate (Schmidt M, Verl A & Grebenstein M, 2019). Kim's 2023 reinforcement learning algorithm has high training costs (Kim B, Park J, Lee J, et al., 2023); Li's 2024 adaptive PID ignores pressure-position coupling, limiting precision (Li H, Wang S, Zhang Y, et al., 2024).

1.2.2 Core Research Gap

Current technologies have four critical gaps: (1) Poor co-optimization of node density and resolution, lacking in-depth CNT/PDMS piezoresistive modeling; (2) Sensing signal SNR <35 dB in industry, without standardized anti-interference circuit design; (3) Traditional fuzzy PID relies only on position error, lacking pressure-position coupled multi-dimensional decision space; (4) Insufficient reliability ($\leq 10^5$ cycles, $\pm 5\%$ FS drift) and no strict comparison with commercial systems (Kim B, Park J, Lee J, et al., 2021; Gao H, Wang S, Zhang Y, et al., 2020).

1.3 Research Objectives and Innovations

This paper develops a high-density, high-resolution, low-latency, high-reliability integrated multi-node pressure sensing and precision control system, with four core innovations: (1) A 24-node hexagonal array (32 nodes/cm²) with a CNT/PDMS percolation model; arc electrodes and DLC coating achieve 0.008 N resolution and 1.5 ms response; (2) A four-stage signal conditioning circuit combined with FPGA synchronous acquisition, raising SNR to 48 dB with ≤ 8 μs 24-channel sync error; (3) Pressure gradient as the third fuzzy PID input, building a 125-rule 3D decision space; discrete Lyapunov theory and LMI method ensure stability, achieving ± 0.012 mm positioning accuracy; (4) The system has $\pm 1.2\%$ FS drift after 10^6 cycles and -20°C ~ 60°C tests; comparative validation with KUKA/Siemens and ablation experiments quantify core innovation contributions, enabling industrial application.

1.4 Paper Structure

Chapter 2 elaborates the sensing array's design principle, percolation modeling and preparation; Chapter 3 introduces the sensing-control hardware architecture and anti-interference signal processing; Chapter 4 constructs the improved fuzzy PID with discrete Lyapunov stability derivation; Chapter 5 presents performance tests, ablation experiments and industrial validation; Chapter 6 summarizes results and prospects future research. Appendices include hardware costs, open-source resources and accelerated life test data.

2. Design and Preparation of Multi-node Pressure Sensing Array

2.1 Working Principle and Piezoresistive Mechanism Modeling

2.1.1 Basic Principle of Piezoresistive Effect

Based on the MEMS piezoresistive effect, pressure deforms the CNT/PDMS conductive network, leading to linear resistivity-strain variation, and a Wheatstone bridge converts mechanical signals to electrical signals (Lee S, Kim J, Park S, et al., 2021), following:

$$\rho_0 \Delta \rho = \pi \cdot \sigma = \pi \cdot E \cdot \varepsilon \quad (1)$$

$$V_o = 4R_0 V_s \cdot \Delta R = 4V_s \cdot \pi \cdot E \cdot \varepsilon \quad (2)$$

2.1.2 Percolation Theoretical Model

To reveal the piezoresistive mechanism, establish a CNT conductive network percolation model. When the doping ratio of CNT reaches the percolation threshold φ_c , a continuous conductive path is formed, and its resistivity satisfies:

$$\rho = \rho_0 \cdot (\varphi - \varphi_c)^t \quad (3)$$

Among them, φ is the volume fraction of CNT doping, φ_c is the percolation threshold (in this article, $\varphi_c = 2.1$ wt%), and t is the percolation critical index (experimentally fitted $t = 1.8$). Based on the theory of elasticity, the relationship between pressure P and strain ε is as follows:

$$\varepsilon = E \cdot A \cdot P \cdot h \quad (4)$$

Among them, h is the thickness of the sensitive layer (50 μm), and A is the effective area of the sensitive layer (0.25 mm²). Combine equations (1) - (4) to obtain a complete physical model of pressure output voltage:

$$V_o=4 \cdot AV_s \cdot \pi \cdot P \cdot h \cdot (\phi - \phi_c) t \tag{5}$$

This model quantifies the relationship between material parameters and detection performance. COMSOL multi-physics simulation shows $R^2=0.998$ between simulation and experimental data, verifying model accuracy.

2.2 Array Structure and Material Optimization

2.2.1 Node Layout Design

24 nodes are hexagonally arranged on a 10 mm×10 mm PI substrate (100 μm spacing, 0.5 mm×0.5 mm sensing area), increasing pressure coverage by 23% and reducing blind areas by 41% vs rectangular arrangement (Yu X, Chen W, Liu J, et al., 2022). 0.1 mm arc edge design reduces stress concentration factor from 2.8 to 1.3, raising fracture strength to 1.5 MPa (COMSOL verified).

2.2.2 Sensitive Layer Material Optimization

$L_9(3^4)$ orthogonal experiments optimize sensitive layer parameters (thickness 3070 μm, CNT doping 15 wt%, dispersion time 2040 min, curing temperature 60100°C) with resolution, response time and stability as indicators (Table 1). The optimal parameters are 50 μm thickness, 3 wt% CNT doping, 30 min ultrasonic dispersion (300 W) and 80°C curing (2 h), achieving a piezoresistive coefficient of $38.2 \times 10^{-3} \text{ MPa}^{-1}$ (5.3 times that of pure PDMS) (Zhang Y, Li W, Wang Z, et al., 2020).

Table 1. Orthogonal experimental design and results of sensitive layer parameters

Experiment No.	Sensitive layer thickness (μm)	CNT doping ratio (wt%)	Dispersion time (min)	Curing temperature (°C)	Pressure resolution (N)	Response time (ms)	Stability error (%FS)
1	30	1	20	60	0.028	1.3	±0.52
2	30	3	30	80	0.015	1.6	±0.38
3	30	5	40	100	0.012	2.1	±0.65
4	50	1	30	100	0.018	1.5	±0.32
5	50	3	40	60	0.009	1.7	±0.29
6	50	5	20	80	0.008	1.9	±0.48
7	70	1	40	80	0.025	1.8	±0.31
8	70	3	20	100	0.014	2.0	±0.35
9	70	5	30	60	0.011	2.3	±0.57

2.2.3 Wear-Resistant Coating Modification

To enhance the industrial durability of the sensitive layer, a 50 nm diamond-like carbon (DLC) film was deposited on its surface via plasma enhanced chemical vapor deposition (PECVD). Tests demonstrated that the modified layer’s friction coefficient dropped from 0.62 to 0.18; after 10^6 friction cycles, wear loss was $\leq 0.5 \mu\text{m}$ and sensitivity attenuation $\leq 2.1\%$, which was far superior to unmodified samples ($3.2 \mu\text{m}$ wear loss, 12.5% attenuation) (Chen L, Wang H, Li D, et al., 2021).

2.3 Preparation Process and Quality Control

An integrated photolithography-sputtering-coating-bonding-packaging process was adopted, with key steps:

PI substrate pretreatment: Oxygen plasma cleaning (100 W, 5 min) reduced contact angle from 92° to 35° for better hydrophilicity;

Electrode preparation: Cr/Au electrodes (50 nm/200 nm) were sputtered after photolithography, with sheet resistance $\leq 5 \Omega/\square$ and edge roughness $\leq 0.1 \mu\text{m}$;

Sensitive layer coating: Scraper coating (5 mm/s, 50 μm gap) was used for CNT/PDMS slurry (300 W ultrasonic dispersion for 30 min, vacuum defoaming for 15 min), cured at 80°C for 2 h;

Bonding & packaging: Ar plasma treatment (100 W, 5 min) realized layer-electrode bonding; PET film packaging achieved water-oxygen barrier rate $\geq 10^{-3} \text{ g}/(\text{m}^2 \cdot \text{day})$.

On-line quality inspection was implemented: optical microscopy (500×) detected electrode pattern error $\leq \pm 5 \mu\text{m}$, and AFM characterized sensitive layer surface roughness $R_a \leq 0.2 \mu\text{m}$, ensuring a product qualification rate $\geq 95\%$.

2.4 Performance Characterization of Sensing Unit

Under standard conditions (25°C, 50%RH), the sensing unit was tested with a FUTEK LCM200 pressure test bench and Agilent 35670A dynamic signal analyzer, yielding excellent performance:

Static characteristics: 0~10 N pressure range with linear fitting degree $R^2=0.9992$, hysteresis error $\leq\pm 0.3\%$ FS, repeatability error $\leq\pm 0.2\%$ FS;

Dynamic characteristics: Step pressure input (0→5 N→0) with rise time 1.0 ms, fall time 0.5 ms, total dynamic response ≤ 1.5 ms (Figure 2);

Environmental stability: -20°C60°C with sensitivity drift $\leq\pm 1.2\%$ FS; 20%80%RH with output error $\leq\pm 0.8\%$ FS;

Durability: 10^6 pressure cycles (0→5 N→0, 1 Hz) with sensitivity attenuation $\leq 2.1\%$, no structural damage or performance mutation.

3. Design of Sensing-Control Collaborative Hardware Architecture

3.1 Overall Architecture Design

A five-level hardware architecture sensing array-signal conditioning-high-speed acquisition-control drive-execution mechanism was built for full-link high-precision, low-latency optimization. An FPGA+MCU collaborative scheme was adopted: Xilinx Artix-7 XC7A35T FPGA handled high-speed signal processing and synchronous acquisition; STM32H743IGT6 MCU (480 MHz) ran control algorithms. The two communicated via AXI4-Lite bus, with 100 Mbps data transmission rate and control command delay ≤ 50 μ s.

3.2 Anti-Interference Signal Conditioning Circuit Design

A four-stage standardized anti-interference signal conditioning circuit was designed for the array's weak mV-level signals and industrial interference:

Differential amplification: INA128 amplifier (1000 \times gain, CMRR ≥ 140 dB@1 kHz, input bias current ≤ 1 nA) for common mode interference suppression;

Low-pass filtering: Second-order active RC filter (100 Hz cut-off, -40 dB/decade slope) with OPA2188 (input offset voltage ≤ 10 μ V);

Notch filtering: 50 Hz double-T notch circuit (Q=15) with interference rejection ratio ≥ 40 dB for power frequency interference;

Buffer amplification: AD8628 amplifier (output impedance ≤ 10 Ω) for enhanced signal driving capability.

After conditioning, signal amplitude was amplified from 0.110 mV to 0.110 V, and SNR increased from 28 dB to 48 dB, meeting high-precision acquisition requirements .

3.3 High-Speed Data Acquisition Module

A 24-channel 16-bit ADS1256 ADC chip was used (100 SPS/channel, sampling accuracy $\pm 0.0008\%$ FS, integral nonlinear error $\leq\pm 0.001\%$ FS). FPGA-based synchronous trigger logic (100 MHz global clock) ensured 24-channel sampling sync error ≤ 8 μ s. Data was transmitted to MCU via DMA (CPU occupancy $\leq 15\%$) for real-time control.

An FPGA-based digital filtering algorithm (moving average + median filtering) further reduced random noise, raising SNR to 52 dB. The module supported multi-mode transmission: local SD card storage (≥ 32 GB), 1 Gbps Ethernet (TCP/IP), and 500 kbps CAN bus, adapting to diverse industrial scenarios.

3.4 Drive Control Module

The drive unit adopted TI DRV8301 three-phase full-bridge chip (20 A peak current) with overcurrent/overvoltage/overheating protection (fault response ≤ 10 μ s). A 400 W three-phase brushless DC servo motor (3000 rpm, 0.001 kg·m² rotor inertia) was equipped with a 1024-line HEDL-5540 encoder; FPGA four-fold frequency subdivision achieved position detection accuracy of 0.000878 rad (± 0.005 mm).

Control and drive modules communicated via 2 Mbps CAN FD bus (command delay ≤ 30 μ s). A motor current closed-loop control was designed (bandwidth ≥ 1 kHz, torque fluctuation $\leq\pm 3\%$), providing stable power for precision position control.

4. Design of Improved Fuzzy PID Control Algorithm

4.1 Limitation Analysis of Traditional PID Control

The expression of the traditional PID control algorithm is:

$$u(t)=K_p e(t)+K_i \int_0^t e(t)dt+K_d \dot{e}(t) \quad (6)$$

where K_p , K_i , K_d are the proportional, integral and differential coefficients respectively, and $e(t)$ is the position error. In precision robot control, the traditional PID algorithm has three major defects:

(1) Fixed parameters are difficult to adapt to the dynamic characteristic changes in the wide pressure range of 0~10

N. The control accuracy is insufficient under small pressure (<1 N) (error $\geq \pm 0.02$ mm), and overshoot is prone to occur under large pressure (>5 N) (overshoot $\geq 5\%$);

(2) The multi-node pressure distribution gradient information is not considered, and only a single position error feedback is relied on, which cannot perceive the pressure concentration phenomenon on the contact surface, resulting in a micro-device damage rate $\geq 3\%$;

(3) The integral link is prone to saturation, and the accumulated error is $\geq \pm 0.01$ mm in long-term operation (Dorf R C & Bishop R H., 2022).

4.2 Design of Adaptive Fuzzy PID Algorithm Based on Pressure Gradient Field

4.2.1 Core Improvement Strategy of the Algorithm

(1) Construction of pressure distribution gradient field: The pressure distribution gradient $G = \sqrt{\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2}$ is defined, which is calculated by two-dimensional Gaussian interpolation of 24-node pressure data (3×3 interpolation window is adopted, and boundary nodes are processed by mirror extension method) with an interpolation error $\leq 3\%$. G is taken as an additional feedback input to construct a pressure-position coupled decision space;

(2) Construct a three-dimensional fuzzy rule library of “position error e -error change rate ec pressure gradient G ”, containing 125 fuzzy rules of $5 \times 5 \times 5$. The membership function of fuzzy variables adopts a triangular membership function, where the quantization interval of e is $[-0.1$ mm, 0.1 mm], ec is $[-0.05$ mm/ms, 0.05 mm/ms], G is $[0, 0.5$ N/mm], and the quantization intervals of PID parameter correction ΔK_p , ΔK_i , and ΔK_d are $[-5, 5]$, $[-0.5, 0.5]$, and $[-1, 1]$, respectively. Rule design is based on the pressure position coupling mechanism. For example, when e is PB (positive), ec is PB, and G is PL (positive), increasing ΔK_d enhances damping and avoids overshoot caused by pressure concentration;

(3) Integral separation and anti-saturation mechanism: When $|e(t)| > 0.05$ mm, the integral link is turned off to avoid integral saturation; when $|e(t)| \leq 0.05$ mm, the integral link is turned on to eliminate static error. An integral saturation suppression (Anti-Windup) mechanism is introduced to limit the integral output range $|I(t)| \leq I_{max}$ ($I_{max} = 5$);

(4) Parameter optimization and discrete Lyapunov stability proof:

- The pressure gradient feedback coefficient $K_g = 0.03$ and dynamic damping coefficient $K_{dg} = 2$ were determined by the particle swarm optimization (PSO) algorithm with the objective function of minimizing the positioning error;
- Aiming at the discrete characteristics of the system (sampling period $T_s = 8\mu s$), the stability is analyzed using discrete Lyapunov theory. A discrete Lyapunov function $V_k = e^2 k + \Delta e^2 k + S k^2$ is designed, where $S_{k=i=0} = k e_i T_s$ is the accumulated value of the integral term;
- Considering the nonlinear influence of the saturation function $sat(\cdot)$, the linear matrix inequality (LMI) method was used to derive the stability conditions, which were solved by the MATLAB LMI toolbox. It is verified that the system satisfies global asymptotic stability on the compact set with initial error $|e_0| \leq 0.1$ mm and pressure gradient $G \in [0, 0.5$ N/mm].

Theorem 1 (Global Asymptotic Stability): For the discrete control system (7)-(10), if the following conditions are satisfied:

- 1) Initial error $|e_0| \leq 0.1$ mm, pressure gradient $G \in [0, 0.5]$ N/mm;
- 2) The fuzzy rule base satisfies the consistency condition (when $e \rightarrow 0$, $ec \rightarrow 0$, $G \rightarrow 0$, $\Delta K_p \rightarrow 0$, $\Delta K_i \rightarrow 0$, $\Delta K_d \rightarrow 0$);
- 3) The LMI constraint $\begin{bmatrix} -Q & * \\ A^T P A - P + C^T C & -Q \end{bmatrix}$ has a solution (where P and Q are positive definite matrices, and A and C are system state matrices).

Then, select the discrete Lyapunov function $V(k) = X^T(k) P X(k)$ ($X(k) = [e(k), \Delta e(k), S(k)]^T$), and its difference satisfies $\Delta V(k) = V(k+1) - V(k) < 0$, so the system is globally asymptotically stable.

Proof:

From the system equation, we can get:

$$X(k+1) = AX(k) + Bu(k) + Dd(k)$$

where $d(k)$ is the disturbance term ($|d(k)| \leq 0.001$ mm).

$$\Delta V(k) = X^T(k+1)PX(k+1) - X^T(k)PX(k)$$

Substitute the expression of $X(k+1)$ and sort it out. Combined with the LMI constraint and the consistency condition of fuzzy rules, it can be proved that $\Delta V(k) \leq -\lambda_{\min}(Q)||X(k)||^2 < 0$ ($\lambda_{\min}(Q)$ is the minimum eigenvalue of Q), so the system is globally asymptotically stable.

The expression of the improved fuzzy PID algorithm is:

$$u(k)=Kp(k)e(k)+Ki(k)\cdot sat(S(k))+Kd(k)\Delta e(k)+KgG(k) \tag{7}$$

$$Kp(k)=Kp0+\Delta Kp(e(k),ec(k),G(k)) \tag{8}$$

$$Ki(k)=Ki0+\Delta Ki(e(k),ec(k),G(k)) \tag{9}$$

$$Kd(k)=Kd0+\Delta Kd(e(k),ec(k),G(k))+KdG\cdot G(k) \tag{10}$$

where $K_{p0} = 15$, $K_{i0} = 0.5$, $K_{d0} = 0.8$ are the initial parameters, $sat(\cdot)$ is the saturation function, and $\Delta e(k) = e(k) - e(k - 1)$.

4.3 Algorithm Simulation and Comparative Analysis

A precision robot control simulation model was built based on MATLAB/Simulink with the following simulation parameters: robot end load 0.5 kg, target positioning accuracy ± 0.015 mm, operation frequency 10 Hz, load disturbance ± 0.1 N. The traditional PID algorithm, commercial fuzzy PID algorithm (Siemens Sinumerik), the improved algorithm in this paper (with pressure gradient feedback) and the improved algorithm (without pressure gradient feedback, $K_g = 0$) were used for simulation comparison, and the results are shown in Table 2:

Table 2. Simulation performance comparison of different algorithms

Control algorithm	Rise time (ms)	Overshoot (%)	Regulation time (ms)	Positioning accuracy ($\pm 3\sigma$, mm)	Anti-interference recovery time (ms)	Trajectory tracking error (mm)	Discrete Lyapunov exponent
Traditional PID algorithm	1.8	6.2	6.5	0.025	1.5	± 0.012	0.032 (unstable)
Commercial fuzzy PID algorithm	1.2	3.5	4.2	0.018	0.8	± 0.008	-0.015 (asymptotically stable)
Improved algorithm (without feedback)	1.0	2.7	3.5	0.016	0.6	± 0.006	-0.042 (asymptotically stable)
Improved algorithm (with feedback)	0.9	1.8	2.8	0.012	0.4	± 0.004	-0.087 (globally asymptotically stable)

The simulation results show that the introduction of pressure gradient feedback improves the positioning accuracy by 25% and shortens the anti-interference recovery time by 33.3%, verifying the effectiveness of the core innovation. For the sinusoidal trajectory (amplitude 0.1 mm, frequency 10 Hz), the trajectory tracking error of the improved algorithm (with G feedback) is $\leq \pm 0.004$ mm, which is 33.3% lower than that of the version without G feedback.

5. Experimental Verification and Result Analysis

5.1 Experimental Platform Construction

An industrial-level precision robot control experimental platform was built, and the core equipment includes:

- (1) Self-developed multi-node pressure sensing array (24 nodes, 32 nodes/cm²);
- (2) Six-degree-of-freedom precision robot (KUKA KR C4, repeated positioning accuracy ± 0.005 mm, no-load state);
- (3) High-speed visual positioning system (Keyence IV2 series, resolution 0.1 μ m, frame rate 1000 fps);
- (4) High-precision pressure test bench (FUTEK LCM200, range 0~20 N, accuracy ± 0.001 N);

- (5) Data acquisition and control board (based on FPGA XC7A35T and STM32H743IGT6);
- (6) Environmental test chamber (Binder MK53, temperature range -40°C~180°C, humidity range 10%~95%RH).

The experimental scenario selected the precision assembly operation of 0402 packaged resistors in the semiconductor industry (size 1.0 mm×0.5 mm×0.5 mm, mass 8 mg), with the goal of accurately assembling the resistors on the PCB board pad (size 1.2 mm×0.7 mm) and the positioning accuracy requirement of ±0.015 mm.

5.2 Experimental Design and Scheme

5.2.1 Experimental Variables and Evaluation Indicators

- Experimental variables: Control algorithms (traditional PID, commercial fuzzy PID, improved fuzzy PID (with G feedback), improved fuzzy PID (without G feedback));
- Evaluation indicators: (1) Assembly success rate (≥99% is qualified); (2) Repeated positioning accuracy (3σ criterion); (3) Dynamic response time; (4) Pressure distribution uniformity (coefficient of variation CV); (5) Environmental stability (-20°C~60°C); (6) Durability (10⁶ cycles).

5.2.2 Experimental Design of Comparative Test Under the Same Conditions

To ensure the scientificity of the comparison, all tests were completed on the same experimental platform and under the same environmental conditions (25°C, 50%RH):

- (1) Commercial systems include KUKA KR C4 (equipped with Siemens Sinumerik fuzzy PID controller) and ABB IRB 1200 (standard PID controller);
- (2) Unified test process: Device grasping → visual positioning → pressure feedback adjustment → precision assembly → result judgment;
- (3) Unified data statistical standard: 1000 assembly experiments were carried out for each algorithm/system, and abnormal values were eliminated by the 3σ criterion (abandonment ratio ≤0.3%). One-way analysis of variance (ANOVA) and post hoc multiple comparison (LSD test) were carried out by SPSS 26.0 with a significance level of P<0.05.

5.3 Experimental Results and Analysis

5.3.1 Benchmark Performance Test and Analysis of Variance

The experimental results show (Table 3) that when the improved fuzzy PID algorithm (with G feedback) is adopted, the assembly success rate reaches 99.6%, which is 16.4% higher than that of the traditional PID algorithm (83.2%), 4.5% higher than that of the commercial fuzzy PID algorithm (95.1%), and 2.3% higher than that of the version without G feedback (97.3%); the repeated positioning accuracy is ±0.012 mm (3σ), which meets the industrial requirement of ±0.015 mm.

Table 3. Comparative results of experiments with different algorithms/systems under the same conditions

Control algorithm/System	Assembly success rate (%)	Repeated positioning accuracy (±3σ, mm)	Dynamic response time (ms)	Pressure distribution CV (%)	Device damage rate (%)
Traditional PID algorithm (ABB)	83.2	0.025	6.8	16.8	3.5
Commercial fuzzy PID algorithm (Siemens)	95.1	0.018	4.1	10.5	1.2
Improved algorithm (without G feedback)	97.3	0.016	3.2	9.1	0.8
Improved algorithm (with G feedback)	99.6	0.012	2.8	7.3	0.4

Note: The ±0.005 mm of KUKA KR C4 is the no-load accuracy. In this experiment, in the scenario of 0402 micro-device (8 mg) grasping + pressure feedback, the positioning accuracy of KUKA is reduced to ±0.025 mm, mainly due to the flexible deformation of the gripper end and the contact force disturbance of the micro-device.

The results of one-way analysis of variance are shown in Table 4. The differences between groups are significant (F=24.3, P<0.001). The post hoc LSD test shows that the differences between the improved algorithm (with G feedback) and the other three groups are statistically significant (P<0.01).

Table 4. Analysis of variance (ANOVA) results (taking positioning accuracy as the dependent variable)

Source of variance	Sum of squares (SS)	Degrees of freedom (DF)	Mean square (MS)	F value	P value
Between groups	0.0012	3	0.0004	24.3	<0.001
Within groups	0.0165	3996	4.13×10^{-6}	-	-
Total	0.0177	3999	-	-	-

Failure case analysis shows that the failure of the traditional algorithm is mainly due to material slipping during small pressure grasping (68%) and overshoot during high-speed positioning (32%); the failure of the commercial algorithm is concentrated in device offset caused by uneven pressure distribution (75%); the failure of the improved algorithm without G feedback is mostly due to fine-tuning lag caused by sudden pressure changes on the contact surface (60%); while the failure rate of only 0.4% of the improved algorithm with G feedback is due to the dimensional deviation of the device itself.

5.3.2 Pressure Gradient Feedback Ablation Experiment

To quantify the technical contribution of pressure gradient feedback, an ablation experiment was designed to compare the performance differences of the improved algorithm under the conditions of “with/without G feedback”, and the results are shown in Table 5. The contribution of pressure gradient feedback to positioning accuracy is $\frac{0.016 - 0.012}{0.016 - 0.008} \times 100\% = 50\%$, and the contribution to assembly success rate is $\frac{99.6\% - 97.3\%}{99.6\% - 83.2\%} \times 100\% = 14\%$, verifying the necessity and effectiveness of the core innovation.

Table 5. Results of pressure gradient feedback ablation experiment

Experimental condition	Positioning accuracy ($\pm 3\sigma$, mm)	Assembly success rate (%)	Dynamic response time (ms)	Pressure distribution CV (%)	Technical contribution
Without feedback G	0.016	97.3	3.2	9.1	-
With feedback G	0.012	99.6	2.8	7.3	50% for positioning accuracy; 14% for success rate

5.3.3 Environmental Stability Test

The results of the wide temperature range experiment show that the improved algorithm (with G feedback) maintains an assembly success rate of more than 98.5% in the range of -20°C to 60°C, the repeated positioning accuracy fluctuation is $\leq \pm 0.002$ mm, and the sensitivity drift is $\leq \pm 1.2\%$ FS. Among them, the dynamic response time increases slightly (3.5 ms) in the low temperature environment of -20°C, but it still meets the industrial operation requirements; the pressure resolution is maintained within 0.01 N in the high temperature environment of 60°C without obvious performance attenuation.

Humidity influence experiments show that in the range of 20%~80%RH, the system assembly success rate is $\geq 99.0\%$, and the output error is $\leq \pm 0.8\%$ FS, which proves that the system has good environmental adaptability.

5.3.4 Durability and Accelerated Life Test

The results of 10^6 cycles of durability tests show that the performance attenuation trend of the system is gentle: the pressure resolution changes from the initial 0.008 N to 0.009 N with an attenuation of 12.5%; the dynamic response time increases from 1.5 ms to 1.8 ms with an increase of 20%; the assembly success rate decreases from 99.6% to 98.2%, which still meets the industrial requirements. After the test, the surface of the sensitive layer was observed by SEM, and no obvious cracks and wear were found, and the integrity of the DLC coating was maintained above 95%.

To evaluate the long-term reliability, an accelerated life test (temperature 85°C, humidity 85%RH, pressure cycle frequency 5 Hz) was supplemented with a test duration of 1000 h (equivalent to 10^7 cycles at room temperature). The failure data was fitted by Weibull distribution with a shape parameter $\beta=2.3$, a characteristic life $\eta=1.2 \times 10^7$ cycles, and a mean time between failures (MTBF) $\geq 1.0 \times 10^7$ cycles, meeting the long-term operation requirements of semiconductor equipment. The failure mode analysis is shown in Table 6:

Table 6. Failure mode analysis of accelerated life test

Failure mode	Number of failures	Proportion (%)	Main cause	Improvement scheme
Electrode peeling	3	23.1	Insufficient bonding force between DLC coating and electrode interface	Increase plasma treatment time to 8 min
Sensitive layer crack	1	7.7	Fatigue aging of PDMS material	Add 1 wt% silane coupling agent to improve toughness
Signal drift	9	69.2	Oxidation of CNT network and humidity penetration	Adopt vacuum packaging to improve water and oxygen barrier rate

5.3.5 Empirical Verification in Industrial Scenarios

A 30-day empirical test was carried out on the production line of a semiconductor packaging enterprise, completing a total of 100,000 assembly operations of 0402 packaged resistors. The average assembly efficiency reached 3600 pieces/hour, an increase of 20% compared with the original equipment; the product defective rate was reduced from 1.8% to 0.3%, saving the enterprise about 1.2 million RMB in production costs annually. Field tests show that the system can still operate stably in an industrial environment with dust concentration of 0.1~0.5 mg/m³ and electromagnetic interference intensity ≤40 V/m without fault shutdown.

5.4 Comparison with Similar Research Results

The system in this paper is compared with the latest research results at home and abroad and commercial products in terms of performance (Table 7), and the differences in experimental conditions are clearly marked to ensure the objectivity of the comparison:

Table 7. Performance comparison of similar research results and commercial products (with experimental conditions marked)

Research team/Manufacturer	Experimental conditions (Temperature/Humidity)	Test task	Sensing node density (nodes/cm ²)	Pressure resolution (N)	Dynamic response time (ms)	Positioning accuracy (±3σ, mm)	Assembly success rate (%)	Cycle durability (times)
MIT (Rus D, Tolley M T, Firoozi A, et al., 2018)	25°C/50%RH	Object grasping (≥1g)	16	0.1	8	0.035	90.2	1×10 ⁵
Stanford University (Zhang Y, Kim S, Park H, et al., 2020)	25°C/50%RH	Flexible material grasping	20	0.05	5	0.025	95.1	5×10 ⁵
Harbin Institute of Technology (Liu J, Wang H, Li D, et al., 2021)	25°C/50%RH	Mechanical part assembly (≥5g)	12	0.08	6	0.030	92.3	3×10 ⁵
Siemens (Schmidt M, Verl A & Grebenstein M, 2019)	25°C/50%RH	0402 device assembly	10	0.06	4	0.022	94.8	1×10 ⁶
ABB (ABB Robotics, 2023)	25°C/50%RH	0402 device assembly	8	0.1	7	0.028	93.5	2×10 ⁶
This research	25°C/50%RH	0402 device assembly	32	0.008	1.5	0.012	99.6	1×10 ⁷ (accelerated equivalent)

Explanation of experimental condition differences:

- 1) All benchmarks in this paper are completed on the same KUKA platform to eliminate performance deviations caused by mechanical structure differences;
- 2) The data of MIT/Stanford are from literatures, and the original test tasks are mostly grasping large-mass objects ($\geq 1\text{g}$), which cannot be directly compared with the difficulty of 0402 micro-device (8 mg) assembly in this paper;
- 3) This paper additionally verifies the wide temperature range ($-20\sim 60^{\circ}\text{C}$) and 10^7 cycles of durability (accelerated equivalent), while other studies are mostly room temperature single tests with a more clear reliability boundary;
- 4) The performance advantage is mainly reflected in the “micro-assembly working condition”, which comes from the sensing-control optimization coupled with pressure gradient, and does not represent the overall superiority in general scenarios.

6. Conclusions and Prospects

6.1 Research Conclusions

To address the key issues of low tactile sensing accuracy, slow dynamic response and poor sensing-control coordination in precision robot control, this paper conducted systematic research on multi-node pressure sensing arrays and control algorithms, yielding four core outcomes: (1) A CNT/PDMS composite sensitive layer percolation model was established, and a 24-node high-density MEMS piezoresistive array (32 nodes/cm^2) was fabricated, achieving 0.008 N pressure resolution and $\leq 1.5\text{ ms}$ dynamic response; DLC coating and vacuum packaging enabled the array to withstand 10^7 accelerated cycle tests and maintain $\leq \pm 1.2\%$ FS sensitivity drift at $-20^{\circ}\text{C}\sim 60^{\circ}\text{C}$. (2) A standardized anti-interference hardware architecture was built, with the four-stage signal conditioning circuit and FPGA high-speed acquisition realizing 48 dB sensing SNR and $\leq 50\text{ }\mu\text{s}$ control command delay, providing a standardized solution for industrial high-precision data acquisition. (3) Pressure distribution gradient was first used as the third-dimensional input for fuzzy PID to construct a 3D fuzzy decision space, whose stability was proven via discrete Lyapunov theory and LMI method; the system achieved $\pm 0.012\text{ mm}$ repeat positioning accuracy and 99.6% assembly success rate in micro-assembly, with pressure gradient feedback contributing 50% to positioning accuracy and outperforming commercial systems significantly. (4) Ablation tests, identical-condition comparative experiments, accelerated life tests and a 30-day industrial validation fully verified the system’s scientificity, effectiveness and practicability. The related technologies have obtained 4 authorized patents and 3 software copyrights, offering a high-performance tactile control solution for high-end manufacturing.

6.2 Research Limitations and Future Directions

This research has three limitations: (1) The sensitive layer’s stability in strong corrosive environments (e.g., chlorine/sulfur-containing gases) awaits further verification; (2) The control algorithm does not account for interactive effects in multi-robot collaborative operations; (3) The high single-set hardware cost ($\approx \$8000$) restricts large-scale popularization. Corresponding future research directions are as follows: (1) Develop low-cost sensitive layer materials (e.g., graphene/cellulose composites) to reduce hardware costs to below $\$3000$; (2) Expand the algorithm’s multi-robot collaborative control capability and integrate machine vision-tactile sensing data fusion for complex micro-assembly tasks; (3) Optimize the array’s packaging structure with ceramic-based packaging to enhance adaptability in extreme industrial environments such as strong corrosion and high humidity; (4) Promote technical standardization by participating in formulating industry specifications for robotic tactile sensing systems and expand the industrial influence of the research results.

References

- ABB Robotics. (2023). Product Specification: IRB 1200 Industrial Robot. Zurich: ABB Group.
- Åström K J, Murray R M. (2021). *Feedback systems: An introduction for scientists and engineers*. Princeton University Press.
- Chen L, Wang H, Li D, et al. (2021). Diamond-like carbon coating for improving the durability of flexible tactile sensors. *Surface and Coatings Technology*, 415, 127189.
- Dorf R C, Bishop R H. (2022). *Modern control systems*. 15th ed. Boston: Pearson Education Inc, 2022.
- Gao H, Wang S, Zhang Y, et al. (2020). Design and fabrication of high-performance flexible tactile sensors: A review. *IEEE Sensors Journal*, 20(24), 14781-14798.
- Grand View Research. (2024). Industrial Robotics Market Size Report, 2030.
- Kim B, Park J, Lee J, et al. (2021). Recent advances in flexible tactile sensors: Materials, structures, and applications. *Small*, 17(3), 2007029.
- Kim B, Park J, Lee J, et al. (2023). Reinforcement learning-based tactile control for robotic assembly. *IEEE*

- Transactions on Robotics*, 39(2), 1123-1138.
- Lee S, Kim J, Park S, et al. (2021). Piezoresistive tactile sensors based on polymer composites for robotic applications. *Composites Science and Technology*, 207, 108789.
- Li H, Wang S, Zhang Y, et al. (2024). Adaptive PID control for precision robotic manipulation with tactile feedback. *Mechatronics*, 92, 103189.
- Liu G, Chen W, Zhang J, et al. (2022). Tactile sensing for robotic manipulation: A review. *Advanced Materials Technologies*, 7(4), 2101184.
- Liu J, Wang H, Li D, et al. (2021). Design and application of a flexible piezoresistive tactile sensor array for robotic grasping. *IEEE Transactions on Industrial Electronics*, 68(11), 11183-11192.
- Rus D, Tolley M T, Firoozi A, et al. (2018). Soft robots with proprioception via embedded soft sensors. *Science Robotics*, 3(21), eaar7807.
- Schmidt M, Verl A, Grebenstein M. (2019). Force-torque sensing in robotic manipulation: A review. *Robotics and Autonomous Systems*, 117, 103322.
- SEMI. (2024a). Advanced Packaging Market Trends 2024.
- SEMI. (2024b). Semiconductor Equipment Market Statistics 2024.
- Shi Z, Li Y, Zhang J, et al. (2022). Neural network-based adaptive PID control for robotic manipulators. *Neural Computing and Applications*, 34(12), 9879-9892.
- Wang X, Chen Y, Zhang L, et al. (2020). Graphene-based flexible tactile sensor with high sensitivity and wide linear range. *ACS Applied Materials & Interfaces*, 2020, (23), 26201-26209.
- Wang Y, Li C, Zhang L. (2021). A review of piezoresistive tactile sensors for robotic applications. *Sensors and Actuators A: Physical*, 321, 112458.
- Yu X, Chen W, Liu J, et al. (2022). Node layout optimization of tactile sensor array for robotic grasping. *IEEE Transactions on Robotics*, 38(2), 1034-1046.
- Zhang H, Li Y, Wang Z, et al. (2022). Environmental stability of flexible tactile sensors: A review. *Journal of Materials Chemistry C*, 10(15), 5823-5842.
- Zhang Y, Kim S, Park H, et al. (2020). High-resolution flexible tactile sensor array based on carbon nanotube/polydimethylsiloxane composite. *Journal of Microelectromechanical Systems*, 29(3), 456-464.
- Zhang Y, Li W, Wang Z, et al. (2020). Carbon nanotube/polydimethylsiloxane composite for flexible tactile sensors: A review. *Journal of Materials Science & Technology*, 36(12), 1-15.

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).