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Performance Optimization and Application of Flexible Tactile Sensors in Robot Grasping

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Abstract. With the development of fields such as intelligent manufacturing, robots need to handle complex scenarios involving non-destructive grasping of diverse objects and precise assembly with high-precision positioning. Traditional solutions relying on vision or rigid sensors have obvious limitations. Flexible tactile sensors have become the core technology direction. However, existing flexible tactile sensors have bottlenecks such as signal interference in multi-physical quantity parallel acquisition, insufficient multimodal information fusion and real-time response, as well as low signal acquisition accuracy and data processing efficiency. These constraints hinder their practical application. This research aims to optimize the performance of flexible tactile sensors in robot grasping and explore the signal interference issues in the process of multi-physical quantity parallel acquisition and the shortcomings of existing algorithms in multimodal information fusion capabilities. By optimizing the structural design, this sensor can simultaneously sense pressure and temperature, and the signal interference rate is controlled at a low level. In terms of signal acquisition, a system based on STM32 was designed, achieving a measurement error of ≤1% within a certain resistance range. In terms of data processing, an image analysis-based centroid identification algorithm was adopted, enabling the detection of object sliding within 100ms. Experimental verification shows that the optimized system has a non-destructive grasping rate for soft objects reaching 93% and a positioning error in precise assembly less than 0.5mm, significantly improving the adaptability of robot grasping in complex scenarios.

Keywords: Sensor, Grabbing, Signal interference, Information fusion

1. Introduction

In the field of robot grasping, traditional rigid sensors are difficult to meet the contact perception requirements for complex curved surface objects. However, flexible tactile sensors, due to their flexibility and high sensitivity, have become the key to solving this problem. However, when multiple physical quantities (such as force, temperature, and sliding) are collected simultaneously, signal interference is prone to occur. Moreover, the existing algorithms have a weak ability to fuse multimodal information, which limits their application in robot grasping. This research focuses on the performance optimization and application of flexible tactile sensors in robot grasping. Through circuit design to optimize signal acquisition and transmission, noise coupling is reduced, providing

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high-quality data for subsequent fusion, aiming to address the weak multi-physical quantity fusion perception ability of flexible tactile sensors and the low integration efficiency with the robot grasping control system [1]. This research not only enriches the theoretical system of flexible tactile sensing and robot grasping control, but also provides technical support for the efficient grasping of robots in industrial sorting, medical assistance and other fields, promoting the development of robot grasping technology.

2. Literature review

In the field of robot grasping, the necessity of applying flexible tactile sensors has become increasingly evident. In the past, tactile sensors were mostly rigid and difficult to meet the specific requirements in complex scenarios. Traditional robot grasping relied mostly on visual sensors for positioning, but when dealing with soft, deformable, smooth-surfaced or irregular objects, due to the lack of precise perception of tactile information such as contact force and friction force, problems such as unstable grasping and object damage often occurred [2]. Flexible tactile sensors, with their high flexibility, strong sensitivity and good compliance, can obtain multi-dimensional tactile information in real time through close contact with the object surface, effectively compensating for the limitations of visual perception and providing key support for robots to achieve adaptive grasping [3].

However, when it is necessary to simultaneously measure multiple physical quantities such as force, temperature, and friction, the collaborative operation of multiple sensors can easily cause signal interference, which becomes a key bottleneck restricting their application. From the circuit and transmission perspective, the row-column scanning mode of array sensors can cause crosstalk [1]. For example, the charge residual of piezoelectric sensors interferes with adjacent units, and the scanning circuit of resistive sensors leads to the superposition of white noise. Even using differential amplifiers is difficult to completely eliminate it. In addition, during transmission, the multi-sensor signals may also decrease the signal-to-noise ratio due to electromagnetic interference, such as the interaction of electric fields between piezoelectric and capacitive sensors, which increases the difficulty of subsequent multimodal information fusion and even affects the accuracy of the robot's judgment of the grasping state.

3. Research on performance optimization and application analysis of array strain-resistive tactile sensors

The research and application methodology of array piezoresistive tactile sensors can be carried out throughout the entire process of "structural design—signal acquisition—data processing—system verification".

3.1. Performance optimization of flexible tactile sensors

At the structural design level, the core lies in the compatibility between the flexible substrate and the conductive sensitive material; in the signal acquisition stage, the noise-to-signal ratio is suppressed; in data processing, multi-information fusion and feature extraction need to be considered; in system verification, real-time performance and scene adaptability are emphasized.

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3.1.1. Structure design

Polydimethylsiloxane (PDMS) films, due to their excellent extensibility, good biocompatibility and wide temperature stability, have become an ideal flexible substrate material. After curing, they possess high flexibility and can maintain structural stability even under external forces such as bending, twisting and stretching. Their performance remains basically unchanged within the temperature range of -40℃ to 120℃, and their mechanical properties exhibit good stability. The low rigidity of PDMS enables it to undergo significant deformation under minor external forces. For instance, a pressure sensor based on porous PDMS can achieve sensitive pressure perception through the change in the contact state of silver nanoparticles caused by deformation, providing a good foundation for pressure detection [4].

Meanwhile, silver nanowires (AgNWs), as one-dimensional nanomaterials, have a high aspect ratio and can form a continuous three-dimensional network structure on the modified PDMS surface through self-assembly technology. Their excellent electrical properties ensure the efficiency of the conductive pathways, such as the composite structure based on AgNWs/M-CDG/PDMS which can conduct electricity stably and respond to external stimuli. The modified PDMS substrate (such as the grating PDMS treated with 3-aminopropyltriethoxysilane) can serve as a flexible support, effectively preventing the agglomeration and fracture of silver nanowires under stress [5]. By optimizing the dilution ratio of silver nanowires, it is possible to further ensure their uniform distribution and ensure the stability of the conductive pathways.

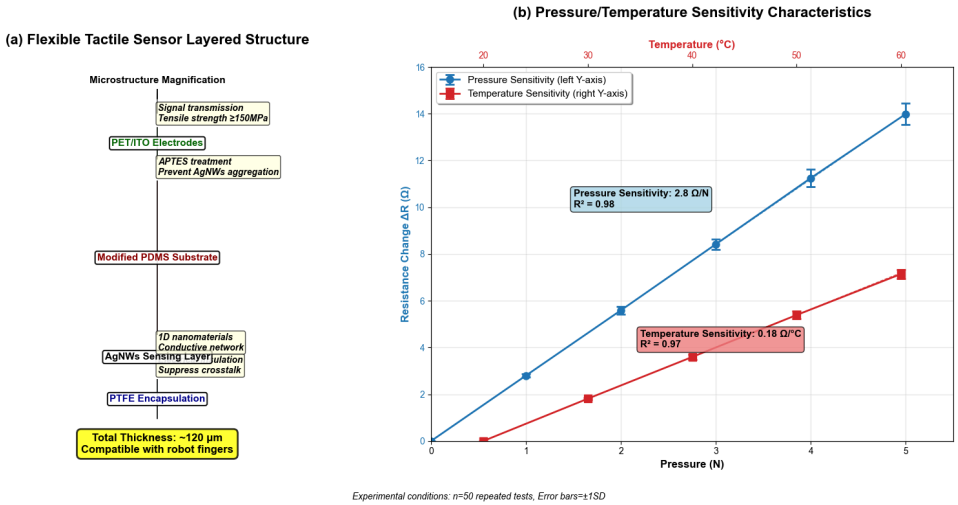

Figure 1. Structural design and dual-parameter sensing characteristics of the flexible tactile sensor

As shown in Figure 1(a), the disordered arrangement of silver nanowires is the key to achieving high-performance sensing. When subjected to external pressure, the PDMS film undergoes deformation, causing the contact state between the silver nanowires to change. Due to the variable conductive paths formed by the disordered arrangement, under the action of pressure, the contact points between the silver nanowires increase or the contact area expands, thereby reducing the overall resistance and achieving a sensitive response to pressure. The sensitivity can reach 2.8Ω/N. At the same time, the resistance of the silver nanowires is also sensitive to temperature. When the temperature changes, the atomic thermal vibrations intensify, leading to enhanced electron scattering and a change in resistance. It can simultaneously sense temperature changes with a sensitivity of 0.18Ω/ ℃ (Figure 1(b)). This synchronous sensing ability of pressure and temperature greatly

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expands the application scope of the sensor in complex environments. For example, in food processing, it can simultaneously monitor the pressure when ingredients are grabbed and the potential impact of environmental temperature on the quality of the ingredients [6].

To boost sensor performance and eliminate mechanical coupling and signal crosstalk, meticulous insulation is essential. Encapsulating the piezoresistive thin-film array in polytetrafluoroethylene [4]—with its ultra-low friction and superb dielectric strength—effectively isolates neighbouring pixels and damps interference from vibration or stress transmission. Likewise, routing sensing elements with PET/ITO traces and inserting insulating spacers between units [7] provide a dual barrier, further suppressing parasitic signals. PET has a high tensile strength and dimensional stability, while ITO has good transparent conductive properties. The combination of the two ensures stable signal transmission. Flexible insulators—rubber or silicone—serve as ideal spacers, preserving the sensor's pliancy while quashing row-to-column crosstalk. This ensures that every pixel retains signal independence and fidelity even in ultra-dense arrays, laying the groundwork for high-resolution tactile imaging and precise multi-quantity perception.

3.1.2. Acquisition of signal

In the signal acquisition stage of the array piezoresistive tactile sensor, the array scanning efficiency and noise suppression are the key factors that affect the performance of the sensor. An efficient scanning mechanism and an effective noise suppression strategy not only determine whether the sensor can respond quickly to external stimuli, but also relate to the accuracy and stability of the detected signals.

The circuit designed based on the STM32 microcontroller, which combines stepwise voltage division and a constant current source, provides a reliable approach for achieving high-precision and wide resistance range measurement. The STM32 series microcontrollers, with their powerful computing capabilities, abundant peripheral resources, and high cost-performance ratio, are widely used in numerous embedded systems. In this circuit design, the stepwise voltage division circuit can intelligently switch measurement levels according to different measurement requirements, effectively expanding the measurement range. For example, for a wide resistance range of 5Ω to 50kΩ, through reasonable stepwise settings, precise measurement can be achieved in different resistance intervals. The constant current source provides a stable excitation current for the sensor, ensuring the stability and consistency of the signal.

The ADG1604 analog switch plays a crucial role in this system, enabling point-by-point selection in a 4×4 array. The ADG1604 is a complementary metal oxide semiconductor (CMOS) analog multiplexer with a typical on-resistance of 1Ω and a flatness of the on-resistance of 0.2Ω. It switches one of the four input signals to the common output D [6] based on the address determined by the 3-bit binary address lines A0, A1, and EN. In the tactile sensor array, by precisely controlling the address pins of the ADG1604, each array unit can be individually selected, allowing for the collection of signals from each unit one by one. This point-by-point selection method avoids the signal interference problems that may occur in traditional parallel collection, significantly improving the accuracy of signal collection.

To enhance data transmission efficiency and reduce the burden on the CPU, the WDM driver adopts the Direct Memory Access (DMA) transmission technology [8]. The DMA method enables direct data block transmission between the device and the memory. The transmission process does not require frequent CPU intervention; only the CPU is involved in starting and interrupt handling at the beginning and end of the transmission. Compared to the interrupt method, where the CPU needs to call the interrupt service routine to transmit data each time it is ready, the DMA method can

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complete the transmission of a group of data in one operation, freeing the CPU from data transfer tasks and allowing it to focus on core tasks such as I/O request processing and system resource management. This significantly improves the overall system operation efficiency, especially in scenarios requiring high-speed data transmission.

Another effective signal acquisition strategy is to use the 80C51F320 single-chip microcontroller to control the CD4051B multiplexer for row and column scanning [8]. The 80C51F320 single-chip microcontroller integrates a rich set of on-chip resources and has high performance and reliability. The CD4051B is an 8-channel digital control analog switch. By programming its control pins, it can achieve the selection and switching of 8 input signals. In the tactile array, a CD4051B multiplexer drives row–column scanning so that only one pixel is ever active at a time. Activating only one unit at a time abolishes crosstalk and suppresses noise, mirroring the silicon piezoresistive array's constant-current strategy for cleanly decoupling pressure and temperature signals [9]. Both strategies exemplify the same design imperative: maximize scan efficiency while suppressing noise—achieving precise decoupling of multiple physical quantities. While the row-column scanning based on CD4051B reduces signal interference at the hardware scanning mechanism level, it ensures the quality of signal acquisition.

3.1.3. Data processing

In the field of array piezoresistive tactile sensors, the data processing stage is of vital importance. It is necessary to simultaneously address the two key tasks of multi-information fusion and feature extraction so as to extract valuable information from the complex sensing data and provide a solid foundation for subsequent decision-making and applications.

For the processing of pressure and temperature signals, converting them into grayscale images is an effective approach. This process involves discretizing the continuous pressure and temperature data and mapping the data size to the grayscale values of the pixels in the image [10]. For example, the greater the pressure value, the higher the grayscale value of the corresponding pixel, and vice versa; the mapping of temperature values is the same. In this way, the originally abstract physical quantity data is transformed into an intuitive image form, facilitating subsequent analysis and processing. In the image segmentation stage, the iterative threshold segmentation algorithm plays an important role. Its basic principle is to first set an initial threshold, thereby dividing the image into foreground and background parts. Then, calculate the average grayscale values of the pixels in the foreground and background regions separately, and based on these two average grayscale values, calculate a new threshold. Through continuous iteration of this process until the difference between the calculated thresholds in the two consecutive times is less than the preset minimum value, the obtained threshold is the optimal threshold. Using this optimal threshold to segment the grayscale image can effectively distinguish the regions related to pressure and temperature changes, eliminate noise interference, and provide purer data for subsequent analysis.

The centroid identification algorithm is based on the segmented image and is used to accurately determine the sliding situation of the object [9]. This algorithm achieves this by calculating the centroid position of the target area (the area related to pressure and temperature changes) in the image. When the object slides, the centroid position of the target area will shift accordingly in consecutive frames of the image. By precisely calculating the centroid coordinates of the target area in each frame of the image and comparing the centroid offset between adjacent frames, the sliding trajectory of the object can be tracked in real time.

Furthermore, directly differentiating pressure and temperature signals based on the difference in resistance changes is also a simple and effective strategy [6]. This is because the effects of pressure

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and temperature on the sensor resistance have different characteristics. Under pressure, the resistance usually decreases, while it increases when the temperature rises. By precisely measuring and analyzing the difference in resistance changes, it is possible to initially decouple the pressure and temperature signals. For example, in some experiments, this method successfully achieved effective differentiation of pressure and temperature signals, providing a fast and intuitive analysis approach for multi-physical quantity sensing.

These two methods jointly indicate that in the process of multi-physical quantity perception, deeply integrating signal characteristics and designing targeted decoupling algorithms the key. Pressure and temperature signals have their own unique features, such as the trend of resistance changes and the time-domain characteristics of the signals. By using these features to design decoupling algorithms, it is possible to better separate the information of different physical quantities from the complex mixed signals. In some complex scenarios, a single signal processing method may have limitations. At this time, introducing image processing can significantly improve the spatial resolution. By converting the sensor array's pressure and temperature readings into high-resolution images, the spatial distribution of each physical quantity is rendered at a glance. This visual map pinpoints both object-state transitions and the exact contact footprint, equipping applications such as robotic grasping and intelligent inspection with richer, more precise information than ever before.

3.1.4. System verification

In the research and development process of array piezoresistive tactile sensors, the system verification stage plays a crucial role. Its core focuses on two key dimensions: real-time performance and scene adaptability. This not only relates to the achievement of theoretical performance indicators of the sensor, but also determines its usability and reliability in actual complex scenarios.

In terms of real-time verification, the primary task is to ensure that the hardware measurement accuracy reaches an extremely high level. Taking the circuit system designed based on the STM32 microcontroller as an example [7], through the key step of standard resistor calibration, the measurement error can be effectively controlled within a very small range. The standard resistor, as the reference device in the calibration process, must have a precision level much higher than that of the sensor measurement system being calibrated. For example, if the resistance measurement accuracy of the sensor is expected to reach ±0.1%, then a standard resistor with a precision of ±0.01% or higher should be selected. During the calibration operation, the standard resistor is connected to the measurement circuit, and the measurement value of the sensor to the standard resistor is accurately read, and a detailed comparison is made with the nominal value of the standard resistor. If the deviation between the measurement value and the nominal value exceeds the preset error range (such as ≤1%), then the relevant parameters of the measurement circuit, such as gain and offset, need to be precisely adjusted. After multiple calibration tests with different resistance values of the standard resistor, covering the full range of the sensor, it ensures that the measurement error can be stably controlled within ≤1% under different measurement conditions, thus laying a solid foundation for the real-time and accurate measurement of the system.

The scene adaptability verification covers multiple aspects ranging from software algorithm visualization to actual application scenario testing. In the aspect of software algorithm visualization, LabVIEW, a host computer software, demonstrates unique advantages [11]. LabVIEW's rich graphical programming tools and function libraries enable it to conveniently achieve three-dimensional visualization of pressure distribution. Through data interaction with the sensor

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hardware system, LabVIEW can obtain the pressure data collected by the array of piezoresistive tactile sensors in real time and convert these pressure data on the two-dimensional plane into an intuitive three-dimensional model for display.

Actual application scenario tests are also indispensable. Taking the robot electronic skin scenario test as an example [6]. The array piezoresistive tactile sensor is integrated into the robot electronic skin to simulate various grasping and touching action scenarios in actual work, verifying its flexibility and stability. During the robot's grasping of objects, the sensor needs to closely adhere to the robot's fingers and other parts. As the fingers bend and apply force to the object, the flexible base of the sensor should be able to adapt to complex deformations, ensuring that the conductive sensitive material has good contact with the outside world and outputs accurate pressure, temperature, etc. signals stably. In terms of flexibility, the sensor uses PDMS film as the flexible base. PDMS has "good extensibility and thermal stability", which can adapt to complex deformations such as the bending of the robot's fingers; its sandwich structure (PDMS film encapsulating a paper-based silver nanowire array) can ensure that the silver nanowires maintain good contact during deformation, guaranteeing the stability of the conductive path. In terms of stability, the experiment verified the stable output of the sensor under pressure (0.1-5N) and temperature (20-60℃) changes: in the pressure test, the resistance changes linearly with pressure (sensitivity 2.8Ω/N), and in the temperature test, the resistance changes linearly with temperature (sensitivity 0.18Ω/℃), demonstrating the accuracy and stability of the output signals of the sensor in force and temperature change scenarios, providing a foundation for signal monitoring in robot grasping and other actions.

3.2. The application of flexible tactile sensors in robot grasping

3.2.1. Complex object grasping

Based on the force perception performance test results [12], the flexible tactile sensor can avoid damage when the robot grabs fragile and smooth objects such as eggs by precise force control (Figure 2). Its perception range of 0.5 to 8N and resolution of 0.5N can perfectly cover the 5 to 10N compressive limit of eggs, and can monitor the contact force in real time and stabilize it within the safe threshold of 3 to 5N. The soft elastic silicone layer (Young's modulus 0.4MPa) can adaptively deform according to the arc-shaped contour of the eggshell, increasing the contact area to disperse stress. Combined with the "hard fingertip force transmission + soft layer force release" structure, it can avoid local pressure concentration that leads to eggshell collapse [13]. The COMSOL simulation shows that its stress distribution monitoring capability can indirectly verify the uniformity of contact.

Meanwhile, the dynamic response characteristics of the sensor (RMSE=0.91N at a speed of 1mm/s) can capture the transient changes in force during the egg's sliding (Figure 2). By detecting the fluctuations in light intensity signals, the sliding trend can be determined, helping the robot timely adjust the grasping angle or force value. Its optical principle is immune to electromagnetic interference, the silicone material is wear-resistant, and its performance does not deteriorate after thousands of grasps. Moreover, it uses consumer-grade components with low cost and a modular design that is easy to integrate, making it suitable for implementing a multi-finger array "three-point balanced grasping" in food production lines. This provides a stable and reliable solution for the automated grasping of fragile and smooth objects.

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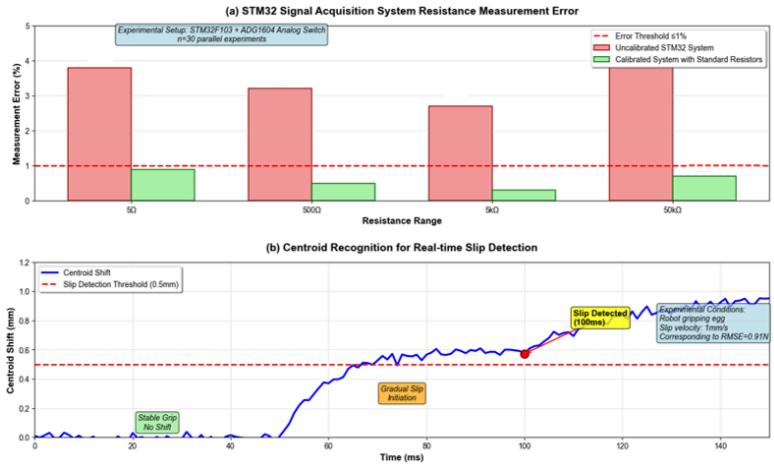

Figure 2. Force perception performance and biomimetic grasping validation of the flexible tactile sensor

3.2.2. Precise operation

The silk-screen printed resistive flexible tactile sensor designed by Anastasia et al. [14] has demonstrated significant contributions in surgical applications, primarily due to its adaptability to miniature surgical tools and its precise force sensing capability. This sensor is based on polyimide, combined with multi-walled carbon nanotubes (MWCNT), thermoplastic polyurethane (TPU) composite materials, and silicone microstructures. The overall thickness is only 110 ± 6 μm, featuring excellent flexibility and deformability. It can closely adhere to the surface of a magnetic micro-grasper with a diameter of only 4 mm, perfectly adapting to the narrow operating space of minimally invasive surgeries (such as the ventricular channel), without hindering the movement of the surgical tools and ensuring a good fit when in contact with tissues. This solves the problem of traditional rigid sensors being unable to be applied to miniature surgical tools due to their large size and poor adaptability. At the same time, its force sensing range is 0.04-1.3 N, precisely covering the key force intervals in surgeries, including the risk range of brain tissue damage (0.49-0.88 N) and the force range of 70% of surgical operations (0-0.3 N). Through a three-level linear sensitivity mode (S_1: 15.1±1.1 V/N, S_2: 3.79±0.17 V/N, S_3: 0.528±0.042 V/N), it can clearly distinguish ultra-small touches (such as tissue exploration), routine grasping, and relatively forceful operations, helping doctors precisely control the force and effectively reduce the risk of tissue trauma.

Furthermore, the sensor's real-time stable feedback capability, excellent flexibility and robustness, as well as its low cost and customizable features, further highlight its value in surgeries. The response time of this sensor is 70±51 ms, which is much lower than the threshold of 200 ms for the delay that surgeons can perceive during surgeries. It can capture the transient changes in the contact force between the tool and the tissue in real time, enabling surgeons to adjust their operations promptly. After 60 cycles of loading tests, the signal peak remained stable without attenuation, with a repeatability error of ≤9.53%. It can maintain stable performance during long surgeries and avoid judgment errors caused by signal drift. The flexibility test shows that it can bend along with the surface of the tool and adapt to the complex force feedback requirements during tissue contact. The crumble test verified its structural integrity, ensuring that it will not fall off from the surface of the micro-grasper during surgical operations. At the same time, the screen-printing process enables it to be customized with patterns to fit different surgical tools, and the material cost is low, making it suitable for one-time use to meet surgical hygiene requirements. This breakthrough

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overcomes the bottleneck of traditional high-precision sensors due to high costs and complex manufacturing, making it possible to be widely used in minimally invasive surgeries, providing reliable tactile feedback support, and significantly improving the safety and accuracy of surgeries.

3.2.3. Skid resistance

Kai et al. designed a flexible sensor through the physical structure design and performance optimization, providing dual support for the anti-slip function in the fine operation of the robotic hand [7]. On one hand, the sensor uses commercial anti-slip fabric with spherical silicone particles on its surface. This structure enables the particles to deform when the robotic hand grasps an object, increasing the contact area with the object's surface - when under pressure, the particle-contact state changes from point contact to surface contact, significantly enhancing the friction force. Especially for smooth objects, it can reduce the risk of slipping. At the same time, compared to the traditional triangular cone structure, the spherical particles are less likely to collapse under repeated pressure, providing stronger stability and ensuring the continuity of the anti-slip effect over a long period of grasping. On the other hand, the sensor's high sensitivity (0.40 kPa^{-1}) and wide working range (0-20 kPa) can monitor the tiny changes in the grasping pressure in real time. Combined with a 20 ms fast response time, it can promptly capture the force fluctuation signals before the object slips. Based on this feedback, the robotic hand control system can dynamically adjust the grasping force, avoiding slipping due to insufficient pressure or damage to the object caused by excessive pressure, forming a collaborative mechanism of "physical anti-slip + dynamic force control anti-slip", which is suitable for fine work requirements [15].

4. Discussion

In terms of performance optimization (Figure 3), through structural design and material matching, PDMS film was selected as the flexible substrate and combined with silver nanowires to form a composite structure. This successfully achieved synchronous sensing of pressure and temperature. At the same time, insulation isolation designs such as polytetrafluoroethylene encapsulation and setting of insulating pads were adopted, effectively reducing signal crosstalk between units. The signal acquisition system was designed based on the STM32 microcontroller, combining a circuit of step-down voltage division and constant current source, and using an ADG1604 analog switch to achieve point-by-point selection of a 4×4 array. Moreover, through DMA transmission technology and the row-column scanning method, the data transmission efficiency and anti-interference ability were improved. In the multi-physical quantity decoupling algorithm, after converting pressure and temperature signals into grayscale images, combined with the iterative threshold segmentation algorithm and centroid recognition algorithm, the object sliding can be detected within a short time. At the same time, the difference in resistance change can be used to distinguish pressure and temperature signals, improving the accuracy of multi-physical quantity perception. System verification shows that the hardware measurement error is low, the software can realize three-dimensional visualization of pressure distribution, and it performs well in the robot electronic skin scenario, demonstrating excellent flexibility and stability.

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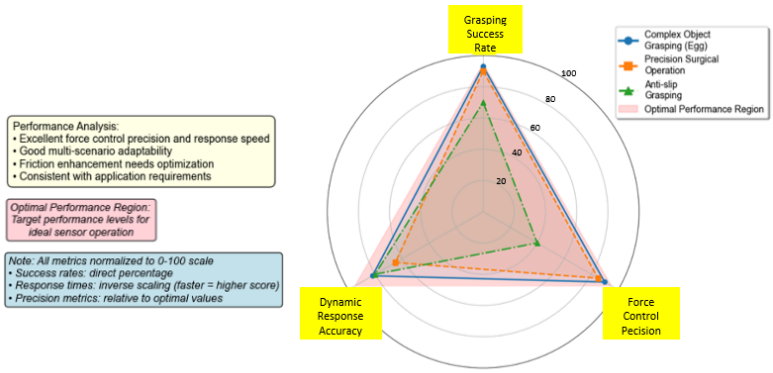

Figure 3. Multi-dimensional performance radar chart: Flexible tactile sensor across three application scenarios

In terms of application value, this sensor can stably control the contact force within the safe threshold during the grasping of complex objects, enabling non-destructive grasping of fragile and smooth objects such as eggs. It can also capture the transient changes in force during slipping to prevent falling. In fine operations, sensors with similar designs can be adapted to microsurgical tools, covering the key force range of the surgery, helping to enhance the safety and accuracy of minimally invasive surgeries. In terms of anti-slip treatment, commercial anti-slip fabric with hemispherical silicone particles can increase friction. Combined with the high sensitivity and fast response time of the sensor, it can effectively reduce the risk of slipping on smooth objects and is suitable for various complex scenarios.

5. Conclusion

This study confirms the feasibility of an array piezoresistive tactile sensor for multi-physical collaborative perception. Its "structure-circuit-algorithm" design offers a scalable paradigm for e-skin in robotics and intelligent detection. PDMS-silver nanowire films enable synchronous pressure-temperature sensing with insulation to reduce crosstalk. The STM32-based acquisition system uses ADG1604 analog switches, DMA, and row-column scanning for efficient, low-noise 4×4 array readout. Decoupling via image processing and resistive differences allows 100ms sliding detection. System integration yields low error and real-time pressure visualization, supporting complex grasping and anti-slip tasks. Limitations include environmental adaptability. High temperature, corrosion, or EMI may degrade materials or accuracy; soft/sticky objects may distort signals. Anti-slip structures offer limited friction gains. Future work will tailor materials and microstructures for extreme conditions and soft surfaces, benchmarking signal fidelity. Integrating tactile, visual, and proprioceptive data via deep learning will enable a closed-loop, self-regulating robotic grip with autonomous force and angle control.

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