New Software Bionic Haptic Actuator Design Based on Barometric Array

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Abstract. To address the limitations of single-point tactile perception in soft biomimetic actuators, such as fixed positioning, limited coverage area, low resolution at long distances from the geometric center, and challenges in maintaining high sensitivity and stability over a broad range, a novel soft biomimetic tactile actuator based on a pneumatic array is designed and manufactured. Using liquid silicone rubber and BMP280 pressure sensor, the actuator was crafted by an injection molding process. Silicone gel was injected into the pressure sensor array, and vacuum extraction created a sealed space within the sensor cavity. The pressure excitation applied on the surface of the actuator could be converted into electrical signals, enabling tactile pressure detection. An STM32 microprocessor is utilized for building haptic information acquisition and processing system, with sensitivity assessed using the Kalman filter algorithm. Experimental results show that the soft biomimetic tactile actuator has high sensitivity and minimal repetition error, which can effectively detects changes in tactile force output, mitigates noise interference, and enhances the precision and stability of physiological pressure data feedback in physiotherapy applications.

Keywords: Pressure sensor array · Kalman filtering · Haptic sensing · Soft bionic actuator

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1 Introduction

Due to its high flexibility, good compliance, excellent adaptability and natural safety interactivity [1–3], soft bionic robots have broad application prospects in intelligent medical [4], health monitoring [5] and human-computer interaction [6]. With the rapid development of machine vision [7] and artificial intelligence [8], solving the accurate and rapid perception of the external environment of soft bionic robots has become the core bottleneck of realizing intelligence [9–11].

Different from visual perception information, tactile perception technology has unique advantages in dynamic characterization of target object features and description of physical characteristics such as stiffness and surface texture of object in non-structural environment [12–14]. Many researchers have explored and studied the haptics of soft biomimetic robots. Matteo Bianchi [15] proposed a simple touch-based method based on Pisa/IIT SoftHand, in which the finger tip is equipped with an inertial measurement unit sensor as a tactile sensing device. By detecting the acceleration resulting from external object contact, object manipulation is achieved, with limited system accuracy. In order to improve the accuracy of tactile recognition, researchers often increase the number of tactile sensor array points or improve the sensor resolution. Zhang [16] designed a magnetostrictive tactile sensor array for measuring pressure, which breaks through the limitation of collecting information from a single contact of the magnetostrictive sensor and increases the detection area of the tactile sensor. The magnetostrictive sensor array is large in size due to structural limitations, and the freedom and mobility of soft robot applications are limited.

Based on this, this paper selects liquid silicone rubber and BMP280 barometer chip as materials, and uses vacuum pumping method to pour barometer chip [17–19] with silica gel to make a pressure array software bionic tactile actuator. The actuator has high sensitivity at a low cost, and by arranging and combining multiple sensing units, it creates an effective sensing region of a specific area, mitigating the limitations of single point contact. In addition, a haptic information acquisition system is designed with discrete Kalman filter algorithm to filter and preprocess the tactile information of pneumatic sensing to obtain smooth and stable tactile data information.

2 Structure Design and Production

In order to enable the robot to accurately obtain tactile information data during work through the actuator and make correct behavioral feedback after accurate analysis of the tactile information data, a soft bionic tactile actuator based on the air pressure array is designed. It is jointly made by cheap air pressure sensor array and silicone software, with better structural flexibility and high safety. The manufacture and maintenance of the actuator is also very simple and the cost is low.

2.1 Physical Design

Pressure Sensor Array. The air pressure sensor array consists of four BMP280 air pressure sensors, and the number of sensors can then be changed according to the application scenario to achieve effective tactile information acquisition in different areas. The BMP280 consists of a MEMS diaphragm with Wheatstone bridge, an instrument amplifier, a temperature sensor, a multiplexed circuit, a digital-to-analog converter and an I2C bus, and its components are very compact and small in package to meet the needs of space-constrained portable electronic devices. In addition, the BMP280 adopts a piezoresistive sensor technology with high precision, high linearity and long-term stability, and supports two interface types I2C and SPI, with a maximum rate of 3.4MHz in I2C mode. In this design, I2C interface mode is used. In the I2C interface mode, the SCK pin is connected to the clock signal line SCL of the master chip, and the SDI is connected to the data line SDA. When multiple BMP280 devices are used at the same time, the SDO pin can distinguish different slave devices under different level states. The technical parameters of the BMP280 pressure sensor are shown in Table 1.

Table 1. Technical parameters of BMP280 air pressure sensor

Parameter name	Parameter values
Working range	300-1100HPa
Operating temperature range	-40 °C-85 °C
Relative precision	±0.12HPa
absolute precision	±1HPa
Working supply current	2.8μA
Response time	5.5 ms

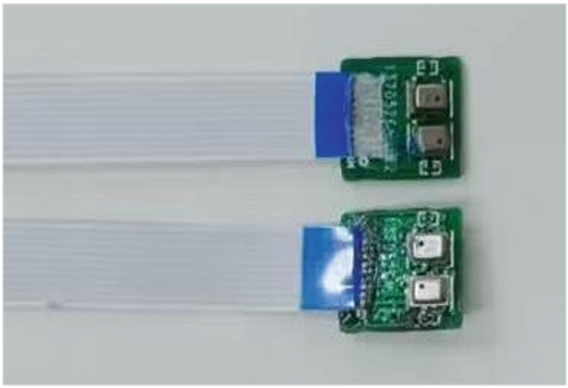


Fig. 1. BMP280 barometer

The size of the packaged barometer is only 2×2.5×0.95 mm, and the surface is distributed with air holes for collecting pressure values. The array obtained after assembling four pressure sensors is shown in Fig. 1.

Design Method of Soft Biomimetic Tactile Actuator. According to the structural principle of the sensor, a kind of soft biomimetic tactile actuator modeled on human skin is designed. The actuator consists of two parts: a pressure sensor array and a silicone software. The silicone software wraps the pressure sensor array in it, and the silicone software can ensure the actuator's safe and flexible contact with the outside world. The actuator can not only realize more accurate tactile information perception in structured environment, but also realize more sensitive tactile information acquisition in unstructured environment, as shown in Fig. 2.

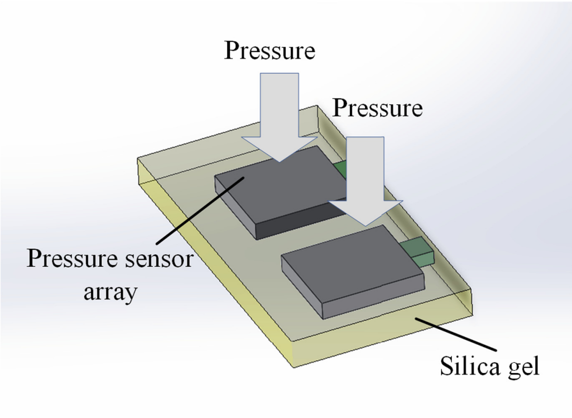
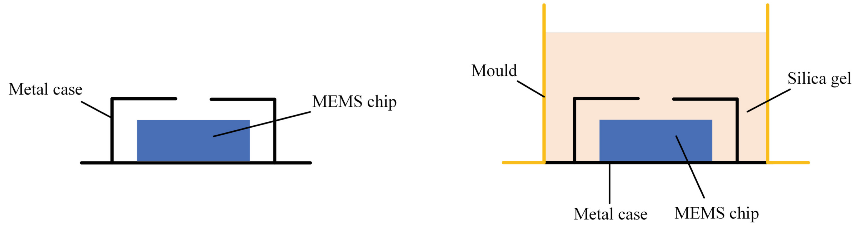


Fig. 2. Software bionic tactile actuator model

The working principle of the soft bionic tactile actuator is based on the gap between the MEMS barometer chip of the air pressure sensor BMP280 and the metal housing, and the air pressure value of the outside air can be sensed through the vent, but the pressure in the form of touch cannot be sensed. To this end, the method of silicone sensor array is adopted, and the air left in the cavity after pouring is extracted by vacuum pumping, so that the sensor cavity forms a closed space, and when the tactile pressure is applied on the surface of the silicone software, it can be transmitted to the MEMS chip, and finally the tactile pressure detection is completed. The sensor array and the silicone software as a whole constitute a tactile actuator. When pressure is applied to the surface of the silicone software, the pressure will be transmitted to the air pressure sensor of the tactile actuator in real time, and the tactile sensing function can be realized, as shown in Fig. 3.



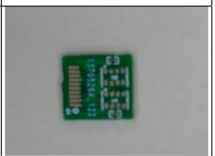
(a) Before the silicone is poured (b) After the silicone is poured

Fig. 3. Section view of BMP280 before and after pouring silicone

2.2 Manufacture Method

Preparation of Materials and Equipment. The preparation of the soft bionic tactile actuator requires materials such as air pressure sensor and silica gel. Vacuum pumping is completed by vacuum pump and heat gun is used to accelerate the forming. The specific materials and equipment for preparation are shown in Table 2.

Table 2. Materials and equipment for the preparation of pneumatic sensors

Name	Type	Sketch map
Air pressure sensor	BMP280	
Silica gel	Food grade silicone	
Vacuum pump	RS-4	
Heat gun	Deer Fairy 858D+ series	

Preparation Method. Considering the size of the air pressure sensor array, four BMP280 air pressure sensors are tightly designed on the front of the integrated board, and then the air pressure sensor array on the integrated board is poured silica gel. The method of injection molding is adopted for silicone pouring, which has the advantages of convenient operation and high efficiency. It is widely used in the preparation technology of soft robot. Medical A and B silica gel with strength of 5 were selected as the main raw materials. The a and b silicone is first mixed in a 1:1 ratio and stirred for 3 to 5 min to fully fuse, then the vacuum pump is used to eliminate the bubbles for the first time, and the defoamed ab silicone is poured on the pressure sensor array. Then the whole thing is put into the vacuum pump again for secondary bubble elimination. Finally, heat with a heat gun to solidify, as shown in Fig. 4.

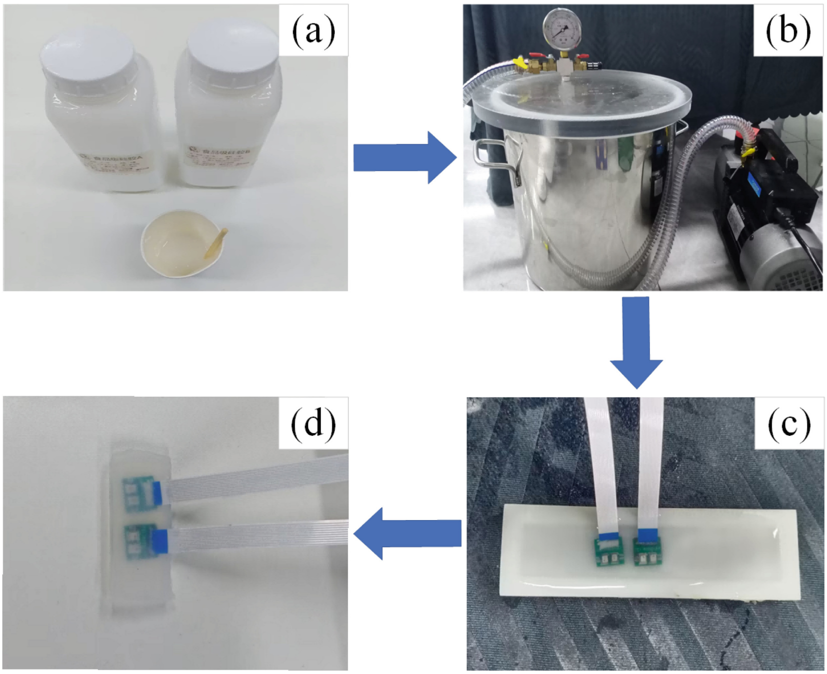


Fig. 4. Manufacturing and preparation process

After the silicone is cured, a layer of silicone software is formed right above the pressure sensor array. By pressing the surface silicone software, the pressure can be transmitted to the barometer, thus completing the detection of tactile information. After trimming it and installing the terminal interface, the soft bionic tactile actuator can be obtained, as shown in Fig. 5.

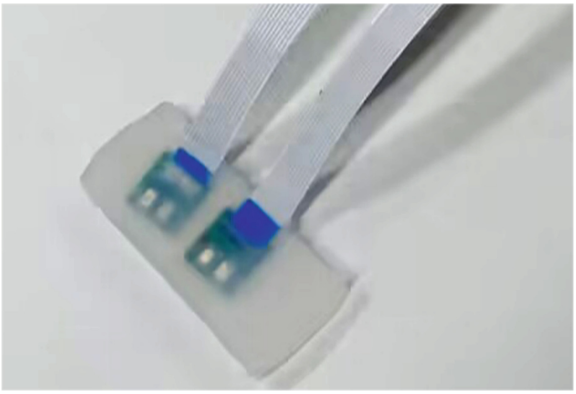


Fig. 5. Soft biomimetic tactile actuator

3 Tactile Information Acquisition System

This section mainly describes the haptic information acquisition system based on Kalman filter to obtain the initial haptic information by using the haptic actuator, and to process the collected data through the Kalman filter algorithm to improve the accuracy and stability of haptic information.

3.1 System Work Plan Design

The haptic information acquisition system adopts a distributed architecture design scheme, and the overall structure is shown in Fig. 6. The system is mainly composed of tactile actuator module, controller module and data display module. The tactile actuator module communicates with the controller module through I2C bus, and synchronously transmits the initial tactile information collected to STM32 MCU. The host computer communicates with STM32 microcontroller through communication converter, and uses Kalman filter method to reduce the noise of the received original sensor data.

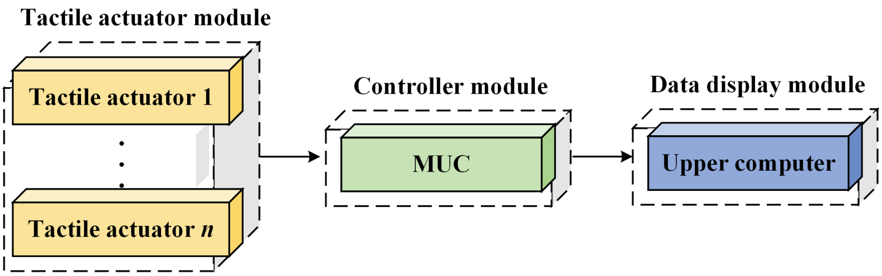


Fig. 6. System overall structure diagram

3.2 Tactile Data Processing Method Based on Kalman Filter

The initial tactile information collected by the pneumatic tactile actuator is affected by the interference caused by environmental noise and the instability in the sensor, resulting in a certain degree of abnormal data, which then affects the accuracy and accuracy of the pneumatic sensor. At present, the widely used filtering algorithms are Kalman filter, particle filter and Gaussian filter. Among them, the Kalman filter algorithm can predict the current state value of the system according to the observed value of the system at the previous time by introducing the equation of state, which can effectively reduce the influence of unstable factors such as noise in the sensing system on the output accuracy of the sensor, and obtain smooth sensor data information [20]. Since the process of collecting tactile data by pneumatic tactile actuator can be regarded as a discrete state system, the discrete Kalman filtering algorithm to filter the collected tactile data information to improve the collecting accuracy.

The discrete Kalman filter can calculate the current time estimate $\hat{X}_{k-1}$ from the previous time state estimate $\hat{X}_k^-$, where A and B are matrix coefficients, $U(k)$ is the control quantity of the measurement model, and its basic state prediction equation is

$$\hat{X}_k^- = A\hat{X}_{k-1} + BU_k \tag{1}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{2}$$

where P_k^- is the system state covariance matrix of priori estimate A, A^T is transposed matrix of A, Q is the system noise covariance matrix, the P_k^- is X_k^- covariance, P_{k-1} is X_{k-1} covariance.

The measurement equation obtained by modifying the prior estimates is

$$K_k = \frac{P_k^- C^T}{CP_k^- C^T + R} \tag{3}$$

$$\hat{X}_k = \hat{X}_k^- + K_k(y_k - C\hat{X}_k^-) \tag{4}$$

$$P_k = (I - K_k\mathbf{C})P_k^- \tag{5}$$

where P_k is the covariance matrix of the system; R is the covariance matrix of measurement noise; K_k is the Kalman gain coefficient matrix; C is the observation model matrix; y_k is the measured value at time k.

For the software bionic tactile actuator designed in this paper, its function is to collect and process tactile information through the actuator, without considering other state variables such as speed or position, and there is only a single model measurement of the pressure sensor. Then Eqs. (1) and (2) can be simplified as follows:

$$\hat{X}_k^- = \hat{X}_{k-1} \tag{6}$$

$$P_k^- = P_{k-1} + Q \tag{7}$$

Substituting Eqs. (6) and (7) into Eqs. (3), (4) and (5) for simplification can be obtained

$$K_k = \frac{P_k^-}{P_k^- + R} \tag{8}$$

$$\hat{X}_k = \hat{X}_k^- + K_k(y_k - \hat{X}_k^-) \tag{9}$$

$$P_k = (I - K_k)P_k^- \tag{10}$$

According to formula (8), (9) and (10), the noise filtering of the data information collected by the tactile actuator can be completed.

4 Experiment and Data Analysis

The sensitivity of tactile information feedback plays an important role in the application of soft biomimetic tactile actuators, which determines the ability and accuracy of the actuators to perceive external stimuli. Tactile actuators with high sensitivity can more accurately simulate human tactile perception, thus playing a key role in several fields such as robot operation, medical device use and virtual reality technology improvement.

In order to evaluate the tactile information feedback sensitivity of the soft biomimetic tactile actuator after silicone pouring, we conducted a tactile sensitivity detection experiment. Based on the tactile perception principle of the soft bionic tactile actuator, the pressure feedback data measured before and after silicone pouring were compared, and the tactile feedback sensitivity after silicone pouring was tested, select the same position to press the tactile actuator point by point, and use the Kalman filter algorithm to reduce the noise of the data. The pressure information data before the silicone pouring was recorded in real time, and the corresponding curve was drawn according to the data. The sensitivity and response of the tactile actuator to the pressing force before the silicone pouring could be observed, as shown in Fig. 7. Similarly, the tactile sensitivity test after silicone pouring was carried out, and the tactile information data was drawn as a graph, as shown in Fig. 8.

According to the analysis of the tactile information data curve, it can be seen that the tactile information data measured by the actuator under the same sampling number is similar to the pressure information data before the pouring, and the soft biomimetic tactile actuator after the silicone pouring still has a good tactile sensitivity. After Kalman filtering, with the increase of filtering times, the influence of the set initial filter value on the filtering model gradually decreases until it disappears. Finally, the filtered tactile information data of the actuator gradually tends to be smooth and stable, which reduces the interference of noise on the real data collected and ensures the effectiveness of the tactile information collected by the actuator during operation. The experiment verifies

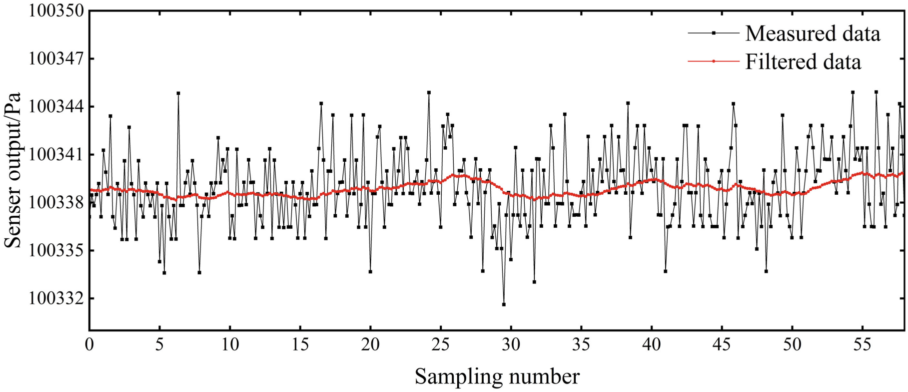


Fig. 7. Sensor output data before silicone pouring

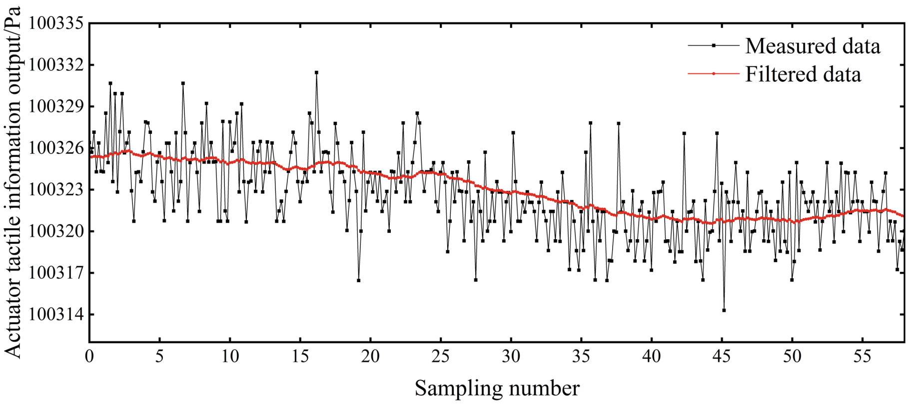


Fig. 8. Tactile information data of actuators after silicone pouring

the sensitivity and data validity of the soft bionic tactile actuator, which can better reflect the ability of simulating human tactile perception and meet the needs of the robot for external tactile perception.

5 Conclusions

In this paper, a soft biomimetic tactile actuator based on air pressure array is designed and made. The actuator is made by using silica gel to cast sensor array, which can mimic human skin to realize tactile sensing function. Experiments show that the tactile information changes can be accurately detected when the pressure is applied at different positions within the effective sensing range of the actuator after effective Kalman filtering. The software bionic tactile actuator designed in this paper can change the shape of the actuator according to the application function requirements, optimize the number and volume of sensor arrays, and provide a new idea for using software actuators for fine planning operations and human-computer interaction tasks in different situations in the future.

References

1. Lin, D., Yang, F., Gong, D., et al.: Bio-inspired magnetic-driven folded diaphragm for biomimetic robot. Nat. Commun. **14**(1), 163 (2023)
2. Yin, C., Wei, F., Fu, S., et al.: Visible light-driven jellyfish-like miniature swimming soft robot. ACS Appl. Mater. Interfaces **13**(39), 147–154 (2021)
3. Wang, F., Wang, L., Shen, F., et al.: High-performance nano-biocomposite ionic soft actuators based on microfibrillated cellulose/ionic liquid electrolyte membrane. Polym. Compos. **44**(2), 963–970 (2023)
4. Lee, H., Kim, S., Yeo, K., et al.: Fully portable continuous real-time auscultation with a soft wearable stethoscope designed for automated disease diagnosis. Sci. Adv. **8**(21), eabo5867 (2022)
5. Wang, C., Wu, Y., Dong, X., et al.: In situ sensing physiological properties of biological tissues using wireless miniature soft robots. Sci. Adv. **9**(23), eadg3988 (2023)
6. Yeon, H., Lee, H., Kim, Y., et al.: Long-term reliable physical health monitoring by sweat pore-inspired perforated electronic skins. Sci. Adv. **7**(27), eabg8459 (2021)
7. Wang, S., Sun, Z.: Hydrogel and machine learning for soft robots' sensing and signal processing: a review. J. Bionic Eng. **20**(3), 845–857 (2023)
8. Wan, X., Huang, Z., Li, Y., et al.: Distributed pneumatic physiotherapy robot for human acupoints. In: 2023 IEEE 12th Data Driven Control and Learning Systems Conference, pp. 429–433. Xiangtan, China (2023)
9. Sun, Z., Zhu, M., Zhang, Z., et al.: Smart soft robotic manipulator for artificial intelligence of things (AIOT) based unmanned shop applications. In: 2021 IEEE 34th International Conference on Micro Electro Mechanical Systems, Gainesville, FL, USA, pp. 591-594 (2021)
10. Bai, H., Kim, Y., Shepherd, R.: Autonomous self-healing optical sensors for damage intelligent soft-bodied systems. Sci. Adv. **8**(49), eabq2104 (2022)
11. Hu, D., Giorgio-Serchi, F., Zhang, S., et al.: Stretchable e-skin and transformer enable high-resolution morphological reconstruction for soft robots. Nat. Mach. Intell. **5**(3), 261–272 (2023)
12. Yao, K., Zhou, J., Huang, Q., et al.: Encoding of tactile information in hand via skin-integrated wireless haptic interface. Nat. Mach. Intell. **4**(10), 893–903 (2022)
13. Siles, E.L.: Soft law for unbiased and nondiscriminatory artificial intelligence. IEEE Technol. Soc. Mag. **40**(4), 77–86 (2021)
14. Wang, X., Chen, C., Zhu, L., et al.: Vertically integrated spiking cone photoreceptor arrays for color perception. Nat. Commun. **14**(1), 34–44 (2023)
15. Bianchi, M., Averta, G., Battaglia, E., et al.: Touch-based grasp primitives for soft hands: applications to human-to-robot handover tasks and beyond. In: 2018 IEEE International Conference on Robotics and Automation , Brisbane, QLD, Australia, pp. 7794-7801 (2018)
16. Zhang, B., Wang, B., Li, Y., et al.: Magnetostrictive tactile sensor array for object recognition. IEEE Trans. Magn. **55**(7), 1–7 (2019)
17. Huang, Z., Li, X., Wang, J., et al.: Human pulse detection by a soft tactile actuator. Sensors **22**, 5047 (2022)

18. Li, S., Wang, J., Li, X., et al.: Information express of soft bionic finger based on visual recognition. In: 2022 IEEE International Conference on Cyborg and Bionic Systems (CBS), Wuhan, China, pp. 240-244 (2023)
19. Wang, S., Dong, X., Liu, G., et al.: Low-cost single-frequency DGNSS/DBA combined positioning research and performance evaluation. Remote Sens. **14**(3), 586 (2022)
20. Liu, H., Hu, F., Su, J., et al.: Comparisons on Kalman-filter based dynamic state estimation algorithms of power systems. IEEE Access **8**, 51035–51043 (2020)