

A Data-Driven High-Sensitivity Biomimetic Whisker Sensor

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Abstract

Highly sensitive, multidirectional, and real-time tactile interfaces are essential for enabling robots to acquire complex contact information during safe interaction, autonomous exploration, and dexterous manipulation. However, existing biomimetic whisker sensors struggle to simultaneously achieve millinewton-level force sensitivity, high directional resolution, and compact structural integration. Here, we present a capacitive-based high-sensitivity whisker sensor (HSWS). Inspired by rodent tactile perception, the HSWS integrates an interdigitated electrode structure with a cross-shaped flexible beam to amplify capacitive responses under weak mechanical stimuli. Furthermore, a machine learning-assisted compensation strategy is introduced to address creep-induced capacitance variations, enabling accurate prediction of contact force magnitude and loading direction despite signal drift. Experimental results demonstrate that the HSWS achieves a 6 mN-level minimum detectable force, a 5° directional resolution, and excellent cyclic stability. The HSWS further demonstrates texture recognition, mobile robot teleoperation, and autonomous exploration, providing a structurally simple, highly integrable, and learning-compensated platform for close-range robotic perception.

1. Introduction

In recent years, rapid development of robotics and intelligent systems have promoted their widespread applications in industrial manufacturing, intelligent services, medical assistance, and exploration of complex environments [1, 2]. These emerging applications place stringent demands on reliable tactile perception interfaces for human-machine-environment interaction [3]. As fundamental components for physical interaction, tactile sensors convert external stimuli such as contact, pressure, sliding and surface textures into measurable electrical signals [4–7]. Compared with non-contact sensing approaches (e.g. vision, radar and ultrasonic), biomimetic whisker sensors exhibit unique advantages in acquiring near-field contact dynamics. Through flexible whisker structures, they operate reliably under challenging conditions, such as low-light environments, optical occlusions, and confined unstructured spaces [8, 9]. Inspired by the biological tactile perception mechanism of mammalian whiskers, those bio-inspired sensors inherently combine mechanical compliance, physical interaction safety, compact integration, and multidirectional perception. By translating whisker deflection into detailed physical metrics, they efficiently capture contact obstacle distributions, and surface topographies, these sensors effectively capture physical contact forces, obstacle distributions, and surface topographies. Consequently, biomimetic whisker sensors have drawn substantial interest for robotic environmental perception[10], obstacle detection [18], texture recognition [11], terrain identification[12], and human-robot interaction (HRI). However, practical deployment in unconstrained interactive scenarios remains hindered by fundamental trade-offs. Existing designs often struggle to simultaneously balance weak-force detection sensitivity[13, 14], high-resolution directional perception[15], compact system integration, and real-time signal decoding.

To tackle these limitations, various biomimetic whisker architectures and sensing mechanisms have been developed. To enhance directional sensitivity, state-of-the-art designs frequently utilize multi-

electrode arrays, distributed sensing units, or complex mechanical decoupling structures to acquire comprehensive force vectors through increased spatial sampling points [16–18]. Although effective in augmenting directional resolution, these multi-channel strategies inevitably increase architectural complexity, expand signal-processing overhead, and complicate hardware integration. For resource-constrained platforms—such as miniaturized robots, mobile platforms, and compact HRI interfaces—there is a compelling demand for tactile sensors that simultaneously achieve high force sensitivity, fine directional perception, signal stability, and high integration density. Consequently, realizing weak contact force detection, multidirectional perception, and real-time decoding using minimal sensing channels within a streamlined structural architecture remains a critical yet unresolved challenge in biomimetic tactile sensing.

Across diverse transduction mechanisms, biomimetic whisker sensors based on piezoresistive [19–21], piezoelectric [22], triboelectric [23, 24], magnetic [25, 26], and liquid metal-based [27] technologies have been extensively investigated. However, each approach exhibits inherent limitations. Piezoresistive devices feature simple structures and facile integration, but their sensing performance can be constrained by material stability and long-term reliability [19–21]. Piezoelectric and triboelectric sensors exhibit high sensitivity to dynamic mechanical stimuli, whereas their native electrical outputs are generally more dependent on time-varying deformation and contact–separation processes, which can complicate continuous quasi-static force measurement [22–24]. Magnetic sensing-based devices offer excellent directional perception capability, but their implementation generally requires magnetic functional materials or components, together with dedicated magnetic-field sensing and signal-processing architectures [25, 26]. Liquid metal-based sensors offer outstanding mechanical flexibility and electrical conductivity, but their practical implementation requires careful management of encapsulation, interfacial integrity, and environmental stability, particularly under large deformation or harsh operating conditions [27]. In contrast, capacitive sensing can effectively transduce mechanical deformation induced by whisker deflection into electrical signals through variations in electrode spacing and effective capacitive coupling area [29–31]. Capacitive sensors offer several advantages, including low power consumption, simple device architectures, stable signal output, and suitability for static and quasi-static force detection [28–32]. Nevertheless, capacitive whisker sensors still face critical challenges in achieving high-performance tactile perception. Under weak mechanical stimuli, the variations in electrode spacing and effective coupling area are typically insufficient, resulting in limited capacitance variation amplitudes. Furthermore, flexible membranes inevitably exhibit creep and hysteresis behaviors during prolonged loading and cyclic deformation, leading to baseline drift and nonlinear deviations in capacitive signals, thereby degrading directional recognition and force estimation accuracy.

To address these challenges, we propose a data-driven, high-sensitivity capacitive biomimetic whisker sensor. The proposed sensor integrates an interdigitated electrode structure with a cross-shaped flexible beam architecture, converting subtle whisker deflections into four-channel, direction-dependent differential capacitance signals. Specifically, the interdigitated electrode configuration enhances capacitance variations caused by micro-deformations, while the cross-shaped flexible beam structure

amplifies membrane deformation induced by the bending moment at the whisker base. Meanwhile, the symmetric four-channel layout captures multidimensional spatial responses necessary for accurate force-direction perception. Furthermore, to eliminate creep-induced baseline drift, a multilayer perceptron (MLP)-based multitask learning model is developed to extract and interpret multichannel capacitive features, enabling simultaneous estimation of contact force magnitude and loading direction. This work delivers a structurally streamlined, highly integrable, and learning-compensated platform for high-sensitivity, multidirectional tactile perception in complex human-machine-environment interaction.

2. Results and Discussion

2.1 Structural Design and Working Mechanism of the HSWS

The structural design of the high-sensitivity whisker sensor (HSWS) was inspired by the tactile perception mechanism of mammalian whiskers and was developed to emulate the transmission, amplification, and signal transduction of external mechanical stimuli in the natural whisker-follicle system. As representative tactile organs in mammals, whiskers play an essential role in spatial localization and obstacle detection under low-light environments, optical occlusions, and confined unstructured spaces. Unlike non-contact sensing approaches such as vision, whiskers acquire near-field contact information through direct physical contact with surrounding objects or by responding to subtle airflow disturbances. Such tactile information includes local surface topography, contact direction, and stimulus intensity. As illustrated in Fig. 1a, the base of a natural whisker is embedded within a follicle. When an external mechanical stimulus causes whisker deflection, a bending moment is generated at the whisker base, resulting in localized stress concentration. Mechanoreceptors distributed within the follicle subsequently transduce these mechanical variations into bioelectrical signals, thereby enabling highly sensitive tactile perception. Inspired by the mechanical transmission and sensory transduction mechanisms of the natural whisker-follicle system, the HSWS couples a boar-bristle whisker with a cross-shaped flexible beam structure. This configuration converts weak external contact stimuli into distinguishable four-channel, direction-dependent differential capacitance signals, thereby enabling simultaneous perception of the loading direction and contact force magnitude.

As illustrated in Fig. 1b, the HSWS mainly consists of a whisker, upper and lower housings, a stationary upper electrode, a cross-shaped flexible lower electrode structure, and silicone oil. The whisker, fabricated from a boar bristle, serves as the primary sensing element for capturing external contact stimuli. It passes through the central aperture of the upper housing and is bonded to the central region of the cross-shaped thermoplastic polyurethane (TPU) membrane, forming a movable whisker base (WMB) that enables mechanical deflection under external loading. The upper electrode is fixed within the cross-shaped groove of the upper housing, while the lower interdigitated electrode is patterned on the surface of the deformable cross-shaped TPU membrane, which is mechanically anchored within the lower housing. The upper and lower housings provide structural support and maintain the stable assembly of

the sensing device. Silicone oil functions as both a dielectric medium between the electrodes and a damping medium within the sensing structure. On one hand, it increases the effective dielectric constant between the electrodes, thereby amplifying the capacitive response. On the other hand, it suppresses mechanical oscillations during the elastic recovery of the TPU membrane, contributing to improved signal stability and measurement reliability.

When an external lateral force is applied to the whisker, the mechanical stimulus is transmitted along the whisker toward its base, generating a bending moment at the whisker root (Fig. 1c). The induced bending moment drives the deformation of the cross-shaped TPU membrane, resulting in the displacement of the lower interdigitated electrode. Since the upper electrode remains stationary while the lower electrode follows the deformation of the flexible membrane, variations in the local interelectrode spacing and effective capacitive coupling area occur, leading to differential capacitance responses among the four sensing channels. Different loading directions generate distinct capacitance variation patterns across the four channels (Fig. 1d), providing multidimensional spatial responses necessary for accurate force-direction perception.

To further elucidate the mechanical–electrical transduction mechanism of the HSWS, the external lateral force (F) applied to the whisker can be simplified as a bending moment (M) exerted at the whisker root:

$$M = Fd$$

where M represents the bending moment generated at the whisker root and d denotes the effective height of the whisker. The induced bending moment further drives the deformation of the cross-shaped TPU membrane, causing the lower electrode to displace relative to the stationary upper electrode. Accordingly, the capacitance of the i -th sensing channel can be approximately expressed as:

$$C_i = \frac{\varepsilon_0 \varepsilon_r A_{\text{eff},i}}{d_i} \quad (i=1,2,3,4)$$

Where ε_0 represents the vacuum permittivity, ε_r denotes the relative dielectric constant of the medium between the electrodes, $A_{\text{eff},i}$ represents the effective capacitive coupling area of the i -th channel, and d_i is the local interelectrode spacing between the upper and lower electrodes of the corresponding channel. Therefore, the deformation of the flexible membrane induced by whisker loading alters both $A_{\text{eff},i}$ and d_i , resulting in four-channel, direction-dependent differential capacitance signals. Detailed derivations of the electromechanical model are provided in Note S1.

As shown in Fig. 1e, the minimum detectable force and angular resolution of the HSWS were benchmarked against previously reported whisker sensors. Benefiting from the optimized four-channel capacitive architecture and cross-shaped flexible beam structure, the HSWS achieves a minimum detectable force of 0.006 N and an angular resolution of 5°, highlighting its high force sensitivity and high directional resolution within a streamlined structural architecture.

The sensing electrodes of the HSWS was fabricated through a screen-printing process, as illustrated in Fig. S1, and the detailed fabrication procedure is described in the Experimental Section. Antioxidants, polymer dispersants, and synthetic resins were incorporated into the silver paste and uniformly mixed to obtain a stretchable conductive silver paste. To improve the interfacial adhesion between conductive silver paste and the TPU substrate, epoxy resin was incorporated into the conductive paste as an adhesion-enhancing additive.

The morphology of the fabricated interdigitated electrode was characterized by scanning electron microscopy (SEM), as shown in Fig. S2. The surface morphology of the conductive silver electrode exhibits a sheet-like sintered structure, and similar stacked-flake features can also be observed in the cross-sectional morphology obtained by liquid-nitrogen-assisted brittle fracture. The thickness of the printed electrode layer is approximately 250 μm . The sensing electrodes were symmetrically distributed in four directions around the whisker axis to enable multidirectional tactile perception. The width and spacing of the interdigitated electrodes are both 0.4 mm. Due to the fluidity of the conductive silver paste, slight lateral spreading occurs before the curing process, resulting in an actual printed electrode line width slightly larger than the designed dimension.

2.2 Output Performance and Sensing Characteristics of the HSWS

To elucidate the mechanical force-transmission process of the HSWS under external contact stimuli and investigate the influence of key structural parameters on the sensing response, a three-dimensional finite element model of the HSWS was established using COMSOL Multiphysics. The coupled deformation behavior of the whisker, flexible substrate, and electrode structures was systematically analyzed. The whisker was modeled using the mechanical properties of boar bristles, with an effective height (d) of 26 mm and a radius of 1.5 mm. The flexible substrate was constructed as a cross-shaped flexible TPU membrane with a thickness of 0.1 mm, a single-arm length of 17.3 mm, and a beam width of 5 mm. The initial gap between the upper and lower electrodes (d_1) was set to 1 mm. The bottom end of the whisker was defined as a bonded connection with the central region of the cross-shaped TPU membrane to replicate the adhesive fixation in the fabricated device. The outer ends of the cross-shaped beams were mechanically fixed within the slots of the lower housing, and fixed boundary constraints were applied to these regions in the simulation. The upper electrode was fixed within the cross-shaped groove of the upper housing and served as a stationary reference electrode. An external lateral force (F) was applied horizontally at the whisker tip to simulate the lateral contact Figure 2. Finite element analysis of force transmission and structural optimization of the HSWS. (a) Average stress variation on the TPU membrane surface under different applied loads (50, 150, and 300 mN). (b) Average displacement response of the interdigitated electrodes under different applied loads (50, 150, and 300 mN). (c) Influence of whisker geometrical parameters on stress transfer. (d) Influence of whisker geometrical parameters on electrode displacement response. (e) Relationship between the applied load and electrode displacement.

stimulus experienced during practical sensing processes. Since both the whisker and flexible TPU membrane undergo relatively large deformations during mechanical loading, geometric nonlinearity was enabled in the finite element analysis to improve the accuracy and reliability of the simulation results.

The capacitive response of the HSWS is governed by the mechanically induced deformation of the sensing structure. Upon application of an external lateral force at the whisker tip, the generated bending moment is transmitted to the central flexible substrate, inducing deformation of the cross-shaped TPU membrane. The deformation-induced displacement of the lower interdigitated electrode relative to the stationary upper electrode alters the local electrode spacing and effective capacitive coupling area, resulting in measurable capacitance variations. Consequently, the electrode displacement response serves as the key mechanical link between external contact stimuli and capacitive signal generation.

First, the mechanical force-transmission behavior of the HSWS under external loading was analyzed. Although the maximum stress is typically concentrated around constrained boundaries and reflects local stress accumulation, it is insufficient to represent the overall deformation state of the flexible membrane. Therefore, the average membrane stress was adopted as a quantitative indicator to evaluate the overall stress-transfer behavior of the whisker structure. As shown in Fig. 2a, as the applied load increased from 50 to 150 and 300 mN, the average stress on the TPU membrane surface gradually increased. This result indicates that the mechanical load generated by whisker deflection can be effectively transferred to the cross-shaped flexible substrate. Meanwhile, Fig. 2b demonstrates that the average displacement of the interdigitated electrode increased monotonically with the applied load, revealing the capability of the HSWS to transform mechanical whisker deflection into measurable electrode displacement for subsequent capacitive signal transduction.

Subsequently, the effects of whisker geometrical parameters on the mechanical response of the HSWS were systematically analyzed. As shown in Fig. 2c, the average stress on the TPU membrane surface increases as the whisker radius and height increase, indicating more effective stress transfer from the whisker to the flexible substrate. Meanwhile, Fig. 2d demonstrates that larger whisker dimensions result in greater displacement responses of the interdigitated electrodes. These results indicate that increasing the whisker height increases the bending moment generated at the whisker root and transferred to the flexible substrate due to the enlarged moment arm, while increasing the whisker radius enhances structural stiffness and facilitates stress transfer. Overall, optimized whisker geometry facilitates mechanical deformation amplification, resulting in larger electrode displacement and enhanced capacitive response.

Figure 2e further elucidates the applied-load–displacement relationship of the HSWS. The electrode displacement exhibits an approximately linear increase with increasing applied load, demonstrating an effective and predictable mechanical transduction process from external loading to structural deformation. This linear displacement response confirms the capability of the HSWS to convert mechanical stimuli into measurable deformation signals, providing a theoretical basis for subsequent capacitive signal transduction and quantitative force estimation.

By balancing the electrode displacement response, device miniaturization requirements, and fabrication feasibility, the geometric parameters of the whisker and the overall HSWS architecture were optimized. To enhance structural robustness during practical operation, the outer ends of the cross-shaped TPU beams were mechanically anchored within the slots of the lower housing, while the upper and lower housings were integrated through a snap-fit assembly. This configuration suppresses undesired displacement of the fixed structural components and improves the mechanical stability of the sensor under repeated loading conditions. According to the finite element simulation results, the optimized HSWS exhibits a compact cuboid architecture with dimensions of $34.6 \times 34.6 \times 5 \text{ mm}^3$. The optimized structural parameters include an initial electrode gap of 1 mm, a whisker effective height of 26 mm, and a whisker radius of 1.5 mm.

The major geometric parameters of the finite element model have been described above, and the detailed material properties and boundary conditions are provided in Note S2.

To further validate the sensing capability of the HSWS under weak mechanical stimuli, multidirectional mechanical loading, and dynamic interaction scenarios, comprehensive performance evaluations were conducted under various loading conditions. The correlations among whisker deformation, capacitive response characteristics, and long-term sensing stability were systematically investigated.

The contact displacement between the stepper motor and the whisker was defined as ΔL , while the lateral bending displacement was defined as ΔB (Fig. 3a). When the contact displacement increased from 0.4 to 2.4 cm, the relative capacitance variation gradually increased as the displacement increased (Fig. 3b), indicating a clear correlation between whisker deflection and capacitive response. Similarly, when the lateral bending displacement increased from 1 to 2 cm, the relative capacitance variation further increased (Fig. 3c), demonstrating that the HSWS can effectively perceive different degrees of whisker deformation. Figure 3d presents the force response of the HSWS under different loading directions. When identical external forces were applied from different loading directions, the sensor exhibited stable output signals and consistent response trends, demonstrating stable multidirectional perception. Furthermore, under a constant applied force of 100 mN, the output signals of the HSWS remained nearly unchanged when the whisker was actuated at different loading frequencies, indicating a frequency-independent capacitive response within the tested range (Fig. 3e).

Figure 3f shows that the relative capacitance variation of the sensor increases linearly with increasing applied force. Since the response amplitudes of the four capacitive channels vary under different loading directions, the direction exhibiting the most pronounced response in the C_1 channel was selected for sensitivity evaluation. The fitted coefficient of determination R^2 reached 0.98, and the calculated force sensitivity was 23.75 N^{-1} , demonstrating the capability of the HSWS for high-sensitivity and quantitative detection of weak external forces. To determine the minimum detectable force of the HSWS, the noise level of the system was evaluated based on the relative capacitance variations under the no-load condition. The standard deviation of the relative capacitance variation was calculated for each of the four channels, and the maximum value was defined as the overall noise level of the sensing system:

$$\sigma = \max(\sigma_1, \sigma_2, \sigma_3, \sigma_4)$$

Where σ_i represents the standard deviation of the relative capacitance variation of the i -th sensing channel under the no-load condition.

When the capacitance variation induced by an external force exceeded three times the standard deviation of the static noise, the applied force was considered reliably detectable. Combined with the force-capacitance sensitivity S_1 , the minimum detectable force was calculated as:

$$F_{\min} = \frac{3\sigma}{S_1}$$

The calculated minimum detectable force was 0.006 N. Furthermore, by continuously applying small forces to deflect the whisker, the capacitance variation was experimentally observed when the whisker was actuated by a force as low as 6 mN, further validating the minimum detectable force of the HSWS.

As shown in Fig. 3g, the HSWS exhibits rapid response and recovery characteristics under an applied load of 120 mN, with a response time of 100 ms and a recovery time of 50 ms, respectively. The fast dynamic response demonstrates that the HSWS can support real-time tactile perception in interactive sensing scenarios.

To investigate the long-term stability and mechanical durability of the HSWS, the sensor was subjected to repeated loading–unloading cycles under a unidirectional loading configuration with an applied force of 120 mN. After 1000 mechanical cycles, the capacitance response exhibited negligible variation, indicating excellent cyclic stability, signal stability, and structural reliability of the HSWS during repeated mechanical deformation (Fig. 3h).

2.3 Multifunctional Tactile Perception and Human–Machine Interaction Enabled by the HSWS

To validate the capability of the HSWS for advanced tactile perception and human–machine interaction, surface texture recognition and remote robotic manipulation experiments were performed. A texture recognition platform was first constructed, where the whisker tip was driven to slide across nine different 3D-printed texture samples, consisting of arch-shaped (A), rectangular (R) and triangular (T) patterns with three characteristic heights of 4, 5, and 6 mm (Fig. 4a). During each measurement, the whisker tip was precisely aligned with the starting position of the texture sample, ensuring stable and continuous contact during the sliding motion.

As shown in Fig. 4b, the differences in surface geometry and feature height among various texture patterns generate distinct whisker deformation and vibration responses, leading to unique multichannel capacitive time-series responses. The acquired capacitive signals were analyzed using a MLP-based classification model, achieving an overall texture recognition accuracy of 97.34% (Fig. 4c and Note S3). The confusion matrix in Fig. 4c illustrates the consistency between model predictions and experimental

labels, providing a quantitative assessment of the classification capability. For instance, among all samples predicted as the A4 category, 99% were correctly identified as A4, whereas 1% were incorrectly assigned to A6. The dominant diagonal elements further confirm the high classification reliability of the proposed HSWS-based texture recognition system.

These results demonstrate that the HSWS is capable of capturing distinct tactile signal responses associated with different surface geometries and achieving high-accuracy texture recognition through a data-driven perception strategy.

To further demonstrate the potential of the HSWS as a portable tactile input interface for mobile robot teleoperation and remote robotic manipulation, a multichannel wireless control system was developed for vehicle navigation and robotic arm manipulation. The integrated system consists of the HSWS sensing unit, an FDC2214 capacitance-to-digital conversion module, a sensor-side STM32 microcontroller, a Bluetooth wireless communication module, a vehicle-side STM32 controller, and execution modules. During operation, external mechanical stimuli applied to the whisker induce four-channel, direction-dependent capacitance variations, which are synchronously acquired by the FDC2214 module and processed by the sensor-side STM32 microcontroller. The extracted capacitance features are converted into corresponding control commands and wirelessly transmitted to the vehicle-side controller via Bluetooth communication. Subsequently, the received commands enable the controlled vehicle and robotic arm gripper to execute predefined motions.

To realize multi-degree-of-freedom (multi-DOF) robotic control, two HSWS units were integrated into a 3D-printed housing to develop a portable tactile control interface. This portable interface allows users to remotely manipulate an intelligent vehicle and its robotic gripper through directional inputs from the two HSWS units (Fig. 4d). Specifically, the right HSWS unit was assigned for vehicle navigation, where the four directional sensing states were mapped to forward motion, left rotation, backward motion, and right rotation of the vehicle. Meanwhile, the left HSWS unit was utilized for robotic arm and gripper manipulation, with the corresponding directional inputs mapped to arm extension, gripper opening, arm retraction, and gripper closing, respectively. As shown in Fig. 4e and Fig. 4f, the HSWS-enabled control system successfully guided the vehicle along designed trajectories and regulated the motions of the robotic gripper. Figure 4g presents the operator hand states and the corresponding vehicle responses, while Fig. 4h records the real-time signal transmission during the wireless control process. The corresponding demonstration is provided in Video S3. These results demonstrate that the HSWS extends beyond surface tactile perception and provides a flexible, portable, and intuitive human-machine interaction interface for real-time mobile robot teleoperation and remote robotic manipulation.

2.4 Multichannel Capacitive Signal-Based Force-Direction Prediction and Visualization System of the HSWS

To demonstrate the capability of the HSWS in perceiving and decoding complex tactile information, a data-driven multitask learning framework was developed for loading-direction classification and contact-

force estimation using multichannel capacitance signals, followed by the construction of real-time tactile visualization and interactive feedback systems.

To obtain multichannel tactile information for loading-direction classification and contact-force estimation, a circular mechanical loading platform was developed to apply controlled external mechanical stimuli with different loading directions and force magnitudes to the HSWS. The four-channel capacitance variations were synchronously acquired using an FDC2214 capacitance-to-digital converter, generating four-channel, direction- and force-dependent capacitive response patterns. The distinct response characteristics among the four sensing channels under different loading directions provided multidimensional capacitive features for subsequent data-driven tactile signal decoding.

Since different loading directions and contact force magnitudes induce distinguishable response patterns across the four capacitive channels, a data-driven multitask learning model was developed to extract multichannel capacitive features and achieve simultaneous estimation of the loading direction and contact force magnitude. As illustrated in Fig. 5a, the proposed model employs a multitask learning architecture that enables concurrent classification of loading-direction states and regression of continuous contact-force values.

The optimized model achieved loading-direction classification accuracies of 99.61% and 97.58% on the training and testing datasets, respectively. To further verify the robustness and generalization performance of the proposed model, an independent validation dataset containing 3350 samples was collected separately. Among these samples, 3262 samples were correctly identified, resulting in a validation accuracy of 97.40%. The confusion matrix of the loading-direction classification results is shown in Fig. 5b.

To further evaluate the contact-force estimation performance of the proposed model, the measured force values were compared with the corresponding estimated values on the testing dataset (Fig. 5c). The horizontal and vertical axes represent the experimentally measured forces and model-estimated contact forces, respectively. Each scatter point corresponds to one testing sample, while the red dashed line represents the ideal estimation condition ($Y = X$). Most data points are concentrated around the ideal reference line, indicating excellent consistency between the estimated and measured contact-force values. The proposed model achieved a mean absolute error (MAE) of 0.0092 N, a root mean square error (RMSE) of 0.0144 N, and a high correlation coefficient (R) of 0.9952. These results demonstrate that the HSWS enables accurate quantitative estimation of contact force magnitude from multichannel capacitive signals.

To enable real-time decoding, visualization, and interactive feedback of HSWS-derived tactile information, a Python-based data analysis and visualization platform and a Three.js-based virtual tactile interaction system were developed.

Figure 5d shows the real-time visualization platform developed using Python. The four-channel capacitive responses of the HSWS are synchronously acquired through the FDC2214 capacitance-to-

digital converter and transmitted to the host computer via serial communication for signal processing. The acquired multichannel capacitance signals are subsequently processed by the Python-deployed joint loading-direction–force estimation model, enabling real-time decoding of the loading direction and contact force magnitude during tactile interaction. The platform provides intuitive visualization of capacitance variations, loading-direction information, and force evolution. Moreover, integrated functions including data acquisition, pause, storage, and export facilitate HSWS performance characterization and data-driven tactile sensing applications.

Figure 5e presents the virtual tactile feedback system constructed using Three.js. The system receives tactile information from the embedded joint loading-direction–force estimation model and maps the estimated loading direction and contact force magnitude onto a virtual whisker model. The predicted loading direction determines the deflection orientation of the virtual whisker, whereas the normalized force value controls the bending deformation amplitude, establishing an intuitive visual representation of tactile stimuli. Through a three-dimensional flexible motion model based on a root rotational node, the virtual whisker exhibits continuous deformation driven by real-time inputs, realizing the transformation from physical tactile perception to real-time virtual tactile feedback.

These two systems collectively demonstrate the capability of the HSWS for real-time tactile signal decoding and interactive visualization, as well as its potential for data-driven robotic perception, human–machine interaction, and virtual tactile feedback.

2.5 Autonomous Environmental Exploration of an Intelligent Mobile Robot Enabled by the HSWS

After demonstrating the capability of the HSWS as a tactile input interface for human–machine interaction, we further investigated its potential for autonomous robotic perception and exploration. In contrast to conventional vision-based perception strategies, tactile sensing based on physical interaction can provide reliable near-field contact information under unknown, confined, and visually occluded conditions. Accordingly, the HSWS was integrated into a mobile robotic platform to realize autonomous obstacle avoidance and environmental boundary exploration tasks.

To realize tactile feedback-driven autonomous environmental exploration, two HSWS sensing units were integrated at the front of a mobile robot to acquire contact information during robot–environment interactions. As illustrated in Fig. 6b, the HSWS-based mobile tactile perception system consists of the sensing units, an FDC2214 capacitance-to-digital conversion module, an STM32-based data acquisition module, a Raspberry Pi inference platform, and a robot-side STM32 motion control module. The HSWS sensing units collect four-channel, direction-dependent capacitance variations induced by whisker contact with external objects. The STM32 module performs real-time signal acquisition and transmission, while the Raspberry Pi executes the trained joint loading-direction–force estimation model to decode the input tactile signals and extract the loading direction and contact force magnitude. Based on the decoded tactile information, the robot-side STM32 controller generates corresponding motion commands, enabling autonomous obstacle avoidance and environmental exploration.

During interaction with external obstacles, whisker deformation induces variations in the four-channel capacitance signals of the HSWS, which are synchronously acquired and digitized by the FDC2214 capacitance-to-digital converter. Figure 6c illustrates the real-time capacitive responses of the HSWS during the autonomous obstacle avoidance process. The acquired capacitance signals are transmitted from the STM32 data acquisition module to the Raspberry Pi inference platform, where the trained neural network model performs real-time tactile signal decoding and extracts the loading direction and contact force magnitude. The decoded tactile information is subsequently transmitted to the robot-side STM32 controller through Bluetooth communication, enabling the generation of corresponding motor control signals for stopping, reversing, and steering operations. Consequently, the robot is capable of autonomously responding to collision events based on tactile feedback, achieving obstacle avoidance behavior without relying on vision-based sensing (Fig. 6a and Video S4).

To investigate the capability of the HSWS for continuous environmental boundary perception, wall-following exploration experiments were performed. As illustrated in Fig. 6d and Fig. 6e, the mobile robot explored the surrounding environment using both S-shaped and linear wall-following trajectories. During the navigation process, the HSWS continuously detected the contact state between the whiskers and environmental boundaries and adjusted the robot motion based on loading-direction-dependent tactile feedback, allowing stable boundary perception and wall-following movement.

The results demonstrate that the HSWS-enabled mobile tactile perception system can achieve obstacle detection, loading-direction recognition, and environmental boundary exploration. This experiment establishes a complete tactile perception-signal decoding-motion control closed loop, covering tactile signal acquisition, information interpretation, and autonomous robotic behavior generation. These findings highlight the potential of the HSWS for data-driven robotic perception, autonomous exploration, and human-machine-environment interaction in unknown environments.

3. Conclusion

In summary, we developed a data-driven, high-sensitivity capacitive biomimetic whisker sensor that integrates biomimetic structural design, capacitive sensing, and intelligent tactile signal decoding for advanced tactile perception. By combining an interdigitated electrode structure, a cross-shaped flexible beam, and a symmetric four-channel capacitive layout, the HSWS converts subtle whisker deflections induced by external mechanical stimuli into four-channel, direction-dependent differential capacitance signals. Compared with conventional approaches relying on complex multi-electrode arrays, distributed sensing units, or mechanical decoupling structures, the proposed HSWS achieves weak-force detection and multidirectional tactile perception within a streamlined and highly integrated structural architecture.

The experimental results demonstrate that the HSWS exhibits high force sensitivity, high directional resolution, and excellent cyclic stability. By incorporating a machine learning-assisted compensation strategy, the multichannel capacitance signals generated by the sensor can be further decoded using a MLP-based multitask learning model for simultaneous loading-direction classification and contact-force

regression, significantly improving the decoding robustness of creep-induced and nonlinear capacitance variations. These results demonstrate that the synergistic combination of high-sensitivity structural design and data-driven signal decoding provides an effective strategy for enhancing the practical applicability of biomimetic whisker sensors in complex tactile perception tasks.

Furthermore, the HSWS was successfully demonstrated in texture recognition, mobile robot teleoperation, and autonomous exploration, highlighting its potential as a structurally streamlined, highly integrable, and learning-compensated tactile interface for close-range robotic perception and human-machine-environment interaction. Overall, the HSWS integrates high force sensitivity, high directional resolution, compact structural integration, and real-time tactile signal decoding, providing an effective platform for data-driven robotic perception and autonomous tactile interaction in complex environments.

4. Experimental Section

4.1 Fabrication Parameters of the 3D-Printed PLA Mold

The polylactic acid (PLA) mold used to support the cross-shaped TPU flexible beam structure was fabricated using a Bambu Lab P1S 3D printer equipped with a 0.4 mm nozzle. PLA filament was selected as the printing material, and a Bambu double-sided textured polyetherimide (PEI) plate was used as the printing platform. In Bambu Studio, the Bambu Lab P1S printer configuration with a 0.4 mm nozzle was selected, and the “0.08 mm High Quality @BBL P1S” slicing profile was adopted. The key printing parameters included a layer height of 0.08 mm, an initial layer height of 0.20 mm, and an infill density of 100%, ensuring sufficient mechanical rigidity and dimensional stability of the fabricated mold. The printing speeds were set to 50 mms⁻¹ for the first layer, 60 mms⁻¹ for the outer wall, 120 mms⁻¹ for the inner wall, and 150 mms⁻¹ for the infill structure. After completion of the printing process, the mold was removed after the build plate had cooled to room temperature. The surface flatness and edge integrity of the mold were subsequently inspected to ensure that the fabricated mold met the requirements for subsequent TPU structure fabrication and device assembly.

4.2 Fabrication of the HSWS

Materials TPU films were purchased from Guangzhou Huanyou Technology Co., Ltd. Conductive silver paste (LY-50) and polymer dispersant $C_3H_5NO_2)_nNH_4$ were purchased from Shenzhen Yilai Technology Co., Ltd. (Shenzhen, China). Sodium tripolyphosphate $Na_3P_3O_{10}$, used as an antioxidant additive, was obtained from Runyou Chemical Co., Ltd. (Shenzhen, China).

Fabrication of Flexible Interdigitated Electrodes The conductive silver paste, antioxidant additive, and polymer dispersant were mixed at a mass ratio of 98:1:1 and stirred using a magnetic stirrer at 30 °C for 30 min. Subsequently, the mixture was ultrasonically dispersed in a water bath for 60 min to prepare the stretchable conductive silver paste. A stainless-steel screen mask with the designed interdigitated

electrode pattern was placed onto the surface of the TPU film, and the stretchable conductive silver paste was deposited onto the TPU substrate through a screen-printing process. During the curing process, solvent evaporation and volumetric shrinkage of the conductive paste promoted closer contact between silver particles, resulting in the formation of a continuous conductive network. After screen printing, the silver paste rapidly dried and established electrical connections between the conductive traces and sensing grids. Finally, the printed samples were cured in a vacuum oven at 130 °C for 20 min to obtain the conductive electrode layers of the upper and lower electrodes. A reserved opening was designed at the center of the upper electrode layer for subsequent whisker integration.

4.3 Fabrication of the HSWS Device

The HSWS sensing unit consists of a whisker structure, upper and lower housings, and a cross-shaped TPU flexible beam. The overall mass of the fabricated device is approximately 12 g. To achieve a balance between force sensitivity and measurement range, boar bristles with a moderate elastic modulus were selected as the whisker material. Individual boar bristles with a diameter of approximately 0.1 mm were purchased from Longyi Brush Manufacturing Factory, Qianshan, Anhui Province, China. Approximately 20 bristles were bundled and bonded using silicone rubber adhesive to form a whisker structure with sufficient mechanical flexibility, toughness, and elastic recovery capability. During the assembly process, the whisker was inserted through the central hole of the upper housing, and the bottom end of the whisker was firmly bonded to the central region of the cross-shaped TPU flexible beam on the lower housing. This configuration formed a deformable moment-transfer structure for mechanical deformation amplification, enabling the conversion of external mechanical stimuli into enhanced deformation of the flexible beam. Approximately 3 mL of phenyl silicone oil (viscosity: 1000 cSt) was injected into the gap between the upper and lower electrodes to enhance mechanical damping within the flexible structure and increase the effective dielectric constant between the electrodes. Finally, the upper and lower electrode assemblies were positioned within the corresponding housings and encapsulated using silicone adhesive (Sil-Poxy) to complete the fabrication and assembly of the HSWS.

4.4 Experimental Procedures and Measurement Setup

The static resistance of the fabricated electrodes was characterized using a digital multimeter (2000, Keithley), and the static and dynamic capacitive responses of the HSWS were recorded using an FDC2214-based multichannel capacitance-to-digital conversion system. The surface morphology of the conductive silver electrodes was characterized by scanning electron microscopy (SEM) after sputter-coating a thin gold layer onto the electrode surface. For mechanical response measurements, the HSWS was mounted at the center of a stepper motor-controlled loading platform, and a force gauge was installed on the motor stage to apply controlled lateral forces to the whisker. During the loading process, the induced capacitance variations and corresponding applied forces were synchronously recorded.

4.5 HSWS-Based Surface Texture Recognition Experiments

Experimental Platform The HSWS sensing unit was mounted on the end-effector of a robotic arm (FR5, FAIRINO), which was programmed to slide horizontally at a constant velocity of 30 mm s^{-1} . The texture samples were fabricated as modular structures with dimensions of $190 \times 70 \times 5 \text{ mm}^3$ and fixed onto the robotic arm testing platform. The spacing between adjacent texture patterns on each module was 40 mm.

Data Acquisition To construct the texture recognition dataset, the robotic arm drove the HSWS sensing unit to repeatedly slide across each texture sample for 100 cycles. During each trial, multichannel capacitance signals were continuously recorded for 2 s for each texture sample. A total of 1800 s of multichannel capacitance time-series data were collected.

Data Processing The collected dataset was randomly divided into a training set (80%) and a testing set (20%). To maintain consistent distributions of different texture categories between the training and testing datasets, a stratified sampling strategy based on texture labels was adopted during dataset partitioning. Before model training, the input features were standardized using the Standard Scaler method.

Classification Model A fully connected neural network model was developed for texture classification. The model takes multichannel capacitive time-series features extracted from sliding windows as input and outputs nine texture categories. The network consists of a feature extraction module and a classification module. The feature extraction network contains four fully connected layers with 256, 128, 64, and 32 neurons, respectively. Batch normalization and Leaky ReLU activation functions are applied after the fully connected layers to extract nonlinear feature representations, while dropout with a rate of 0.2 is introduced after selected layers to reduce overfitting. The classification module maps the extracted features to nine output categories corresponding to the nine texture samples. During model training, the cross-entropy loss function was adopted, and the Adam optimizer was employed for parameter updating. After training, the classification performance of the model was evaluated using the confusion matrix obtained from the testing dataset.

4.6 Multitask Direction Classification and Force Estimation Model

To achieve simultaneous estimation of the loading direction and contact force magnitude of the HSWS, a joint loading-direction–force estimation model was developed based on the multichannel capacitance signals generated by the sensor. The continuously acquired four-channel capacitance signals were processed using a sliding window with a length of 13, and temporal features within each window were extracted. For each capacitance channel, six types of temporal features, including instantaneous variation, mean value, standard deviation, maximum value, minimum value and average variation rate, were calculated. Therefore, a total of 24-dimensional input features were obtained from the four

capacitance channels. The model outputs consisted of the corresponding loading-direction category labels and continuous contact-force values. The developed neural network adopted a multitask learning architecture consisting of a shared feature extraction module, a loading-direction classification branch, and a contact-force regression branch. The shared feature extraction module was composed of three fully connected layers containing 512, 256, and 128 neurons, respectively. Each fully connected layer was followed by a batch normalization layer and a Leaky ReLU activation function to extract deep nonlinear representations from the multichannel capacitive features.

The loading-direction classification branch consisted of two fully connected layers with 64 and 32 neurons, respectively, and finally outputs 73 categories, including one stationary state and 72 directional states.

The contact-force regression branch was constructed using the same fully connected architecture with 64 and 32 neurons and generated a continuous contact-force output. A ReLU activation function was applied at the output layer to constrain the estimated contact-force values to non-negative values.

During model training, a total of 15,770 samples were used, with 80% assigned to the training dataset and 20% to the testing dataset. The model was trained using the Adam optimizer with an initial learning rate of 5×10^{-4} , a weight decay coefficient of 1×10^{-5} , and a batch size of 32. A cosine annealing learning rate strategy was employed over 600 training epochs. After model training, an additional 3350 samples were independently collected as a validation dataset, and the model performance was evaluated using both the testing dataset and the independent validation dataset.

Declarations

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Declaration of competing interest The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors declare that there are no competing interests.

Data availability Data supporting the findings of this study are available within the article and its Supporting Information, and from the corresponding authors upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process During the preparation of this work, the authors used ChatGPT (OpenAI) to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Figures

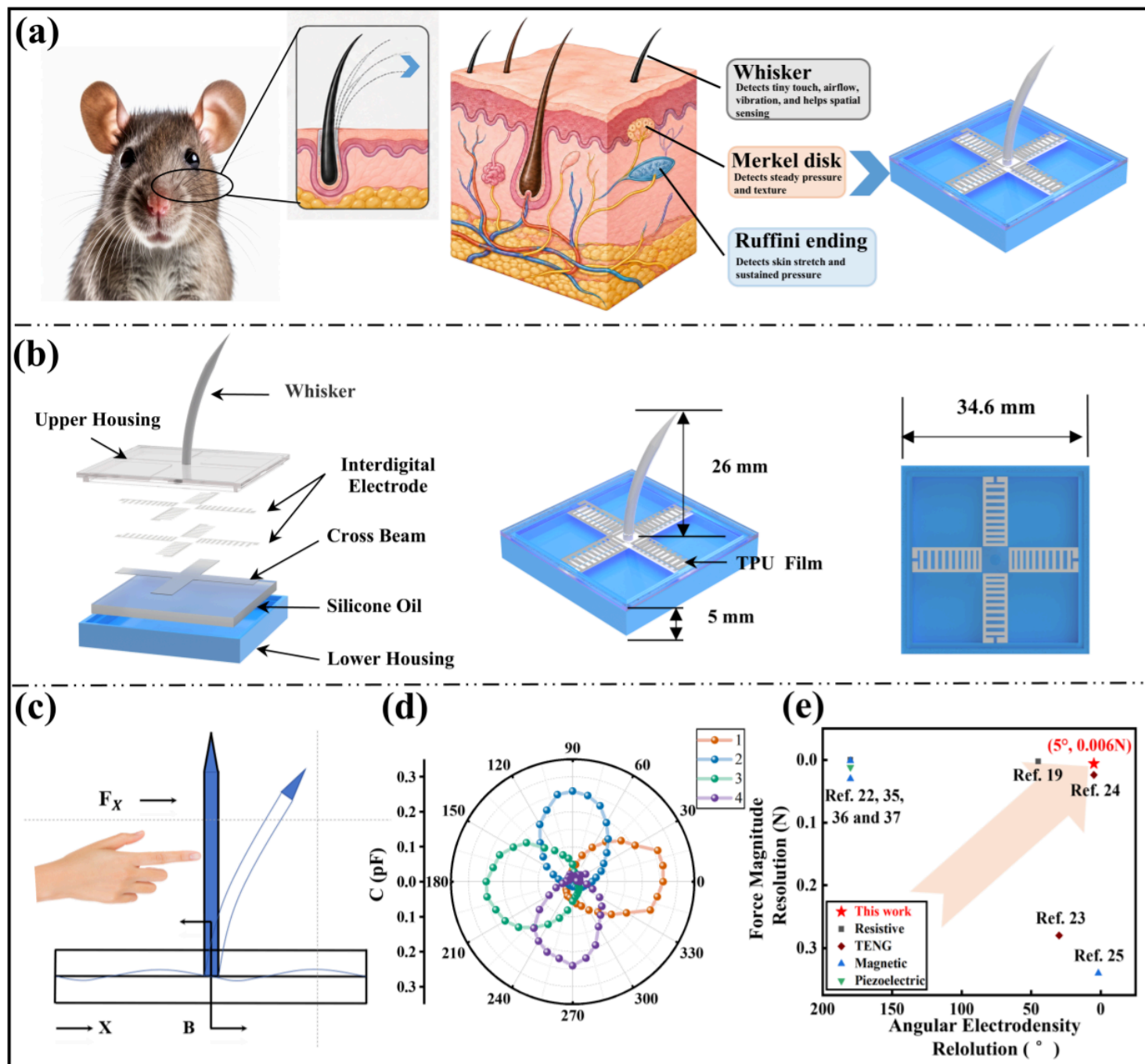


Figure 1

Structural design and working mechanism of the biomimetic whisker sensor. (a) Design of the whisker sensor inspired by the follicle structure of rodent whiskers. (b) Overall architecture and enlarged schematic details of the HSWS. (c) Schematic illustration of capacitance variation in the sensing unit under an externally applied lateral force F . (d) Direction-dependent differential responses of the four sensing channels under different loading directions. (e) Comparison of the minimum detectable force and angular resolution of the proposed HSWS with previously reported biomimetic whisker sensors.

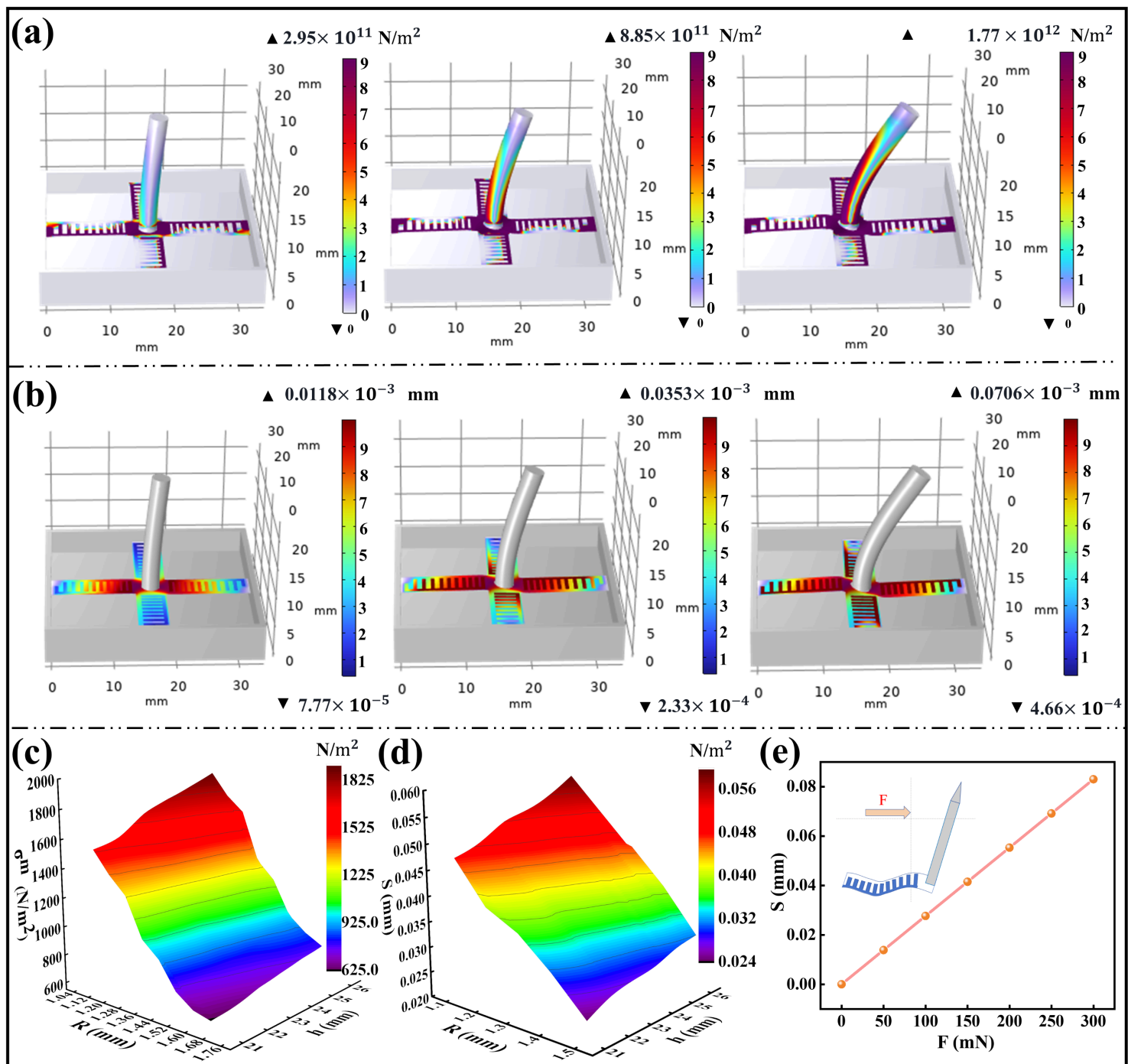


Figure 2

Finite element analysis of force transmission and structural optimization of the HSWS. (a) Average stress variation on the TPU membrane surface under different applied loads (50, 150, and 300 mN). (b) Average displacement response of the interdigitated electrodes under different applied loads (50, 150, and 300 mN). (c) Influence of whisker geometrical parameters on stress transfer. (d) Influence of whisker geometrical parameters on electrode displacement response. (e) Relationship between the applied load and electrode displacement.

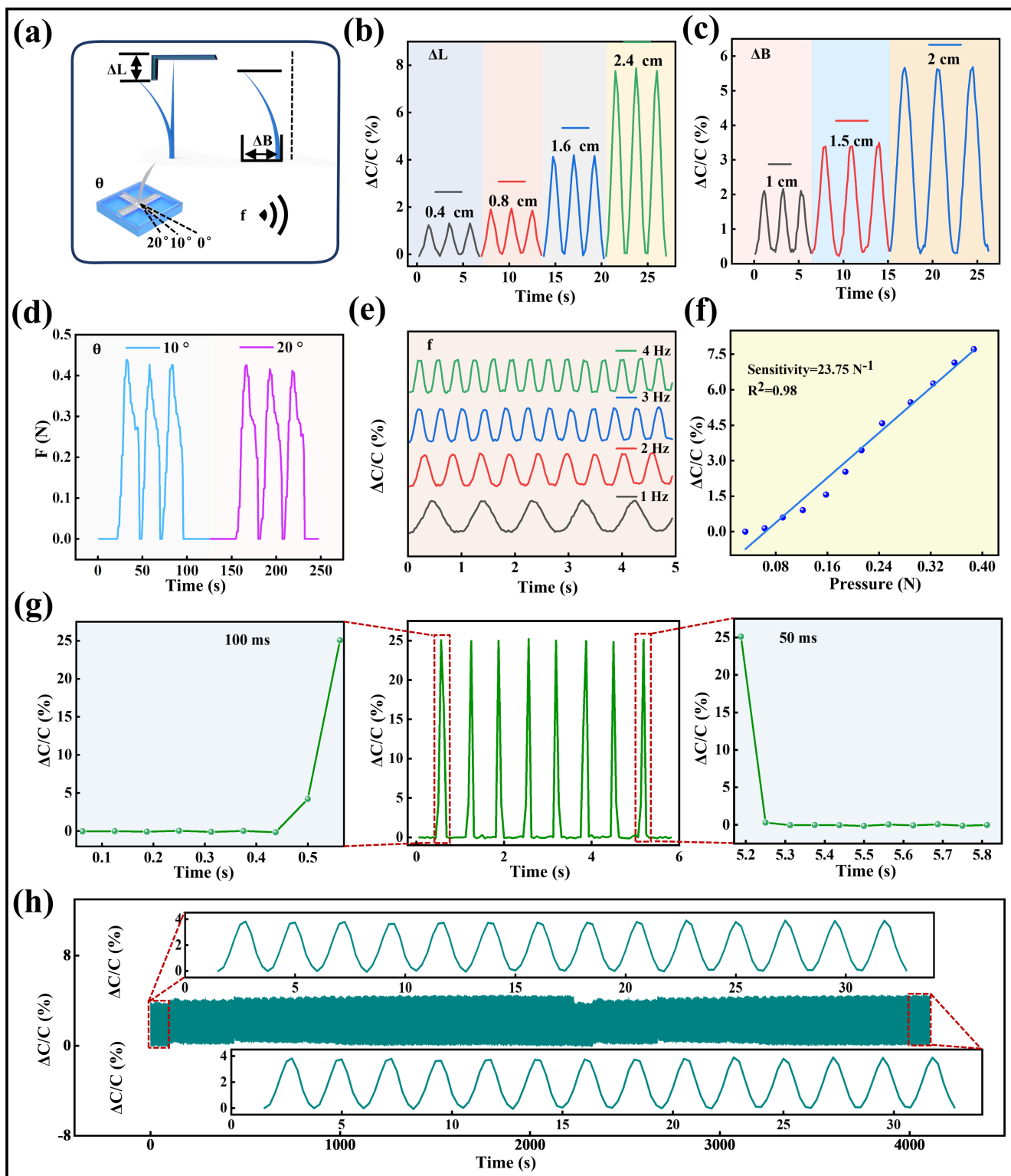


Figure 3

Characterization of the mechanical–electrical response performance of the HSWS under various mechanical stimuli. (a) Schematic illustration of whisker deformation under different loading modes. (b) Relative capacitance responses of the HSWS under different contact displacements (ΔL). (c) Relative capacitance responses of the HSWS under different lateral bending displacements (ΔB). (d) Directional response stability of the HSWS under different loading directions. (e) Frequency-independent output

response of the HSWS. (f) Force-dependent linear response and sensitivity of the HSWS. (g) Response and recovery characteristics of the HSWS under an applied load of 120 mN. (h) Cyclic durability and signal stability of the HSWS over 1000 loading–unloading cycles.

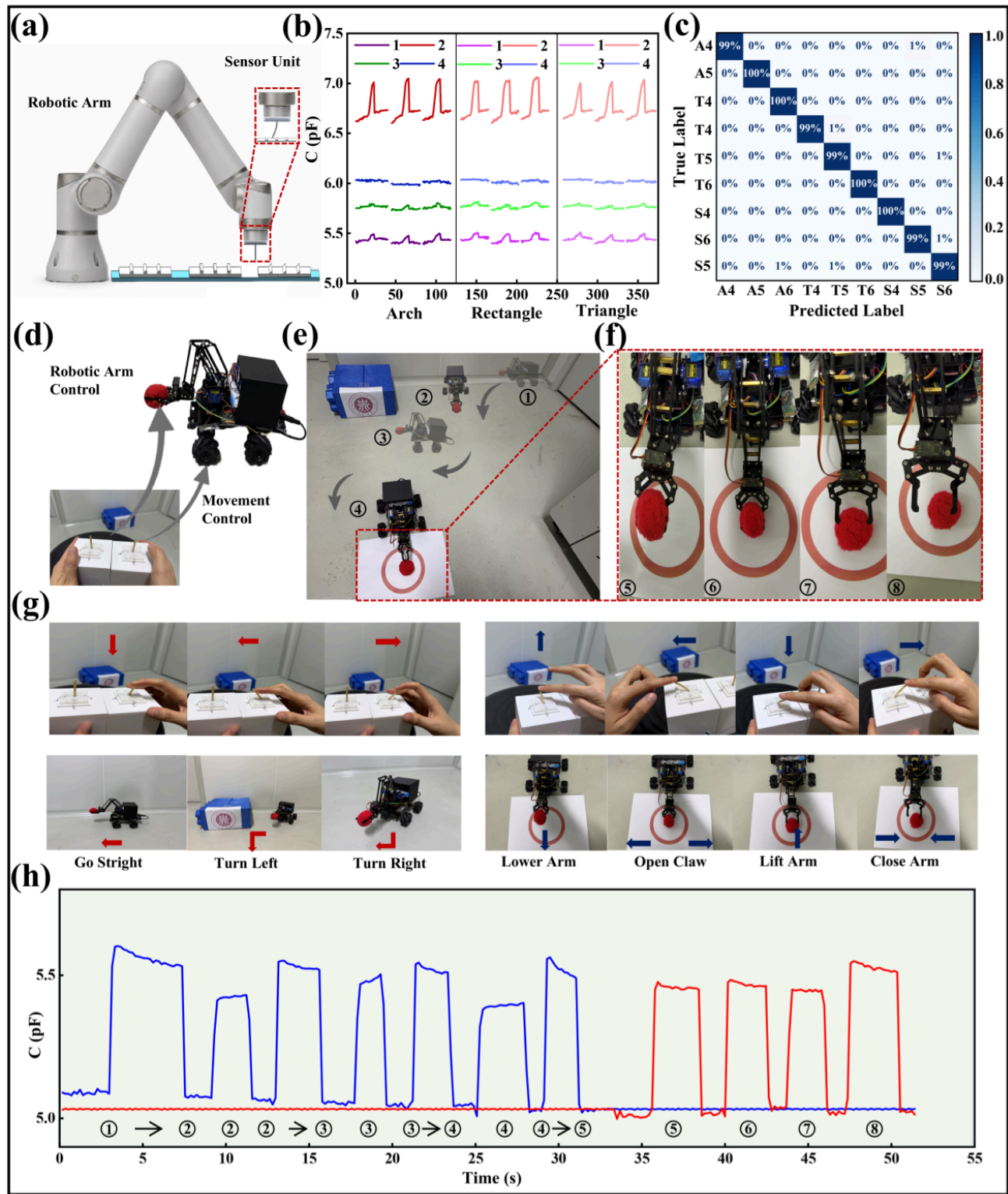


Figure 4

Multifunctional tactile perception and remote human-machine interaction enabled by the HSWS. (a) Experimental configuration for surface texture recognition. (b) Multichannel capacitive responses of the HSWS when sliding over nine different texture samples. (c) Confusion matrix of texture classification results. (d) Demonstration of an HSWS-enabled remote robotic control system. (e) Sequential images illustrating the motion trajectory of the remotely controlled vehicle. (f) Image sequences capturing the motion states of the robotic arm and gripper. (g) Operator hand gesture states and corresponding vehicle motion states. (h) Real-time signal transmission during HSWS-enabled remote robotic control.

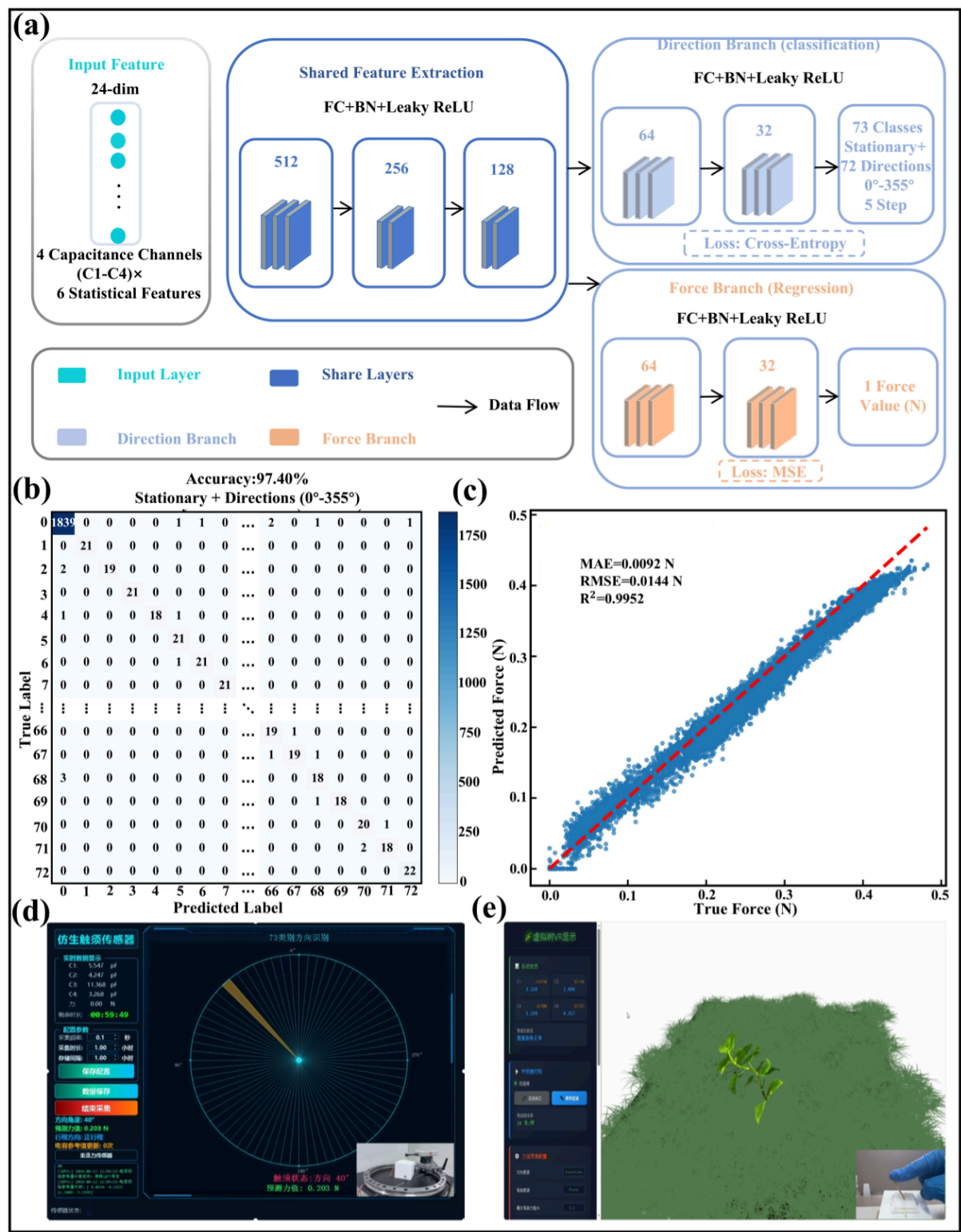


Figure 5

Multichannel tactile signal decoding and visualization platform enabled by the HSWS. (a) Architecture of the joint loading-direction classification and contact-force regression neural network. (b) Confusion matrix for loading-direction classification. (c) Correlation between measured and estimated contact-force values. (d) Python-based real-time data analysis and visualization platform. (e) Three.js-based virtual reality (VR) interaction system for real-time tactile feedback visualization.

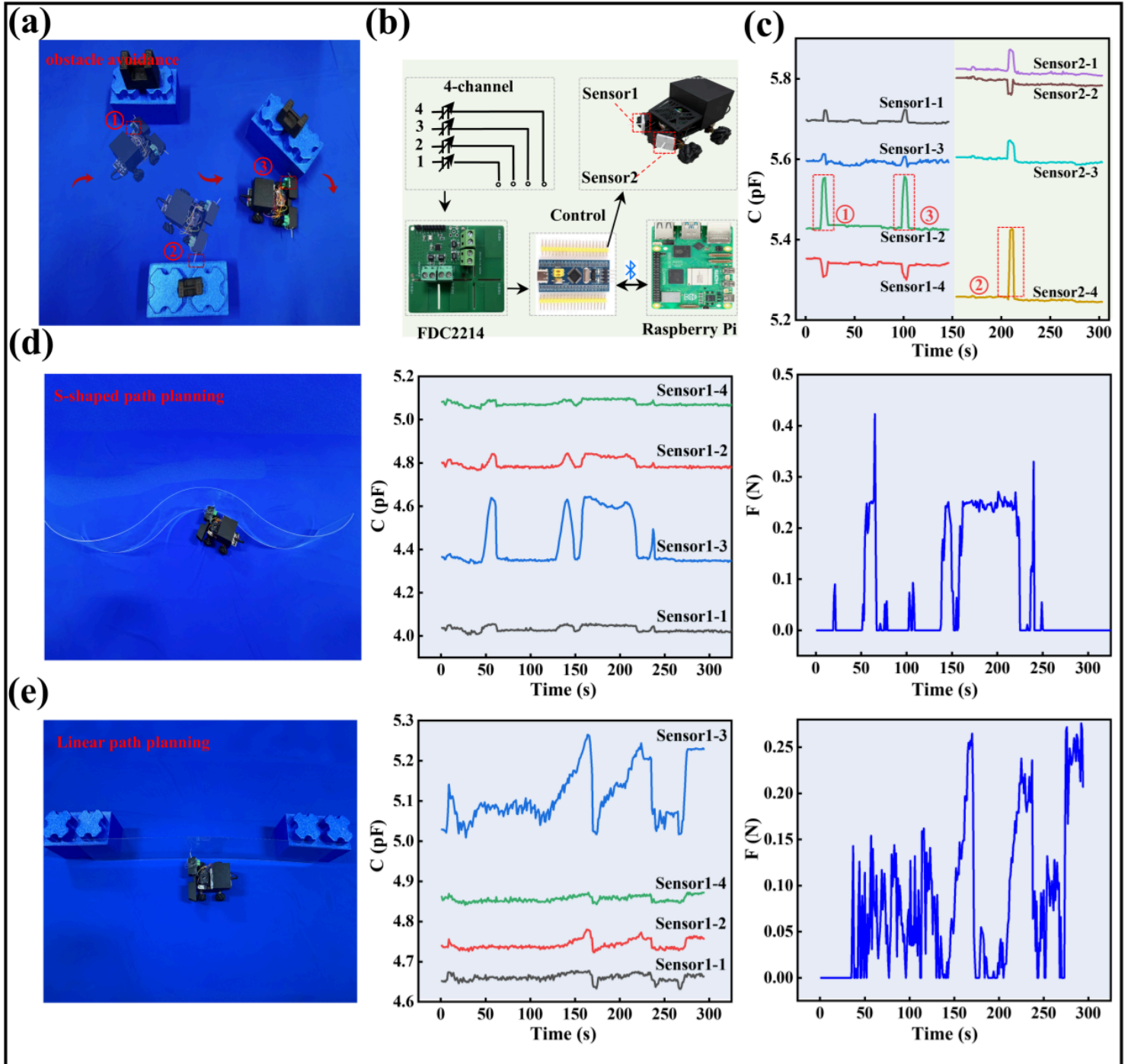


Figure 6

Autonomous robotic exploration enabled by HSWS-based tactile perception. (a) Schematic diagram of autonomous obstacle avoidance using the HSWS-equipped mobile robot. (b) HSWS-integrated mobile tactile perception system. (c) Real-time four-channel capacitive responses of the HSWS during autonomous obstacle avoidance. (d) S-shaped wall-following exploration trajectory and corresponding capacitive and force responses. (e) Linear wall-following exploration trajectory and corresponding capacitive and force responses.

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