3D Multimodal Sensing and Feedback Finger Case for Immersive Dual-Way Interaction

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1. Introduction

With the rapid development of virtual reality (VR) technology, artificial intelligence, and the Internet of Things, a new era of immersive interaction with the digital world has emerged. In this context, a novel soft finger case with 3D multi-modal sensing and feedback functions (3D-SFC) is presented. The device leverages multiple material properties to create a modulated fingertip haptic feedback for the perception of orientation and force, triboelectric nanogenerator (TENG) sensing with dynamic and static responses and control of movement, and thermal feedback based on resistive heating of TENG electrodes. The integrated TENG tactile sensing unit in the device is capable of recognizing the texture of an object’s surface, providing users with a more natural and intuitive way of interacting with digital objects. The spatial consistency of multi-modal sensing and feedback enhances human-machine interaction in various fields such as healthcare, manufacturing and assembly, and gaming, etc. The proposed device represents a new intelligent sensing solution for achieving cross-space sensory interaction, opening up new possibilities for the future of VR and digital interaction.

1. Introduction

With the advances of humanoid robots and metaverse concepts, the requirement of more intuitive human–machine interfaces (HMIs) are drastically increased.[1–7] The conventional visual and audio-based communication, together with the hand-held controller and the simple vibrational haptic feedback, are experiencing the limitation of delivering a more realistic sensation for conducting complex operations.[8,9] As one of the most important sensations of humans, the direct delivery of tactile information through skin mechanoreceptors and neural pathways is showing higher recognition efficiency than reading the displayed tactile sensing data.[10] Therefore, the dual-way transmission of multi-modal tactile sensation becomes a promising solution to improve the cognition of the operation environment and the potential risks in teleoperation or virtual reality applications.[11] The approach of enabling the fusion of sensing and feedback functions is then worth continuous investigation.[12–14]

Haptic feedback technology mainly focuses on the regeneration of physical perception via diversified actuation or stimulation mechanisms,[9,15–18] so that the skin mechanoreceptors or muscle spindle can receive the corresponding stimulus.[8,10,19–21] The current research can be categorized into three main directions, including cutaneous feedback, kinesthetic feedback, and temperature feedback.[22–25] Owing to the material property and the structural design, various sensations can be recreated, such as pressure, softness, roughness, strain, torque, rotation, twisting, cold and hot, etc.[26–31] And the neural stimulation technology may also be integrated into hybrid feedback systems to further improve the quality and effectiveness of haptic feedback in the future.[32–35] Among them, the cutaneous feedback receives great attention due to the need to perceive the physical properties of the interactive object. Edouard.L et al. have developed a hydraulically amplified electrostatic actuator with an array design, which can create both the tactile distribution and the trajectory of the dynamic motion.[23] In terms of vibrational feedback, Ji et al. designed a soft dielectric elastic actuator that can generate vibration-sensitive feedback from 1 Hz to 500 Hz.[36] In addition, pneumatic actuation is also considered an important haptic feedback approach due to its flexibility, stretchability, and capability to produce multi-modal feedback.[36,27] On the other hand, most of the precision operations are controlled by the human hand, i.e., in teleoperation surgery, the study of using mimilastical design to realize multi-modal and multi-dimensional haptic feedback on finger is still limited.[10,19] Meanwhile, the monitoring of the haptic...
feedback status is also rarely reported, which leads to the lack of the system diagnosis.

Tactile sensors as the most essential component in human–machine interactions, can obtain multi-dimensional mechanical stimuli as input signals to initiate manipulation or monitoring functions.[37–42] To establish a close-loop human–machine interactive system, it is necessary to combine tactile sensors and haptic feedback devices to build dual-way tactile communication.[43–49] Hence, several mechanisms of detecting mechanical stimuli are frequently studied, including piezoresistive, capacitive, piezoelectric, and piezoelastic effects, to gather information on pressure, strain, texture, shear force, etc. Among them, triboelectric nanogenerator (TENG) sensors are featured with the availability of materials, scalability, tunable structure, and low cost,[44,50–55] which shows great compatibility for integrating with haptic feedback devices. Sun et al. proposed a ring-shaped sensing and feedback device using a silicone-based TENG bending sensor and vibrator, the proposed device enables continuous finger motion sensing and vibrational and thermal feedback.[56] Zhu et al. proposed a smart glove with a TENG sensing array distributed inside the finger case, which can be used for detecting both the bending and deflection of each finger.[13] Furthermore, with the aid of machine learning algorithms, the additional hidden information in sensing data can then be extracted for advanced analysis and manipulation, such as object recognition, motion identification, etc.[5,13,41,56–58]

Nicely, compared to wearable tactile sensors, the research on haptic feedback is still limited.[43,59–62] The fusion of tactile sensing and haptic feedback is even rare. Most of the current wearable systems with these two functions are usually combining the sensors and the haptic feedback units together. However, this is quite challenging to guarantee the spatial and functional consistency between the tactile information detected by sensor and the regenerated perception via feedback actuators, especially for remote communication.[14,63] To facilitate seamless dual-way tactile communication, the fusion of tactile sensing and haptic feedback with multi-dimensionalities and multimodalities can be considered a promising solution. Here, we propose a soft finger case with the fusion of three dimensional and multi-modal sensing and feedback functions (3D-SFC) by utilizing the dual properties of two functional materials. Specifically, nickel-chromium (Ni–Cr) alloy possesses dual functions, including electro-resistive heating and the electrode of a triboelectric sensor. While the silicone-based elastomer shows good stretchability for pneumatic actuation and electronegativity for triboelectric sensing. The proposed finger case includes a wraparound pneumatic haptic feedback unit made of a silicone membrane, as well as an embedded Ni–Cr electrode for thermal haptic feedback and TENG tactile sensing. Owing to the specific distribution of the haptic feedback units, the 3D tactile perception can be regenerated, including pinch, insertion, sliding, etc. In addition, the sequential control of multiple units can even mimic dynamic interactive events, such as water waves, twisting, rolling, etc. Moreover, the TENG sensor can detect pressing, surface texture, as well as pneumatic actuation, which can be applied for manipulation and monitoring. As shown in Figure 1a, the proposed 3D-SFC realizes the multi-dimensional and multi-modal tactile sensing and haptic feedback in VR space to boost the training experience. In general, this device offers a concept of integrating sensing and feedback functions into a single unit with a facile design. It provides an accessible approach for enabling tactile communication in various applications, such as medical operations, entertainment, industrial productivity, and teleoperation in extreme environments.

2. Results and Discussion

2.1. Design and Working Mechanism

The design of the 3D-SFC is shown in the left part of Figure 1b. It is structured to achieve 3D haptic feedback to the fingertips, with pneumatic actuation to the bottom, front, left, and right sides of the fingertips. The pneumatic haptic feedback to the fingertip is achieved by using the stretchability of the silicone membrane and the air pump to achieve the expansion of the membrane. Each haptic feedback unit can be actuated individually. The right part of Figure 1b shows the distribution of the functional parts inside the finger case. The multi-modal sensing and feedback functions provided by 3D-SFC aim at mimicking the functions of the skin mechanoreceptors, e.g., fast adaptation and slow adaptation. A photo of the 3D-SFC is shown in Figure 2a. The multi-dimensional haptic feedback of 3D-SFC enables the regeneration of both static and dynamic perception for various activities (Figure 2b). In the meantime, the Ni–Cr electrode embedded in pneumatic chamber can be connected to the power supply for activating the electro-resistive heating, and thus, the thermal feedback is easily realized.

As shown in Figure 2c, d, the working mechanism of TENG-based tactile sensing and monitoring of pneumatic feedback refers to the contact and separation modes of TENG. For monitoring the pneumatic haptic feedback, the inflation of the pneumatic chamber causes the separation of two triboelectric layers, Ni–Cr alloy and silicone membrane with different electronegativities, and then, induces charge transfer via a connected external circuit. It finally generates a triboelectric output in response to the interaction between Ni–Cr and silicone caused by pneumatic actuation. In terms of tactile sensing, the silicone membrane deformed under pressing, and causes the contact between Ni–Cr and thermoplastic urethane (TPU) based finger case for triboelectric traction. The triboelectric output is then generated for tactile sensing. As a result, the fusion of sensing and feedback functions ensures spatial consistency of dual-way tactile communication for human-machine or human-human interactions. In addition, a polyethylene laminate film with a hemisphere-shaped microstructure pattern is bonded to the bottom sensing unit to increase the sensitivity to the surface roughness.

2.2. Characterization of Pneumatic Haptic Feedback with TENG Sensor-based Monitoring

For haptic feedback, the tactile information perceived by the user is conducted by pressing, pinching, rubbing, etc., to stimulate the mechanoreceptors in the human skin. The quality of the regenerated perception through a feedback device is important to ensure the understanding of the operating status. As shown in Figure 2b, the actuator provides haptic feedback on the bottom,
Figure 1. 3D multimodal sensing and feedback finger case (3D-SFC). a) Robotic teleoperation with the aid of augmented tactile perception and stimulation offered by 3D-SFC. b) Schematics of the structure of the finger case.

front, left, and right sides of the fingertip, with the capability of individual control. The pneumatic actuation is characterized by the pressure of the input air, as shown in Figure 2e,f. From 100 kPa to 114 kPa, the feedback force for the 6mm × 8 mm size pneumatic chamber increased from 0 N to 0.61 N, and the expansion displacement increased from 0 mm to 5.2 mm. The feedback force for the 6mm × 6 mm size pneumatic chamber increased from 0 to 0.473 N, and the expansion displacement increased from 0 mm to 4.05 mm. The finite element analysis (FEA) of the pneumatic chamber with different sizes and thicknesses under pneumatic actuation is shown in Figure 2j and Figure S1 (Supporting Information). Driven by the input pressure, the pneumatic chamber expands better and is able to stimulate the different parts of the fingertip with tunable tactile information.

Meanwhile, in the case of a massive distributed haptic feedback array, a diagnosis system that can monitor the actuation of the individual pneumatic chamber is required. In this work, the TENG-based monitoring of feedback is seamlessly integrated into each chamber. The TENG sensing signal for a pneumatic actuation pressure of 115 kPa with an actuation frequency of 0.5 Hz is shown in Figure 2g. The good repeatability indicates the ability of using a TENG sensor to monitor pneumatic actuation. Figure 2h shows the open circuit voltages of the TENG sensor for monitoring pneumatic actuation at varied input pressures. It shows a relatively good sensitivity to the variations of the actuation pressures. In Figure 2i, the open circuit voltages of the TENG sensor for monitoring pneumatic actuation at different frequencies under the same input pressure are given. The output voltage shows a slight decrease as the actuation frequency increases. For low-frequency actuation, the silicone membrane can be fully expanded and recovered in each cycle to generate the maximum output signals, as the voltage output of triboelectrification is proportional to the area of contact and separation. With the increase in actuation frequency, the silicone membrane in the previous cycle does not have enough time for complete expansion and recovery due to the fast actuation, which causes less area change during the contact and separation. Therefore, the voltage output from triboelectrification decreases as the actuation frequency keeps increasing.

Notably, although the TENG tactile sensing and TENG-based monitoring of pneumatic feedback are done by the same Ni–Cr electrode, there is no conflict of sensing signals between the
Figure 2. Pneumatic haptic feedback and sensing principle of the finger case. a) Photos of the finger case. b) 3D pneumatic feedback from finger case. c) Schematics of the pneumatic chamber with the cross-sectional view. d) Working mechanisms of TENG-based monitoring of pneumatic actuation and tactile sensing by the pneumatic chamber. e) Displacement of two silicone membranes under different air pressures. f) Pneumatic actuation forces generated by different silicone membranes under different air pressures. g) Open circuit voltage for TENG-based monitoring of pneumatic actuation for five cycles at 115 kPa. h) Open-circuit voltage signal for TENG-based monitoring of pneumatic actuation from 109 kPa to 121 kPa. i) Open-circuit voltage signal for TENG-based monitoring of pneumatic actuation with different frequencies at 115 kPa. j) FEA results at 115 kPa for two types of membranes.

Two functions. Because the tactile sensing and the monitoring of pneumatic feedback belong to two different stages. For the tactile sensing stage, the TENG sensors can obtain multidimensional tactile information, while the haptic feedback is no longer activated, as the user already can touch and feel the real object. For the haptic feedback stage, the TENG sensors can simultaneously monitor all of the pneumatic chambers, and there are no tactile sensing signals involved, as the user cannot touch and feel the real objects. For practical application, the software can easily categorize the sensing signals by identifying whether the user is at the sensing stage or the haptic feedback stage.
2.3. 3D Haptic Feedback for Comprehensive Perception Regeneration

Conventional haptic feedback techniques usually possess two dimensional stimuli. However, the actual interactive event often encounters multi-dimensional forces exerted on the skin, such as shear force, normal force, etc. The proposed 3D-SFC can provide controllable and multi-dimensional feedback by changing the input pressure and the actuation sequence to the pneumatic chambers individually. It allows more tactile information to be regenerated during interactions, such as pinching, squeezing, grasping, etc.

As shown in Figure 3a(i,ii), the fingertip touches the surface of the virtual object in different orientations, and the corresponding pneumatic chamber is activated accordingly. More poses of touching the table can be seen in Figure S2a (Supporting Information). As illustrated in Figure 3a(iii) and Figure S3b (Supporting Information), the tactile information conveyed by hand-object contact and hand-hand interactions differed, such as lifting a coffee cup and grasping fingers. It indicates the necessity of utilizing the 3D pneumatic chamber array to improve the cognition of the user.

The tunable input pressure and sequential activation of the pneumatic chambers are essential for recreating the dynamic perception. In Figure 3b, when the finger contacts the virtual sponge, the bottom pneumatic chamber is activated. As the pressing force keeps increasing on the virtual sponge, the fingertip sinks into the deformed sponge and initiates higher input pressure to the bottom pneumatic chamber (Figure 3b(ii)). Additionally, two side pneumatic chambers are also actuated with relatively lower input pressure. Overall, the fingertip with a wrapped and squeezed feeling can be replicated via the tunable haptic feedback, based on the virtual event. Figure 3c shows a comparison of the skin contact force generated by the actuation of the pneumatic chamber at different input pressures. The contact forces with different design parameters of the pneumatic chamber are also given in Figure S4a (Supporting Information). The larger diameter of the chamber provides less contact force under the same input pressure.

In addition to the static feedback generated by pneumatic actuation to replicate contact status, dynamic tactile information, such as sliding across a rough surface, is also an important sensation in understanding the overall properties of a specific object. As shown in Figure 3d, to mimic the water wave passing through the fingertip, the feedback units are sequentially activated from the left side to the right side of the finger, or vice versa. This allows the peak and valley of the virtual water wave to be reconstructed. In addition, in order to mimic the feeling of the finger touching surfaces with different textures, the tunable frequencies of the pneumatic actuation are applied. In Figure 3e, the bottom and the front side pneumatic chambers are actuated alternately to simulate both the texture and the direction of sliding (also can be seen in Figure S3a,b, Supporting Information). In general, the 3D pneumatic haptic feedback with high tunability offered by the TENG sensor and the control algorithms can improve realism and real-time dual-way tactile communication with more comprehensive perception.

2.4. Thermal Haptic Feedback Based on Resistive Heater

Perception of temperature is one of the most important sensations provided by the human skin when interacting with other objects. It can assist the object recognition and risk awareness of the operating environment. In terms of the proposed 3D-SFC, as a Ni–Cr alloy wire is applied as the electrode of the TENG sensor and encapsulated in the lower bottom of the pneumatic chamber. Using the electro-resistive heating effect, the alloy wire can be heated to realize the thermal feedback. As shown in Figure 4a, in the virtual interaction, when the fingertip touches a hot object, the Ni–Cr alloy wire is supplied with electricity and heated, in order to replicate the hot sensation of the virtual object. Together with the pneumatic haptic feedback unit, the device can provide multi-modal haptic feedback for a more immersive experience.

In Figure 4b, the input power required to heat the Ni–Cr alloy wire from 31.4 °C to 103.5 °C ranges from 0.2 W to 1.2 W. The response time of the Ni–Cr alloy wire inside the silicone shows that the higher the input power, the faster it heats up to a specific temperature, indicating that adjustable input power can improve the response time (Figure 4c). As depicted in Figure 4d, the response time of the Ni–Cr alloy wire was evaluated with and without silicone inside the heater at an input power of 0.9 W. The Ni–Cr alloy wire without silicone takes approximately 25 s to reach a temperature of 72.5 °C. For the Ni–Cr alloy wire inside the silicone, a delay of almost 100 s was observed. As a simple demonstration shown in Figure 4e, for the virtual interaction when the fingertip touches the coffee cup, the pneumatic chamber will be actuated to provide tactile perception. At the same time, the Ni–Cr alloy wire within the silicone is heated giving a hot feeling to the finger. Meanwhile, as thermal feedback is often accompanied by haptic feedback, the effect of temperature on the TENG signal of monitoring the pneumatic actuation is evaluated in Figure 4f. As a result, there is almost no influence on the TENG signals within a certain temperature range. FEA simulation of a Ni–Cr alloy wire based on thermal feedback at different input voltages is shown in Figure S6 (Supporting Information), to analyze the temperature produced by the thermal feedback unit of Ni–Cr alloy wire under different applied voltages, and evaluate the deviations of the simulated results for further optimization. The governing equation between the input power and the temperature can be found in supporting information. Overall, the utilization of dual properties of Ni–Cr materials and the fusion design of 3D-SFC ensures simultaneous haptic and thermal feedback, which is essential for real-time multi-modal interaction with good spatial consistency.

2.5. TENG Tactile Sensing with Static and Dynamic Responses

The Ni–Cr alloy wire encapsulated inside the silicone-based air chamber not only can be used as a resistive heater and sensor for monitoring pneumatic feedback but also can be applied as an intuitive HMI for obtaining multi-modal stimuli when engaging with the real object. To enhance the sensitivity, a polyethylene laminate film (Figure S7, Supporting Information) with a hemispherical-shaped micro-pattern is bonded to the TENG sensor (Figure 5a). In addition to the detection of the contact force caused by interacting with real object, the surface texture of the real object can also be identified and differentiated. The bottom
Figure 3. 3D pneumatic feedback with TENG-based monitoring for comprehensive regeneration of skin perception regarding virtual events. a) Single point pneumatic feedback for mimicking the normal force exerted on the virtual table ((i–iii) multiple points pneumatic feedback for mimicking the normal and shear force when holding a virtual cup. b) Changing of activated pneumatic chambers when increasing the pressure on a virtual sponge. c) FEA simulation of the pneumatic haptic feedback forces driven by different air pressures. d) Sequential activation of pneumatic chambers for mimicking the dynamic perception when touching virtual water waves. e) Pneumatic feedback of fingertips sliding across virtual surfaces with grating patterns of different densities.
Figure 4. Characterizations of electroresistive based thermal feedback. a) Schematics of Ni–Cr alloy wire heater and pneumatic feedback for virtual space interaction. b) Relationships between the temperature and the supplied power for thermal feedback. c) Comparison of heating temperature and response time of thermal feedback unit under different power. d) Comparison of response time of thermal feedback with and without silicone at an input power of 0.9 W. e) Pneumatic feedback and thermal feedback before and after fingertip contact with a virtual hot coffee cup. f) TENG-based monitoring of pneumatic actuation under 115 kPa when the temperature of the pneumatic chamber rises from 25°C to 45°C.

of the sensor is shown schematically in Figure 5a. Figure 5b indicates the process of using 3D-SFC to detect the surface roughness of specific objects. Figure 5c(i,ii) show the characterization results for closed-circuit and open-circuit voltages generated by the contact forces ranging from 1 to 5N, respectively.

To mimic the sensory function of skin mechanoreceptors, e.g., slow adaptation (SA) and fast adaptation (FA) receptors for static and dynamic sensing respectively, the as-fabricated TENG sensor is applied to verify the detection of surface roughness (Figure 5d). The objects with different surfaces were examined. The output signal of the TENG sensor when sliding over line pattern polymer and abrasive paper is given in Figure 5e,f, and Movie S2 (Supporting Information). The positive and negative major peaks indicate that the sensor device is touching and leaving the surface of the object, respectively. Because of the sliding-induced vibrations of the fingerprint and the surface microstructure, the waveform between two major peaks represents the signals generated by sliding on the surface of the object, as the TENG sensors are usually featured with good response time to the dynamic stimuli. For the line-patterned surface, a periodic structure generates a relatively consistent output waveform in terms of minor peaks. The featured original TENG signals can mimic the FA receptors of the human skin for surface differentiation. On the other hand, as can be seen from the open circuit voltage signals marked in red, the response to the continuous force applied during the sliding process is similar to the SA receptors of the skin, allowing the presence of loading forces to be identified. In general, the fusion of these two TENG signals can partially mimic the function of the skin mechanoreceptor. The roughness identification of other material surfaces is also shown in Figure S8 (Supporting Information).

3. Applications and Demonstrations
3.1. Intuitive HMI Enabled by 3D TENG Tactile Sensing

In the field of HMIs, the intuitiveness of human–machine interactions during robot teleoperation or virtual training eventually becomes a standard for evaluating the advances of the next generation of HMIs. The effective method of manipulation can greatly reduce the training and maintenance costs (Figure 5g(ii)). Owing to the wrap-around structure of the chambers, it is
Figure 5. TENG tactile sensing with both dynamic and static responses. a) Schematic of contact and surface texture sensing. b) Identifying glass and sandpaper. c) Characterizations of i) close circuit voltage and ii) open-circuit voltage signals from TENG sensing at 2 Hz of contact and separation under different forces. d) Comparison of perceptual information from fast-adapted and slow-adapted receptors in the skin. e) Original TENG signals and open-circuit voltage signals when the fingertip slides across i) a polymer film with a line pattern, and ii) abrasive paper, the scale bar is 3 mm. g) i) Schematics of gesture-enabled intuitive human–machine interactions, ii) Photo of alphabet writing, iii) The process of alphabet writing and corresponding TENG signal.

It is possible to collect the finger movement in different directions by sliding on any surface. To create a real compact wearable HMI, the 3D-SFC is integrated into a glove, together with a control module that includes pneumatic pumps, a customized microcontroller unit (MCU) with a TENG signal acquisition and processing unit, and a lithium battery, as shown in Figure S9 (Supporting Information). The photos of the MCU with wireless transmission module are shown in Figure S10 (Supporting Information).

The TENG sensors located at the positions of pneumatic chambers can detect the vertical and lateral movement of the fingertip on the surface. The corresponding signals represent the motion trajectories for teleoperation control (Figure 5g(iii)). The demonstration is to implement a finger case-based interface to control...
the mouse for simple alphabet writing. The four sensor units are connected to the MCU via a processing circuit, and the signals are transmitted wirelessly to the computer’s communication serial port, where the designated interface for writing settings collects and processes the information to determine the corresponding control movement commands, as shown in Figure 5g(iii). Figure 5g(iii) shows the acquired signals from the TENG sensors during alphabet writing. The positive peak indicates the contact direction, that shows the direction of the finger movement. The controllable item, i.e., the cursor or the robotic arm, will keep moving until the presence of the negative peak (can also be seen in Movie S3, Supporting Information).

3.2. Multi-Modal Sensing and Haptic Feedback Applications in Virtual Assembly Training

For a better illustration of the sensing and haptic feedback functions during a complete training process, virtual assembly training is demonstrated. A series of assembly operations in virtual space (Figure 6a(i)) is performed to test the functions of 3D-SFC, including pneumatic feedback for regeneration of the static and dynamic perception, thermal feedback, TENG tactile sensing, and TENG-based monitoring of pneumatic actuation (Figure 6a(ii)). As shown in Figure 6b and Movie S4 (Supporting Information), Step 1, the operator slides across the surface of the bolt, and the bottom and the front pneumatic chambers are alternately actuated to generate vibrational feedback at a frequency of 2 Hz. The surface texture of the bolt is then transmitted to the operator for identification. With the aid of a metallic connector between the 3D-SFC and the glove, a restoring force can be created for bending the finger to press the TENG sensor inside the finger case. In step 2, the bolt is then held and moved to the specified position for assembling, followed by holding a hot nut and fitting into the bolt, while the respective haptic feedback is done by the actuation of the bottom unit of the finger case. Normal and shear forces and thermal feedback during the rotation of the nut are transmitted by the finger case. During this process, the bottom and right sides of the 3D-SFC are alternately actuated at a frequency of 0.5 Hz for multi-dimensional feedback. In addition, the TENG signals of monitoring the 3D-SFC actuation in Steps 3 and 4 are also illustrated in Figure 6b, and the signals corresponding to the SA and FA functions are also included, showing the capability of mimicking the static and dynamic perception during the twisting. Overall, the multi-modal sensing and haptic feedback delivered through this finger case provides a possible direction for enabling the delivery of comprehensive tactile information in virtual training and education.

4. Conclusion

The advances in haptic feedback and flexible sensors have boosted the functionality and comfortability of wearable devices for better human–machine interactions. However, to achieve spatial consistency during dual-way communication and compact design with multi-modal functions, the fusion of sensing and haptic feedback technologies is still worth further study. The proposed finger case with multi-dimensional and multimodal sensing and feedback functions offers a concept of using dual-material properties of the selected materials, to reduce the system complexity. Specifically, the design of the silicone pneumatic chamber and Ni–Cr wire enables the tunable 3D haptic feedback with dynamic perceptions, while the actuation can be monitored by TENG sensors. In addition, these TENG sensors with the capability of both dynamic and static responses can act as tactile sensing units for recognizing the operational actions and the surface textures. Moreover, the properties of electro-resistive heating of Ni–Cr also enable thermal feedback function. In the end, the demonstrations show the capability of a complete 3D-SFC-based wearable system for conducting training and manipulation programs with enhanced tactile information, which can greatly facilitate training efficiency. In general, it offers a more accessible solution for establishing highly compatible tactile communication for a wide range of applications in productivity, micro-nano manipulation, medical operation, training and education, etc.

5. Experimental Section

Fabrication of Finger Case Module: The external frame of the finger case and the parts connecting the components are 3D printed in a soft material of TPU. The air inlet of each pneumatic feedback module was above the front-side feedback unit. The air channels are designed at the bottom of the front side unit and the width and distance between them was designed to be 1 mm. The pneumatic chamber molds were 3D printed in polyactic acid (PLA) material. Eco-flex silicone A and B solutions (ratio: 1:1, type: 00–30, smooth-on) were mixed and poured into the molds and cured at room temperature for 120 minutes. The size of the silicone film for the lower, left and right side pneumatic chambers of this actuator was 6 mm × 8 mm with a thickness of 1 mm. The size of the silicone film for the front side pneumatic chamber was 6 mm × 6 mm with a thickness of 1 mm. The silicone film was attached to the Ni–Cr electrodes at the frame with Eco-flex silicone (ratio: 1:1, model: 00–30, smooth-on).

Fabrication of Thermal Feedback and Triboelectric Sensing Module: The bottom unit was U-shaped with a total length of 14 mm, width of 9 mm, and thickness of 3.5 mm. The sensor mold was 3D printed in PLA material. Eco-flex silicone A and B solutions (ratio: 1:1, type: 00–30, smooth-on) are mixed and poured into the mold. U-shaped Ni–Cr alloy wire encapsulated in the Eco-flex. The curing time was 120 minutes at room temperature. A polyethylene thermocompression film with surface microstructure was placed on the bottom of the sensor. The individual elements are connected to each other using Eco-flex (ratio: 1:1, type: 00–30, smooth-on).

Characterization Experiments: The power supply (model: UDP3305S, rated voltage: 30 V) was connected to the air pump. The pneumatic chamber was connected to the barometer (model: SNDWAY, SW-S128) and the air pump (rated voltage: 12 V) by means of air tube (inner and outer diameters 1 mm and 2 mm respectively). By increasing the voltage to reach the corresponding pressure, the triboelectric open circuit voltage signal of the pneumatic chamber and TENG sensing unit was measured with an oscilloscope (model: RIGOL, MSO2032A) with an electrostatic meter (model: KEITHLEY, 6514). The force of the film deformation was measured with a force gauge (model: CHINO SENSOR). The Ni–Cr alloy wire was energized, and the corresponding temperature was measured with a thermal imager (model: FLIR-ONE-PRO-IOS). The simulation software used was COMSOL Multiphysics. Deformation and Displacement

The pneumatic chamber was fixed on a horizontal table. Then fixing the laser range finder (model: SNDWAY) on the upper side of the pneumatic chamber and keeping a fixed distance. By measuring the distance between the laser range finder and the film, the displacement of the film deformation in the pneumatic chamber was calculated.

Measurement of Deformation Force: The pneumatic chamber was fixed on a horizontal table top. Then, the force sensor (model: CHINO SENSOR) was fixed on the upper side of the pneumatic chamber.
Figure 6. Demonstration of applications of augmented sensing and feedback. a) i) Application to training and assembly and operational process in the virtual factory workshop, and ii) Tactile perception for operator in real space. b) Application scene, operator perception, pneumatic and thermal feedback of 3D-SFC, and corresponding signal in operational process.
deformation force of the silicone film was measured by contacting the sensor surface with the bulging deformation of the silicone film.

**Sensing and Feedback Control Systems:** Design to implement a wearable, portable sensing feedback glove. Arduino nano was used as the microcontroller to implement the sensing and feedback circuits. Design of the TENG signal pre-processing circuit, including voltage bias circuit, operational amplifier circuit, and low-pass filter circuit. A small 3.6 V air pump was used to control the pneumatic module. The interface to control the air pump and heating wire, the TENG signal processing circuit, and the Arduino microprocessor are packaged on a printed circuit board.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interests.

**Author Contributions**

T.C.: Conceptualization, Methodology, Validation, Data curation, Formal analysis, Investigation, Visualization, Writing-original draft, Writing-review and editing. Funding acquisition. Z.D.: Conceptualization, Methodology, Validation, Investigation, Visualization, Writing-original draft, Writing-review and editing. M.L.: Data curation, Formal analysis, Investigation. M.Z.: Conceptualization, Methodology, Validation, Investigation, Visualization, Writing-original draft, Writing-review and editing, Funding acquisition. Z.D.: Conceptualization, Methodology, Analysis, Investigation, Visualization, Writing-original draft, Writing-review and editing. H.L.: Data curation, Formal analysis, Investigation. Y.Z.: Data curation, Review and editing. M.Z.: Conceptualization, Methodology, Validation, Investigation, Writing-review and editing, Funding acquisition.