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A soft haptic interface for programmable patterns of touch

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A silicone encapsulation of an array of vibrating motors serves as a conformal haptic interface that delivers vibrational feedback to the user. The development of haptic interfaces providing tactile feedback opens another sensory channel allowing human interaction with machines through the sensation of touch.

With advances in technology and software, humans have been seeking more ways to interact with computer systems and other types of machines through the sensation of touch. Due to the development of concepts such as virtual/augmented reality, metaverse, digital twin, and the Internet of Things, the universe of haptic interfaces to deliver sensory experiences has been expanding.[1] Haptic interfaces are devices that enable manual interaction with computer systems and have a broad range of applications including assisting surgical operations, interactive learning, physical rehabilitation, and assisting individuals with sensory impairments.[2–4]

For example, the use of electrodes located on a residual limb of an amputee can provide real-time, tactile feedback from touch sensors on a prosthetic hand, therefore assisting amputees in controlling the prosthetic.[5] Beyond medical applications, tactile feedback can also enhance a virtual or augmented reality experience beyond using only visual or auditory inputs.[6] However, current haptic interfaces have limitations in usability caused by bulky and heavy designs, lack of comfortable interfaces, large area coverages, and hardwired connections.[7] Interfaces with these characteristics impede movement, limiting their applications.

A recent paper published in *Nature Electronics* reports the development of a lightweight, skin-integrated haptic interface that resolves many of these issues.[8] The design leverages wireless communication and power delivery approaches and incorporates arrays of vibro-tactile actuators with stretchable-control electronics.[9] It allows patterns of programmable haptic stimuli to be delivered across the body beyond the fingertips at the desired resolution. The new, versatile design offers a reduction in size and weight and does not require hardwired connections.

This interface consists of an array of hexagonal islands that are physically and electrically connected. As shown in Figure 1A, the interface consists of key components, including a lithium polymer battery, Bluetooth low-energy (BLE) interface, inductive loop coil, near-field communication (NFC), circuit board, and a haptic actuator, that are encapsulated by two thin layers of silicone elastomer. A double-sided flexible printed circuit board (FPCB) supports various components, including the actuators and small-scale FPCB for NFC. The FPCB consists of a layer of polyimide and is patterned with copper traces on the top and bottom. The actuators incorporate brush-type eccentric rotating mass (ERM) vibration motors. The actuators are mounted on the FPCB, and the NFC tag is mounted on a separate, smaller FPCB that is connected to the main board. They can be independently controlled, as each island contains a single actuator and driver circuit. Within each island, the actuators receive power and control signals from surrounding islands, which each supports an electronic subsystem. Islands are distributed at various densities across the skin at locations that address the requirements of the application. The arrays produce vibrations at resolutions that meet or exceed the requirements based on two-point discrimination tests on various parts of the body. The arrays are also built in different sizes, depending on which part of the body they target. Islands are connected by serpentine-shaped structures (Figure 1B) that provide electrical interfaces to the main power source and control unit. Each serpentine is 700 μm wide, 2.6 mm in end-to-end length, and 210° in arc angle. Finite element analysis indicated that the maximum effective strain in the copper remains below the yield strain during ranges of motion (bending, twisting, and stretching) relevant to mounting on large surfaces of the body (Figure 1C). Serpentine-shaped connections are an essential component of the design as they allow for flexibility and conformity of the interface when the user moves.

Groups of seven islands are known as "blocks" and either form control blocks or form expandable blocks. Within each block, each island supports a different electronic subsystem, including (1) power supply circuits, (2) a control unit with a port expander integrated circuit, and (3) wireless systems that incorporate an NFC interface and Bluetooth platform. The battery-powered version uses five rechargeable lithium-ion polymer cells, while the battery-free version

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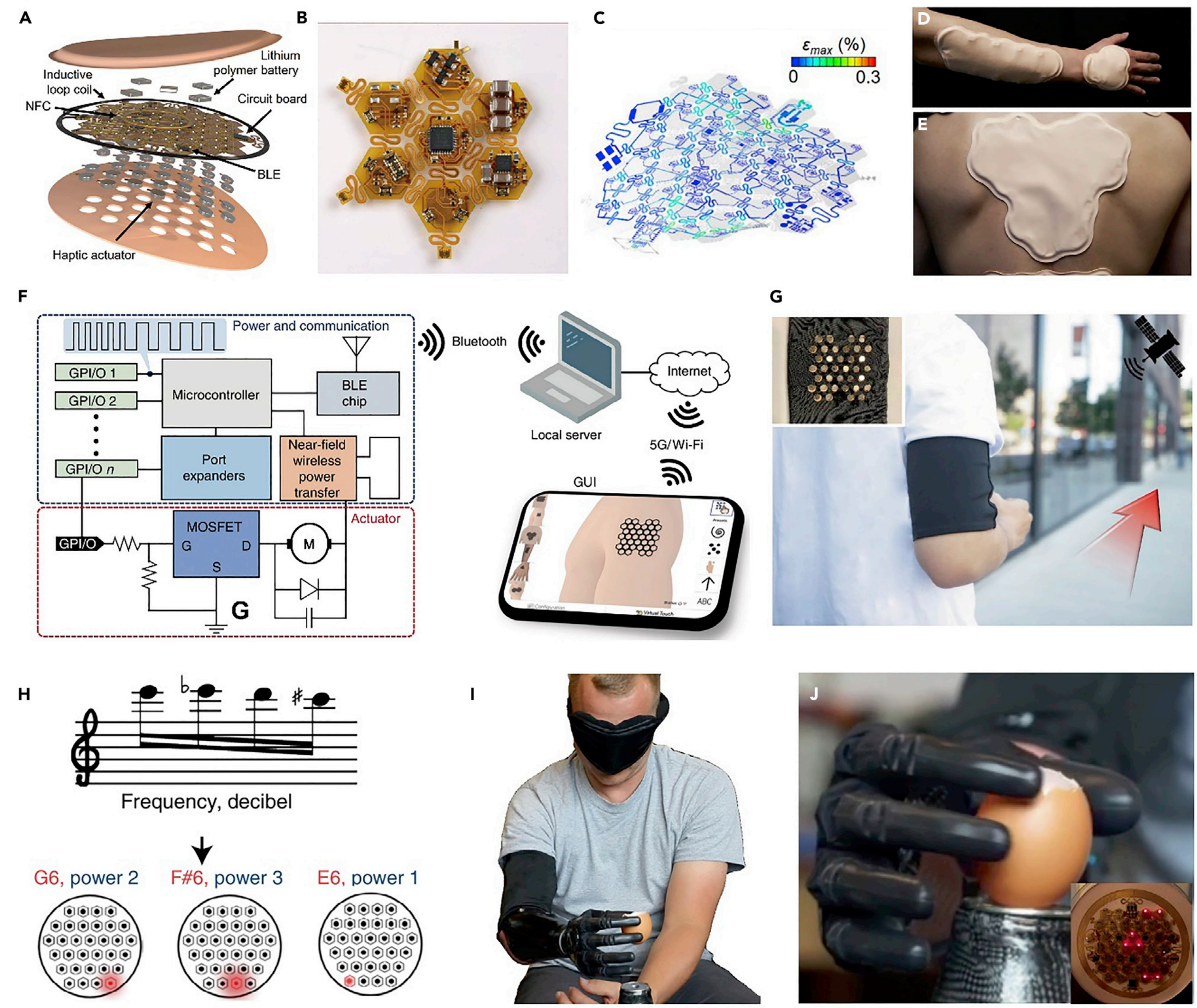

Figure 1. Design and applications of the wireless haptic interface

(A) Illustration of the electronic components and overall structure of the soft interface.
(B) Photograph of a control block containing a microcontroller, wireless communication unit, power management unit, and set of actuators.
(C) Illustration of circuitry within a block.
(D) Photograph of haptic interfaces fabricated through the assembly of prefabricated building blocks on the lower hand and side of the hand.
(E) Photograph of haptic interfaces fabricated through the assembly of prefabricated building blocks on the upper back.
(F) Circuit and block diagram for the wireless haptic interface.
(G) Photograph of GPS-based navigation system that uses the haptic interface in an armband. The inset shows the inner armband where actuators are exposed.
(H) Diagram depicting the translation of musical notes to haptic representations.
(I) Photograph of the sensory replacement process through a haptic interface applied to a prosthetic arm.
(J) Photograph of the prosthetic hand grasping an eggshell. The inset shows the resulting tactile vibration pattern that the actuators produce.

utilizes wireless inductive power harvesting with an inductive coil loop and transmission antenna. The coil offers the array superior mechanical flexibility relative to its battery-powered counterpart. The maximum harvested power is 1.8 W for an input power of 8.0 W at the transmission antenna.

Stitching blocks together can yield large arrays. Every system includes at least one control block, which consists of an array of seven actuators, circuits for power management, wireless communication, and a microcontroller. The remaining expandable blocks consist of an array of seven actuators and a port expander. Prefabricated building blocks are a key component of the design. It allows for the assembly of haptic interfaces with different shapes, sizes, and configurations that stem from the same base technology. For example, the smallest interface contains 21 actuators consisting of one control block and two expandable blocks (Figure 1D). This creates a shape designed for attachment onto the dorsal side of the hand. The largest system consists of 147 actuators consisting of one control and 20 expandable blocks (Figure 1E). This creates a shape designed to naturally fit over the upper back.

Figure 1F displays the circuit and block diagrams of the system. A microcontroller that uses custom firmware provides logic controlling the operation state of each actuator. Port expanders use a serial communication protocol (I^2C) to support modular expansion options. Each expander contains 16 general-purpose input/output (GPI/O) pins. The microcontroller generates digital pulse-width-modulated (PWM) signals with amplitude-shift keying (ASK) modulation manipulating any actuator in the array at a programmable frequency and duty cycle. PWM signals allow for smooth changes in the speed of the ERM motors allowing control over the intensities of the tactile feedback. Metal-oxide semiconductor field-effect transistors address the power requirements of the actuators by driving the ERMs through direct interfaces to the regulated power sources (battery bank or wireless power harvesting unit).

In this study, the haptic interface has been utilized and tested in three different applications. First, the haptic interface was used to provide directions for navigation (Figure 1G). This application enhances spatial awareness for the user, as they no longer need to rely on audio or video inputs for navigation directions. Information from a global positioning system (GPS) was passed into the haptic interface, which outputs 17 pre-programmed patterns of actuation to the user. These patterns included 16 patterns that conveyed directional information and 1 pattern that signaled "arrived at destination." During the testing, light-emitting diodes (LEDs) served as visual representations of haptic points of engagement. The 17 haptic patterns were identified with an accuracy of 85.4%, proving the interface's efficacy.

In the second application, the interface integrated vibrational accompaniments into music (Figure 1H). Artists can better express the qualitative or emotional features of music or speech. This application was tested with an interface of 36 actuators. The output of a microphone transforms digital commands that assign individual musical notes to different actuators. Users were able to distinguish diverse musical tempos such as 216, 170, 120, and 60 bpm with an average accuracy of 89.5%. The ability of the interface to successfully transcribe musical notes into haptic notes is limited by the delays in the wireless packet delivery and the speed of the BLE link. In addition to music, this interface can be used to translate speech into haptic form.

The final application utilized the haptic interface as a sensory replacement for an amputee to control a robotic prosthetic (Figure 1I). In this application, a multitude of sensors distributed across the prosthetic arm's fingers determined the physical nature of the contact with an object. With tactile feedback, the amputee can indirectly sense the force and physical nature of contact with the object, which allows for better control over the prosthetic. The efficacy was proven with an "eggshell test," where the amputee was tasked with grasping an eggshell without breaking the shell. With haptic feedback, the subject was able to grasp the shell and hold it without breaking it. Without haptic feedback, the amputee broke the shell upon grasping (Figure 1J).

Increasing the modes of interaction with the skin can help to further develop this interface. This includes modes such as shear and surface normal vibrations, static displacement, and patterns of heating and cooling. In addition, the disadvantages of silicon adhesive include irritation, moisture buildup, and reduction in adhesive strength and can be improved upon by further development of the encapsulation material and structure, such as integrating active materials or electronic textiles.[10] The development of this haptic interface is exciting, as it offers a boundless range of applications in sensory experiences that can be developed. Due to the prefabricated building block structure, this approach can potentially provide full-body coverage at varying actuator densities. The scalable manufacturing techniques also increase the number of potential applications. Thus, this technology can be applied to further advance current concepts by better delivering sensory experiences.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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