Multimodal Haptic Display for Virtual Reality: A Survey

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(Invited Paper)

***Abstract*—Human haptic perception system is complex, involving both cutaneous and kinesthetic receptors. These receptors work together and enable human to perceive the external world. To simulate immersive interaction with virtual objects in virtual reality scenarios haptic devices are desired to reproduce multiproperties of virtual objects, support multigestures of human hands to perform fine manipulation, produce haptic stimuli for simultaneously stimulating multireceptors (including cutaneous and kinesthetic receptors) of human haptic channel, and thus invoke realistic compound haptic sensations. In recent years, such multimodal haptic devices have emerged. In this paper, we survey the latest progress on multimodal haptic devices, identify the gaps, and put forward future research directions on the topic.**

***Index Terms*—Haptic interfaces, haptic perception, multimodal haptics, virtual reality.**

I. Introduction

THE NEED for multimodal haptic devices (MHDs) comes from application fields such as virtual reality (VR), where a high-fidelity haptic interaction with virtual objects in virtual reality scenarios is simulated. Existing haptic devices are not capable of invoking compound haptic sensations and display multiple properties of virtual objects, including softness, texture, temperature, three-dimensional (3-D) shape and weight, etc.

The other drive for MHDs is due to the fact that the existing devices cannot provide integrated stimuli to simultaneously activate multiple receptors of human haptic channel. Human haptic perception system is complex and consists of diverse kinesthetic and tactile sensing mechanoreceptors. These receptors work in a synergetic manner to enable human to perceive the external world. Traditional force or tactile feedback devices mainly target at stimulating a subset of these receptors. In the recent years, many MHDs have been developed; however, their simulation fidelity is still far from matching with human haptic perception.

Research and development of MHDs promotes understanding human multimodal haptic perception mechanisms on one hand, such as, examination of how the detection and discrimination threshold of one modality may change when combined with another modality simultaneously; and provides an initiative to robotics and haptic technologies on the other hand, such as, in order to provide highly spatial resolution stimuli that are compatible to the resolution of the receptors in human's skin, novel materials and actuation approaches with embedded distributed sensing and control technologies need to be explored.

To this end, we survey the state of the art in research and development of MHDs, quantify the metrics characterizing MHDs, identify the research questions and gaps, and point out the future research directions.

II. Definition and Quantified Metrics of Multimodal Haptic Devices

In this section, we define an MHD and specify the functions and requirements for a high-fidelity MHD.

A. Definition

By an MHD, we mean the device is able to produce multimodal haptic stimuli, including forces, vibration, thermal stimuli, and shape. This type of devices is able to support multigestures of human hands to perform fine manipulation, and simultaneously stimulate multireceptors (including cutaneous and kinesthetic receptors) of human haptic channel. To ensure realistic sensations, the haptic stimuli for stimulating different receptors should be displayed in a consistent spatial and temporal manner, i.e., the spatial collocation error and the temporal delay among these multidimension stimuli need to be smaller than human's discrimination threshold. With a multimodal haptic device, users are able to perceive multiproperties of virtual objects in virtual reality applications.

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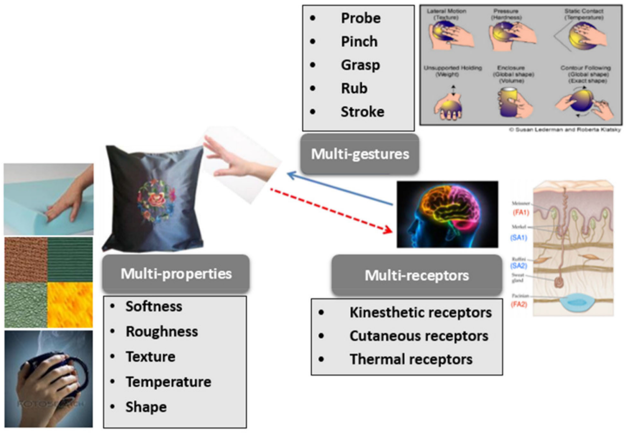

Fig. 1. Example to illustrate the three domains involved in multimodal haptic interaction.

Fig. 1 depicts a scenario where one touches a virtual silk pillow. This involves the three domains that are involved in multimodal haptic interaction, which are object domain, manipulation gesture domain (i.e., exploratory procedures [1]), and perceptual receptor domain [2]. As the silk pillow possesses multiproperties, different haptic sensations are produced when one adopts different gestures. For example, the softness can be felt when pinching the pillow, the smoothness can be felt when sliding a finger along the silk material, and the small bumps, edges, and texture can be felt when the finger slides within the embroidery regions. Also, one can have the cool sensation of the silk with a resting contact.

In the past three decades, huge number of haptic devices have been developed, and thus it is impossible to cover all these devices in one survey paper. By emphasizing the importance of the "3M" features shown in Fig. 1, we narrowed the area of our review. For example, we excluded ground-based or desktop-based kinesthetic feedback devices [106], force feedback gloves for providing kinesthetic feedback [107], and those pure thermal display devices [60]. Recently, a few surveys have existed exploring the combination of a few types of haptic stimuli, including wearable devices for kinesthetic and/or cutaneous feedback [108], surface haptic devices for kinesthetic and/or cutaneous feedback [109]. As a complementation to these existing surveys on multimodal haptic stimuli, our paper is focused on the literatures that can provide insights and lessons to developing haptic feedback devices that possess all the "3M" features shown in Fig. 1.

The above-mentioned three domains or the "3M" features are elaborated briefly below.

1) Multiproperties of Virtual Objects: Haptically perceivable properties of an object include three categories: material, geometric, and hybrid properties. Principal material properties include five aspects [3]: hardness (hard/soft), warmness (warm/cold), macro roughness (uneven/flat), fine roughness (rough/smooth), and friction (moist/dry, sticky/slippery). Geometric properties generally comprise shape (both global shape and local geometric features) and size (such as area, volume, perimeter, bounding-box volume, and so on) [2]. Weight is a hybrid property reflecting an object's material (i.e., density) and its structure (i.e., volume).

2) Multigestures for Haptic Interaction: Haptic perception of surface and object properties is tightly bound to the nature of contact, i.e., whether an object is pressed against the finger or explored over time, and how it is explored. Lederman and Klatzky (1987) described a systematic relationship between exploration and object properties in the form of a set of exploratory procedures (EPs) [1]. An EP is a stereotyped pattern of manual exploration observed when people are asked to learn about a particular object property during voluntary manual exploration without vision.

For example, the EP associated with queries about apparent warmth or coolness is "static contact," which involves placing a large skin surface against an object without motion. Other EPs include "pressure" (associated with compliance), "unsupported holding" (weight), "enclosure" (volume, coarse shape), "lateral motion" (texture), and "contour following" (precise shape). The EP associated with a property during free exploration is also found to be optimal, in that it provides the most precise discrimination along the given dimension [1].

3) Multireceptors of Human Haptic Channel: The characteristics of multireceptors of human haptic channel propose diverse requirements for the stimuli in MHDs. These receptors work in an integral manner to enable human to perceive the external world; and they possess diverse characteristics, including spatial resolution, discrimination threshold, and temporal bandwidth. Locations of these mechanoreceptors in human body, and their spatial and temporal characteristics are summarized in Table I.

By stimulating multireceptors, an MHD invokes both kinesthetic and tactile sensation. Kinesthetic sensation includes force sensation (normal and tangential contact force, gravitational force, inertial force), torque sensation (bending and twisting torque), kinesthetic stiffness (the ratio between force and displacement), and movement sensation or proprioception. Tactile sensation includes surface contact sensation (e.g., slight touch, pressure, vibration), the sensation caused by physical features (e.g., friction, texture, skin stretch, and tactile stiffness that is related to nonuniformed local deformation of skin within the contact area), the sensation caused by geometric features (e.g., 3-D shape, fine geometric features such as bump, groove, contour, edge etc.), thermal sensation and pain sensation.

B. Functions and Requirements

"Digital clay" is a concept of haptic device that can support direct touch and manipulation by bare hands without wearing or holding any device in the hand [4], [5]. To fulfill this concept, the MHD's functions need being defined.

First, with response to user's gestures and the simulated virtual objects, an MHD can be controlled to formulate a desired 3-D shape; and its surface features can be modulated to manifest different surface properties. The surface temperature of the device can be controlled to invoke varying thermal sensations. Furthermore, users can lift the device to feel the weight of a virtual object or to push the device to feel a static or moving

TABLE I
CHARACTERISTICS OF HAPTIC RECEPTORS IN SKIN, TENDONS, AND MUSCLES

Category	Name of the receptor	Location	Perceived feature	Feature sensitivity [2]
Cutaneous mechanoreceptor	Merkel disk (slowly adapting type I)	basal epidermis and hair follicles	pattern/form, texture	• Maximally sensitive to very low frequencies (< 5 Hz) • Point-localization threshold : ~1–2 mm on the fingertip
	Ruffini ending (slowly adapting type II)	cutaneous tissue	finger position, stable grasp	
	Meissner corpuscle (rapidly adapting type I)	thick hairless skin	low-frequency vibration	• Temporal changes in skin deformation (5 to 40 Hz)
	Pacinian corpuscle (rapidly adapting type II)		high-frequency vibration	• Temporal changes in skin deformation (40 to 400 Hz)
Thermoreceptor	A Delta fiber	dorsal root ganglia	cold	• Respond within a temperature range of 5°–45°C • Minimum thermal diffusivity difference required to tell materials apart is 43%
	C fiber	in the nerves of the somatic sensory system	warm	
Nociceptor	A Delta fiber	dorsal root ganglia	pricking pain	
	C fiber	in the nerves of the somatic sensory system	burning pain	
Kinesthetic receptor	Muscle spindles	within the belly of muscles	changes in muscle length,	
			muscle length change rate, and the forces	
	Golgi tendon organs	the junction between the muscle fibers and tendon	force	• Differential threshold for force averages 7-10% over a force range of 0.5-200, and the threshold increases to 15-27% for forces smaller than 0.5 N
	Joint receptors	capsules and ligaments of joints	joint position and motion	• Differential threshold of limb movement is 8% (range: 4-19%) • Differential threshold of limb position is 7% (range: 5-9%)

obstacle. To ensure an integral sensation, the device should be able to simultaneously exert multimodal stimuli at expected locations on the user's body. For example, when a fingertip is touching a virtual object, multimodal stimuli including softness, friction, thermal sensations should be simultaneously exerted on the skin of the fingertip.

Second, the MHD should be able to support direct touch and active exploration between a bare hand and virtual objects, and support multiple manipulation gestures, especially simultaneous contacts between multiple fingers and the object, and distributed contacts between the palm and the object.

Third, the device should be able to simulate multiple objects, including rigid, elastic, plastic and fluid objects, etc. The object can be static or moving to simulate dexterous manipulation between hands and the object.

Quantitative specifications of an MHD can be defined in two levels. The first level is the specifications for each single modality, including the accuracy of the stimuli, the spatial resolution of the stimuli on user's body, the temporal response and the frequency range of the stimuli, and the form-factor, including the exerting site of the stimuli on user's body, the contact area, and number of contact points. The second level is the integral performance among multiple stimuli, including the number of the contributing modalities, and the error of spatial and/or temporal registration among the contributing modalities.

III. TAXONOMY OF MULTIMODAL HAPTIC DEVICES

There are different ways to categorize MHDs according to, such as the number of simulated modalities, the supported gestures, and the form factor, etc. In this survey, MHDs are classified, in terms of the form factor, into ground-based devices, handheld devices, and wearable devices. Fig. 2 shows their representative devices along with the simulated modalities per device.

A. Grounded Multimodal Device

Ground-based haptic devices have promoted the spread of haptic technologies successfully. Representative commercial products include Phantom devices, Omega and Sigma devices, etc. Most of these devices simulate only force feedback. It is logic to extend the function of these devices to incorporate cutaneous feedback by adding a customized end-effector. Kammermeier *et al.* presented two basic approaches for the mechanical coupling of kinesthetic and tactile subsystems [6]. One is a parallel kinematic mechanism, which forms a multifingered feedback device generating vibrotactile, thermal, and wrist/finger kinesthetic stimuli. Another is a serial kinematic mechanism. The approaches were verified using a prototype, in which a single-fingered kinesthetic display was combined with a tactile actuator array. The array was used to provide spatially distributed tactile shape display on a fingertip.

By mounting a Tactile Labs haptuator (TL-002-14R) on the stylus of a Phantom Omni haptic device, Culbertson and Kuchenbecker prototyped a device to render friction, hardness, and microscopic roughness during surface material exploration [7]. The virtual surfaces were simulated using a combination of friction, tapping transient, and texture vibration models. Similarly, by integrating a cable-driven force feedback device and a squeeze film effect tactile display, Yang *et al.* developed a device that couples lateral force and variable friction tactile feedback [8]. The finger position was tracked by the cable-driven device while the cable tensions to exert force feedback. The vibration

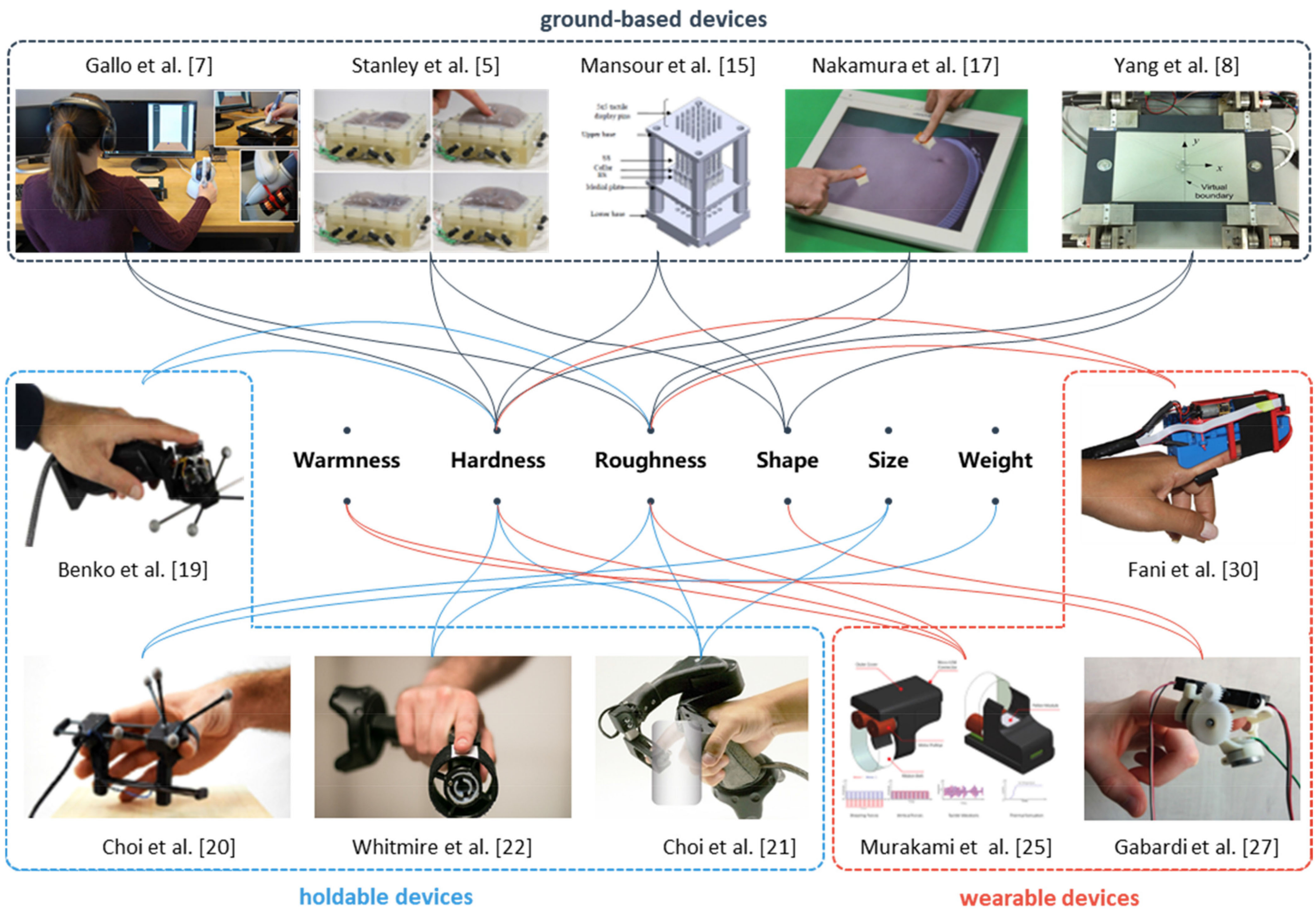

Fig. 2. Photo of representative multimodal haptic devices.

amplitude was modulated to control the friction coefficient of the tactile display.

As computer mouse is the most widely used interface, there have been various studies in extending a traditional mouse to provide multimodal haptic sensations. Yang *et al*. developed a haptic mouse that is able to convey kinesthetic and tactile information simultaneously [9]. The mouse can provide 2-degrees-of-freedom (DoF) translational force feedback, vibration, normal pressure, skin stretch and thermal feedback. The mouse can also simulate small-scale shapes and roughness of surface textures using cutaneous cues generated by a 6×8 pin array. A thermal feedback unit composed of a heat conduction plate and a temperature sensor was embedded into the tactile display system [10], [11]. Strese *et al*. presented a tactile mouse that is able to display five tactile dimensions, in which macroscopic roughness is displayed using a servo motor and electromagnets, microscopic roughness using a voice coil actuator, thermal conductivity using a Peltier element, hardness using a servo motor, and friction using electromagnets and a ferromagnetic plate. Results of user studies showed an 89.6% recognition rate for surface material property ratings in the absence of visual and audible clues [12].

Recently soft actuators have been introduced into the design of MHDs. Using the combination of particle jamming and pneumatics, Stanley and Okamura presented a tactile display that is capable of independent control of both shape and mechanical properties [13]. A four-cell array of particle jamming cells with basic measurements of its shape and stiffness output capabilities was developed, in which a flexible membrane filled with a granular material changes its rigidity with the application of a vacuum. Various sequences of cell vacuuming, node pinning, and chamber pressurization allow the surface to deform into a variety of shapes.

Pin-array can simulate both shape and texture, thus being widely used for designing MHDs. Hribar and Pawluk. presented a device consisting of a pin matrix and a thermal display [14]. The pin matrix produces tactile texture information such as brushstroke sensation to the fingers, and the thermal display simulates the warm-cold spectrum of colors. Mansour *et al*. designed a multimodal tactile display device that can display both surface shape and stiffness of an object by matrix of a 5×5 pin units [15], [16].

Electrostatic effect has also been utilized for designing MHDs. Nakamura *et al*. proposed a device consisting of a contact pad and an electrostatic visuo-haptic display. This device can provide softness sensation to vertical pushing and lateral reaction force to lateral exploration [17]. By using electroadhesion brake which is controlled as function of the normal pushing force, the device can provide softness sensation through controlling contact area. Hashizume *et al*. developed a tactile device combined with magnetic and electrostatic fields to express various textures [18]. The system physically deforms and changes the physical force between the finger and the device. The magnetic field generates force to push up and down using ferrofluid. The electrostatic field generates force to horizontal directions using electrovibration.

B. Handheld Multimodal Device

In order to provide a large workspace to enable large-scale body movement, handheld devices have been studied. A further advantage of handheld devices is easy to be put on and off. In recent years, handheld controllers have emerged as the dominant interaction interface for commercial VR devices (e.g., Oculus Rift and HTC Vive). However, these controllers can only provide vibrotactile feedback. Recently, several efforts have been devoted to develop handheld devices with multimodal haptic feedback.

Benko *et al*. proposed two handheld haptic devices called NormalTouch and TextureTouch [19]. The former renders object surfaces and provides force feedback using a tiltable and extrudable platform. The latter renders the shape of virtual objects including detailed surface structure through a 4×4 matrix of actuated pins. These devices can deliver 3-D shape output in a compact and lightweight handheld form factor. Furthermore, they are able to provide a human-scale force in rendering 3-D shapes for both cutaneous (i.e., haptic sensations on the finger surface) and kinesthetic feedback (sensation of actuating and displacing the finger).

To design a MHD which can simulate touching, grasping, gravity, and inertia, Choi *et al*. combined a gripper type device with cutaneous asymmetric skin stretch [20]. The device can simulate kinesthetic pad opposition grip forces and weight for grasping virtual objects in VR. The MHD is mounted on the index finger and thumb, and enables precision grasps with a wide range of motion. A unidirectional brake creates rigid grasping force feedback. Two voice coil actuators create virtual force tangential to each finger pad through asymmetric skin deformation. These forces can be perceived as gravitational and inertial forces of virtual objects.

Choi *et al*. proposed a multipurpose controller, Claw, which augments the typical controller functionality with force feedback and actuated movement to the index finger [21]. The controller enables a variety of force and tactile renderings for the common hand interactions: grasping, touching, and triggering. It can render 3-D shapes and the sensation of holding a rigid or soft object between the user's fingers. It also generates various textures when users rub virtual surfaces with their index finger, and enables a gun trigger sensation.

Whitmire *et al*. proposed Haptic Revolver, which is a reconfigurable handheld controller that renders fingertip haptics when interacting with virtual surfaces [22]. The device can render touch contact, pressure, shear forces, textures, and shapes using a rotating wheel beneath the index finger. Haptic Revolver's core element is an actuated wheel that raises and lowers the finger from underneath to render contact with a virtual surface. As the user's finger moves along the surface of an object, the controller spins the wheel to render shear forces and motion under the fingertip. The wheel is interchangeable and contains physical textures, shapes, edges, or active elements to provide different sensations to the user.

Pen is an important type of handheld devices. Kyung *et al*. developed a pen-like device with a built-in compact tactile display and a vibrating module [23]. Three representation methods (force, tactile and vibration feedback) have been compared with three texture groups which differ in direction, groove width and shape. Similarly, Culbertson and Kuchenbecker proposed a tool-mediated device that is able to change the perceived friction between the tool and the underlying material [24]. By changing the position of a solenoid plunger, braking forces are applied to a rolling steel ball, the vibrotactile texture signals are generated using a haptuator to present microscopic roughness.

C. Wearable Multimodal Device

With a handheld device, one can simply pick it up and begin using it without having to strap anything to the fingers. However, they normally restrict hand postures during interaction between the hand and virtual objects. Compared to handheld controllers, finger-mounted wearable devices can support diverse hand postures and to provide more natural interaction experiences.

Murakami *et al*. developed a fingertip haptic display with integrated force, tactile and thermal feedback in a miniature form factor [25]. The apparatus can render vertical forces by pulling the belt, shearing forces by sliding the belt, textures by converting the textural audio signals into dc motor pulsewidth modulation commands and thermal sensations with the peltier module [26].

Gabardi *et al*. developed a fingertip device with potentials of full haptic and thermal rendering of contact with virtual surfaces [27]. The device can orient a plate around the user fingertip with two rotational DoFs actuated by two servo motors. A voice coil actuates the plate in the finger direction in order to provide the user with the tactile feedback about both the textures and the surface features. The thermal feedback is provided through two coplanar aluminum plates controlled in an independent way. Each plate has a thermistor embedded in order to close the thermal control loop. The choice of dividing the aluminum plate and controlling the two half independently allows providing the thermal illusion called "thermal grill" or "synthetic heat." A portable realization of this same concept, named Active Thimble was developed [28]. A voice-coil actuator was introduced for simulating fast contact transition, and the overall system mobility was reduced to three-DoF: two for the orientation and one for control of the contact force at the fingertip. Gabardi *et al*. [29] further improved the Active Thimble by replacing sheathed tendon actuation with DC motors mounted directly on the joints.

Fani *et al*. presented a fabric-based display for multicue delivery that can be worn on user's finger and enable both active and passive softness exploration [30], [31]. It can also induce a sliding effect under the finger-pad. A desirable stiffness profile can be obtained by modulating the stretching state of the fabric through two motors. Two different modes of interaction can be obtained: a passive mode, where the user receives a mechanical stimulation from the lifting mechanism pressing the fabric against the finger-pad, and an active mode, where the finger actively probes the interaction surface for softness.

Prattichizzo *et al.* [32] presented a wearable three-DoF fingertip device that consists of two platforms: one is located on the back of the finger, supporting three small dc motors, and the other is in contact with the volar surface of the fingertip. The motors shorten and lengthen three cables to move the platform toward the user's fingertip and reorient it to simulate contacts with arbitrarily oriented surfaces. The direction and amount of the force is varied by controlling the cable lengths.

MISSIVE is a wearable device on the upper limb [94]. This device delivers tactile cues through combinations of vibration, radial squeeze, and lateral skin stretch. Experimental results showed that the device outperformed a strictly vibrotactile system in terms of both cue identification accuracy and user preference.

Tactile array has been widely used in multimodal devices. Caldwell *et al.* [33] presented a device able to combine normal indentation and shear stimuli, with the objective of stimulating a wide range of mechanoreceptors, with localized stimuli from dc to 400 Hz. A pin array was used to provide information about shape and edges. Gallo *et al.* developed an electromagnetic-pneumatic actuation to operate a 2 × 2 array of tactile cells [34]. Each cell provides a repetitive stimulation with a force and an indentation. The temperature of the display is controlled using a peltier element attached to an air-cooled heatsink. The tactile cells deliver distributed tactile information with forces up to 200 mN, displacements of over 1 mm, and a bandwidth of 2 Hz. Moy *et al.* [35] introduced a compact fingertip device using a pneumatically actuated tactile display molded from silicone rubber. The tactile display consists of a 5 × 5 array of elements. Elements are placed 2.5 mm apart from each other and have a diameter of 1 mm. Pin and air balloon arrays provide spatially distributed tactile information. Huang *et al.* proposed a multimodal sensory feedback system for upper limb amputees [115]. Their device can provide vibrotactile and mechanotactile stimulation by using a custom-designed multimodal stimulation array.

Finger exoskeleton is another important type of wearable devices. Leonardis *et al.* [36], [37] presented a wearable skin stretch device for the fingertip. An asymmetrical 3RSR mechanism allows compact dimensions with minimum encumbrance of the hand workspace and minimum interfinger interference. Tanaka [38] presented a haptic glove able to provide kinesthetic feedback to four fingers using pneumatic balloon actuators and cutaneous feedback to two finger pads using air jet nozzles. Kim *et al.* [39] developed a wearable hand exoskeleton able to provide 1-DoF kinesthetic feedback to each finger and vibrotactile stimuli at the fingertip. Khurshid *et al.* [40], [41] developed a wearable device able to provide grip force feedback, along with independently controllable fingertip contact, pressure, and vibrotactile stimuli. Stergiopoulos *et al.* [42] developed a two-finger exoskeleton for virtual reality grasping simulation. It allows full finger flexion and extension and provides kinesthetic feedback in both directions. Chinello *et al.* [43] presented a wearable fingertip device composed of two parallel platforms: the main body is fixed on the back of the finger, housing three small servo motors, and the end-effector is in contact with the volar surface of the fingertip. In order to make and break contact with the skin, the mobile end-effector is controlled moving toward the user's fingertip, and to simulate contacts with arbitrarily oriented surfaces. Pacchierotti *et al.* proposed a device that can simulate both contact forces and vibrations, where a cutaneous feedback solution is provided by mounting a custom cutaneous display to the master controller [114]. Chinello *et al.* presented a 3RRS wearable fingertip device for rendering both stiffness and vibrations [116].

TABLE II
ACTUATION METHOD OF EACH MODALITY IN EACH DEVICE

Modality	Actuation method
Softness	Pneumatics [13, 35], Deformable Contact Pad [17], Ferrofluid and Magnetic Field [18], Shape Memory Alloy Spring [15], Stretch Belt [30]
Roughness	Pin Array [14, 19, 33, 35], Electroadhesion [17], Electrovibration [18], Electromagnetic [44], Voice Coil Actuator [21], Haptic Wheel [22], Motor and Stretch Belt [25, 30], Piezoelectric Ultrasonic Actuator Array [45]
Temperature	Peltier [9, 14, 25, 46]
Shape	Particle Jamming [13], Pin Array [9, 15, 19, 35, 47], Electromagnetic and Pneumatic [44], Mobile Platform [19, 43], Haptic Wheel [22], Piezoelectric Ultrasonic Actuator Array [45], Dielectric Elastomer Actuator [48], Pneumatics [38]
Vibration	Linear Resonant Actuator [21], Voice Coil Actuators [40], DC Motor [42]
Skin stretch	Tactile Array [33], Mechanism [36]
Contact and pressure	Servo Motor [21, 22], Mobile Platform [43], Tactor Array [47], Pneumatic [33], Dielectric Elastomer Actuator [48], Mechanism [36], Voice Coil Actuators [40], DC Motor [42]
Mass/Inertia	Skin Stretch [20]
Force/Torque	Mobile Platform [19], Servo Motor [21], Haptic Wheel [22], Stretch Belt [25], Pneumatics [38], DC Motor [40, 42]

IV. Gap Toward Multimodal Haptic Devices

Concerning the three domains proposed in Section II-A, we can compare the existing devices with the desired functions of a high-fidelity MHD, thus to identify the gaps.

In the aspect of the simulated modalities, only a few devices can simultaneously simulate the three basic modalities (softness, texture, and thermal feedback). No device can simultaneously simulate the five modalities (softness, texture, thermal, 3-D shape, and weight). In view of simulating both the five modalities and more modalities such as vibration, contact forces, and torques, no such MHDs exist.

Considering integration issues among multiple modalities, the spatial interference issue has not been rigorously studied in existing MHDs. Table II summarizes the actuation method for the simulated modalities in existing MHDs. Each stimulus is delivered by a different type of actuator, which has its own volume. When multiple modalities are integrated, spatial interference among different actuators is a big issue. One example is thermal display, in which the large-sized cooling module prevents the thermal device from being integrated with other modalities in a compact space. The spatial layout is a key challenge as the

TABLE III
METHOD OF SENSING HUMAN BEHAVIOR AND CORRESPONDING CONTROL STRATEGY IN TYPICAL DEVICES

Form factor	Sensing method and target gestures
Grounded device	Phantom(Dragging, Pressing, Tapping) [7], Conventional Mouse(Dragging, Grabbing, Pressing) [9, 14], Visual Screen(Dragging) [17], Marker and Camera(Dragging) [18]
Holdable device	Force Sensor(Pressing) [19], Force Sensor(Grasping, Touching, Triggering) [21], Retroreflective Spheres(Translating and Rotating) [19, 20], Proximity Sensor(Thumb Position) [21], Vive Tracker(Translating and Rotating) [21, 22], Encoder(Sliding) [20]
Wearable device	Hololens(Translating and Rotating) [25], Infrared Sensor(Pressing) [30], Encoder(Pressing) [30], Encoder(Grasping) [40, 42], Marker and Optical Tracker(Translating and Rotating) [28, 29, 36], Force Sensor(Pressing) [32], Pressure Sensor(Pressing) [33], Sensing Glove(Translating and Rotating) [38]

multimodal stimuli need to be exerted in a collocated way on the users' skin.

A related unexplored issue in existing MHDs is how to quantify the spatial registration error and the level of temporal consistency among all involved modalities. According to the high spatial resolution and diverse temporal bandwidth of receptors in skin, a high-fidelity haptic device need to produce high spatial density of haptic stimuli that match the temporal characteristics of the target receptors.

In the aspect of the supported gestures, as shown in Table III, most devices can only simulate less than four types of gestures. In robotic teleoperation and VR shopping scenarios, much more gestures are needed to ensure the realism of the interaction task, as diverse gestures may produce different haptic sensations. It is a great challenge if not an impossible task to mimic all gestures.

Therefore, in most existing devices, simplification methods were adopted to reduce the number of gestures that need to be tracked, or to reduce the tracking DoF of the hand. For example, in Claw, three interaction modes were defined (touch, grasping, and gun mode) [21]. The switch of the modes is based on detection of the movement of the thumb by an optical proximity sensor that is integrated into the controller's thumb rest. The sensor detects when the thumb is on the thumb rest. Similar approaches were used in the Grabity device, in which an efficient motion tracking solution was achieved by adopting a subset of hand gestures (i.e., pad opposition grasps between index finger, middle finger, and thumb) [20]. By using this type of simplification methods on gestures, it is possible to achieve a tradeoff between simulation fidelity and compactness of the device. Table III summarizes the methods of sensing human behavior in typical devices.

V. CHARACTERISTICS OF MULTIMODAL PERCEPTION

Understanding the perception characteristics of multimodal haptic cues is a prerequisite to develop effective multimodal devices. This section summarizes the progress on this topic.

A. Five Dimensions of Tactile Perception

Excluding the shape of objects, Okamoto *et al.* summarize five dimensions of tactile perception, including macro roughness (uneven/flat), fine roughness (rough/smooth), warmness (cold/warm), hardness (hard/soft), and friction (moistness/dryness and stickiness/slipperiness) [3]. According to the summary [3], roughness, hardness, and warmness can be referred as the fundamental dimensions of tactile perception. Among the three fundamental dimensions, hardness or roughness is more prominent than warmness, although their contributions vary across studies. For example, Bensmaïa and Hollins [49] reported that roughness and friction rather than the warmness factor contributed to the perceived dissimilarities between materials.

B. Perceptual Mechanisms of Various Haptic Stimuli

The mechanisms of tactile perception have been studied in depth, although some aspects are still not well understood. Here we summarize basic findings while further details could be found in the review articles by Jones and Lederman [1], Lederman and Klatzky [2], Bensmaïa [49], Tiest [50], and Okamoto [3].

Roughness perception can be divided into two levels: macro roughness and fine roughness. Their perceptions are mediated by different mechanisms, since the microscopic and macroscopic roughness appears to be perceived by different mechanoreceptors in the human skin [2], [3]. The surface material structural threshold between coarse and fine textures was determined as approximately 200 μm [49]. For coarse surface roughness, it is known from neurophysiology studies that the spatial distribution of Slow-adapting type I (SAI) units contributes to roughness perception [51]–[53], whereas the temporal information on skin vibration that is caused by exploring rough textures has an insignificant effect on the perception [54], [55]. In contrast, for finer surface roughness, the contribution of the vibratory information is clearer [56], [57]. Fine roughness results from high-frequency vibrations during surface-tool or surface-finger sliding motions and is perceived by the FA2 receptors between 40 and 400 Hz [2]. Thus, FAI and FAII units are related to the perception of fine roughness.

Friction perception is mediated by the skin of the finger pad. Skin stretch or adhesion of a finger pad to textures has been considered to mediate the perception of friction, and one suggestion is that the stick-slip phenomenon between a finger pad and a frictional texture influences the friction perception [58], [59]. One may doubt that the frictional and fine roughness dimensions are the same. However, it appears reasonable that the perception of friction is based mainly on skin stretch related to textures, whereas the perception of fine roughness is based on vibration of the finger pad.

The perception of warmness and coldness is attributed to the heat transfer property between textures and finger skin [1], [29], [31], [60]–[62]. Transient receptor potential (TRP) ionchannels on free nerve endings have been identified as heat and coldness receptors [63], [64]. For instance, TRPV1 responds to heat stimuli above approximately 43 °C. TRPV2, TRPV3, and TRPV4 also respond to stimuli that are warmer than human body temperature. These ion channels are activated in different temperature bands. The perception of temperatures below human body temperature is mediated by receptors, such as TRPA1 and TRPM8.

The perception of softness or elasticity is attributable to tactile cues [65], [66], although the perception of the spring constant of materials is considered to be related to force information. In the mechanism for the tactile perception of softness, the contact area between the finger pad and the target object is important. In [67] and [68], tactile softness displays have been designed to control the contact area between their contactor and finger pad. However, it is unclear whether the pressure distribution in the contact area, the history of area changes, or another type of information are dominant.

C. Haptic Illusion Effects for Multimodal Haptic Devices

Haptic illusion has been widely used to meet the compact-size requirement of MHDs. One typical mechanism is to utilize tactile feedback to simulate kinesthetic sensation (e.g., weight sensation) that normally is simulated by using grounded devices. Muscle spindles and golgi tendon organs in human arm sense weights proprioceptively [69]. At the same time, mechanoreceptors on finger pads sense weights by being pressurized or distorted laterally [52]. By combining proprioceptive and tactile feedback, humans sense weights naturally. However, haptic systems creating proprioceptive weight sensation are generally bulky and heavy because they need to be grounded externally with multiple linkages. Therefore, it is desirable if weight sensation be created using only tactile feedback.

Minamizawa *et al.* investigated the role of proprioceptive and tactile sensation for weight simulation [70]. According to their work, tactile sensation without proprioceptive sensation provides certain perceptive cues that help differentiate weights. Researchers have also attempted to use ungrounded, wearable devices to simulate the weight of virtual objects using skin stretch [71], [72]. Amemiya and Maeda created a slider-crank mechanism to generate asymmetric vibrations and showed that these vibrations can be used to change the perceived heaviness of an object [73]. This mechanism required the user to always keep the device oriented toward gravity and the asymmetric vibrations were created using a bulky mechanical apparatus. In the Grabity device [20], Choi *et al.* used a vibration actuator and a skin deformation mechanism for rendering inertia and mass of a virtual object. To create the sensation of gravity and inertia, they adapted two voice coil actuators to a mobile gripper type haptic device. Different magnitudes of asymmetric vibrations were utilized to generate various levels of force feedback.

Another mechanism is the thermal grill effect, which refers to the burning pain that can result from touching interlaced warm and cool bars [74], [75]. Painful burning sensations have been reported in response to stimulation with alternating hot (36–42 °C) and cool (18–24 °C) innocuous temperatures on the palm of the hand, with the most elevated and consistent pain ratings occurring in response to temperature combinations of 20/40 and 18/42 °C. This illusion is helpful to eliminate the usage of a bulky cooling device for simulating cold sensation.

Sensory saltation is a well-known spatial illusion involving mislocalization on the skin. In this illusion, a series of short pulses delivered successively at three different loci on the skin is perceived as a stimulus that moves progressively across the skin "as if a tiny rabbit were hopping" in a smooth progression from the first stimulator to the third [76]. The illusion can occur with as few as two and as many as 16 taps [76]. The temporal separation between the stimuli also influences the strength of the illusion with intervals between 20 and 250 ms being optimal. As the interval between the presentation of stimuli is reduced, the taps are perceived as being much closer spatially until at an interval of about 20 ms, where no spatial separation can be perceived [77]. At interstimulus intervals of 300 ms or more, the taps are localized accurately [78]. This illusion may be used for simulating the sensation of vibrotactile flow and for reducing the number of vibrators on human body.

Haptic illusions between multimodal stimuli have also been studied. A number of illusions related to weight perception have been demonstrated, for example, thermal/weight [79], size/weight [80], and material/ weight [81] illusions, as well as the "golf-ball" illusion [82]. These variations in weight perception may provide guidelines for developing new MHDs.

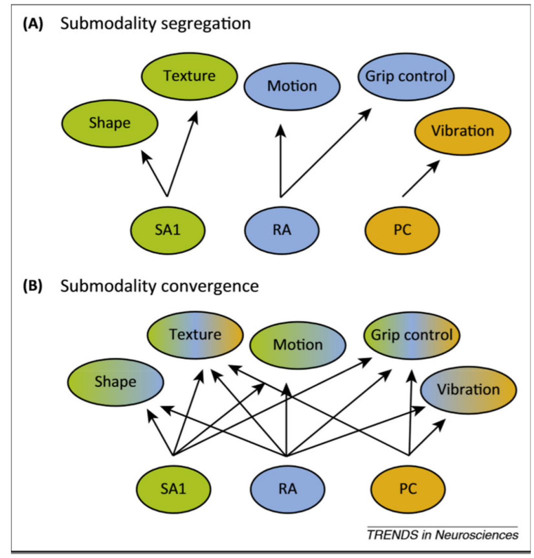

Fig. 3. Coupling mechanism among different modalities [111].

D. Coupling Mechanism Among Modalities

As shown in Fig. 3, submodality segregation and convergence is an inherent mechanism of human perception systems [111]. Understanding of the interaction effect between different types of stimuli may provide guidelines for designing novel MHDs. For example, the effect of thermal stimuli on the perception of vibration stimuli has been widely studied. Tactile sensory acuity and the perceived intensity of tactile stimuli can be influenced by the temperature of the device contacting the skin and by the temperature of the skin itself.

Two-point and gap detection thresholds decrease (i.e., enhanced sensitivity) when the tips or edges of the devices in contact with the skin are either cooled or warmed [45], [83]. These effects have been termed thermal sharpening and are attributed to highly localized thermal gradients on the skin which facilitate the detection of spatially dispersed tactile stimuli [83].

In contrast, when the skin is cooled, tactile acuity is impaired as shown by the decline in sensitivity to changes in pressure [47], roughness [33], and vibrotactile stimulation between 150 and 250 Hz [48]. The decrease in tactile acuity when the skin is cooled is attributed to a decline in the sensitivity of cutaneous mechanoreceptors which are known to alter their discharge rates in response to cooling the skin [35], [36].

The effects of warming the skin on tactile acuity are smaller and less robust. Green [117] reported that warming the skin resulted in a slight increase in thresholds for frequencies of vibration above 80 Hz, but Verrillo and Bolanowski [118], [84] observed no changes in vibrotactile sensitivity for frequencies between 15 and 500 Hz when skin temperature was increased from 30 to 40 °C. More recently, Zhang *et al*. [119] noted that with increases in skin temperature up to 43 °C there was a decrease in vibrotactile thresholds at 25 Hz, but at this temperature there was no effect on vibrotactile amplitude discrimination. Another study examined the effect of cold temperature in perceived magnitude of vibrotactile stimuli. Results showed that among four different mechanoreceptors, only Pacinian channel was affected by skin temperature [41], so high-frequency perceptual characteristics was affected by temperature variation.

While the above studies have demonstrated the effect of the temperature of an object or the skin on tactile perception, other studies investigated the influence of tactile stimuli on thermal perception. Singhal and Jones explored whether the simultaneous presentation of thermal and tactile cues enhances user performance and if the two types of sensory signals can be processed independently or interactively [85]. Thermal pattern identification was measured in the presence of concurrent vibrotactile feedback on the thenar eminence on the hand. The results indicated that with concurrent tactile stimulation warm stimuli (89%) were easier to identify than cool stimuli (76%). These thermal–tactile interactions indicate that in multimodal displays the ability to perceive independent channels of communication can be influenced by the concurrent presentation of other sensory cues.

Quek *et al*. developed a tactile display aiming to augment kinesthetic force feedback with skin stretch feedback [113]. Results show that the addition of skin stretch causes a significant increase in the perception of stiffness, and this effect increases with higher amount of applied skin stretch.

VI. Future Research Topics

In order to fill the gap for simulating high-fidelity multimodal haptic sensations, future research and technical challenges are discussed below.

A. Open Questions on Multimodal Perception

To design MHDs, more studies are needed to understand the perception characteristics when multimodal haptic stimuli being perceived simultaneously.

First, the detection and/or discrimination threshold for a single modality has been widely measured [86]. However, it is unclear how these thresholds may change when a user simultaneously perceives two modalities. As summarized in Section V-D, some work has been performed to explore the coupling effect between thermal and vibration, which provide useful guidelines for developing thermal-vibration integrated display. More rigorous studies are needed to reveal the coupling effect among other modalities. Considering the various haptic stimuli to be rendered by an MHD, the coupling effects of certain modality combinations (e.g., the coupling effect between texture and softness, or between temperature and softness) are still unclear. Quantification of these effects is necessary for development of novel MHDs.

For example, it is an interesting question to examine the coupling effect between texture and thermal perception. In one aspect, under a cool or hot temperature, discrimination threshold for textures might be different. Quantified measurement of the difference needs to be obtained for defining the stimuli signal for an integrated texture-thermal device. In the other aspect, the influence of texture on the just noticeable difference of temperature perception could be measured.

Another fundamental question is to investigate effective haptic illusions to promote the development of MHDs. Although there are well-known illusions (such as skin stretch for simulating weight sensation, thermal grill effect, etc.), the question remains open to effectively utilize these illusion effects to design MHDs and explore novel haptic illusions.

Last but not the least, as spatial and/or temporal registration errors among the multiple stimuli are unavoidable in an MHD, a further question is the effect of spatial and temporal registration errors on the perception results of the involved modalities.

B. Sensing Gestures to Simulate Fine Manipulation

To simulate direct touch and fine manipulation between a bare hand and virtual objects, diverse gestures need to be simulated, including tapping, grasping, sliding, pinching, rubbing, manipulation, etc. Just for the grasping gesture, there is a rich family of gestures [88]. For fine manipulation using complex gestures, a small movement of the fingers may produce different contacts between the hand and the object, thus invoking different contact force and tactile sensations. For example, different gestures of touching a garment may cause subtle different sensations (e.g., pressing, pulling, palpating, and rubbing). Therefore, the sensing system of an MHD needs to be sufficiently accurate to capture the slight change in the gestures and thus to simulate subtle force sensations of touching fine features on the surface of the virtual objects. Effective sensing approaches need to be developed to ensure the accuracy and sensitivity of capturing the fine movement of the fingers and/or the palm.

Another question is the robustness of hand motion tracking. When the fingers press the surface of the device and produce both normal deformation and lateral movement, they may indent into the surface of the device and thus be occluded by the device. Classic camera-based capturing method may be not effective to work under the above occlusion scenarios. Novel sensing approaches need to be explored to ensure the robustness of hand movement measurement. For example, distributed tactile sensors like artificial skin [89] can be mounted on the surface of the device to accurately detect the movement of the fingers and/or the palm.

A further question is to explore the relationship between the form factor and the supported gestures. A handheld device is easy to be put ON and OFF even when users are wearing a head mounted display, but it is unable to simulate those gestures that require direct touch between five fingers and objects. In order to hold the stylus of a handheld device, the palm and the three fingers are always occupied by the real contacts with the stylus, which greatly reduces the supported gestures of the handheld devices. In the contrary, compared with handheld devices, a wearable device is able to support more diverse interaction gestures of five fingers. However, it is time consuming to be put ON and OFF, and not easy to adapt for users with different hand sizes. To find a tradeoff solution, novel form-factor should be explored to combine the advantages of handheld and wearable devices.

Last but not the least, the preferred EP for a specific property may be useful for developing effective MHDs. For example, previous work indicates that hardness perception results from specific exploration patterns such as tapping on an object surface, pinching an object, or pressing on the surface [90], [91], [92]. Therefore, we need to know the accessible properties for a given EP, and whether two EPs can be combined to explore a specific property. Each property has its preferred gesture and thus requires the adoption of different sensors for tracking the gestures. For example, temperature is normally perceived by static contact, while softness and texture are normally perceived by pressing and lateral motion, respectively. How and where to mount the sensors to track these different gestures, and ensure no interference or occlusion between sensors and mechanical structures, is yet an open problem.

C. Actuation Integrating Force and Tactile Feedback

Most current tactile displays were implemented on a rigid structure, which prevents a tight contact between the actuator and a curved part of a body such as hands or arms. For example, the most widely used thermal module is rigid peltier, which is hard to be integrated with a softness display device. Suppose, when a peltier plate is covered on top of a softness device, the softness sensation will be masked. Likewise, it is hard to embed a rigid peltier plate within a 3-D shape display. A thermal display module usually needs an air or water cooling system, which has a big size and thus making its integration with other modalities hard in a compact space. Therefore, novel flexible actuators for producing thermal stimuli are needed to integrate thermal display with other haptic stimuli.

The emerging soft robotic and soft haptic technologies provide opportunities and challenges to the design of novel actuation systems. A number of actuating methods for controlling soft material surface shapes have been explored, including pneumatic actuation [93], shape memory polymers [94], and liquid crystal elastomers [95]. Recently, a programmable 3-D shape approach of transforming two-dimensional (2-D) planar surface to target 3-D shapes was proposed by using elastomeric membranes embedded with inextensible textile mesh [96]. These approaches proposed promising solutions for simulating 3-D shape for MHDs.

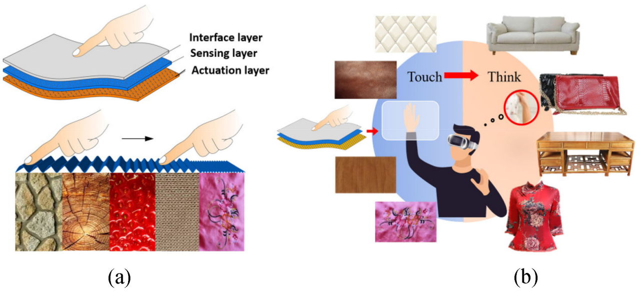

Fig. 4. Active skin for displaying thermal stimuli and macro-micro textures. (a) Multilayered structure of the skin. (b) e-shopping scenario.

In order to provide multimodal stimuli, including both 3-D shapes and surface properties, such as texture and temperature, one open question is to develop an extensible skin that can be wrapped around the surface of a 3-D shape display. This skin may have three layers, including interface layer, sensing layer, and actuation layer. When the shape display deforms, the skin can be extended to conform to the new shape. As shown in Fig. 4, with embedded actuators and sensors, the skin can actively produce thermal stimuli, macro and micro textures. Moreover, it is ultra-thin and extensible to follow the deformation of the wrapped shape display.

Inspired by the animal phenomenon of raising dermal structures, Hu *et al*. developed a texture-changing skin, which consists of a mixture of Goosebump and Spike Texture Units (TUs) [97]. Each set of TUs is controlled separately via a fluidic conduit network. By combining an elastomer body with a column-shaped cavity, the Goosebump TU can transform from a flat initial surface to a smooth bump under positive pressure, and produce a slight dent under negative pressure. The Spike TU is composed of a conical upper spike and a cylindrical bottom cavity. It hides its sharp tip in the dent under negative pressure and deforms into a thorn under positive pressure. Goosebump and spike like texture array with inflated or deflated air pressure can produce different textures for MHDs. However, it is difficult to enlarge the spatial density of the TUs for simulating micro-scale roughness, as huge number of actuation units need to be introduced into the soft structure.

Although some novel actuating solutions have been proposed in producing skin-like textures, high spatial density and thin-thickness are major obstacles for combining these solutions into MHDs. For example, Rafsanjani *et al*. designed kirigami skins by simply embedding an array of cuts into a planar thin sheet [98]. Utilizing highly stretchable kirigami surfaces with mechanical instabilities, the skin can transform from flat sheets to 3-D-textured surfaces akin to the scaled skin of snakes. However, it is an open question how to make the skin thinner enough to be wrapped on the surface of existing 3-D shape display device.

To produce multimodal haptic sensation, novel functional materials that can simultaneously support multimodal actuation are expected. For example, as shown in Fig. 5, a thin-film flexible

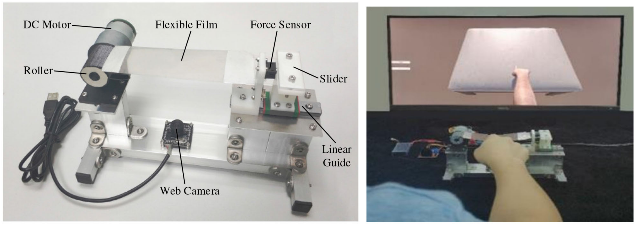

Fig. 5. Thin-film flexible membrane for texture and softness display.

membrane was controlled to provide both texture and softness feedback [99], in which the texture is produced by the electrostatic effect on the membrane, and the stiffness is simulated by controlling the tension of the membrane.

D. Control Strategy to Simulate Free and Constraint Space

While soft actuators like pneumatic-driven soft actuators have shown promising prospect for acting as shape and softness display [5], [93], and producing skin-like textures [97], [98], one open question is the nonlinear deformable behavior of the soft actuators, which challenge the construction of kinematic or force models for controlling the haptic stimuli accurately. In order to ensure the control accuracy, the nonlinear mechanical behavior of the actuator needs to be modeled. Actuators made from soft elastomer and powered by fluids do not yet have well-understood models or control algorithms, primarily because their intrinsic deformation is continuous and highly compliant. Current models for soft robots do not capture their dynamics [100]. Improved dynamics models will lead to more capable controllers. One possible option is to capture the main nonlinear behaviors and regard the difficult-to-model part as the modeling disturbances. For example, Yao *et al*. proposed an active disturbance rejection adaptive controller for tracking control of a class of uncertain nonlinear systems with consideration of both parametric uncertainties and disturbances successfully [111], [112]. Based on this approach, the control problem can be transferred into a nonlinear system with large uncertainties.

To enable closed-loop control of the haptic stimuli, multiple sensors need to be embedded into the body of the actuators and the sensing units should be distributed and collocated with the actuating units, otherwise the control accuracy may be degraded. For example, flexible and distributed thermal sensors need to be mounted on the contact site between user's hand and the thermal actuators to enable closed-loop temperature control. This challenged the compact requirements of structural design and fabrication.

To obtain realistic haptic simulation, one open question is how to simulate the responsive switch of the distinct sensation between free space and constrained space. One issue is the delay of soft actuators for producing responsive haptic sensations. For example, the response time of pneumatic control soft actuators is normally about 100 ms [101], which has a big gap toward the 1 kHz update rate required by haptic simulation.

Moreover, the rendered multimodal stimuli should match the user's manipulation intention. Using contact-state control in Haptic Revolver, Whitmire *et al*. proposed a simple yet effective idea of integrating multimodal haptic feedback [22]. A pad-wheel was controlled to separate or contact human skin, thus producing free space or constraint space sensation. Similarly, CLAW operates in three haptic modes, which are decided based on the user's thumb position and VR scenario [21]. When the user tucks away the thumb, off the thumb rest, the controller is in its default "Touch" mode. A proximity sensor detects when thumb and index finger align, and switches the controller into "Grab" mode. When the user has "grabbed" a gun, the rotating arm locks in place and mimics a gun, and the finger module acts as a trigger.

In Grabity [20], a gesture-based control approach was proposed to adapt haptic feedback for diverse gestures by a simple solution of tracking the index fingertip. Four types of manipulation intentions can be simulated to produce significantly different haptic sensations including tapping, grasping, the sensation of weight, and the inertia of the virtual object. It remains an open question to leverage these simplified yet effective control approaches to design MHDs that can provide distinct haptic sensations for diverse manipulation gestures.

E. Structural Design and Fabrication

As each modality has its own components of sensing, actuation, transmission, structure, and control components, the integration of multiple modalities may lead to a bulky size. In order to ensure the multimodal sensation to be simulated in a consistent manner, new structural solutions need to be explored to ensure a compact arrangement of the modules from multiple modalities.

When integrating multimodal stimulus modules, one needs to decide which module should directly contact the skin as the spatial layout may directly influence user's sensation. For example, for either texture or thermal stimuli, it is better to exert the stimuli directly on the skin. However, because the module of each stimuli has a volume, it is hard to allow both texture and thermal modules contacting the skin directly. One natural solution is that the texture module (such as an electro-vibration surface) contacts directly with the skin, while the thermal module is mounted under the texture module. This layout ensures the sensation of feeling textures, however, it may mask the thermal sensation, unless the texture module can propagate the temperature quickly without loss. In the other aspect, if the thermal module is put between the skin and the texture module, the thermal feedback can be ensured while fine features of the texture sensation may be masked.

In order to integrate multiple stimuli in one compact structure, novel rapid fabrication methods [102] for soft actuators with embedded electronics can be exploited, such as multimaterial 3-D printing [103], shape deposition manufacturing [104], and soft lithography [105]. These methods can be combined to create composites with heterogenous materials (for example, rubber with different stiffness moduli), embedded electronics, and internal channels for actuation [100]. Advance in new materials with programmable stiffness and roughness properties, distributed tactile sensing, microfabrication and assembly technology will enable the creation of increasingly more capable MHDs.

VII. Conclusion

Though current multimodal haptic feedback devices are still unable to match the spatial resolution and/or temporal bandwidth of human's haptic perceptual systems, this field is promising because of the strong demands from both providing immersive sensations in VR and ensuring dexterous manipulations in teleoperation. The exploration of developing high-fidelity MHDs will push the advancement of novel sensing, actuation, and control technologies. It will also open a window for understanding the multimodal haptic perception characteristics of human being.

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