Vibrotactile Display: Perception, Technology, and Applications

This paper spotlights the vibrotactile display, which activates a specific set of mechanoreceptors in the skin using low-cost, easily embedded but easily misused tactor technology.

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ABSTRACT | This paper reviews the technology and applications of vibrotactile display, an effective information transfer modality for the emerging area of haptic media. Our emphasis is on summarizing foundational knowledge in this area and providing implementation guidelines for application designers who do not yet have a background in haptics. Specifically, we explain the relevant human vibrotactile perceptual capabilities, detail the main types of commercial vibrotactile actuators, and describe how to build both monolithic and localized vibrotactile displays. We then identify exemplary vibrotactile display systems in application areas ranging from the presentation of physical object properties to broadcasting vibrotactile media content.

KEYWORDS | Haptics; tactile perception; tactile rendering; vibrotactile display; vibrotactile perception

I. INTRODUCTION

The tactile (cutaneous) sense enables humans to perceive object properties through skin contact, while the kinesthetic (proprioceptive) sense lets one perceive the positions, movements, and forces of one's own body. Within the field of haptics, tactile rendering encompasses the processes associated with modeling and reproducing the physical stimuli that induce tactile sensations; vibrational feedback on a touchscreen is a representative example. Kinesthetic rendering does the same for kinesthetic sensations, e.g., force feedback in a 3-D computer-aided design program. The umbrella term of haptic rendering refers to both types, tactile and kinesthetic.

Tactile rendering can display natural, intuitive, and rich information with relatively low complexity and cost. Research in this area dates back to as early as the 1920s, when Gault began to test the feasibility of transferring speech into vibrotactile stimuli [1]. Since then, our knowledge about tactile perception and rendering has steadily progressed. Classical examples include Vibratese (the first tactile language) in the 1950s [2] and the Optacon (the first visual-to-tactile translator) in the 1970s [3]. This persistent research effort enabled the commercial success of some haptics products in the 2000s and the rapid growth of the field thereafter. See [4] for a more complete history of tactile rendering.

Among the wide variety of tactile displays, those that create vibrations are currently more widespread and better understood than approaches that modulate other tactile sensations, such as static pressure, skin stretch, or friction. This paper presents a comprehensive introductory review on vibrotactile display for readers with little expertise on haptics. We cover vibrotactile perception, vibrotactile actuators and displays, presentation of physical and abstract information, and applications to multimedia.

II. VIBROTACTILE PERCEPTION

This section presents fundamental insights about vibrotactile perception that are useful for the design of effective vibrotactile displays and applications. This knowledge can particularly help designers choose what vibrotactile signals to render. Further comprehensive and in-depth reviews on this topic are available in [5]–[9].

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TABLE 1 Basic Characteristics of the Four Mechanoreceptive Tactile Channels (Afferent Units) in the Glabrous Skin

Neural Channel[a]	SA I (NP III)	RA (FA I, NP I)	SA II (NP II)	PC (FA II, P)
End Organ	Merkel Disk	Meissner Corpuscle	Ruffini Ending	Pacinian Corpuscle
Sensory Adaptation[b]	Slow	Fast	Slow	Fast
Receptive Field[c]	Small	Small	Large	Large
Frequency Range (Hz)[d]	< 5	3–100	15–400	10–500
Perceiving Property	Pressure, Fine Details	Flutter	Stretch	Vibration

- [a] The name of each psychophysical or neural channel has a few variants as shown inside the parentheses. This paper follows the convention of [8].
- [b] The SA (slowly adapting) channels tend to maintain their response level for a sustained stimulus, and they are responsible for perception of spatial properties. The RA (rapidly adapting) channels cease to respond immediately after a stimulus is applied, relaying temporal properties.
- [c] Each afferent unit responds to a mechanical stimulus only if it is applied within a certain area on the skin. This area is called the receptive field of the afferent unit. A smaller receptive field leads to a higher spatial sensitivity.
- [d] Different sources report minor differences in the frequency range over which each channel responds. This table relies on [5], [7], [9].

A. The Four-Channel Theory

Tactile perception is complex, and its neurophysiology and perceptual basis are still under active research. One of the most established frameworks in vibrotactile perception is the four-channel theory: glabrous (nonhairy) human skin contains four types of mechanoreceptors (sensory cells that detect skin deformation) [8]. These four touch-sensing channels differ in the type of mechanical stimuli to which they respond, as summarized in Table 1. In comparison, hairy skin has considerably different characteristics (e.g., hair-follicle receptors, lower density of Pacinian corpuscles), and its neurophysiology and psychophysical basis are still relatively unknown [6], [10].

The rapidly adapting (RA) and Pacinian corpuscle (PC) channels govern vibrotactile perception in glabrous skin. The PC channel exhibits spatial summation, wherein the sensitivity to a tactile stimulus grows with the area in contact with the skin until it is saturated. The PC channel is also capable of temporal summation, wherein the sensitivity to a tactile stimulus improves with the stimulus duration until saturation.

B. Single Body Site

The simplest situation for tactile rendering is to stimulate one site on the skin. In this case, the first perceptual property to consider is perceptibility: *can the user feel the vibrotactile cue being rendered?* Psychophysics researchers represent the sensitivity to physical stimuli via the absolute (detection) threshold: the weakest stimulus intensity that allows the human to robustly perceive the presence of the stimulus [11]. The absolute thresholds of vibrotactile stimuli strongly depend on the vibration frequency. Each of the tactile perception channels has frequency-dependent absolute thresholds, and for each frequency, the channel with the smallest threshold determines the absolute threshold at that frequency. If a stimulus is strong enough to stimulate multiple channels, all of these channels respond and contribute to perception [12]. In glabrous skin, the SA I channel shows constant absolute thresholds of about 5 μm of deflection regardless of frequency; this channel typically dominates thresholds at frequencies below 100 Hz. At higher frequencies, the thresholds are determined by the PC channel, which has a U-shaped threshold curve across frequencies. The minimum threshold (smallest detectable displacement) is usually observed between 150 and 300 Hz, and it can be smaller than 0.1 μm. As is common in tactile perception, these absolute thresholds are affected by a number of factors, such as body site, contact area, stimulus duration, stimulus waveform, contact force, skin temperature, the presence of other masking stimuli, and age [6]. For example, if contact area or stimulus duration increases, all of the thresholds of the PC channel decrease because of the summation effect. See [6] and [8] for reviews on absolute tactile thresholds measured under various direct-skin stimulation conditions, and see [13] and [14] for information about tool-transmitted stimulation conditions.

Once a stimulus is known to be perceptually detectable, the question becomes: *can the user distinguish between the different vibrotactile cues being displayed?* This capability is quantified by the discrimination threshold or just noticeable difference (JND), the smallest difference between two stimuli that leads to reliable discrimination. Since difference thresholds depend on the strength of the reference stimulus, discriminability is generally represented by a Weber fraction, the ratio of the difference threshold to the reference level. According to Weber's law [11], Weber fractions of the same kind of stimuli tend to remain constant regardless of reference level. Although vibrotactile perception is known to show some exceptions to this law [7], Weber fractions mostly cluster around 10%–30% for vibration intensity (but can range between 4.7% and 100%) and mostly around 15%–30% for vibration frequency (ranging between 2% and 72%) [15]. In our experience, at least 20%–30% of a difference in amplitude or frequency is necessary for robust discrimination between vibrotactile stimuli in practical applications. It is worth noting that the actual number of identifiable stimuli is also restricted by other perceptual and cognitive factors related to information transmission [16].

The next perceptual question is: *how strong does a certain vibrotactile cue feel to the user?* When a stimulus intensity I (in physical units) is above its absolute threshold, the human perceives its magnitude as $\psi(I)$ (in perceptual strength). The two are related by Steven's power law:

$\psi(I) = kI^e$ [11]. The exponent e determines the growth rate of the perceived magnitude, and it ranges from 0.35 to 0.86 for vibrotactile stimuli [14]. The exponent depends on the stimulation conditions [17], particularly on stimulus frequency [14]. This interaction means that perceived intensity is a function of both the amplitude and the frequency of a vibration. Similarly, both amplitude and frequency affect the perceived pitch of a vibration [18]. This nonorthogonal perceptual property is seldom known by application developers, and it needs to be addressed with care, for example, by using equal sensation contours that describe how amplitude and frequency must vary to yield the same perceived intensity [12], [14].

Another important question is: *how good are users at judging the timing of vibrotactile cues?* Human tactile perception is generally considered to have high temporal acuity. For example, we can distinguish successive pulses with a time gap as small as 5 ms [8]. This tactile sensitivity to time is better than that for vision (25 ms), but worse than auditory acuity (0.01 ms) [6]. Further temporal variations can be brought into a vibrotactile signal by changing its amplitude over time (known as the envelope), which elicits the perception of rhythm. Humans are quite sensitive to tactile rhythmic differences with high discrimination and recognition abilities [19], [20]. This fact can contribute to the design of a multitude of meaningful vibrotactile stimuli in real application domains.

Finally, one may wonder: *can vibrotactile cues elicit any other perceptual effects?* The subjective impressions of vibrotactile stimuli certainly have an important role in tactile system design. If the frequency of a vibration is below 3 Hz, it is perceived as slow kinesthetic motion [21]. From 10 to 70 Hz, one feels rough motion or fluttering, and from 100 to 300 Hz, smooth vibration [21]. In the perceptual space of vibrotactile stimuli, such qualitative differences are expressed by two distinct perceptual axes composed of 40–100- and 100–250-Hz vibrations, respectively [22]. Furthermore, the subjective quality of a vibrotactile stimulus can be controlled by modifying the envelope of the stimulus amplitude. For example, multiplying a low-frequency envelope function with a high-frequency sinusoidal function (amplitude modulation) produces low-frequency, rough sensations that are distinct from the original high-frequency smooth vibrational sensations [23]. Such methods are especially useful for vibrotactile actuators with a limited bandwidth to control the subjective impression and discriminability of their output.

C. Multiple Body Sites

The human central nervous system can accurately register the location of a tactile stimulus applied to sites all over the body [7]. This stimulation easily catches and guides one's attention in the direction of the cue; for example, a single tap on the right shoulder usually makes a person turn to the right. This natural map between body position and egocentric orientation is a great asset for tactile displays that stimulate multiple body sites. To exploit this advantage, designers need to understand: *how well can a user distinguish vibrotactile cues applied to neighboring locations on the body?* Traditionally, this spatial discriminability has been measured using a two-point threshold, the shortest separation distance needed for two simultaneously applied stimuli to be reliably perceived as distinct. Although researchers still use aesthesiometers to gather two-point thresholds for clinical studies, the accuracy of such measurements as an indicator of spatial acuity is questionable. One confounding factor is that two closely placed probes can increase the intensity of stimulation, which provides additional cues [6]. Current touch scientists rely more on point localization thresholds and grating orientation discrimination thresholds, both of which lead to a higher spatial resolution. The former improves on two-point threshold testing in that only one stimulus is applied on the skin at a time [24]. The latter finds the smallest spatial period of gratings for which orientation can be reliably distinguished [25]. All of these thresholds representing tactile spatial acuity vary significantly across the body because different areas of skin have different mechanoreceptor innervation densities. We should also note that these thresholds are generally measured with a static skin indentation. Vibrotactile stimuli with different frequencies applied through contactors with different shapes and sizes will almost certainly influence spatial discrimination and localization [6], so custom experiments are usually required. For example, the localization accuracy of 250-Hz vibrotactile stimuli around the waist was 74% with 12 equidistant tactile actuators (tactors), 92% with eight tactors, and 97% with six tactors [26]. This high identification ability with the natural orientation mapping makes multielement vibrotactile displays a viable solution for directional cueing.

The second question on this topic is: *what will a user perceive during spatial and temporal patterns of vibrotactile stimuli?* Several perceptual illusions enable us to use a linear array of tactors to induce vibrotactile sensations that continuously move on the body. For example, in sensory saltation (also called the cutaneous rabbit), tactor 1 produces three short pulses. After a short time gap, tactor 2 does the same, and then tactor 3. This pattern elicits the perception of an illusory "rabbit" climbing from the position of tactor 1 to that of tactor 3, continuously on the body [27]. In addition, apparent tactile motion can be created by controlling the start and end timings of successively activated tactors [6]. A phantom tactile sensation can also be made between two tactor positions by controlling the time gap or the intensity difference between the two stimulations [28]. These three tactile illusions can be used to create well-defined flow-like sensations for directional displays and special game effects, even using 2-D tactor arrays on the skin [29]. A thorough review on robust haptic and tactile illusions can be found in [30].

D. Active and Passive Touch

The final important factor one must consider is the distinction between touching and being touched. In passive touch, tactile stimuli are transmitted to the user without the user's active motor involvement; for example, the vibration ringtones of a phone are externally triggered and do not depend on the user's movements. In contrast, active touch refers to situations where tactile stimuli are produced in response to the user's exploratory movements; for example, vibrotactile feedback on a touchscreen might depend on where and how the user touches the screen, much like an active-touch interaction with a real texture. Active touch generally has higher perceptual performance owing to the various human exploratory patterns tailored to each tactile property [31]. It should, however, be noted that active movements might also impair tactile perception, evidenced in several cases of tactile suppression [32].

III. VIBROTACTILE ACTUATORS

A designer who wants to incorporate vibrotactile cues into a certain device or application needs to make two main hardware decisions: what type of vibrotactile actuators to employ, and how to spatially arrange and mount them so their vibrations can be felt by the user. These decisions can profoundly influence the effectiveness of the resulting system, so this section explains the main actuator options to consider, and the next section summarizes how to build an effective vibrotactile display. Even with these guidelines, the complexity of vibrotactile perception and the importance of the mechanical coupling with the skin make it difficult for one to know ahead of time how well a certain design will work. We have thus found that quick prototypes, frequent tests with potential users, and design iteration help ensure a high level of functionality for the resulting system.

A wide variety of actuators can be used to create an oscillating movement that a human can feel. At a minimum, a vibrotactile actuator needs to be able to turn on and off under computer control. More sophisticated actuators can create a range of sensations that vary across amplitudes, frequencies, and waveforms. Other important engineering considerations generally include size, shape, cost, availability, robustness, speed of response, input requirements, power consumption, and potential interference with other system components. Good overviews of haptic actuators can be found in [33]–[35]. Below we discuss the main commercially available options one should consider when creating a new vibrotactile display system; examples of several options are shown in Fig. 1. GlobalSpec [36] can often be a useful tool for identifying and comparing suitable actuator models, though specialty vibrotactile actuators do not appear in this catalog. Table 2 provides a qualitative comparison of the most common types of vibrotactile actuators to aid application designers. Note that almost all vibrotactile actuators require drive circuitry to raise the power of the computer's analog or digital output.

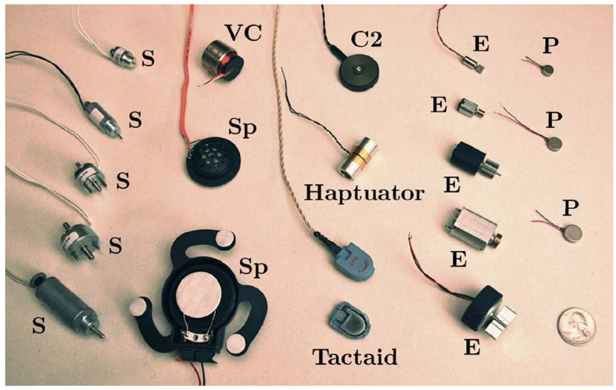

Fig. 1. *Sample actuators for vibrotactile display. S: Five solenoids of varying sizes. VC: A commercial voice coil without bearings. Sp: Two audio speakers. C2: A C2 tactor from EAI. Haptuator: A Haptuator from Tactile Labs, Inc. Tactaid: One complete Tactaid from AEC and one opened to show the suspension inside. E: Five shafted/cylindrical eccentric rotating mass motors. P: Three shaftless/pancake eccentric rotating mass motors. A U.S. quarter appears at bottom right for scale.*

A. Linear Electromagnetic Actuators

The physical phenomenon most commonly used to create vibrotactile stimuli is the electromagnet: an electrically conductive wire (such as copper) is covered with an electrically insulating material (such as varnish) and wrapped into a continuous coil. Passing a constant electrical current through the coiled wire creates a steady magnetic field that is strongest inside the coil. A piece of ferromagnetic material (such as steel) brought near the energized coil will be physically pulled toward the electromagnetic field; the force will disappear when the current turns off. A permanent magnet (which has its own magnetic field) will be either attracted to or repelled from the energized coil, depending on its physical orientation and the direction current is flowing through the wire. Applying an oscillating electrical current to the coil creates a magnetic field that similarly varies over time, providing a straightforward method of producing tactile vibrations. This same physical principle is used in audio speakers to create the broad-frequency air pressure variations humans perceive as sounds.

A coil that encloses a movable piece of ferromagnetic material is commonly called a *solenoid*. Solenoids are widely used for industrial applications and are manufactured in a vast range of sizes by many suppliers worldwide. The solenoids most relevant for vibrotactile rendering are the smallest commercial versions, which have dimensions on the order of 10 mm. Such devices typically need a spring to return the movable element to its starting position when the electrical power is turned off. Attention should be paid both to the static stiffness of that spring and to the resonant frequency that results from its use with the moving mass; mechanical resonance produces large output movements for small inputs at a given frequency, an effect

TABLE 2 Comparison of Common Vibrotactile Actuator Types

Actuator	Affordability and Availability	Mechanical Simplicity	Electrical Simplicity	Customizability	Expressiveness
Solenoid	Medium	Medium	Medium	Medium	Medium
Generic Voice Coil	Low	Low	Medium	High	High
Vibrotactile Voice Coil	Medium	High	Medium	Low	High
ERM Motor	High	High	High	Low	Low
Piezoelectric Actuator	Low	Medium	Low	Medium	High

Affordability and Availability refers to the ease with which a designer can acquire an actuator of the given type. **Mechanical Simplicity** and **Electrical Simplicity** show how straightforward it is to integrate the given actuator into a typical vibrotactile display. **Customizability** reveals whether an actuator allows the designer to modify its properties after purchase, e.g., through selection of a spring. Finally, **Expressiveness** indicates the range of vibrotactile sensations that a given type of actuator can create. These ratings provide broad guidelines to aid application designers, but individual actuator options will vary. See the text for additional details and actuator types.

one may want to leverage in vibrotactile rendering. Note that the sensations delivered by a solenoid may be somewhat inconsistent because the force on the moving element strongly depends on its position within the magnetic field, a factor that is influenced by the device's orientation relative to gravity, the mechanical properties of the surface it is contacting (typically skin), and the recent history of applied waveforms. Solenoids may also heat up during use.

A coil that encloses a movable permanent magnet is typically labeled a *voice coil*. Several manufacturers offer general-purpose linear voice coil actuators that can be used in vibrotactile rendering, typically with dimensions on the order of tens of millimeters. Models with built-in linear bushings are convenient, but the static friction present at the sliding interface can prevent small vibrations from being felt and will somewhat distort the feeling of larger vibrations. Linear ball bearings tend to have lower static friction, but their motion usually generates parasitic vibrations that can be perceived by the user. Voice coils without built-in bushings are more complex to integrate into a custom system, as the designer must constrain the two pieces to stay aligned while allowing one piece (the coil or the permanent magnet) to move relative to the other. Such devices typically need a spring to return the moving element to center, so the common solution is one or two flexible membranes. Another possible option is to adapt audio speakers to create detectable tactile vibrations, e.g., [37]. As with solenoids, the electrical signal applied to a voice coil must vary over time to create vibrations. Unlike solenoids, voice coil actuators typically have linear dynamics, so the vibrotactile output is reasonably consistent and easy to model [38], aside from the static friction mentioned above.

Several companies manufacture voice coil actuators specifically for vibrotactile rendering; their ease of integration and the availability of past performance data make them attractive options for many projects. Engineering Acoustics, Inc., (EAI, Casselberry, FL) created the *C2 tactor* for applying vibrations directly to the skin. Its flat cylindrical housing has a diameter of 30.5 mm and a thickness of 7.9 mm, making it relatively easy to enclose in garments and devices. Its design centers on a 7.6 mm diameter contactor that is preloaded against the skin, with a suspension designed to resonate at 250 Hz when contacting skin for maximum perceptibility [39]. EAI also manufactures low-frequency tactors for operation at frequencies below 100 Hz. Tactile Labs, Inc. (Montreal, QC, Canada) designed the *Haptuator* for embedding into handheld tools and devices. Its long cylindrical housing has a diameter of 14 mm and a length of 29 mm. Unlike the C2, its design centers on a moving magnet that is not meant to touch the skin, and it is optimized to render frequencies above 50 Hz [40]. For smaller devices, Precision Microdrives (London, U.K.) [41] and other manufacturers offer voice-coil-based linear resonant actuators (LRAs) with dimensions on the order of 10 mm and resonant frequencies around 200 Hz. The slightly larger *L-type vibrator* from Alps Electric Co. (Tokyo, Japan) can also be used to play high-bandwidth vibrotactile signals [42]; it is not sold individually but can be scavenged from old Nintendo DS Rumble Packs. Another small electromagnetic actuator commonly used in haptics is the Tactaid, which creates inertial vibrations via a coil in close proximity to a suspended magnet [43]. Tactaids were previously manufactured by Audiological Engineering Corporation (AEC, Somerville, MA) but are no longer available.

B. Rotary Electromagnetic Actuators

Rotary direct current (dc) motors constitute the second main way of using electromagnetism to produce vibrotactile sensations. Such motors are designed to rotate continuously when a constant voltage or current is applied; thus their internal structure is more complex than that of a solenoid or a voice coil, but they can produce oscillating sensations when driven with a steady command. Most commonly, an off-center mass is affixed to the output shaft so that its rotation exerts large radial forces on the body of the motor, as occurs in laundry machines when the clothes are off center. It is important to realize that this design inherently couples both the frequency and the amplitude of the resulting vibration to the motor's rotational speed (in cycles per second, or hertz). The user will feel small, slow vibrations when a small voltage is applied to the motor, and they will feel strong, fast vibrations for large input voltage. Thus, one cannot use this actuator type to render vibrations at arbitrary combinations of frequency and amplitude. Furthermore, internal static friction typically prevents such motors from rotating when the applied voltage is very small, and they also take a short time to spin up, causing a delay in the start of the vibrotactile cue.

Designers can choose from a wide variety of commercially available eccentric rotating mass (ERM) motors. For example, Precision Microdrives provides a broad inventory ranging from tiny motors for delivering vibrotactile alerts in mobile devices up to much larger actuators typically used in manufacturing and massage applications [41]. The main categories one finds are: 1) shafted motors, where the eccentric mass is visible, sometimes called cylindrical or pager motors; 2) encapsulated cylindrical motors, which have a similar design but cover the rotating shaft to prevent interference with surrounding items; and 3) shaftless motors, where the eccentric mass is fully enclosed, often made in a flat form factor called a coin or a pancake motor. The simplicity and reliability of eccentric rotating mass motors make them a popular choice despite the rendering constraints discussed above.

C. Nonelectromagnetic Actuators

The other main approach to creating vibrotactile sensations takes advantage of the piezoelectric effect, wherein particular solid materials change shape when subjected to an electrical voltage. This effect is reversible, so piezoelectric materials are also commonly used as sensors (converting mechanical deformation to electrical signals). Vibrotactile display applications typically use multilayer *ceramic piezoelectric actuators* shaped like a disk or a beam, e.g., the Sony TouchEngine [44]. Such actuators respond to applied inputs very quickly and can output arbitrary waveforms, but they also typically require inputs on the order of 100 V, making system integration challenging. A more recently available option that also leverages the piezoelectric effect is electroactive polymer (EAP) actuators, which use elastomers rather than ceramics and can achieve much larger deformations for lower drive voltages, although electrical and mechanical breakdown can limit performance [45], [46]. Artificial Muscle, Inc. (Sunnyvale, CA) has commercialized EAP technology for haptics as ViviTouch.

A small sampling of other technologies can also be used for vibrotactile rendering. Notably, shape memory alloy (SMA) actuators are metals that remember their original shapes and will alter their mechanical properties in response to temperature changes. The effect relies on reversible phase changes within the solid metal alloy. Though SMA actuators can be small and have a high power-to-weight ratio, they are also known to have slow response times, large hysteresis, and high energy consumption [47]. Another common limitation of low-mass mechanical transducers like piezopolymers and some SMAs is that they do not have the power to move the skin without pushing off a cumbersome mechanical ground. The rather high stiffness of the skin creates a need for relatively heavy vibrotactile actuators like the common ones discussed above. Still another option is *pneumatic actuation*, wherein controlled air pressure changes are used to move, expand, or contract mechanical elements in contact with the user's skin [33]. Pneumatic systems can be compact and light, but they typically require a high-pressure air source, and they can struggle to output high-frequency signals. Though many good options exist, there is still a need for further innovation in vibrotactile actuator design.

IV. VIBROTACTILE DISPLAYS

The second half of creating an effective vibrotactile system lies in arranging and mounting the selected actuators. The two main paradigms are: 1) to vibrate an entire rigid object to deliver a widespread vibrotactile cue; and 2) to embed one or more actuators in an object or a garment to deliver localized vibrotactile cues. In both cases, the designer needs to create a consistent mechanical coupling between the actuator's vibrations and the user's skin. Slight changes to such a system can drastically affect the user's ability to feel and comprehend the rendered signals. Here we provide practical guidelines for successfully implementing both types of displays. The constraints imposed by a particular application may require creative solutions, which are best discovered through prototyping and quick user tests. The range of items that can be turned into vibrotactile rendering systems using these techniques is nearly endless, most commonly including mobile phones, game controllers, remote controls, computer mice, styli, thimbles, gloves, arm bands, vests, belts, shoes, and chairs. Fig. 2 shows four examples from our own research.

A. Monolithic Vibrotactile Displays

When the user holds a small, solid object or tool, the appropriate choice is typically to *vibrate the entire rigid device*. As discussed in Section III, vibrotactile actuators usually consist of two pieces that move relative to one another, such as the magnet and the coil in a voice coil actuator or the eccentric mass and the motor body in an

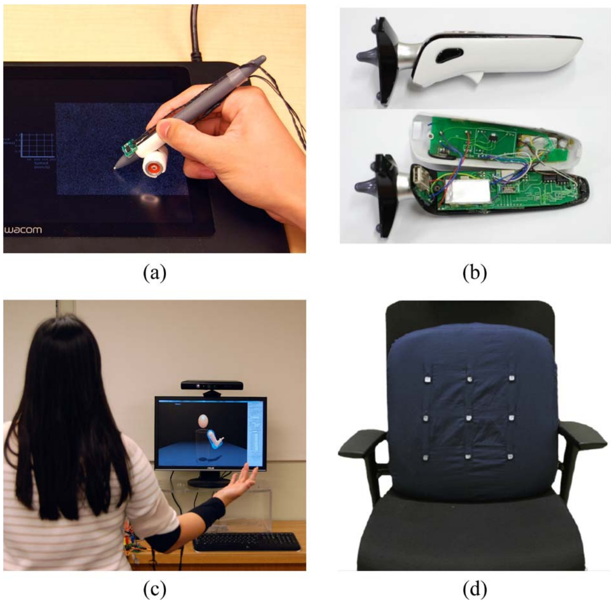

Fig. 2. ***Sample vibrotactile displays. (a) and (b) are monolithic handheld devices, while (c) and (d) deliver localized vibrotactile cues. (a) The TexturePad from [49]. A Haptuator vibrates the stylus of a Wacom tablet to simulate the feel of touching a real texture. (b) The gesture-recognizing remote controller from [50]. An ERM motor and an LRA deliver vibrotactile cues to the user. (c) A new version of the sleeve from [51]. Eight ERM pancake motors (four in the wristband and four in the armband) guide the user's arm motion. (d) The chair back from [52]. A three-by-three array of ERM motors displays the location and intensity of visually salient items in a video as it is viewed.***

eccentric rotating mass actuator. For this type of display, one of the actuator's pieces must be rigidly attached to the frame of the interface object, and sufficient space must be provided for the other actuator element to move freely. If the body of the actuator is not rigidly affixed to the object, it will not effectively transmit vibrations to the user's hands. Furthermore, the object needs to be sufficiently rigid; flexible objects will bend near the actuator and prevent the vibrations from propagating to all parts of the device.

For a fixed actuator size and activation level, the magnitude of the created vibrations will be inversely proportional to the mass of the object [38], so designers should seek to minimize the overall weight of the device. If needed, more than one actuator can be used to increase the sensation magnitude. Loose elements such as button covers and wires will be subjected to the vibrations and can audibly rattle if not secured. Designers wishing to quantify the vibration-output performance of such a system can attach a small high-bandwidth three-axis accelerometer near the finger placement locations and record the vibrations that occur when the device is activated in a user's hands, as done in [48]. Note that the location and strength of the user's grip will affect the size and shape of the resulting vibrations.

B. Localized Vibrotactile Displays

When the application involves a large object, a wearable device, and/or multiple stimulation sites, the optimal vibrotactile rendering paradigm is to *vibrate one or more small zones*. One common instantiation of this approach is an array of closely packed vibrotactile elements, such as pins, for fingertip exploration. Rather than a rigid coupling, the designer should seek a lightweight and highly flexible connection between the element(s) delivering the vibrotactile cues and the rest of the system. With C2 tactors, this flexible coupling is already part of the device, a design that can be mimicked with custom tactile actuators built from solenoids and voice coils. If the entire actuator housing vibrates, as with Tactaids, ERM motors, and some other options, the way in which each actuator is connected to the rest of the system needs to be thoughtfully selected to create consistent well-localized sensations. The connection between neighboring actuators should be flexible in the direction of the actuator vibrations—along the axis of solenoids and voice coils and in the plane perpendicular to the shaft of ERM actuators. This design objective is often accomplished with stretchable fabric or elastic bands; stiff materials such as belt leather usually perform poorly because they prevent the actuator from moving and spatially distribute any vibrations that do occur. The actuator's electrical wiring should also be carefully chosen to allow movement and avoid transmitting the sensations to nearby skin; ultraflexible stranded cables from manufacturers such as Daburn Electronics and Cable (Dover, NJ) [53] are a good choice. Finally, the system should be designed to gently press the active vibrotactile zones against the user's skin to ensure signal transmission, with care taken to avoid any sharp edges or other uncomfortable surface features. This goal of good tactor contact can be difficult to achieve with wearable systems because users can span a wide range of body sizes and may be moving their limbs; repositionable tactors and individually adjustable garment components are the best solution [54].

V. APPLICATIONS: PHYSICAL INFORMATION DELIVERY

As the first of three broad application areas discussed in this paper, vibrotactile displays can adeptly communicate *physical information* to the user. Here, vibrations are typically provided in response to motions or actions performed by the user in a simulated physical world. The tight coupling between the user's movement and the resulting vibrotactile sensations requires such systems to have minimal time delay. Research in this area has mainly focused on two topics: conveying physical object properties and indicating the location of object contact.

A. Material Properties

Interacting with the physical world generates a rich array of tangible vibrations, especially when one touches items through a handheld object or tool [9]. Strong vibration transients occur at the beginning and end of contact, and vibrations are continuously generated as one object slides along or cuts through another. These signals contain useful information about the characteristics of the two objects as well as how they are moving. As overviewed in [55], the vibrations that occur during a certain type of interaction can be measured, modeled, synthesized during virtual interactions, and played on a vibrotactile display for increased realism over kinesthetic feedback alone. Two examples overviewed in [55] are to use vibrotactile feedback to increase the apparent hardness of virtual surfaces during tapping and to increase the realism of simulated biological tissue during cutting. Other interesting recent examples include dragging a stylus across virtual textured materials (e.g., canvas) on a touchscreen [48], [49] [Fig. 2(a)] and walking across virtual ground surfaces (e.g., gravel) on active floor tiles [56]. To achieve realistic renderings, these projects use actuators that provide excellent control over the output vibrations, such as a grounded dc motor directly coupled to the tool or a linear voice coil actuator. Furthermore, they all focus on delivering vibrotactile cues that realistically adjust to the present physical conditions of the interaction, such as the contact speed of the tapping tool, the closing speed of the scissors, the scanning speed and normal force of the stylus, and the contact force of the user's foot.

B. Contact Location

Vibrotactile displays can also be employed to notify the user of the body location of a contact occurring in a virtual world. Unlike rendering material properties, where the generated signals closely match what one feels in the corresponding real interaction, sustained stationary contact with a real physical object does not cause sustained vibrations. Unfortunately, it is not yet technically feasible to apply grounded contact forces across large areas of the human body, especially during movement. On the other hand, a large number of vibrotactile actuators can be integrated into a garment and activated independently to indicate contact location, an overarching approach known as sensory substitution. This method has been used with the vibrotactile TactaVest in a military simulation to notify the user of body collisions with virtual objects outside the view of a head-mounted display [54]. A similar scheme and a sleeve equipped with 24 ERM motors enabled users to feel the location of contact between their arm surface and a virtual 3-D puzzle during reaching tasks, plus learn four simple arm movements from karate [57]. More recently, this idea of using vibrotactile feedback to teach kinesthetic arm movements has been gaining momentum, typically using about four ERM motors distributed circumferentially in a band on each limb segment, as in [51] [Fig. 2(c)]. Here, the hope is that vibrotactile feedback will speed the motor learning process over visual feedback alone, but current results are mixed. A related use of vibrotactile feedback is as a balance prothesis for people with vestibular disorders. The tilt of the head can be measured, e.g., using inertial sensors, and it can be fed back to the user using a set of vibrotactile actuators to help restore the impaired sense of balance [58].

VI. APPLICATIONS: ABSTRACT INFORMATION DELIVERY

Vibrotactile displays can deliver *abstract information* with high reliability when the stimuli are optimized for the context of use. Research over the past ten years has shown the efficacy of this communication modality, especially when 1) visual or audio information is unavailable or deteriorated; 2) the user's sensory capacity is overloaded; 3) redundant sensory cues are desired; or 4) ambient and complementary signals are useful. This section describes major applications in this domain.

A. Communication

The most traditional and perhaps crucial use of vibrotactile displays is in communication devices for people with sensory impairments. The commercial exemplar in this category is the OPtical to TActile CONverter (Optacon), which was developed in the 1970s as a reading aid for the visually impaired. The Optacon displays the image from a handheld optical scanner on the fingertips of the user's other hand using a binary vibrotactile pin array driven by piezoelectric beam actuators [3]. The Optacon is no longer in production although dedicated users still exist. The current commercial focus is instead on electronic Braille systems, while the research community has recently been concerned with the tactile display of more detailed information such as geometric shapes [59].

Transferring speech into vibrotactile stimuli for the hearing impaired was one of the most important research topics early in haptics. The primary approach was a tactile vocoder, which spectrally partitions speech into multiple signals that are displayed using a set of independent vibrotactile actuators [60]. The efficacy of tactile vocoders was examined in a number of studies, both alone and in combination with lip reading. Research in this direction, however, is no longer active.

B. Navigation

As discussed earlier, the body site of tactile stimulation provides a natural cue for egocentric orientation. This fact has been exploited in the development of tactile navigation aids that use compass readings and Global Positioning System (GPS). For instance, a navigation system that conveys direction using an eight-tactor belt and distance by tactile pulse-period modulation was shown to be effective for pedestrians, a helicopter pilot, and a fast boat driver [61]. A similar tactile navigation system was tested in strenuous outdoor environments under the context of military operation, and it even outperformed visual displays under conditions with a high cognitive and visual workload [62]. Similar navigation aids can also be used by the blind, with mobile devices, and in vehicles.

C. Mobile Devices

Upgrading the limited user interface (UI) of mobile devices with vibrotactile feedback has been an attractive topic owing to its commercial impact. The use of vibrotactile feedback dates back to pagers, one of the earliest mobile devices to include an ERM motor for silent alerts. This tradition has been inherited by contemporary cellular phones and smartphones that are equipped with more advanced tactile displays, and now mobile devices are a high priority testbed for new ideas in tactile rendering.

Evolved from silent alerts, the design of a large number of recognizable vibrotactile stimuli has been a central issue; see [63] for a dedicated review. The resulting cues are called haptic icons [64] or tactile icons (tactons) [65], and they can deliver useful abstract information, such as the identity of a caller or the urgency of a call. Research has shown that more than 80 tactile icons can be robustly distinguished and that amplitude, frequency, envelope, and rhythm are all useful variables for tactile icon design, with rhythm being most powerful [66]. Moreover, multimodal icons that include tactile icons have been receiving increased attention. Multimodal icons present a variety of new research problems such as the congruence between visual and tactile stimuli [67].

A recent trend in mobile devices is to install a large touchscreen without a physical keypad. An obvious drawback is the lack of tactile feedback during key presses. Vibrotactile feedback can improve the accuracy and completion time of text entry on a touchscreen, while significantly reducing the user's subjective workload [68]. For this purpose, various tactile signals have been designed and compared in terms of task performance and user preference [69], [70]. Since touchscreens are not limited to mobile devices, adding natural and effective tactile feedback to more general touchscreen interaction paradigms is gaining further significance.

Another notable area of research attempts to unify tactile UI solutions supported on the level of operating systems (OSs). The key components are the design of tactile effects that match the look and function of various visual UI components supported in an OS and seamless integration of the tactile components into the OS. This need is accelerated by the rapidly increasing use of tablets with a large touchscreen. A commercial solution already exists for Android (Integrator from Immersion Corporation, San Jose, CA).

D. Vehicles

Driving a vehicle is a classic example of situations that entail very high visual-audio sensory demand for the user and consequently can benefit from haptic feedback. Related research has been pursued in two directions. One is toward the simplification of complex manual controls by the use of a unified controller with improved sensory feedback. The iDrive system from BMW, which includes a rotary knob with kinesthetic feedback, is a representative commercial example [71]. Adding vibrotactile feedback to such a controller to deliver abstract information such as menu state can enlarge its information transmission capacity [72].

The other direction is the use of haptic warnings against hazardous driving situations. Most such systems provide the driver with vibrotactile warning signals through the vehicle's seat, seat belt, or steering wheel. The location of the hazard is usually coded via the site of vibrotactile stimulation [73]. For example, it is effective to vibrate the steering wheel for a forward collision warning or the right seatback for a rightward lane drift warning. Some commercial automobiles are already installed with a multimodal warning system that includes vibrotactile feedback.

VII. APPLICATIONS: MULTIMEDIA

As evidenced by the recent emergence of 4-D films, haptic feedback has great potential for making *multimedia* experiences more expressive, vibrant, and realistic. This section introduces recent research that leverages vibrotactile rendering in multimedia applications, with an emphasis on authoring, modeling and compressing, and broadcasting vibrotactile content. Also see [35] for a broader review.

A. Authoring

In multimedia applications, tactile stimuli need to be presented in synchrony with visual and auditory stimuli and their semantics. Therefore, software tools that help designers compose tactile scenes are highly valuable.

Two extreme approaches exist for tactile content authoring. In one approach, tactile scenes are made from scratch using software dedicated to that task. For example, spatial tactile effects can be manually synthesized frame by frame from video files and then presented by a wearable tactile display [74] or an array of vibrotactile actuators placed on a chair [29]. The spatial correspondence between the visual and tactile stimuli is a key factor for this design. For audio stimuli, a graphical editor that uses a musical score metaphor can enable one to quickly create vibrotactile patterns [75].

In the other extreme, tactile content is generated automatically from video or audio files, even in real time. For example, a tactile stimulus that highlights the spatial location of an important visual event could enhance the video-watching experience. For this purpose, a visual saliency map can be computed to predict where the viewer will look in each frame of a video; this map can then be used to determine the body sites and intensities of vibrotactile stimulation [52] [Fig. 2(d)]. For sound, the sense of beat can be amplified by the playback of vibrotactile stimuli emphasizing the low-frequency energy of a sound signal [76]; this bass-boosting function is already common in commercial products. As an alternative, a music signal can be divided into multiple frequency bands and delivered onto multiple body sites via vibrotactile signals, especially for the hearing impaired [77].

In order to achieve the optimal balance between quality and efficiency, software tools for tactile content authoring need to provide a complete frame-by-frame design interface along with effective automated content production capabilities. This is, however, an open research task.

B. Modeling and Compression

Storage and bandwidth requirements are critical in multimedia applications. A decent body of research regarding haptic data compression exists, especially in the context of telepresence (controlling a remote robot). Since kinesthetic feedback has a high priority in telepresence systems, the primary goal has been compression of force data without noticeable degradation of the perceptual quality. Compared with tactile rendering, kinesthetic feedback has different perceptual properties as well as more strict constraints on rendering stability and communication delay. Thus, existing kinesthetic data compression algorithms (see [78] for a review) may not be directly applied to tactile rendering. In contrast, studies dedicated to tactile data modeling and compression are rare; one interesting example [79] uses the absolute thresholds of vibrotactile perception to do frequency-domain signal compression. Further endeavors specialized in tactile rendering are necessary. To this end, we may be able to adapt more advanced audio compression algorithms, given the signal-level similarity between audio and vibrotactile signals.

C. Broadcasting

Broadcasting tactile scenes is probably the utmost goal of this line of research. However, since the term "Touch TV" was coined about ten years ago [80], the progress of related research has been rather slow. Some notable recent developments include a touchable 3-D video system that renders haptic cues from depth images [81] and an effort to broadcast touch data in the MPEG format [82].

Tactile broadcasting will require an entire ecosystem of technology and business. On the tactile technology side alone, we need affordable displays, good content production tools, and efficient broadcasting methods, to name just a few. Even though tactile broadcasting is in its embryonic stage, its impact on society could be significant. In fact, multisensory broadcasting is already listed in the technology roadmap for broadcasting engineering. In light of these recent trends, vibrotactile broadcasting deserves considerable attention.

VIII. CONCLUSION

Vibrotactile rendering excels at displaying natural, intuitive, and rich information with relatively low complexity and cost. Still, the peculiarities of vibrotactile perception and the novelty of vibrotactile technology can make it difficult for designers new to this area to create effective displays. In writing this paper, we tried to capture all of the information an interested individual would need to begin this process, drawing on our own experiences developing such systems. We began by overviewing the relevant aspects of human vibrotactile perception, focusing on the questions a designer might wonder about when choosing which vibrotactile signals to use for which purpose. We then progressed to discussing the main types of commercially available vibrotactile actuators, mentioning the benefits and drawbacks of each, as no one option is appropriate for all applications. The next section provided guidelines for the two basic approaches to turning actuators into a vibrotactile display (vibrating an entire rigid object or vibrating one or more small zones), emphasizing the importance of the mechanical connection between each actuator and the user's skin. We then turned our energy toward showcasing well-executed vibrotactile displays and rendering systems in the three broad areas of physical information delivery, abstract information delivery, and multimedia in the hope that they may inspire designers to create new tactile rendering systems for these applications and others we have not yet envisioned. ■

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