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The Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-Based Haptic Technologies Through Fidelity

Stefan Josef Breitschaft, Stefan Heijboer, Daniel Shor, Erik Tempelman, Peter Vink, and Claus-Christian Carbon

***Abstract*—After decades of research and development, haptic feedback is increasingly appearing in consumer products. While the prevalence of haptic feedback is increasing, the integration rarely offers increased fidelity to previous generations. We argue this is because of the tremendous complexity of successful haptic design engineering, but critically, also because of information saturation. With novel cutaneous feedback technologies and companies emerging almost daily, the multi-disciplinary nature of haptics and the marketing-driven terminology used to stand out in a crowded market makes it challenging to select and integrate actuators correctly. To manage this complexity and facilitate the interdisciplinary exchange of user requirements and material affordances, we introduce a novel classification criterion for haptic actuators focused on the bandwidth and fidelity of potential effects. We introduce vocabulary for describing the precise experience the actuators and corresponding systems should deliver. Lastly, we summarize currently commercially available cutaneous-based haptic technology. In the nearby future, the same criterion and language can also prove valuable for steering technology development of new and improved actuators and enabling novice and experienced practitioners to understand and integrate cutaneous feedback in their products.**

***Index Terms*—Haptic feedback, haptic technology, interaction design, vibrotactile feedback, surface haptics, haptic experienc.**

I. INTRODUCTION

THE FIELD of haptics is experiencing growth unlike ever before. The average haptic practitioner's background is shifting towards user interaction (UI) and user experience (UX) rather than the psychophysics or roboticist academic community. While haptics is a small part of modern product UI and UX, they are increasingly relied upon to "close the loop" and confirm an action or add tactile information to an action. Haptic startups are increasingly winning prizes and admiration at trade shows, like the Consumer Electronics Show (CES), indicating a growing interest in haptic feedback in both the business and consumer markets [1], [2]. With the current combined market valued between $7B to $19B and with predicted growth of 7–16% expected year to year through 2026, demand shows little sign of abating [3].

Part of this growth is from technological advances in actuator technology and part of this growth is driven by a paradigm shift in interface design– with flat, glass touchscreens increasingly being the default. One of the great contradictions in modern interface design is that we are in the age of flat, formless and featureless displays. Yet, haptic perception has never been more critical. Designers have traded physical knobs and buttons for virtual, two-dimensional interface elements. This surface featurelessness has led to a fusion of interactive and non-interactive surfaces in products, with haptic features playing a pivotal role in distinguishing interactive and non-interactive surfaces. The challenge of converting digital objects into feel-able items with active haptic technologies is tackeled by an increasingly diversified pool of hapticians. Thus, many practitioners find themselves overwhelmed with literature that primarily focuses on the "what and how" - or usability and technical aspects. Additionally, little guidance is available on the "why," leading to the question of "How can we create compelling touch interactions?"

The haptics industry has only recently begun to come together and discuss a set of technical metrics and requirements to standardize high-definition haptic feedback [4]. Herein lies the problem we aim to solve in this paper: providing a new starting point for those entering the discipline, starting not at the actuator [5] or around perception science [6], [7] but instead on experience, fidelity, and interaction design [8]–[10].

II. TOWARDS A USER EXPERIENCE-CENTRIC CATEGORIZATION OF HAPTIC TECHNOLOGY

There are plenty of recent review papers on haptic technology in the literature. Yet, they do not fully address an up-to-

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date overview of commercially available haptic technologies that practitioners can implement.

In contrast to previous papers that have classified haptics by physical principles, technical operating principles, or even technical parameters, we propose a framework based on a psychological/perceptual-driven approach. We categorize technologies based on their fidelity and bandwidth for displaying a haptic feedback signal or set of signals [11].

The focus of currently available reviews is either a) overly broad, with a focus on terminology and application areas of haptics in general [12], b) tailored to a particular field of application, such as robotics or automotive [13], c) focused on specific types of haptic actuator technologies, such as dielectric elastomers [14] or novel haptic actuation materials [15], d) focused on particular perceptual phenomena – e.g., haptic technologies that can be used to create artificial touch sensations [16] or e) an overview/review from a haptic company in the form of self-published white papers [17]–[19]. Besides missing links towards application and integration, most reviews also focus on research devices rather than technologies with a mature status [20].

Banter's review on haptic enriched touchscreens and touch surfaces is one of the most recent overview papers on commercially available technologies [21]. However, overviews on haptic technologies are outdated very quickly due to the pace of innovation. Since the launch of the iPhone in 2007, haptic technology has been reinvigorated, leading to the birth of several haptic startups, acquisitions of small firms, penetration, and implementation of haptic technologies by suppliers.

Additionally, the sheer extent of detail in many review papers can be overwhelming for practitioners who are not familiar with the world of haptics and simply want to acquire an overview of which technology suits their application. For practitioners, it is crucial to understand both the working principles of different technologies and the users' experience.

Haptic experience can hardly be expressed by a comparison of mere technical parameters. In a recent paper, *Psychology of Design*, Carbon [22] plays the advocate for a deeper psychological turn in design. A techno-centric perspective ignores human-centered design by neglecting the constructive and association-based nature of perception. Touch has memory – context and prior experiences influence the user's perception of haptic stimuli [23], [24].

III. THE HAPTIC FIDELITY FRAMEWORK

With this paper, we target the progressively expanding multi-disciplinary field of haptic practitioners. Hence, we need a systematization that can address various backgrounds and levels of expertise. A fidelity- and experience-based categorization supports haptic practitioners in selecting the appropriate technological approach for their interaction purpose.

A. Technical Prerequisites

Haptic feedback is a broad term that encompasses several sub-modalities of touch [6]. Haptic technologies in consumer electronic and screen-based devices mainly convey feedback via cutaneous information. While technologies that convey haptic information via kinesthetic [25], mid-air interaction [26], electrotactile [27] or thermal cues [28] can be valuable to interfaces, this review paper is tailored haptic technologies most relevant to consumer devices: cutaneous technologies that convey information picked up by mechanoreceptors.

This framework will only review technologies requiring direct physical skin contact between finger and surface and technologies that convey haptic feedback mainly via tactile information, such as skin deformation, pressure, and vibrotactile perception.

B. Different Stages of Fidelity

Uniquely, we aim to categorize haptic technologies by their haptic fidelity. Fidelity does not refer to the quality or mechanical perfection of the isolated haptic result, but to a technology's ability to convey a broad range of perceivable scenarios and experiences. Although some higher fidelity technologies can generate similar feelings as their lower fidelity counterparts while providing additional data within the same signal, fidelity rankings are not perse hierarchical. Tradeoffs also exist as fidelity increases. The relatively blunt nature of low fidelity haptics can shake heavy masses, something most delicate and precise high-fidelity haptics cannot achieve. The orange waveform in Fig. 1 illustrates the progressively increasing fidelity that accompanies the increased responsiveness and bandwidth as you move through the framework.

Starting with *Low Fidelity* (*LoFi*) haptics in the top right corner of the Haptic Fidelity Framework, LoFi haptics are depicted by the orange line as having vague reverberating vibrations with no clearly defined start and termination. The only haptic experience possible is a perceived vibration – an example here would be simple rumbles or on/off buzzes.

Moving further clockwise, we encounter *Medium Fidelity (MeFi)* haptics. These technologies communicate a crisp demarcated haptic event in a clear direction or axis, and some even convey various intensities in exercised forces. Typically, MeFi haptic solutions can simulate the mechanical workings of buttons and switches.

As we continue to expand our bandwidth and fidelity, we find *High Fidelity* (*HiFi*) haptics. HiFi haptics can present complex waveforms and patterns that simulate localized textures with debossed elements, different friction coefficients, or various compliance levels by a simulation of mechanical compression of materials.

The fourth and final category exemplifies the circular nature of our fidelity framework, with technologies that sit at the intersection between the low- and high-fidelity level. These technologies enable surfaces to morph or emulate material hardness changes and thus can also vibrate and simulate texture. From a technological perspective, the vibrations caused by those technologies are the same as you would experience in LoFi technology. Crispness is limited by the actuators' soft and slow movements. However, the LoFi haptic experience is augmented with morphing surface features which contribute to a beyond-HiFi experience. Thus, we believe there to be a connection to morphing surfaces between low- and high fidelity. As Morphing Surface actuators are not categorized as haptic feedback technologies, they will not be described further in this review.

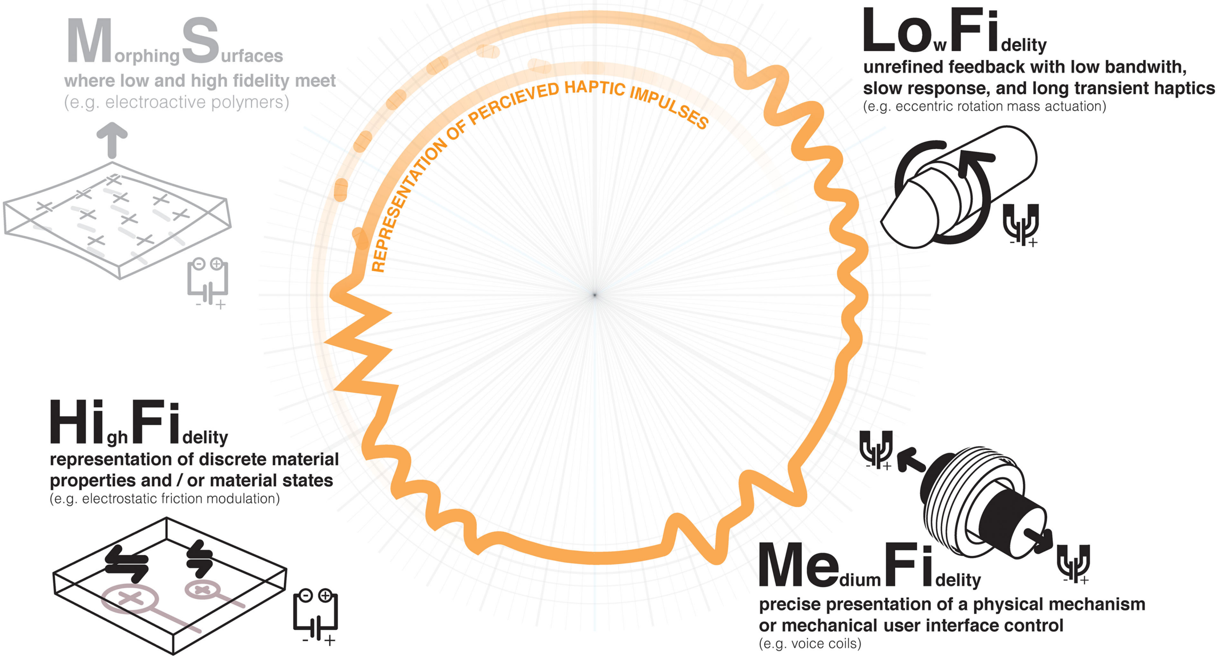

Fig. 1. Within the Haptic Fidelity Framework technologies are categorized according to their fidelity level (low, medium and high). The orange line schematically illustrates the prototypical haptic event (in the form of an acceleration curve) that becomes increasingly distinct with higher fidelity.

C. Actuation Method

The mechanism with which a cutaneous feedback device develops the impulse to stimulate the skin can vary. Below we offer a quick summary of primary actuation methodologies.

Rotating (R) feedback devices convert angular momentum into a vibrotactile impulse. Rotational devices rely on imbalanced rotor shafts to create vibration – usually an approximation to a sine wave. Typically, a stator produces an electric field that causes a rotor to turn generating the angular momentum

Oscillating (Os) feedback devices produce a linear movement by converting electromagnetic energy into kinetic energy. Most oscillating systems can be modeled as mass-spring-damper systems and achieve sharp, precise movements. Some can be over-damped to produce either deceleration or acceleration of components to approximate square waves.

Material deformation (M) actuation relies on the expansion/contraction (M-Ex) or twisting/flexing (M-Fx) of material or chamber due to the application of an external force. Standard methods use shape-memory materials, pneumatics, or piezoelectric materials.

In addition to cutaneous haptic feedback, Electrostatic (Es) actuation can also convey haptic feedback over extremely short distances (μm) without any skin contact. Electrostatic feedback applies an electrical charge potential between display and user. By varying the charge intensity and charge polarity, an electrostatic display can repel or attract parts of the skin, creating linear and shear movement. Due to the highly localized nature of electrostatic displays, large impulses are difficult to be generated.

D. Building Blocks of Haptic Systems

Haptic systems bridge electronics, driver boards, actuators, software, firmware, and lastly, a mechanically affected surface, enclosure or housing (see Fig. 2). These electronics may include analog components or booster circuits to increase the actuator's voltage or a dedicated haptic microcontroller (μC). The μC converts haptic parameters and timing to a signal that drives the actuator, converting electrical signals into haptic sensations. Sometimes, control electronics and actuators will be integrated into mechanical stacks that cannot be separated for space or latency concerns.

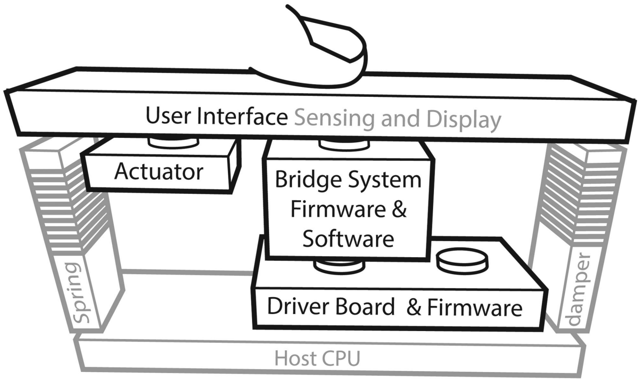

Fig. 2. A haptic system is other than just the sum of its parts. It incorporates a multitude of interconnected components that influence the haptic experience.

The last ingredients for a haptic system are firmware and software that allow the system to communicate and operate. Firmware is a low-level layer of software stored on μCs. Since many haptic technologies and companies are constantly developing, the firmware may vary over the lifespan of an implementation.

With firmware that can minimize the limitations of their actuators, systems can move up the fidelity framework, and

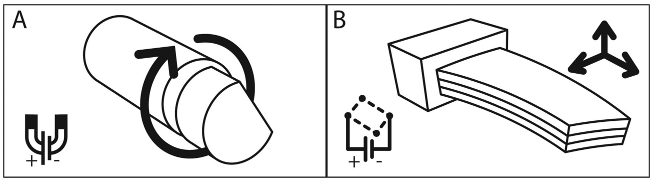

Fig. 3. (A) ERMs are based on the electromotor principle where vibration is caused by an eccentric mass attached to a DC motor. (B) Piezo benders are composed out of bimorph piezo materials, meaning once current is applied the bender produces movement in a certain direction.

thus haptic implementations can exceed the fidelity provided by actuators alone. Haptic software permits the user to configure haptic patterns by code or by offering platforms that substitute code with numerical or graphical representations of haptics, such as sine waves, bitmaps, or sliders (e.g., HapticLabs.io [29]) or translate waves from audio-files into haptic patterns (e.g., Lofelt Studio [30]).

Haptics APIs and other specific programming information can be IP sensitive and often only be obtained after NDAs are in place. LoFi and MeFi haptics are becoming standard practice in HMI systems, and corresponding brand-related secrecy, hardware, and software has begun to play a role in platform election. (e.g., the inclusion in the Arduino platform actually means clear democratization of products).

IV. HAPTIC TECHNOLOGIES

Here we classify haptic systems or individual components via the Haptic Fidelity Framework. First, we describe the general haptic feeling and experience at every fidelity level based on timeliness, intensity, density, timbre, design principles, and technical complexity [10]. Second, we describe currently available haptic systems and technologies. An overview of the different stages of fidelity with corresponding types of working principles and technologies is given in Table I. Table I also describes approximate technical parameters for each actuation principle. Haptic drivers are included in this overview as they are an integral part of haptic systems. They will only be reported briefly in our text as they are based on different key drivers features than actuators, such as gain, frequency range and communications protocols. A detailed description would exceed the scope of this paper.

A. Low Fidelity Haptics

LoFi haptics was the first to be widely implemented in consumer electronics products, such as mobile phones and gaming controllers. To this day, they are still the most used haptic actuators in prototyping haptic interactions because of their relatively low cost and complexity level. In general, LoFi haptics provides the feeling of buzzing, rumbling – mere vibration. Their diffuse vibrational feel limits LoFi use-cases to notification of an incoming call or a rumble to augment specific situations in gaming. Temporal aspects of LoFi haptics can be generalized as delayed, diffuse, imprecise, blunt, and transient. This is most applicable to technologies using a rotating principle with relatively low damping values and a long spin-up time due to the inertia (see Table I). Because of the latency, short and precise "click" effects are hard to achieve, leading to potential unsatisfactory interplay with other sensory modalities. Driver ICs can be used to enhance responsiveness.

Although the intensity can vary, LoFi haptics typically couple amplitude and frequency behavior, meaning that one cannot be modulated independently from the other. Some systems allow for variation in frequency by adjusting parameters such as voltage or current. The perceived intensity of the vibration can be quite considerable but easily pose the risk of being annoying and unpleasant when overused [31]–[33]. Additionally, a considerable, mostly unwanted soundscape often accompanies the haptic signal.

Feedback cannot b4e localized at specific positions on a screen or product without using complex suspension systems as the rotating mass is shaking the whole device, making these systems most suitable for handheld or wearable devices. Moreover, LoFi haptic feedback will typically not be uniform due to the form factor and position of the actuator inside the product. On the upside, available actuators are low-cost, highly accessible in different form factors, and can easily be integrated to create haptic systems. This makes them popular for prototyping and hardware sketching [9]. Due to the wide variety of available actuators and LoFi haptics' relatively monotonous haptic possibilities, this category will not be considered as extensively as other haptic systems.

1) Eccentric Rotating Mass (LoFi — R): Eccentric Rotating Mass actuators (ERM) work much like an improperly loaded washing machine. When a mass is unevenly distributed around a point of rotation, oscillation occurs; see Fig. 3A. Larger masses and faster rotation increase the magnitude of the vibration. ERMs are available in many different form factors and are rather cheap. They can easily be integrated and controlled with votage or pulse width modulation (PWM) signals. Hobbyist-focused suppliers such as Adafruit [34] and Sparkfun [35] provide systems that include pancake-style ERM actuators with Arduino-based breakout boards, making ERMs popular for rapid prototyping or early product mockups containing haptic feedback. Precision Microdrives [36] and Grewus [37] provide different styles of ERM-based actuators, including pancake-style or PCB-mounted variations.

While not needed, fidelity can be improved with easily accessible driver circuits and firmware improve system responsiveness via breaking and back driving (e.g., DRV260X series from Texas Instruments [38], Dialog Semiconductor's DA728X series [39]). Some suppliers already package their standard capacitive controllers with output libraries/features, e.g., pulse width modulation, specifically for haptic actuators [40].

2) Material Deformation – Piezo Bender (LoFi—M-Fx): Piezo actuators exist in different form- and size-factors with single- and multi-layered piezoceramic elements. In contrast to single-layer piezos, multi-layer piezoceramic elements contain several electrode layers resulting in a higher displacement and force, but also thicker actuators. There are also bimorph piezo elements, which consist of metal or silicon substrates that have piezoelectric layers glued to each side (one side is contracting while the other is expanding), leading to bending movement. Hence, they are often referred to as piezo benders.

While many piezo bender actuators are used for very specific MEMS (Micro-Electro-Mechanical Systems) purposes, such

TABLE I
SUMMARY OF HAPTIC TECHNOLOGIES DESCRIBED WITHIN THE HAPTIC FIDELITY FRAMEWORK (APPROXIMATED VALUES)

Fidelity	Actuation Principle	Product	Force (G-p.p.)	Frequency Range (Hz)	Operating Voltage (V)	Rising Time (ms)	Recovery time (ms)	Operation current (mA)
LoFi	Eccentric Rotating Mass	e.g., Adafruit, Sparkfun, Precision Microdrives, Grewus	C: 0.15-2.5 B: 0-20	0 - 200	C: 1.5-5 B: 1.5-12	80-100	50-100	100-500+
	Piezo Bender	Murata Piezo Vibe	0-1.2	200 - 300	1.8 - 3.5	< 10	n/a	5-10
MeFi	Piezo-electric Polymer	Piezotech, HAPPINESS-Project	displacement up to 8 µm	1500-7000	6-35	< 1	n/a	20
	Electroactive Polymer (EAP)	ELFIAC (Senseg), Nexipal (Wacker), Electro-Mechanical Polymers (Novasentis)	3.5	1 Hz – few kHz	100 - 500	< 5 (EMP)	n/a	~30
	Solenoid	Standard Actuators (e.g., Johnson Electric), Niceclick (TRAMA), Custom-purpose Solenoids (e.g., Automotive industry)	varies	varies	varies	varies	varies	varies
	Linear Resonant Actuator	Voice-Coil-Acuator: LoFelt L5, Grewus Exciter, Sparkfun Surface Transducer, Actronika Hapcoil, Taptic Engine (Apple)	0-15	0 - 15000	0-3.3	5-15	5-15	200 – 500+
		Multdimensional LRA: Alps Haptic Reactor	2-4	X: 120 - 180 Y: 300 - 360	2.7-3.3	5-15	5-15	depends on haptic driver
		Linear Ram Actuator: Nanoport Tachammer	Imp: 0-27 Trad: 0-11	0.5 - 200	3.6 - 10	Imp: 0.2 Trad 5.1	Imp 6.3 Trad 7.5	800*
	Shape Memory Alloy	Seidensha, Cambridge Mechatronics	up to 20	XXX	0-5V (AC) 0-12V (DC)	depends on voltage	n/a	n/a
	Singlelayer Piezo	Piezoelectric Diaphragm (e.g., Murata), Kyocera (ring & rectangular shaped)	0.5-5	0-1000	0-120	5-15	5-15	5-15
	Multilayer Piezo	TDK PowerHap & PiezoHapt, Murata, Kyocera	2.5-20	0-1000	0-120	5-15	100	5-15
HiFi	Software-Enhanced Piezo	Aito HapticTouch, Boreas CapDrive IC, Kyocera Haptivity	3.5-8 (technically up to 50G)	150-400	60-400	2-15	5-15	5-15
	Bending Wave	Lotus (CEA), Redux Labs	N/A	n/a	n/a	N/A	N/A	n/a
	Electrostatic Friction Modulation	TanvasTouch, Senseg Tixel	N/A	N/A	>100	N/A	N/A	n/a
	Ultrasonic Friction Modulation	Hap2U	N/A	>20 kHz	>40	N/A	N/A	200-1000

Note: The provided values are an approximation based on reference designs and vary upon system integration. For detailed values see the respective technical specification sheets. This table does not include haptic drivers. N/A = not applicable, n/a = information was not available at the time of writing the manuscript or cannot be shared due to confidentiality, C = Coin, B = Barrel; *800 mA required to power haptic driver

as opening valves, the Piezo Vibe by Murata Manufacturing [41] is an example of a piezo bender actuator that can be used to create a rumbling feeling. It uses the piezoelectric effect to deform its ceramic layers in order to produce a vibrating feeling (Fig. 3B). Due to its low power consumption and very small size, it is primarily targeting wearable devices.

B. Medium Fidelity Haptics

Consumer electronic devices have recently shifted to haptic systems that can simulate a button press or mechanical click feedback on solid and featureless surfaces. Hence, one of the main driving aspects of MeFi haptic feedback is to substitute mechanical, visually moving, tactile switches with electro mechanical actuators to retain a monolithic appearance of haptic systems.

In terms of temporal aspects, the fundamental difference to LoFi feedback is increased responsiveness and controllability of the actuator, avoiding long transient vibrations. This allows for haptic effects that convey the feeling of ”haptic clicks”. Actuators can be programmed to convey longer-lasting vibrations but are limited by their frequency bandwidth. Latency and response time are considerably lower than those of LoFi actuators but generally higher than those of HiFi systems (see Table I).

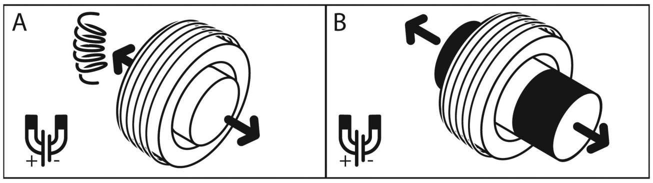

Fig. 4. (A) Solenoid and (B) Voice-Coil actuators are both based on the electromagnetic working principle. Displacement is created by the interaction of a coil, which acts as an electromagnet once voltage is applied to and a moving mass which is either a ferromagnet (A) or a permanent magnet (B).

The intensity of the haptic impulse correlates to the form factor of the actuator and the amount of mass actuated. In automotive contexts, larger MeFi haptic actuators generate a strong impulse even though actuated mass is often more than a kilogram. The more typical implementation of MeFi haptics in handheld and mobile devices demonstrates the size adaptability in MeFi haptics. Audible noise can still accompany intense MeFi haptics in poorly isolated enclosures. The conciseness of the haptic event is influenced by the dampening of the vibrational impulses. The actuator's integration in the haptic device's mechanical stack becomes increasingly complex as actuated mass (linked to haptic display size) increases.

Although there are exceptions, most MeFi actuators do not rotate or swivel but move a single axis by using the electromagnetic working principle (1-DoF instead of 2-DoF, see Fig. 5). This linear movement can change the perceived character of the device depending on the orientation relative to the user. It can be a design factor to consider during integration.

Due to the wide variety of form factors and output forces, it is difficult to summarize the haptic timbre of MeFi haptics. A key trend to note is that complexity of haptic systems increases as the fidelity of the feedback increases. From a mechanical perspective, MeFi systems are not more complicated to integrate or tinker with than LoFi actuators, making them a valuable resource for hardware sketching [9]. Some MeFi components are easily accessible via electronics distributors. Yet, companies often use custom-specific and proprietary actuators, such as Apple's Taptic Engine and CoreHaptics API.

1) Medium Fidelity — Oscillating (MeFi — Os): MeFi actuators based on an oscillating electromagnetic working principle can be described as solenoid or linear resonant actuators (LRA). Both yield a similar haptic impression. They differ in their technical setup (see Figs. 4 and 5).

a) Solenoids: In general, solenoid actuators are based on an electromagnetic working principle and consist of a coil, which generates an electromagnetic field, a steel slug suspended within the coil, and a spring system or endplates that limit the movement of the slug (see Figs. 4A and 5A). Current applied to the coil excites an electromagnetic field which moves the steel slug unidirectionally to its end position. Subsequently, a suspension system will push the steel slug back to its starting position. The force the solenoid can convey is directly connected to the force of the magnetic field [42].

Off-the-shelf and standard solenoid components for haptic actuation from suppliers like Johnson Electric [43] or Adafruit [44] can be found at nearly all major electronics distributors (e.g., Conrad, Mouser, Digikey). Even though they are often used for controlling valves, they can also be used to create a haptic experience (e.g., [9], p.146 "The Knocker"). Probably one of the "most felt" medium-fidelity haptic actuators is Apple's Taptic Engine found in MacBooks. The laptop version of the Taptic Engine seems to differ regarding to actuation technology for handheld and computing devices, with the magic trackpad known from MacBooks resembling a solenoid. Four electromagnetic coils pull a ferromagnetic rod connected to the trackpad surface in a lateral direction [45].

Niceclick is a patented haptic system by Trama Engineering [46] that tries to mimic the feeling of a conventional button with a haptic dome made out of spring metal, rubber, or a combination of them. They speak of "Touch 4-D" which integrates sensing in a lateral (x-, y-axis) and normal direction (z-axis). Feedback is given in a vertical direction by an electromagnet that attracts a ferromagnetic element. Soft supports within the actuator act as a spring-damper system [47]. Together with Grewus, Trama focuses on the automotive industry to provide a fully integrated interface solution to reduce cost and make interfaces safer to use.

For a couple of years, there is increasing use of active haptic systems in the context of seamless automotive control panels [48], [23] and enabling touchscreen with haptic feedback [49]–[52]. As there are specific requirements for integration, haptic systems are mostly custom-built and covered by non-disclosure-agreements. Thus, it is often unclear whether voice coil or solenoid-based technologies are used. Additionally, the driving measures regarding dampening are also opaque. High actuation forces typically suggest solenoid-based systems. Another proprietary haptic solution for the automotive industry is the Bosch NeoSense [53], [54]. Uniquely, it contains confirmation haptics – button press and clicks – as well as search haptics which enables the user to feel buttons through different textures [23].

b) Linear Resonant Actuators (LRA): LRAs and solenoids differ in whether, respectively, a permanent magnet or only a ferromagnetic material is used (Fig. 5). LRAs are based on an electromagnetic working principle and consist of a permanent magnet, a spring, and a coil. By applying current to the coil, an electromagnetic field is produced, creating a magnetic interaction between the permanent magnet and the electrically induced coil. Polarity can be reversed, meaning push and pull forces on the magnet can be created. In such systems, either the coil or the magnet is stationary while the other will move. As a result, the magnet can move bi-directionally on a single axis perpendicular to the coil. As a rule of thumb, the maximum force the actuator can produce depends on the magnetic field's strength. Constant forces are also possible with this kind of actuator [42].

Typical LRAs are produced by Precision Microdrives [55], and Jinlong Machinery [56]. They offer a range of different linear resonant actuators for actuation in either y- or z-axis, depending on the final application or the shape and placement of the spring actuation. Variations to the typical cylindrical form factor, such as flat actuators used in mobile phones, are offered by Actronika [57]. As with any mass-damper system,

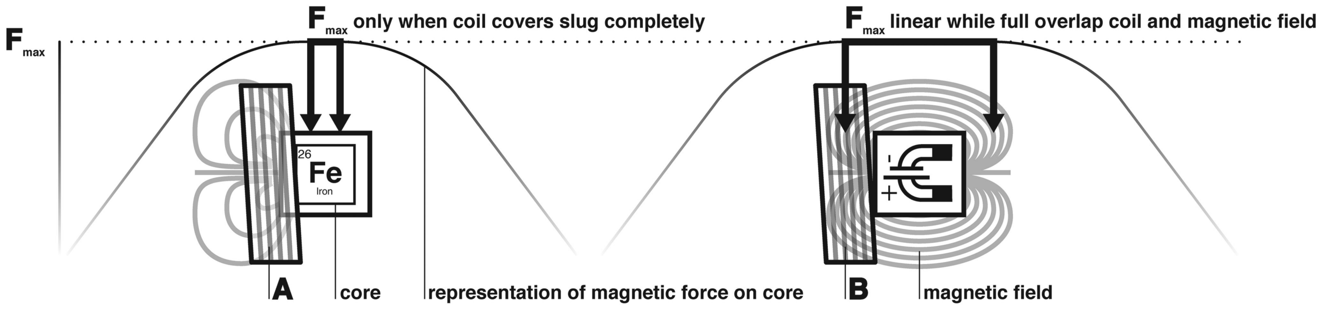

Fig. 5. A graphical representation on the magnetic force in and a cross section of (A) Solenoids, and (B) LRAs. As visible in (A), the ferromagnetic core will only start to create its magnetic field when the coil starts to overlap, reaching a maximum in the magnetic field when coil and core fully overlap. In (B), the coil will already fully interact with the magnetic field even before overlapping the core. Since the core's magnetic field will not be affected by the electromagnetic field of the coil, the resulting force will remain constant – assuming the current remains constant as well.

there is a resonant frequency to the oscillations. An LRA's efficiency increases the closer it actuates at its resonant frequency. As such, LRAs produce noticeable vibrations in a very narrow frequency band. Thus, in their most simple configuration, LRAs have variable amplitude and a fixed frequency. LRAs are driven by the alternating current polarity at the resonant frequency. Isolating the actuator itself, the resonant frequency is typically between 150-300 Hz, coinciding with the peak frequency response rate of the skin [5], [6]. However, resonance values change when the product and actuator are combined. Coinciding with the developments in other actuators, Cirrus Logic [58] offers microchips that are both capable of driving an actuator and sensing the actuation by measuring current and voltage. The limited range of products and the use of dedicated actuators versions allow for maximum actuator efficiency and thus a high-quality haptic experience [59].

Voice-coil actuators (VCA), an improvement on the LRA principle of operation, are just starting to rise in popularity. Common examples include Apple's handheld version of the Taptic Engine, which seems to be based on an LRA-principle [60], the LoFelt L5 actuator [61], Tactile Labs' range of Haptuators [62], and the Exciter by Grewus [63]. However, rather than oscillating a cone and compressing air, a voice coil actuator moves a mass and excites the skin. The voice coil can run over a large frequency range solving the traditional limitation of an LRA. The voice coil design is difficult to drive, typically requiring filtration of the signal, and has a non-linear response curve across frequency and amplitude ranges.

Interestingly, voice coils can directly be driven by audio amplifiers and due to the similar structure of a loudspeaker the actuator can also be used for audio feedback, such as Sparkfun's Surface Transducer [64] and Grewus' Exciter [63]. The most well-known VCA these days is the mobile form of the Taptic Engine, found in Apple's iPhone and AppleWatch product lines. With Core Haptics in iOS 13 Apple gave developers much more freedom in using the Taptic Engine to create haptic impulses [32]. Third-party integrations like the LoFelt Studio provide a haptic design toolkit to ease the creation of immersive haptic experiences [30]. The VCA has also recently entered the gaming market, with Foster's VCA technology being integrated into the Sony Playstation 5 [65].

Another modification of the LRA basic design, a multidimensional (MD) LRA, offers additional DoF, with each axis using a unique resonant frequency. By biasing movement across multiple axes, MD LRAs can present wider spectrum actuation than traditional LRAs. Alps offers actuators that can control haptic effects in multiple directions by suspending the coil in the housing between two magnetic endplates. The Alps Haptic Reactor [66] has two resonance points for vibration. The Alps Quadra even has four resonance points for greater bandwidth. This novel approach has helped drive the adoption of Alps technology in many current game controllers and TV remotes [67].

The TacHammer, which Nanoport [68] classifies as a Linear Magnetic Ram, seems to combine the basic principles of a voice-coil and a solenoid actuator. The TacHammer series offers a broad range of changeable impact disks and spacers to influence the actuated mass. One significant difference to regular LRAs is the suspended magnet that provides different modes of operation: (1) impact, where the magnet hits the endplate on one side and (2) traditional, which drives the ram into a magnetic brake on the other side of the actuator resulting in a vibrating effect by working as a traditional LRA [69].

Besides the actuator, drivers are essential for a haptic system with solenoids to function (see Fig. 2). The type of driver is becoming more and more of a differentiating factor for haptic quality as fidelity increases. Major haptic driver suppliers for MeFi actuators are, for example, the Cypress' CY8C20xx6H product family, Microchip's MTCH810 drivers, and Texas Instruments' DRV25XX/DRV26XX drivers [40], [70], [71]. Dongwoon is a driver supplier that includes Immersion-certified haptic libraries [72]. Texas Instruments also has versions of their drivers that come supplied with Immersion's libraries. Adafruit uses a TI DRV2605-chip [73] on their Arduino-compatible breakout-boards.

2) Medium Fidelity – Material Deformation (MeFi—M): There are also MeFi actuators that create haptics via material deformation. They include piezoceramic-based or shape memory alloys that actuate by expanding/contracting or foil-based actuators that actuate by twisting/flexing.

a) Piezoceramic Based Actuators (MeFi—Ex): Piezo-related haptic feedback is based on the piezoelectric effect. Piezoelectric materials consist of piezo crystals that convert

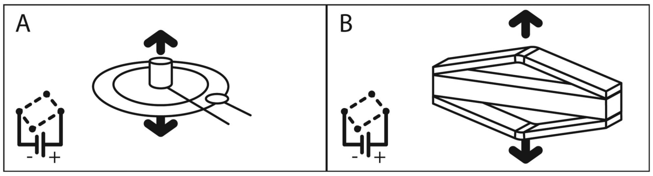

Fig. 6. (A) Piezoceramic material expands when voltage is applied, leading to the bending of the bonded rigid substrate. (B) The PowerHap consists of a multilayer piezoceramic element with two conic metal domes, that produce displacement as a result of the voltage-induced expansion of the piezoceramic material.

voltage to mechanical displacement and vice-versa. In addition to being able to sense user input such as a press, this smart material can move or deform surfaces with relatively small displacements but high accelerations and precision. In general, piezo elements are relatively thin and energy-efficient in comparison to most LoFi and MeFi actuators (Fig. 6).

Disk-like piezo actuators with single-layer piezoceramic elements are probably the most known and cheapest piezo actuators (Fig. 6A). Murata [74] offers a range of what they call piezoelectric diaphragms, while Kyocera Corporation [75] also offers ring and rectangular-shaped single plate piezo elements. Multilayer piezo elements can be bought from Murata, Kyocera Corporation [76], and TDK.

TDK sells a distinctive line of more expensive and powerful multi-layer piezo actuators [77] for a variety of automotive as well as information and communication use-cases [78]. Similar to a piezo disk, the Piezohapt is a flat actuator with a multilayer piezo glued to a thin metal surface. This way it delivers vibrations over the whole metal surface, which can be used beneath display components [79]. The Powerhap (Fig. 6B) can be described as two oppositely cone-shaped metal domes ("Cymbals") with multiple piezo layers in between [80]. There is also an additional version that consists of just the cross-section of the Powerhap. When voltage is applied, the piezo layer's length or size decreases and makes the domes contract in height, creating the haptic effect. TDK offers a proprietary driver that allows the Power- and Piezohapt to be driven up to 60V or 120V depending on their size and force for simple clicks [80].

Texas Instruments has various dedicated piezo drivers with an integrated voltage boost circuit in their product lineup (e.g., DRV2700, DR8662). They claim that startup time of 1.5ms is lower than those of competitors [71].

b) Foil based Actuators – (MeFi—Fx): Electroactive polymers (EAP) are smart materials that change size and shape when exposed to an electric potential. Dielectric elastomer actuators (DEA) are a class of EAPs. The basic principle of DEAs is based on two conductive layers of electrodes with a non-conductive flexible or stretchable polymer in between. The two conductive layers will be charged oppositely and attract each other (governed by the Coulomb force), thereby squeezing or stretching the material in the middle. The conductive material and the substrates and isolation can be varied (Fig. 7B). Stretched and relaxed states can be evoked by alternating the polarity of current. This physical movement can lead to a tactile experience. Tactile experience is described chiefly by a vibration that can be adjusted by varying frequency and amplitude.

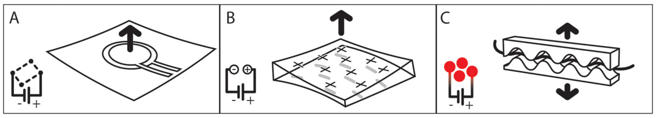

Fig. 7. (A) Piezoelectric polymers have been used to produce transparent film-type vibrotactile actuators. (B) EAP-actuators are based on an electrostatic principle. Two mutually charged layers attract each other while a conductive in between is stretched or flexed. (C) Shape memory alloy wires will shrink when joule-heated once current is applied.

Despite much research on using electroactive polymers as haptic actuators, only a few companies offer industrialized products, most of the research results in one-off prototypes. Following the general working principle in Fig. 7A, piezoelectric polymers (PVDF) have been used to produce transparent film-type vibrotactile actuators [81], [82]. The EU-funded HAPPINESS project (Haptic Printed Patterned Interfaces for Sensitive Surfaces) aims to replace mechanical components within car interfaces by using more "soft" and flexible printed actuators that combine touch sensors with localized haptic feedback [83]–[85]. Piezotech [86] provides different kinds of printed piezopolymer actuators that are also suited for haptics.

Following an electrostatic working principle explained in Fig. 7B, other companies have produced actuators on squeezable and stretchable substrates. Senseg released a novel kind of actuator in 2019 – the Elastomeric Film Actuator, or in short, the ELFIAC.[1] The elastomer films make it a flexible and highly adaptable actuator in terms of size and shape. The actuator structure is composed of stacked printed electrodes on foil layers, with micropillars between the electrodes. Wacker [87] is releasing a range of EAP laminates acting as an actuator. A silicone film separates opposingly charged electrodes. Applied voltages lead the electrodes to attract and cause the silicone film to be squeezed and expand in shape. Multiple Nexipal layers can be stacked to enable larger strokes. As a last example, Novasentis [88] is selling EMP (Electro-Mechanical Polymer) actuators especially for the mobile, wearable, and gaming market. A thin electroactive polymer film is bonded to a rigid substrate, and when a voltage is applied, vibrations can be created. Novasentis' actuators enable localized and programmable feedback, even at relatively low operating voltages. When driven with high frequencies, these actuators can produce sound. For the driver, Novasentis has teamed up with Microchip [89] to provide a driver that can deliver up to 250V for haptic actuators.

c) Shape Memory Alloy Actuators (MeFi—Ex): Shape memory alloy (SMA) based actuators switch between two different form states when heated or cooled by driving current through the metal for joule heating. While displacements are relatively large, most applications use SMA actuators to create displacement for purposes other than tactile feedback, e.g., as

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[1] Senseg's website is out of service upon the submission of this paper in February 2021. Information on the ELFIAC (https://www.senseg.com/wp-content/uploads/2019/08/Senseg_ELFIAC_whitepaper_launch_edition_AUG2019.pdf) can be accessed via archive.org

opening mechanisms in valves. SMA actuators are relatively slow in actuation and recovery time, and the risk of mechanical fatigue is high [90]. Additionally, some of the SMA's characteristics, such as operating temperature, mismatch with functional requirements for specific markets. Seidensha [91], [92] and Cambridge Mechatronics [93] have shown actuators that can provide non-visible haptic feedback using SMA-actuators. Two dented inter-fitting elements with an SMA wire in between are pushed apart when the wire contracts (Fig. 7C). Compared to other similar haptic technologies, the resulting feedback is relatively silent while the haptic remains quite clear and precise.

C. High Fidelity Haptics

Within the category of HiFi haptics, haptic feedback is tunable to a level that exceeds pure vibrations and enables extensive haptic languages [94]. While previous technologies rely on vibrations to provide haptics, some HiFi technologies are based on friction stimuli. The common denominator of these HiFi haptic technologies can be explained as the possibility to provide haptic sensations that simulate material properties, textures, or shapes without it being a physical characteristic of the surface. Bandwidth in terms of sensations reaches from precise button click simulations and complex surface textures to compliant material.

Describing the temporal characteristics of HiFi haptics involve an almost immediate response, i.e., a lower latency than MeFi haptics and "crispness" of the haptic sensation (see Table I). Systems are, in general, more geared towards providing localized actuation at the fingertip rather than actuating larger surfaces. Also, a few HiFi technologies will require the user to actively explore the surface by pressing or sliding. Some haptic technologies are more suitable for rendering textures and providing feedback with more complex impulse characteristics. Others are primarily intended and more suitable for a little higher quality MeFi haptics sensation, such as mimicking "clicks". HiFi experiences are rarely defined by the actuator's properties. Often the driver, system, and rendering algorithms behind the actuator enable more complex haptic effects.

Levesque *et al.* [95] and Levesque, Oram, and MacLean [96] conducted an initial exploration of friction stimuli in the context of UI use-cases, such as target acquisition, slider, selection, and drag-and-drop tasks. Friction stimuli have been used to augment virtual textures and interfaces elements, such as buttons [20]. Nevertheless, user-centered haptic evaluations of such stimuli in applied user settings are still scarce [97], [98].

HiFi haptics also involves new means of providing haptic feedback, which go beyond vibration-based systems. By controlling the friction coefficient between finger and surface (friction modulation), haptic systems can render textures that feel like embossed ridges or slippery surfaces. Though providing an extensive set of possibilities to restore haptics on otherwise featureless surfaces, it is also challenging to design for these approaches [97]. Basdogan, Giraud, Levesque, and Choi [20] review the current state of friction modulation regarding perceptual mechanisms, rendering algorithms, and applications purposes. HiFi systems are in most cases provided by specialized haptics companies as part of research programs, or OEM-specific disclosed development programs. Though development kits may be available for tinkering and selling purposes, most proof-of-concept projects with OEMs or suppliers require specific knowledge and customized hardware. This also applies to the even more exclusive, proof-of-concept haptic prototypes provided by various research groups or material suppliers.

1) Software-Enhanced Piezoceramic Haptic Feedback: It is essential to distinguish between actuators, drivers, and corresponding software as most companies begin to specialize. Because haptic fidelity increases signal complexity, there is a greater demand to control actuators via a graphical user interface or a simple to use software package. The complexity enabled by these software solutions makes the software/firmware the primary technology of piezo-based HiFi haptic systems. Software-enhanced refers to the influence of control electronics on driving piezo actuators. There are a few companies that specialize in driving piezo actuators. Most drivers are claimed to be very energy-efficient and include piezo pressure sensing.

The Dutch-Finnish company Aito [99] mainly focuses on sensing and driving off-the-shelf single-layer piezo disks, as shown in Fig. 6A. The Aito system employs conventional single-layer piezo disks from regular manufacturers like TDK, Murata, or Kyocera. Next to actuating a complete surface (similar to a trackpad actuation), Aito's proprietary system can provide localized haptic feedback by tightly integrating piezo disks into a mechanical stack of the interface (the actuation layer only adds 0.3 mm thickness to the entire UI stack). Local actuation in z-direction, which means only providing haptic feedback where the finger is touching the surface, is possible with a wide array of material overlays, such as wood and even steel—also in the context of automotive prototypes [98]–[100]. Important for haptic practitioners is the possibility to fine-tune haptic effects with the AITO UX Design Studio, which comes with different evaluation kits (Haptile Trackpad or Haptic-Touch). Next to having flat single layer piezo disks in different form factors, Kyocera provides multi-layer actuators that show larger displacement [76]. Kyocera's haptic system Haptivity is currently available as an evaluation kit [100]. It is able to recreate the feeling of real buttons in-car interfaces and entails both their multi-layer piezo actuators and discrete driver.

The CapDrive IC by Boreas [101], a Canadian startup, also uses multi-layer piezos to sense and provide haptic feedback for mobile, wearables, and automotive purposes. In contrast to Aito, Boreas mainly uses the TDK Piezohapt and Powerhap actuators to actuate entire surfaces instead of providing localized feedback under the fingertip, with the exception of the side buttons on their mobile phone demo [102]. With the biggest type of Powerhap there is a maximum displacement of 230 μm possible. Boreas also provides a development kit (Boreas BOS1901 PCB) for driving 60V with a dedicated haptics software studio to test and design haptic effects. There is close cooperation between TDK, Boreas and Immersion to provide haptic solutions for a wide array of different markets, such as smartphones, gaming and automotive [103].

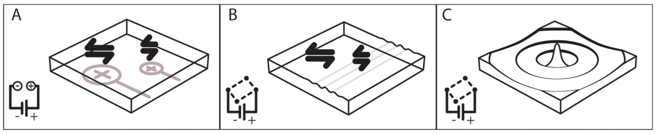

Fig. 8. (A) Electrostatic friction modulation increases the friction force between a sliding finger and surface by varying the attraction force of a voltage-induced conductive layer while (B) ultrasonic friction devices decrease friction force by creating ultrasonic waves via piezoelectrics. (C) Bending waves produced by an algorithm-controlled actuation of piezoelectrics leads to a highly localized surface deflection.

2) High Fidelity – Friction Modulation: Variable Friction displays are a relatively new type of surface haptics that create haptic feedback by changing friction on the bare finger during a lateral movement across a surface instead of using vibration impulses. Previously mentioned technologies are mostly vibration-based haptics, while the following types are friction-based. Two types of mechanisms can be described: (1) increasing or (2) decreasing friction (see Fig. 8).

a) Electrostatic Friction Modulation: Increasing friction on haptic displays is based on the principle of electrostatics [104]. A recent in-depth description of the current affairs of electrostatic devices is given by Osgouei [105]. Electrostatic friction modulation refers to attraction between charge in the screen and charge in the skin. Most modern electrostatic friction modulation devices refer to the effect of electroadhesion, meaning any change in adhesion due to an increased electrostatic force, without referring to the type of charge or frequency. A smaller subset of electroadhesion refers to electrovibration, which deals with only AC signals and a limited vibration range that humans can feel [104]. Initial psychophysical studies employing electrovibration devices were carried out by Bau, Poupyrev, Israr, and Harrison [106] using the Tesla Touch device. Breitschaft, Pastukhov and Carbon examined the effectiveness of electrostatic friction modulation in an automotive dual-task context [107]. In the early 2010s Nokia [108] and Microsoft also worked on devices using electrovibration [109].

Advantages over vibration-based technologies are that devices are solid-state, noise-optimized, low-energy, and low latency. Haptic effects are fully software-defined [110]. Tanvas [111], a US-based startup, offers commercially available development kits including their proprietary TanvasTouch electrostatic friction modulation technology [110]. Together with the automotive supplier Innolux they provide an automotive solution for the TanvasTouch technology [112]. Senseg, which have been the first company to offer electrostatic friction modulation in the early 2010s now offer the Tixel[2] (formerly E-Sense) in conjunction with their proprietary high-voltage driver as a technical solution for electrostatic friction modulation [113]. Earlier iterations of their technology have been integrated into prototypes by Toshiba [114].

b) Ultrasonic Friction Modulation: Ultrasonic actuation decreases friction on haptic surfaces during haptic exploration. Vibration of the surface at an ultrasonic level by piezoceramics creates an “air-cushion” and reduces the contact area of the fingertip and surface. This results in a lower friction sensation on the bare finger while it is sliding across the surface. Biet, Giraud, and Lemaire-Semail [115] refer to this as the “squeeze film effect”. For an in-depth review see [20]. Pioneering work on the design of ultrasonic devices, such as the TPad, has been done by a research group from Northwestern University [116], [117]. In 2014 Fujitsu released a haptic sensory tablet prototype using ultrasonic vibrations [118]. Microsoft presented a Lumia prototype with ultrasonic haptics [119]. In recent years Hap2U, a french-based startup, worked towards the commercialization of ultrasonic friction modulation devices. They built several prototypes using friction haptics on different materials and form factors [120], [2]. Haptics can be tested and evaluated using their Xplore Touch demo kit. Like electrostatic devices, ultrasonic actuation has a very high bandwidth of haptic effects, from rendering simple “clicks” to complex textures.

3) High Fidelity — Bending Waves: Bending waves, or time-reversal wave focusing, have also been described as an effective way to render precise, highly localized, and multi-touch-capable haptic clicks. Waves produced by piezo-electrics attached to the sides of the surface propagate through the surface and concentrate at specific locations at the surface leading to a very small deflection [121], [122]. CEA’s concept involves not only hardware components but also a complex algorithm to control the output of the device and propagation of waves through the surface. LOTUS (Localized Feedback Tactile Feedback on Smart Surfaces) has so far only been shown as part of a CES demonstration [123]. To date, Redux Labs, a formerly U.K.-based company, has been the only company to distribute demonstrators using bending waves. They were acquired by Google [124].

V. DISCUSSION

While we believe in our approach’s advantages, we acknowledge it has some limitations worth discussing. We hope this classification methodology and review can help novice practitioners design haptics beyond a mere technological perspective through a deeper understanding of the user behavior and user experience evoked by these devices.

The first shortfall is our prioritization of a psychologically and qualitative driven view of sensation over a physiological or quantitative focus on perception. Our proposed clustering prioritizes what users believe they feel rather than exploring neuroscience or technical features. While a technical and physical understanding of a technologies’ perceptual impact is essential for integrating an actuator into a device, it is even more important to convey compelling haptic experiences to users [10]. Psychological factors, such as experience, context, and task demand [22], [23], [24], [10], [125] need to be considered in how a user perceives haptic feedback. Our fidelity-based categorization aids practitioners with different backgrounds and

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2. Senseg’s website is out of service upon the submission of this paper in February 2021. Information on Tixel (https://www.senseg.com/tixel/) can be accessed via archive.org.

levels of expertise and supports the matching of haptic requirements to actuator effects.

A second limitation is that we only address a single submodality of haptic feedback, namely cutaneous feedback ignoring that the immersion and realism of haptic feedback are driven by the user's multimodal and cross-sensory engagement or stimulation [126]. Indeed, the combination of feedback demonstrated by morphing surfaces shows how augmentation or combination of multiple LoFi feedback can increase a haptic actuator's true fidelity. However, the focus on cutaneous technologies, which are most relevant for UI and UX practitioners due to their frequent implementation in consumer electronics – and automotive devices, allows for an accessible and comprehensible overview.

A third limitation is that we simplify haptic systems by mostly reviewing the actuator itself, and if applicable, the actuator-driver combination in a reference design. The individual implementation of an actuator can have a drastic result on the fidelity of the haptic feedback. Although we mention multiple examples of features in the haptic equation that lead to higher fidelity, e.g., closed-loop systems, this review does lack contextual information on features such as mechanical integration, haptic surface properties and spring-damper systems. We argue that devices using the same actuator technology but implementing different electronics or mass-damper systems will have a similar level of fidelity due to the basic actuator's haptic characteristics. We chose to apply a simplified view of haptic devices, looking primarily at the actuators to provide a comprehensible overview of current technologies.

Finally, we acknowledge that this overview on currently available technologies may already be outdated at the time of publication, with companies discontinuing or introducing new products. Some references that were part of initial literature research (April 2020) were no longer available upon submitting this paper as companies have potentially been restructured or discontinued. The proposed overview of technologies is a snapshot of the current industry (January 2021).

VI. CONCLUSION

With innovations in haptic feedback occurring almost daily, and an ever-growing appetite for haptic feedback in devices, we expect the challenge of intuitively and quickly understanding the capability of an actuator to remain. We have arrived at a point where haptic technology offers multiple tiers of fidelity and multiple methods to create it. Thus, there is a growing need for standards and classification methods to help isolate the technical signal from the marketing noise.

This paper presents a method tailored to those new to the discipline, allowing them to select actuators and their respective hardware stacks quickly and intuitively. Additionally, through this review methodology, we offer the ability to evolve feedback upward, encouraging practitioners utilizing lower fidelity actuators to consider what might be possible if they utilize a higher fidelity technology.

Standard libraries or signal generation toolkits should be considered for the community to explore haptics easier and faster and, in this way, spread HiFi haptic use more throughout daily interactions. Only now, the haptic industry comes together to work on a common set of industry-wide standards for "HD-Haptics". While the HW complexity of HiFi haptic systems limits their integration and adoption, and the patent strategies limit iteration and innovation, there remains much to be optimistic about in haptics.

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