Improving User Experience using Haptic Feedback

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ABSTRACT

This research describes methods of improving the user experience when interacting with simulated digital objects. The addition of haptic feedback creates another layer of depth and realism in simulations. We are currently limited at best to virtual or augmented reality in three dimensions with audio feedback and are often limited further to two dimensions on a flat screen. In the case of blind users, even this isn't available. Haptic feedback, or the leveraging of your sense of touch, is often considered one of the most important human senses, at least in the context of making objects seem real. Additionally, fewer people lack a sense of touch as compared to being blind. Being able to feel the objects you're interacting with is crucial in everyday life, making it the logical next step in the evolution of user interaction with virtual objects.

In this paper I will cover a variety of technologies which researchers and companies are pursuing for use in haptic feedback, including wearable haptic gloves, miniature robots, and mid-air ultrasound patterns. In the past, technology has limited our ability to produce haptic feedback, but advances in technology mean we now have excellent opportunities for advancing the field of haptics and improving the experience of users.

Keywords

Haptic feedback, user interaction, ultrasound, swarm user interfaces

1. INTRODUCTION

What would you consider the most important of the five ruling senses? In the modern world, people are constantly surrounded by stimuli from everything they interact with - but the senses aren't always in equal balance. We certainly, as a society, favor some senses over others. The perception of sight is frequently observed as the most important of our senses, as reflected throughout society by our reliance on visual cues. Computers and the way we interact with them are no different - our primary form of interaction is clearly on the screen with our sense of sight. Admittedly we have the mouse and keyboard to actually steer our way throughout the digital space - but without our sense of sight, most users would find interaction incredibly challenging. The addition of feedback for our other senses came quickly in the form of sound, as it is a rather natural follow up to bring music and other audio to computers for playback. Beyond visual and audio feedback however, there is very limited exploration of computers communicating with us through our other senses.

The inclusion of touch interaction has been popularized in science fiction to the extent that modern devices now have touch screens. However, this touch interaction in science fiction often came with the ability to physically feel the digital space you're interacting with. This might mean something as simple as touching a digital dial and feeling resistance as you turn it, or something as incredible as shaking hands with a digital projection. While we're certainly a long way off from shaking hands with a digital replica of Einstein, there are a handful of technological breakthroughs which allow us to sense resistance on dials and feel shapes under our fingertips for artistic design.

First we will give a brief introduction and background for the idea of haptics. The background will include some of the origins and olders technologies in wearable haptics, including both gloves and simple fingertip feedback providers. Moving forward we will discuss two principle emerging forms of haptic feedback. I'll describe the technologies and give an overview of some of the challenges faced and how they hold up to various situations. The first of these technologies is robotic swarm user interfaces, including two separate systems, Zooids and Ubiswarm. The second emerging technology in this paper is the use of ultrasound to project shapes mid air. To wrap things up, there will be an analysis section comparing all of these technologies and looking at how we might move forward in the future. Finally, a conclusion with a reminder of what we've covered throughout the paper.

2. BACKGROUND

A very simple example of haptic feedback is the vibrations that most recent gaming console controllers provide. When something in the game happens, often an explosion in a first person shooter game or perhaps catching a fish in a hunting game, the remote will vibrate indicating said event occurred and maybe even the strength of it. Below we will see the origins of such modern haptic feedback - wearables.

2.1 Wearable Haptic Systems

As computers and embedded computation devices become ubiquitous, wearable interactive devices have also become quite common. I myself make use of a smartwatch everyday, and one of the more useful features of the watch is that it

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provides haptic feedback for notifications, applications, and navigation. As an example - when I ask Google to direct me to the nearest grocery store in a city I visit, the watch will vibrate differently depending on whether and which way I am supposed to turn. Imagine taking this to the next level - instead of just having a watch which provides feedback, why not have an entire glove? Embedding electronics in gloves is something we've done for a while now, both in medical settings and for consumers. This includes the use of haptic feedback for therapy and also for focusing sensory attention on a desired target.

2.1.1 Older Haptic Gloves

In *Virtual Reality Simulation Modeling for a Haptic Glove* [6], researchers used a *Rutgers Master II* haptic glove connected to a personal computer to allow the user to interact with a virtual environment. The study points out that for good human interaction, it is important to model the haptic feedback to be the correct shape - in this case, the shape of the hand of the user, or at least the fingers [6]. They describe the shape using a digital mesh, with points on the mesh having values for the amount of force applied there, following Hooke's deformation law and the vector decided by a *"point-based haptic interaction algorithm"* [6]. The total vector is calculated with

$$F = k * d_m * N_{surface\_m}$$

where k is the object stiffness and d_m is a vector representing the distance between the surface point and the haptic point along the normal defined at the surface point N [6]. This research brought forth a good deal of interest in using gloves for modeling haptic feedback and could be considered the starting point of much of the research currently ongoing. The two primary use cases the researchers tested were for a ball game and for modeling digital putty. Both pieces of software contained fully modeled forms of either the ball or the putty being entirely deformable, and the haptic feedback provided matched the modeled shapes' meshes.

2.1.2 Haptics Evolve: The Kinect

As previously mentioned, modern gaming consoles are an excellent example of someplace where haptic feedback has been introduced to the public, if only on a basic level. The Kinect, a motion and gesture tracking system engineered by Microsoft, is a prime example of such technology. While it may seem as though this is more of a form of input than a way of providing haptic feedback, here we see that the two are closely related, and in this case one allows for the success of the other. The Kinect allows the user to experience the virtual world they're interacting with at the tip of their fingers. A group of researchers sought to enhance this experience and allow for sensation when pinching the virtual environment [1]. This allows for the user to receive feedback for turning, pinching, and generally manipulating objects through the kinect.

The guiding principle behind the design is to provide something lightweight and wearable in contrast to some previous models for haptics, which had the user grounded to one area due to the limitations of the technology of the day. The pads work on the thumb and the index finger with three motors providing vibrations allowing for the the distribution of a sense of cutaneous feedback, but are unable to provide significant kinesthetic feedback. This means that the haptic feedback is limited to giving sensation to the skin of the user, and can not provide resistance to movements the user might initiate, such as reaching or grabbing [1]. However, pulsations of feedback could be sent to the fingers, thus providing a sense of touch similar to brushing your hand against a surface or a light breeze. While this is rather limited in potential feedback, the upside to this is that the prototype remains lightweight and is not constraining the user to a limited space, as the pads are wireless. The project uses the pads in addition to the kinect to track the user's hand through space and provide feedback as the user approaches objects in the virtual space, primarily basic shapes. While the fingertip feedback is not nearly as immersive as using a mesh-representative glove, it is far more lightweight and allows the user more freedom of motion. Additionally, the use of only the fingertips means that the user is free to hold objects with that same hand - most of the haptic feedback gloves currently being developed are too clunky to allow the user to hold objects while also receiving feedback from a modeled object.

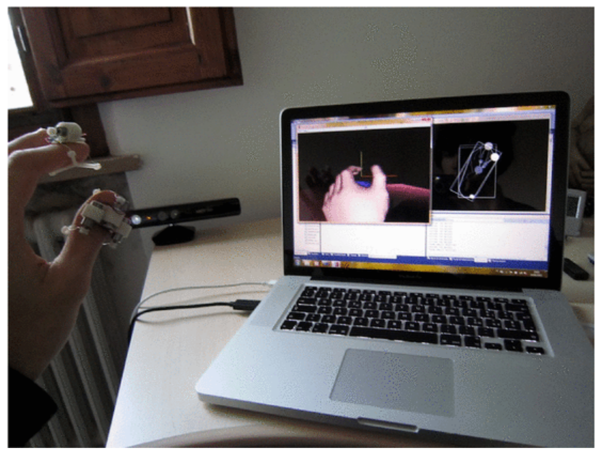

Figure 1: The Kinect used with the pinch sensors [1]

3. EMERGING METHODS IN HAPTICS

3.1 Robotic Swarm User Interfaces

Many modern technologies draw inspiration from popular media, and of course older systems of similar technologies. Older technologies focus less on digital systems and more on analog mediums which require physical interaction through knobs and buttons. The downside of this was that while the user may feel the physical presence of the interaction, the number of possible ways of interacting with said component were limited - you can only turn a knob so far, and the button on your dashboard doesn't (usually) change color when pressed.

A swarm user interface, or a SUI, is a user interface made of independent self-propelled elements that move collectively and react to user input. Swarm robotics is a relatively young field. Their main draw is being a way of physically interacting with the real world through virtual measures and the virtual world through physical measures. Below, we will see that the use of swarm robotic interfaces will serve a very similar role to that of the Kinect fingertip feedback providers. While neither one makes use of the mesh proposition as a glove might, they both provide similar lightweight alternatives by giving vibrative feedback.

3.1.1 Zooids

Previously swarm robotics was out of reach, if only because our ability to efficiently control a high number of individual robotic components has only recently been powerful enough. Ivan Edward Sutherland, the father of computer graphics, once described the ultimate human interactive display as being *"a room within which the computer can control the existence of matter"* [5]. The idea is rather similar to Star Trek's HoloDeck - once again, an excellent example of technology drawing from popular media.

Zooids [5] are an early attempt at creating such a space, though in this case, on a very restricted level and only on flat surfaces. While the zooids won't have the scale of a whole room, they could certainly start on a small scale. The idea of a zooid comes from the biological term describing a single animal that is part of a greater [hive-minded] animal. [5] This research takes that idea and recreates it with a swarm of miniature robots, each approximately 3 cm in diameter, which together act as a a singular mind and individually can be used to mimic pixels in solid representations. They can move very rapidly as a group, as fast as around 50 cm/s [5], allowing for quick redrawing of what the user should be seeing. They are also able to react to user input, meaning that their detection of touches from the user can affect their positioning and what they do next.

The ability to react to user input is a key aspect of a swarm user interface, which the authors define as *"human-computer interfaces made of independent self-propelled elements that move collectively and react to user input"* [5]. The important things to take from this definition are that to qualify as a swarm UI, the system components must be free to move apart from one another, they must be self-propelled, have the ability to move as a collective if needed, and must react to user input as stated above. The downside to the zooid model is that they lack the ability to reproduce color and they must be used on a flat horizontal surface.

3.1.2 UbiSwarm

Building on Zooids, we have the UbiSwarm model [4]. The UbiSwarm system is designed to address a number of the issues found with the zooid system, particularly their limitation to a horizontal plane. The research I will describe focused largely on the impact that the system might have on users by varying three key parameters of swarm motion. The first of these parameters is bio-inspired motions, including rendezvous, dispersion, random, torus, and flock [4]. The second piece is speed, varying from fast to slow, and the third parameter is smoothness. Smoothness had three different options - smooth, synchronously jittery, and asynchronously jittery [4]. Such a system could be showing displays of useful daily information on your refrigerator, such as weather, agenda, and other such daily reminders, easily done with the magnetized and mobile swarm.

The reason that swarm robotics provide such versatile haptic and tactile feedback is because they are able to conform to the environment around them, making them ideal for situations where you don't want to be tied to a single location, nor the burden of carrying around a glove. They are also able to follow the user and provide both visual and haptic feedback. This is an important distinction from other methods discussed, where the implementation of a haptic feedback solution usually only provides haptic feedback and no visual feedback. The relevant downsides to swarm robotic interfaces are mostly related to visual feedback. Chief among these is the lack of resolution associated with such interfaces - despite advances in technology we don't have a stable solution for high resolution physical displays which act as a swarm. The researchers described the following scenario as an example of how the UbiSwarm interface could assist someone in everyday life [4]:

> *"In the morning, Jen prepares to get dressed. On the wall, UbiSwarm forms an umbrella icon and today's temperature. Jen dresses accordingly and heads to the kitchen. UbiSwarm collectively push a plate of her favorite donuts to the center of the kitchen table. At work, she prepares a cup of tea. As soon as the tea bag touches hot water, the robots slowly circle around the cup and disperse after a minute. Every 30 minutes, UbiSwarm flocks toward and taps Jen to remind her to stretch and take a break. Back home, she prepares steak for dinner. In the kitchen, the robots locate and move salt, pepper, and olive oil for her to use. Before going to sleep, she decides to read a book while lying down. Robots slowly move toward the bed and shine light. She makes final adjustment by moving them by hand. After Jen falls asleep, the robots turn off the light and disperse back to their charging stations".*

These interactions are not particularly complicated, and could even be seen as primitive in comparison to the full capabilities of a hypothetical future swarm UI with improved movement and resolution. In the future, swarm user interfaces could be leveraged for complicated three-dimensional modeling, but for now the basic idea of providing both haptic feedback and an interactive physical interface is quite appealing.

3.1.3 Ubiswarm Results

The UbiSwarm researchers conducted a robust survey of how users react to the swarm system, which they provided in video form to a group of 1067 participants. The users were asked to watch the provided video, and then record their reactions as well as respond to some additional questions provided by the researchers [4]. The reactions and related answers were then analyzed to determine how the swarm influenced the users in a number of ways according to a predetermined set of parameters we will see below. This initial experiment analyzed how users reacted to the various types of motion the swarm interface displayed. The experiment took a swarm of 10 robots and replicated a variety of behaviors, speeds, and degrees of smoothness with the intent of invoking reactions in the participants. The parameters described above can be generally represented by the images shown in Figure 2.

The participants were asked to self report on how the display of the swarm affected them, split into a number of categories which deal with different aspects of the influence of the swarm. The first category was emotion - participants were asked to choose whether the swarm invoked valence (the intrinsic attractiveness/"good"-ness), emotional arousal, or dominance (sense of control). Note that in any of the cat-

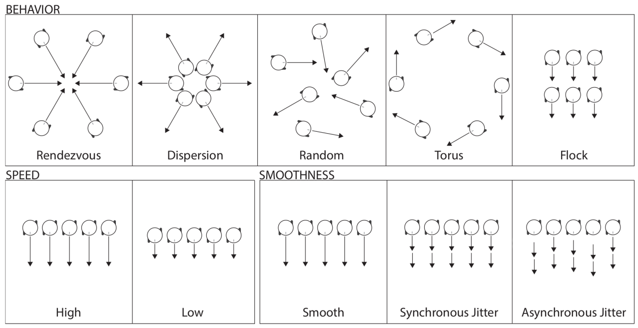

Figure 2: Swarm Motion Parameters [4]

egories, a participant is not limited to merely one reaction. The second category was user experience - the user might describe the interface as hedonic, pragmatic, or attractive. The third category had to do with HRI (human-robot interaction) metrics - animacy, likeability, and perceived safety of the robots. The results of the experiment indicate that for the purpose of invoking a response in humans, the most important important variables are speed and smoothness, as expected by the researchers. In fact, in terms of likability, smoothness was the only variable which had statistical significance. The other factors, while they may have had some impact, were not found to be statistically significant. Faster movements had higher animacy ratings, which I found rather surprising. Unsurprisingly, rendezvous was found to be the behavior with the most animate reaction.

The results of the study suggest that a successful swarm user interface should employ smooth, speedy transitions between phases in order to gain the attention, urgency, and likability that is paramount to a successful user interface. Note that because the swarm is physically present in your abode, it's definitely in the best interest of the designer of the interface to make you feel comfortable allowing a roving band of robots to roam the room.

3.2 Ultrasound Mid-Air Shapes

Despite the benefits of a swarm-based robotic interface, they have a number of downsides ranging from cost to having the need to refuel or in this case, recharge. They also do not make use of the idea of meshes - sacrificing mesh availability for portability. Another system which could avoid some of the drawbacks of both of the above models is the use of ultrasonic waves to generate haptic feedback mid-air. This is made possible by the vibrations exerted by the waves [3]. Because of this, we can see a similarity to the glove implementations of haptic feedback. The nature of the acoustic waves allows them to easily map to a meshed shape - allowing for haptic feedback on more than just a singular small area. Despite not applying any direct strong force, the waves are able to stimulate the surface of one's hand in a manner that mimics our sense of touch, thus making it feel as though the user's hand is colliding with some surface. Unfortunately, the pressure felt by the user and exerted by the acoustic arrays are non-linear with regard to the actual sonic pressure, and the relationship is actually proportional to the square of the real sonic pressure. The radiation force F induced by the sound pressure p on the boundary So is approximated by:

$$\int_{S_0} \alpha \frac{\bar{p^2}}{\rho c^2}$$

where $1 \leq \alpha \leq 2$ is a constant dependent on the reflection coefficient (how greatly the force is being reflected by the ultrasonic array), ρ is the density of the air and c is the speed of sound in the air in question. [3] Note that the little dash above the p indicates that p is a vector and not merely a single-dimensional variable. This goes to show that the use of ultrasonic waves is largely dependent on the surrounding environment - and is thus more useful in some environments than others. Note also that depending on array arrangement, we will have vastly differing performance. Makino et al. [3] elected to use an octagonal array formation to improve the effectiveness of the system, as it provides a good balance of accuracy and cost. Makino et al. used the T4010A1 from Nippon Ceramic Co which emits 40-kHz ultrasound at 121.5 dB in S.P.L (spatial pulse lengths) at 30-cm distance.

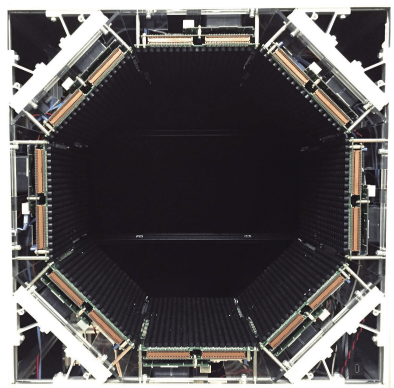

Figure 3: The ultrasonic emitter array used by Makino et. al. for shape simulation.

Arranged in an octagonal manner, these were used together to create the illusion of feedback in the center. Shapes simulated include a star and cubes among several others. The downside of these systems is that there is some noise which comes from them (it is sonic, after all), and thus for the sake of maintaining a closed system and focusing on the haptic feedback the users were given noise-cancelling devices.

Makino et al. asked a group of thirteen participants between the ages of 22 and 30 to identify two different aspects of geometric shapes. The first thing requested was that the participants identify whether or not two lines emitted by the ultrasonic array were facing the same direction. The users were allowed to use one or both hands, and had a fifteen second window to respond. The second question asked of them was to determine the difference in position of two parallel lines. Note that the term "limen" speaks of a threshold below which a stimulus is not perceived or is not distinguished from another. The effectiveness of the system can be analyzed by looking at the average difference between where the study participants thought the boundaries were and where they actually were. Below in Figure 4 we can see the results of the angle experiment.

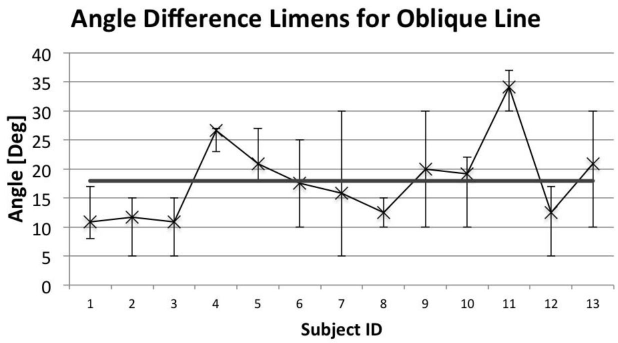

Figure 4: Angle difference limen for oblique line among all participants. The bold line shows the average angle [3] as being 17.9$\pm 6.6^{\circ}$

Here we can see that the average user gets the angle wrong of the line wrong by an average of 17.9 degrees. For individual users the average varies - for example, we can see that user 2 averaged around 12 degrees off from where the line actually was angled. The actual angle may have really been 20, for example, but they would give an answer of 32 degrees, with the difference varying between 5 and 15 degrees. It would appear as though some individuals were better at the experiment than others, though all things considered the users were overall well capable of providing adequate feedback. The researchers do note that one of the participants was not even able to identify a change in angle of 30 degrees, but it should be expected again that some are better suited towards the technology than others. They also note that this participant had difficulty finding a way of identifying the forms entirely, which would explain their difficulty in separating one shape from another. As seen in Figure 5 the second experiment can build a similar graph of the differences in expected vs real placement:

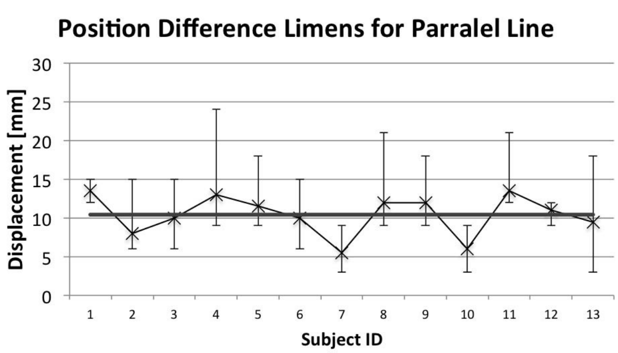

Figure 5: Position difference limen for parallel line among all participants. The bold line shows the average displacement across subjects [1] as being 10.4$\pm$2.5mm

Considering the thickness of the projected lines was 10 mm, these results are quite promising. The placement of most of the error bars indicates that the majority of participants were able to distinguish the lines being projected, and in good time. Because the average error and the width of the line were both 10mm, this suggests that the majority of user error can likely be attributed to the user finding either the upper or lower edge of the line instead of finding the center of the line. After all, it can be rather difficult to find the center of an object by merely feeling it. This suggests that the perceptual spacial resolution of an ultrasonic line is close to that of the acoustical resolution of an ultrasonic line [1]. Makino et al. mention that although this system works well for static objects, dynamic objects which change based on user motion are much trickier. This requires sophisticated sensors with excellent response times. While certainly feasible, the computational and hardware requirements make this more of an issue for future iterations of the technology.

4. ANALYSIS

The emerging technologies described above are massive steps forwards in the realm of haptic feedback, and are certainly cutting edge in the field which will improve user interfaces in the future. Our ability to interact with digital media in new ways is always adapting and improving, making it probable that said future iterations could be soon forthcoming.

There are of course downsides to the methods described, and some of the methods are more suited to some situations than others. Gloves, for example, are impractical in everyday use but may become a common source of feedback in media such as gaming and art. Medical practitioners may also find the glove quite useful for training simulations; a glove which can provide resistance and haptic feedback is undoubtedly a better training mechanism than pure digital interaction, and working on live patients is not ideal if a practitioner is still in training. Unfortunately, haptic gloves are rather bulky and heavy for use while walking around doing your daily tasks.

Robotic swarms might one day replace billboards and other public displays, as they are able to move and adapt to the environment around them, interacting with customers in a mall or hospital. The potential open-air applications of an interface which adapts to the surface it's on are limitless, particularly so if we are able to design the swarms to form full three-dimensional shapes, like you might see in Big Hero 6. This would allow for the swarm to take the shape of products the user might enjoy, produce a facsimile of another person for three-dimensional video calls, or be molded by the user to take artistic forms. Imagine being a sculptor, and having the ability to sculpt a swarm which can be told to undo certain actions - never find yourself at the mercy of your mistakes again. Perhaps one day we could even simulate entire buildings with the swarms for use in habitation design.

Unfortunately the robotic swarms seem to be the least practical at our current level and state of technology. While they are certainly capable of displaying information in a helpful manner, and the user has some interactive capability with them, they are severely limited in capability for now and are a rather expensive option. At their current state of development, it may not seem evident that swarm user interfaces are a viable form of haptic feedback, but they do provide some. While limited, the reason for their inclusion in this paper is mostly due to their future potential. Despite current limitations, they are a rapidly evolving field and the potential to have tactile interfaces on a variety of surfaces is motivation enough for some groups to pursue the technology. At best right now they are mediocre displays, but in the future they may represent our most viable form of variable environment haptic feedback.

The use of ultrasonic waves to produce haptic feedback is perhaps the most enticing of the described technologies, if only because it is already in use in some products. The AirPiano[2] is one such example - a manipulable mid-air keyboard would be a great boon to digital musicians, because a projector is far easier to move around than a full physical keyboard; plus it can be multipupose, and conform to a variety of other shapes of musical instruments. Additionally, the mid-air systems are perfect for home appliances and vehicular systems. The haptic feedback they provide is ideal for a situation such as the the controls for a stove top, fridge, or dishwasher. All of this can be done with minimal encroachment into the personal space of the user, as opposed to the glove, and also do not have the concern of complicated computational processes like the swarm interfaces do (or the charging issues). Unfortunately the ultrasonic haptics are currently limited to a small space, but considering the pace at which technology improves, it seems probable the capabilities of ultrasonic systems will only grow.

5. CONCLUSION

In the end, all of the technologies we have at our disposal are bound to evolve and grow. Throughout this paper we were introduced to the idea of a number of haptic feedback systems: Gloves and other wearables, robotic swarm interfaces, and ultrasound projectors are all groundbreaking technologies in improving user interfaces. A comparison of the various methods and an introduction to their faults has given us a good idea of where the field of haptic feedback will go in the future.

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