REVEL: Tactile Feedback Technology for Augmented Reality

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Abstract

REVEL is an augmented reality (AR) tactile technology that allows for change to the tactile feeling of real objects by augmenting them with virtual tactile textures using a device worn by the user. Unlike previous attempts to enhance AR environments with haptics, we neither physically actuate objects or use any force- or tactile-feedback devices, nor require users to wear tactile gloves or other apparatus on their hands. Instead, we employ the principle of *reverse electrovibration* where we inject a weak electrical signal anywhere on the user body creating an oscillating electrical field around the user's fingers. When sliding his or her fingers on a surface of the object, the user perceives highly distinctive tactile textures augmenting the physical object. By tracking the objects and location of the touch, we associate dynamic tactile sensations to the interaction context. REVEL is built upon our previous work on designing electrovibration-based tactile feedback for touch surfaces [Bau, et al. 2010]. In this paper we expand tactile interfaces based on electrovibration beyond touch surfaces and bring them into the real world. We demonstrate a broad range of application scenarios where our technology can be used to enhance AR interaction with dynamic and unobtrusive tactile feedback.

CR Categories: H5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces, Input devices and strategies, Haptic I/O.

Keywords: augmented reality, haptics, tactile displays, tangible interfaces, augmented surfaces, touch interaction.

Links: DL PDF

1. Introduction

Augmented Reality has recently emerged as one of the key application areas of interactive computer graphics and is rapidly expanding from research laboratories into everyday use. The fundamental premise of AR is to enable us to interact with virtual objects immediately and directly, seeing, feeling and manipulating them just as we do with physical objects. Most AR applications, however, provide only visual augmentation of the real world and do not provide the means to let the user *feel* tactile, physical properties of virtual objects or to enhance the physical world with computer-generated tactile textures. The absence of tactile feedback does not allow us to take advantage of the powerful mechanisms of the human sense of touch and diminishes the quality of the experience.

REVEL is an augmented reality (AR) tactile technology that allows us to change the tactile feeling of real world objects by augmenting them with virtual tactile textures (Figure 1). It is based on the principle of *reverse electrovibration* where a weak electrical signal is injected anywhere on the user's body, creating an oscillating electrical field around the user's fingers. As the user then slides his or her fingers on the surface of an object, the user perceives highly distinctive tactile textures overlying the physical object. By tracking touch locations, tactile textures can be dynamically modified in real time and enhanced with visual augmentation if required. The user's hands remain free and unencumbered, so that users can continue their natural interaction with the world around them, unconstrained by tactile feedback technology. In a broad sense we are programmatically controlling the user's tactile perception.

REVEL advances our previous research on electrovibration-based tactile displays for touch surfaces, i.e., TeslaTouch [Bau, Poupyrev, et al. 2010]. In TeslaTouch the electrical signal was injected into the surface electrode of the touch screens, the classic technique to design tactile displays based on electrovibration, e.g., devices for the blind proposed in the early 70s [Strong, 1970]. In all these displays, including TeslaTouch, the tactile sensation is localized within a specific device augmented with tactile feedback, which is not scalable. Indeed, to add virtual tactile sensations to more objects or devices, all of them must be instrumented with tactile feedback apparatus. REVEL produces the same tactile effect, but reverses this dependency on individual object instrumentation. It instead injects tactile signals directly into the user's body, so that the user becomes the carrier of the tactile signal at all times. The world and objects remain passive, requiring no instrumentation with additional technology. Therefore, this technology potentially allows for the creation of truly ubiquitous tactile interfaces that can be used anywhere and anytime.

Figure 1: *The user feels virtual tactile textures on a real object while observing them on a AR display. Note, that the object is* not *instrumented with any tactile actuation apparatus.*

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The development of reverse electrovibration-based tactile displays requires an in-depth understanding of the basic physical principles of electrovibration. It involves the investigation of the interaction of electrostatic fields with human body, environment and various materials, as well as the exploration of the effect of their various properties on tactile sensations. Developing this body of knowledge and techniques that allow designing tactile feedback "in the world" is one of the important contributions of this paper that advances the state of the art in electrovibration-based tactile interfaces.

In designing REVEL we were also motivated by a broader vision of tactile displays that presents tactile stimuli by *altering user tactile perception* [Kruijff et al. 2006]. Such tactile displays do not require environmental instrumentation and could be used anywhere, leading to the design of a truly ubiquitous tactile augmented reality as envisioned by early AR pioneers [Azuma 1997]. We refer to this new class of tactile devices as *intrinsic haptic displays*. In this paper we discuss some of the implications, advantages and limitations of such intrinsic haptic displays and present a range of novel applications that implement intrinsic haptic displays by using REVEL technology. Exploring the concept of intrinsic tactile displays in the context of AR environments and applications is another important contribution of this paper.

2. Background and Related Work

Augmented reality systems 1) combine real and virtual objects in a real environment, 2) run interactively and in real time, and 3) register real and virtual objects spatially in relation to each other [Azuma et al. 2001]. Although visual augmentation has been a primary focus of research and development, it has always been understood that AR would eventually apply to all the senses, not just sight. In fact, nearly two decades ago researchers speculated that:

> " … *a user might run his hand over the surface of a real desk* […] *Then the tactile effectors in the glove can augment the feel of the desk, perhaps making it feel rough in certain spots* [Azuma 1997]".

The tactile augmentation, therefore, was envisioned as a technology that would inject artificial tactile sensations into the real world, which is a challenging problem. There have been a number of techniques proposed to implement it.

2.1 Force Feedback

The most common approach to enhancing AR environments with haptics is to use traditional force-feedback devices, such as Phantom™, to provide active force feedback to virtual objects registered in the real world [Bianchi et al. 2006; Knoerlein et al. 2007; Vallino and Brown 1999]. Although this approach is important in such applications as medical simulators, it requires instrumenting environments with complex haptics apparatus and limits user mobility to small workspaces. Furthermore, articulated force-feedback haptic devices are not effective in providing high-bandwidth tactile feedback [Burdea 1996] and require specialized tactile feedback apparatus [Minsky et al. 1990]. Crucially, the user experiences virtual tactile stimuli indirectly through an intermediate tactile apparatus, breaking the metaphor of augmentation of the real world with virtual data.

2.2 Actuation of the Environment

Actuation of physical environments is another approach to add tactile feedback to augmented reality. In this approach the embedded actuators physically alter the environment to communicate required tactile properties. For example, the FEELEX device uses an array of actuated pins underneath its flexible surface. When a virtual graphic is projected on top of the surface, pins move up and down, displacing the flexible substrate and creating a 2.5 dimensional physical shape aligned with a projected image that can be felt by hand [Iwata et al. 2001]. Such actuated surfaces can range in scale from a finger to a desktop device to the wall of a building [Bau et al. 2009; Poupyrev et al. 2004]. Although engaging and often visually impressive, the tactile resolution of such displays does not yet allow us to create fine tactile textures, thus limiting its use in AR systems. Vibrotactile, electrostatic and ultrasound friction tactile technologies can also be used to enhance physical objects and environments with tactile sensations [Amberg et al. 2011; Poupyrev and Maruyama 2003; Strong and Troxel 1970]. However, instrumenting every object or surface in the environment with a dedicated tactile actuation technology is not feasible and cannot be used in large environments or mobile augmented reality systems.

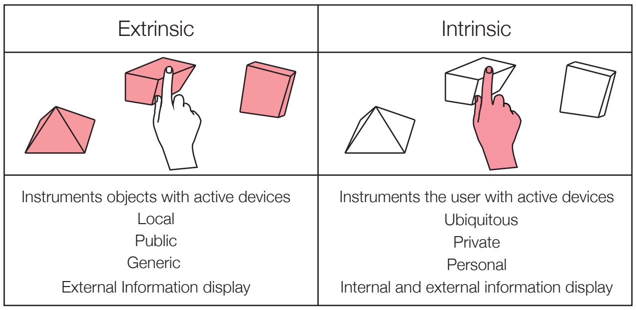
2.3 Tangible Interfaces

Tangible interaction offers another alternative to add tactile feedback to augmented reality applications. Originating in early VR explorations of passive tactile feedback [Carlin et al. 1997], it suggests using existing physical objects, either passive props or active input devices, to enhance AR visual display with tactile sensation [Schmalstieg, et al. 2000; Woodward et al. 2004]. The tangible approach has been extensively investigated on interactive surfaces that have become popular recently [Fitzmaurice et al. 1995; Rekimoto and Saitoh 1999; Ullmer and Ishii 1997] as well as with marker-based AR environments where the user manipulates physical cards that become a placeholder for virtual objects [Kato et al. 2000; Poupyrev et al. 2002]. Although a popular and important class of AR interface, tangible augmentation requires users to wear or hold devices or cards in their hands, which impedes their natural ability to interact with the physical world. The interface provides tactile feedback for virtual objects, but it does not allow us to enhance real world objects with virtual tactile feedback – the ultimate goal of AR tactile augmentation. Furthermore, since passive objects are used to provide tactile displays, the tactile feedback cannot be computationally controlled.

2.4 Wearable Haptics

All the approaches described above attempt to create tactile feedback by instrumenting the physical environments with tactile apparatus. An alternative approach in designing AR tactile interfaces is to *instrument the user* with wearable tactile displays, such as tactile gloves, finger enhancements, tactile shoes, vests and exoskeletons, see for example [Kron and Schmidt 2003; Niwa, et al. 2010; Rekimoto 2009; Ryu and Kim 2004; Takeuchi 2010; Tan and Pentland 1997; Tsetserukou et al. 2010]. The tactile feedback can be provided everywhere and instrumentation of the environment is not necessary. However, the user's body has to be instrumented with tactile feedback apparatus, inhibiting natural interaction with everyday objects and environments. Indeed, while the users are able to perceive tactile sensations generated by the AR tactile display, they cannot perceive all the richness of the physical objects and materials.

In this work we were motivated by emerging research efforts that attempt to alter a user's haptic perception by using direct neuromuscular stimulation [Kruijff, et al. 2006; Tamaki et al. 2011]. In these interfaces weak electrical stimuli are used to trigger somatic and kinesthetic sensations that are interpreted as pseudo-haptics events. The resulting tactile displays are mobile, lightweight and can be used anywhere. The user's hands and body



Extrinsic	Intrinsic
Instruments objects with active devices Local Public Generic External Information display	Instruments the user with active devices Ubiquitous Private Personal Internal and external information display

Figure 2: *Extrinsic versus intrinsic AR tactile displays.*

remain free, and tactile sensations are triggered only when necessary. The challenge of using these haptic displays is that the ability to control muscles is currently not well understood and, therefore, the precise rendering of desired tactile sensations is not possible. Furthermore, this technology could also be uncomfortable and obtrusive for the user.

2.5 Categories of Haptic AR Displays

Augmented reality tactile displays can be essentially categorized as either *extrinsic* or *intrinsic* (Figure 2).

Extrinsic haptic AR displays are *integrated in the environment, instrumenting objects, workspaces and surfaces* [Jeon et al. 2009]. They can provide sophisticated haptic sensation, but they are essentially *localized* and *not scalable* – indeed, instrumenting each and every object or surface with tactile actuators is impossible due to cost, size, power consumption and other limitations. Extrinsic tactile displays are *generic* and *public* in the sense that when two users are interacting with such a display, they are receiving exactly same tactile feedback. The majority of AR tactile displays that we review in this section belong to the *extrinsic* category.

Intrinsic haptic AR displays *augment the user* and provide tactile feedback by *altering user's tactile perception*, either by wearable haptic apparatus, such as tactile gloves, or directly stimulating the neurosensory mechanisms of user tactile perception. Intrinsic haptic displays are *ubiquitous*, as they only require the augmentation of the user, not the entire environment. Therefore, they are highly *scalable* and can potentially be used anywhere. In addition, intrinsic tactile displays are *private* and can be *personalized* for each user. Intrinsic tactile AR displays are significantly less researched, and designing such displays is the focus of this paper.

Haptic AR technologies also differ in whether they provide tactile feedback for *virtual* or for *physical* objects. The majority of previous research is focused on adding tactile feedback to virtual objects, significantly fewer results has been achieved in tactile augmentation of the *physical world* (see e.g., [Huang et al. 2010; Niwa, et al. 2010; Nojima et al. 2002]) In this work, we propose intrinsic tactile displays that can be used for augmenting *both* physical and virtual objects with virtual tactile sensations.

3. REVEL: Augmented Reality Tactile Display

REVEL is a novel tactile display technology for AR systems and applications that allows us to augment both physical and virtual objects with virtual tactile sensations by instrumenting the user. REVEL's design is based on a novel tactile effect that we call *reverse electrovibration*. In the remainder of this section we describe the principles of operation and implementation details of the REVEL tactile technology. We then describe the design of various applications in the following section.

3.1 Reverse Electrovibration

Reverse electrovibration is a novel use of the fundamental physical effect of *electrovibration* – an electrically-induced mechanical skin vibration. Since its discovery in the early 1950s [Mallinckrodt et al. 1953], electrovibration has been used to design a broad variety of tactile devices for the visually impaired [Strong and Troxel 1970; Tang and Beebe 1998] as well as tactile interfaces for touch screens and interactive surfaces, e.g., TeslaTouch [Bau et al. 2010].

The classic explanation of the electrovibration effect is presented in Figure 3 [Kaczmarek et al. 2006]: When alternating current (AC) is injected into a conductive object covered by a thin insulator, a distinctive rubbery tactile sensation is perceived by a finger sliding on the surface of the object. This is because the AC signal creates an intermittent electrostatic force $\overrightarrow{F_e}(t)$ that attracts the finger to the conductive surface. While this force is too weak to be perceived when the finger is static, it does modulate friction $\overrightarrow{F_r}(t)$ between the surface and sliding finger, creating a strong friction-like tactile sensation. Note, that the user is not electrically neutral, but connected to ground via impedance *Z'*.

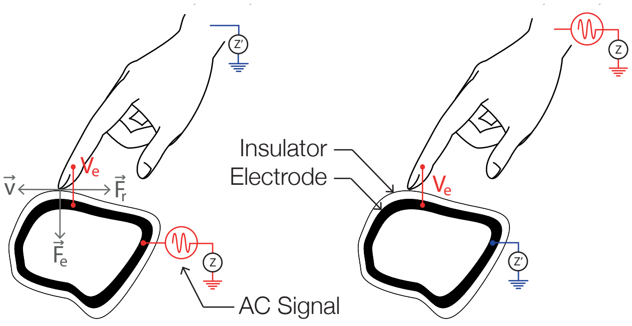
It is important to stress that this tactile sensation does *not* result from electrical current stimulating tactile receptors in the finger, but is purely mechanical as we discussed in detail in TeslaTouch [Bau et al. 2010]. The currently accepted model of electrovibration describes it as a capacitive element where the conductive object and finger's ionic fluids form two plates of a capacitor while the dry outer skin and thin insulator form this capacitor dielectric layer [Grimnes 1983]:

$$\left\|\overrightarrow{F_e(t)}\right\| = \frac{\varepsilon_0 A V^2(t)}{2\left(\frac{T_s}{\varepsilon_s}+\frac{T_p}{\varepsilon_p}\right)(T_s+T_p)}, \qquad (1)$$

where $\overrightarrow{F_e}(t)$ is the electrostatic force; V is the voltage across finger and electrode, $\varepsilon_0, \varepsilon_s, \varepsilon_p$ are the permittivity of space, outer skin and insulator; T_s is the skin thickness; T_p is the insulator thickness and A is the contact area [Kaczmarek et al. 2006].

While Equation 1 is an approximation, it shows major variables that affect the design of *any* electrovibration tactile display:

- *voltage* across the finger and the electrode,
- *insulator* properties,
- *skin* properties, and
- *area* of contact.



a) Electrovibration b) *Reverse*-Electrovibration

Figure 3: *Electrovibration versus Reverse electrovibration: (a) AC signal is injected into the object; (b) AC signal is injected into the user. Both produce equivalent tactile sensation.*

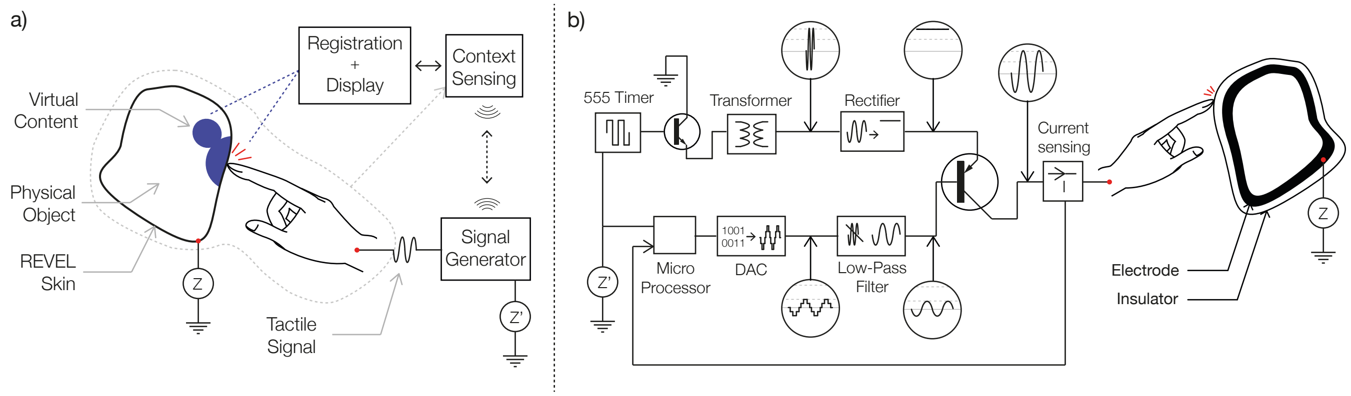


Figure 4: *REVEL: Reverse electrovibration tactile AR display: a) system diagram; b) details of tactile hardware implementation*

Equation 1 illustrates that the *absolute voltage* or *potential difference* between the user and the object controls the strength of the perceived tactile sensation. The polarity of voltage is not important and, therefore, *reverse configurations is equally effective*, i.e., when the signal is injected into the user and the object is simply connected to ground (Figure 3). We refer to this configuration as *reverse electrovibration*.

Although *reverse electrovibration* appears to be a rather trivial observation, it is, nevertheless, far from obvious. In fact, since the discovery of electrovibration more then half a century ago, we are unaware of any previous attempts to design reverse electrovibration tactile interfaces in spite of some of the very attractive interaction properties that they possess.

First of all, injecting the signal into the user rather than into the object does indeed create *the same tactile sensation*. It follows from the basic principles of electrovibration (Equation 1) and was confirmed in informal user studies where none of our twelve subjects were able to discriminate between direct and reverse electrovibration tactile configurations.

Second, it allows for the design of intrinsic tactile displays by instrumenting the user with a small wearable tactile signal generator that can be attached anywhere on the user's body: embedded in a shoe, the handle of an umbrella, or clothes. Little instrumentation of the environment is required, and it is completely passive.

The following section presents the details of the design and implementation of reverse electrovibration tactile display and its application in designing AR interactive systems.

3.2 Design of Reverse Electrovibration Tactile Display

Figure 4a presents the design of an AR tactile display based on reverse electrovibration. A *tactile signal generator* worn by the user communicates with an *AR display* and a *context-sensing* system. This, for example, can be an overhead projector and computer vision tracking system that recognizes when the user is touching a *physical object* augmented with virtual content.

The context-sensing system triggers the signal generator to inject a *tactile AC signal* into the user's body. Thus, when the user is sliding fingers on the surface of a physical object, he or she would feel virtual tactile textures when necessary, e.g., when the user's fingers touch *virtual content* overlaid on the physical object.

Although the physical object is completely passive, there are two crucial requirements that must be met for REVEL system to function. First, the surface of the object or the parts of it that are touched by the user must be conductive and covered with a very thin layer of insulator (Figure 3). Second, the conductive surface of the object and tactile signal generator should share a common electrical ground (Figure 4a). We will discuss these design requirements in detail later in this section.

To summarize, a REVEL tactile display includes three key components: 1) a signal generator, 2) insulator and conductor layers wrapped around the object, we refer to this as REVEL skin, and 3) the electrical coupling of signal generator and objects to a common ground. Each of the components of this framework is a design variable allowing for a wide range of systems designs. The rest of this section discusses each component.

3.2.1 Signal Generator

The *signal generator* creates various tactile sensations by injecting an AC electrical signal into the user's body. Properties of the generated signal have a significant effect on the nature of the tactile sensations' quality and intensity.

Signal amplitude has the most immediate effect on a tactile sensation's perceived intensity: as the amplitude increases the tactile sensation becomes more prominent. As we reported in TeslaTouch, the perceived tactile intensity is frequency dependent: signals between 50 Hz and 300 Hz feel most intense [Bau, et al. 2010]. The insulator's thickness and its dielectric constant also

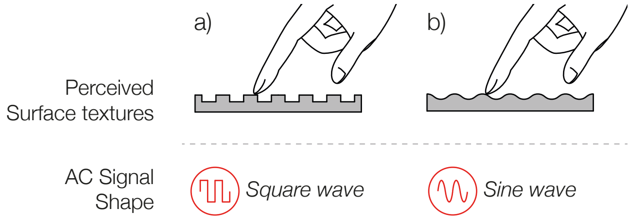


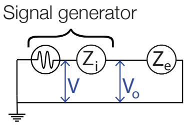
Figure 5: *Feelings of square- and sine-shaped signals.*

Figure 6: *Various embodiments of REVEL.*

have significant effect on sensation intensity, e.g., thicker insulator would require higher voltages, while keeping them below the breakdown voltage of the insulator. In our previous studies the amplitude and frequency ranges were typically 20 –200 Vpp and 20 – 1000 Hz [Bau, et al. 2010].

Interplay between the signal *shape*, *frequency* and *amplitude* allows us to produce a rich variety of tactile sensations. For example, a square wave feels more intense and sharper than a sine wave; the difference is comparable to sliding the finger on a grid of smooth versus sharp bumps (Figure 5). More subjective evaluations of various combinations of signal frequencies and amplitudes were reported in our earlier studies [Bau, et al. 2010].

While designing REVEL we discovered that the *internal impedance* of a signal generator has a significant effect on tactile sensation intensity. A user touching an object is equivalent to the additional load Z_e being connected to the signal generator, reducing the actual output voltage that produces the tactile sensation:



$$V_o = \frac{Z_e}{Z_e + Z_i} V\,, \qquad (2)$$

where V represents the desired output voltage, Z_i the internal impedance of the signal generator, V_o the actual output voltage, Z_e the impedance of the load, including the user and impedance to ground through the object. *Low internal impedance* of the signal generator, therefore, ensures that there is minimum discrepancy between expected and actual amplitudes of tactile signal.

Although the signal generator must be *in contact with the user's body*, the exact location of the contact is not fixed. Hence, there is a lot of freedom as to where the signal generator can be located, e.g., the handle of a cane, a shoe, a chair and so on (Figure 6). Furthermore, it does not have to be connected to the skin directly and a layer of clothing between the generator and user's skin does not reduce the effectiveness of tactile feedback.

3.2.2 REVEL Skin: Designing Compatible Objects

For physical objects to be compatible with the REVEL, they need to be coated with an insulator-covered electrode, a structure that we refer to as *REVEL skin* (Figure 4).

There are many off-the-shelf objects and components around us that can be used immediately. For example, any object made of anodized aluminum is a-priory REVEL compatible and can be used without any modification. In fact, in our early exploration of electrovibration tactile feedback in TeslaTouch we used off-the-shelf capacitive touch screens constructed using layers of indium tin oxide (ITO) coated with silica as is, without any changes [Bau, et al. 2010]. However, limiting design of tactile interfaces only to ready-made objects significantly inhibits the use and application of REVEL tactile technology. Designing truly ubiquitous tactile displays that can be used with a broad variety of physical objects and across multiple environments requires an understanding of materials and manufacturing techniques that allow us to produce REVEL skins at will.

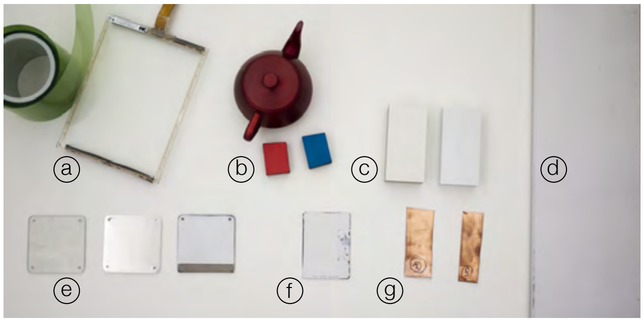


Figure 7: *REVEL Skins: a) SiO_2 coated ITO panel and ITO rolls coated with vinyl; b) Anodized aluminum; c) Electro-coated aluminum; d) Drywall covered with copper emulsion and enamel paint; e) 3D printed resin, vacuum-plated and spray painted; f) Spray-painted nickel-plated ABS; c) vinyl and varnish coated copper plates.*

Manufacturing REVEL skins for various objects, such as a 3D printed teapot or an entire wall in an office space consists of two steps: 1) *Adding a conductive layer*, e.g., painting the object with conductive paint, nickel plating it using vacuum deposition techniques, or covering it with layers of transparent and conductive ITO films among others. 2) *Insulating the electrode with a thin dielectric layer*, such as painting it with thin layers of varnish, electroplating it with paint or anodizing it. Figure 8 presents a gallery of some of the materials and techniques we used in REVEL.

The dielectric constant and thickness of the insulator are key design variables: for a given insulator thickness, a high dielectric constant ε_p would increase the tactile sensation intensity (Equation 1). An optimal insulator is a thin dielectric with a high relative permittivity, e.g., TiO_2 with ε_p ~100. Furthermore, the surface finish of the REVEL skin has to be smooth, yet not glossy, in order to not interfere with electrovibration.

The outer layers of the human skin may act as an insulation layer without requiring one to coat the electrode with additional insulator [Strong and Troxel 1970]. Sweat, however, lowers the insulation properties of the skin and decreases the tactile sensation. By coating the electrode layer, we make tactile display less sensitive to sweat and allow high amplitudes of tactile signal without reaching the skin breakdown voltage (~100V [Grimnes 1983]).

3.2.3 Electrical Coupling and Common Ground

Both the signal generator that is attached to the user and the physical object that is being augmented with tactile sensations have to be *electrically coupled* to a common electrical reference, a ground. Although, it is possible to leave one of these components unconnected, the common electrical reference enables us to create a consistent potential difference between the user's finger and the object's conductive surface.

The easiest approach to establishing a common ground is to ground the user by using explicit wiring, such as a wrist strap, the approach that we used in TeslaTouch [Bau, et al. 2010]. The explicit wiring of the user, however, restricts the user's mobility and is not appropriate for AR applications. Figure 9 presents some alternative approaches to establishing a common electrical ground. For example, a layer of conducting paint on the wall can be wired to a conductive antistatic vinyl floor, which is then connected to the earth outlet of the building's electrical system. The signal generator embedded in the user's shoe will then be connected to the common ground when the user steps on the carpet. Crucially, all the connections do not have to be direct – they can be connected via a *capacitive link* through non-conductive insulating materials such as clothing, shoes or even air (Figure 9).

One of the key challenges in designing intrinsic tactile displays such as REVEL is to ensure *consistency of tactile sensation* across environments and contexts: a tactile stimulus has to feel *identical* no matter where the user is located or what he or she wears on a

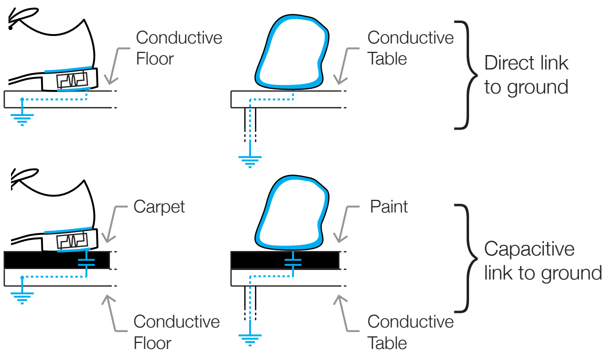


Figure 8: *Ground coupling strategies*

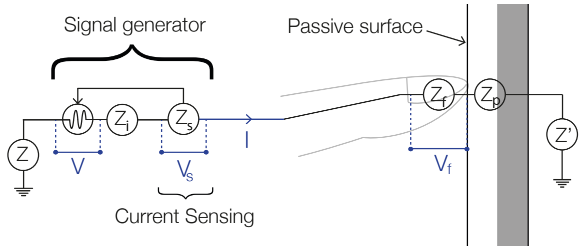


Figure 9: *Keeping the current constant results in the same tactile sensation independently from changes of impedances Z', Z, Z_p.*

specific day. As we have discussed in a previous section, the actual intensity of the tactile stimuli will depend on various impedances introduced into the system, in particular, the impedances of capacitive links connecting REVEL to a common ground. For example, if the signal generator is connected to an electrical ground via an insulating carpet, then the change of carpet thickness, dirt, spilled water or simply carpet replacement will change its impedance and therefore the intensity of tactile sensation.

To maintain constant tactile sensation we have to *dynamically adjust* signal amplitude depending on all the varied impedances connecting user, signal generator, conductive objects and grounds (Figure 9). Although measuring each impedance individually is impossible, we observe that the strength of tactile sensations depends *only* on the voltage V_f between the user's finger and the conductive layer on the object, which must be kept constant. This means that we should keep the *current constant*, which can be achieved by implementing a *constant current feedback* mechanism that monitors the *average* current flowing through test impedance *Zs* and adjusts the total signal amplitude to keep current constant. To this end we implemented a *goal-seeking feedback* mechanism, where a reference current is set during a calibration process. The voltage generator then compares the output from a current-sensing mechanism to the reference and adjusts the voltage output to reduce the difference (Figure 4b and 9).

3.2.4 Safety of REVEL

Although the voltage required for REVEL operation is relatively high, the amount of current flowing through the user is in the microampere range, with a maximum of 150 uA. These current values are safe [Bau, et al. 2010] and imperceptible to humans, being significantly lower than the current perception threshold (~1mA [Webster 1998]). As a comparison, a static electric spark that we receive from the doorknob has voltage levels in thousands of volts, with current values beyond perception thresholds, but does not present any immediate health safety concerns. Introducing current-limiting circuitry further improves the device safety in cases when used with power sources capable of driving extremely high levels of current, e.g., Lithium Ion batteries.

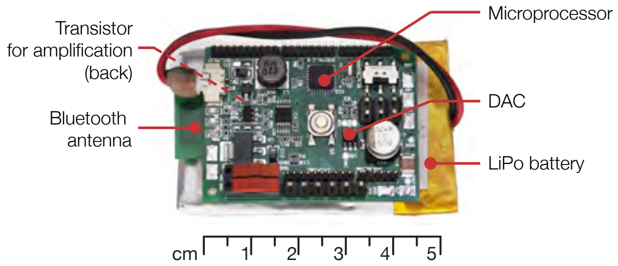


Figure 10: *REVEL signal generator board.*

3.3 REVEL Implementation

3.3.1 REVEL Controller

The overall diagram of the REVEL signal generator and currently implemented board are presented in Figures 4b and 10. An Atmega328 microcontroller generates a low-amplitude signal using a 12 bits digital-to-analog (DAC) converter. Different signal shapes are stored in the microcontroller flash memory and their frequencies and amplitudes can be independently controlled using an on-board Bluetooth module. The signal is smoothed using a low-pass filter and then amplified using a transistor amplifier and high-voltage DC supply. A high-voltage DC is obtained on board by amplifying a 5 V input supply using a flyback transformer circuit. A 555 timer switches a transformer on and off using a transistor switch creating a high frequency and high voltage signal rectified to produce a 300 VDC supply, which is then used to amplify the tactile signal. The output current is limited to 150 uA. The signal frequency range is 10 to 1000 Hz and maximum power consumption is ~300 mA at 5 V. The board is battery powered.

Current sensing is implemented by measuring the voltage drop across a small resistor connected in series. A reference current value is set during a calibration process by associating current reading to a tactile sensation created with a given voltage in a controlled environment with controlled impedances *Z', Z, Z_p*. A variation in impedance to common ground will result in a change of output current. This change is compensated for by a goal seeking feedback mechanism implemented on the REVEL controller that matches the output current to the reference current by adjusting the output voltage. In our present implementation, the output settles in less than ~500 ms when a change in impedance occurs.

3.3.2 Tactile Texture Rendering and Registration

REVEL applies a tactile signal to the entire user's body and all of the user's fingers will experience the same tactile sensation. The

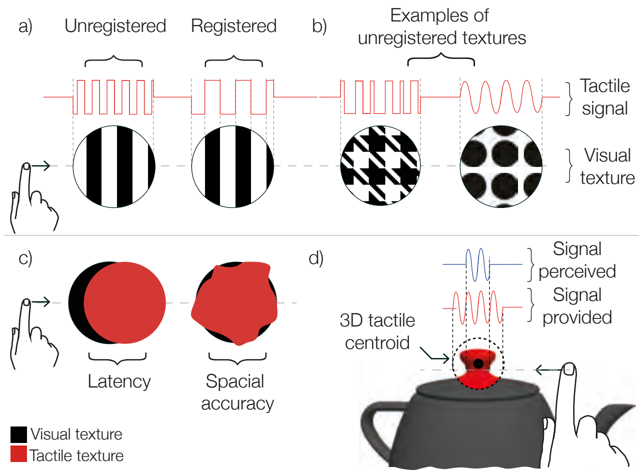
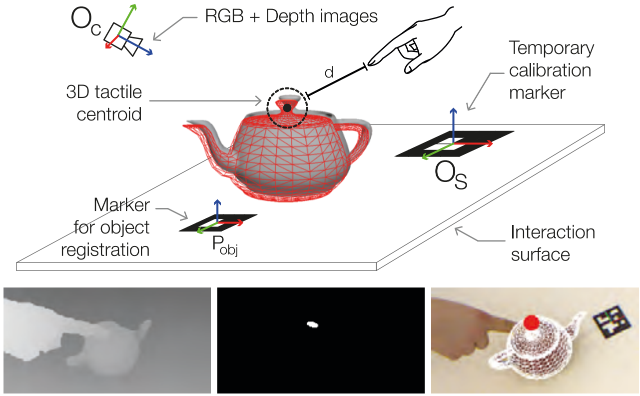


Figure 11: *Rendering tactile textures*



Depth image Touch detection Object registration

Figure 12: *Touch sensing on surfaces and objects in REVEL.*

tactile rendering in this section is described for a single finger.

In REVEL tactile textures can be rendered on a physical object as either registered or unregistered to a visual texture (Figure 11a). A registered texture maps variations in the tactile signal to spatial variations of the visual texture. Unregistered tactile textures, on the other hand, *qualitatively* reflect the visual texture without establishing precise spatial relationship between visual and tactile signals (Figure 11b). We found that unregistered textures are highly effective for fine-grained tactile textures, because the users are not able to perceive any discrepancy between visual and tactile information. Therefore precise spatial registration of visual and tactile textures and high tracking precision are unnecessary. In most of our applications we are using unregistered textures.

In the case of 2D visual content, we define a tactile mask that virtually overlays the displayed images. Each pixel of the tactile mask contains the identification number of a specific tactile sensation. When the user touches an image the identification number of the tactile sensation corresponding to the touch location is pulled from the mask and supplied to the REVEL control device. It then generates the appropriate tactile sensation.

To assign tactile textures to specific areas of 3D physical objects, we specify tactile areas using *tactile centroids*, defined with a center point and a radius in the object's 3D coordinate system (Figure 11d). When the user's finger crosses into the tactile centroid and touches the physical object, the tactile signal is provided and the user feels the tactile sensation associated with the area. This approach provides a flexible strategy for assigning tactile textures to any area of the object as well as for encompassing the object entirely.

3.3.3 Touch Sensing on Surfaces and Objects

As in TeslaTouch we implemented REVEL using capacitive and optical touch sensing on mobile devices and interactive tabletops [Bau, et al. 2010]. For augmenting arbitrary physical objects and interactive walls we implemented real-time 3D tracking using a Microsoft Kinect building on work by Andy Wilson [Wilson, 2010A]. Our tracking technique enables the user to sense touch on a broad range of 3D surfaces, including walls, tables and arbitrary physical objects.

Figure 12 presents the basic tracking setup. After registering color and depth images from the Kinect cameras, corrected for lens distortion, we use a temporarily placed ARToolkit marker to define a primary touch-sensitive interaction surface O_s. We compute a matrix that transforms 3D hand coordinates from camera coordinate system O_c into 3D coordinates relative to O_s. We then isolate the hand pixels from the background and compute the 3D coordinates of hand pixels relative to O_s using the transformation matrix. This allows for the easy detection of touch events and coordinates on the interaction surface [Wilson 2010A], which we then use in augmented surface scenarios.

Once the interaction surface is calibrated, we can sense the position of the user's finger relative to physical objects placed on it. We put a small ARToolkit marker on the table next to the object (Figure 12) to register the physical object and its virtual model. We compute the distance between the user's finger and the center of tactile centroids assigned to an object as we discussed earlier. When the user's finger intersects tactile centroid boundaries, the associated tactile signal is provided by REVEL and a tactile sensation can be experienced on the object. Although we also implemented tracking of user's finger relative to individual facets of the 3D model we have found that a simpler tactile centroid approach was sufficient for our application scenarios.

The Kinect hardware's accuracy decreases with distance: at 2 meters the accuracy of tracking is ~3 mm in the image plane and ~1 cm in depth [Wilson 2010A]. After calibrating a touch surface as described above, the average error of tracking was ~5 mm when the camera was placed 130 cm above the surface. This error produces spatial variability on the edges of textured areas (Figure 12c). This means that spatial resolution of textures augmented with tactile feedback should be lower than the tracking error.

The latency of tracking observed with our implementation was ~150 ms, which is similar to previously reported results [Wilson 2010B]. This latency produces a delay between visual stimuli and tactile stimuli due to a mismatch between the actual and measured positions of the user's hand. This delay produces a misalignment between visual and tactile textures (Figure 11c), with an offset proportional to the speed of the hand. This offset is perceivable mostly on large touch surfaces, where hand movements are the fastest. For example, on a wall display, moving a hand at 50 cm/s results in a 7.5 cm offset between visual and tactile textures. The average movement speeds are much lower when exploring physical objects, and the delay in these scenarios is less noticeable.

The speed and accuracy of tracking can be improved by combining REVEL with other tracking strategies, e.g., Vicon™ systems. We found, however, that the performance of Kinect was sufficient for our simple illustrative application scenarios presented in the next section of the paper.

4. Designing Tactile AR Experiences with REVEL

The REVEL tactile technology allows designing new and exciting AR experiences that are either difficult or impossible to create with existing tactile AR technologies. Because REVEL is an intrinsic tactile technology no active instrumentation of the environment is required, and tactile feedback can be added easily and inexpensively. This section provides application examples illustrating AR applications that are possible with REVEL. We focus on enhancing traditional AR applications with tactile feedback, such as interactive surfaces and tangible AR interfaces. We conclude with some of the more speculative applications of REVEL that extend beyond classic AR and allow us to augment living and working spaces with high fidelity tactile displays.

4.1 Tactile Augmented Surfaces with REVEL

REVEL can enhance augmented touch surfaces with rich, personal tactile feedback. Although research on augmented surfaces has a long history [Matsushita and Rekimoto 1997], with the recent emergence of inexpensive commercially available tracking and

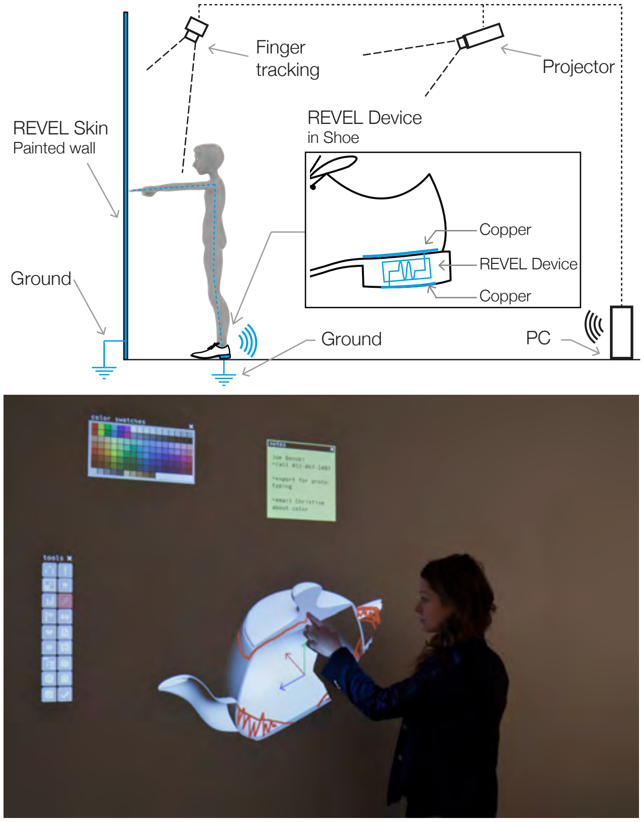


Figure 13: *Enhancing interactive walls with tactile feedback.*

projection technologies, augmented surfaces have been rapidly moving from research labs into homes and offices [Microsoft].

Instrumenting large interactive surfaces with traditional tactile feedback, such as vibrotactile actuation, is difficult for a number of reasons. First, the advantage of interactive surfaces is that any surface can be used for interaction, e.g., kitchen tables, walls and doors, floor, bookshelves and so on. Actuating such surfaces as an interactive table or wall would require the mechanical vibration of hard planes of glass, plastic or another solid material. As the size of the surface increases, it would also require more power to actuate them, as the weight of the surface would also increase. Furthermore, with the increase of surface size, it starts behaving as a flexible beam, attenuating vibrations, and producing a significant amount of sound. Actuating solid surfaces such as walls and floors is impossible without completely re-engineering them.

With REVEL technology it is relatively easy to provide tactile feedback to almost any interactive surface, whether dedicated or ad-hoc, including solid structures such as beams, walls, floors and ceilings. In our exemplary implementation (Figure 13) a part of the laboratory drywall was painted with conductive paint coated with a thin layer of white varnish, creating a smooth white projection surface (Figure 7d). Conductive floor tiles were directly connected to earth ground. A REVEL device was embedded in the shoe worn by the user, where the tactile signal was injected into the user's foot, while the bottom of the shoe's heel provided a link to the ground (Figures 7 and 13). When the user's finger slides on the wall the user can perceive tactile sensations.

We use Microsoft Kinect as described in the previous section to track the user's finger position on the wall. A desktop computer communicates with the REVEL device over Bluetooth to modulate tactile sensations depending on where the user is touching the virtual graphics. We mapped four different unregistered tactile textures (sine waves, 50 – 80 Hz, 200 Vpp) to various elements of a projected image, e.g., the lid, handle and body of the teapot, as well as providing tactile feedback for drawing operations (Figure 13).

The described application example is scalable and can be extended to enhance interaction with various types of interactive surfaces of any size and shape, e.g., spherical [Benko et al. 2008]. Many different materials can be used to create REVEL skins, e.g., transparent ITO film can be used to instrument furniture and anodized aluminum plates could be installed instead of painting the wall. The tactile feedback apparatus is inherently mobile. In the future users may wear small mobile projectors that would allow for augmenting any surface at any time in an ad-hoc manner with very little environmental instrumentation [Willis et al. 2011].

4.2 Tactile Augmentation for Video See-Through AR

Since Sutherland's seminal work on head-mounted displays in the 1960s, optical and video see-through AR has been explored in a broad range of applications that overlay digital content on the physical world, e.g., [Rekimoto et al. 1995]. With the increase in computational power and the broad availability of cameras and high-resolution displays in mobile devices, see-through augmented reality is rapidly becoming mainstream.

We use REVEL technology to allow users not only to change the *look* but also the *feel* of physical objects by augmenting them with virtual tactile textures interactively and in real time (Figure 1 and 14). We nickel-plated the back of a handheld touchscreen device and connected the REVEL signal generator to the nickel-plated surface from the inside of the case. In this way the tactile signal is

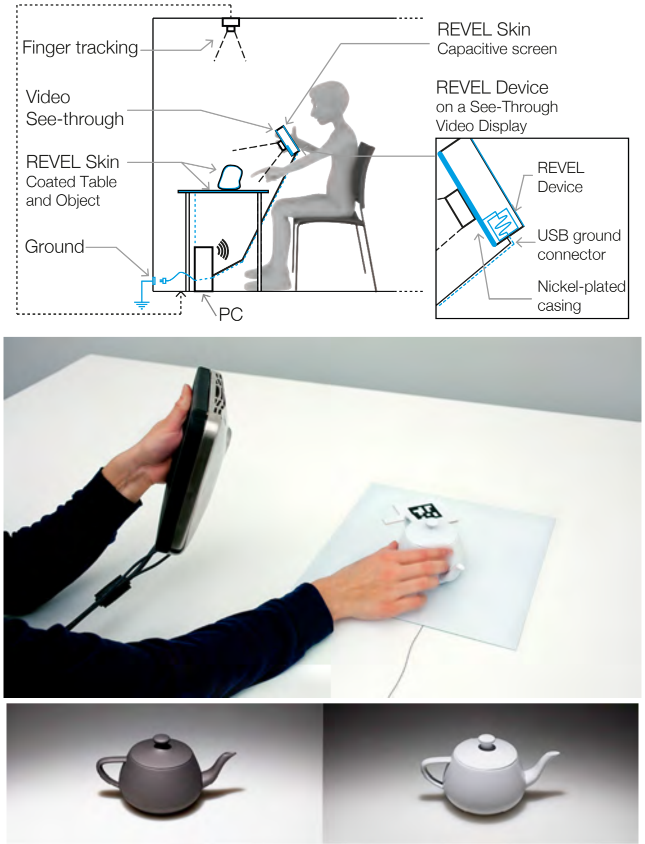


Figure 14: *Augmenting physical objects with tactile feedback in video see-through AR applications.*

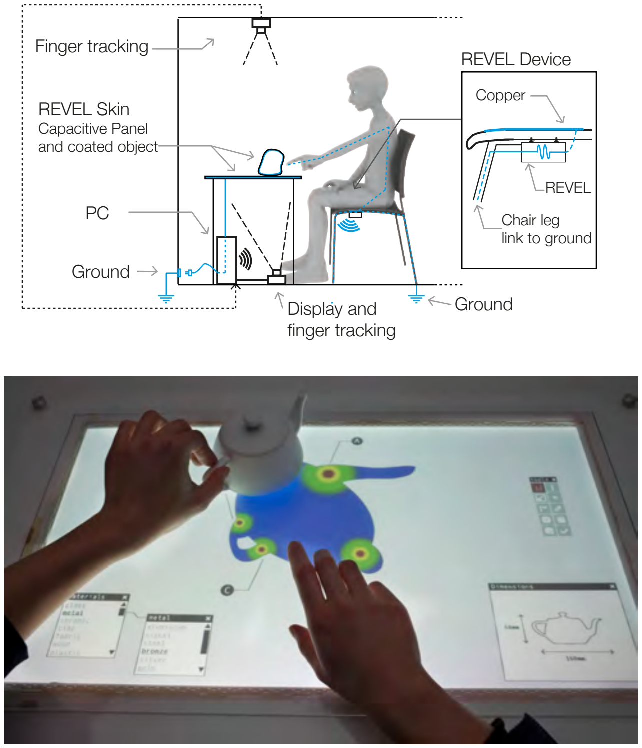


Figure 15: *Exploring tactile feedback in tangible AR.*

injected into the user through the device's case that the user holds in his hands while experiencing an augmented reality view. A 3D-printed teapot was painted with nickel-based paint, sprayed with a thin layer of white enamel paint and placed on a white painted aluminum plate on a table. The aluminum plate and handheld display device were sharing a common ground as both were connected to the computer ground line via the USB (Figure 14 top). Thus, when the user's fingers slid along the top of the teapot programmable tactile sensations were clearly perceived.

A virtual 3D model of the teapot was texture-mapped and registered to the physical teapot as described in the previous section. We tracked the position of the user's finger relative to the teapot as described above. Five tactile signals varying in shape and frequency, with constant 200 Vpp amplitude were mapped to 5 visual textures that the user could apply to the physical object by selecting them from an on-screen palette (Figure 1).

The handheld device was equipped with a capacitive touchscreen by 3M that allowed the user to feel the tactile properties of augmented physical objects directly on the touchscreen. A ground electrode of the touchscreen was connected to the ground of the tactile signal generator. Therefore, the same capacitive touchscreen was used both for touch input and tactile feedback without any modification. The same REVEL technology allowed for providing tactile feedback both on the touch screens and physical objects.

This application of REVEL demonstrates many interesting possibilities in designing AR tactile applications. For example, the video see-through display does not have to be held in the hands, but could be a head-mounted display [Poupyrev et al. 2002], leaving hands free to explore and feel virtual textures on the objects. Being able to touch virtual objects and feel their features directly in the real world reinforces the perception of the physicality of virtual elements and lowers the gap between virtual and physical sensations in augmented reality applications.

4.3 Tactile Feedback for Tangible AR

REVEL can enrich tangible AR applications by enhancing them with programmable tactile sensations. Tangible interfaces often combine interactive touch surfaces with tangible objects tracked on top of the surfaces. They are used to manipulate displayed information and themselves can be enhanced with visual virtual attributes [Rekimoto and Saitoh 1999].

We used REVEL tactile technology to 1) add virtual tactile textures on top of the tangible objects placed on interactive surfaces, and 2) enhance the feeling of the virtual data augmenting them on the surface. We injected the tactile signal into the user's body through the electrode placed on the chair that the user sits on (Figure 15). The REVEL driver's ground line was connected to the metal legs of the chair, which were placed on the conductive flooring tiles connected to the common earth of the building. The glass plate of the interactive surface was coated with ITO, a transparent conductor, and thin layer of silica insulator. The conductor was connected to the same earth line as the driver and, as a result, the user feels a strong tactile sensation when sliding fingers either on the surface of the glass table or on a tangible object placed on it (Figure 15).

A classic rear-projection with diffused infrared illumination and computer vision tracking configuration [Matsushita and Rekimoto 1997] was used to track the position of the user's fingers on the table surface. We used the ARToolkit library to track the position of 2D markers attached to the bottom of the physical object – the 3D-printed and enamel-painted teapot. When the user placed the teapot on the interactive table, a virtual shadow provided additional data about the teapot, e.g., its stress points. Two levels of stress were mapped to two distinct tactile textures that could be felt *both* on *the table surface* as well as on *the teapot itself*. We tracked the position of the fingers touching the teapot using techniques presented earlier. Tactile centroids associated to a 80 Hz-200 Vpp tactile signal were positioned at stress points located on top of the lid, on the spout and two on the teapot handle (Figure 15), and a low intensity tactile texture was mapped on the rest of the teapot body.

The presented exemplary application demonstrates that REVEL can be used to augment a broad variety of tangible AR interfaces where tactile sensations can be presented *both* on the *augmented surfaces* and on the *objects* themselves, combining two previous example applications.

4.4 Beyond Visual

The examples presented earlier demonstrate that the REVEL technology can provide rich tactile sensations to both physical and virtual objects in a broad variety of augmented reality applications. The inherent properties of this tactile technology, however, offer several new and exciting opportunities that go beyond classic visual AR. We discuss them briefly in this section. Note that all applications presented in this section are speculative proposals that have not yet been implemented but could be implemented using REVEL – and that we are interested in exploring through our future development of this technology.

One interesting possibility of REVEL is adding *tactile textures to physical prints*, e.g., where illustrations in physical books, posters and packaging could have programmable tactile textures. These textures may change depending, for example, on the time of day, expiration date of the product or current weather. In another example, the tactile texture of a book cover could be programmed to help the user easily identify the book by feel by sliding his or her hand over a dense row of books on a library shelf.

Figure 16: *Augmenting environments with tactile displays.*

REVEL can add *personalized and private* tactile feedback in public touch displays. Personal customization of computing devices is important as it allows for more effective and enjoyable interaction, e.g., user-defined interaction shortcuts and themes. Users wearing a REVEL device could have personalized interface element feelings on any device they used, e.g., a public ATM. In another example, REVEL can provide "tactile guidance" where the user could feel the password hints on public touch screens in case the user has forgotten them. Personalization would also be effective in collaborative applications where two or more users are accessing the same collaborative tactile surface (Figure 16).

Our tactile technology can also be effectively used as an *assistive technology for the visually impaired,* helping them to navigate and identify objects by feeling tactile changes in the environment. Personal assistive devices are expensive and their application scope is usually limited to a single task, such as a Braille reader. REVEL promises to enable a broad variety of assistive applications using one single inexpensive wearable device. For example, an invisible conductive pattern along a corridor wall could lead a visitor to the exit (Figure 16). Alternatively, it could be used as an information display, e.g., a switch may feel rough when the device is on, or a food package feel rough when it has expired.

Finally, REVEL technology could be used to provide an *internal ambient information display*. There are a multitude of sensations that warn or alert us, e.g., pain, fear, body orientation and others. In the same way, the REVEL intrinsic display can provide a new digitally-controlled internal sensation that can be mapped to an important event or variable, e.g., time. For example, a REVEL device could alter the user's sense of touch as a reminder to take medication. As the time to take medication approaches, the world around the user would start *feeling different* because the REVEL technology would start injecting a tactile signal to the user's body.

5. Limitations of REVEL

The REVEL technology presented in this paper is significantly different from all the previous approaches to creating ubiquitous, wearable tactile displays in that no mechanical devices are worn or manipulated by the user. With our technology the tactile sensation is "injected" into the user's body, and the user perceives this sensation when he or she interacts with physical objects. The resulting technology is lightweight, inexpensive, can be used anywhere and at anytime to add tactile sensations to both virtual and real objects. At the same time is has a number of limitations.

First, in order to feel tactile sensation with REVEL technology the user must slide his or her fingers on the surface of objects. In other words, we can only *augment active human tactile interaction* within a physical environment and cannot create a standalone haptic display for the stationary user, e.g., in entertainment or vehicle control applications (e.g. [Israr and Poupyrev 2011]).

Second, although REVEL does not require active instrumentation of the environment with haptic actuators, it still requires *passive instrumentation of objects and surfaces* to make them compatible with REVEL technology, as well as establishing common grounding strategies. Although this requires certain infrastructure, it is still on an order of magnitude less cumbersome and less expensive than using any other currently developed active tactile technology. Once such infrastructure is established, very little maintenance is required to support REVEL.

Third, skin condition affects the operation, e.g., *excessive sweating*. This, however, is a limitation similar to all modern touch technology -- such as the projective capacitive touch sensing used in modern mobile phones and tablet computers. Some care must be taken to operate REVEL with dry, clean hands.

Finally, the object needs to be in contact with a common ground, through its contact with the surface of a grounded table for example. As a result, objects cannot be held in one hand and touched with the other hand, and must remain in contact with the tabletop. The tactile sensation provided by REVEL can only be experienced when the objects remain in contact with the table or other element of infrastructure connected to the common ground.

6. Conclusions

This paper introduced REVEL – a new technology for lightweight augmentation of real and virtual objects with programmable tactile sensations. To our best knowledge, this is the first tactile technology that allows for true tactile augmentation of physical environments in the sense that it can enhance existing physical objects with artificial tactile sensations. The range of applications presented in this paper demonstrates some of the very exciting opportunities that this technology presents, but it only scratches surface of future possibilities. Tactile augmentation of real and virtual environments remains a largely unexplored area. Many exciting and useful applications could be invented and implemented, and we hope that the current work will encourage the reader to explore this exciting direction of research and development.

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