# Creating Embedded Haptic Waveguides in a 3D-Printed Surface to Improve Haptic Mediation for Surface-based Interaction

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**Abstract.** Vibrotactile feedback is affected by the properties of the material and structure that transmit vibration from an actuator to the entire device surface. The stimuli felt by the skin may be distorted or attenuated at different locations of the device surface. Therefore, it is important to understand how the source vibration can be properly mediated or guided throughout the device to achieve globally uniform or localized vibrotactile feedback. This research[1] evaluates three off-the-shelf waveguide materials and one custom designed 3D-printed ABS structure for creating localized and global vibrotactile signals. The three materials included Gorilla glass, Plexiglas, and aluminum. The 3D-printed waveguide used horizontal and vertical shafts that lowered its impedance load, thereby effectively mediating source vibration along one direction throughout its structure. Results indicate that, compared to the three off-the-shelf materials, the 3D-printed waveguide was more efficient at haptic mediation and creating localized effects using virtual exciter. Our findings support the use of this novel technique of utilizing calibrated 3D-printed waveguides to improve vibrotactile feedback in mobile and handheld devices.

**Keywords:** Vibrotactile feedback, Surface-based interaction, Haptic Mediation, Virtual actuators, Constructive wave interference, Embedded haptic waveguides.

## 1 Introduction

Until recently, while designing vibrotactile feedback more focus was placed on developing the ideal actuation components and specific feedback signals than how these signals should be relayed to the user. However, as put forward by Farooq [1], the mediation of signals created by the actuation component should also be considered in designing haptic feedback. Farooq asserts that "Haptic Mediation" is necessary because in most cases the placement of an actuator and the point of contact with the device are not co-located. Therefore, environmental noise and other internal and external device inefficiencies can drastically alter the signal delivered to the skin. A signal traveling from the source to various points on a device surface may be lowered in terms of magnitude and

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may be altered in terms of phase and frequency components due to the impedance of each intermediary component. Importantly, these factors may affect signal transmission or propagation of the "intended tactile stimuli" as it travels through different materials, each having different structures and physical properties [5].

To reduce signal distortion such as intensity attenuation and spectral degradation, it is possible to utilize haptic waveguides that can channel or mediate the source signals more efficiently. In fact, waveguides have been widely used in various audio-based devices for decades [2, 3]. Depending on the material properties as well as the structural design of the waveguide, applied signals may be enhanced to create more reliable and consistent global device actuation. In this paper we examine 3+1 (3 existing and 1 3D-printed) materials and possible design structures for waveguide efficiency in mobile device interaction by creating a device overlay for touchscreens using a Microsoft Surface Pro 4 tablet. The goal for this research is to improve previous techniques [4, 6, 7] of providing global and localized actuation for surface-based interaction.

## 2 Related Work

Vibrotactile feedback has been a popular method of providing haptic signals in various devices. [2, 6, 9]. In most of this research the generated signal is intended to propagate and mediate uniformly, distributing the vibration energy across the entire device. Previous studies have shown that it is possible to utilize both hard (solid) mediation [1] and soft (liquid / gel) mediation [5] to relay tactile signals within a mobile device. Testing indicates that hard mediation requires densely layered materials with specific elasticity. One study [5] found correlation between physical properties such as Youngs's Modulus ($Y < 70$GPa) and material density ($\rho < 2.80$g/cm3) of the object and its efficiency to transfer vibration signals. Similarly, with regards to soft or liquid mediation, the same study showed that bulk modulus ($>2.80$GPa) and density could play an important role. It was observed that lower density mediums were more efficient at relaying the intended signal. However, in either case the medium needs to be calibrated specifically for a certain frequency to avoid filtering or clipping of the intended signals.

Global device actuation is the most common technique of providing haptic signals especially in less efficient mediation elements. In most cases this type of actuation is confirmational in nature and does not require precisely calibrated signals. Essentially, a single high intensity signal can be generated throughout the entire device to create the global actuation. In contrast, providing localized haptic actuation can be complex, inefficient and may require an array of vibrotactile actuators embedded underneath the interaction surface. Previous research [4, 5, 8, 9] into "Haptic Mediation" shows that signals effectively mediated within a device can greatly reduce the energy needed to create vibrotactile feedback for both global and localized device actuation. Moreover, research into "Intelligent Haptic Mediation" [4] also demonstrates that calibrated opposing vibration signals from two or more actuators can be modulated to interact and create constructive wave interference or virtual exciters for localized actuation.

Constructive wave interference is a method of providing localized actuation signals using virtual actuators. They can be created by modulating the propagation of standing waves along the surface of actuation from two opposite sides. Coe et al., [4] found that it was possible to create discrete localized low-frequency actuation in between the two surface-mounted actuators by adjusting the independent high-frequency direct-signals from each actuator thereby, creating adjustable indirect actuation points. Virtual actuators can be an excellent tool for providing localized actuation on any interaction surface (i.e. touchscreen or smart surfaces), without the use of a dense actuator array. According to Coe et. al., precisely calibrated virtual exciters also require less energy to create similar actuation thereby making the setup more affordable and more efficient, which is ideal for mobile device interaction. In this study, we extend this research to evaluate 3+1 different materials and structures as the surface of actuation to create virtual exciters for generating localized actuation more efficiently on solid surfaces. Our focus was on using haptic waveguides to evaluate  possible improvements on two fronts: 1) their ability to mediate reliable entire-device actuation (global actuation through direct feedback), and 2) their efficiency at localized actuation by creating virtual exciters.

## 3 Using Waveguide as Solid Mediation

It is well established that vibration propagation is dependent on the material properties of the medium [3]. There is a close correlation between the material properties (ρ, Y) of the waveguide and the resonance frequency of the system [8]. It would be beneficial to adjust these properties and calibrate the optimum structure for a specific frequency. In most cases this calibration is not possible without changing the material of the waveguide. However, in 3D-printed structures made from Acrylonitrile Butadiene Styrene (ABS plastic), this can be done by varying its density or fill rate that affect its stiffness (Y = 1.79 - 3.2 GPa). Therefore, any waveguide design can be developed by using composite materials to both mediate and isolate vibration signals as needed, to contain the applied wave energy from dissipating uncontrollably throughout the entire surface. To mediate haptic signals, we focused on creating a low impedance load to develop mediation within the specified waveguide. As a waveguide is essentially a medium where the wave propagation is bounded in two directions of space and free in the third one [8], it should be possible to create calibrated wave guides using a 3D printer.

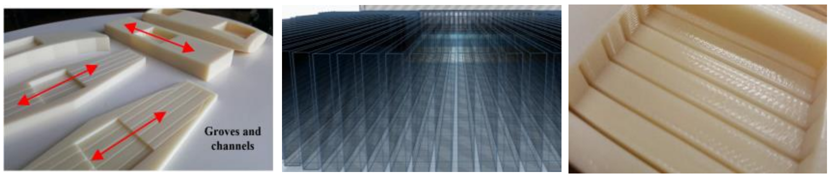

**Fig. 1.** Multiple iterations of the 3D-printed waveguides.

## 4 Experiment Design

Two sets of technical measurements were taken to evaluate the difference among the 3+1 waveguides. To test the effectiveness of the different waveguides in creating virtual exciters, we replicated the setup created by Coe et. al., [4]. Whereas, to gauge the overall signal mediation and energy transfer among the materials, we recorded the surface displacement at various distances from the actuation source. In addition, we conducted a user study to evaluate the perceived differences between two discrete points on the 3+1 overlays. We mounted all 3+1 waveguides to the touchscreen of a Microsoft Surface 4 tablet (Fig. 2). Unlike prior work with touchscreen overlay and constructive wave interference to create virtual exciters [4, 8], for the purpose of this study we did not focus solely on transparent materials. The dimensions (295×205mm) and thickness (2mm) of each waveguide were kept constant. The Gorilla glass 3 had a density (ρ) of 2.39 g/cm3 and Young's Modulus (Y) of 69.3GPa, whereas the 5052-H32 aluminum Sheet had a ρ of 2.68g/cm3 and the same Y of 69.3GPa with a modulus of elasticity (E) of 70.3GPa. The Plexiglass had a rated ρ of 1.18g/cm3 and E of 3.1GPa. We also replicated the attachment mechanism illustrated by Coe et. al., [4] where all the waveguides were attached to the Surface Pro by using a frame to ensure that wave propagation was bound in the two in-plan directions (x-axis and y-axis). For the vertical (z) axis we used a 1mm silicone tip to create free movement in the third direction. Although most of tested surfaces were not transparent, this setup was used to try replicate the apparatus discussed by Coe et. al. as closely as possible to ensure a meaningful comparison.

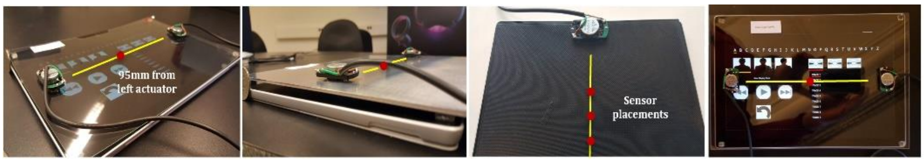

**Fig. 3.** Measuring wave propagation and virtual exciters within the 3+1 surfaces.

## 5 Results

Results from both sets of measurement show that the current version of the custom-designed 3D-printed waveguide was more efficient at haptic mediation and at creating localized actuation through constructive wave interference, as compared to the off-the-shelf Gorilla glass, Plexiglas and aluminum waveguides.

Looking at the results from the displacement sensor we see that it was possible to create Constructive Wave Interference (CWI) on all four surfaces. Figure 4: left, shows each surface with both the direct (from the physical actuator) and indirect (through virtual the exciter) feedback signals propagating through the four surfaces. The direct signal dissipates naturally the further we move away from the left Tectonic actuator and should be the weakest close to 95mm away. Whereas the indirect feedback is the result of the interference from the direct signals between the two opposite Tectonic actuators. The interference maximum caused between the two Tectonic actuators occurs around 95mm from the left actuator in all four surfaces, however their relative peaks vary depending on the surface's efficiency to propagate the direct signal as well as the effectiveness of the virtual exciter being created at that point.

Data of the user study showed (Fig. 4 right) that the Gorilla glass and aluminum waveguides were least efficient and were described to have the most perceived variation between signals felt between Points A & B. On the other hand, Plexiglas was rated slightly better but most participants described the signal at both points to be either very similar or identical for the 3D-printed EHWs surface with one participant considering it to be the baseline (control) condition in the experiment.

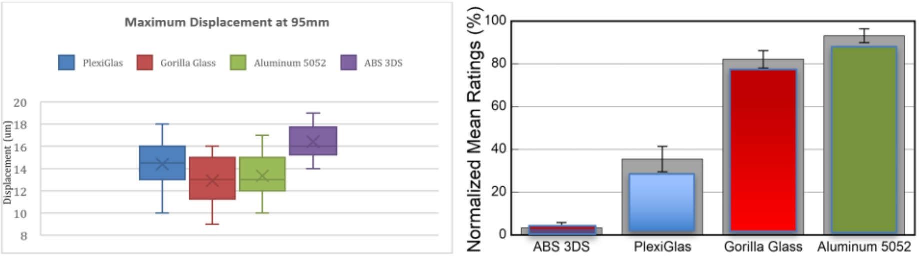

**Fig. 4.** Variance in displacement for CWI in um (left) and perceived differences between signals at points A and B (right) through constructive wave interference (virtual exciter) on the 3+1 waveguides

Results from the wave propagation setup (Fig. 5) showed that at system resonance, each surface altered the applied signal by integrating it with parasitic vibrations. This was more evident for aluminum and Gorilla glass waveguides. The Plexiglas waveguides did not introduce much parasitic vibrations but did attenuate the signal to a much weaker state. Whereas the 3D-printed waveguide was noticeably better at maintaining the amplitude and the waveform of the applied signal throughout the measured frequency range.

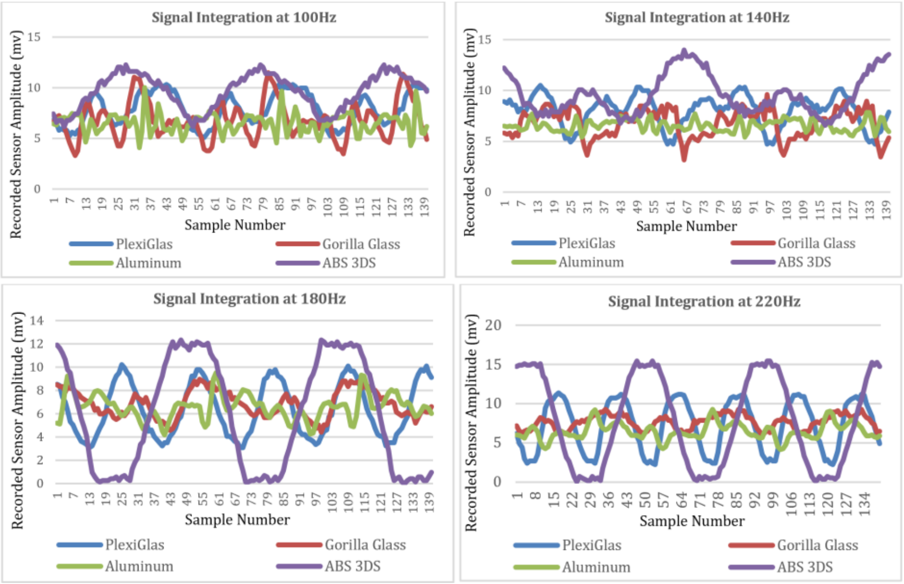

**Fig. 5.** 100Hz (top left), 140Hz (top right), 180Hz (bottom left) and 220Hz (bottom right) signals recorded at 95mm from the source actuator to illustrate distortion / attenuation in the 4 surfaces

## 6 Conclusion

This research focused on evaluating three off-the-self waveguide materials and one custom designed 3D-printed structure for creating well controlled localized feedback (using virtual exciters) and global device actuation. The 3D-printed waveguide utilized specifically designed horizontal and vertical shafts embedded within its structure to lower its impedance load [6] and increase its efficiency at mediating actuation from the source to the point of contact. Moreover, by using a precise printing process and dissolvable support material (SUP706) along with the embedded design structure, it was possible to calibrate the physical properties (ρ and Y) of the 3D-printed waveguide for a given bandwidth of applied signals (100Hz-200Hz). Similar to the approach proposed by Dhiab and Hudin [8] of localizing calibrated actuation signals, the current research illustrates that the properties of the calibrated waveguides can affect the efficiency of vibration propagation, thereby affecting both global and localized actuation signals. Utilized this approach it is possible to improve existing techniques of providing global device actuation using hard and soft mediation, as well as localized actuation through virtual exciters created by constructive wave interference. The results from the present study indicate that custom waveguide can be useful in both application areas and should be further tested to improve the reliability and efficiency of vibrotactile feedback for surface-based interaction.

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