Embedded Haptic Waveguides to Improve Tactile Feedback

Designing a custom 3D-printed surface to enhance signal mediation

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***Abstract*—The physical properties of an interaction surface can significantly alter the characteristics of a vibration signal during its transmission from the actuator to the point of contact. This distortion can integrate and attenuate the applied signal before it reaches the skin contact significantly altering the intended perception. Thus, efforts need to be made to identify and regulate vibration mediation throughout the entire device to achieve uniform global vibrotactile-feedback. Our research proposes a novel concept of 3D-printing Embedded Haptic Waveguides (EHWs) within the interaction surface to improve signal propagation. The EHWs are designed to lower impedance load, effectively creating multiple mediation channels to relay actuation throughout the device. To evaluate the efficiency of our EHW design we compare it to three commonly used off-the-shelf materials (Gorilla glass, Plexiglas, aluminum) and one unmodified 3D-printed ABS surface. Results indicate that the customized 3D-printed EHW surface was more efficient at signal propagation and created similar perceptual feedback throughout the entire surface for the applied signals. These findings suggest that the EHW design has the potential to enhance global-device actuation for surface-based interaction in mobile and handheld devices.**

Keywords—Haptic mediation, Vibrotactile feedback, Embedded Haptic Waveguides, Global device actuation.

I. Introduction

Meaningful vibrotactile feedback requires developing ideal actuation components, specific feedback signals along with an efficient mechanism to relay the signals to the user. As discussed by Farooq [1], the mediation of signals created by the actuation component should also be considered in designing haptic feedback. Such mediation is necessary because in most cases, the placement of an actuator and the point of contact with the device are not co-located. For this reason, environmental noise and other internal and external device inefficiencies may change the signal delivered to the skin. This attenuation can lower the magnitude, alter the phase, and integrate the frequency of the applied signal, changing the overall stimuli depending on the user's point of contact on the device. Furthermore, as the signal travels through different materials within the device, each having distinct structures and physical properties [2], the resultant signal may become indistinguishable from the intended applied signal. To resolve this issue, different mediation techniques have been used [3, 4], which include creating channels of solid / liquid structures to relay signals from the actuator to the point of contact [2, 5]. In most cases these channels are two-dimensional overlays on top of the surface of interaction (touchscreen) mediating partial feedback-signals across the device. In this research, we propose a novel technique of utilizing Embedded Haptic-Waveguides (EHWs) that are 3D-printed within the surface itself to help mediate vibrotactile signals throughout the entire device. Similar to the structure of acoustic waveguides [6, 7, 8, 9, 10] we discuss how to 3D-print custom-designed "EHWs" for surface-based interaction. The aim of this research is to build on our previous work in signal mediation [2, 3, 4, 5] by providing more efficient techniques of global device actuation for surface-based interaction.

II. Related Work

Vibration signals have been used to provide haptic feedback in various devices [11, 12, 13, 14]. In most cases the generated signal is expected to propagate uniformly, distributing the vibration energy across the entire device. However, as discussed by Farooq et al., due to the nature and assembly of current interaction devices, each component within the device may attenuate and distort the applied signal [15]. To reduce this, the precisely generated actuation signals need to be mediated effectively to the point of contact. Our previous studies show that it is possible to utilize both hard (solid) mediation [3] and soft (liquid / gel) mediation [4, 5] to relay tactile signals within a mobile device. Findings suggest [2] that physical properties such as Youngs's Modulus ('Y' less than 70 GPa) and the density ('ρ' less than 2.80 g/cm3) affect the object's efficiency at transferring vibration signals. Nevertheless, even the most efficient surfaces attenuate the applied signal unchecked as the vibration energy dissipates within the material. To avoid this, it would be far more efficient to create isolated mediation channels within the materials, which relay the feedback signals to the point of contact. These multi-layered channels can ensure that the vibration energy of the applied signals remain within a narrow surface area, thereby reducing the energy dissipation and ensuring that the signal may transfer further without attenuation. Unfortunately, it is challenging to create varied density channels / grooves within a single-block structure. To achieve this, we utilized polyjet multifilament 3D printers to create custom-designed EHW within the interaction surface.

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Using this technique, we created a composite interaction surface overlay and compared its efficiency at relaying actuation signals in relation to existing material used in current mobile devices.

III. EMBEDDED HAPTIC WAVEGUIDE (EHW)

A. *Using Waveguides as Solid Mediation*

Using waveguides for vibration propagation is not a new concept [6], as they have been incorporated in auditory mediation for many years [7, 9]. Essentially, a medium that supports vibration propagation is constructed into a channel or duct, which forces vibration pressure to vary in the direction of propagation, causing a pressure gradient to travel perpendicular to the cross-section of the duct [8]. As the wave reaches the end of the transmission line, it can either be reflected in the same direction (through low impedance load), reflected in the opposite direction (through high impedance load) or absorbed altogether (through equivalent impedance load) [20]. In this research, we utilize the reflection of haptic signals in the same direction within a custom-designed 3D-printed screen overlay to enhance haptic feedback for entire device actuation.

B. *Designing 3D-Printed Waveguides*

A waveguide is essentially a medium where the wave propagation is bounded in two directions of space and is free in the third [16, 17]. For that reason, it should be possible to create calibrated waveguides using a 3D printer. As discussed, there is a close correlation between the material properties (ρ, Y) of the waveguide channels and the resonance frequency of the system [7]. These properties can be calibrated to optimize a structure for a given frequency range. In most cases, this calibration is not possible without changing the composite material of the waveguide [18, 19]. However, in a 3D-printed structure, this can be done using fill rate and combining composite materials (PLA, ABS, etc.). Moreover, we found that it was also possible to create multiple waveguides within the 3D-printed object by designing 1.5mm wide chambers or shaft-like indentations inside the object (Fig. 1) with a ratio of empty space to solid waveguide of 1:1. Using this process, we were able to develop three-dimensional waveguides specifically calibrated for predefined actuation frequencies [2].

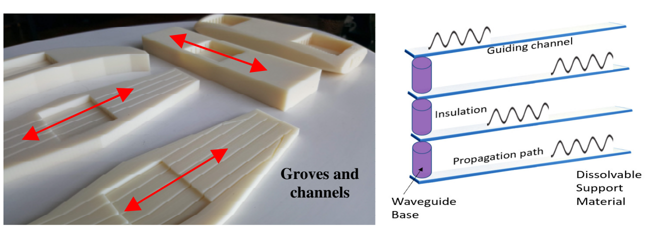

Fig. 1. 3D-printed Embedded Haptic Waveguides (EHW) design

The 3D-printed waveguide was created using ABS and PLA plastic composites. To maximize mediation properties, we created horizontal and vertical shafts / grooves within the waveguide that were parallel to the travel direction of the intended signal (Fig. 1). These sub-surface isolated shafts acted as low impedance loads, ensuring that the actuated signal was effectively relayed throughout the device. *(Exact structural details are discussed in the patent application and can be shared on request)*. The printing process was done using a Stratasys Fortus PolyJet printer with multiple extruders. Added support material (SUP706) was introduced during the printing process and was later removed by placing the finished 3D-printed waveguide in a sodium hydroxide solution. After this process, the 3D-printed waveguide overlay was rinsed and dipped in a glycerol bath to improve its overall strength.

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IV. EVALUATING 3D-PRINTED EHW

To gauge the efficiency of the overall signal mediation and energy transfer in the 3D-printed EHW structure, we compared it to three conventional materials: Gorilla glass 3, Plexiglass acrylic composite, and ridged aluminum-magnesium alloy. These materials were selected as they are commonly found on current mobile and tablet devices and have varied material properties (ρ, Y). Each was cut to fit the Microsoft Surface Pro 4 tablet and mounted on its touchscreen as an overlay (Fig. 2). Moreover, we also tested a similar 3D printed ABS plastic material without any embedded waveguides. The dimensions (295x205 mm) and thickness (2 mm) 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 69.3 GPa, whereas the 5052-H32 aluminum sheet had a ρ of 2.68 g/cm3 and the same Y of 69.3 GPa. Plexiglass had a rated ρ of 1.18 g/cm3 and E of 3.1 GPa while ABS at 80% fill-rate had a Y of 1.4-3.1 GPa. All waveguide-overlays were attached to the Surface Pro using a frame to ensure that propagation was bound in the two in-plane directions (x and y-axes). To create free movement in the vertical (z) axis, we used a 1 mm silicon tip.

Fig. 2. MS Surface Overlay of Plexiglass (left) and actuator on EHW (right)

A. *Apparatus*

A single Tectonics TEAX14C02-8 actuator was affixed in the center of each waveguide overlay. Eight different sinusoidal frequency signals (80, 100, 120, 140, 160 180, 200, and 220 Hz) were then applied to each waveguide-overlay using the MDD10A driver. With help of a S61DSP optical displacement sensor, we recorded the maximum displacement at 95 mm from the actuator. We also used a unidirectional piezoelectric sensor (WS-16025YDW) to measure the vertical components of vibration introduced by the actuator at the same point of contact (95 mm from the actuator). This measurement informs the comparative signal integration and attenuation among the different waveguide-overlay materials, and helps to evaluate the signal propagation through each material.

B. *User Study*

For the user study, our goal was to collect information regarding how the participant perceived the same actuation signals propagating through Gorilla glass, Plexiglas, aluminum and the 3D-printed EHW. Twenty-two university students (8

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male, 14 female) felt a 120 Hz sinusoidal signal generated by the TEAX14C02-8 actuator *(same setup as above)* on each surface at two discrete points, 28 mm (A) and 190 mm (B) away from the actuator. After touching points A and B on each surface, the participants were asked to identify the perceived difference in intensity, distortion and sensitivity. The participants wore a noise cancellation headset (Sony MX1000 M3) to block auditory cues while interacting with the two points on the four surfaces (Fig. 2).

V. RESULTS

Results from both the physical and psychological measurements show that the current version of the custom designed 3D-printed waveguide-overlay was more efficient at mediating haptic signals, as compared to the off-the-shelf overlay materials and ABS 3D printed plastic. Measurements of attenuation and signal degradation on the five surfaces (Figures 3 and 4) illustrate that the 3D-printed waveguide was better at maintaining signal integrity while reducing attenuation and signal decay through the frequency range (80-220 Hz).

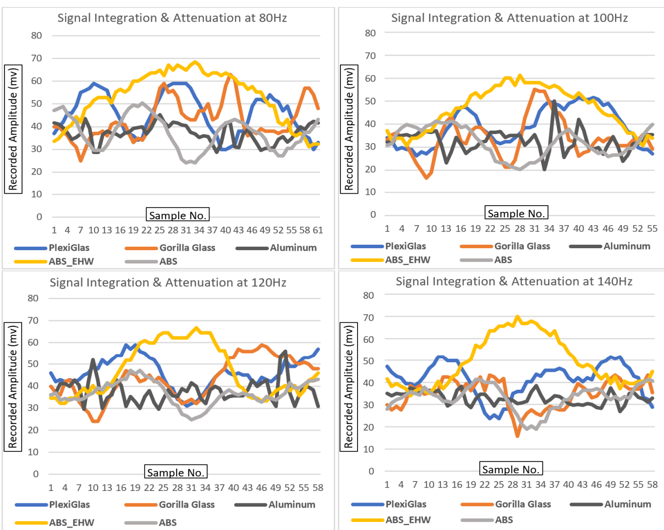

Fig. 3. Recorded signals at 95 mm from actuator on all overlays (80-140 Hz)

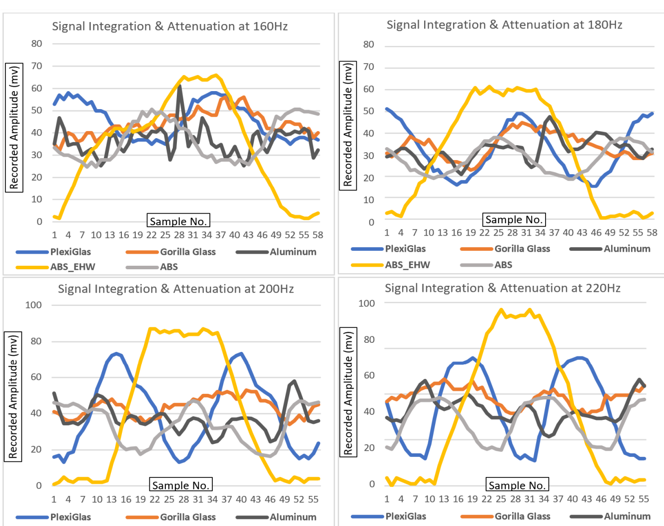

Fig. 4. Recorded signals at 95 mm from actuator on all overlays (160-220 Hz)

Physical measurements show that both the aluminum and Gorilla glass overlays attenuated the applied signal altering the waveform substantially. Similarly, signal degradation and integration in Plexiglas and generic ABS plastic overlays was also visible but not as severe as can be seen in aluminum and Gorilla glass overlays at 140 Hz. Frequencies above 180 Hz showed that all five surfaces were attenuating the applied signal. However, Gorilla glass and aluminum surfaces exibited far more parasitic vibrations, whereas the custom 3D-printed EHW performed considerably better. User study results validate these finding further as the participants considered actuation at both points to be similar for 3D printed EHW, while this was not the case for the other 3 overlays (Fig. 5). As expected, users rated the signals felt at Points A & B as distinctly different far more frequently for Gorilla glass, aluminum and Plexiglas as compared the 3D-printed EHW.

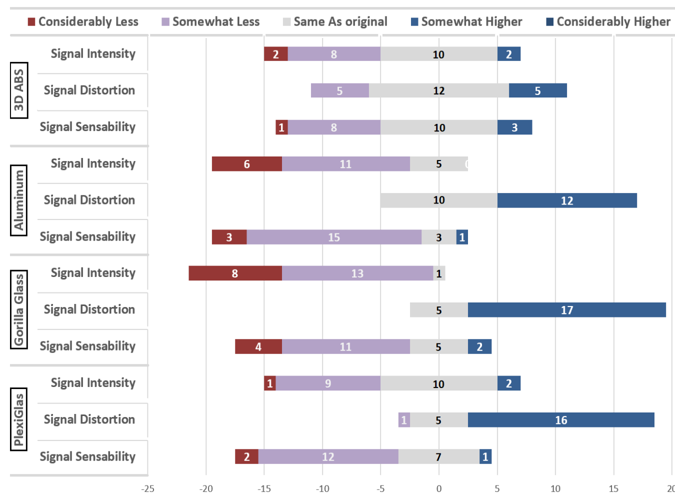

Fig. 5. User response to difference in signal parameters between Point A / B

VI. CONCLUSION

This research evaluated three off-the-shelf waveguide materials, one generic 3D-printed ABS and one custom designed 3D-printed EHW material for creating well-controlled device actuation. Results from the wave propagation setup showed that at system resonance, each surface altered the applied signal by integrating it with parasitic vibration. This was more evident for aluminum and Gorilla glass waveguides. The Plexiglas and common ABS waveguides did not introduce much parasitic vibration but did attenuate the signal. In contrast, the 3D-printed EHW waveguide was noticeably better at maintaining the amplitude and waveform of the applied signal and recorded the least attenuation. Results from the user study indicated that the improvements in signal integrity and attenuation between the 3D-printed waveguide and the remaining materials were perceivable. Users were not able to distinctly identify change in characteristics of the applied signal between Points A and B on the EHW waveguide. This illustrates, that a custom designed EHW can be useful in mediating actuation signals efficiently and avoiding signal attenuation or integration, ensuring that the intended signal reaches the point of contact, intact. We propose that further testing of EHWs design should be carried-out to evaluate the improvements in creating feedback for vibrotactile interactions.

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