8th International Conference on Sensors Engineering and Electronics Instrumentation Advances (SEIA' 2022),
21-23 September 2022, Corfu Holiday Palace, Corfu, Greece

Type of Presentation:

Oral: ☒
Poster: ☒
The same: ☐

In-person: ☒
Virtual in Zoom: ☐

Topic:

<Sensor Applications>

Creating Dynamic Vibrotactile Output using Magnetorheological Fluid as Signal Mediator

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Summary: Current challenges in creating reliable vibrotactile feedback within noisy environments can be addressed by developing a dynamic actuation platform. This research proposes the use of an AI-driven dynamically adaptive process to generate, mediate and verify tactile signals created for surface-based interaction. The framework consists of three components: Active Actuation Engine (AAE), Dynamic Real-time Signal Mediation (DRSM) and User Sampling Feedback Loop (USFL). The proposed method uses a novel approach of generating, propagating, and sampling the output signals in real-time through a dynamic onboard feedback loop. This technique consistently optimizes the intended feedback, using existing actuation technologies and effectively relays the feedback signals from the source to the point of contact, delivering the output in such a way that reduces signal attenuation and integration across a wide range of environments and applications.

Keywords: Haptic Mediation, In-car Interaction, Human Computer Interaction, Piezoelectric Sensors, Vibrotactile feedback, Magneto-Rheological Fluids.

1. Introduction

Tactile communication in mobile devices is generally relayed through discreate vibration signals encoded to deliver specific information [1]. A common trade-off of such an approach is between developing realistic natural feedback compared to synthetic encoded signals that can ensure higher Information Transfer Rate [2] (ITR). The result of this trade-off is often dictated by the system's power specifications hence limiting the type of feedback that can be generated within a mobile device. Therefore, in the pursuit of creating optimized and power-efficient tactile communication, current systems often side-skirt issue related to usability, signal mediation, and environmental signal degradation. This leads to output signals being unreliable and often unpleasant or unintuitive for specific conditions, making the haptic interaction unrefined or an underwhelming part of the interaction experience.

To fix this issue, efforts have been made [18] to develop more efficient and dynamic actuation components, which can cope with signal degradation and various environmental conditions. However, these components often require additional energy and custom driving circuitry essentially reducing overall efficiency. Improving the entire user experience cannot be achieved until the generated vibrotactile feedback is consistently reliable across multiple interaction scenarios and usage environments. One way to counter these issues is to ensure that haptic output is not merely developed to encode redundant information provided using other modalities [3] but should be created as a unique dynamically adjustable output customized for user interaction and environmental noise.

Some researchers have identified these issues and instead of simply emphasizing on improving the efficiency of the actuation source [4] or enhancing the perceptual outcome of the created signal [5] are focused on developing dynamic and active actuation. This involves research in dynamic actuation [6, 7, 8] that further improves the entire haptic feedback loop, starting from how the source of the feedback generates the intended signal, the actuation source, its mediation within the device, and the signal integrity at the point of contact. Using the combination of an efficient actuation mechanism and calibrated vibration signals, some implementations can convey meaningful system information [9, 10] within the tactile sensitivity range using similar power envelop available in current mobile devices.

The goal of our research is to optimize areas of tactile signal generation, mediation, and delivery by using various machine learning and AI techniques to deliver a robust and reliable actuation experience across a wide range of environmental conditions. Our previous work focuses on the various bottlenecks within the actuation and delivery of tactile feedback. Currently there are three key challenges which need to be addressed to optimize haptic feedback for mobile and hand-held devices, 1) actuation delivery oversight, 2) fixed actuation model, and 3) delivery feedback loop within the system.

2. Limitations of Current Vibrotactile Systems

2.1. Actuation Delivery Oversight

Most haptic systems that generate actuation throughout the entire device assume the output signals propagate and reverberate uniformly, distributing the vibration energy across the device equally. In most cases this is not ideal as the uncontrolled propagation of the applied signal must travel through various materials with often differing efficiency to relay the created signal. Therefore, substantial energy losses may occur as the intended signal travels through each material as discussed by Dhiab and Hudin, 2019 [9]. On the other hand, devices with multiple actuator arrays designed to create localized actuation, can also be affected by the medium, these signals need to travel through. The propagation of these signals can greatly vary if the intended signal travel through plastic, silicon or glass thereby delivering unreliable actuation due to interference and integration caused by the mediation material.

As discussed in recent research [8, 11], propagation of actuation signals needs to be understood 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 may be altered in terms of phase and frequency due to the impedance of each intermediary component [4, 12]. For that reason, the efficiency of the transmitted signal (i.e., intended tactile stimuli) reduces substantially as it travels through different materials, each having different structures and physical properties [13].

2.2. Fixed Actuation Model

The fixed actuation model utilized in current haptic system is another fundamental limitation within the device. Most vibrotactile feedback is generated using electromagnetic or piezoelectric actuation sources that are controlled using predefined actuation signals with little to no capacity to amend the actuation in real-time. These driving mechanisms take a static approach to generating feedback signals [1, 9] and coupled with the inefficient delivery of the applied feedback, the generated signal may have considerable variance and degradation as it reaches the point of contact [14]. Although some single actuation devices focus on creating mechanical and electrical efficiency, however, this is limited to translating the electrical energy into mechanical motion within the actuation source only. Similarly, in a multi-actuation setup, instead of creating dynamic adjustment within each source to counterbalance the overall signal most implementations focus on creating maximum amplitude irrespective of how the final signal is relayed within the surface of interaction [15, 16].

Due to this approach, system efficiency becomes coupled with the narrow performance parameters of the actuation source (resonance frequency, acceleration, latency, displacement etc.) rather than using the overall system capabilities, especially in a multi-actuation setup. Our research into Constructive Wave Interference [6] and Haptic Waveguides techniques [7, 8] show that complex natural haptic signals can be created by improving the actuation driving mechanism thereby creating more dynamic feedback using existing actuation technologies. This technique has the potential to create natural localized feedback signals that are not only efficient but can be more adept at replicating complex interpersonal tactile signals than conventional high powered actuation systems.

2.3. Delivery Feedback Loop

Perhaps the most limiting factor in current implementations of haptic systems is the absence of a reliable feedback loop [16]. Most haptic systems do not employ sensors within the propagation cycle to understand and evaluate if the intended signal was properly generated by the actuator or effectively relayed to the point of contact. Furthermore, in the presence of environmental noise, even if the signal is properly generated and effectively relayed to the skin, environmental variances can greatly affect how the signal is perceived by the user [12] (Fig. 1). Such calibration or feedback loops are common in creating visual and auditory feedback, however, are fundamentally absent in haptic systems, even though most of these devices are operated in noisy environments.

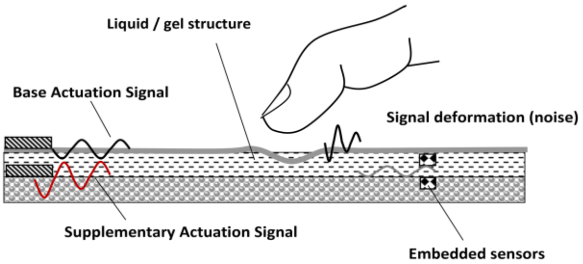

Fig. 1. Illustration of the Active Actuation using fluid / gel to mediate actuation signals from the source to the point of contact over a mobile device touch screen.

If we look at all three limitations, it means that haptic output from the source is mostly static or fixed and can only generate predefined simulated mechanical signals irrespective of the usage scenario or environment, thereby either becoming redundant, irrelevant or simply annoying to the user in a given environment. Due to this variability users ignore or turn off haptic feedback in day-to-day usage scenarios, which in turn creates a negative feedback loop for developing and researching advance haptic interaction techniques for multimodal interaction. This issue becomes even more complicated when devices and tactile signals play an integral part of the interaction process (i.e., where auditory and visual modalities are otherwise engaged or unavailable [8, 19]), and the user is reliant on the delivery of consistent tactile cues to ensure stable communication, such as in a moving vehicle.

3. Design of Magneto-Rheological Fluid Based Actuation System

Achieving reliable haptic feedback requires a fundamental shift in how feedback signals are created, relayed, and delivered to the point of contact from the source of actuation. In mobile devices the source of these signals has limited room for adjustment, therefore the resultant signals need to be effectively relayed to the point of contact with minimum attenuation and integration. The bruit force technique utilized in some standalone haptic systems is not efficient for mobile devices, thus a dynamic actuation medium needs to be able to relay the created feedback efficiently from the source to the point of contact. To achieve this [12] authors have been developing and testing various methods to dynamically relay vibrotactile signals from the source (actuation) to the point of contact (touch point of the device). The proposed method in this research uses a novel approach of generating, propagating, and sampling the output signals in a real-time feedback loop to onboard the actuation source, consistently optimize the intended feedback, using existing actuation technologies (Fig. 2). The framework consists of three components: Active Actuation Engine (AAE), Dynamic Real-time Signal Mediation (DRSM) and User Sampling Feedback Loop (USFL).

Fig. 2. Active / Passive Actuation Engine with Lofelt L5 actuators (left) Mediation Enabled: MRF in fluid State, (right) Mediation Disabled: MRF in solid State.

3.1. Active Actuation

Our AAE system dynamically alters the output signals from the (multiple) actuators in real-time. The current implementation [20] uses two Lofelt L5 actuators stacked on top of each other within a magnetically shielded chamber. This is necessary to ensure their efficiency in the presence of surrounding MR fluid and corresponding magnetic coils. The actuators create linear actuations around the rigid frame to generate the necessary haptic output (Fig. 3).

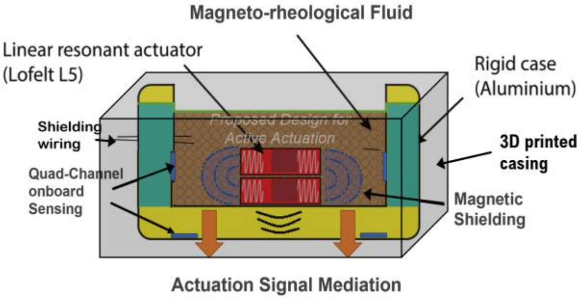

Fig. 3. Illustration of the Active Actuation Engine with Lofelt L5 actuators and MR Fluid for dynamic signal adjustment and embedded 4-Channel sensing.

3.2. Signal Mediation through Active Fluids (MRF)

In our previous research we demonstrated that signal mediation can be improved by creating solid [7, 9, 10], liquid [16] and even mixed mediation materials within the interaction device (or surface of interaction). Such materials utilize channels within the medium relaying the intended signals (i.e., pressure waves) to the Point of Contact (PoC), instead of attenuating them throughout the device. In Liquid Mediation [17], the viscosity of fluid mostly determines which frequency signals are relayed and which types of signals will be attenuated within the device. In most cases viscosity of a fluid cannot be altered, therefore this technique was also static in nature. To resolve this, we use dynamically controlled magneto-rheological Fluid, (Fig. 4) as an independent channel capable of relaying or isolating the propagation of the intended signals, hence creating Dynamic Realtime Signal Mediation (DRSM).

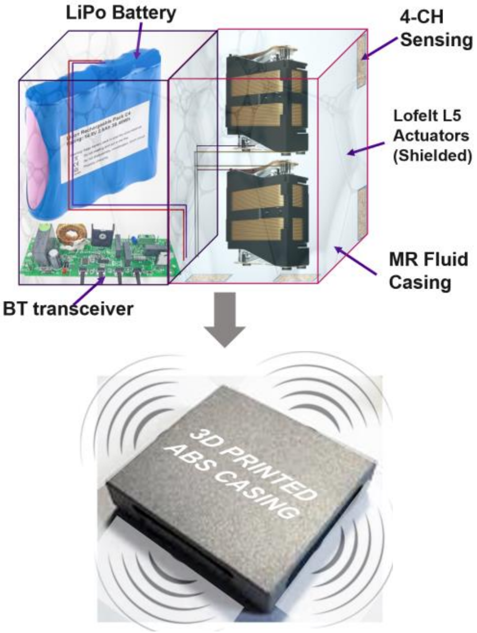

Fig. 4. 3D-printed casing (bottom) of the Active Actuation Engine (AEE) containing the Bluetooth

transceiver, onboard battery, dual L5 actuators shielded from the MR Fluid (top).

3.2. Signal Feedback Loop

To create a signal feedback loop we use the onboard 4CH sensor array, to measure the actuation and delivery efficiency of the generated signal. Moreover, the onboard sensors also provide information on environmental noise and using this data the system develops signal modulation multiplier (SMM) which can be used to dynamically adapt the source-output. Furthermore, an AI-Driven component of the SCFL (Fig. 5) can added to the system in the future that can automatically predict SMM values depending on common interaction properties (i.e., touch point location, distance from actuator, contact pressure, contact area, impedance of finger, environmental noise, device orientation, etc.).

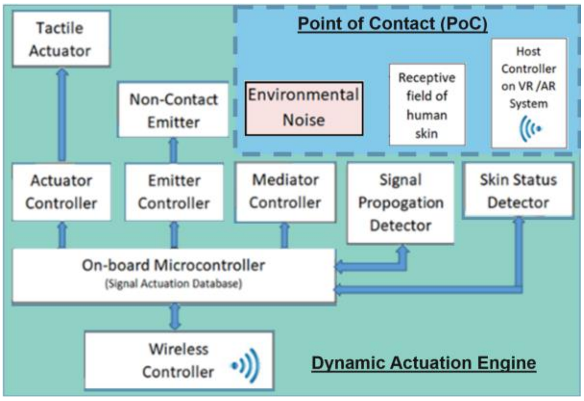

Fig. 5. Illustration of how to create a Dynamic Feedback Loop for Realtime signal mediation and delivery.

4. In-Car User Testing

The proposed framework consisting of three components: Active Actuation Engine (AAE), Dynamic Real-time Signal Mediation (DRSM) and User Sampling Feedback Loop (USFL) has been tested in other user studies [6, 7, 8, 10, 20]. In this research we will discuss work carried out to evaluate the possible improvements using Dynamic Realtime Signal Mediation using MR fluids within a moving vehicle. The current design of the "Dynamic Actuation System" discussed above used embedded the custom AEE / L5 components with signal mediation layer (MR fluid suspension) within a Microsoft Surface Pro, tablet. The touchscreen device was used as the main interaction surface and the "Dynamic Actuation System" was attached to the rear of the device. During pilot testing we noticed that if the tablet device was place on its back once the actuation was triggered the mechanism created audible noise, as it knocked against the flat surface / table. Therefore, the placement of the device was adjusted to ensure no audio output was generated during actuation.

The tablet was placed at an angle of 110 degree on a horizontal surface and attached to the top of the dashboard (see Fig. 6) of the vehicle. To evaluate this setup and measure possible improvements in delivering actuation to the point of contact using MR fluid as a mediator of vibrotactile feedback, we recruited 8 professional drivers to drive the test vehicle on a 460m straight section of the Nokia Tyres Track (NTT). The participants drove the test vehicle at 60km/h while carrying out basic in-vehicle interaction tasks. These included 1) using a custom designed onscreen keyboard for text entry, 2) in-app traverse through dynamic menus and, 3) adjusting the custom 5-buttom media controls, as instructed. Confirmation vibrotactile feedback was provided for each task, using the onboard AAE device illustrated in Fig. 4. Two sets of conditions were created during the tasks, one yielding haptic feedback through Dynamic Realtime Signal Mediation using MR fluids: and the other through conventional actuation using the AEE setup.

Fig. 6. Placement of the AEE unit and Microsoft Surface Pro device in the test vehicle.

The drivers were asked to prioritize driving over the interaction tasks while researchers measure performance in both primary and secondary tasks for each condition. The onboard sensors along with sensors on the MS Surface Pro touchscreen were used to measure the signal being delivered to the user at the point of contact. After each condition, participants were asked to rate the intensity and usefulness of the provided touchscreen feedback. The results showed that using Magneto-rheological fluid as the mediation layer enhanced the actuation signal by 18%. Subjectively the improvement was more noticeable when the test vehicle was moving at higher speeds on the track. This could be because the MR fluid also acted as a low-pass filter because it was calibrated for actuation signals between the 20-50Hz range. Therefore, it may have blocked out some of the higher frequency noise radiating through the touchscreen.

5. Discussion

Using a dynamically modified medium to relay and adjust vibrotactile signals delivered to the point of contact can improve haptic feedback, especially within noisy environments. The ability to monitor the propagation of vibration feedback through various surfaces has not been extensively studied. The “static actuation” model, where feedback is relayed through the entire device and not verified at the point of contact, can result in signal integration and attenuation. This research proposes the use of a dynamically adaptive process for generating, mediating, and verifying vibrotactile signals created for surface-based interaction. Authors test the use of Active Actuation Engine supported by dynamic haptic components (Lofelt L5 actuators), Magneto-Rheological fluid as a two phased mediation / isolation material, and an onboard sensor array for creating Signal Correction Feedback Loop. Extensive user and environment testing is required to validate the results; however, initial findings suggest having a dynamically adaptive mediation layer between the actuator(s) and point of contact in a mobile device can improve signal propagation.

Furthermore, utilizing magneto-rheological fluid to dynamically mediate actuation signals, have the added potential to ensure that the feedback loop and onboard sensing assembly does not increase the device size or power requirements. The current setup using a 4-CH embedded sensory array proved sufficient in identifying integration within the output signal. In combination with the signal modulation multiplier (SMM), using SCFL it was possible to reduce signal integration and deliver reliable haptic signals to the point of contact even in the presence of environmental noise in a moving vehicle. Authors postulate that further improvements can be made to the SCFL component of the system, to incorporate machine learning techniques and better analyze / classify the propagated signal in the presence of environmental noise. Thus, modeling how standing and sub-surface wave propagation may be optimized within the mediation material (MRF), creating reliable and optimized actuation signals within various devices irrespective of the environmental conditions.

Acknowledgements

This research is part of the Adaptive Multimodal In-Car Interaction (AMICI) Project funded by Business Finland (decision # 1316/31/2021), and the Augmented Eating Experience (AEE) Project funded by Academy of Finland (decision # 326415).

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