Haptic Mediation through Artificial Intelligence: Magnetorheological Fluid as Vibrotactile Signal Mediator

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***Abstract*—Although, systems providing multimodal haptic feedback have evolved in the last five years, most implementations still use tactile feedback as a secondary support mechanism to auditory and visual modalities. It can be argued that there is a need to redesign current interaction systems and the technologies utilized for providing feedback to ensure the role of haptics can be enhanced further. New embedded actuation systems can unlock the true potential of haptic communication and improve the efficiency of tactile output and power consumptions within today's mobile and handheld devices. Additionally, 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. Our approach looks at vibrotactile feedback from a holistic point of view and targets creating reliable end-to-end communication across devices and environments. This research shows how to improve the three individual components of vibrotactile feedback, and to integrating the collected output in such a way that reduces signal attenuation and integration across a wide range of environments and application.**

Keywords*— *Vibrotactile feedback, Haptic Mediation, Magneto-Rheological fluid, Human Computer Interaction, Piezoelectric Sensors.

I. INTRODUCTION

Current vibrotactile systems provide haptic feedback through discreate signals encoded to deliver specific information [1]. A trade-off between creating more natural actuation output, versus highest Information Transfer Rate [2] (ITR) within system power specifications, limits the type of feedback that can be generated. This can translate into haptic output being unrefined or an underwhelming part of the interaction experience. Improving the entire user experience cannot be achieved until the generated vibrotactile feedback is consistently reliable across multiple interaction scenarios and usage environments. This essentially means that haptic output can not be simply created to encode redundant information provided using auditory and visual modalities [3] but should be developed as a unique dynamically adjustable output customized for user interaction and environmental noise.

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. Some research in dynamic actuation [6, 7, 8] focuses on improving the entire haptic feedback loop, starting from how the source of the feedback generates the intended signal, 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. However, there are still three key challenges with these approaches, 1) inefficient delivery of the signal, 2) static actuation, and 3) the lack a dynamic feedback loop within the system.

II. LIMITATIONS OF CURRENT VIBROTACTILE SYSTEMS

A. *Inefficient Delivery*

If we look at how tactile signals are delivered to the skin contact, we can see that in most haptic systems with global actuation [4], the generated signal is intended to propagate and reverberate uniformly, distributing the vibration energy across the entire device equally. However, this uncontrolled propagation of the applied signal can cause substantial energy losses as it travels through different physical materials as shown by [9]. Similarly, for localized actuation, or in a system with multiple actuator arrays, the absence of an effective pathway to transmit actuation signals can yield to interference and integration of the signal creating unreliable feedback [11, 12]. Moreover, environmental noise and other internal and external device inefficiencies [13] can drastically alter the signal delivered to the skin.

B. *Static Actuation*

Another issue with the current haptic feedback techniques is that the actuation source and driving mechanism take a static approach to generating feedback signals [14]. Due to the inefficient delivery of the applied feedback, signal variance and degradation limit the flexibility of the system to generate subtle perceivable variances within the feedback envelope [15]. This is the reason why in a device with a single actuation source, mechanical and electrical efficiency is preferred over the ability to generate wider channels of signals within the perceptual spectrum of human skin. While in a multi-actuation setup, complex signal processing and delivery takes a back seat to raw power and the ability to localize feedback on the surface of interaction [1, 9]. 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.

C. Lack of Dynamic Feedback

Lastly, an inherent flaw in the current approach of providing haptic feedback is the lack of a viable feedback loop within the system [10, 11]. Any stimuli provided outside a laboratory-controlled environment requires a confirmation or feedback loop to optimize and refine the stimuli in question, calibrating the original signal with reference to the usage scenarios and environmental noise [12]. Calibration of visual and auditory feedback is a common practice, yet very few efforts or standards have been put forward to do the same for haptic feedback (like active noise cancellation for audio), especially for mobile and wearable devices which mostly operate in noisy environments. This means that the actuation provided in current systems is essentially static 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.

III. System Design

To solve these problems and achieve reliable haptic feedback [12] across different devices we 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. The framework consists of three components: Active Actuation Engine (AAE), Dynamic Real-time Signal Mediation (DRSM) and User Sampling Feedback Loop (USFL).

A. Active Actuation

The AAE actively adjusts the output of the onboard (multiple) actuation components with respect to the intended encoded signal. In our current device we utilize two Lofelt L5 linear actuators which are magnetically shielded to limit signal contamination from the surround MR fluid and corresponding magnetic coils. The actuators create linear actuations around the rigid frame and create the necessary haptic output (Fig. 1).

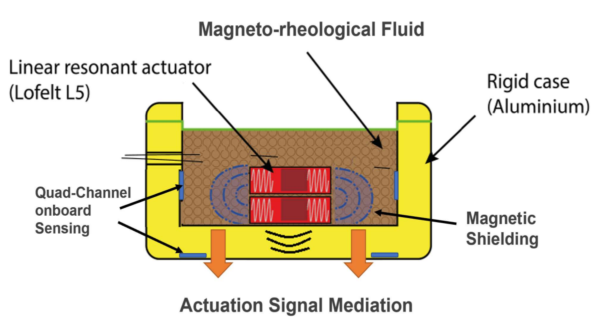

Fig. 1. Illustration of the Active Actuation Engine with lofelt L5 actuators and MR Fluid for dynamic signal adjustment and embeded 4-Channel sensing.

B. Signal Mediation through Active Fluids (MRF)

As previously demonstrated signal mediation can be enhanced by creating solid [7, 9, 10], liquid [16] or even mixed mediation materials within the interaction device (or surface of interaction). This can be achieved using specifically designed channels that relay the actuation signals (i.e., pressure waves) to the Point of Contact (PoC), instead of attenuating within the device uncontrolled. Earlier research in Liquid Mediation [17], used a specific viscosity liquid to statically, conduct vibration signals to the point of contact i.e., Liquid Screen Overlay (LSO). However, our system uses a hybrid approach to mediation. Using a dynamically controlled magneto-rheological Fluid, (see Fig. 2) as an independent channel that can actively relay or isolate the propagation of actuation signals, as necessary during user interaction, we can create Dynamic Realtime Signal Mediation (DRSM).

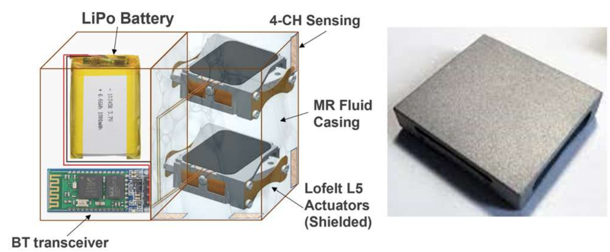

Fig. 2. Casing structure of the Active Actuation unit contianing the Bluetooth transeiver, onboard battery, dual L5 actuators sheilded from the MR Fluid.

C. Signal Feedback Loop

The Signal Feedback Loop uses the onboard 4-Channel sensor array to identify environment and interactional parameters and calculate how these factors affect the created feedback signals, and subsequent modification that is needed to continue providing a reliable output (Fig. 3).

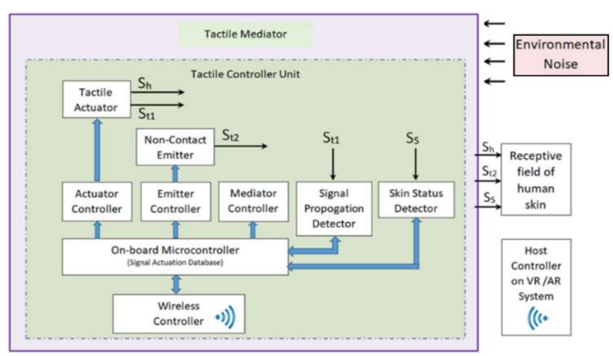

Fig. 3. Illustration of how to create a Dynamic Feedback Loop for realtime signal mediation and delivery.

Therefore, once an actuation signal is created, the Signal Correction Feedback Loop (SCFL) utilizes onboard sensors, to identify properties (i.e., touch point location, distance from actuator, contact pressure, contact area, impedance of finger, environmental noise, device orientation, etc.) and calculates a signal modulation multiplier (SMM) which can be used to dynamically adapt the source-output for the specific use case or environmental scenario. An AI-Driven component of the

SCFL can added to the future iteration of the system to further complement the Signal Generation module, thereby completing the feedback loop to deliver consistently reliable actuation signals at the Point of Contact (POC) with minimum switching delay.

IV. System Evaluation and Testing

To evaluate the current design of the "Dynamic Actuation System", we embedded the custom AEE / L5 components with signal mediation layer (MR fluid suspension) within a Microsoft Surface Pro, tablet. The tablet was placed at an angle of 45 degree on a horizontal surface (table) and two environmental conditions were simulated. First condition was generated to replicate an automotive usage scenario (mid frequency vibration noise). This was achieved using a ButtKicker vibration device attached to the frame of the horizontal surface (table). The device was used to create vibration feedback through the entire surface, simulating environmental noise experienced in a moving vehicle. We used a combination of a piezoelectric sensor array and accelerometers in a moving vehicle (Porsche Cayenne turbo 2008) at 70 km/h on paved highway, to record the environmental vibration. The noise was then played through the ButtKicker device on a loop while the participants interacted with touchscreen on the Microsoft Surface Pro.

The second condition involved low frequency environmental noise, similar to interference caused by walking or running. The orientation and placement of the Microsoft Surface Pro device was kept identical to the first condition and the ButtKicker device was used to relay noise output in a range of 10-20Hz. We then had users carryout common touchscreen and In-vehicle Infotainment tasks (text entry, menu selection and gestures) using the touchscreen. Both scenarios were repeated twice, once with the AEE and Signal mediation layer (MR fluid suspension) activated and once with the layer turned off. The results showed that using the MR fluid-based mediation layer improved the output of the actuation component by a minimum of 18% (Fig 4). The users recorded this improvement as perceivable across both scenarios, however, they felt the improvement to be much higher for the condition with higher frequency environmental noise (using the ButtKicker device to simulate moving vehicle). Furthermore, the onboard sensor within the "Dynamic Actuation System" was able to accurately record the environmental noise generated by the ButtKicker device within both scenarios. Therefore, in future implementation it is possible to update the primary actuation signal parameters in real-time and ensure the originally generated signal and received signal are calibrated, keeping them consistent even in haptically noisy environments using Signal Correction Feedback Loop (SCFL).

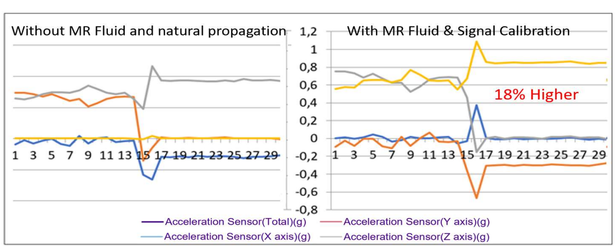

Fig. 4. Illustration of the difference between dynamic actuation using MR fluid mediation turned Off (left) and On (right).

V. Conclusion

This research proposes the use of a dynamically adaptive process for generating, mediating and verifying vibrotactile signals created for surface-based interaction. Our approach looks at vibrotactile feedback from a holistic point of view and targets creating reliable end-to-end communication across devices and environments. We study 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. Comprehensive user testing is still in process due to COVID issues. However internal testing shows that the current approach of utilizing magneto-rheological fluid to dynamically mediate actuation signals, can greatly improve signal integrity and limit attenuation. Moreover, the 4-CH embedded sensory array can identify integration within the output signal and the with the help of the signal modulation multiplier (SMM) using SCFL it is possible to substantially reduce signal integration and deliver reliable haptic signals to the point of contact even in the presence of environmental noise. In future research we plan to utilize machine learning techniques to analyse and classify data collected from the onboard sensor array and dynamically modify the usage parameters of the system. The aim is to adjust the MR fluid in real time and further remove any delays between switching from conductive to isolative properties of the system.

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