# Haptic Servos: Self-Contained Vibrotactile Rendering System for Creating or Augmenting Material Experiences

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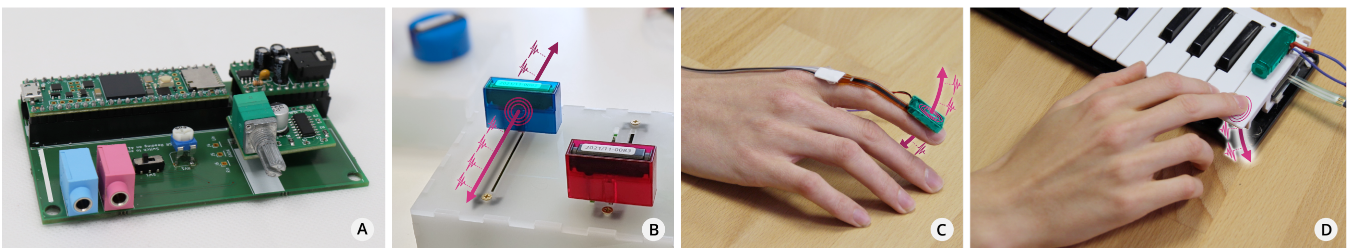


**Figure 1: Haptic Servos enable rapid rendering of diverse material experiences. (a) The open source Haptic Servo shield, compatible with the Arduino IDE, encapsulates all timing-sensitive elements, to create a rich variety of material experiences. We demonstrate how Haptic Servos can be deployed by example of (b) dynamically rendering the material experience on tangible user interfaces, (c) creating on-body material experiences, and (d) augmenting the experience of everyday objects (here piano key).**

## ABSTRACT

When vibrations are synchronized with our actions, we experience them as material properties. This has been used to create virtual experiences like friction, counter-force, compliance, or torsion. Implementing such experiences is non-trivial, requiring high temporal resolution in sensing, high fidelity tactile output, and low latency. To make this style of haptic feedback more accessible to non-domain experts, we present Haptic Servos: self-contained haptic rendering devices which encapsulate all timing-critical elements. We characterize Haptic Servos' real-time performance, showing the system latency is <5 ms. We explore the subjective experiences they can evoke, highlighting that qualitatively distinct experiences can be created based on input mapping, even if stimulation parameters and algorithm remain unchanged. A workshop demonstrated that users new to Haptic Servos require approximately ten minutes to set up a basic haptic rendering system. Haptic Servos are open source, we invite others to copy and modify our design.

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## CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *User studies*; User interface toolkits.

## KEYWORDS

haptic feedback, haptic rendering, material experiences, prototyping, toolkit

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# 1 INTRODUCTION

When we manipulate any object, we experience many of its material properties through vibration [1]. For example, when we break a stick or crumple a plastic bottle, information about the consistency of the stick or the rigidity of the bottle is mediated through vibration. These vibrations are typically not consciously perceived as vibration, but rather as material properties of the objects we are interacting with. *Virtual material experiences* can be created or modified by carefully measuring the forces resulting from user motion (such as pressing a finger onto an object) and then designing vibrotactile signals that closely match the motion. We refer to this as motion-coupled vibration.

Researchers have demonstrated a wide range of such *virtual material experiences* [18, 23, 45, 59]. In all these systems, material experiences are rendered in three steps: (1) user actions are measured with high temporal resolution (2) then based on predetermined parameters and input mappings [18, 23, 59] or through lookup tables [45] electrical control signals are generated (3) which are then used to drive a wide-bandwidth vibrotactile actuator providing the user with corresponding vibrotactile feedback. These systems are exciting because they can haptically provide detailed material information, without actually requiring the user to be handling the corresponding object, much like a display can present colors and shapes of an object, without actually recreating it. Similarly, such systems might allow designers to create an object but determine the material properties later in the process. For example, a designer might produce multiple identical 3D printed objects, and then provide each object with unique tactile qualities. However, one key hurdle for implementing such systems lies in their requirements of high-frequency sampling, low system latency, and high-fidelity tactile output which, together, are non-trivial to meet. We address this challenge by proposing that haptic rendering mechanisms can be thought of as servomechanisms, encapsulating the demanding hardware aspects and exposing a simple interface that adheres to the standard interface of RC servos.

To enable novice hapticians[1], designers, practitioners, and hobbyists, to easily create diverse *virtual material experiences*, we present **Haptic Servos** Figure 1 A. A *Haptic Servo* handles the details of creating motion-coupled vibration, enabling the haptic designer to instead focus on the higher-level functionality of the device or interaction they are creating. All timing-sensitive elements are contained within the firmware of the *Haptic Servo* to ensure the minimal latency required for creating diverse material experiences. Our approach is conceptually inspired from how a servo motor and its corresponding control libraries[2] encapsulate the underlying hardware aspects of driving a geared motor while exposing an easy way for controlling it. This reduces the barriers for designers and novice hapticians to create rich material experiences.

*Haptic Servos* are compatible with the Arduino IDE and can be easily integrated into an Arduino sketch. Through a lookup table that contains unique combinations of key parameters for vibrotactile rendering, *Haptic Servos* can render 180 parameter combinations, supporting rapid and easy prototyping of material experiences for novice hapticians. Additionally, to provide higher detail of fine-tuning, *Haptic Servos* support individual parameter tweaking, which can further expand the rich vocabulary of material experiences. To help the research community replicate *Haptic Servos*, we open-source our hardware design and firmware[3].

The perception of material experiences generated using motion-coupled vibration is time-sensitive and hence, system latency plays a crucial role [44, 58, 67]. To ensure that *Haptic Servos* provide a high degree of control for rendering time-sensitive materials experiences, we systematically characterized the overall latency of the system. With a latency of approx. 5 ms, *Haptic Servos* offer high temporal resolution, which can enable the rendering of highly articulated high-fidelity material experiences.

Through two empirical studies, we evaluated the qualitative experience and ease-of-prototyping. In the first experiment, micro-phenomenological analyses of qualitative interviews with expert hapticians show that the material experiences rendered by *Haptic Servos* are perceived as very natural. Since the vibrotactile feedback was tightly coupled with the actions being performed, the participants perceived the integrated experience combining tactile and motor elements. This enables the rendering of rich material properties to objects. In a design workshop, we evaluated the ease with which hapticians, designers, and practitioners can prototype custom material experiences with *Haptic Servos* for three diverse application scenarios: tangible UIs, body feedback, and industrial design. Overall, results from these studies show that *Haptic Servos* can (1) render high-fidelity motion-coupled tactile effects and (2) users with no or little prior experience in hardware design can use *Haptic Servos* to quickly and easily prototype material experiences.

# 2 CONTEXT & RELATED WORK

The experience of touch is multifaceted and combines various modalities. For example, thermal receptors mediate temperature and moisture information, open nerve endings mediate pain, bulbous corpuscles and Merkel cells mediate forces, and Pacinian and Meissner corpuscles mediate vibration [21]. In our work, we focus solely on experiences mediated through vibration.

## 2.1 How and What We Touch

Tactile experiences are often discussed in terms of *how* the touch is performed [26, 56]. *Active* touch relates to an exploration of the object or interface initiated by the user, while *passive* touch relates to moments where the user is touched by another person or object. Perceiving an object's properties is ideally performed by active exploratory procedures [13], while passive touch has less sensory acuity [16].

Touch can also be discussed in the context of *what* is being touched. Interestingly, touch as a sense which enables us to perceive two distinct types of stimuli [22]. One way of experiencing touch, is as a *distal* stimulus. A distal stimulus origins from a location external to the body; for example, a landslide might cause the ground to rumble, or a kitchen mixer might cause the work-surface of a kitchen to shake. When we perceive these stimuli, they are independent of our actions. We feel the vibrating counter no matter if we scan it or not. The type of tactile stimulus we are more commonly aware of when engaging with physical objects are *proximal*.

[1] we follow the same definition for "novice haptician" as Seifi et al. [54]

[2] such as the Arduino Servo Library https://github.com/arduino-libraries/Servo

[3] https://github.com/sensint/Servo_Haptics

Here, the stimulus is co-located with our body, for example, if we touch a texture, we experience this texture at the part of the body in contact with it and we experience the texture to exist at the location we are touching it. More importantly, we need to engage with it to experience it: To experience a texture, we require relative motion between our finger and a material, which leads to a stimulus that is synchronized to our actions.

Proximal and distal stimuli appear to relate to active and passive touch, insofar as distal stimuli unfold without synchronization to our actions while proximal stimuli unfold proportionally to the interaction between the body and the stimulus. However, even though proximal stimuli are experienced with higher acuity for active touch, they are also experienced passively, and while active touch might mask elements of distal stimuli, they are still perceivable, even during active touch.

## 2.2 Proximal Perception & Vibration

Katz assumed that proximal stimuli are mediated by pressure and the distal stimuli are mediated by vibration [22]. However, today we understand that proximal touch experiences are also mediated through vibration. For example, when we break a twig, or when we move our fingers over a textured surface, we cause vibrations. These vibrations are experienced as part of the material properties of whatever we might be interacting with. A well understood example is the perception of textures: Bensmaïa and Hollins have shown that the vibration of the finger, caused by touching a texture, accounts for 80% of variability in the similarity rating of the same participants on the same textures [2]. This suggests that the Pacinian corpuscles primarily mediate the experience of texture [2]. Romano and Kuchenbecker demonstrated that users can be made to experience textures on flat surfaces by creating a vibrotactile signal proportional to speed and pressure of the users' actions [45]. Strohmeier et al. demonstrated that users can even experience such textures in the absence of the normal force that a surface might provide; they created texture experiences in midair [58]. Another example of proximal experiences mediated through vibration are experiences of compliance. Kappers et al. have demonstrated that there are a plethora of compliance cues, many of which are associated with skin deformation [3]. It has been shown in practice that vibrotactile cues, closely coupled to changes in exerted pressure, are sufficient for compliance and deformation experiences to emerge [23, 24]. Moreover, Heo et al. used changes in force and torque applied to a device by the user to generate the experiences of bending, twisting and stretching of the device [18] and also created a haptic illusion of compliance based on tangential force provided by the user [17]. Furthermore, Lee et al. demonstrated that vibrotactile feedback coupled to holding, squeezing and sliding of fingers can generate experiences of textures and compliance which helps in precisely manipulating objects in virtual reality [28]. Many more examples can be found in the HCI literature (e.g.: [25, 29]).

All systems mentioned here, which use vibration for creating proximal stimuli, share many implementation details. They have a method for high resolution sampling of human action and use this information for modulating parameters of a vibrotactile signal. This suggests that these known vibrotactile effects are merely special cases of a larger space of vibrotactile material experiences. It is reasonable to assume that they are in fact all different manifestations of the same underlying perceptual mechanism. Correspondingly, *Haptic Servos* are designed as a generic system, which is not intended to create any specific material experience, but rather address their underlying mechanism, so designers can implement arbitrary systems. This is further explored in the qualitative exploration of Section 4.2, where we use *Haptic Servos* to determine how these experiences unfold and if the underlying perceptual mechanism is consistent.

## 2.3 Proximal Output in HCI

If we apply the distinction between distal and proximal experiences to vibrotactile feedback used for HCI purposes, we find that most HCI systems cater to the distal aspect of vibrotactile perception. For example, when a smartphone buzzes (e.g., because we have received a text-message) we experience this vibration originating distally, from the device. Even if we look towards more complex haptic experience design [49], the focus on distal experiences remains. For instance, a number of prototyping and design tools for haptic symbols exist [52, 53, 69]. However, these are designed along a time dimension. Because their patterns do not interact with human actions, they are perceived as external, distal stimuli. Work exploiting apparent tactile motion where a virtual vibrotactile stimulus is moved over the human body by interpolating the intensity of a grid of actuators [19, 50] is also based on distal stimuli. The experience is of a stimulus originating externally, that is moving over one's body. Similarly, actuator systems designed for on-body feedback, such as the epidermal feedback device by Withana et al. [68], and recent development in the field of chemical haptics [31] currently function independently of user actions. What these systems have in common is that the stimuli are created with fixed parameters, which are not modulated by human action.

Though rare, examples of proximal vibrotactile feedback in consumer devices exist. A well known example is the 3D Touch mechanism used in many Apple devices, which provides a compliance illusion by means of a pressure-synchronized tactile cue[4] Similarly, within HCI and haptics research communities, such proximal feedback can be found, most notably used for vibrotactile feedback in the examples introduced in the previous sections [18, 23, 45, 58]. We design *Haptic Servos* to support the deployment of proximal vibrotactile feedback devices – devices which create material experiences through vibration – as we believe these are currently underrepresented in the literature and have untapped potential both in researching perception and interaction, as well as for improving consumer devices.

## 2.4 Generating Vibrotactile Output

High resolution vibrotactile signals generation is non-trivial and is often done using DAQs [7, 34] or Audio Interfaces [42]. More rarely, one can also find systems that use embedded solutions [60] using either DAC output or dedicated driver chips[5]. DAQs have both high resolution sensing and output capabilities, but are expensive

[4].https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/3d-touch/
[5]https://www.ti.com/product/DRV2605L

and do not support a rapid-prototyping workflow. Audio Interfaces are capable of creating high resolution output, and high-end audio interfaces together with custom software are capable of creating relatively low latency output systems [42]. Using commercial audio-pipelines is convenient, enabling users to directly focus on the tactile experience, which is why it is used in many haptic toolkits, such as Stereohaptics [20] and Vitaki [33]. However, if one wishes to add sensing to such systems, one typically introduces additional hardware in the sensing-actuation loop, which again adds unwanted latency.

Looking towards embedded solutions, most custom driver chips are also not designed or used for the type of continuously modulated signal required for rendering material experiences. Consequently, custom microcontroller based solutions are the ideal path forward for low latency high resolution vibrotactile rendering. An example of this is bARefoot, a vibrotactile shoe [60]. Here, the authors report the 8 bit DAC used as a limiting factor. The prototyping suite by Wittchen et al. can create 8 independent channels of vibrotactile output, but does not have any mechanism enabling sensor control [69]. In contrast, the system by Dementyev et al. enables such control: Their vibrotactile haptics platform even provides vibration output on 16 channels from a single microcontroller. However, their system uses a relatively low sampling rate of 2kHz [10] to maximize the concurrent channels of vibrotactile actuation.

Generally speaking, systems based on commercial audio can have output with high resolution and sampling rates, but often with relatively high latency. Microcontroller based systems on the other hand can have very low latency, but often at the cost of low sampling rate and a bit depth. Creating multi-channel systems using custom embedded solutions typically requires reduction in signal fidelity, and for commercial audio-based systems requires purchasing expensive multi-track audio interfaces. *Haptic Servos* address these impracticalities. They provide low latency high resolution audio output, modulated by sensor input.

### 2.5 Haptic Design Tools

The role of haptic designers and their training and education is an active topic of discussion in both industry and academia [48], and strategies of how haptic designers work are actively being studied with the intent to develop better tools for novices [54]. This has lead to collections and libraries to facilitate discovery of devices [55] or tactile effects [72]. Other work provides platforms for sketching and designing haptic designs through direct manipulation [51, 69, 70] – a particularly creative exploration in this area is the use of vocalizations to sketch out haptic feedback [8]. Others have presented design tools for creating haptics using visual metaphors [36, 37], software tool-chains for connecting sensors and (remote) actuators in hardware [14, 30] or the development of dedicated experimental platforms to deploy arbitrary haptic symbols [11].

Haptic Servos provide a complimentary approach. Rather than creating a new tool-chain for haptic design, the intent is to create a powerful actuator which can be integrated in existing tool chains and devices. This is why we use the servo-motor metaphor in naming our device. In the same way that a servomotor encapsulates a complex control process in a discrete device which the user need not worry about, we abstract away the bulk of the complexities of

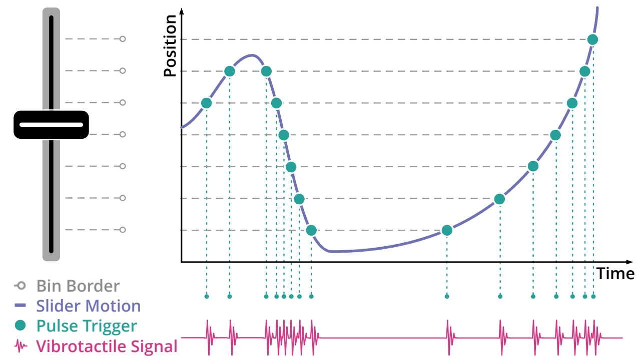



**Figure 2: The range of a sensor (e.g., a slider) is divided into bins of equal sizes. While moving the slider, a vibrotactile pulse is triggered at each crossing of a bin-border. Hence, the dynamics of the perceived pulse sequence is coupled to the user's motion.**

creating a specific type of haptic feedback, which can be used to create material experiences. While a traditional RC servo-motor controls the position, the haptic servo controls the output waveform, proportionally to human action. While the RC servo measures the error in terms of position, the haptic servo measures the error in terms of correlation between waveform and dynamics of human action.

*Haptic Servo* also alludes to the final form factor of the device we envision. Our ultimate design goal is a completely self-contained device, which contains actuator, sensors (possibly using inertial measurement, or back-EMF voltage [11]) and control electronics in a single housing. We imagine such a device (or even multiple) might easily be integrated in many of the existing prototyping tool-chains, multiplying their efficacy.

## 3 HAPTIC SERVOS

The purpose of *Haptic Servos* is to create proximal tactile experiences, which include material properties such as compliance and texture as well as physical experiences such as force – from now on, we will simply call these *material experiences*. This is achieved by measuring a human action with an analog sensor and generating a tactile signal based on that action. The resulting tactile signal consists of a series of pulses that occur at a density that correlates with the change in the measured signal (Figure 2). For example, when rotating a knob, tactile pulse density correlates with the speed of rotation; when pressing a button, pulses are generated based on changes in applied force. The overall density of the vibrotactile pulses and the vibration parameter of the individual pulse can be controlled by the user. In the future, we imagine *Haptic Servos* to be completely self-contained components. A designer can then easily integrate one or multiple haptic servos into a prototype, in the same way that we can currently deploy RC servo motors in prototypes.

### 3.1 Technical Design Considerations

We envision *Haptic Servos* to be a versatile platform that enables easy prototyping of material experiences. However, for rendering

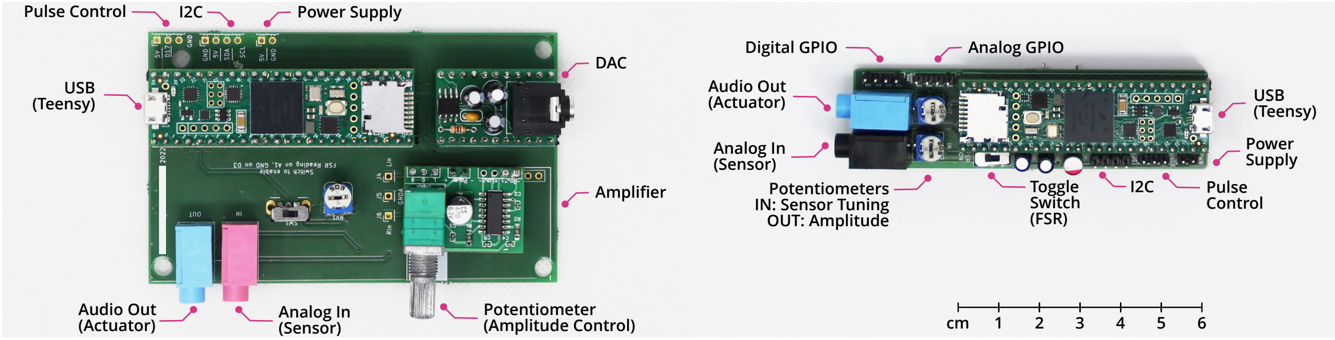



**Figure 3: Two instances of the Haptic Servo shield with several ports for I/O, communication, and power supply. Left, a version that can be equipped with off-the-shelf breakout boards, and on the right a version with reduced footprint and surface mounted ICs.**

material experiences, several technical requirements need to be considered:

*3.1.1 Latency.* Anecdotally, when perceiving a virtual material experience, such as a friction rendering, the fidelity of the experience is perceived as highest mid-movement, and lowest at movement onset and when ending the movement. We believe that this is an effect of latency, as latency would be experienced most prominently during changes in movement, and least during constant movement. Prior work has also argued that latency is a crucial metric that can have a significant influence on the overall tactile experience [58] and there are reports of latency being experienced as a type of inertia [57]. Literature reports multiple values of latency in haptic rendering systems, for instance, $25ms$ [58], $45ms$ [66] and $60ms$ [23].

The timing sensitivity of motion-coupled vibration is similar to issues around the synchronization of sound and action in music [60]. Hence, we take inspiration from auditory perception, as there are many parallels between acoustic and vibrotactile perception, and the effects of latency on audio perception have been studied extensively [9, 32, 44, 67]. Based on the recommendations provided in acoustic perception literature, we aim to have a latency of less than 10ms (<10ms) for *Haptic Servos*.

*3.1.2 Sensor Sampling Rate.* Previous work has reported sampling rates of 125 Hz [61], 240 Hz [58] and >2000 Hz [59]. In anecdotal reports and in our own experience, higher sampling rates result in *crisper* experiences, while lower sampling rates can result in experiences which feel less clearly defined. We therefore intend to sample the human actions as fast as technically possible, i.e. in the current firmware version approx. 125 kHz on a Teensy 3.5. To be clear, vibrotactile perception is most sensitive at comparatively low frequency: Pacinian cells are most sensitive at approx. 250 Hz [65] (though different studies find slightly different values for this). The analog sensory processing path, however, is very sensitive to signal onset [21]. This high frequency is therefore not required for rendering high-frequency signals, but for optimizing the signal onset of individual pulses. A low sampling rate can lead to something similar to hysteresis, where a specific pulse occurs at different times or locations depending on the direction which the user is moving when encountering it. High sampling rates improve the synchronization between tactile pulse onset and human movement dynamics. Capturing human actions at very high temporal granularity enables us to create material experiences which feel crisp, hard, and exact.

*3.1.3 Signal Fidelity.* Another important technical consideration that is crucial for rendering realistic material experiences is signal fidelity. Prior work which used embedded systems for generating vibrotactile signals motivates the need for having high signal fidelity [60], as the system was limited by the hardware (8-bit DAC on ESP32). This limitation can be overcome by using hardware with higher available bit-depth to produce high-fidelity signals.

Taking these technical details into consideration, we set our target for a latency under 10 ms, while maximizing the sampling rate (>120kHz in our case) and generating high-fidelity control signals that are comparable to commercial audio (16bit, 44.1kHz).

## 3.2 Usability Considerations

The design of *Haptic Servos* is centered around two key considerations about usability:

*3.2.1 Simplicity and Discoverability over Control.* As we intend *Haptic Servos* to be used in early stages of the design process, the *Haptic Servo* should support designers to rapidly reach a stage where their idea can be tested. Working with *Haptic Servos* should support intuitively discovering and exploring interesting experiences in practice, rather than offline fine-tuning of parameters. This is supported by the explicit choice to *not* give the designer full control over all stimulation parameters. Instead, the goal is to merely provide enough ability for customization to explore variations of a design, similarly to how a servo motor merely allows the designer to set a target value, but not modify the algorithm of how to get there.

*3.2.2 Compatibility with Existing Tools.* To make integrating *Haptic Servos* into existing projects effortless, maximum compatibility with existing toolkits should be ensured. We do not want designers to require custom control libraries or custom electrical interfaces.

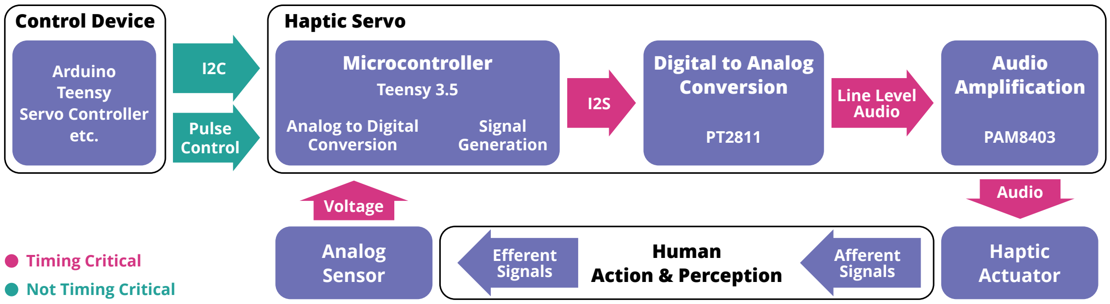



**Figure 4: The components needed in the process of rendering material experiences using a Haptic Servo.**

## 3.3 Implementation

A *Haptic Servo* requires a microcontroller that samples a sensor (input) and generates a signal based on specified parameters and sensor dynamics. The *Haptic Servo* must also have a way of transforming this digital signal into an electrical control signal. It then requires an amplification circuit to provide enough power, so the signal can drive a haptic actuator. To keep the *Haptic Servo* as generic as possible, we defined the input as an analog voltage and the output of the *Haptic Servo* as the amplified control signal (AC voltage), making it compatible with a wide range of actuators (LRAs, voice coil actuators and piezos with correct amplification) as well as audio speakers for supporting rapid prototyping.

*3.3.1 Hardware.* For our proof-of-concept device (Figure 3 left), we use off-the-shelf hardware and open source software. This was done to make our system more easily reproducible. We used a Teensy 3.5 microcontroller and generated the signals using the Teensy Audio Library [6]. For full 16 bit analog output, we used the PT8211 Audio Kit by PJRC and for amplification, we used the PAM8403 by AZDelivery. Here, the loop between vibrotactile output and analog sensing is closed by the human, who perceives the feedback and acts accordingly (Figure 4).

The PT8211 and the PAM8403 are connected to the Teensy with a hardware shield , together forming the physical *Haptic Servo*. As shown in Figure 3, the *Haptic Servo* shield has two primary I/O ports for connecting to the sensor and the haptic actuator. To support tinkering and experimentation, these are implemented with 3.5 mm audio jacks. These are convenient as they are built to mechanically withstand frequent connection and disconnection, while being sturdy enough to not accidentally disconnect.

The *Haptic Servo* also has two communication ports and a power port. These are implemented as regular pin-headers, so a standard servo cable or a 4pin I2C cable can be used. Future versions will include shrouding to hold cables securely and prevent cable rotation. All designs including schematics will be provided open source in our GitHub repository[7] for reproduction.

*3.3.2 Form Factor.* The device described above is easy for others to reproduce. However, ultimately we wish all elements of the Haptic Servo, including the actuator, to be self-contained. As a step towards this goal, we have also produced a version which saves space by using a custom PCB rather than breakout boards (Figure 3 right). Both devices have their benefits and drawbacks (ease of reproduction vs ease of integration) we will provide source materials for both designs. The next step with regard to form-factor is to choose a discrete microcontroller which we will use to replace the Teensy. This shield with a smaller print can be used for handheld and wearable applications.

*3.3.3 Servo Compatibility.* To maximize the ease with which a *Haptic Servo* can be integrated in existing prototyping ecosystems, we chose to maximize compatibility with regular RC servos. For this purpose, the *Haptic Servo* has a pulse-control port, which is pin-compatible with a standard servo cable. Additionally, the *Haptic Servo's* parameters can be set using Pulse Width Control. In a standard RC servo, the target angle is selected by sending pulses ranging from 544 to 2400 $\mu s$ for -90 to +90 degree respectively. In a *Haptic Servo*, the values are used to select what the material experience should feel like.

The intention behind this is to leverage the existing infrastructure built for servos. For example, to create a prototype with multiple *Haptic Servos*, one might use an Arduino and a servo shield[8]. The servo shield then correctly powers each *Haptic Servo*. The designer will then be able to control the software aspects of the material experience using the standard Arduino servo library. No special knowledge or special purpose tools are required to use or interface with the *Haptic Servo*.

There are two code examples shown in Appendix A, the first highlights how one might gradually scan through all output parameters on a single *Haptic Servo*. The second shows code that adapts the parameters of three haptic servos.

*3.3.4 Algorithm.* To create the control signal, the resolution of the ADC is divided into a number of discrete bins. When a sampled sensor value changes enough to enter a new bin, an AC pulse (i.e., audio signal) with a given waveform, duration, amplitude, and frequency is generated as shown in Figure 2. When the signal changes fast, pulses are generated rapidly. When the signal changes slowly, the pulses are generated proportionally slower.

The relevant variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range). The vibration specification of each pulse is determined by the type of waveform used, as well as the duration,

[6] https://github.com/PaulStoffregen/Audio
[7] https://github.com/sensint/Servo_Haptics
[8] such as those provided by Adafruit: https://learn.adafruit.com/adafruit-16-channel-pwm-slash-servo-shield

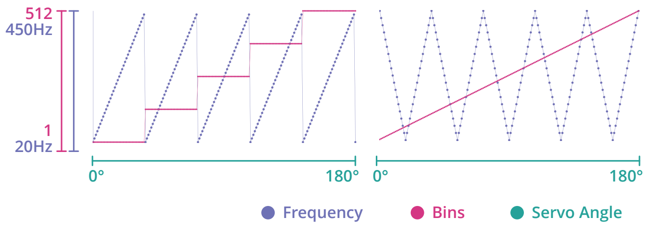



**Figure 5: Two models of parameterization considered when mapping angles to vibrotactile parameters. Based on these models, we created lookup tables used in the Haptic Servo firmware to select combinations of the vibrotactile parameters.**

amplitude, and frequency of that waveform. As the duration should ideally be coupled to the frequency to minimize clipping artifacts (we found that both a full period and a half period work well), duration can be derived from frequency. The amplitude should always be set as high as possible, to leverage the full available bit-depth of the *Haptic Servo*. However, the amplitude of the output signal can be adjusted with a physical potentiometer on the *Haptic Servo*. This leaves the frequency and number of bins as primary parameters to consider when designing a vibrotactile material experience.

*3.3.5 Selecting Material Parameters.* This strict adherence to RC servo standards creates an interesting point of friction. Pulse Width Control works well for a single parameter, such as position, however the parameter-space for generating the vibrotactile feedback is multidimensional. Here, we take inspiration from systems common in audio design, where a multidimensional device supports a user continuously morphing between presets using a single knob, as for example implemented in the Steinberg Sweet Spot Morphing DSP effects[9].

The simplest way of achieving this for two variables would be to choose an appropriate number of levels for these parameters (such that their product is 180 or less) and have each angle correspond to a unique combination. While this guarantees all possible combinations, it might be confusing for novices to explore as they will experience strong discontinuities in the experience as they increment or decrements the angle (Figure 5, left). An alternative would be to choose a dominant dimension, which linearly increases with the angle, and a supplemental dimension which oscillates back and forth as the angle increases (Figure 5, right). While this does not enable the same strict counterbalancing of values, it has the benefit that neighboring settings will always feel similar. This enables a novice to first roughly explore the experiences (e.g., with 10-step increments) and then, once they have found something that feels good, start fine-tuning it by exploring neighboring settings.

We chose to provide control over the frequency of the pulses and the number of bins. As the effect of frequency has been found to be more important than bin numbers for creating distinct experiences [61], we set frequency as the primary parameter and the number of bins as supplementary. While this dimension reduction process was necessary due to the strict adherence to RC Servo standards, we believe that this implementation is beneficial for playful exploration and serendipitous discovery of parameter combinations. In the firmware of the Haptic Servo, a lookup table is used to select a combination of frequency and bin number based on the value sent to the servo.

*3.3.6 Expert Users (I2C).* Even for RC servo motors, the limited communication ability of Pulse Width Control poses a problem for expert users. This has led to the development of 'smart' servos, such as the Dynamixel series[10]. These use a 4-wire connection and have a serial bidirectional interface next to the power leads. Similarly, for expert users, the *Haptic Servo* has an I2C port exposed. This enables expert users to set *waveform*, *frequency*, *duration*, *amplitude*, and *number of bins*, as well as request the current sensor value from the servo.

# 4 EVALUATION

We validate our design on different levels. As one of the primary technical goals of the Haptic Servo was minimizing system latency, the first evaluation is a technical characterization of system latency. Here we demonstrate that we meet our own technical design goals. The second evaluation explores the experiences which can be achieved with the haptic servo, and is to our knowledge the first study showing that a fixed signal creation algorithm can lead to qualitatively distinct experiences, based on input modality. Finally, in our third evaluation, we explore if the Haptic Servo does indeed support designers.

## 4.1 System Latency

*4.1.1 Overall Latency.* To establish the overall latency, we collected a set of 1000 measurements with an automated setup. A Teensy 4.1 (running at 600 MHz) was used to measure the time between a signal-change at the analog input of the Haptic Servo and the resulting response in the control signal generated by the Haptic Servo (powered by a Teensy 3.5 running at 120 MHz). Measurements were separated by a random amount of time to mitigate aliasing effects.

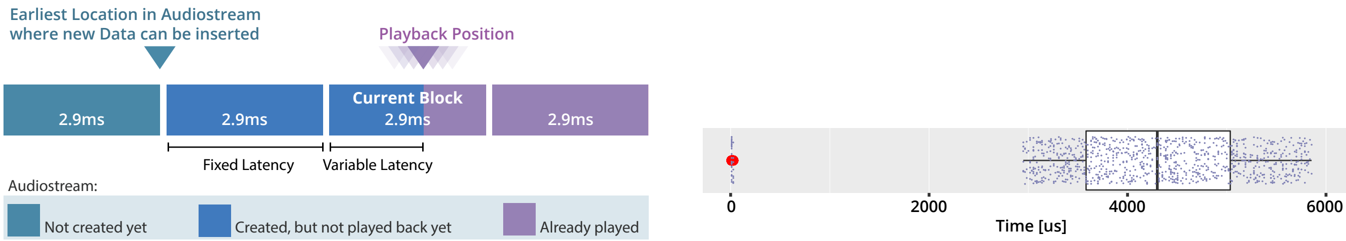
We found the delay times to be evenly distributed between 2.95 and 5.85 ms, with a mean of 4.35 ms and a standard deviation of 0.86 ms. Figure 6 shows a box plot of all measures, with jitter applied to better show the distribution. The raw results of these measurements are shared in our GitHub repository[11]. This result shows that the Haptic Servo's temporal properties are well below the 10 ms we established as our upper bounds. It should be highlighted, that this is not the overall system latency, but just those parts of the latency which we have influence over. In addition to the latency reported here, we must also consider that the actuator also has a rise time (time taken for the actuator to achieve its maximum output in response to a given input signal), which is in turn influenced by how the actuator is mechanically integrated with the rest of the prototype. For example, attached to an object that weighs 100g, the actuators we use require an additional 6ms to reach 10% of transient acceleration[12].

[9] https://www.youtube.com/watch?v=PzV9k0u0ou4

[10] http://www.dynamixel.com/

[11] https://github.com/sensint/Servo_Haptics

[12] http://tactilelabs.com/wp-content/uploads/2020/11/HapCoil_One_datasheet.pdf




(a) Example State of Audiostream when a Pulse is added.

(b) System latency measures (n=1000).

**Figure 6: The audio library processes information in chunks of 128 bytes, or 2.9 ms. When a bin change occurs, the playback position of the current block in the audio buffer could be at any position with equal probability, causing the variable part of the latency (Figure 6a). The following block is already being calculated in preparation for writing to the buffer. This causes the fixed part of the latency. As the block duration is 2.9 ms, the average latency is 4.35 ms and the frequency at which the highest possible latency oscillates is the inverse of a block duration, so 344.8 Hz. We measured the system latency (n=1000), i.e. sensor input reading to digital-to-analog converter output, where each point represents a single measurement with the automated setup (Figure 6b) supporting the above explanation. The red point indicates outliers.**

*4.1.2 Code Execution Times.* To better understand where the latency occurs, we analyzed code execution times. We found that these were negligible, summing up all code blocks to only 8.08 microseconds ($\mu s$) on average, with a standard deviation of 2.373 $\mu s$ over 1000 measurements. The bulk of both the time and variability was introduced by the analogRead() function, which required 7.55 $\mu s$ to execute. This highlights that the code executions times are negligible, compared to overall latency.

*4.1.3 Towards Optimizing Latency.* The current version of the Haptic Servo uses the Teensy Audio Library to generate control signals. In standard settings, the library uses a DMA channel with 256 samples, which is written to in blocks of 128 samples[13].

At any time, there is one 128-sample block which is currently being written to the I2S audio port, and one block which is currently being processed by the audio library. At a sampling rate of 44.1 kHz, each block is approximately 2.9 ms long. The delay time and variability we measured is consistent with a new pulse starting at the beginning of the following block. Theoretically we would then expect the delay times to be at a minimum of 2.9 ms (128 samples) and 5.8 ms (256 samples) at a maximum, with an average delay time of 4.35 ms and a standard deviation of 0.86 ms which exactly matches our measured values.

The first step towards optimizing the latency might be to write a library which bypasses the DMA, potentially writing directly to the I2S port, or implementing a ring-buffer. If required, further optimization might then be achieved by improving code execution times, in particular by directly reading and writing directly to the ADC registers, rather than using the AnalogRead() function provided by the Arduino environment [14].

## 4.2 Qualitative Experience Evaluation

As Haptic Servos' primary purpose is to create novel experiences, we conducted a qualitative study to explore how these experiences were perceived. We focus on the following questions:

- *Can a general purpose device for creating material experiences function across different implementations?* To understand if Haptic Servos can be used as the general purpose device they are intended to be, we analyze the experience of using a haptic servo with set parameters using three different types of human action as input.
- *How do isometric actions and isotonic actions differ when augmented with a Haptic Servo?* We provide additional experiential data by comparing isotonic (slider, knob) input to isometric input (pressure button).
- *How does the experience of action-coupled vibrations produced by the Haptic Servo unfold differently from the experience of continuous vibration?* Finally, to better understand the perceptual mechanism which Haptic Servos make use of, we compare interactions using Haptic Servos to interactions with continuously vibrating objects.

To address these open themes, we chose to conduct micro-phenomenology inspired elicitation interviews. These have previously been used to identify structures in experiences [41] in general, as well as the exploration of haptic illusions [63], and the experience of vibration [35].

*4.2.1 Experiment Setup.* For this study, we used a Tangible UI (TUI) setup further outlined in Section 5.1. The TUIs use either pressure-buttons, sliders, or rotary knobs as interactive elements (Figure 7). These elements lead the user to perform different actions: rotation and displacement for the knobs and sliders respectively, and push on the pressure-buttons. This also enables a comparison between isotonic (sliders, knobs) and isometric (pressure button) actions. Each TUI element is connected to a Haptic Servo. To ensure that the difference between elements is purely the type of action that the user performs, the Haptic Servos were set up identically for each task (100 Hz, 50 bins). The continuous comparison signal was a 100 Hz sine wave generated by a Teensy 3.5.

*4.2.2 Participants.* We invited six HCI researchers (3 male, 3 female – aged 24 to 30) to participate in a study that explored the experiences created by Haptic Servos. The participants were of a

[13] see also: https://github.com/PaulStoffregen/cores/blob/master/teensy3/AudioStream.h
[14] Pedro Villanueva provides examples on GitHubhttps://github.com/pedvide/ADC

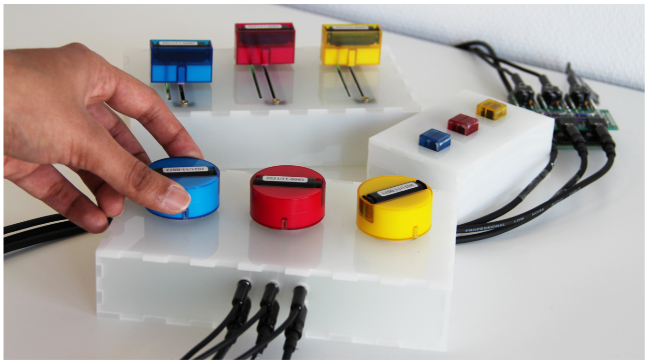


**Figure 7: Three forms of tangible user interfaces (rotary knob, sliders, buttons) that are augmented with vibrotactile feedback. A user is interacting with the rotary knobs.**

variety of nationalities (Turkey, India, Colombia, Italy, Germany, and the UK) but were all residing in nearby cities. Three participants were expert hapticians, while the other three were HCI graduate students.

*4.2.3 Task.* Each participant was provided with two of the three devices (Figure 7). For each device, participants were first asked to interact with a non-actuated TUI element. Then they interacted with an element which was vibrating continuously at a constant frequency as a control condition. At this point, the first micro-phenomenological interview was conducted. As the test condition, participants were then asked to interact with a Haptic Servo generating motion-coupled vibration, followed by a second micro-phenomenological interview. After a 5-minute break, this process was then repeated with the second device, for a total of four interviews. This was followed by a short semi-structured interview in which participants were encouraged to speculate about causation of the experiences and make comparisons to other experiences they have had. The entire process took approximately one hour per participant and was audio-video recorded for later transcription.

*4.2.4 Interviews.* As the interactions with the tactile feedback occurs quickly, many details are overlooked at the time of experience [38]. To gather fine-grained pre-reflective detail of how the experience unfolds, we used a method inspired by micro-phenomenological interviews [39][15] to bring the participants back into an evocation of a specific moment of the experience and guide them through each step as it occurs. In effect, this slows down the experience and allows the participant to examine aspects of their interactions as they occurred in the moment of experience. From the interview, we then extracted the diachronic (chronological events during the experience) and synchronic (dimensions of experience and sensorimotor perception during a particular moment) aspects of the participants' experiences [40].

*4.2.5 Analysis.* The interviews were transcribed at the level of utterances and experiential structures were analyzed [64]. First, question and answer pairs were numbered and any satellite dimensions – that is, recollections which deviate away from the specific evoked experience – were identified to be ignored in analysis. Then the structures of the experiences and commonalities between the experiences were identified. Finally, C. Reed and N. Sabnis collaboratively conducted an inductive, reflexive thematic analysis [6] of the entire interview to determine salient connections between participants' perceptions and interactions [4, 5].

## 4.3 Findings of Micro-Phenomenological Analysis

We found that the experiences unfolded systematically and involved two key phases: *exploration* followed either by *dissociation* of vibration and action for continuous vibration or *integration* of vibration and action when using the Haptic Servo. This was constant within interactions done by the same participant and across participants. Figure 8 presents a selection of initial interactions with each of the devices. These show the diachronic temporal structure of the interaction, together with the synchronic perceptual dimensions of the experiences. Here, we show the structure of P2's interaction with sliders and buttons in each vibration condition as they relate to P4's interactions with the knobs, as a representative sample of all interviews.

*4.3.1 Interacting with Continuous Vibration.* The experiences described start with the initial perception of the vibration; here, users note the quality of the vibration. In continuous vibration interactions, this leads to a sense of dissociation between the vibration and TUI element: The user tests various motions and tries to identify the interaction. Because there is no connection between the user and the vibration of the device, this can lead to a mismatch or confusion. P2 describes that there is a contrast between the smoothness of the device and the "buzzing" of the vibration. Generally, interactions with the continuous vibration devices are short and participants disengage quickly. Participants describe the vibration as coming from the device itself. The final understanding of the interaction generally consists of the user perceiving that the element is vibrating, but not doing anything else.

*4.3.2 Interacting with Haptic Servos.* After a short exploratory action, which typically leads to an "Aha!" moment, a connection between vibrotactile experience and the action is made. This results in an integrated experience combining both the tactile and motor elements. The participants were then able to identify the quality of the perceived "pulse" (a "crunchy" or "snapping" sensation). This was followed by lengthier and more repetitive action: participants move over two pulses, varying their speed or their pressure, and run to the extremes of the device's range to determine where these pulses are placed. With the Haptic Servo-controlled button, P2 experiences a sensation of something being loose underneath. They feel the button moving around on top of whatever this is, resulting in a crunchy or sticky feeling. For P4, the Haptic Servo-controlled knob felt like there was a set of elastic threads underneath. Their rotation caused the threads to catch and then break, resulting in an opposition to their movement. They also described this as being a "sticky" texture. The feedback is experienced as a result of movement of the hand or finger, rather than the device itself, and

[15]The interview was led by C. Reed, who has completed micro-phenomenology interview training and is in the process of being certified in the discipline

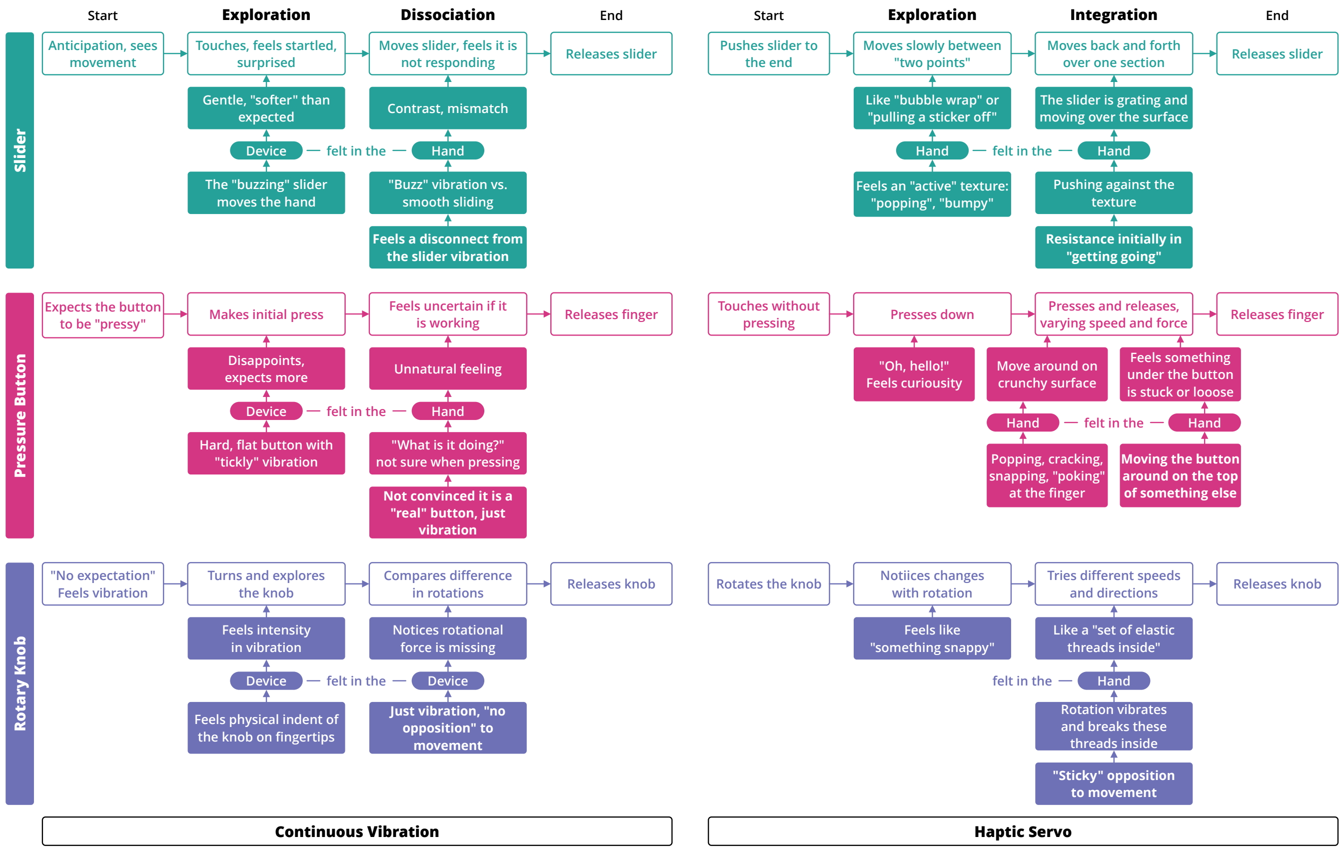



**Figure 8: The phases of exploration and identification (either as dissociation or integration) during interaction with sliders (teal), buttons (magenta), and knobs (purple), revealed through micro-phenomenological interviews. These phases are consistent through experiences with the different sensor elements and among different participants.**

is associated to moving over or against an object or texture, usually felt as being under the device or inside the box housing the devices.

*4.3.3 Reflections on Micro-Phenomenological Analysis.* These experiences demonstrate that Haptic Servos are able to provide consistent experiences across individual users and TUI elements. Although each user will experience nuances unique to their own perception, interaction with the vibrotactile feedback is structured similarly. Continuous vibrations provide an experience of information separate from human input, potentially making them useful for passive interaction (e.g., system alerts). Action-coupled vibrations provide an experience of relationship and connection between user and ui-action. This is potentially useful in conveying a sensation of control, and dialogue with the system in return (e.g., tuning parameters). The phases of each interaction type followed the same general structure, even for different modalities (i.e.: isotonic and isometric) demonstrating how the Haptic Servo functions as a general purpose device for different implementations.

## 4.4 Findings of Thematic Analysis

The thematic analysis supports the observations from the micro-phenomenology inspired interviews. We use four main themes to describe participants' perceptual experience during the interaction: Interaction Phases, Mapping Perception, Feature Perception, and Sensory Perception (Table 1).

*4.4.1 Interaction Phases.* Participants' experiences occur in a structure as described through the micro-phenomenological interviews: participants first describe their expectation based on the visual look of the elements and their initial approach to explore them. We again see the two major phases of exploration through repetition of particular behaviors to determine interaction and connections to their action. Participants are successful in mapping aspects of their gesture to the haptic feedback with motion-coupled vibration. Otherwise, there is often a mismatch, which results in confusion. Perception of an input-output path is missing: *"[With this vibration] there's something wrong with the button, or something wrong in the way I'm holding it. So I was confused whether that is an actual feedback. Or I am probably not doing it correctly"* (P3). These Interaction Phases are determined and experienced through Mapping, Feature, and Sensorimotor experience, which help to establish a connection between movement and action:

*Mapping Perception.* This analysis also revealed several additional details about the perception of the interaction from a reflective

**Table 1: The four main themes of participants' perceptual experience during the interaction with the Haptic Servos.**

| Theme | | General Description |
|---|---|---|
| Interaction Phases | **Expectation** | Based on previous experience or the characteristics of the element (shape, visible vibration, etc.), participants form expectations for the interaction. |
| | **Exploration & Repetition** | Expectation drives initial contact with the element: participants explore the elements with different speeds, pressures, and other input to uncover the interaction. |
| | **Connection & Mapping** | Some interactions yield connections and participants are able to make mappings between their actions and the resulting tactile feedback. These are typically directional or functional connections. |
| | **Confusion & Mismatch** | Other interactions lead to confusion: participants are sometimes unable to perceive a relationship between their action and the feedback. |
| Mapping Perception | **Association of Interaction** | Participants associate the interaction as they perceive it with other experiences, including to material properties and textures, different triggers, other devices and objects, and other sensory experiences. |
| | **Perceived Functionality** | Participants often directly are able to understand the functionality of the interaction and correctly identify the Haptic Servo implementation. |
| | **Emotion & Reaction** | The interaction is often paired with an emotional response: confusion occurs with mismatched input and output and intrigue with mappings and connections |
| Feature Perception | **Comparison of Feedback** | Assessments are made in comparing elements and feedback types. Participants are able to connect different elements and make interaction judgements for one element based on the context of another. |
| | **Feedback Type** | Participants divide their perception into two large categories: vibrations and pulses. These are distinct perceptually and have different qualities. |
| | **Feedback Parameters** | Participants perceive several features which make up the feedback. These features include strength, frequency, proximity, friction, timing, force, texture, and activeness. |
| Sensory Perception | **Multi-Modal Interaction** | Participants understand their interactions through a multi-modal sensory-based interaction. This is done through visual, auditory, and kinesthetic images and perceptions. |
| | **Feedback from Elements** | Participants identify that the feedback is caused by and comes from the element itself. The element moves independently of the user's body and may cause movements or reactions for the user. |
| | **Feedback from the Body** | Participants also identify cases where the feedback is generated by the body or its movement. The element moves in response to movement or the user feels they are moving the element over a surface. |

standpoint. Participants were able to perceive mappings clearly when they existed, referring to physical objects, textures, and other haptic feedback from their day-to-day life to describe them. For instance, there were associations of "a slightly loose key on your keyboard" (P2) or tracing across a "wavy surface" (P6). When a mapping was present, participants commented that the interactions were "intriguing" (P2) and "pleasant," (P4) as the feedback encouraged exploration of movement. For continuous vibration and control elements where there was no feedback, participants initially worried that they were not interacting with the device correctly or that it was not on, before ultimately concluding that the vibration must either be inactive or non-present.

*Feature Perception.* Participants associated a number of relevant features with the feedback they experienced, including specific parameters of the signal (frequency, timing) and other more subjective features such as activeness, strength, and force. For instance, P5 describes noticing low frequency *"bass"* vibrations coupled to motion as feeling *"like you're dragging on the thing [slider]"*. Textures and friction were associated with the action coupled vibrations, yielding consistent feelings of friction and of "sticky" or "crunchy" elements. Overall, participants referred to continuous actuation as "vibration"; for action-coupled interaction, participants exclusively referred to the feedback as a pulse, trigger, or texture element (e.g., P6 describes "bumps"), rather than vibration.

*Sensorimotor Experience.* Together, these subjective analyses reiterate that users perceive feedback differently depending on how it is coupled to their motion. We find that this experience is consistent when using Haptic Servos, regardless of their implementation element. In continuous vibration, users perceive vibration and independent elements which are situated away from the body in a distal experience: the element itself was understood to be vibrating and acting independently of the body. In motion-coupled vibration provided by Haptic Servos, users perceive a proximal interaction wherein the element itself does not vibrate, but rather responds as the user moves it over a surface or against something resistant. This feedback is instead seen as a result of the body, caused by movement, and not the element itself. The perception of the vibration is so closely linked with movement, that it can even be experienced as happening within the body itself. P6 describes this as feeling *"it was kind of as if it was my joints, feeling that it was very local,"* while P1 describes feeling as if the vibration was internal, *"touching in my tendons."* Both forms of feedback provide different and unique cues to users; however, with Haptic Servo implementations, we determine that the overall quality and structure of experience is consistent among different sensor implementations used in interaction.

*4.4.2 Reflections on Thematic Analysis.* The thematic analysis therefore supports the findings of the micro-phenomenological inspired analysis. We demonstrate here that the stages of interaction, and how the users perceive their action's effect on the feedback, shape experience. As well, associations with lived experience and the different parameters set within the Haptic Servo's rendering help to shape the interaction. The implementation of the Haptic Servo in different form factors (knobs, sliders, buttons) shows its versatility in creating unique isotonic and isometric interactions; participants are subject to the same kind of signal in relation to the body, but the feedback feels more like a compliance and reduction in counter-force when pressing into the isometric buttons (e.g., a loose keyboard key or something crunchy) and more of a texture or addition of counter-force when using the isotonic slider (e.g., bumps and waves).

Returning to our research questions outlined in 4.2, this evaluation and demonstrates how the Haptic Servo is able to convey distinct interactions through isotonic and isometric actions using continuous and action-coupled feedback. Exploration of the initial vibration perception demonstrates the distinct phases in participants' interaction experiences, understanding, and connection to the devices. Although the interaction with different elements have slightly different connotations and expectations for interaction behavior, the Haptic Servo is able to render a consistent feedback experience.

## 4.5 Workshop: Prototyping with Haptic Servos

We believe that haptic design research benefits from shared platforms and standards. For this reason, we intend to not only publish our *Haptic Servo* design, but also actively work towards the adoption of our platform by other research groups and designers. To investigate if *Haptic Servos* can be used for rapid prototyping of material experiences, we conducted a workshop-style study, which is one of the commonly used approaches for evaluating toolkits and prototyping platforms [27]. While the previous exploration was designed to address specific theoretical questions we had about how *Haptic Servos* servos mediate experience, this workshop was primarily motivated as a sanity check, to see if and how others would use our system.

There were five participants in the workshop, three of whom are currently pursuing their PhD in Haptic Feedback design, and two their PhD in HCI for VR. None of the participants work with low-level electronics in their day-to-day research, instead focus on developing for platforms such as Ultrahaptics or Generic VR controllers. The workshop was video-recorded for our own reference. Participants all came from the same research group. This research group was selected as members of the group had expressed interest in such technology.

- **P1:** PhD student in VR and HCI, basic Arduino knowledge, no haptic feedback experience.
- **P2:** PhD student in VR and HCI, psychology background, basic Arduino knowledge, no haptic feedback experience
- **P3:** 3rd year PhD in Haptics for HCI, experience with Bela and Beagleboard, but not in low level control of haptics.
- **P4:** 1st year PhD in Haptics for HCI, basic Arduino knowledge
- **P5:** 3rd year PhD in Haptics for HCI, experience with electronics prototyping, but not in low level control of haptics.

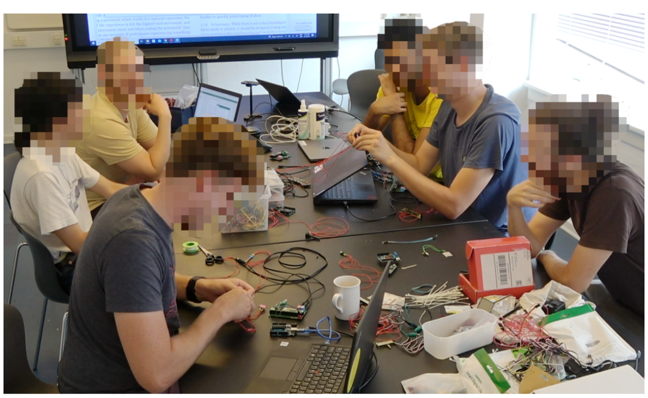


**Figure 9: Frame from the video recorded during the workshop**

Participants were instructed to set up basic haptic feedback systems, to evaluate whether Haptic Servos would be useful in their own research, and to assess if the design was intuitive for a new user. Participants received a brief explanation of the system using Figure 4 and Figure 3 of this paper for visual explanation. They were then each handed a Haptic Servo as well as a sensor of their choice. We provided rotary and linear potentiometers, force sensitive resistors, and flex sensors for the participants to explore. All participants were able to set up a basic system in in 8 to 12 minutes, including instructions. Participants were then asked to adjust the parameters of the Haptic Servo using an additional Arduino and the servo library. Here, participants who already had Arduino installed required ∼10 minutes, while those who had to first install Arduino took ∼20 minutes. This shows evidence, that a new user can rapidly create prototypes using Haptic Servos.

Regarding customization of feedback parameters, P1 commented that *"oh cool, the different values feel ... distinctly distinct"*. However, workshop participants were not particularly worried about specific mapping of servo values to parameters, it was enough that they could tweak the experience. Instead, they were more interested in experimenting with different sensors and how they affected the resulting experience. Participants also spent time exploring how the sensation changed with different sensors and with ways of interacting with the sensors, for example attaching a flex sensor to the body, as compared to using the flex-sensor as a type of whisker. This highlighted that Haptic Servos do indeed support playful exploration, as we intended.

Generally, the Haptic Servos performed as expected, and participants found them useful. For example, P4 stated that *"This would be helpful for setting up a quick prototype for trying out an idea"*. A simple improvement suggested by participants was adding an LED to indicate if the Servo had sufficient power. A problem area identified was that the debounce algorithm used in the version of the firmware used for the workshop performed well for some sensors and less well for others, leading to glitches. This suggests that future versions of the firmware will require more careful signal conditioning. This might be implemented with a calibration procedure on startup, or after connecting a sensor.

After concluding the workshop, two of the Haptic Servos were given to P4, as they intend to use them for an upcoming research project.

*4.5.1 Retrospective Insights & Limitations.* We had many internal discussions about the design of the pulse-controlled protocol and how this abstracted away the parameter selection process. We anticipated this as a potential friction point, expecting to update the system based on user feedback. In practice though, none of the participants expressed further curiosity on the specifics of the parameter mappings. We believe this had two reasons. First, it did indeed support the type of playful exploration we were aiming at. Second – and this highlights a potential limitation of the system – participants assumed that they would only use *Haptic Servos* for prototyping, but not for a final design.

A second potential limitation is highlighted by the strong effect of sensors on the experience. As reported, participants were particularly interested in exploring the experience with different sensors. This is because each sensor had its unique output response curve, some linear, some exponential, some arbitrary. This highlights that the sensor choice when using *Haptic Servos* is not neutral, but an important part of the design process. Participants enjoyed this, during our session, however it highlights that *Haptic Servos* might benefit from additional signal-conditioning. This might be designed to work in harmony with a future calibration procedure at startup.

## 5 HAPTIC SERVOS IN USE

To better explain how a Haptic Servo operates, and to showcase some opportunities they provide, we designed three demo applications as shown in Figure 1. Please also refer to our video-figure. Our video shows these in action, together with a sonification of the tactile feedback. We also mention our follow-up research where haptic servos were used for tactile augmentation.

### 5.1 Tangible UIs

Experts working with digital image, video, and audio editing tools often use additional tangible control devices. These are particularly useful when, for example, editing more than one parameter at once. However, depending on the specific application or menu currently in focus, the physical controller might switch its function. Using Haptic Servos, the device can easily be set so that each function has a fixed material experience, so that the user immediately feels what part of the program they are interacting with. We implemented three tangible controllers, each using a different sensor and input modality but all controllers use the HapCoil-One[16] (a wide-bandwidth LRA by TactileLabs) to provide vibrotactile feedback (see Figure 7 and Figure 1 B). We used these devices for our qualitative study (see Section 4.2). In a rapid prototyping context, such a setup could easily be implemented using an off-the-shelf servo-shield for Arduino for setting up power and communication leads using the Pulse Control port. A designer could then set the different experiences using the Arduino servo library.

### 5.2 Body Feedback

The second example highlights that not only the experience of other materials can be modified, but also the experience of one's own body. Here, we applied a thin film flex-sensor to the finger as well as a haptic actuator (Taptic Engine). Connecting both to a Haptic Servo adds additional cues to the finger movement. Such mechanisms could in the future be used to enhance one's proprioceptive experience, for learning fine motor skills or for bio-feedback and self-regulation. Unconscious actions such as breathing could be made more accessible [43, 62] or even shareable between people [12, 15]. Here we chose to use a Taptic Engine as the actuator, due to its small form factor, which also highlights the general purpose nature of the Haptic Servo (see Figure 1 C).

### 5.3 Industrial Design

Synthesizers and digital instruments are controlled with a MIDI controller. As this device creates no sound of its own, the primary considerations when assessing the quality of such a device is the tactile behavior of its keys. In our third example, we show how a budget MIDI controller can be augmented by a Haptic Servo to convey a more pleasing tactile experience. This augmentation provides opportunity to design learning applications which use altered material properties as an additional communication channel. Similarly, the tactile experience can be designed to provide additional feedback on key-travel, pressure or aftertouch (see Figure 1 D).

### 5.4 Application in Research

There are currently multiple ongoing research projects building on Haptic Servos. This includes work on tactile symbol design, where we use the tangible UI setup presented here as a tool to enable rendering of motion-coupled and continuous vibration for broadening the tactile symbol design vocabulary [46]. A branch of Haptic Servos is also used for the design of shoes for tactile augmented reality to generate rich experiences of walking on different surfaces [71].

## 6 DISCUSSION

Re-framing motion-coupled vibrotactile feedback, designed as a servomechanism, opens up a number of doors. Haptic Servos encapsulate many of the more complex aspects of creating vibrotactile material experiences, which allows both expert and novice haptic designers to focus on the actual design task, rather than implementation details. Modeling the interface closely after regular RC servos further supports this, as off-the-shelf hardware and software can be used. This is not only beneficial in easily sourcing parts, but also enables novices to find documentation and instructions faster, as tutorials and instructions on interfacing with regular servo motors largely apply to Haptic Servos as well. Finally, Haptic Servos might easily be integrated in existing ecosystems for supporting rapid prototyping, such as [14, 30].

Haptic Servos not only make the process easier, but also provide new design opportunities due to their scalability. As our applications highlight, Haptic Servos can be a valuable industrial design tool, for making products such as MIDI keyboards feel more pleasing, as well as an interaction design tool for making multipurpose input devices more intuitive.

### 6.1 Experiences Created with Haptic Servos

Not only do we present a new device for supporting vibrotactile feedback design, our evaluations of *Haptic Servos* also provide new insight into tactile experiences:

*6.1.1 Proximal vs Distal.* Our qualitative analysis of the resulting experiences reflects the distinction made between proximal and distal vibrotactile perception. Continuous vibration is experienced as originating from the device, which mirrors how we described

[16]The HapCoil-One is also known as Haptuator Mark II-D (http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/)

distal vibrotactile perception. Once synchronization between action and vibration is achieved and understood by the user, the perceptual mode switches. Users speak of the vibration being in the hand or caused by the hand. This matches how we think of proximal vibrotactile experiences. It should be highlighted that this switch is not a matter of degree. Much like a bi-stable image (such as the rabbit and duck illusion[17]) is experienced as either one or the other mode, but never both concurrently, so does the perception of the vibration switch between the distal and proximal mode.

*6.1.2 Body Based Feedback.* As the tactile actuation by a Haptic Servo is perceived as integrated with the movement, rather than external, this opens up interesting opportunities for movement augmentation from a motor control perspective (c.f. [47]). In motor control, researchers typically distinguish, feedback provided by trainers or technologies (*augmented feedback*) and feedback provided by one's own body (*intrinsic feedback*). As the feedback provided by Haptic Servos is experienced as originating from one's own body and actions, there is an opportunity to provide augmented feedback which is experienced as proximal, intrinsic feedback with Haptic Servos. This opens up exciting new applications for learning and motor control technologies.

*6.1.3 Perceptual Mechanisms.* Our analysis showed that, to a large extent, the experiences resulting from interaction with Haptic Servos are dictated by the specific implementation and what type of coupling between action and tactile stimulation this creates. However, while the experiences created by interacting with Haptic Servos can vary based on the specific implementation, in our analysis we found that the structure of the experience is consistent. This highlights that the experiences created share the same perceptual mechanisms, which are addressed by the Haptic Servo.

The specific structure of the experience – the initial exploratory phase followed by an integrated perception of action and vibrotactile actuation – does also highlight an experiential limitation of our current implementation. While the Haptic Servo creates an interaction which is *like* a material experience and the resulting experience has the resemblance of a material experience, it remains an imitation. Participants require an initial exploratory action, before the experience of action and the vibrotactile actuation are integrated. After the initial action and before the integration phase, we observed that the participants experienced something like an *"Aha moment"* which enables the perception to switch from the distal to the proximal mode. We find this observation fascinating, and hope to explore it in more detail in the future. It is currently not clear if this is a general perceptual mechanism or a limitation of Haptic Servos.

## 6.2 Implications for Design

As we highlighted starting out, the tactile properties of an object are often amongst the first cues we use to judge the quality of an engineered object. For example, the tactile response of a keyboard or the feeling of a laptop hinge are important factors in assessing the quality of their industrial design.

Haptic Servos enable new ways of exploring such tactile features: Similarly, to how a 3D render might be created using different colors, now a physical prototype can be implemented and designers can explore different material properties post-hoc. For example, one might 3D print a generic object, and then explore how it is experienced with various material properties.

Haptic Servos also change how we can think about the materials our design consists of. As both sensor-behavior and user actions influence the resulting experience, the sensor choice becomes an important design decision. The designer can experiment with sensors that have different response curves, as a further dimension of signal design. This means, the sensor, quite literally, becomes a design material, as do the actions that the device affords.

## 6.3 Limitations and Future Work

*6.3.1 Hardware.* The main limitations of the current implementation of Haptic Servos is that it does not yet have the desired form-factor we are aiming for, as the current iteration of the Haptic Servo is a proof-of-concept device. It is implemented as a Teensy shield for convenience. However, the Teensy has many features which a Haptic Servo does not need and is the most expensive component (~ 47 Euros) in the haptic servo (~ 63 Euros). Once we are satisfied with the feature set of the Haptic Servo, we intend to search for a cost-efficient alternative, on which we can optimally implement the required features with a minimal footprint. This will allow us to design a device which – like a servo-motor – is not significantly more bulky than the actuator alone. Once such a device is implemented, it will also become obvious that to integrate multiple sources of vibration, one would simply use multiple haptic servos.

*6.3.2 Software.* There are also limitations on the software side. The current implementation uses the Teensy Audio Library, again for sake of convenience. This library enabled us to experiment with initial implementations, and will allow others to easily build on our work (for example, by experimenting with alternative waveforms, or with the ADSR object provided by the library). A drawback of the library is that the latency and jitter with regard to synchronization of pulses to analog signal changes is higher than necessary. In the future, we intend to provide either a branch of the audio library or a new library optimized for tactile feedback.

*6.3.3 Knowledge Transfer.* With regards to usability, our workshop highlighted that researchers perceived Haptic Servos as a tool for early prototyping, but not for building complete systems. This highlights that we need to further work on making Haptic Servos more accessible and their features more transparent. Currently, we use Haptic Servos as the core of multiple systems and experiments in our research group. Further non-technical improvements on the usability and accessibility will be required for others to adopt Haptic Servos in the same way. However, through open sourcing our work and engaging in dialogue by means of workshops, demos, and publications we intend to ellicitate the necessary involvement of others to collaboratively achieve this goal.

# 7 CONCLUSION

In this paper, we highlight that haptic rendering systems can be thought of as servomechanisms. We implemented such a servomechanism for creating vibrotactile material experiences called Haptic

[17] https://en.wikipedia.org/wiki/Rabbit-duck_illusion

Servo. Our implementation is designed to easily integrate with off-the-shelf prototyping systems, as it adheres closely to the standard interface of RC servos. This enables expert hapticians, designers, practitioners and novices easier access to designing vibrotactile material experiences. As Haptic Servos are self-contained and can create a signal automatically – that is, without continuous monitoring of a control device or user intervention – they can be rapidly deployed in versatile applications. We demonstrated this by using Haptic Servos in a tangible UI, an on-body feedback mechanism, and an augmented keyboard. Using the tangible UI, we conducted a qualitative study, which revealed that, from a perspective of subjective experience, the general purpose of Haptic Servo performs as desired. We also highlight that the type of action that is augmented by the Haptic Servo influences the resulting design: isotonic actions are experienced as having added counter-force, while isometric actions are experienced with reduced counter-force. Finally, the workshop with five researchers demonstrated that users new to haptic servos were able to set up a basic rendering system within 10 minutes.

This opens up new doors for thinking about tactile design. Using Haptic Servos, designers can experiment with different material properties, similarly to how designers might render a design in different colors. Our work points towards a new direction for vibrotactile material design, but there is much more to explore. To support others in building on our work, all code and circuits are open source, and we look forward to supporting others in branching, remixing and copying our designs.

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# A EXAMPLES FOR CONTROLLING HAPTIC SERVOS

Listing 1 demonstrates how to cycle through the Haptic Servo’s material experiences (5 s for each experience) using the Arduino servo library. This code can be flashed on any Arduino compatible microcontroller. This microcontroller connects to the Haptic Servo using a standard servo cable (GND, VCC, Signal – see Pulse Control in **Figure 3**).

```
#include <Servo.h>

// create an instance of the Arduino servo library
Servo haptic_servo;
// define the pin where the haptic servo is connected
static int servo_pin = 9;
static int max_angle = 180;
// set the initial value for the configuration
int current_angle = 0;

void setup() {
  haptic_servo.attach(servo_pin);
}

void loop() {
  // set the haptic servo's configuration
  haptic_servo.write(current_angle);
  if (current_angle == max_angle) {
    // reset the configuration position
    current_angle = 0;
  } else {
    // increment the vibration config (servo angle)
    current_angle++;
  }
  // wait for 5 seconds
  delay(5000);
}
```

**Listing 1: Cycle through the material experiences of a Haptic Servo.**

Listing 2 demonstrates how one might connect three Haptic Servos to a microcontroller (e.g., Arduino). In this example we assume that there is a tangible UI with three UI elements, such as sliders, potentiometers, or buttons. The designers have, through tweaking and experimentation found a configuration (config_A) that stands out compared to another (config_B). This can be used to tactually highlight a single UI element. In the current application each UI element is highlighted for a minute, sequentially. In a final implementation one might make such highlights contextually relevant.

```
#include <Servo.h>

static int hs_num = 3;
// create 3 instances of haptic servos
Servo hs[hs_num];
// define the pin where the haptic servos are connected
static int hs_pins[hs_num] = {9, 10, 11};
// 100 bins at 250 Hz, feels like bright but deep press
static int config_A = 167;
// 10 bins at 40 Hz, feels dull and bumpy
static int config_B = 42;


void setup() {
  for (uint8_t i=0; i<hs_num; i++) {
    // attach haptic servos to GPIO pins
    hs[i].attach(hs_pins[i]);
    // and set vibration config (servo angle)
    hs[i].write(config_A);
  }
}

void loop() {
  //use the first haptic servo as tactual highlight
  hs[0].write(config_A);
  hs[1].write(config_B);
  hs[2].write(config_B);
  // wait for 60 seconds
  delay(60000);

  //use the second haptic servo as tactual highlight
  hs[0].write(config_B);
  hs[1].write(config_A);
  hs[2].write(config_B);
  // wait for 60 seconds
  delay(60000);

  //use the third haptic servo as tactual highlight
  hs[0].write(config_B);
  hs[1].write(config_B);
  hs[2].write(config_A);
  // wait for 60 seconds
  delay(60000);
}
```

**Listing 2: Use multiple Haptic Servos at once with individual material experiences (vibration configurations).**