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Perception-centric design considerations for low-cost haptic emulation in prototypes

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Abstract

User-testing is crucial in modern product design. The perception-centric design philosophy aims to cut costs and improve responses to low-cost prototypes by including aspects like thermal properties, texture, weight, sound, and haptic feedback. This paper introduces a set of considerations for integrating low-cost vibrotactile haptics into prototypes. Derived using an action-based research process, it addresses product characterisation, actuation, control, and integration. Multi-sensory prototypes in early-stage design could be vital for the sustainable prototyping of the future.

Keywords: prototyping, haptic interactions, design activities, user experience, user-centred design

1. Introduction

Every product design process will utilise some level of prototyping (Pahl et al., 1984). The 2020 UNESCO International Monetary Fund report estimated annual global research and development spending to be $1.7 trillion (International Monetary Fund, 2023; UNESCO, 2020). Much of this was allocated to user testing, requiring the creation of multiple expensive, high-fidelity models for accurate feedback (Maguire, 2001). Recent advancements in reconfigurable prototypes have demonstrated the potential for reducing expenditure while increasing iteration capability (Kent et al., 2021). However, this is only valuable if the prototype faithfully represents the design without negatively impacting user testing (Felton et al., 2020). Therefore, a compromise exists between prototype realism and minimising expenditure, either through reconfigurability or perception-centric design. Reconfigurable models could replace dozens of physical prototypes, and open up the possibility for end-users to collaboratively navigate the design space with designers, facilitating richer feedback (Mathias et al., 2019). Perception-centric design aims to maximise user engagement, realism, and economisation by understanding where best to focus efforts; either reducing the fidelity of non-contact/low-impact elements or increasing the fidelity of high-impact elements (Cox et al., 2022).

Haptic feedback is often overlooked in early prototyping, especially when using virtual methods. It is often later in the design process where it is considered but by this point changes are restricted due to costs and time constraints. Therefore, defining and recreating the user experience of a product earlier in the design process could vastly improve the product design process.

This paper details the development and use of a novel method for low-cost reconfigurable active vibrotactile haptics for perception-centric prototyping. The contribution of this paper is a set of considerations for future designers looking to develop their own low-cost vibrotactile prototypes, developed from the key findings of this action-based research process. Furthermore, an evaluation of the value proposition and aims for future developments and research are discussed.

2. Background

Experimental psychologists first started documenting and categorising human sensation in 1830 (Gibson, 1968), with the first references to ‘haptics’ (concerning the sense of touch) recorded in the late 19th century (Grunwald, 2008). The emergence of digital computing has led to a new wave of research in the mid-20th century, aiming to improve interactions between humans and machines through haptic responses and feedback (Stone, 2001). The initial focus in the development of haptics was to enable teleoperation and telepresence (Draper, 1994), but recent advancements are seeing significant application to virtual environments and product design scenarios, such as prototyping (Kern et al., 2023).

2.1. Physiology and cognition of touch

Figure 1 shows the components of a haptic experience. There are two key categories: cutaneous, relating to the receptors in the skin, and kinaesthetic, relating to receptors in muscles, tendons and joints (Lederman and Klatzky, 2009). This paper focuses on the vibrotactile response, a subset of cutaneous.

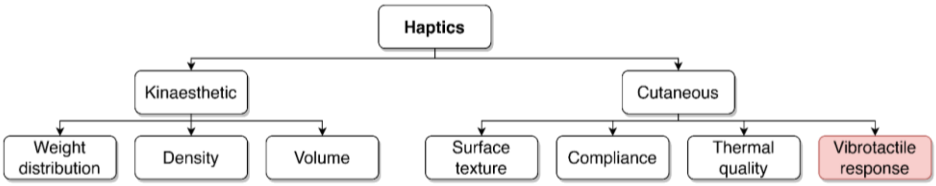

Figure 1. Components of haptics (Lederman and Klatzky, 2009; Sundaram et al., 2019)

Qualities of a perceived object (such as texture, weight, hardness, volume, and thermal properties) are inferred primarily from haptic interactions, processed from several different sensory receptors. Each receptor has different detectable frequency bandwidths suited to different perceptive actions such as feeling texture (<10Hz), and stroking/fluttering (<800Hz). Receptors are placed at varying depths within the skin with a range of spatial resolutions (Huang et al., 2022). To add further complexity, haptic and auditory senses can interact at pitches above 100Hz (Bernard et al., 2022); and all perceptual systems theoretically carry equivalent weighting (Gibson, 1968; Yantis, 2014). This is however misleading, as specific senses provide varying amounts of information depending on the stimuli. This is often modelled using multimodal distributions (Helbig and Ernst, 2008).

Beyond the sensory level, different people may interact in significantly different ways with the same object. Therefore, within the field of design, the sense of touch is arguably the most difficult form of user interaction to model and design for. It is also one of the most important user interfaces to consider as most designed products involve touch-based interaction through ergonomic elements.

2.2. Haptic technology

There are relatively few examples of prototypes that afford configurable haptic experiences, though interest in this field is growing. Currently, examples are limited by the technological capability of current haptic effectors (Huang et al., 2022), however there are a myriad of potential new methods being trialled. These include vibrotactile and electrotactile techniques used either on the back of the finger (Mazursky et al., 2021), in a glove (Sundaram et al., 2019), or on the fingertip skin (Withana et al., 2018). Haptic feedback for keyhole (robotic) surgery has also long been pursued by medical engineers as it has proven to significantly improve surgeon performance (Overtoom et al., 2019; Stone, 2001). Kern et al., (2023) discusses the growing use of haptic technology in product design, to improve the immersion and realism of prototypes and virtual environments, and improve user feedback. However, this field is still young, and requires high financial and resource costs to implement in real scenarios.

2.3. Aims and methodology

There exists some taxonomical literature outlining existing haptic technologies by wearability (Adilkhanov et al., 2022), and actuators (Huang et al., 2022), as well as examples of their utility in product design (Kern et al., 2023); however, there is no comprehensive categorisation of the steps involved in integrating emulative vibrotactile haptics at low cost. The aim of this paper is therefore to investigate methods of implementing emulative vibrotactile haptics; achieved via an action-based research process, exemplified by a case study based on the creation of a prototype of a common power drill in Section 3. Section 4 translates the findings from this process into a set of recommendations and considerations for designers seeking to implement low-cost vibrotactile haptics into their prototypes. The four key considerations were identified to be to be the product type, and the actuation, mounting and control methods.

3. Action based research of low-cost haptic prototype development

This section presents a chronological action-research investigation into how low-cost emulative vibrotactile technology could be implemented in early-stage prototypes. Owing to the scarcity of related literature on simple, cheap haptic emulation for prototyping, an action-based research strategy developed collaboratively by the authors with over 60+ years of combined design experience was deemed a sensible option (Brydon-Miller et al., 2003). This characterisation study then facilitated the production of a set of considerations based on the problems faced and decisions made throughout the study. The product chosen for this case study was a cordless electric drill, as it has several interactive elements, and a well-defined use case. Vibrotactile haptic emulation was selected as it offers relatively low cost (can be implemented for <£10), and has been successful in a range of consumer electronics in emulating haptic effects such as button presses (Kern et al., 2023). The task used to exemplify a typical multisensory prototype creation task was the creation of a prototype that would respond to a trigger pull interaction with representative vibration and sound feedback.

This section continues by describing the process followed, outlining requirements and potential solutions for each stage, and concludes by summarising the selected final design in Section 3.5.

As this paper focuses on how a low-cost vibrotactile prototype may be characterised and created, and as there is already evidence that this type of feedback can be beneficial for design applications (Kern et al., 2023), an in-depth user study to investigate the application of the final design is not included.

3.1. Product characterisation

Before the creation of the prototype, an existing product was characterised to inform how the prototype should behave (i.e. at what frequencies and amplitude it should vibrate). Of course, it will not always be possible to use an existing product to inform the behaviour of a prototype. However in these cases either a single functional prototype could be built and characterised, or the important characteristics could be estimated through rough calculation or simulation. Laser vibrometry was selected to characterise the dynamics of the existing drill, allowing the Fourier spectra in Figure 2 to be created.

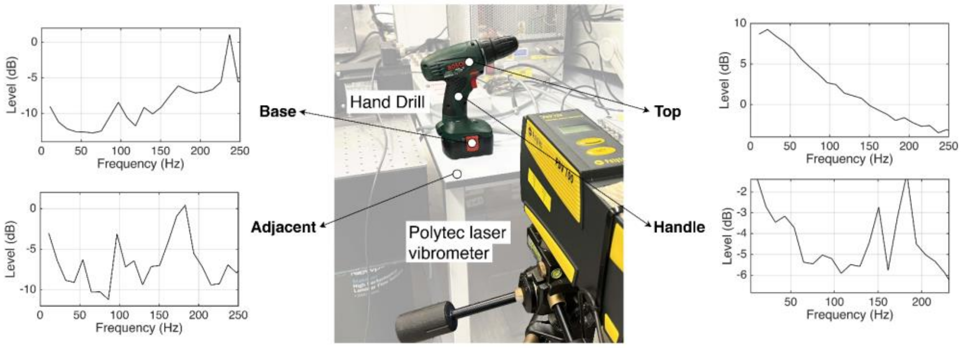

Figure 2. Dynamic analysis of a power drill, cropped to <250Hz

This analysis provided a map of the frequency and amplitude behaviour of the device, and it was found that the response was localised, due to the location of the different moving parts within the device, and the resonant behaviour through it. This is likely to be common to many different product types and should be considered when creating this type of prototype.

Two other important traits were identified when defining the vibrotactile requirements of the prototype: the axes of oscillation and the required precision of vibrotactile behaviour. However, as the test case in this study is an early stage prototype, high precision and accurate vibration orientation was unnecessary.

3.2. Actuator selection

The next step taken was to gather information and provide a breakdown of the most common actuator types available. This was subsequently followed by a selection process based on qualitative and quantitative analysis such as mass and box volume, spool times, and frequency bandwidth. This step was required to select the most appropriate actuator for the scenario.

Haptic actuators can be based on force, thermal, or nerve-stimulation interfaces (Huang et al., 2022). The focus of this paper and probably the most common purposeful haptic response of consumer products is vibrotactile (Huang et al., 2022). Creating a vibrotactile response requires the generation of an oscillating force and/or motion, which can be achieved with a variety of actuators. There are several methods of creating this oscillation, but the most common are electromagnetics and piezoelectrics. This leaves a selection of motors, which, in decreasing order of commonality include Eccentric Rotating Mass (ERM) motors, Linear Resonance Actuators (LRA), and piezoelectric haptic motors (G. G. Poyraz and Ö. Tamer, 2019; Yu et al., 2019), with the latter discarded for use in this investigation due to the high associated cost (DRV8662EVM driver from Texas Instruments costs $99), as well as the additional complexity that comes with high voltage systems.

Table 1. Types of vibrotactile actuators (G. G. Poyraz and Ö. Tamer, 2019; Yu et al., 2019)

Eccentric Rotating Mass (ERM)	Linear Resonance Actuator (LRA)	Piezoelectric haptic motors
+ Simple + Cheap	+ Faster response + Smaller volume	+ Simultaneously detect pressure and create a response
- Amplitude depends on frequency - High power	- Lower force amplitude - Require resonance calibration	- High voltage required - Expensive new technology

ERM motors utilise an off-centre mass attached to a DC rotational motor in order to create vibrational feedback in both axes perpendicular to the motor shaft. This is cheap and easy to implement however requires time to spool-up before there is reaching a uniform behaviour. These motors can come in a wide range of different shapes and sizes, most commonly either shaped as a barrel or coin.

LRA motors work in the same way as the actuation found in a loudspeaker. An AC powered coil of wire controls the linear displacement of a mass using a magnetic field. Very precise effects can be produced in one axis with negligible spool time; however the operating frequency bandwidth tends to be smaller due to the low masses, and LRA motors must be operating at or near resonance to be most effective. These motors typically come in a coin shape however can also use lateral rectangular mass oscillation.

Both types of motors can be controlled using Pulse Width Modulation (PWM) in order to produce a range of frequencies such as those characterised in section 3.1.

The five motors were selected for testing, based on cost and availability, are shown in Figure 3. The cost of each was approximately $3 per unit (with the exception of the large ERM motor costing $8) although they often required bulk orders. ERM motors were widely available and easy to acquire in the UK, and the LRA motor required importing from China.

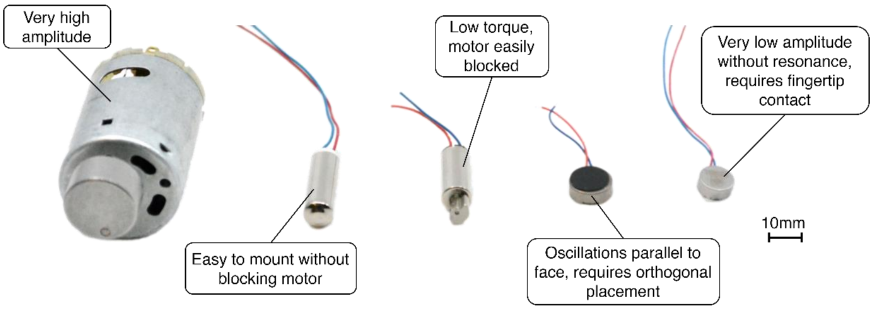

Figure 3. Motors analysed in this paper along with qualitative observations, left to right: large ERM (72g); waterproof barrel ERM (4g); barrel ERM (3g); coin ERM (1g); coin LRA (1g)

To record motor responsiveness, or "spool time", a microphone was fixed in contact with each motor and the time taken between engagement and uniform vibration was measured over two repeats. Another test was conducted to test for the most prominent frequencies produced by the motors. This test utilised Pulse Width Modulation (PWM) to sweep through the entire voltage range. A brief 200ms pulse of each PWM value was transmitted to the motors while under freely supported conditions. The resulting audio recordings, taken using a contact microphone, were then subjected to spectral analysis using an audio processing software (Audacity ®, 2023) to identify the most prominent frequencies.

The LRA motor was unable to be tested in the same way, as the precise movements of the linear actuator were controlled by the microcontroller. Therefore the limits in frequency were bounded by the limits of the microcontroller output, however the amplitude was much less consistent than ERM motors. There was only a small window around the resonant frequency which could be used (Vybronics, 2019).

A photogrammetric study was also attempted using a slow-motion video recording, however due to low motor masses and high wiring rigidity, it was challenging to avoid out-of-plane displacements.

The spool times and ERM frequency ranges are shown in Figure 4. It is interesting to note that spool-down times were longer than spool-up times, possibly due to the activation force being higher than the mechanical resistance. Regardless, the spool-down time will only constrain the use of more precise effects. The LRA motor had far greater precision with spool times two orders of magnitude lower than the ERM motors, however this was at the cost of a significantly lower oscillatory mass. The waterproof barrel motor had the best spool times of the ERM motors, though all were still within the order of human reaction times so would be plenty suitable for user-facing applications. Another important consideration at this stage was the size and mass of the actuators. In the case of an electric drill, each identified option is sufficiently small and light enough to be incorporated into the prototype without affecting the mass and shape of the prototype, so could all be potential candidates for use.

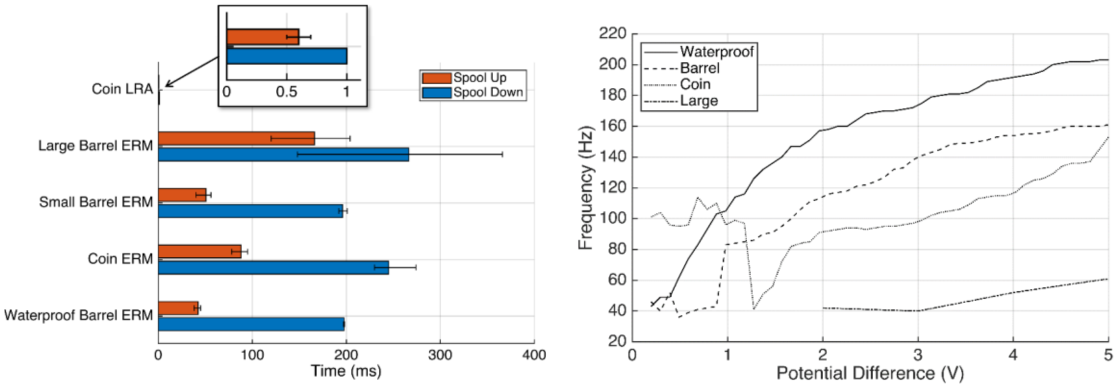

Figure 4. Left to right; motor spool times and ERM frequency bandwidth from 0 to 5V PWM

The frequency bandwidth of the motors is visible in Figure 4, lying approximately within the range of 50-200Hz. At lower PWM voltages, the vibration harmonic appeared less distinct, resulting in an unsteady trend, however this became clearer at higher voltages likely due to greater amplitudes. This mapping then allowed the emulation of specific frequencies characterised when analysing the products. The key findings of this analysis were that a contact microphone can serve as an accurate low-cost method of dynamic actuator analysis, and that both LRA and ERM motors are well suited to low-cost, vibrotactile haptic emulation; the latter being more easily acquired. Common ERM spool times are all within human reaction times and have an approximate frequency range of at least 50-200Hz.

3.3. Control

Initially, testing was done using Arduino UNO and MEGA microcontrollers, however later the design switched to the smaller, cheaper ESP32 with in-built capacitive touch-sensing support (ESP32, 2023). The DRV2605L haptic driver was also found to be a helpful tool for more precise LRA/ERM driving, with 122 different preset effects that could be spliced together, as well as audio input to vibration capability (Texas Instruments, 2023).

A method of switching was also required alongside the controller, several options for this are shown in Figure 5, utilising both capacitive and physical switching methods. Adhesive copper foil was found to be low latency, minimally invasive, and fully adjustable; although wiring could be intrusive if not routed internally and thin foils have lower durability compared to other options. Conductive 3D printing filament was perhaps a more refined, durable solution, though at the cost of reduced flexibility and increased implementation difficulty. Capacitive touch-sensing with the ESP32 microcontroller could be used with either the foil or the conductive filament by recording a moving average of capacitance, and detecting when the gradient reached a threshold for turning the motor on or off. Physical buttons were found to be less responsive than capacitive options due to travel times, and the button's tactility was undesirable in this scenario.

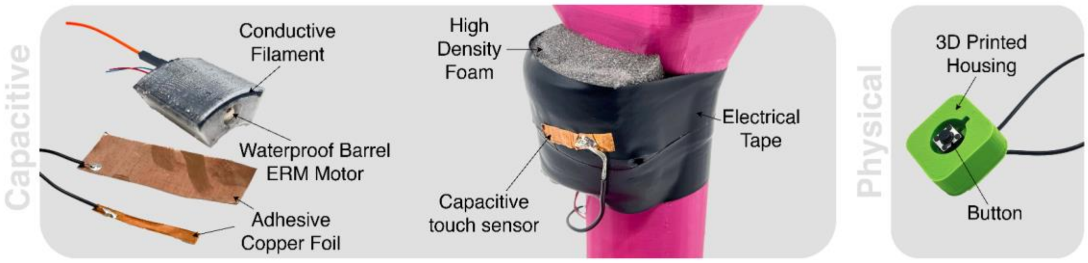

Figure 5. Selection of methods and tools devised for vibrotactile integration in prototypes

The ESP32 boards are compact and low-cost, with built-in capacitive touch-sensing capability that was found to be suitable for this application. Capacitive touch sensors using adhesive foil are adjustable and low latency, which is also ideal for this scenario. The drawbacks of this method was the difficulty of wire routing (though this could be resolved if considered earlier in the design of the prototype itself) and of the foil's potential fragility, though this was not found to be a problem when interacting with the prototype.

3.4. Mounting

As in Figure 6, the three key decisions made to determine the implementation of the vibrotactility were:

1. Wearable or prototype integrated vibrotactile hardware
2. Localised or general vibrotactile feedback
3. Hardware mounting location

The vibrotactile hardware was integrated within the prototype to reduce the impedance on user dexterity. The haptic effects were generalised across the prototype through the use of a single motor mounted in the upper section of the prototype, as this reduced prototype complexity and is a fair representation of the final product. Finally, the motor and control hardware was mounted within the prototype body to minimise interference with the user. The power supply was external to the prototype to simplify the design. Several methods were trialled for mounting the motor within the prototype. A solid 3D printed adapter worked effectively, but took several iterations to obtain a satisfactory design. A flexible mount made from foam was created very quickly, but dampened and reduced the vibration which was not acceptable in this case, so the solid 3D printed mount seen in Figure 6 was used.

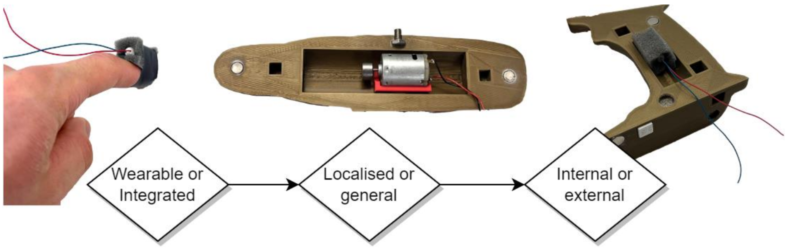

Figure 6. Potential hardware placements

3.5. Final design and evaluation

The technology chosen for each component of the prototype was driven by cost, availability of resources, ease of implementation, and capability of realistic haptic sensation. Despite its slightly higher cost, the large barrel ERM motor ($8) was selected due to its high amplitude capable of reproducing the low-frequency oscillations present in a drill. This higher cost was balanced by superior capability to accurately emulate the drill's operation, and at $8 this part was still inexpensive. A capacitive copper foil touch sensor was wired into the handle for actuation (<£1). This was selected for its low latency inputs, minimal haptic interference, negligible cost and full customisability. The wiring was tucked away within the body of the prototype to avoid interfering with user dexterity. An ESP32 microcontroller (£6) was selected for driving the motor response using the in-built capacitive touch-sensing libraries; without the use of the DRV2605L as this prototype did not require complex haptic effects. The final prototype is shown in Figure 7, where each feature is classified against the considerations made in Section 4. When plugged in, the capacitive touch sensor on the trigger was enabled, allowing the user to turn on and off the ERM motor. The overall cost of the vibrotactile addition to the prototype was less than £15, and total development time was 1 month by an engineering student intern, demonstrating that vibrotactile feedback in a prototype can be implemented at low cost.

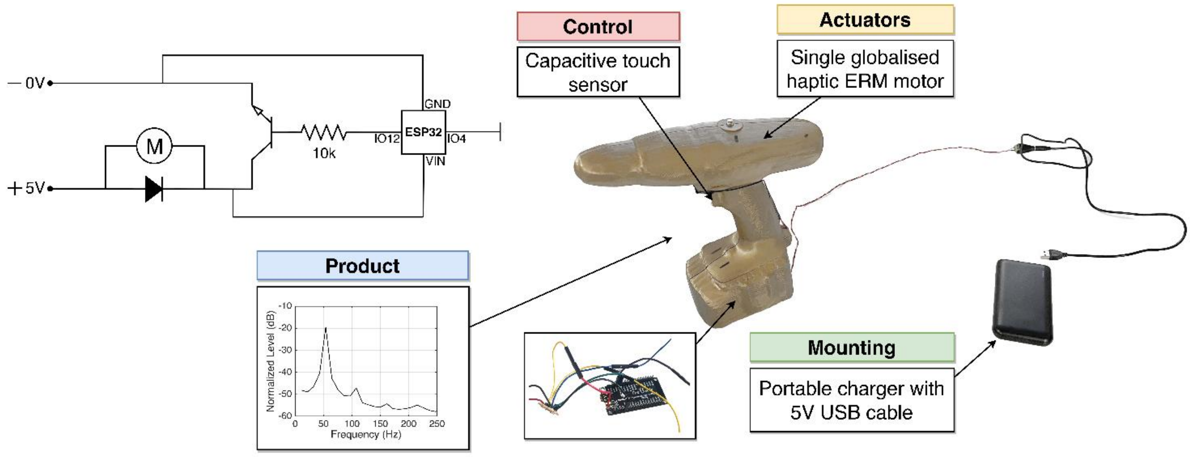

Figure 7. Circuit architecture and final prototype with contact microphone frequency response

Although not an in-depth user study, the prototype was sufficiently responsive that when demonstrated at the ICED 2022 Marketplace, all test users (25+) found the prototype to be more realistic than an inert model. Further testing is required to fully characterise the prototype's realism against working and inert models to verify the benefits of this approach, but this initial testing has proven to be positive.

4. Findings and considerations from the action-based research

The steps and findings from the conduction of this action-based research were categorised and compacted into a set of general considerations for when producing low-cost vibrotactile prototypes. The four key categories of considerations found were as follows: Product, Actuation, Control, and Mounting.

Table 2. Key findings from action-research

P1	The frequency response of an object is significantly localised.
P2	There are often multiple frequencies involved in product emulation, the most significant are likely nearest moving parts.
A1	A contact microphone can serve as an accurate low-cost method of dynamic analysis.
A2	LRA and ERM motors are best suited to low-cost haptic emulation, the latter being more easily acquired.
A3	ERM spool times are all within human reaction times. ERM motors have an approximate range of 50-200Hz.
C1	ESP32 boards are compact, low-cost, and include capacitive touch sensing capability.
C2	Capacitive touch sensors (using adhesive foil or conductive filament) are adjustable and low latency.
M1	Vibrotactile integration can be local or global, internal or external, and wearable or integrated.
M2	Foam can provide a simple rattle-free motor bedding (at the cost of some damping) while also allowing compliance with user inputs.
M3	Mounting decisions depend on the size of the prototype, intensity of required effects, and whether or not wireless capabilities are required.

Table 2 presents key findings categorised under these headings. These insights can be applied by future designers seeking to implement vibrotactile prototypes. P1 and P2 reveal the potential need for multiple motors to create accurate localised vibrotactile emulation, though a simpler approach using a single motor was found to be successful in this case. A1 also shows that this does not require costly equipment. Section 4.1 reflects on the development process used to create the final prototype demonstrated in Section 3.5, and the learning from the various decisions made throughout. A summary of the product considerations that were made during the creation of the final prototype is shown in Figure 8, framed as a set of requirements for future designers to consider when creating their own low-cost vibrotactile prototypes, with a range of examples included. Lastly, some recommendations for future work are made.

4.1. Considerations for designers creating low-cost vibrotactile prototypes

Product Vibrotactile feedback will not be appropriate for all products being developed, and different product classes will have very different haptic characteristics. As such, suitability and the key haptic parameters shown in Figure 8 must first be assessed by considering each of the requirements and their respective questions. The headings in Figure 8 were derived from what the authors believe to be the key determinant factors of the product type that will affect how low-cost vibrotactile haptic prototypes can be created, based on the learning throughout the action-based research process outlined in Section 3. Some of these requirements are easier to answer, such as the requirement for wireless operation (this will require high efficiency electronics, or a wired power source), or low mass/volume motors. However others require further investigation, such as the required frequency, force amplitude and vibration axes. Examples for how to explore some of these requirements are given in Section 3.1. Contact microphones were found to be a strong candidate for conducting frequency identification due to their simplicity and low cost, however a laser vibrometer, accelerometer, or slow motion camera can also be used.

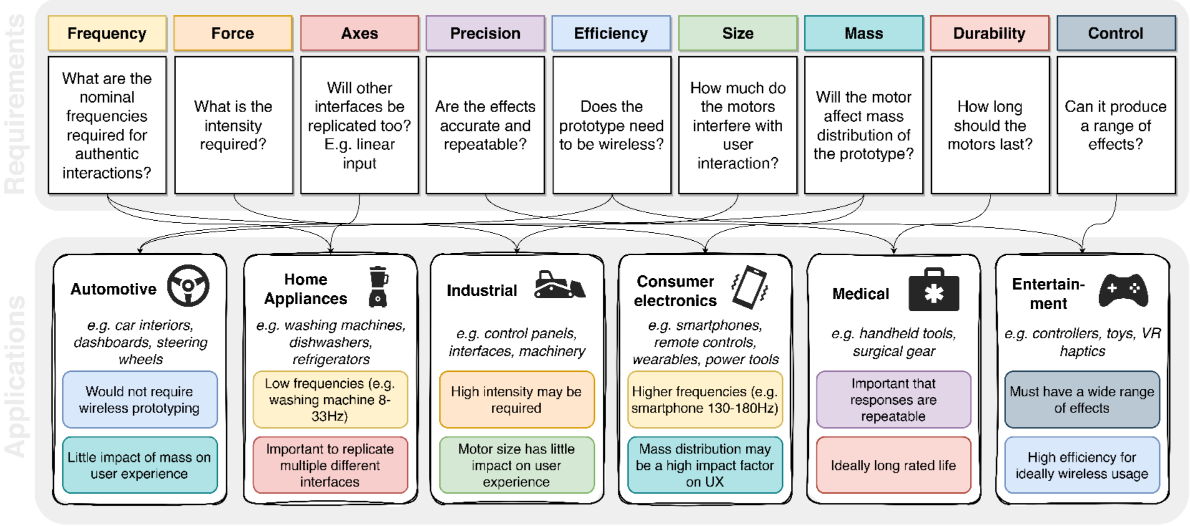

Figure 8. Identified prototype considerations mapped to example applications

Actuators With the relevant characteristics defined, appropriate actuators can be selected to best create the vibrotactile response of the proposed product, and any additional desired interfaces. Key considerations for actuator selection are primarily technical in nature, including required frequency, response time, amplitude, and viable motor size. Section 3.2 gives an overview of common actuator types and an example motor characterisation process.

Control Approaches to control and power requirements vary with different actuators, and there are many methods of interfacing that affect invasiveness towards actuator effects and user interactions. For many prototyping applications, capacitive touch-sensing adhesive foil can serve as a low-cost, highly adjustable method of actuation. However other methods may be used such as physical actuators, hand tracking, or even "Wizard of Oz" styled external control by a facilitator. Most microcontrollers offer sufficient capabilities for vibrotactile prototyping, however for more precise effects a haptic driver such as the DRV2605L may be required. An example control design process is outlined in section 3.3.

Mounting Placing electronics greatly depends on the physical characteristics of the actuators and control system, such as whether it must be wireless and whether it prioritises adjustability or refinement, as well as the requirements and form of the final product. Additionally, haptic effects could be localised or globalised, depending on the size and precision requirements of the model. For most applications where the frequencies required fall in either the low or high band alone, a globalised approach could be the most economical (such as that shown in section 3.5). For larger prototypes and those with more complex frequency requirements, multiple actuators may be required. Haptic hardware can also be wearable, however this would likely affect user behaviour (Yang et al., 2017).

4.2. Future developments

This paper represents the refinement of just one facet of a broader perception-centric prototyping philosophy. There is considerably more work to be carried out. Studies could build on this paper specifically by researching other haptic elements from Figure 1 or testing more complex multimodal localised vibrotactile haptics. Or they may focus more broadly on enhancing psychological responses to lower-cost prototypes through any of the constituent elements of prototype fidelity (Cox et al., 2022).
It is clear there are financial benefits to this cost-effective approach to haptic integration, however more in-depth user studies are needed to quantify the economic, temporal, and strategic value offered by this low-cost implementation of vibrotactile feedback in prototypes.

5. Conclusion

Prior to this paper, categorising and detailing the steps involved in low-cost vibrotactile haptic integration of prototypes had not been extensively explored. Continuing from existing work aiming to maximise prototype fidelity while minimising expenditure (i.e. perception-centric design), the reported research has developed a set of considerations for both the technological implementation and the required parameters for the integration of vibrotactile feedback into a prototype. Devised from an action-based research study, this aims to reduce expenditure and provide a resource to direct designers towards the requisite knowledge for implementing low-cost vibrotactile haptics. For example, through the use of simple methods such as the contact microphone product characterisation verified in this paper.
This study has similarly opened up a great deal more questions such as quantifying the value from this practice, investigating the role played by different senses when interacting with a prototype, and determining which of these are most important to a perception-centric approach. This set of design considerations demonstrates the refinement of just one example of a broader perception-centric approach, aimed at optimising psychological responses. Touch is a cornerstone of ergonomics and product design, and this methodology could be key to improving the value derived from prototyping processes of the future.

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