MSc Robotics Dissertation Proposal

Optimisation of Vibrotactile Haptic Feedback for Source Discrimination of Urgent Signals Under Cognitive Load

By

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1 Aims & Objectives

This project seeks to integrate an existing vibrotactile sleeve with the Covvi Hand, a production-ready actuated upper limb prosthetic. Both are shown in Figure 1. This hardware will then be used to validate or invalidate two hypotheses:

H1: Users of haptic feedback devices will perform better in a signal recognition task when their attention is undivided, compared to performing the same task under cognitive load.

H2: By providing specific signal patterns, performance on the signal recognition task under cognitive load will be improved.

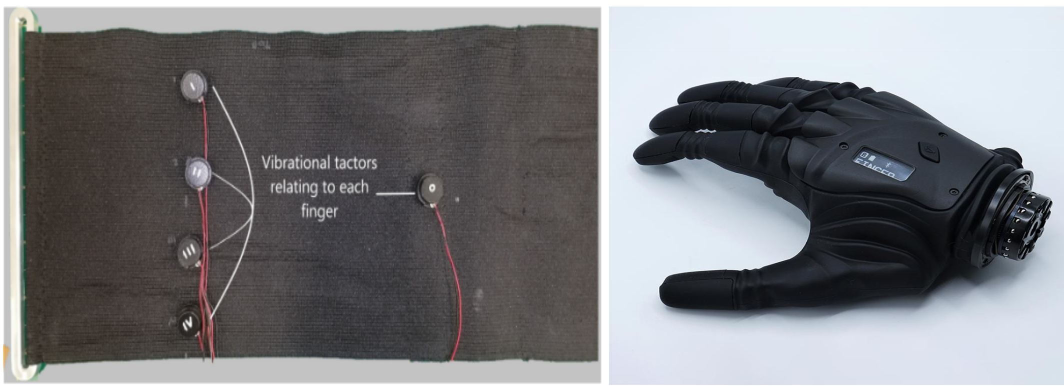
Validating hypothesis **H1** will demonstrate the need for novel methods of haptic-feedback signalling for users under cognitive load. If hypothesis **H2** is validated, we will have provided a method to increase the perception of haptic signals to the user with everyday applicability, as outlined in section 2. The fundamental aim of this project is therefore:

To optimise vibrotactile feedback for perception and discrimination of urgent haptic signals under cognitive load, in the context of actuated prosthetics.

The specific objectives of the project are as follows:

1. Review key results found by *Alex Smith et al.* [1][2] in their evaluation of multi-channel feedback arrays in relation to digit discrimination. Assist Alex Smith in their next study to gain first-hand experience with the current software and hardware being used, as well as experience running a user study.
2. Work with the Covvi Hand [3] to enable integration of the vibrotactile feedback array. Enable vibration feedback such that the closing of each digit corresponds to a unique motor in the array.

3. Investigate alternative motor actuators with the aim of decoupling frequency and amplitude of vibration so that these can be varied independently. Conduct an investigation into the effect of modulating motor frequency, amplitude and relative phase difference on user perception of haptic feedback.
4. Develop novel vibrotactile feedback patterns with the aim of maximising both user perception and discrimination for the signal source.
5. Design and run controlled trials with human participants to measure user perception of each feedback pattern and discrimination for which digit of the Covvi hand is being closed. Compare user performance with and without external cognitive load.



(a) Vibrotactile Array Sleeve

(b) The Covvi Hand

Figure 1: The hardware being used in the project. Image (a) was used with permission from Alex Smith, the creator of the vibrotactile sleeve [1]. Image (b) was used with permission from Covvi Ltd [3].

2 Motivation

The addition of haptic feedback to robotic systems finds motivations across a wide range of industries and applications. Touch sensation provides heightened immersion in augmented and virtual reality, an application being championed by companies such as Meta [4] and Ultraleap [5]. With the rise of robotic surgery devices [6], implementation of haptics may provide sensory feedback similar to pre-robotic surgery, without losing the precision that allows for minimally invasive surgery.

A key motivation for haptic feedback in a system is to allow for user operation without visual confirmation of all actions. This is particularly evident for users of actuated upper limb prosthetics. The natural human hand relays complex sensory feedback when touching or grasping an object, providing a person with texture and temperature information, as well as their own grip force [7][8]. This allows the person to discern the degree of contact with the object, such as whether they are securely holding it or not, with no requirement for visual confirmation. In contrast, while contact between a prosthetic hand and an object will provide some measure of torque on the residual limb [9], this does not equate to the fine-motor control required for confident use without visual confirmation [8][10]. This may be one contributing factor to the high abandonment rate of modern prosthetics[11][12], their current functionality does not restore enough dexterity to the user.

Taking an elasticated arm-band approach to haptic-feedback integration for actuated prosthetics provides general application for a wide range of limb differences without the requirement for a tailored fit. It also implies the possibility of compatibility with a variety of different prosthetic devices, given it is not built into the prosthetic itself. Humans often perform tasks with their hands without looking, such as dressing and undressing, holding a mobile phone whilst talking into it or walking while holding an item. Haptic feedback may provide prosthetic users with a much wider range of functionality and a higher confidence that they can operate their device without constant visual monitoring.

Many daily tasks require not only that we forgo visual confirmation, but we must also use our hands without paying constant attention to what they are doing. For example, if you are carrying shopping bags while having a conversation, your attention may be on the conversation but your fingers still provide sensory feedback so you do not drop the bags. The investigation of user perception of haptic feedback under cognitive load - and how to improve this - will provide a contribution that helps upper limb prosthetics move toward a real-world functionality comparable to biological hands. Furthermore, improved perception of haptic signals can help users to avoid damage to expensive prosthetics. Highly perceptive signals could alert a user in the case that their prosthetic is becoming too hot if it were resting near an active gas hob, or receiving water damage if something is spilt on it without the user realising. This is in essence a sensory substitute for pain, one of nature's most essential feedback mechanisms and a vital advancement to modern prosthetics.

In addition, this technology has utility in fields where users require perceptible sensory input without interrupting their current audio-visual task. Examples include teleoperation of robotic hands without visual confirmation of actions, non-startling sensory feedback for use in high-pressure scenarios such as nuclear decommissioning (warning of radiation damage to the robot) and navigation in darkness.

3 Literature Review

The literature regarding haptic feedback devices and attention can be sorted into several themes each relating to an aspect of this project proposal. These have been separated into sections below for clarity.

3.1 Haptic Feedback

Haptic systems include *"Real and simulated touch interactions between robots, humans, and real, remote, or simulated environments, in various combinations."* [13]. *Cipriani C et al.* [14] demonstrated experimentally, that users will integrate haptic feedback into their control method for using a robotic hand, meaning this feedback has a real influence on user behaviour. Further, many studies demonstrate the utility of haptic feedback. *Katzschmann R et al.* [15] utilised haptic feedback in conjunction with time-of-flight sensors to provide visually impaired users with an obstacle avoidance method which leaves their hands free for use, unlike a traditional white cane. *Wildenbeest J et al.* [16] investigated the effects of providing different levels of haptic feedback in teleoperation assembly tasks. They found that low-frequency haptic feedback provided significant overall improvements in minimising completion time and reversal rate (the number of steering corrections per task). However, more substantial haptic feedback, including a "full spectrum of haptic feedback" via direct-controlled equivalent, provided only marginal gains in overall task performance. This indicates that, for some applications, additional haptic feedback beyond low-level simple feedback may have depreciating performance improvements.

3.1.1 Sensory Substitution

This phenomenon is the use of one sensation to provide information about another sensation of a different type or position. For example, the use of vibration on the skin to indicate the closing or opening of the digits of a robotic hand [2]. In the case of prosthetics, some measure of sensory substitution is inherently unavoidable; information from the prosthetic digits must be conveyed to the user by some mechanism other than identical sensation.

Another major application for sensory substitution is indicating pain or damage to a robot. Triggering Nociception - pain reception in the human body - is not ethically viable, yet pain responses often indicate important stimuli. In teleoperation, it is not appropriate for the operator to feel pain if the robot is damaged, but substituting this feedback means the user is still aware of it. *Sobhani M et al.* [17] have pioneered work on immersive virtual reality in conjunction with teleoperation of a robot, with the application of more intuitive operation of nuclear decommissioning robots. Haptic feedback, such as vibrations of increasing amplitude, could be used to inform the operator that the robot is taking radiation damage, without requiring a visual interruption which could cause operator mistakes.

Two main components must be considered when describing sensory substitution, modality and location. Modality describes the type of sensation. Research indicates that modality-matching, the use of the same type of sensation as the one the system is attempting to convey, can provide better user discrimination [18]. Specifically, the use of pressure stimulation was demonstrated to outperform vibrotactile stimulation in the discrimination of which digit of a robotic hand had pressure applied to it. While this may suggest that mechanotactile actuators are the superior choice, as pointed out by *Smith et al.* [1], vibrotactile sensors have the advantage of being more compact and requiring less power contributing to their widespread use in practical haptics research [19].

The complexity of the sensation being substituted may also impact the best choice of haptic feedback. *Smith et al.* [2] uses five vibrotactile motors to investigate the optimal array morphology for conveying haptic feedback for each digit of a robotic hand. Study Participants made errors in discriminating between the active motors partly due to the nature of vibrations as waves propagating through the skin. Constructive and destructive interference will affect vibration amplitude at different positions on the skin [20]. For this reason, complex tactile sensation combinations may be better simulated with other modalities.

3.1.2 Vibrotactile Feedback

As mentioned, vibrotactile feedback is widely used in academia as the most convenient and cost-effective form of haptic feedback [21][22]. Commercially, it is ubiquitous for delivering "silent" notifications to smartphones and watches. Though it has limitations in terms of sensory substitution, clever use of placement, signal characteristics and, in particular, training can far outweigh any lack of intuitiveness this modality struggles with [2][23][24].

Vibrotactile feedback has been previously found to be less pleasant than other types of haptic feedback, though it is more clearly perceived under cognitive load. [25]. This issue should be addressed, as users may abandon devices they regard as unpleasant to use. It may be that novel feedback patterns can elicit the same level of perception at a significantly lower vibration amplitude, decreasing discomfort for users. This will be investigated as part of the project. One can also consider to what extent haptic feedback distracts from the user's current activity. In this study, this will be accounted for by measuring performance in the task along with perception and discrimination of the feedback signal.

Given users find continuous vibrotactile feedback unpleasant, many studies have turned to the principle of Discrete Event-driven Sensory feedback Control (DESC) in their implementation [1][14][15][26]. Feedback is delivered in individual bursts every time a state changes in the sensor. The user is notified only of changes, receiving no feedback while the current state persists. This has the key benefit of reducing user desensitisation to the vibrations, improving their perception of each signal. *Chaubey P et al.* [27] found that upper limb prosthetic users became fully desensitised to continuous vibrotactile feedback after 66 seconds on average. Discrete signals additionally will consume less battery power, an important consideration for the battery life of actuated prosthetics.

Given its strength in perceptibility and superior utility for discrete signalling, vibrotactile feedback is well suited as a substitution for pain or other urgent signals; those which are not used moment-to-moment, but must not be missed when they are sent.

3.1.3 Soft Robotic Actuators

Outside of vibrotactile actuators, the limitations of rigid actuators necessitate the investigation of soft robotic actuators as an alternative for providing modality-matching feedback without bulky, high-powered hardware which would be impractical for the application of haptic-enabled prosthetics. Indeed, biomimicry dictates that soft actuators may provide the minimum level of sensory substitution possible in this context, given their smaller profile and compliance to the shape of the body [28]. This has been leveraged for providing touch sensation in conjunction with virtual and augmented reality [29].

Study participants are also found to rate shear sensations such as pinching or squeezing actuated by shape-memory-alloy soft actuators, as more pleasant than vibrotactile feedback [25], this is important considering the high abandonment rate of modern prosthetics [11], [12]. Unlike vibrotactile feedback, squeezing or skin shear tactile feedback may be more appropriate for continuous application, as opposed to the DESC method. This has applications for conveying the continuous application of pressure, often used directly in fingertip haptic devices [19].

Soft actuated haptic feedback is more easily missed as cognitive load is increased, in comparison to vibrotactile feedback [25][30]. This can be seen as a positive aspect, in the sense that the feedback may not interrupt the user's focus on important tasks such as driving. It can also be seen as a drawback as the user may miss essential alerts if their attention is not on the device.

3.1.4 Combined Modality Haptic Feedback

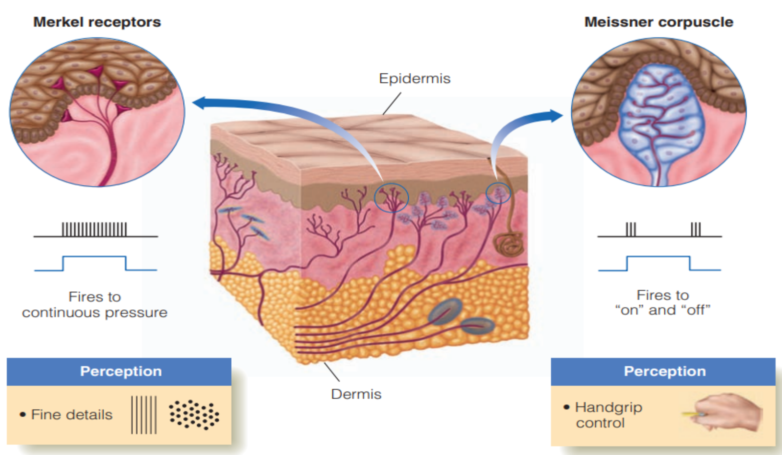


Figure 2: A cross-section of human skin showing the shallow mechanoreceptors for continuous and transient contact [31]. Deep mechanoreceptors (which can sense vibrations) are visible as blue pods in the dermis layer.

The above research indicates that a combination of vibrotactile and soft-actuator feedback may be ideal to maximise user comfort without sacrificing their perception of urgent signals.

The future solution to maximise real-world utility would reserve vibrotactile feedback for urgent alerts, making use of more pleasant soft-actuated squeezing or pinching for moment-to-moment feedback. Different sensations are conveyed by stimulating different aspects of the human somatosensory system, multimodal haptics allow an exponential increase in deliverable sensations due to submodality convergence; the phenomenon of different combinations of stimulated tactile receptors producing different sensations such as texture, vibration and shape [32]. Indeed, to achieve fine dexterity in teleoperation or prosthetics, users must be provided feedback which stimulates both shallow and deep, sustained and transient contact mechanoreceptors [33]. These are displayed in Figure 2.

The combination of compression, shear and vibrotactile feedback has been explored by *Zhu M et al.* with the PneuSleeve device [34]. The researchers suggest applications such as notifications, navigation prompts and remote social touch using this device. For sensations increasing in importance, one could envision a sensory phase from soft-squeeze to hard-squeeze to vibration as the importance of acquiring the user's attention increases. Vibrations are generated by stimulating all the soft actuators at once and are reported as differing in sensation to vibrations from a rigid motor.

While multimodal haptics certainly constitutes a key area of future research, current systems are too bulky to be truly functional for portable technologies.

3.2 upper limb Prosthetics: Attention & Operation Without Visual Confirmation

A 2016 review of the needs of upper limb prosthetic users [7] found that 98% of users desire a feeling of grasping force and temperature; fundamentally a request for haptic feedback integration in their devices. This review found tactile sensation integration was second in desirability only to having greater manipulation and grasping abilities - an improvement that will itself be realised through haptic feedback integration in control mechanisms [14][33][35].

Due to proprioception, humans can operate their biological limbs for many tasks without visual confirmation (without looking) or indeed conscious thought [36]. To move toward this ability for prosthesis users, researchers must consider the cognitive load on users required to operate their devices as well as how to provide sensory information about the device when the user is not looking at it. Operation of current actuated prosthetics can require a large cognitive load due to reductive control strategies being used to activate multiple grip types in the hand [7][37]. Dedicated training contributes to a reduction in abandonment rate [38] and improved user performance [39], but the literature is inconclusive on whether this is due to a reduction in cognitive load during operation. Ultimately,

Figure 3: Covvi Prosthetics with socket attached to the retention ring of the hand. Used with permission from Covvi Ltd [3].

the use of appropriate haptic feedback can help lessen the cognitive load on users [40] as well as offer a method of informed operation without visual confirmation.

To maximise user operation without visual confirmation, the highest possible haptic signal clarity must be achieved, so that users can rely on their assessment of haptic feedback during operation. *Antfolk C et al.* [18] demonstrated that pressure stimulation outperforms vibrotactile stimulation in user discrimination of stimulation location. This is expected given the shallow mechanoreceptors responsible for pressure detection have a much finer field of influence compared to the deep mechanoreceptors detecting vibrations, in addition to the propagation of vibrations through the skin. Further, this study found that accounting for a user's "phantom map" - the phenomena some amputees experience of having phantom sensation corresponding to each digit of the lost hand at specific points of the residual limb - can further improve the localisation of haptic stimuli. This study indicates the use of pressure sensation as optimal for improving dexterous operation of prosthetics.

However, to allow users to confidently train to operate their prosthetic device without visual confirmation, the first consideration should be robust safety features for both the operator and their device, given the typically high cost of actuated prosthetics [7]. For this, users require clear, highly perceptible signals that are unlikely to be missed, even if the user is under cognitive load. Based on the literature discussed in the section 3.1, vibrotactile feedback is best suited for this requirement, delivering highly perceptible signals which encourage the user to return visual attention to the device. Once the user can rely upon receiving this feedback when necessary, they will feel less pressure to check on the device during proprioceptive operation. This will improve the quality of their training and thus their ability to operate the device without visual confirmation.

3.3 Wider Applications

In addition to prosthetics, improvements in haptic technologies are being driven by consumer demand for more immersive virtual and augmented reality experiences, as well as the desire for more dexterous teleoperation of robots. Multimodal haptic technology is the key to the development of both fields as the solution for stimulating multiple aspects of the human somatosensory system [32]. As mentioned in section 3.1, haptic feedback has utility for individuals with disabilities other than limb differences, such as navigation prompts for the visually impaired [15]. Haptic feedback improves dexterity in teleoperation tasks [16], [41], which has major applications for safety-critical tasks such as nuclear decommissioning using combined virtual reality and teleoperation [17]. In each of these applications, the use of vibrotactile feedback to convey urgent signals may be considered. For safety-critical tasks, the controlled phased feedback from soft-actuated squeeze to vibration, as suggested in section 3.1.4, would be appropriate.

3.4 Summary

While there are many interesting avenues being explored in haptic feedback today, achieving fine dexterity in the application of upper limb prosthesis remains dependant on dedicated user training to form new neural pathways [10], as well as on the number of configurations the prosthetic is capable of [7]. Until haptic-enabled prosthetic systems reach feedback levels comparable to the natural hand, its impact will be more significant if it is used discretely to draw user attention to the prosthetic itself. Haptics, particularly vibrotactile stimulation, is perfectly suited to quickly acquire the user's attention. Once the user is focused on the prosthetic, further haptic feedback provides a less significant contribution to their ability to manipulate it relative to the level of training the user has had with the device [8].

Hence, I propose the use of discrete vibrotactile feedback in upper limb prosthetics as the delivery mechanism for urgent feedback, such as damage to the hand - effectively a substitute for pain. In addition to the high cognitive load of controlling actuated prosthetics [7], users must be able to carry out tasks day-to-day which will require varying levels of attention. The question of how to maximise the user perception and localisation of these urgent signals while under cognitive load remains. The dissertation project proposed seeks to answer this question.

4 Impact Assessment

The impact of this research is most clearly detailed by considering it separately in each context.

4.1 Political & Legal Impact

It is unlikely this work will have major political or legal consequences as the aim of improving vibrotactile haptic feedback is building on existing technology, as opposed to fabricating something completely new. It should be noted that there may be legal repercussions if the feedback algorithm developed were strong enough to move from causing discomfort to pain; the researchers are aware of this and keen to emphasise that the study seeks to achieve a high-performance substitution for pain and will acquire all prerequisite ethical approval before human participants are subject to any feedback system developed. Since the system aims at alerting users to critical information, it may be the case that this technology enables employees to better abide by section 7a of the 1974 Health and Safety at Work etc. Act [42], a positive legal impact. The question of ethics in this study hinges on the same issue outlined above. Provided the developments to the vibrotactile sleeve cannot cause physical pain, the study is ethically sound. Therefore there is no significant ethical impact as a result of this study.

4.2 Economic Impact

The economic impact will be dictated by which applications of this technology come to fruition. If it is used only to improve the utility of upper limb prosthetics, the economic impact will be low; while these prosthetics are expensive, the addition of haptic hardware is comparatively cheap and the market for these devices is specific and marginal. This technology may enable prosthetic users to apply for a wider range of jobs requiring improved reactivity to touch. The successful integration of the haptic sleeve with the Covvi Hand may have economic ramifications for Covvi as a company - potentially impacting their future design choices and ultimately performance against competitors. However if the wider applications envisioned in section 2 are realised, the use of the haptic technology developed in this study has the potential to be much more widespread. This would increase the economic impact, the major cost being licensing the software, which would be owned by the University, as opposed to the relatively cheap vibrotactile motors and sleeve.

4.3 Environmental Impact

Environmentally, the haptic sleeve draws little power, especially compared to upper limb prosthetics as a whole. A production-ready version would almost certainly draw power from the prosthetic battery. The lifetime of the vibrotactile sleeve is unknown. While the industry standard is 1×10^5 cycles of active and passive at a frequency of 1Hz (≈ 28 hours of active operation), retail motors can outperform this by some margin [43]. Without a longitudinal study on the sleeve, we can only estimate that with average daily use of ≤ 50 essential vibrotactile alerts, the vibrotactile sleeve would operate for a minimum of 5 years before replacement motors are required. Ultimately, with its long lifetime and small material requirement, the vibrotactile sleeve has a small environmental impact. Some vibrotactile motors can contain precious metals, the environmental impact of these could be significant if manufactured on an industrial scale.

4.4 Social & Cultural Impact

Finally, considering the study from a social or cultural perspective, the ultimate aim is to achieve a positive impact. This work seeks to contribute to the many advancements in modern prosthetics, increasing the number of tasks performable by users and further closing the dexterity gap between natural hands and advanced upper limb prosthetics. This allows for better social integration of prosthesis users as they can participate in a wider range of activities as their devices improve. Prosthetic advancements are not dependant on a particular culture, though they are overwhelmingly more likely to have an impact in wealthier societies given the high cost of devices in the current market [44]. It is exceedingly unlikely that the study will have a negative social or cultural impact as opposed to having no impact, in the result of a null hypothesis. The hardware additions being considered are inexpensive as stated and so do not further reduce the accessibility of these devices by any significant margin.

5 Risk Register

Risk	Preventative Measures	Response Action	Risk Rating (low) 1-5 (high)
Laptop breaks down.	Backup all dissertation research and data to the cloud.	make use of desktops available in the BRL, as well as at UWE and UoB.	**2** - laptop relatively new but subject to frequent use each day.
Unsuccessful in integrating the Covvi Hand with the Vibrotactile sleeve.	Begin integration work in spring (per the timeline - Figure 4) to give more time for understanding the hardware in time for summer study.	The OpenBionics Brunel hand [45] has already been successfully integrated with the Vibrotactile sleeve and is available as a backup.	**4** - integration will be a complex challenge and Covvi have yet to release their supporting hardware for research on the hand.
Vibrotactile feedback causing harm to study participants	Careful reference to existing standards with regard to acceptable vibration amplitudes. Extensive testing ahead of user study	Study trial halted immediately. BRL first aid practitioner summoned if required.	**1** - While the intention is to deliver urgent signals, this can be done at intensities much lower than those required to cause pain.
Human study approval delayed or not granted	Approval will be requested in spring (per the timeline - Figure 4) and requested through supervisor who has existing approval for user studies.	Study focus will shift to further developing vibrotactile integration with the Covvi Hand and integrating features beyond urgent signals.	**1** - Similar studies under the same supervisor and using the same hardware have already been approved and carried out in the BRL.

6 Timeline

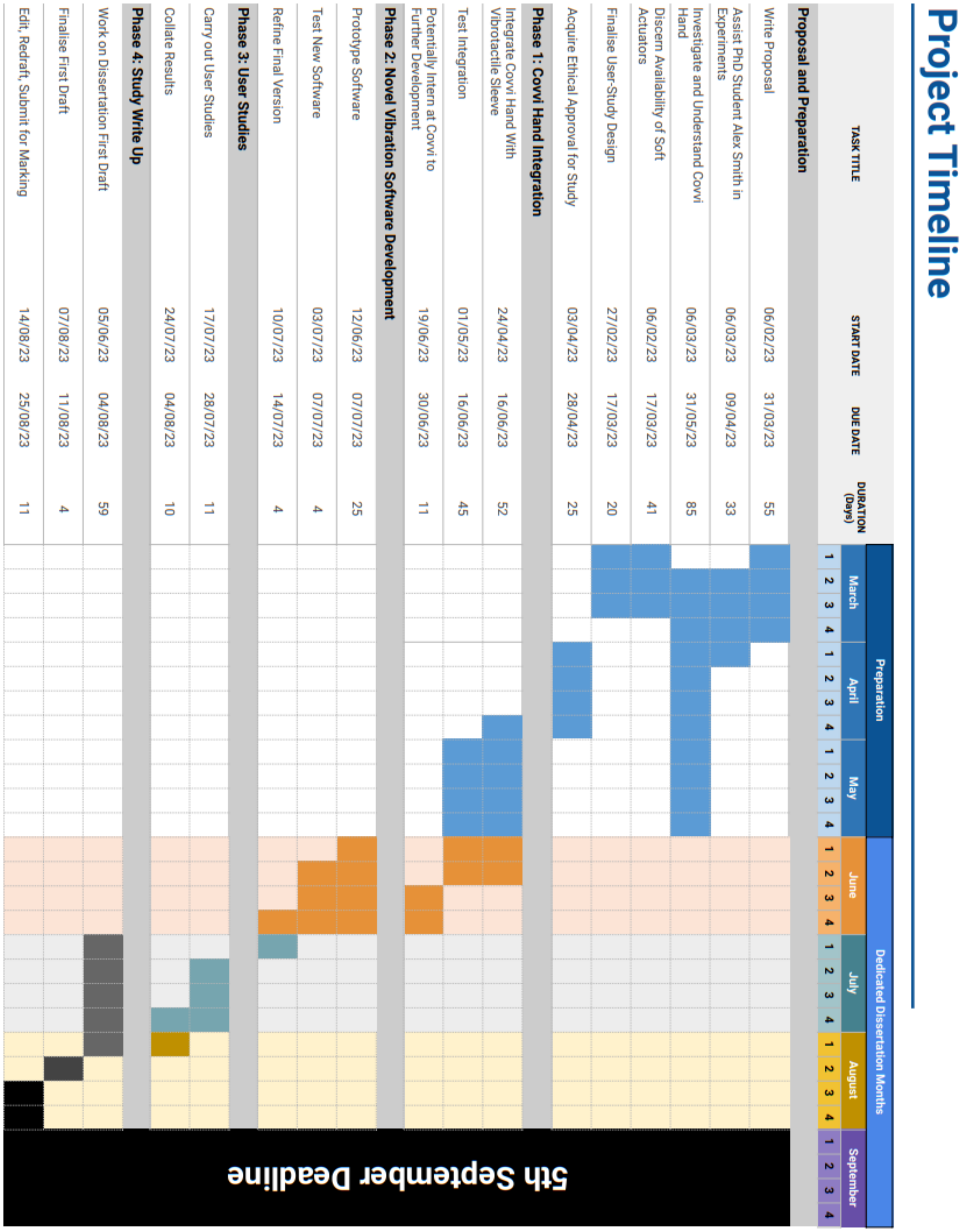


Figure 4: The projected project timeline, rotate the PDF 90° anti-clockwise to view.

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