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Investigation of Electro-tactile Feedback Mechanisms for VR Gloves

Graduation Project Final Report

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Statement of Authenticity

We hereby declare that in this study

1. all the content influenced from external references are cited clearly and in detail,
2. and all the remaining sections, especially the theoretical studies and implemented software/hardware that constitute the fundamental essence of this study is originated by our individual authenticity.

Istanbul, June 2024

Berkant Bakışlı, Eren Taşdemir

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Investigation of Electro-tactile Feedback Mechanisms for VR Gloves

(SUMMARY)

This project focuses on enhancing immersion in Virtual Reality (VR) by developing electro-tactile feedback mechanisms for VR gloves. Immersion is a crucial aspect of VR, as it significantly impacts user experience and engagement. Traditional feedback mechanisms like audio and haptic feedback in controllers have been explored extensively, but tactile feedback remains underdeveloped. This project builds on previous studies, such as the work by Tanaka et al., which achieved tactile feedback through electrical stimulation of the Median and Ulnar nerves using electrodes placed on the dorsal side of the hand.

While the literature survey highlights various approaches to tactile feedback, our project proposes a comprehensive system consisting of hardware, microcontroller firmware, an OpenVR-compatible driver, and a demo application. The tactile feedback mechanism utilizes electrical stimulation, specifically targeting the Median and Ulnar nerves. This method, inspired by Tanaka et al., involves placing electrodes on the dorsal side of the hand to stimulate touch in the palmar side effectively.

Hardware: The hardware includes electrodes placed strategically in the form of a glove on the dorsal side of the hand, to optimize the electrical stimulation of the hand on the palmar side. The electrical circuit creates effective stimulation signals.

Firmware: The microcontroller firmware is designed to handle the electrical stimulation signals, ensuring precise control over the feedback mechanism.

Driver and Communication Stack: An OpenVR-compatible driver facilitates communication between the VR system and the tactile feedback hardware, ensuring seamless integration and interaction with VR environments.

Demo Application: A demo application showcases the capabilities of the developed system, allowing users to experience enhanced tactile feedback in VR scenarios.

An experimentation environment was set up to test the effectiveness of the developed system. The experiments involved various scenarios where different combinations of locations on users' hands were stimulated through the electro-tactile mechanism. The experiments aimed to assess the accuracy and the feel of the stimulation delivered by the system.

For the evaluation, the project's aim to satisfy all of the evaluation criteria stated in the interim report was achieved. The developed system is compared with existing solutions, highlighting its advantages in providing realistic tactile feedback without restricting hand movement. The project's approach offers a significant improvement in immersion and user experience in VR applications, compared to other existing solutions and research in the VR area.

Future work includes refining the electro-tactile feedback mechanism, expanding the

range of tactile sensations, and integrating the system with more VR applications. Further research might focus on enhancing the portability and usability of the device, making it more practical for widespread use.

In conclusion, our project successfully developed an innovative electro-tactile feedback mechanism for VR gloves, enhancing immersion and user experience in VR environments. By building on previous research and integrating advanced hardware and software components, the project provides a promising solution for more realistic and immersive VR interactions.

Sanal Gerçeklik Eldivenleri için Elektro-dokunsal Geribildirim Mekanizmalarının Araştırılması

(ÖZET)

Bu proje, VR eldivenleri için elektro-dokunsal geri bildirim mekanizmaları geliştirerek Sanal Gerçeklikte (VR) bulunma hissini artırmaya odaklanmaktadır. Kullanıcı deneyimini ve sürükleyiciliği önemli ölçüde etkilediği için sanal gerçeklikte bulunma, sanal gerçekliğin çok önemli bir yönüdür. Sanal Gerçeklik kontrolcülerinde ses ve dokunsal geri bildirim gibi geleneksel geri bildirim mekanizmaları kapsamlı bir şekilde araştırılmıştır, ancak dokunsal geri bildirim yeterince gelişmemiştir. Bu proje, elin dorsal tarafına yerleştirilen elektrotlar kullanılarak Median ve Ulnar sinirlerin elektriksel uyarımı yoluyla dokunsal geri bildirim elde eden Tanaka ve arkadaşlarının çalışması gibi önceki çalışmalara dayanmaktadır.

Literatür araştırması, dokunsal geribildirime yönelik çeşitli yaklaşımları vurgularken, projemiz donanım, mikrodenetleyici aygıt yazılımı, OpenVR uyumlu bir sürücü ve bir demo uygulamasından oluşan kapsamlı bir sistem öne sürmektedir. Dokunsal geri bildirim mekanizması, özellikle Median ve Ulnar sinirleri hedef alan elektrik stimülasyonunu kullanır. Tanaka ve arkadaşlarından esinlenen bu yöntem, palmar taraftaki dokunmayı etkili bir şekilde uyarmak için elin dorsal tarafına elektrotlar yerleştirmeyi içerir.

Donanım: Donanım, elin palmar tarafında bir elektrik stimülasyonu sağlamak için elin dorsal tarafına bir eldiven şeklinde stratejik olarak yerleştirilen elektrotları içermektedir. Elektrik devresi etkili stimülasyon sinyalleri oluşturmaktadır.

Aygıt Yazılımı: Mikrodenetleyici aygıt yazılımı, elektrik stimülasyon sinyallerini işlemek ve geri bildirim mekanizması üzerinde hassas kontrol sağlamak için tasarlanmıştır.

Sürücü ve İletişim Yığını: OpenVR uyumlu bir sürücü, VR sistemi ile dokunsal geri bildirim donanımı arasındaki iletişimi sağlayarak VR ortamlarıyla sorunsuz entegrasyon ve etkileşim sunmaktadır.

Demo Uygulaması: Bir demo uygulaması, geliştirilen sistemin yeteneklerini sergileyerek kullanıcıların VR senaryolarında gelişmiş dokunsal geri bildirimi deneyimlemelerine olanak tanımaktadır.

Geliştirilen sistemin etkinliğini test etmek için bir deney ortamı kurulmuştur. Deneyler, kullanıcıların ellerindeki farklı konum kombinasyonlarının elektro-dokunsal mekanizma aracılığıyla uyarıldığı çeşitli senaryoları içermektedir. Deneyler, sistem tarafından sağlanan uyarımın doğruluğunu ve verdiği hissi değerlendirmeyi amaçlamıştır.

Değerlendirme için ise, projenin ara raporda belirtilen tüm değerlendirme kriterlerini karşılama hedefine ulaşılmıştır. Geliştirilen sistem mevcut çözümlerle karşılaştırılmış ve el hareketini kısıtlamadan gerçekçi dokunsal geri bildirim sağlama konusundaki avantajları öne çıkmıştır. Projenin yaklaşımı, VR alanındaki diğer mevcut çözümler ve araştırmalarla karşılaştırıldığında, VR uygulamalarında sürükleyicilik ve kullanıcı

deneyiminde önemli bir gelişme sunmaktadır.

Gelecekteki olası çalışma alanları arasında elektro-dokunsal geri bildirim mekanizmasının iyileştirilmesi, dokunma hissi aralığının genişletilmesi ve sistemin daha fazla VR uygulamasıyla entegre edilmesi yer almaktadır. Daha ileri araştırmalar, cihazın taşınabilirliğini ve kullanılabilirliğini artırmaya odaklanarak yaygın kullanım için daha pratik hale getirebilir.

Sonuç olarak, projemiz VR eldivenleri için yenilikçi bir elektro-dokunsal geri bildirim mekanizmasını başarıyla geliştirerek VR ortamlarında sürükleyicilik ve kullanıcı deneyimini artırmıştır. Önceki araştırmaların üzerine inşa edilen ve gelişmiş donanım ve yazılım bileşenlerini entegre eden proje, daha gerçekçi ve sürükleyici VR etkileşimleri için umut verici bir çözüm sunmaktadır.

Contents

1 Introduction and Project Summary **1**

2 Comparative Literature Survey **2**

3 Developed Approach and System Model **3**

3.1 Developed Approach 3

3.1.1 Tactile Feedback through Electrical Nerve Stimulation 3

3.1.2 Hardware 4

3.1.3 Firmware 6

3.1.4 Driver 7

3.1.5 Demo Application 7

3.2 System Models 9

3.2.1 Data Model 9

3.2.2 Structural Model 10

3.2.3 Dynamic Model 11

4 Experimentation Environment and Experiment Design **12**

5 Comparative Evaluation and Discussion **14**

5.1 Evaluation 14

5.2 Comparative Analysis 15

6 Future Work **16**

7 Conclusion **17**

1 Introduction and Project Summary

Virtual Reality has been gaining prominence in the tech industry ever since the inception of the technology, which was first born in the form of stereoscopes, which are essentially optical tools that enable humans to feel immersed in static pictures. As the world stepped through technological advances, this has evolved into head-mounted displays, which are the most common VR devices in the market.

Immersion shows itself as one of the primary expectations of people from Virtual Reality. In a study conducted by Jang and Park examining the roles of presence and enjoyment in the adoption of VR games, the importance of immersion was emphasized and the tendency of the overall VR technology development in the direction of improving immersion and reality was noted [1]. In the study, they also noted that users feel more immersed in the virtual environments by interacting with objects if there is a high degree of presence, which they described as users' experience in virtual reality and feelings of immersion in the virtual environment fostered by VR technologies. They also concluded that players' continual intention to use VR technologies was highly impacted by perceived presence in the virtual environment and the effect of this was even greater than that of perceived cost and enjoyment.

To achieve a higher level of immersion, different feedback mechanisms have been invented. These feedback mechanisms range from specifically crafted audio to haptic feedback in the controllers. Tactile feedback, however, is missing in most of these solutions. This topic is an active field of research and there were several different attempts to deliver tactile feedback to users. Examples can be given as the haptic glove by Meta Reality Labs [2], and the force feedback glove by Fang et al. [3]. A lesser-known type of tactile feedback is through electrical stimulation. In a 2012 study, Kajimoto aimed to render tactile feedback on the hand using a cylindrical device covered with hundreds of small electrodes on the surface [4]. This device, held by the user, precisely stimulates the mechanoreceptors under the skin, replicating the feeling of touch.

More recently, an award-winning study conducted by Tanaka et al. [5] solved the problem of Kajimoto's device constantly needing to hold the device, which severely limited its usability. Tanaka et al. proposed stimulation through electrodes located on the back side of the hand to achieve stimulation, completely freeing up the palmar side of the hand.

Our project aims to build upon the system built by Tanaka et al., enabling further capabilities such as temporal multiplexing, and integrating it with textile technologies to make the device portable and easier to use, enabling the device to be used conveniently in practical applications. The device has also been complemented by software to unlock its full capabilities in a smooth way for users.

2 Comparative Literature Survey

Conceptually, our project takes its foundation from the study published by Tanaka et al., which proposes a system for rendering tactile feedback on the palmar side of the hand through the use of electrodes placed on the dorsal side, stimulating median and ulnar nerves [5]. In this study, they achieved 11 separate zones that can be stimulated for touch. Initially, we replicated the findings presented in this study for our project. Then, we aimed to further improve the design and usability of the system by bringing the electrodes together on a glove and creating a robust software stack.

In another study, Kajimoto aimed to render tactile feedback on the hand using a cylindrical device covered with hundreds of small electrodes on the surface [4]. This device, held by the user, precisely stimulates the mechanoreceptors under the skin, replicating the feeling of touch. While directly stimulating the mechanoreceptors is effective in stimulating touch, the device requires to be held constantly and forces the hand in a certain posture. These reduce the comfort of use, while also making grasping other objects in VR impossible. The glove format of our project does not suffer from said issues.

In 2021, Meta Reality Labs Research team published a blog post [2] showcasing their prototype haptic glove. This glove uses physical actuators placed on top of fingers, moving accordingly to the input to invoke tactile feedback. In the post, they also note the impracticality of using mechanical actuators due to the heat output, while mentioning the need for hundreds of actuators for a realistic sense of touch.

Another study aiming for virtual tangible object interactions [3], published by Fang et al., uses retractable wires to put the hand in a certain position while rendering tactile feedback through force. The system uses a device that is placed on the shoulder and controls the wires attached to the glove. This system, in contrast to the others aforementioned, can also render force feedback, creating a more realistic experience. However, due to the retractable wires, the system significantly hampers the free movement of hands. Our design allows for more flexibility for hand movement, enabling the possibility of a wide range of object interactions.

Another project called Lucid Gloves tries to achieve haptic force feedback from household or easily obtainable materials for a fraction of the cost of retail haptic solutions [6]. It uses servo motors to restrict the movement of the fingers, emulating the feeling of grasping things in Virtual Reality. While this solution achieves realistic force feedback, it lacks precise control over the location of the touch, and its being clunky might restrict the movement of the hands. They have also modded some games to work with their glove, and similarly, we have created a compatible interface on our driver to work with existing games.

A study by Chan and Torah has demonstrated the use of textile-based electrodes for haptic feedback VR applications. That device, however, has only six channels and a very simple electronic circuit, resulting in a limited range of sensory feelings [7].

3 Developed Approach and System Model

Our system consists of 4 main parts: hardware, microcontroller firmware, OpenVR compatible driver with device communication stack, and our demo application.

3.1 Developed Approach

3.1.1 Tactile Feedback through Electrical Nerve Stimulation

To achieve tactile feedback through electrical stimulation, the project utilizes the methodology proposed by Tanaka et al. [5]. This method achieves electro-tactile feedback by stimulating two nerves, namely the Median Nerve and Ulnar Nerve, through electrodes placed on the dorsal side of the hand. The electrode placements and electrical signal levels were decided based on the findings of the 6-month experiments in the article [5].

In the experiments of Tanaka et al., it was discovered that if the distance between the stimulation electrode at the back of the hand and its respective ground increases, then the stimulation is felt at the palmar side of the hand rather than the dorsal side. Therefore, the ground electrodes are placed on the back of the hand, close to the wrist.

This presents another problem where stimulating the dorsal side of the hand results in stimulation in both the palmar and dorsal sides. The mitigation of this problem lies in sending stimulation signals that are on a strength that is above the stimulation threshold of the palmar side mechanoreceptors but below the threshold of the dorsal side. There is a big difference between the number of mechanoreceptors on the palmar side (around 18000) and the dorsal side (around 300) [8], which results in a difference between the thresholds, therefore enabling our approach.

Due to the presence of a tendon layer on the proximal side of fingers [9], a proximal electrode is not able to render stimulation on the proximal side of fingers. However, anodic stimulations are already felt closer to the root of the finger, rather than directly below the electrode, as seen in Figure 3.1. This comes with the problem of not being able to stimulate the distal side of the finger. However, as mentioned by Kajimoto [10] and replicated by Tanaka et al. in their stimulation mechanism, cathodic currents are applied to the distal electrodes to shift the perceived sensation closer to the fingertip, achieving stimulation on the distal side.

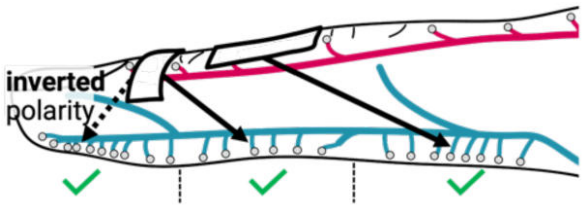


Figure 3.1: Stimulation locations compared to the electrode locations [5]

Lastly, to tackle inter-finger interference, separate ground electrodes were placed on the hand for the ulnar and median nerves, eliminating cross-finger currents. The final placement can be seen in Figure 3.2.

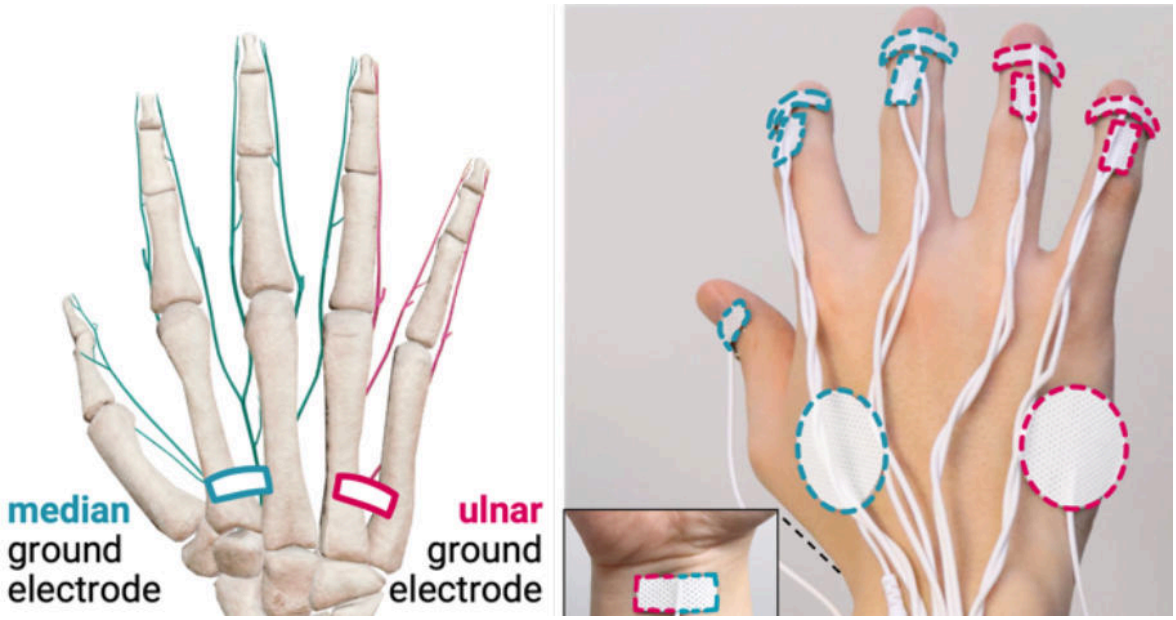


Figure 3.2: Electrode locations compared to nerve paths [5]

During our experimentation with users, test subjects stated that a stimulation signal with a frequency of 120 Hz and a pulse width of 330µs felt the most natural, closest to the real touch feeling.

3.1.2 Hardware

Our hardware is built to create tactile feedback and includes a bespoke power supply unit that creates the direct current voltages our device requires, an electrical circuit that creates the stimulation signals with the desired intensity and sends them to the set locations, and a wearable device in the form of a glove that delivers the signals to the points of contact with high precision.

The power supply unit is built with battery charging and protection circuits (TP4056), adjustable voltage converters (XL6009), and 2 Li-Po batteries for portable use. Using this power supply unit; 5V, 36V, and 72V direct current voltage levels are created. As a prototype, this unit is implemented over breadboards, and the outputs are connected to the rest of the circuit using a single cable as the necessary SMD components could not be obtained.

The electrical circuit for creating stimulation signals first uses a microcontroller (Seeed Studio XIAO SAMD21) that includes a high-resolution digital-to-analog converter (DAC), then the output of the DAC is used as the input of a voltage controlled load independent current source. The voltage controlled load independent current source is implemented with a low-power dual operational amplifier (LM358PWR), an NMOS

transistor (IRF540 THT or 2SK2055 SMD), and two BJT PNP transistors (BDX54C THT or BF623 SMD). The output of the voltage-controlled load-independent current source is then passed through an analog switch to redirect the signal to the desired electrodes in the wearable device. The schematic of the circuit is given in Figure 3.11.

For the final product, the electrical circuit is built on a custom-manufactured PCB. The PCB includes external connections for the microcontroller, HC-05 Bluetooth module, power, and electrodes. To contain the PCB, microcontroller, and Bluetooth module, a custom box is designed and 3D printed as can be seen in Figure 3.3.



Figure 3.3: Box Design

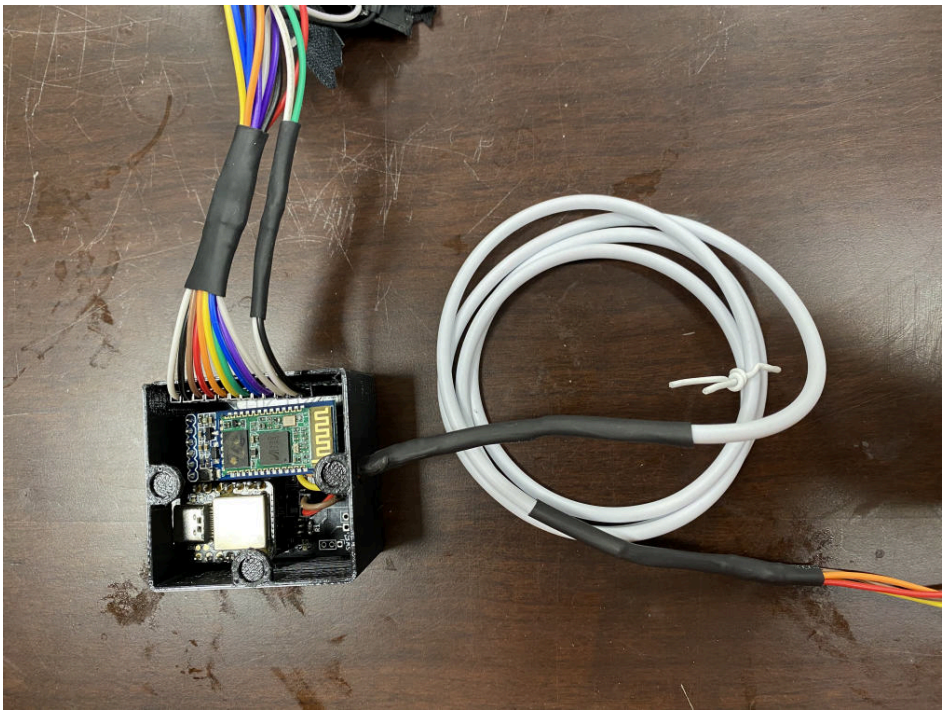


Figure 3.4: Assembled Device

The wearable device is created from a standard glove base. For the electrode placements, several cutouts are made in the glove at the right locations. Electrodes are im-

plemented using Shieldex® brand silver coated woven conductive fabric, and a sponge-like fabric for applying pressure on the electrodes. Electrode connections are made using conductive stainless steel yarn and these yarn connections are then crimped to regular copper jumper cables for connection with the circuit. Textile electrodes and cables are fixed in place on the glove using a fusible film layer on top.



Figure 3.5: The Developed Glove

3.1.3 Firmware

Our microcontroller firmware receives commands from a serial interface and controls the electrical circuit.

In the main loop, the firmware first evaluates received serial commands. Serial commands are in the form of $IxJxKxLxMxNxOxPxQxRxSxTxUxVxWxXxYx$ where x is the strength value, a value between 0-1023, and $IJKLMNOPQRSTUVW$ prefixes correspond to each location in the hand where stimulation is possible, as shown in Figure 3.9. Frequency and pulse-width parameters can also be encoded in the command using X and Y prefixes, respectively. Serial input is given over a Bluetooth connection with the integrated HC-05 Bluetooth module in the circuit.

After the serial inputs are evaluated, the stimulation cycle begins. During the stimulation cycle, the stimulation signal is generated with the set parameters. The signal is only given to one electrode at a time to reduce interference between channels and division of the current, to achieve a clean stimulation. To achieve multi-location stimulation when using only one electrode at a time, a temporal multiplexing approach is utilized. In each cycle, stimulated electrodes, and the direction of current between

electrodes, if necessary, are alternated using the analog switch. Since the switching takes around 20µs and the pulse width used is around 330µs, this quick alternation was found not to be perceivable.

Our source code for the firmware can be found at https://github.com/JVTTeam/JVTFirmware.

3.1.4 Driver

The driver facilitates the communication between the applications and the device, providing a stable interface for the applications to supply the feedback data.

The driver is built as an OpenVR driver, allowing it to be automatically loaded with VR games. This also allows for extensibility in the driver, enabling easy integration for hand tracking and such features. As the driver is loaded, it initializes structures from the communication sub-module.

The communication sub-module of the driver handles the communication between applications and devices. For applications to write feedback data, it creates a named pipe interface. This interface expects integer feedback strength values for each location in the finger, whose values are calculated by applications using collision locations and the surface features of the interacted objects. After an application sends feedback values to this named pipe, the driver forms the serial command in the expected structure of the firmware and sends this message over to the serial port where the device is connected. For compatible operation with existing applications that support force feedback in the form of OpenGloves interface (used by LucidGloves project [6]) the driver creates a compatible interface as well, which translates the feedback data to the format of our device. This allows our device to readily work with some widely popular VR games, such as Half-Life: Alyx.

The driver also has support for connecting with two devices at a time, allowing both hands to be used for tactile feedback at the same time.

The system architecture of our driver is shown in Figure 3.10. Our source code for the driver can be found at https://github.com/JVTTeam/JVTDriver.

3.1.5 Demo Application

Our demo application is built to showcase the features of our system. It has been built in Unity as a 3D game. Due to not having access to a VR headset with hand-tracking capabilities during the development process and to allow use without a VR setup, a hand-tracking approach through external cameras has been implemented. Google's MediaPipe Hand Landmarker model [11] has been used to detect Euclidean coordinates of various points in the hand, as seen in Figure 3.6. This data is then passed through a UDP connection, to enable the use of cameras outside of the host system. This is all handled in the Python script JVTHandTracking, where the source codes can be found

at https://github.com/JVTTeam/JVTHandTrackingPython. Additionally, the Hand Tracking script can be seen in action in Figure 3.7.

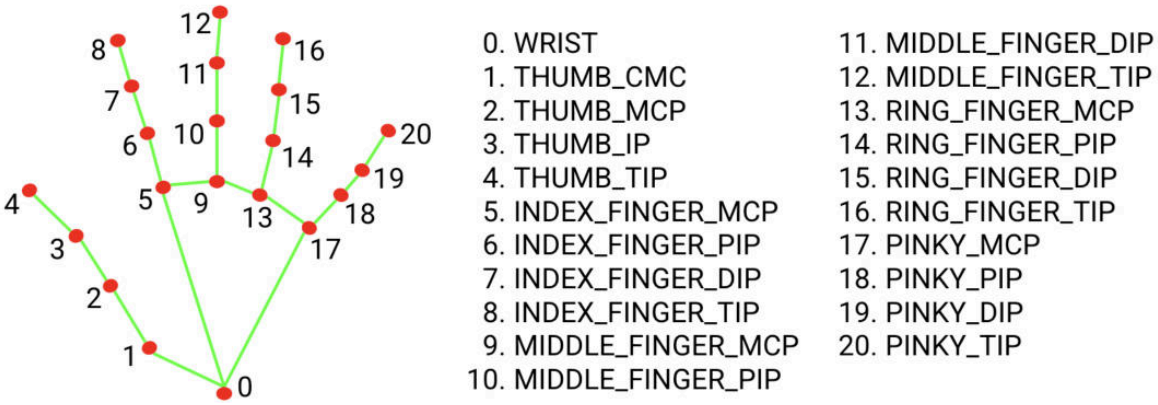


Figure 3.6: Points detected by MediaPipe Hand Landmarker [11]

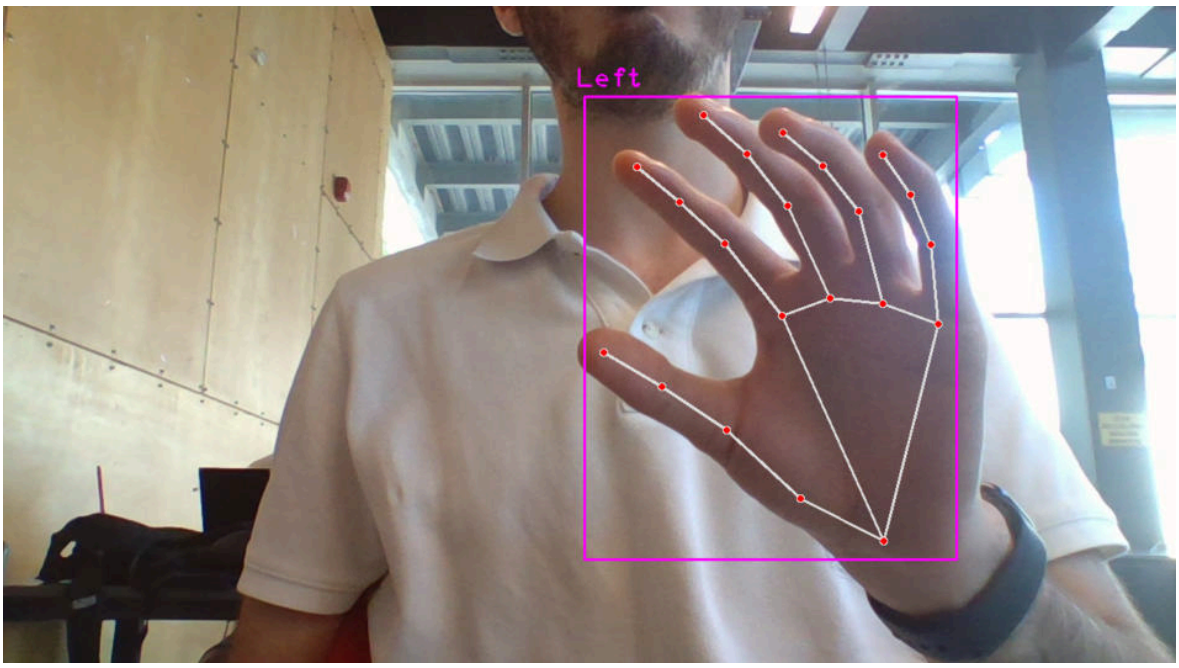


Figure 3.7: JVTHandTracking script in action

The points are then received in Unity through UDP, and mathematical operations are done on the coordinates to render a 3D hand model on the screen.

The demo features a set of 3D objects of varying shapes and sizes on a surface. A user can touch and grab those objects with just a move of their hands. The collisions of the 3D hands and the in-game objects are then calculated for all of the possible stimulation points and then passed to the named pipe interface supplied by the driver.

This way, input is taken from the user in the form of points detected through the camera, and output is given to the user in the form of electrical stimulation on the wearable device.

A screenshot from the demo application in use can be seen in Figure 3.8.

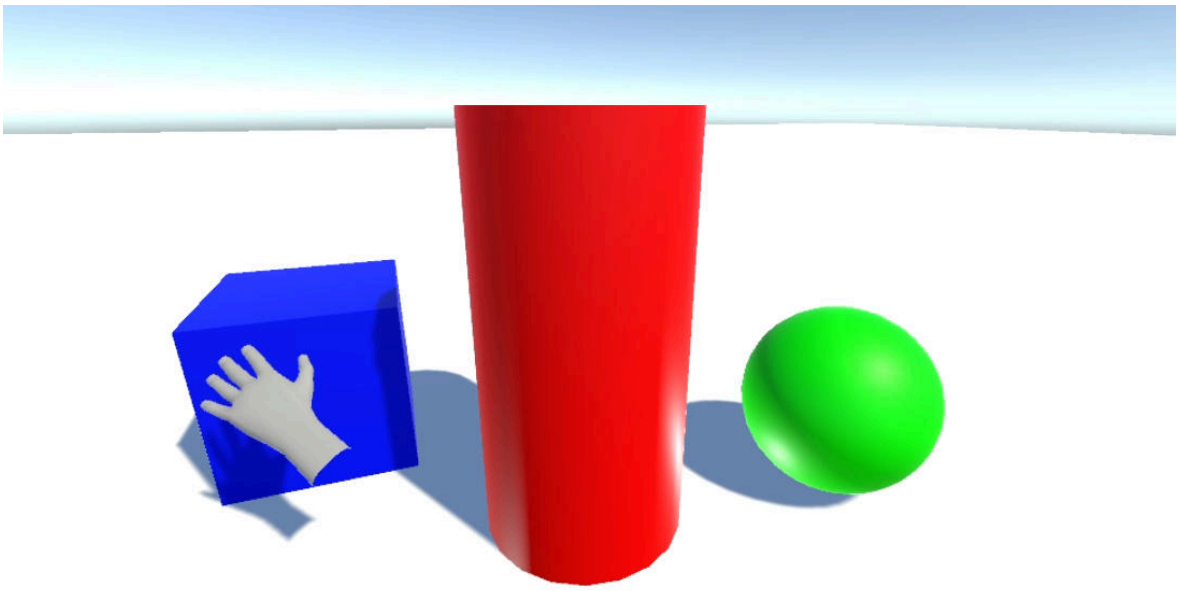


Figure 3.8: Demo application in use

Our source code for the demo application can be found at https://github.com/JVTTeam/JVTDemo.

3.2 System Models

3.2.1 Data Model

The stimulation signal format in the firmware, as mentioned in Section 3.1.3 maps to the locations on the fingers as shown in Figure 3.9.

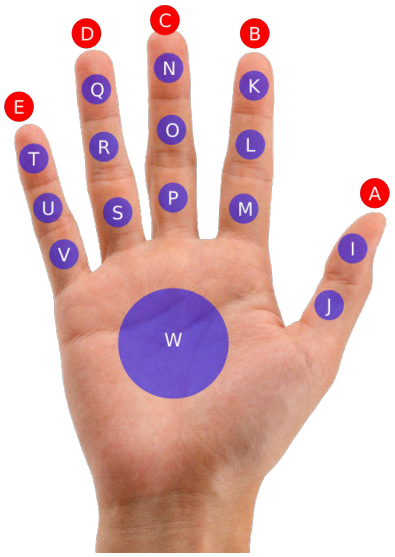


Figure 3.9: Map of where stimulation zones correspond to at the hand

Our driver employs a heavily object-oriented approach, consisting of two packages. The UML Class Diagram of the driver design can be seen in Figure 3.10.

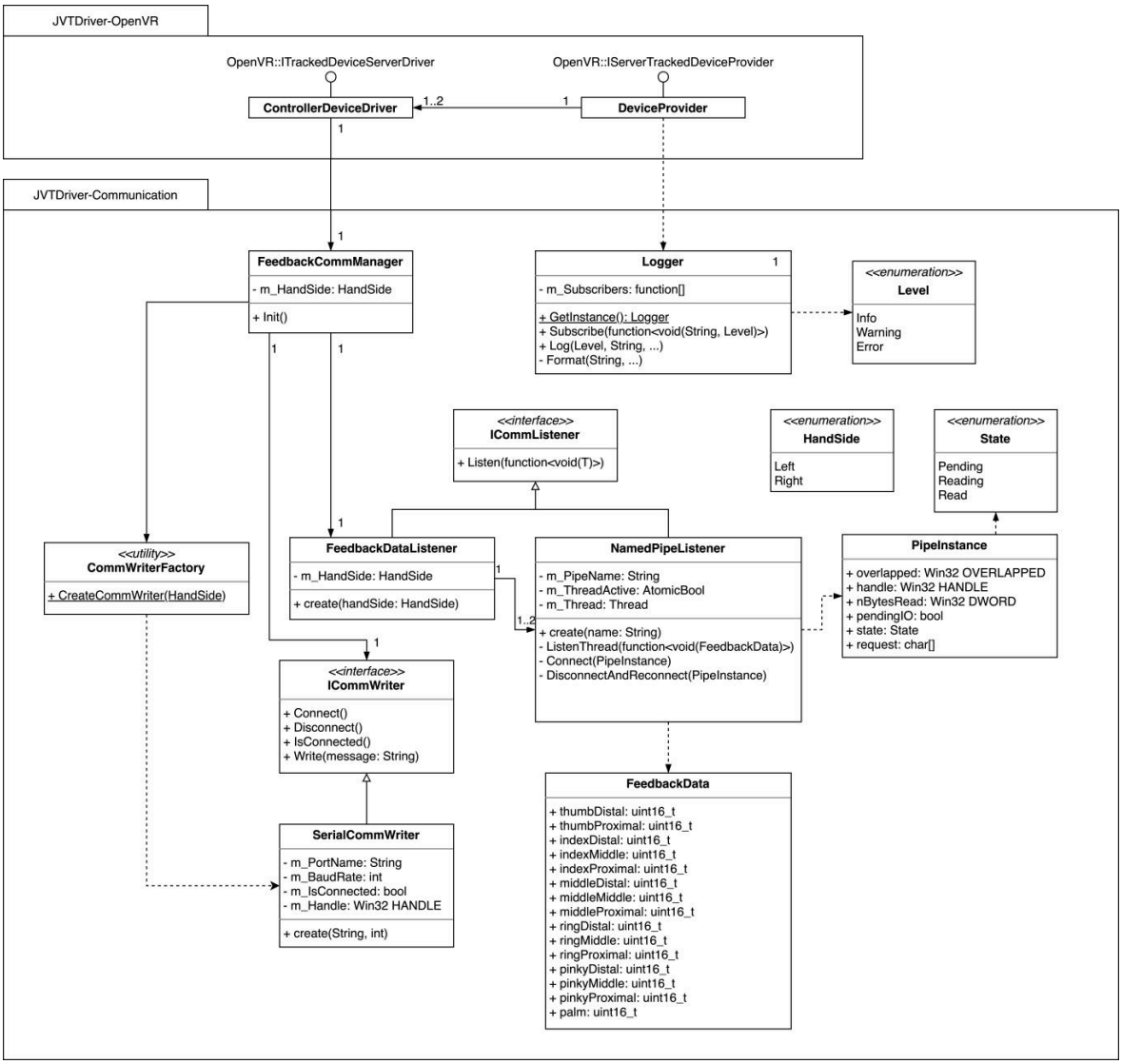


Figure 3.10: The architecture and design of our driver

3.2.2 Structural Model

Our hardware structure can be seen in the schematic in Figure 3.11.

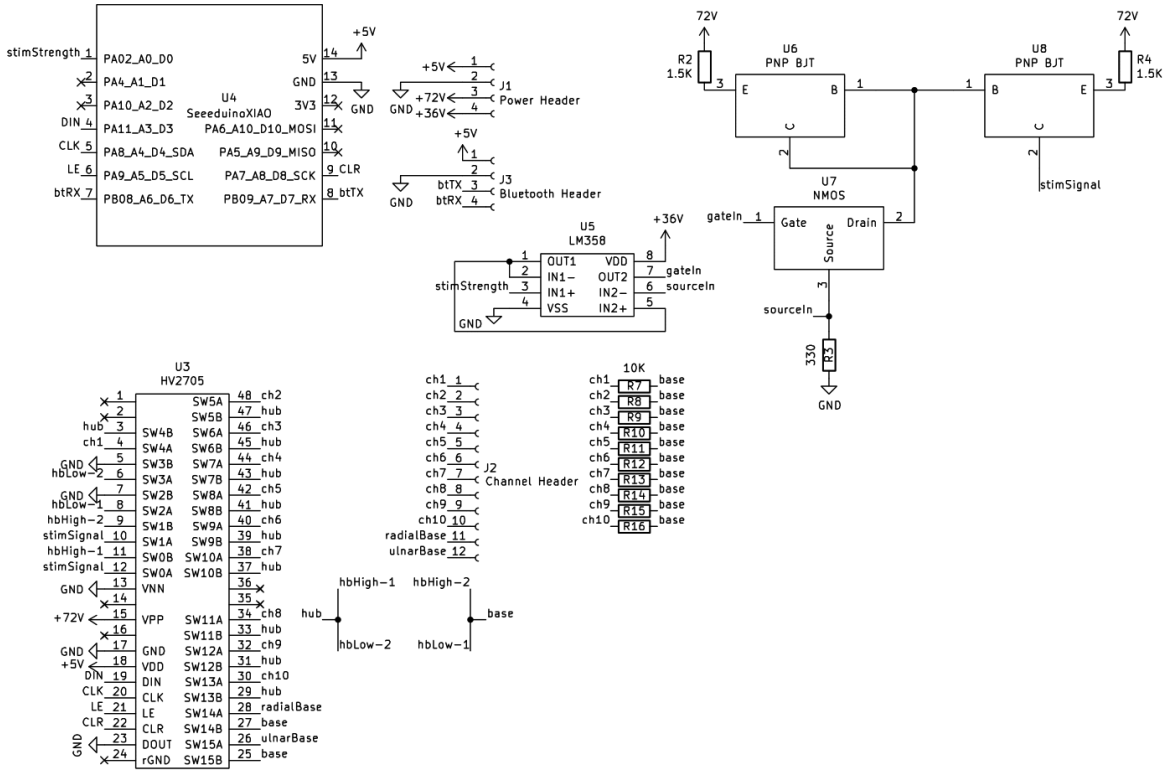


Figure 3.11: Schematic of the Electrical Circuit

3.2.3 Dynamic Model

The sequence diagram showing the interactions of the user, the wearable device, the firmware, the driver, and an application can be seen in Figure 3.12.

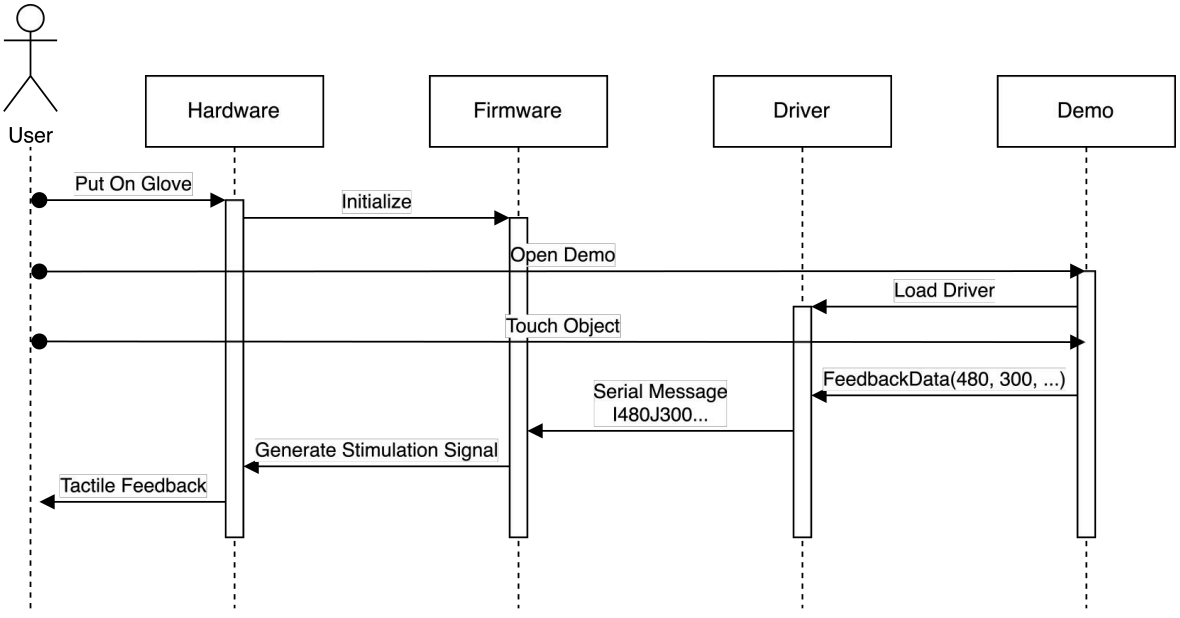


Figure 3.12: Main use case sequence diagram

4 Experimentation Environment and Experiment Design

The experimentation of our project was done in two separate phases: testing during development and user experience surveys.

During the development of the hardware, an oscilloscope was used to probe various stages of the electronic circuit, to fine-tune the electrical characteristics of the device to generate a healthy electrical signal safe for an exposed human hand. This way, a constant current source was configured properly and safely for the use case of electrical stimulation. Then, a detailed analysis was done on the analog switch of the system to find the internal electrical characteristics. All of the collected data was put together to build the final version of the circuit.

After the circuit was finalized, the whole system was tested on five volunteering users. The user tests consisted of two stages:

1. **Incremental Stimulation**: The stimulation strength was incremented in small steps for each channel to find exactly at which stimulation level users felt a touch sensation and the location of the touch. Similarly, the stimulation was increased further up until the point where users reported an uncomfortable feeling. This way, the minimum and maximum signal strengths were noted for every user. Although there were fluctuations, most of the users had a similar range of usable stimulation strength levels, where the variance was 21 percent between the testers with the highest and lowest stimulation ranges.
2. **Temporal Multiplexing Blind Test**: A sequence of various stimulation combinations was given to the users, in a medium stimulation strength calculated from the previous step. The users were asked where they felt the touch sensation. Most of the time, the users have stated that a sensory feeling was achieved where the test cases intended. There were some cases where the feeling was not in the targeted area, but it was still within the same finger. It was observed that this was due to the electrode placement on the hands of the users.

When it comes to the details of the achieved sensory feeling, users reported that it feels "tingly" at the first instant the stimulation is activated, however, it leaves its place to a proper pressure feeling quickly. One user has reported an "electrical" feeling, and it has been mitigated by changing the frequency and pulse width parameters of the stimulation signal.

The tests have been conducted systematically by utilizing our Controller UI, JVTControlUI, where the source codes can be found at https://github.com/JVTTeam/JVTControlUI. The UI can be seen in Figure 4.1.

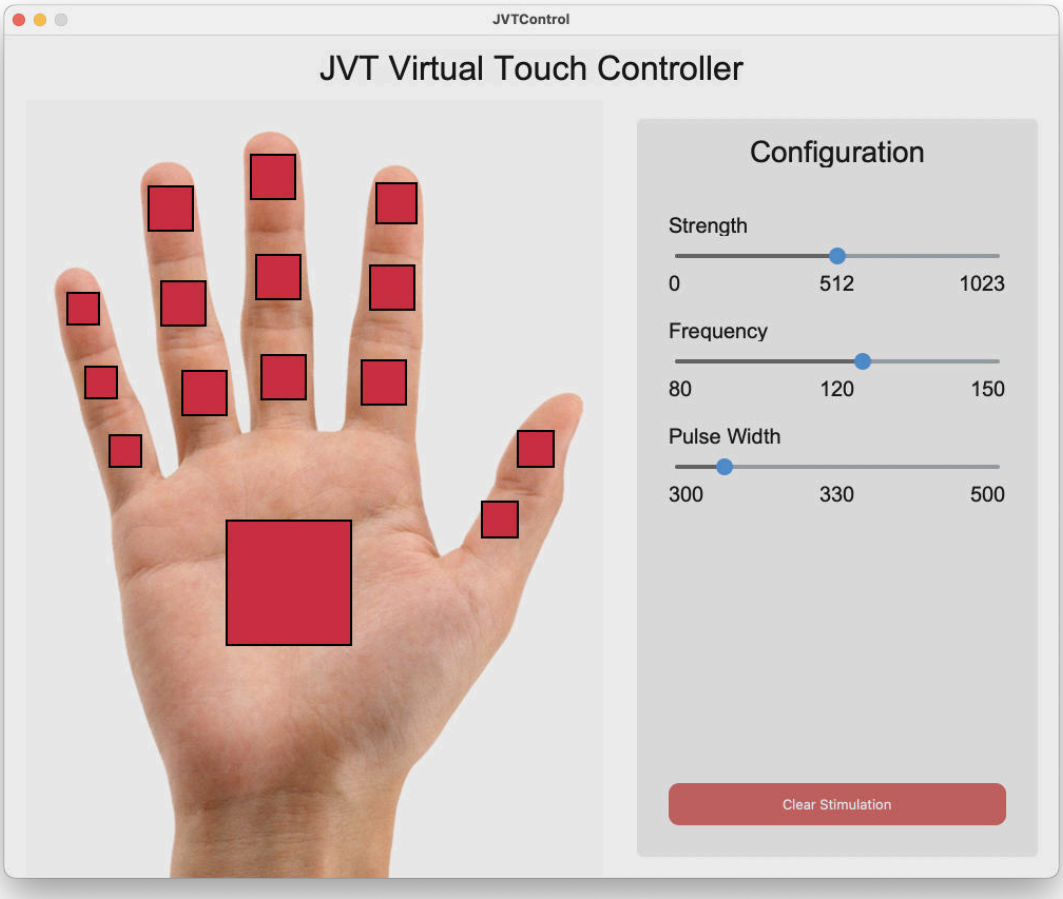


Figure 4.1: The control UI

5 Comparative Evaluation and Discussion

5.1 Evaluation

The final product has full hand coverage, specifically in 15 regions. Careful electrode placement eliminates the overlap in the middle section of the index, middle, ring, and pinky fingers, and this is achieved thanks to the ability to fix the locations of the electrodes in the textile-based wearable device. This region count is even larger than the initial plan from the evaluation criteria *Full hand coverage (11 regions) with the electro-tactile glove* from the interim report.

The control interface, JVTControlUI has 100% coverage over the capabilities of the device. Therefore, it is a quintessential tool for experimenting with and testing the device. It also has an extremely simple-to-use user interface which makes it very easy to specify the kind of stimulation to deliver. This is in line with the evaluation criteria *Interface to control and test 100% of the capabilities of the electro-tactile glove* from the interim report.

Additionally, the driver is also able to access all of the features of the hardware through Bluetooth, making the system portable and wireless. It also simplifies the usage of the device, as only the driver installation step is needed before the device is ready to use.

The demonstration application puts all of the aforementioned components together and brings together a platform, able to test out all of the features of the device. No need for specific VR equipment is required, as the JVTHandTracking script can move real hands into the virtual reality environment through computer vision. This is in line with the evaluation criteria *Demonstration application to cover 100% of the capabilities of the electro-tactile glove* from the interim report.

In our experiments of the device with volunteering users, the question *"Were you satisfied with the device?"* was posed to the testers. All of the testers have stated that they were satisfied. Some feedback and improvement points were also received from the testers, and they can be seen in further detail in Section 4, though testers have explicitly stated that they were still satisfied. This is in line with the evaluation criteria *At least 70% positive feedback from testers for the electro-tactile glove* from the interim report.

A comprehensive literature research has been conducted, and the findings were utilized throughout the project. The literature survey is presented in this report in Section 2, in line with the evaluation criteria *100% documentation and presentation of the literature researched* from the interim report.

Lastly, the driver's interface has been condensed down to just communicating with a named pipe, and its installation process is free of any additional steps. The driver can just be downloaded and run, substantially simplifying the process. The documentation on how to communicate through the named pipe is provided in the repository of the driver. This is in line with the evaluation criteria *100% documentation coverage of all of the driver software* from the interim report.

5.2 Comparative Analysis

When it comes to comparative analysis between our approach and similar work from literature, there are three main similar projects from before:

- **Tanaka et al.** [5]: This study could be considered the main basis of our project. However, this study utilized off-the-shelf electrodes instead of having them embedded in a wearable device as in our approach, making it harder to put on and take off. This also came with the problem of being prone to wrong electrode placement, resulting in meaningless sensations on the hand. There were a lot of exposed wires, making it harder to set up with brand-new electrodes. The variability with the electrode placements also resulted in an overlap of stimulated areas in the middle sections of four fingers, limiting the number of zones to 11 rather than 15. Additionally, the software stack published on the researchers' website was lacking in usability, as no driver was ever made. Also, all control inputs were taken through the serial interface without any abstractions, making it harder to program practical applications fit to run with their device.

- **Kajimoto** [4]: This study was more of a proof-of-concept than an applicable solution, as it required a handheld device to stimulate the mechanoreceptors. It obstructed the hand fully and gave no room to use the hands both as input for some other application and output for electro-tactile feedback.

- **Chan and Torah** [7]: This study had a very low amount of channels. Additionally, it only provided anodic stimulation signals, reducing the number of possible stimulation zones down to 6, compared to the 15 zones our device has. The study also lacked a software stack for application integration, hindering its usability in practice.

- **Meta** [2]: This glove works by utilising microfluidic actuators. The contraption to achieve haptics through microfluidics comes with the price of size and weight, hindering the dexterity of the hand, and limiting the use of the device when holding real-life objects, as it can completely block the movement of the hand, where the parts of our device on the hand are only consisting of various kinds of fabric, which is lightweight and flexible.

- **LucidVR** [6]: This glove utilizes mechanical force feedback to block the movement of the hands, making it tiring to use over an extended period due to the extra friction created by the strings and the spools. Additionally, the glove is very heavy and chunky due to the large amount of servo motors used, which also contributes to the previous aspect. It is also more prone to breakdowns due to having a large amount of moving parts, whereas our device has no moving parts.

6 Future Work

The focus of our project was investigating the possibility of rendering multi-channel electro-tactile feedback on a textile-based wearable device with user-friendly and easily portable drivers, compatible with industry-standard frameworks. However, with the constraint of having to finish the project within one academic year, some future improvement points were discovered but were not managed to be achieved.

- **Stimulation to feel textures**: Germani et al. [12] achieved electro-tactile feeling of textures in their study. A more complex circuitry can be designed, along with its complementary software to add texture to the touch sensation, as right now the only feeling is pressure. However, this requires very thorough research.
- **Multi-zone electrode calibration**: As the hand size, skin resistance, and precise nerve locations differ from person to person, and as the system requires very specific placement of electrodes on the hand, the wearable device does not work at its best for everyone. A multi-zone electrode setup can be built and an automatic calibration step could be added to the driver, to deliver the ideal stimulation signals to the best electrodes for that specific user.
- **A different wearable device format**: One of the ideas when working with a wearable device with a glove form factor was to instead have rings to be put on to fingers, and the wrist electrode and ground electrode implanted into a hand wrap for the base of the hand. This way, the problem of a glove not fitting the hand, or staying loose and losing out on full electrode contact could be mitigated.

7 Conclusion

Based on the findings of previous research, an electronic nerve stimulation system was created to achieve precise tactile feedback at several locations at the hands of a user. The hardware required to achieve said tactile feedback was implemented in a compact box with full Bluetooth connection support and the ability to run with battery power. The electrodes have been implanted into a glove by utilizing state-of-the-art textile technologies to allow seamless use by end users. A robust software stack consisting of firmware and a driver was also created to fully utilize the system conveniently and seamlessly. The driver allows for applications that support tactile feedback to be further developed by providing an easy-to-use interface for application developers. A 3D demo application was developed to showcase the capabilities of our system to potential users. Additionally, a basis was created for further improvement points, and we believe that with these improvements, the device shows promising value to be turned into a successful commercial VR product in the future.

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