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Projekt dyplomowy

Construction of VR gloves with a Force Feedback based on an existing project

Budowa rękawic VR ze sprzężeniem zwrotnym (Force Feedback) na podstawie istniejącego projektu

Autorzy: Jacek Budny, Maciej Kowalik
Kierunek studiów: Teleinformatyka
Opiekun pracy: dr inż. Jarosław Bułat

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Introduction

The primary objective of this engineering thesis was to construct a prototype based on an existing open-source virtual reality glove project. This glove has advanced features such as force-feedback capabilities and finger position tracking. The integration of these functionalities aims to offer users an immersive experience, allowing them to engage in virtual environments with a level of realism other wisely not achievable. By simulating tactile sensations and capturing hand movements, this glove stands at the forefront of technological evolution in the realm of virtual reality. The potential implications of such advancements are vast, promising to reshape how individuals interact with and perceive virtual worlds.

The inspiration for starting this project was varied, originating from a strong interest in the fast-growing VR field. More than just interest, the project was driven by an aspiration to learn about and contribute to the latest advancements in virtual reality. Approximately two years prior, the journey began when the authors of this project found an early version of an open-source VR glove project. In its initial phases, the gloves featured just finger tracking. Notably, it is worth mentioning that this open-source project was started by a high school student. Inspired by this, there was a determination to create the prototype. In addition, this sparked a desire to learn more and make improve upon the existing design.

In this engineering thesis, Jacek Budny was involved in modifying 3D models, designing the control board housing, printing parts, developing the circuit board and assembling the glove. Maciej Kowalik focused on researching the current situation in the VR industry, testing the glove, developing a test environment and comparing the glove with existing solutions on the market.

1 Virtual reality gloves

This chapter explores the current state of the VR market and discusses various solutions related to force-feedback in VR gloves. However, before looking at recent progress, it is essential to know about the history of virtual reality.

Virtual reality, often seen as a relatively modern technology, has its origins from many years ago. To define its beginnings, a clear definition is important. For our discussion, we consider virtual reality as a device that requires computer operation (thus excluding simple 3D images and movies) and has dual screens showing slightly different views. Using this definition, one of the earliest VR systems dates back to 1968, created by Ivan Sutherland alongside his student, Bob Sproull. This system, known as the "Sword of Damocles", was a large ceiling-mounted device displaying basic wireframe environments.

After this early period, VR technology continued to evolve, though it didn't become widely popular with consumers. A significant moment came in 2013 with the introduction of Oculus's DK1 — a basic VR headset which utilized inexpensive smartphone displays. This innovative approach led to a crowdfunding success, surpassing its target tenfold. It became widely popular due to streaming platforms like YouTube. In subsequent years, both Oculus and HTC independently released their own VR headsets with advanced features, including 6 degrees of freedom for both rotational and positional tracking. These updated versions also introduced VR controllers, allowing users to interact more naturally with virtual environments.

1.1 Current virtual reality market situation

The virtual reality (VR) sector is experiencing a significant surge in popularity. Recent statistics emphasize this trend, with the NPD Group reporting sales of approximately 9.6 million VR and AR units in 2022 alone. Such impressive figures naturally attract industry giants and innovators, leading to a wave of VR device releases and developments. Here are some of the key players shaping the VR market:

- **Oculus (owned by Meta)** - a pioneer in the VR domain stands as the current market leader. Their success can largely be attributed to the Oculus Quest line of VR/AR headsets. Moreover, Meta's broader vision is evident in their recent actions to develop the metaverse.
- **Apple** - is renowned for its selective approach to technology investments. The tech giant is set to debut its first VR/AR headset in early 2024.
- **HTC** - initially, HTC, alongside with Oculus, dominated the VR market. However, their market share has since diminished, and they no longer hold the dominant position they once had.
- **Valve** - known mainly for its famous Steam platform, Valve initially collaborated with HTC. Later on, they went on their own and launched a high-quality VR headset that received a lot of praise.
- **Sony** - using its large gaming ecosystem, Sony launched the PlayStation VR series designed for their gaming systems. Because of how easy it is to use

with PlayStation consoles without requiring a powerful computer, Sony secured about a third of the market in the third quarter of 2023.

– **Other Contenders** - several other entities are worth noting for their contributions or potential impact on the VR market. **Microsoft** and **Pico** are among these, with **Pimax** also making its mark.

1.2 Available virtual reality glove solutions

Virtual reality technology has been advancing steadily, aiming to make users feel even more connected to digital worlds and experiences. As these virtual environments become more detailed and lifelike, there's a growing need for controllers that can capture detailed hand movements. The progression of VR controllers, from simple handheld tools to more sophisticated versions, showcases this ongoing effort. A key part of this progress is adding force-feedback features. These features aim to recreate the feeling of touching and handling virtual objects, making the transition between the real and virtual worlds smoother. As VR continues to grow, finding control methods that feel natural and immersive becomes even more important. Different approaches have emerged, each presenting its own set of solutions and challenges for creating realistic force-feedback experiences.

– **Pulley system with servomechanisms** [1] - this approach employs ropes attached to each finger, which are manipulated by servomechanisms. By either pulling or blocking these ropes, it allows for both tracking finger movement and providing force-feedback. Its appeal lies in its straightforward design and dual functionality.

– **Locking mechanism** [2] - utilizing servomechanisms, this method focuses on extending parts to physically hinder the movement of fingers. Its design is notably compact, making it a favorable choice for those looking to maintain a sleek profile.

– **Blocking each finger joint** [3] - this technique capitalizes on the inherent joints present in each finger. By integrating hinges and utilizing servomechanisms, it restricts finger movement by blocking these natural pivot points. While this method offers an intuitive approach by taking advantage of the finger's anatomy, the complexity might increase due to the need for multiple components per finger.

– **Pneumatic artificial muscles** [4] - in this method, the use of artificial muscles, like the McKibben artificial muscle, is necessary. These muscles contract when a small tube filled with air is pressurized. The result is a force-feedback mechanism that feels more organic. However, the external devices needed to generate and regulate the required air pressure can introduce bulkiness.

– **Pneumatic gel muscles** [5] - similar to the previous method, this approach employs a type of artificial muscle. However, by integrating a thermoplastic elastomer within the muscle structure, it achieves higher force outputs even at reduced pressures. This enhancement, while beneficial, doesn't eliminate the need for external pressure sources.

2 Development of the prototype

This chapter outlines the development process of a virtual reality glove prototype, with a particular emphasis on the second, more refined prototype developed by the authors. Additionally, the first prototype is referenced in certain sections for context and comparison.

2.1 Description of the LucidGloves project

The engineering thesis involved the construction of a glove based on the LucidGloves[2] project, an attempt to create virtual reality gloves with feedback. The solution was originally created by user `lucas-vrtech`, with the involvement of many other contributors. The main goal of the project is to create a cost-effective and simple-to-use virtual reality glove that facilitates intuitive interaction with the virtual environment through feedback. With this feature, the glove allows users to feel the impression of holding objects in the virtual world, thus enhancing a realistic tactile experience. The engineering thesis is dedicated to the construction of the fifth prototype, in line with the numerical sequence of the base project.

LucidGloves project history

The project focuses on the development of the virtual reality glove by continuously improving successive prototypes to gradually increase their functionality and usability. The initial model, referred to as prototype number three, featured technology capable of tracking the user's finger positions. Then, in the fourth prototype, a significant improvement was made in the form of force feedback. This system was based on a set of motors and ropes, allowing the user to experience more realistic touch and movement impressions when interacting with objects in the virtual world. The fifth prototype focused primarily on miniaturizing the modules and abandoning the rope system in favor of 3D printed components. This step was intended not only to further improve ergonomics and user comfort, but also to ease the manufacturing and assembly process of the glove.

LucidGloves project structure

The project consists of several key elements, below is a brief description of each part.

- **3D Printing** - contains 3D models of the parts to be printed, along with a brief description of the printing parameters. The files was share in STL format.
- **Parts** - enumerates all necessary mechanical and electronic components for constructing the glove.
- **Electronic wiring diagram** - contains a description of the implementation of the connections and a schematic diagram showing the structure of the connections of electronic components.
- **Glove assembly instructions** - contains a step-by-step guide for assembling the glove.

– **Software -** contains the source code for the microcontroller, which manages the glove's functionality.

2.2 3D printing of parts

3D printed parts form the foundation of the virtual reality glove, playing a crucial role in its functionality and user comfort. In order to obtain the best results, a thorough process of preparation of these elements, was conducted. The adopted approach involved printing individual pieces, testing their fit, and subsequently refining these pieces by altering their size and shape. This stage resulted in modification of some elements, as detailed later in the text, while others were left unchanged. The included exploded view drawing provides a visual overview of all the glove's components, enhancing a better understanding of their arrangement and function. To improve clarity, the Figure 1 displays only one module responsible for finger operation, though there are five such modules in total. Except for the Rigid Mount, each part of the glove required five prints.

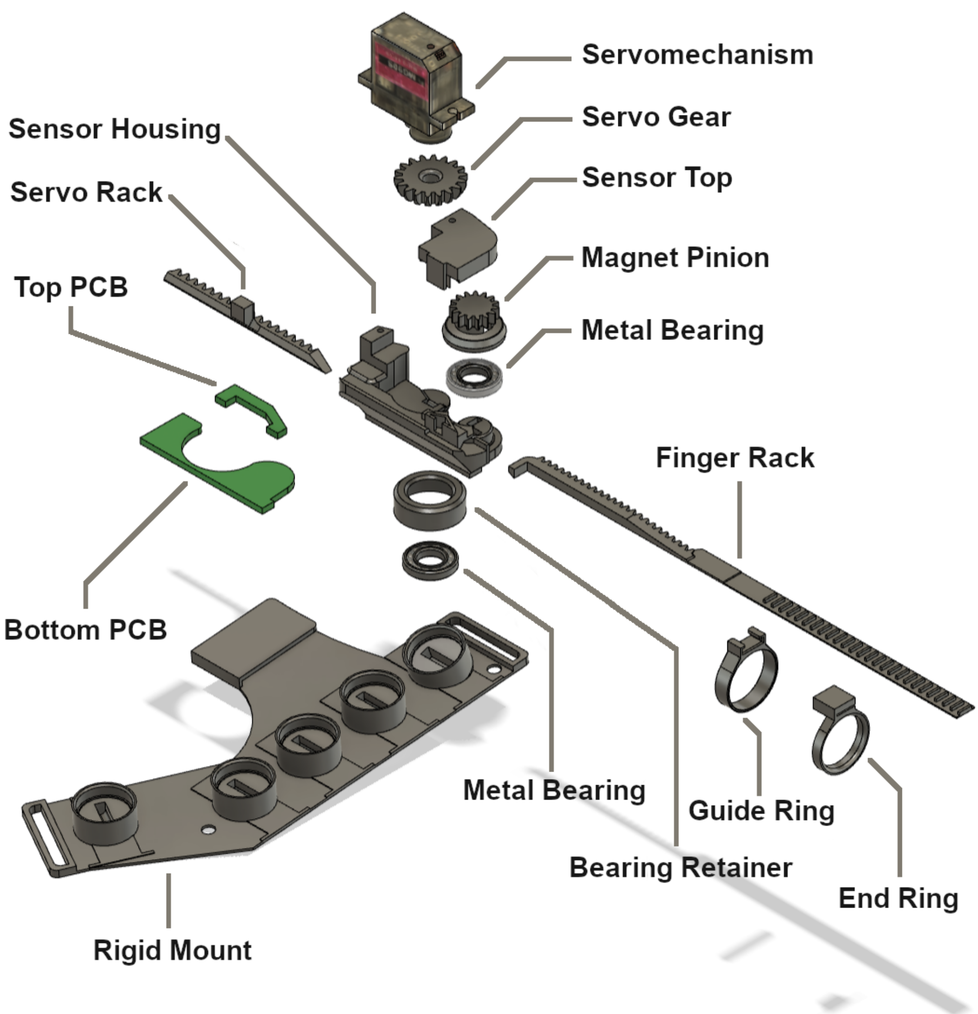

Figure 1: Exploded view of the VR glove

In this step, the authors modified the Sensor Housing, Rigid Mount, and Magnet Pinion, and additionally designed a custom part: the control board housing. Below is a detailed description of this process:

- **Sensor Housing** - this component is critical, as it positions the elements responsible for force feedback and three Hall sensors that gather data on finger position. Embedded on it are two bearings whose tight fit is crucial for the strength and proper functioning of the glove. Lack of fit can result in modules falling out during use, blocking the mechanisms and restricting finger movement. Therefore, it was necessary to adjust the part to ensure the bearings are permanently embedded. The adjustment involved editing the component's mesh to increase the diameter of the pins to for mounting the bearings. The modified planes are highlighted in blue in the Figure 2.

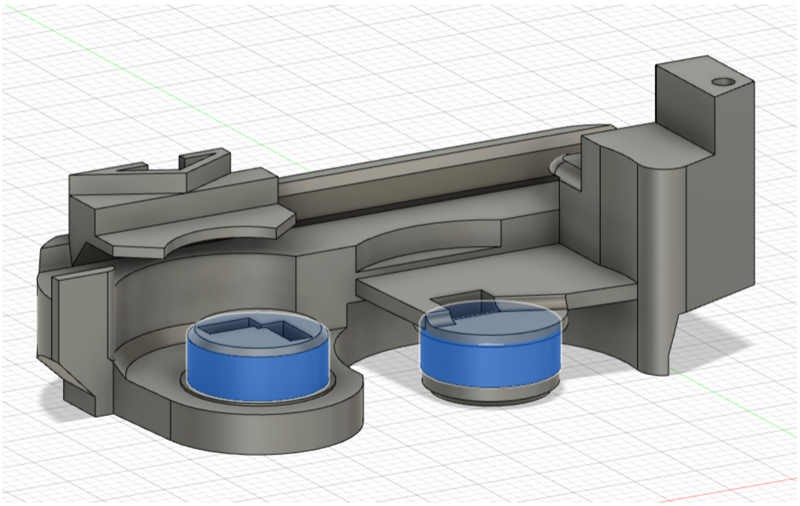

Figure 2: Sensor Housing 3D model

Due to the complex shape of the element, the correct printing process required the creation of supports[1]. These supports are essential for maintaining the position of elements above them during printing. Both types of supports, those touching the build plate and those based on the model itself, were necessary. The Figure 3 shows the placement of the supports (highlighted in blue).

[1]Supports are structures added to a 3D model during the slicing process, designed to support overhangs and bridges while printing. These structures are removed after the print is finished.

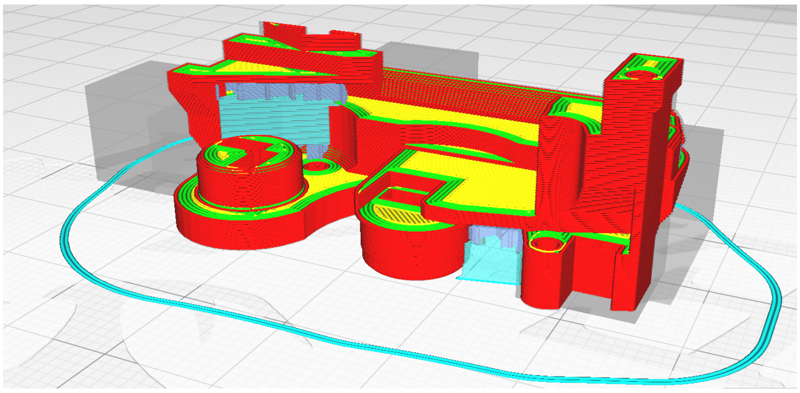

Figure 3: Sensor Housing print view

Initially, the module included in the primary Github project was used, but it has a flaw that complicates the development process of the glove. The issue was the requirement to create connections between sensors using wires, a technique prone to errors and complexity. Consequently, a decision was made to use a modification[6] created by user `codingcatgirl`. This project includes a modified Sensor Housing module and PCB design for connecting Hall sensors. This modification simplifies the assembly process and reduces the risk of making an unreliable electronic connection that can result in glove failures.

– **Rigid Mount** - attaches all parts to the hand and holds the magnets essential for determining finger spacing. To enhance the fit to the hand and reduce backlash at the connections to the bearings, the size of this part was decreased by 3 percent. The more durable seating of the bearings resulted in more precise force feedback. Additionally, the smaller size facilitated a more ergonomic arrangement of the modules in relation to the user's fingers, thereby increasing comfort.

– **Magnet Pinion** - in conjunction with the Finger Rack, this module forms a mechanism that transforms the linear motion of the finger into rotary motion. Magnets integrated into this component utilize this motion to allow capturing data on finger flexion. This module, which is mounted on a bearing, needed an adjustment in its original design due to backlash. The modification involved reducing the diameter of the part that is adjacent to the bearing. The modified plane is marked in the Figure 4.

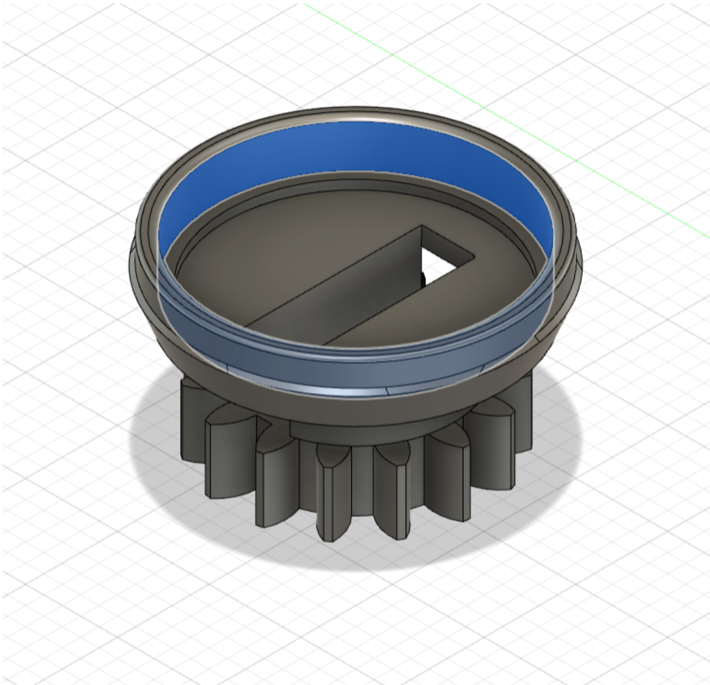

Figure 4: Magnet Pinion 3D model

Continuing with the description of the parts, it is worth focusing on the housing of the control board. This housing, specifically designed by the authors for their custom-developed board, aims to ensure the glove's comfortable usage. It securely accommodates the control board in a position that enhances usability. The enclosure features designated openings for mounting the control board. It is attached to the Rigid Mount using a specially designed bracket, dimensioned based on precise measurements to create an effective mounting design. Adequate clearances were provided to maintain the proper functionality of the mounting mechanism. It is shown in the Figure 5.

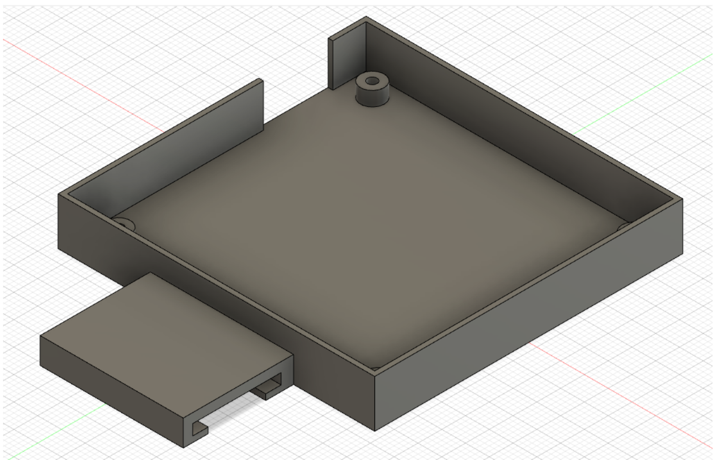

Figure 5: Project of control PCB housing

All components were printed using a Creality Ender 3 printer with PLA material at a filament temperature of 200 degrees Celsius and a build plate temperature of 50 degrees Celsius. These parameters were adjusted based on experience from previous printing projects, where their use yielded satisfactory results in the form of good quality prints. The layer height was selected to balance print detail and speed. The models used to construct the glove do not contain much detail, so a height of 0.2 mm was a reasonable choice allowing quicker printing times. The Ultimaker Cura software, a popular slicer for 3D printing that allows for the adjustment of printing parameters, was utilized to create GCODE files, which are the instructions for the printer. Autodesk Meshmixer was used to edit 3D part meshes.

During the testing process, significant conclusions were reached, suggesting potential enhancements in the glove's further development through modifications to the Magnet Pinion and Finger Rack. One conclusion is the need to increase the precision of the connection between these components, for example, by increasing the number of teeth, to minimize the backlash. A second conclusion is the necessity to reduce the diameter of the pinion, which would result in more rotations in the range of finger movement. Both strategies would increase the precision of finger position measurements.

2.3 Overview of electronic components

The selection of electronic components for the virtual reality glove was guided by the project requirements outlined on GitHub. In the versions developed by the authors, a decision was made to retain these components to ensure compatibility and simplify launch of the prototype. However, a thorough analysis of these components was conducted to gain a deeper understanding and potential future enhancements of the project. In the following text, a brief description of the most important electronic components is presented, along with conclusions that may affect the further development of the glove.

The first component to focus on is the ESP32-DevKitC V4 development board. In the project, the version with the ESP32-WROOM-32U was used, which is a Wi-Fi + Bluetooth MCU module equipped with a dual-core processor. The choice of a microcontroller from the ESP-32 series is justified due to its wide communication capabilities, data processing efficiency, and ease of programming and configuration. Additionally, a major advantage that simplifies the design of the control board is the presence of a voltage regulator producing 3.3 V to power the microcontroller. Furthermore, with the approaching end of support[7] for the ESP32-WROOM-32U, due to the introduction of a newer version of the processor, the use of an updated version of the module, such as the ESP32-WROOM-32E, should be considered.

The next component, proposed in the LucidGloves project, is an analog multiplexer. Its use is necessary due to the limited number of analog inputs of the microcontroller, which are insufficient for direct data reading from all Hall sensors. For this purpose, the CD74HC4067 chip, a 16-channel analog multiplexer/demultiplexer[8], was used. Its selection is based on the ease of implementation, as it operates at the same voltage as the microcontroller, thus simplifying integration in the current phase of the glove's development. Considering future development scenarios discussed in the next chapter, the reliance on this chip may eventually become redundant.

The process of gathering information about finger positions is based on measuring the magnetic field generated by magnets. For this reason, Hall sensors OH49E[9] were used in the project. The advantages of this integrated circuit include a wide operating voltage range from 2.3 V to 10 V, which allows it to be powered by microcontroller voltage, as well as the 5 V used to power servo mechanisms. This facilitated a simpler design, enabling only a 5 V supply to be delivered to the modules handling each finger. Another benefit of these sensors is their linear characteristic, allowing for direct measurement of the magnetic field strength without the need for conversion, simplifying the measurement procedure.

2.4 Development of the control board

The basic project on GitHub provided only general guidelines regarding the development of a control board for a virtual reality glove. Therefore, one of the objectives of this engineering thesis was to create this kind of board. Several methods were considered on how to achieve this aim, including construction based on a breadboard, self-manufacturing of the board using the thermal transfer and etching method[2], and ordering a professionally made board from a PCB manufacturer.

It was decided to use the method of self-manufacturing by thermal transfer and etching. There are two reasons for this decision. The first is to save money and time, due to the early stage of the project's development, it was not decided to order a professional PCB from a manufacturer to reduce costs that could result from design errors, which were unknown at that stage. The possibility of ordering PCBs from a Chinese manufacturer was considered to reduce costs, but this would have involved a long production time. The second reason for choosing self-manufacturing was the confidence that a self-made board would last longer than a board based on a breadboard.

With this approach, it was possible to create a control board in a shorter time and start testing it, which led to a deeper understanding of the specifics of the control board project. This will provide a detailed description of the design process and, in the later stages of development, can help improve it.

The design process of the control board started with the development of a schematic diagram, which was based on the schematic included in the project description on Github. The schematic diagram from Github is shown in the Figure 6.

[2]The process used in PCB fabrication, where a circuit design is first transferred onto a copper-clad board using heat and pressure. Following this, an etching solution removes the exposed copper, leaving behind the circuit layout protected by the transferred toner.

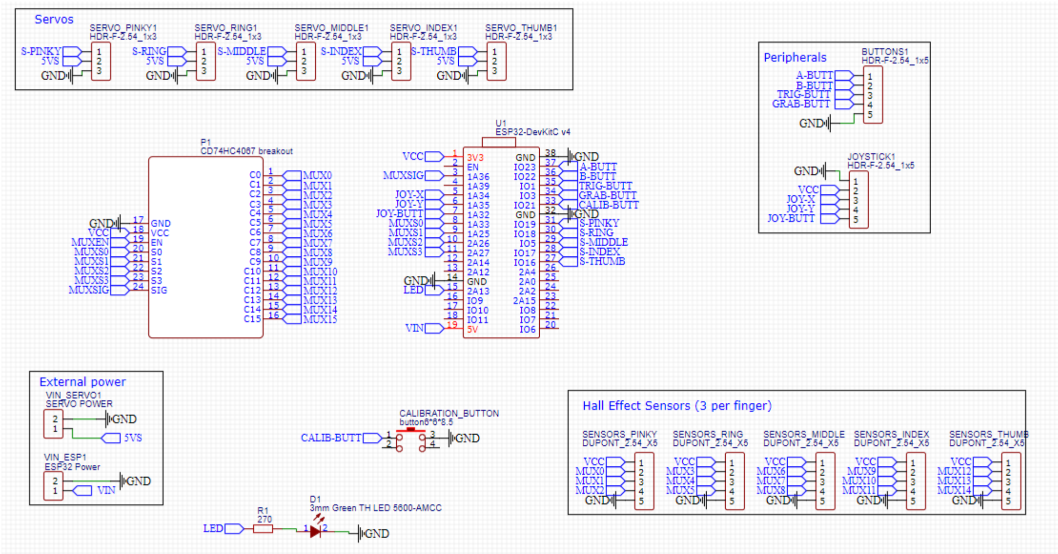

Figure 6: Schematic diagram Source: LucidGloves repository[10]

The schematic diagram designed by the authors is presented in the Figure 7.

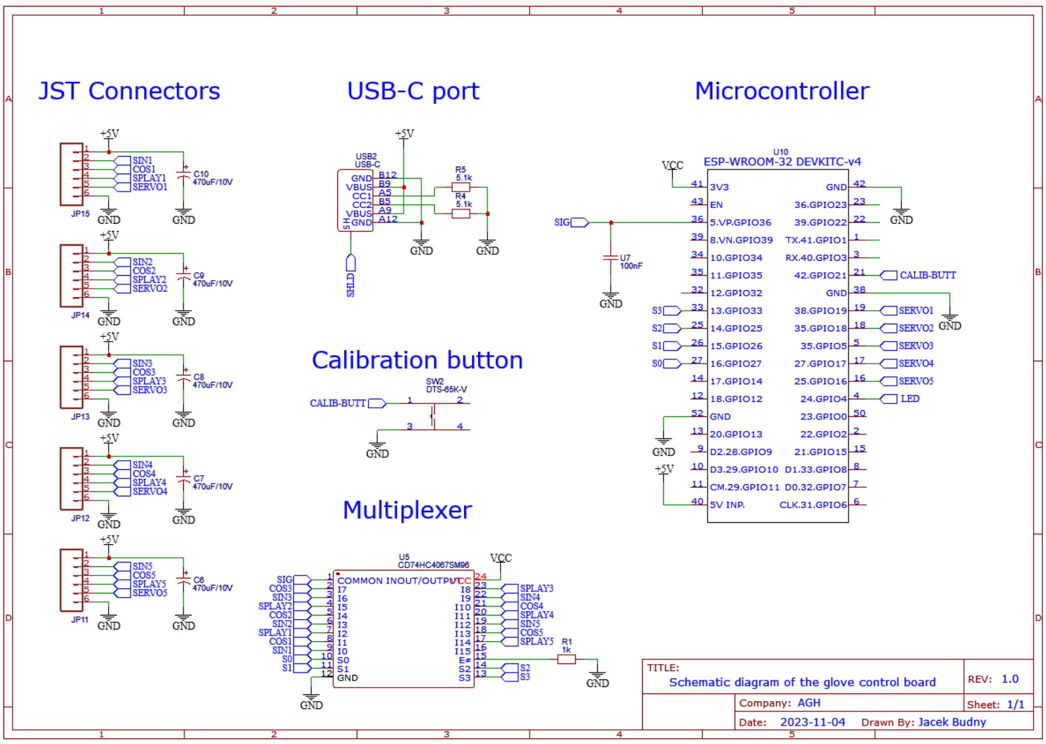

Figure 7: Schematic diagram of control board

Several key aspects were focused on during the development of the project:

– Power supply - to properly power electronic components, an additional USB-C port was added, allowing the connection of a power bank. Crucial here was the experience gained in designing the first version of the control board, in which the additional power port was not originally implemented. This oversight resulted in the microcontroller resetting during servo operation caused by voltage drops. The problem was due to the excessive current load on the computer's USB port. A typical USB port can deliver about 0.5 A. The glove during operation of all servomechanisms, can consume up to 2 A of current. Based on the documentation of the USB-C standard[11], two 5.1 kΩ pull-up resistors have been connected to the CC line. Their presence informs the power source of the high current consumption of the device. Power supplies that are compatible with the standard are able to provide a current of 3 A. In addition, 470 µF capacitors have been added to reduce voltage drops caused by servo operation.

– The Sensor Housing modules modification includes additional PCBs (Figure 8), simplifying construction. These were connected to the control board using JST connectors. The modification involves supplying only 5 V to the module, which powers the Hall sensors and servos.

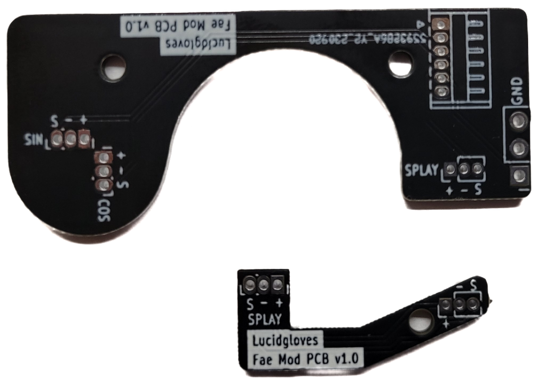

Figure 8: PCBs proposed in the modification

In the original design, the sensors were powered by 3.3 V and the servos by 5 V. Thanks to the modification, each module requires one wire harness. In the original version there were two harnesses leading to each module. This change positively affected the appearance of the glove.

– Noise minimization - in order to reduce noise, the information from the ESP-IDF documentation[12] was used, which recommends adding a filter capacitor to the analog input. A 0.1 µF capacitor was incorporated for this purpose.

After completing the schematic diagram, the focus was on designing the PCB schematic. The designed board, shown in the Figure 9, has dimensions of 62 mm by 60 mm.

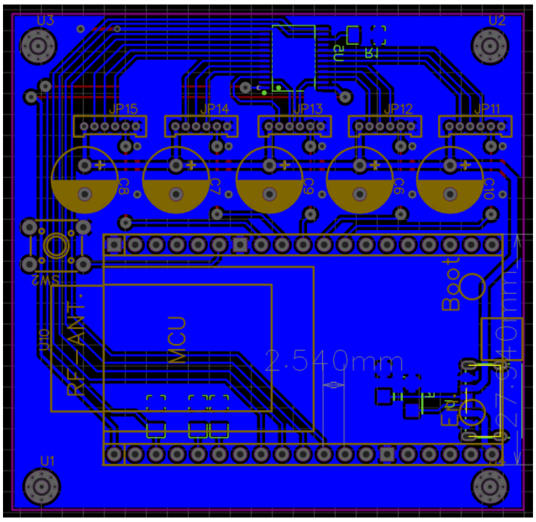

Figure 9: PCB design

The next step was to manufacture the PCB and assemble the electronic components. PCB during the process is shown in the Figure 10.

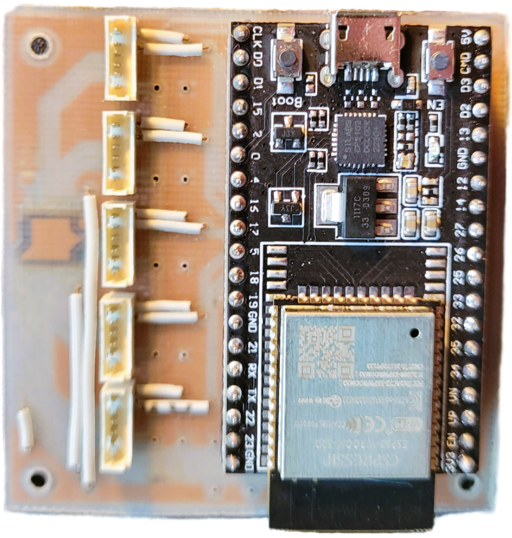

Figure 10: PCB during fabrication

During the development of the control board, following conclusions were reached that could impact the further development of the glove.

- The use of additional PCBs in the Sensor Housing module represents a notable improvement in the glove's design, simplifying its construction and increasing durability. A potential future modification involves transitioning from analog readings by the microcontroller to application of an ADC converter in each module. This enhancement could improve the quality of data from the Hall sensors by diminishing signal interference. Additionally, this modification would further reduce the wiring needed for module connections and eliminate the necessity for a multiplexer.

– Ensuring high-quality power supply is crucial for the glove's operation. It is recommended to power the Hall sensors and servomechanisms through separate power lines to mitigate significant interference. This issue is discussed in more detail in section 3.3.

– It was noted that the method of self-manufacturing PCBs imposes many design limitations, leading to unnecessary project complications. It is suggested that future board versions be ordered from a manufacturer.

2.5 Prototype construction

After preparing all the components, the next phase focused on carefully assembling of the virtual reality glove prototype.

Initially, the components produced by 3D printing were processed to remove the supports necessary during printing and to eliminate any imperfections created during the process.

Attention was then directed to assembling the modules responsible for operating the fingers. The crucial component in this regard was the Sensor Housing. The first step involved mounting the PCBs along with Hall sensors. A right-angled JST connector for board connection and pin header for servo mechanism connection were previously soldered to the bottom PCB. At this stage, thorough testing of solder pads was conducted using a multimeter to exclude the possibility of short circuits. In the Figure 11 assembled sensor housing PCB is shown.

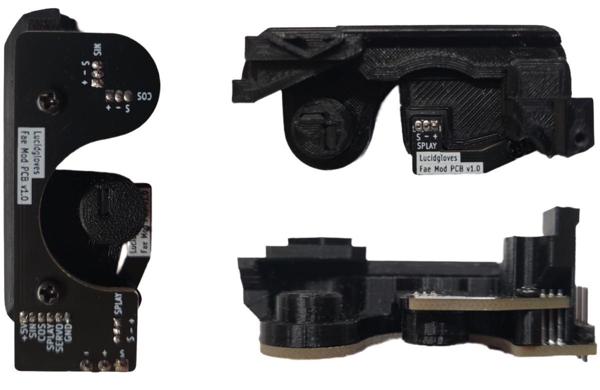

Figure 11: Sensor Housing with assembled PCBs

Further on, the Magnet Pinion was prepared. In this element, a set of magnets was placed in a specially designed slot, after which the bearing was pressed in. The entire assembly was mounted on the top pin in Sensor Housing.

The next step was to mount the Servo Rack and Finger Rack components, which were stabilized with the Sensor Top, mounted in a special holder at top of the Sensor Housing. Finally, using a soldering iron, a Servo Gear was pressed onto the servo shaft and the entire assembly was attached to the Sensor Housing, using screws. The position of the Servo Rack was calibrated, setting the servo mechanisms to a 0-degree position using a microcontroller with special software.The assembly steps for the modules responsible for operating fingers were repeated five times.

The next task was to prepare the Rigid Mount, shown in the Figure 12. This process entailed positioning magnets in designated slots, pressing bearings into place, and securing them with Bearing Retainers. Finally, velcro was attached to the Rigid Mount to the longitudinal opening.

Figure 12: Rigid Mount with magnets and bearings

At this stage, the previously prepared modules responsible for finger operation were attached to the Rigid Mount. The control board was then mounted in the electronics housing, and the entire assembly was attached to the Rigid Mount using a special holder. The modules and control board were connected with wires, and the wires from the servo mechanisms were organized.

At the end of the assembly process, after the glove was placed on the hand, Guide Rings were placed on the Finger Rack, followed by the mounting of End Rings, adjusting their position to the user's finger lengths. An additional fabric glove was used to ensure better stability of the glove on the hand. Assembled glove is shown in the Figures 13 and 14.

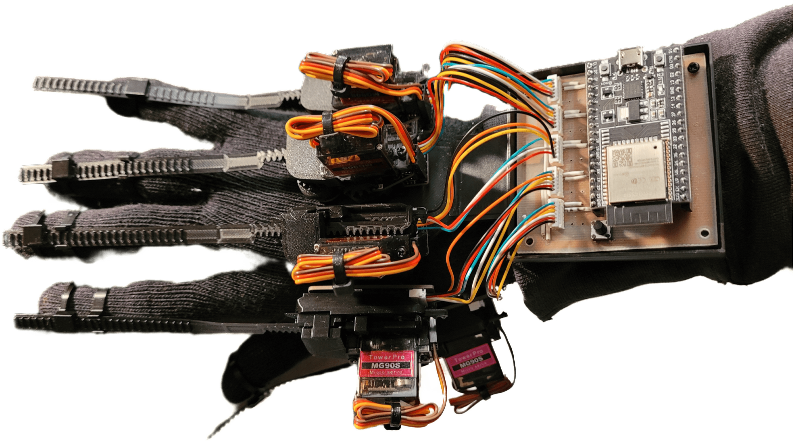

Figure 13: Assembled glove

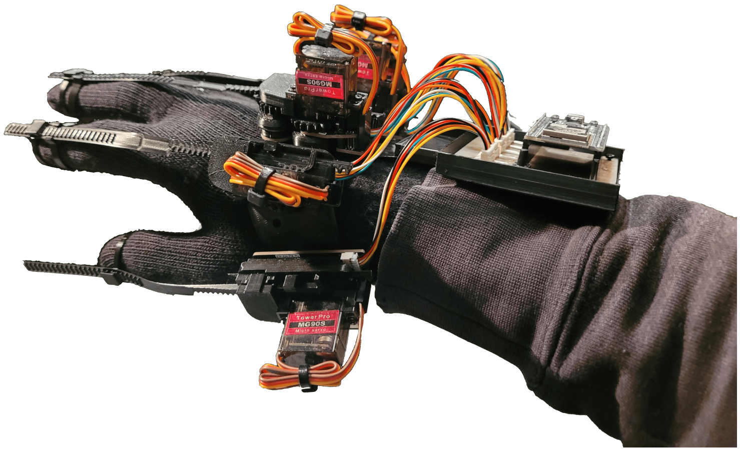

Figure 14: Assembled glove

3 Functionality assessment and conducted tests

This chapter will outline the initial setup of the gloves, detail the environment in which they were tested, present the conducted tests, and conclude with a comparison to other similar products.

3.1 Setup of the gloves

Initially, due to the use of an ESP-32 Dev Board, it was necessary to download a driver enabling communication with computers via virtual COM ports. Upon installation and connecting the glove, it was recognized in the device manager, being assigned a specific COM port.

Subsequently, the software designed for the gloves was downloaded. The COM port settings were adjusted within the software, and the software was then uploaded to the ESP-32 board. For this project, Visual Studio Code with the PlatformIO extension served as the IDE.

To validate the correct execution of the aforementioned steps, a port monitoring program was initiated. The displayed output, as depicted in the Figure 15, confirms the accurate transmission of data from the glove.

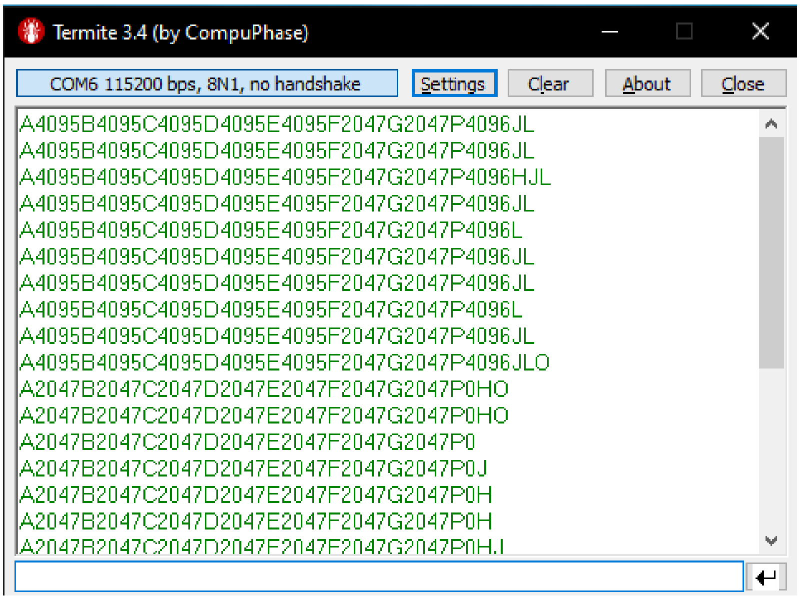

Figure 15: Data transmitted by the glove via the COM port.

Following this, the OpenGloves driver was acquired through the Steam platform. This driver is developed by LucidVR and aims to be a universal and open-source driver that can allow communication between VR gloves and SteamVR. It has features such as force feedback, full finger tracking, tracker positioning and offsetting, buttons and joystick inputs. It also allows communication through Bluetooth, USB or Named Pipes. Additionally, it comes with a UI debugging application that offers managing driver configuration, VR glove calibration and force feedback testing [13]. The version downloaded from the Steam platform also comes along with a standard SteamVR demo adapted for glove compatibility.

The VR system, comprising the headset, controllers, and gloves, was initiated. A debugging tool was activated for final glove configuration. Subsequent to these adjustments, a VR system reboot was performed, ensuring all components were operational and calibrated.

3.2 Testing environment

The testing environment for the VR gloves was developed using the Unity3D engine, specifically with Editor version 2020.3.10f1. This environment was based on the LucidGloves publicly available demo, which itself was a basic SteamVR VR demo enhanced with force-feedback functionality. The LucidGloves demo comprised two primary modifications:

- **FFBManager** - This script is tasked with computing and applying the appropriate force-feedback levels. Additionally, it manages the environmental objects that interacts with the force-feedback mechanism.
- **FFBClient** - Attached to every interactable object, this script signals the FFBManager when a user touches an object, indicating that force-feedback should be applied.

Utilizing the LucidGloves demo as a foundation, a specific testing environment was designed to match the project's goals (Figure 16). This environment features a confined space with two extended tables on one side and two smaller tables on the opposing side. Adjacent to these tables is a wall displaying a timer.

The first elongated table has various pickable objects, with 2 unique shapes. Parallel to this, the other elongated table showcases corresponding spots, highlighted with blue silhouettes. When an object is correctly placed on its matching spot, the silhouette transitions to a green color.

Opposite the elongated tables is a smaller table, featuring items designed solely for force-feedback testing. Adjacently, the smaller table houses a button depicted as a floating cube positioned above a rectangular base. Pressing this button initiates or halts the timer.

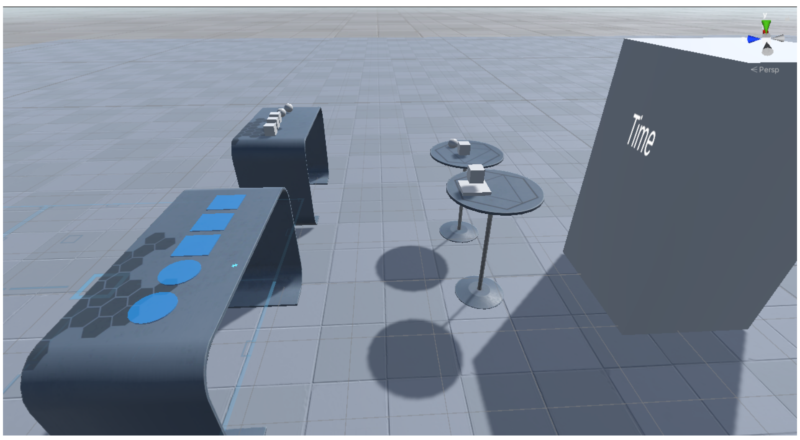

Figure 16: Side view of testing environment.

3.3 Functionality tests

Although VR technology is not new, it only became consumer-available less than a decade ago. This early stage in the market means that there is a lack of well-established standards for testing and evaluating the quality of VR products. While parameters such as per-eye resolution or field of view (FOV) for headsets are more defined, the assessment of VR gloves presents unique challenges. Most VR glove models are currently in the prototype phase and are not readily available to the public. Given these circumstances, two primary types of tests were conducted:

– **Basic Functionality Test** - This aimed to assess the core functionalities of the gloves, specifically focusing on finger tracking and force-feedback.

– **In-depth Test** - A comprehensive evaluation was conducted to examine specific parameters and to compare the gloves' performance with standard controllers.

To initiate the comprehensive testing, it was crucial to first validate the basic functionality of the gloves. The initial assessment was conducted in a controlled testing environment using two straightforward methods:

– **Finger Tracking Assessment** - Following glove calibration, the fingers underwent a series of rapid opening and closing movements to evaluate tracking accuracy.

– **Force-Feedback Test** - Force-Feedback Test: The responsiveness of the glove's force-feedback mechanism was examined by quickly moving the hand toward and away from an interactable object.

Subsequent evaluations focused on assessing finger tracking post-force-feedback tests. These assessments identified two primary issues related to finger tracking:

– Over time, the fingers in the virtual environment exhibited involuntary curling, which restricted their range of motion. Further investigations revealed coding errors in the glove's calibration process, particularly the lack of adjustments for values exceeding the calibrated range.

– Interference from the magnetic fields, primarily intended for finger spacing tracking, affected the glove's ability to accurately detect finger curling. The magnetic fields generated by magnets designed for finger spacing tracking were found to interfere with the sensors responsible for detecting finger curling. This interference was confirmed by observations where a finger moved sideways instead of the expected curling. The issue was examined across two distinct prototypes, differentiated by their sensor voltage levels (5V and 3.3V).

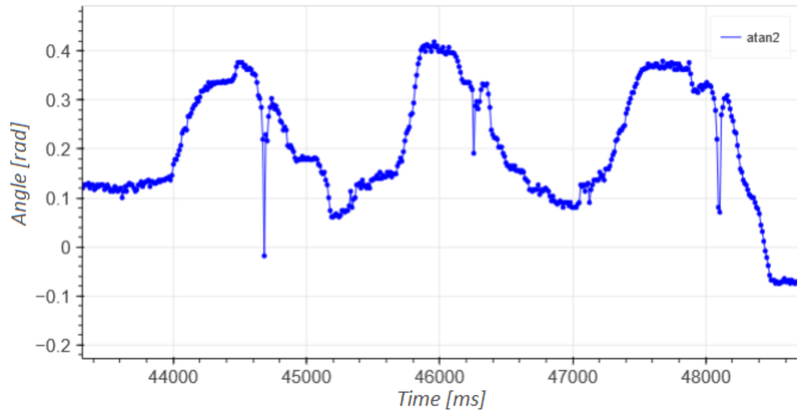

Figure 17: Effects of the magnets with 5V voltage.

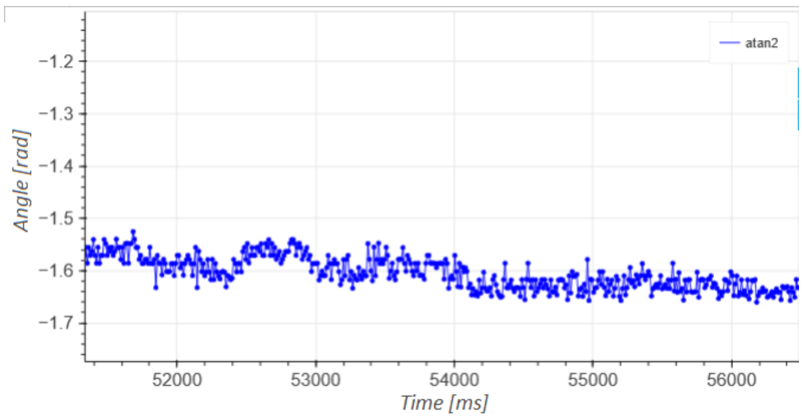

Figure 18: Effects of the magnets with 3.3V voltage.

From the data presented in the Figures 17 and 18, it's evident that the magnets intended for finger spacing tracking introduced significant interference. However, an intriguing observation emerged when the voltage was adjusted from 5V to 3.3V: the interference caused by the magnetic fields diminished considerably, suggesting a potential solution to the issue.

Another significant challenge encountered during force-feedback testing was the inconsistency in tracking the finger positions. After the force-feedback was applied and the servo motors ceased their movement, the finger positions no longer behaved correctly. To investigate this behavior further, modifications were made to the code, allowing the servo motors to toggle on and off at a frequency of 10 times per second. Subsequent tests involved recording the motion of a finger as it opened and closed slowly. The outcomes of these tests are depicted in the Figure 19.

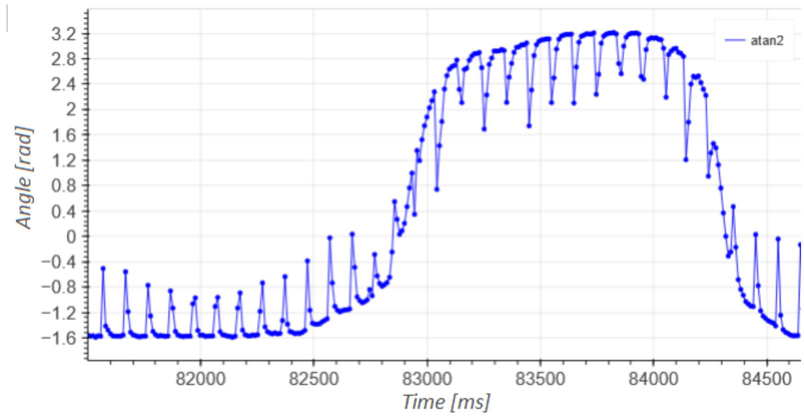

Figure 19: Effects of servomechanisms on finger position detection.

The assessment indicated that the servomechanisms significantly influenced the accuracy of finger positioning. Additionally, the capacitors utilized in the circuit board proved insufficient in reducing this interference.

To address the identified challenges in finger tracking, several solutions were proposed:

– Refine the existing code, potentially rebuilding it from scratch for enhanced clarity and efficiency.

– Adjust the voltage supplied to the sensors to a level of 3.3V.

– Establish a distinct power line for the Hall effect sensor to minimize interference from the servomechanisms.

Developing comprehensive tests posed challenges, primarily due to the absence of standardized guidelines. While considering various testing methodologies, such as latency assessment of force feedback, we identified several possible approaches. These included tasks such as shape identification without visual cues and evaluating the efficiency of gloves relative to standard controllers in executing basic tasks. One proposed experiment involved participants wearing the glove, calibrating it, and subsequently transferring objects between tables measured by a timer. This process would then be replicated with a standard controller. This comparative approach aimed to determine the efficiency difference between the VR glove and traditional controllers. Furthermore, participants would provide feedback on their immersion levels using a 7-point Likert scale, chosen for having a true neutral rating and being sufficiently accurate compared to a 10-point scale [14]. Regrettably, due to unresolved finger tracking issues, this experiment could not be expanded to a broader audience, rendering the results inconclusive.

However, a separate assessment focused on force-feedback latency was conducted. Utilizing 30FPS recordings, the movements of the servomechanisms were captured alongside those of the monitor. Force-feedback was activated ten times in both a testing environment and a debugging program. Subsequent analysis of the recordings identified the start and end points of force-feedback actions. The data from these analyses were then used to compute averages and determine measurement errors based on frame duration. Detailed results of this assessment are presented in the Figure 20.

	Average latency	Measurement error
Debugging program	460 ms	66 ms
Testing environment	344 ms	66 ms

Figure 20: VR glove force-feedback latency

It's evident that the average latency observed in the debugging program surpasses that of the testing environment. This difference occurs because the servomechanisms in the debugging setting traverse the maximum allowed range, whereas in the testing environment, their movement is influenced by the object's shape. Realistically, the application rarely demands the full range, suggesting that the force-feedback latency likely hovers around 344 ms. Furthermore, the perceived delay diminishes even further as the glove activates force-feedback when approaching an object, well before it is picked up. Yet, measuring this delay proves challenging due to variations among users and scenarios; for instance, a more dynamic setting might yield quicker responses compared to a static one.

3.4 Comparison with existing projects

To benchmark this project against existing products, five distinct VR gloves were selected. Four are commercially available, while the fifth, although still under development, was accessible for preorder through a crowdfunding campaign. They include:

- **Haptx G1** - arguably the most advanced VR glove on the market, the Haptx G1 features 135 microfluid actuators capable of both force-feedback and touch simulation. It tracks finger curl and spacing. However, its bulkiness and the accompanying heavy backpack, which weighs around 10 kg, pose mobility challenges. Moreover, their lifespan is limited to 18 months, and they carry a premium price tag of $5,495.

- **Manus Prime 3 Haptic XR Gloves** - lightweight and durable, these gloves have a swappable batteries lasting up to 10 hours. While they feature finger curl tracking and five vibrotactile sensors, they lack force-feedback. They retail for approximately $3,300.

- **Teslasuit Teslaglove** - it adopts an external exoskeleton approach, pulling fingers to induce force-feedback. Notably, its 45 tactile sensors across the fingertips offer an immersive experience, even simulating actions like breaking objects. Yet, it lacks native finger spacing support and demands an external tracking solution, making its $15,000 price point a significant investment.

- **SenseGlove Nova** - while the SenseGlove Nova opts for a more simplistic force-feedback method via wires, its design prioritizes user comfort and adaptability. However, its limitations include the lack of finger spacing tracking and the lack of of pinky finger tracking. On a positive note, the glove incorporates three tactile sensors distributed across key touchpoints, priced at approximately $5,350.

– **Bifrost Pulse** - though yet to hit the market, these gloves resemble an earlier prototype by LucidGloves. They feature force-feedback, finger curl tracking, and five tactile sensors. Their distinct open-glove design and affordability, priced at $300, contributed to a successful crowdfunding campaign, exceeding their goal by over threefold.

Comparatively, the developed prototype integrates force-feedback and finger curl tracking. While it lacks splay functionality and tactile feedback, its adaptability to various glove materials offers flexibility. Though it requires external tracking solutions, its cost-effective components total around $75, and its construction is feasible using household tools.

Conclusions

Within the scope of an engineering thesis, a project involving the creation of two virtual reality gloves with force feedback was realized, based on the existing LucidGloves design. This process began with a thorough analysis of the mentioned project, which provided a deeper understanding of the key technical challenges and issues. Subsequently, the prototype development phase began, using the resources of the LucidGloves project while also introducing original innovations such as a specially designed control board and its enclosure. The components of the project were adapted to maximize the utility and functionality of the glove. Following the construction process, the gloves were tested. The results of these tests indicated that the project represents an effective attempt to create a functional virtual reality glove with efficient feedback, which is also affordable.

The authors of the thesis proposed a range of their own solutions aimed at further improving the glove. Among these were the use of PCBs in constructing modules responsible for finger operation, the separation of power supplies for Hall sensors and servomechanisms, and the shortening of the analog signal path through the use of ADC converters. The thesis also suggested a methodology for testing gloves, marking a step forward in this field, which is yet unregulated by industry standards. The authors also compared their project with existing market solutions.

In summary, the future of virtual reality glove technology appears promising, especially in the context of the growing popularity of VR technology. As we continue to develop these technologies, we can expect significant innovations that will revolutionize the way we interact with digital worlds.

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