DESIGN AND DEVELOPMENT OF A FORCE HAPTIC FEEDBACK DATA GLOVE FOR ENHANCED PROFESSIONAL TRAINING SIMULATIONS

Alyazid Idrissi
SEMS Departement
Queen Mary University of London
London, United Kingdom

Abstract_ The following paper discusses the development of force haptic feedback data, that tracks finger positioning and hand position and orientation. The goal is to improve professional training simulation by offering a more tactile and immersive feel in a Virtual environment improving the learning rate, and retention rate of the participants. The report begins by outlining its goals and background, comparing them to existing research, development and products. This is followed by the methodology where the system design, components, mechanical structures, software and data handling. Describing in detail the inner workings, the logic behind the choices, and the way the data is collected, processed and transmitted between components of the system. The results section of the report discusses the overall system performance based on the data and feedback; it also elaborates on the accuracy of the haptic feedback and the gloves integration with unity, this section ends by analyzing the user experience and feedback highlighting how said data is important to the development of the technology. Another important part of the report is the financial viability where its analysis the products viability while also discussing costs. The reports conclude by analyzing the results in the discussion and acknowledging the limitations and challenges while also comparing to existing solution in the space of professional training and finalizing by suggesting future directions for the work and the spaces where it can be improved. GitHub Link: ***https://github.com/yaz-gear/final-project/tree/main***

Acknowledgments_ I would like to express my immense gratitude to my professor Dr. Lorenzo Jamone, for their invaluable guidance and support throughout this journey. I am also thankful to the SEMS department of Queen Mary for offering the necessary funds and facilities to allow me to develop my project. Special thanks to my colleagues, peers and seniors who offered their encouragement and insight. I am deeply grateful to my family and friends for their understanding and support throughout this journey. Lastly, I appreciate anyone who offered any type of assistance with this project. Thank you all.

I. INTRODUCTION

A. Background

In recent years, the use of VR (Virtual Reality) technology has surged in almost every industry including but not limited to production, entertainment, design. One industry that benefited from this integration is the professional training space which offers a risk-free environment for practice and training. A crucial component that enhances the effectiveness of VR training is emersion, where research has shown that higher immersion consistently corelates to a higher retention rate [1]. One of the components that improves immersion is feedback, fooling the senses into believing what the eyes see, accepting the virtual environment as real. Data gloves that provide tactile feedback have been at the forefront of this technology. These gloves are crucial for enhancing user realism as hands not only allows humans to interact with their environment but also house some of the most sensitive nerves in the body. By integrating said gloves, VR training becomes more effective significantly improving outcomes.

B. Problem statement

Most current training simulations lack any source of realistic haptic feedback, which is essential for tasks that require a more precise hand movement. Existing solutions are either extremely costly and unavailable, making them an unviable option for widespread adoption, or lack the necessary feedback for most applications. The following project ais to create an effective data glove that is affordable and offers force haptic feedback with a pulley system, potentiometers, servo motors and an MPU. The integration with unity enhances realism while also offering an open-source platform allowing for easier widespread adoption. The main challenges the project faces include accurate finger tracking, realistic force feedback, and VR integration. Addressing said challenges will provide a cost-effective solution to improve professional training in fields such as medicine and engineering [3].

C. Objectives

The primary goals of the project are:

1. Design and development of a functioning data glove

- Designing and developing a glove that integrates with the pulley system and offers finger tracking and force feedback with the help of servo motors and Potentiometers.

2. Implementation of a pulley system responsible for both finger tracking and force feedback

- Designing and making a pulley system that successfully tracks finger movement while also allowing for force haptic feedback allowing for the sensation of touching objects in a virtual environment.

3. Integration of an MPU for hand tracking

- Incorporating an MPU (Motion Processing Unit) into the glove allowing for hand position and orientation tracking in real time enhancing the realism and allowing for easier use of the glove.

4. Connection and communication with an ESP32

- Ensuring a strong and seamless connection between the components (PC, MPU, Servo Motors, Potentiometers) and the ESP32.

5. Code integration for Unity integration

- Develop the code that integrates into unity in C# allowing to receive data from the ESP32, and translates it into the game engine, while also sending the necessary data for the servo motor activation.

6. Code integration for the ESP32

- Develop firmware that integrates into the ESP32 in C++ allowing it to initialize the sensors and control the Servo Motors while also sending the correct data to unity and receiving the Motor controls

7. Calibration and testing

- Calibrating all the sensors to work in the glove ensuring accurate tracking and feedback, while also including a calibration sequence that accounts for hand size differences. Conduct thorough testing with the help of external users validating reliability and performance.

8. Cost analysis and feasibility study

- Perform a detailed cost and feasibility analysis of the data glove for deployment in a professional training environment.

The objectives mentioned above ensure that a clear road map for the project development is present and allows for clear consideration of each aspect of the project.

II. Literature Review

A. Haptic Feedback in VR

The haptic feedback technology is a technology that provides simulated physical sensations, improving the user's immersion and realism in a virtual world. It works by adding other stimuli of physical nature to the already existing stimuluses of sound and visuals. There is multiple forms of haptics including vibrational, force, electroactive polymers (EAPs), ultrasonic, thermal, microfluids, pin-based, and electroactive among others. The most popular among these haptic technologies is vibrotactile, where it transmits vibrations using small motors like coin motors often placed in the hand. In applications such as professional training and gaming this technology is crucial as it offers a more realistic manner of interacting with the environment [10]. In more recent years haptic feedback has been deployed in professional training where research has consistently shown that it improves retention rates and skill acquisition. This technology is growing at a significant rate expected to reach a market cap of over $19 billion dollars by the year 2025 [7]. Currently, multiple companies and universities are researching how to improve the technology and improve limitations such as complexity and cost [5].

B. Data Gloves

1) Overview of Data Gloves

Data gloves are an integral part of VR and haptic technology, allowing the users a more natural way of interacting with the virtual environment, like the way they interact with the real-life environment offering an overall greater realism and immersion. These gloves are extremely important for haptic feedback as the hand houses some of the most sensitive nerves in the body and is usually the first point of physical interaction between humans and their environment [15].

2) Types of Data Gloves

Data gloves can be categorized by the type of sensing mechanism they use to track the movements:

- Optical: these gloves use optical fibers embedded in the gloves fabric to detect finger movements. The bending of the optic cable results in a change of light transmission which can be quantified into movement.

- Resistive: these gloves use a resistive sensor, usually made from conductive rubber that changes resistance based on bending. This resistance change is quantified into finger bending.

- Inertia: inertia glove units use MPU to track hand and finger movement more directly.

- Electromagnetic: these gloves use electromagnetic sensors to detect changes in magnetic fields. These gloves can be extremely accurate but are extremely sensitive, making a nonviable option in most cases.

3) Applications in VR

As stated above data gloves are an integral part of enhancing immersion in VR, this makes them extremely popular in fields such as gaming, industrial simulation, professional training and medical training where skills need to be a muscle memory. In professional training, VR is used to simulate the task the professional needs to do while the data gloves allow him to interact with the task as he would in the reality improving the overall training exercise [19].

C. Force Feedback Mechanisms

In haptic devices such as data gloves force feedback mechanism are crucial with providing tactile feedback that simulate real-world sensations to the user. Motors, actuators and servos are the usual mechanism that applies force to the user, to simulate either resistance or vibrations when touching or manipulating an object in a 3D environment. This enhances the user's emersion by allowing them to "feel" what they are interacting with.

The current technology has various approaches to force feedback. These include direct drive systems that use motors or servos to apply force directly to the user, indirect systems, such as pulley-based designs that control force, and vibrational systems that give the feeling through vibrations with coin motor. Each approach has its own issues in relation to complexity, responsiveness and cost. For professional training the greater the accuracy and response of force feedback compared to the real world the greater the outcome [19].

This project chooses a pulley system integrated with servo motors to offer precise control while maintaining a compact cost-effective solution.

D. Potentiometers and Servo Motors in Haptic Feedback

1) Role of Potentiometers in Position Tracking

Variable resistors such as potentiometers are some of the most widely used technologies used for finger and hand tracking in Data Gloves. By converting movement into an electrical signal potentiometer offer precise and continuous data. This data is important for real time monitoring of position and transmitting it to the virtual environment, ensuring that the virtual hand mimics the real hand of the user.

2) Function of Servo Motors in Haptic Feedback

Servo motors are extremely important in delivering accurate haptic feedback to the user's finger. In the glove, servo motors are connected to a pulley system that can provide resistance when the virtual fingers encounter an object, similarly, by dynamically adjusting the tension, the servos can provide the sensation of gripping or squeezing an object; this would enhance the realism of the training simulation. The force feedback with servo motors would allow the user to experience a more tangible response, improving overall engagement [29].

E. MPU for Hand Position and Orientation

1) How MPUs Track movement

MPUs or Motion Processing Units are a sensor array that combines a gyroscope and an accelerometer to track orientation and position in 3D space. The accelerometer tracks linear acceleration along the X, Y and ZS axes, while the gyroscope tracks rotational movement around these axes. By processing the two sets of data, hand position can be tracked in the 3D environment with relative accuracy.

2) Integration with Haptic Devices

Usually in applications such as data gloves, MPUs are used writs position and orientation, complementing other sensors that track finger position. This connection allows for a better connection between the user's hand movement and the haptic feedback allowing for greater accuracy and a more realistic interaction with the virtual environment.

F. ESP32 in Wearable Technology

1) Feature of The ESP32 Relevant to The Project

The ESP32 is one of the most popular and versatile microcontrollers, it's small and includes wireless technology making it ideal for wearable technology. Its CPU that has dual cores allowing for multitasking, enables simultaneous data processing from multiple sources such as the potentiometers and MPU in a data glove. The ESP32 also has low power consumption, which allows a longer battery life for a wearable. Finally, its numerous GPIO pins support various peripherals, such as cases that include an array of sensors.

2) Comparison with other Microcontrollers

Compared to other microcontrollers on the market such as the Arduino UNO and the STM32, the ESP32 has wireless capabilities integrated in it, compared to the rest that need an external module. Similarly, unlike the other choices the ESP32 has more GPIO pins, a more versatile and powerful platform. This is all while keeping a similar simple coding track unlike the STM32 that typically requires more complex coding and does not integrate with the Arduino IDE that has extensive community support.

G. Integration with Unity

Unity is one of the most popular and widely used platforms to create a 3D VR environment, making it an ideal choice for the integration of a data glove. The integration with include the development of custom code to interface the Unity API with the ESP32, and the straightforward to use C# that Unity uses makes it perfect for this application. The gloves sensors send the data that they collect from the user's hand to Unity where it is processed and attached to the appropriate joint, so that it can move in VR. Not to mention unity extensive research background where multiple studies use unity as their basis due to its flexibility and adaptability to the users need. Finally, most professional training simulations use unity as their basis due to easy platform and extensive assets [25].

H. Applications in Professional Training

1) Existing use Cases of VR in Training

VR in industries that require professional training has become transformative to say the least. VR allows a pilot to practice maneuvers where a plane is crashing that could save hundreds of lives in the future, instead of being unprepared in the case of an accident. A doctor uses VR to simulate operating on a patient with zero risk while also gaining the muscle memory and knowledge that was before only gained in the operating room. In manufacturing, VR allows workers to familiarize themselves with machinery and tools before interacting with them, increasing safety and lowering the risks. These applications demonstrate VRs undeniable ability to improve the hands-on training of professionals along a multitude of fields [14].

2) Benefits of Haptic Feedback in Training

Haptic Feedback provides tactile and force sensation to the user that mimics real life, this sensory input improves the immersion and enhances the VR training. By allowing the trainee to experience life like sensation such as resistance, textures and force, muscle memory is improved along with motor skills. In fields such as surgery, haptic feedback allows the user to feel the blade and the resistance of the tissue enhancing the experience. The inclusion of more haptic feedback in VR training is a necessity, as it increases engagement, skill retention and offers a more comprehensive learning experience [6].

I. Summary

1) What is Learned From the Literature Review

The literature review above highlights the importance of Haptic Feedback in enhancing user immersion in VR, specifically in professional training. It shows that although various data gloves and feedback mechanisms exist, most current solutions lack the cost and complexity that would make them more accessible. This literature review ends by exploring the growing trend that is integrating wearables with development platforms like Unity.

2) Identified Gaps and Opportunities

Despite the leaps that have been made in this technology a gap remains in cost and integration. Current gloves often struggle to stay cost efficient while also offering complex real time tracking and haptic feedback, limiting their effectiveness in professional training. These gaps present an opportunity for developing a more precise, responsive and affordable data glove tailored specifically for professional training simulation.

III. METHODOLOGY

A. 3.1 System Design

1) Overview of the System

The system is a haptic glove designed to simulate the touching of an object in virtual environment for professional training simulation. To track finger bending the system use potentiometers connected to a pulley system that is connected to the tip of the fingers, based on the increase in resistance in the potentiometer, the finger bends in the VR environment where each join is mapped from 0-90 degrees. The hand position and orientation are tracked using an MPU connected to the back of the wrist that is then calibrated accordingly. Finaly the haptic feedback works using servo motors connected to the drum of the potentiometer, when an object is touched in VR the haptic motor move to stop the drum from moving forward, stopping the finger from bending further, once the object is not touched anymore the servo motor returns to its resting position. All of these sensors and motors are connected to an ESP32 that is wirelessly or wirily connected to a computer running the simulation, the glove is powered using an external battery. The components of the glove are held into it using 3D printed parts.

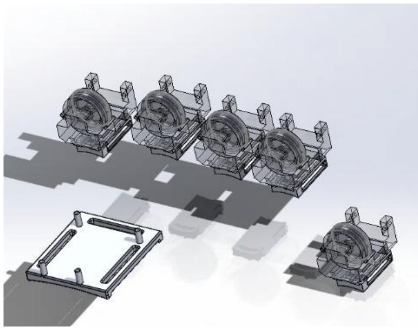

Figure 1: 3D model of system.

2) Design Rationale

The design is guided by the need for a cost effective, accurate data glove that is both responsive and capable of simulating realistic touch sensations for professional training applications. Potentiometers were chosen for their reliability, low-cost, accuracy and low latency. Servo motors were chosen for their precise angle control, important to generating the force haptic feedback. The MPU was chosen for its accurate tracking and simple integration. The ESP32 was selected as the central processing unit due to its powerful capabilities, low power consumption, high versatility and wireless connectivity. Unity was chosen as the platform used for integration due to its low cost and ability to create immersive environments. The overall design prioritizes both function and cost, ensuring the system can be adopted widely.

B. Hardware Components

The following section details the components and hardware used for the data glove. The components below were carefully selected to meet the requirements of the system design.

1) The Gloves Components

The main components of the glove are

- The Motherboard: an ESP32 development board with both WIFI and Bluetooth was chosen to serve as the central processing unit.
- 5 Potentiometer: the potentiometers chosen are B10k Ohm variable resistors model number RV097NS, chosen for their compact and reliable design.
- 5 Servo motors: The MG90 XTVTX metal head servo motors were chosen due to their lightweight, reliable and strong properties.
- MPU: the Hailege MPU 6050 GY-521 is chosen due to its small size, accuracy and extensive support.
- Jumper Cables: pack of ELEGOO Dupont wires with female to female, female to male, and male to male; choose due to their compatibility and ease of use when prototyping.
- 5V Power bank: 5V power bank from Anker Is used, but the power can also be supplied from the device the gloves are connected to.
- Glove: Blackrock super grip gloves are used as the outside texture helps with the sensation of touch, and the tough build ensure longevity, while the fabric ensures breedability during long sessions.
- Badge Reels: these are normal badge reels that are repurposed to be used for the retraction mechanism of the pulley system.
- ESP32 base: 3D printed; responsible for holding the ESP32 to the wrist and creating tension for the finger bases.
- 5 Finger modules: 3D printed; responsible for holding the retraction mechanism and haptic mechanism.
- 5 finger bases: 3D printed; responsible for connecting the ESP32 base with the Finger modules.
- 5 spools: 3D printed; Responsible for the retraction mechanism.
- 5 haptic spools: 3D printed; Responsible for the haptic mechanism.
- Velcro strap: responsible for holding all the 3D printed components

(references to all components are in Appendix A and C)

2) Choice of Components

The selection of the components above is inspired by the need of precision, compactness, affordability and ease of integration. The 3D printed components were designed with a tolerance of 0.2 mm to ensure accuracy, while FDM (Fused Deposition Modelling) technology with PETG (Polyethylene terephthalate glycol) were used to ensure cost is kept down while maintaining a relative precision and strength. Repurposed parts such as the badge reals also are used to keep costs down while achieving the same performance.

C. Pulley System for Force Feedback and Finger tracking

1) Overview of Pulley System

The pulley system of the glove is designed to provide force feedback by stopping the movement of the fingers past the point where the glove assumes the object is. The system uses a system of cables connected to tissue that is connected to the fingertips of the glove. The pulley system went through multiple iterations, some included cables that went all the way to the fingertips, the final design was chosen to allow so flex when gripping to simulate the feeling of applying more force to the object.

Figure 2: initial design of haptic and finger tracking module.

2) Integration with Potentiometers

The potentiometers are inside the finger base and are connected to the spool, the spool has a spring repurposed from the badge real to pull the cable back when the fingers are extended, this spool turns the potentiometer when the fingers are moved to translate finger movement into linear distance.

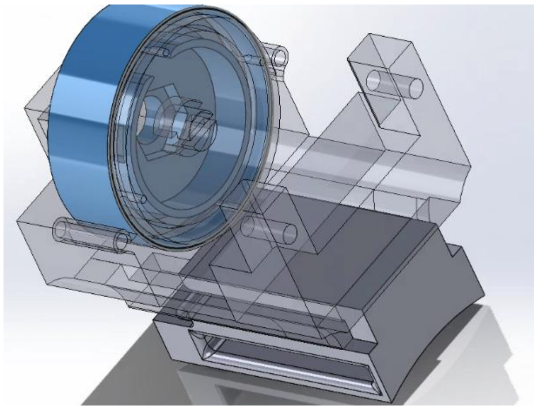

Figure 3: 3D model of Potentiometer integration.

3) Integration with Servo Motors

The servo motors are connected to the back of the finger module and interact with the haptic spool that has a screw in the back, the haptic spool rotates with the potentiometer, when an object is touched in the virtual environment the servo motors moves its wiper in front of the screw to stop the finer from moving forward.

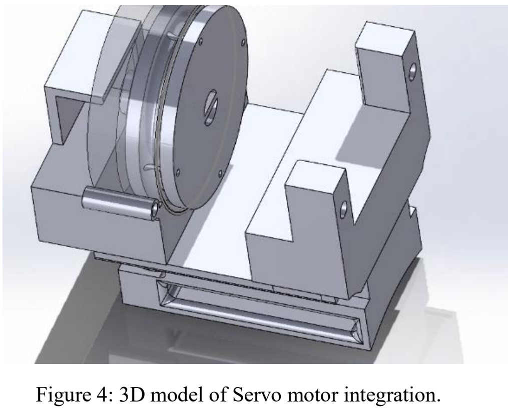

Figure 4: 3D model of Servo motor integration.

D. Software Development

1) Firmware for the ESP32

The firmware in the ESP32 was developed to receive Realtime data from the Gloves sensors, this includes the five potentiometers for finger tracking and the MPU for hand tracking; following this the firmware publishes the data collected from the sensors constantly through the serial bus. At the same time the code initiates the servo motors and keeps them on standby waiting for the command of from Unity to turn on one of the 5 Servo motors. The servo motors angle in the code is decided based on the resistance of the potentiometer related to the finger.

(All code can be found in Appendix B)

2) Firmware and Integration of Unity

To integrate the glove directly with unity a script for hand control and feedback must be added. The unity script is written in C# and is responsible for receiving the data from the ESP32 code and using it to calculate each of the finger angles and the hand position and rotation in 3D space. Additionally, the script triggers the motor connected to each finger that touches an object by sending a turn on command to the ESP32 code. This integration ensures real-time synchronization between physical movement and hand movement in the virtual environment while also providing realistic haptic feedback.

(All code can be found in Appendix B)

E. Calibration and Testing

1) Calibration

Calibration ensures that the data glove accurately tracks finger and wrist movements delivering precise haptic force feedback. The calibration process involves aligning the readings from the potentiometers and the MPU sensor with actual physical positions. For the potentiometers each fingers range is mapped to its respective finger increasing tracking accuracy, this is than used to change the mapping in the Unity code ensuring optimal tracking accuracy. The MPU is calibrated using a standard procedure, where the sensor is aligned to a flat surface to establish a flat surface, followed by dynamic calibration accounting for noise such as gravity. The servo motor is calibrated by adjusting the position the wiper moves two when an object is moved and mapping that to ensure accurate force feedback, this is done to each finger individually to further ensure accuracy.

2) Testing

Testing is conducted to ensure the glove's accuracy, responsiveness and usability in the Unity environment. Specifically with professional training in mind three types of tests have been conducted to test different aspects of the system:

A. Position tracking Accuracy test: the glove is worn; finger joint angle is recorded at various angles in Unity. These readings are than compared to real angles using data collected using a protractor.

B. Force Feedback effect test: during this test multiple tasks are performed, this will be timed and tested for both when haptic feedback is activated and when it's not activated.

C. Durability testing, this testing will entail the use of the glove for a maintained period, then the same angle in the simulation is compared to the angle measured to test for variation.

(all results from the test are either in the results/discussion section of the report or in appendix D)

IV. Results

A. System Performance

The data gloves developed in this project present effective real-time tracking of finger and wrist movements, tracking that is essential for its intended application in professional training simulation. The potentiometers used for finger tracking provided accurate angle measurements with minimal delay. The MPU tracks wrist position and orientation in 3D space accurately, while the finger angle tracking is accurate within 4 degrees on average which is more than acceptable for the following applications.

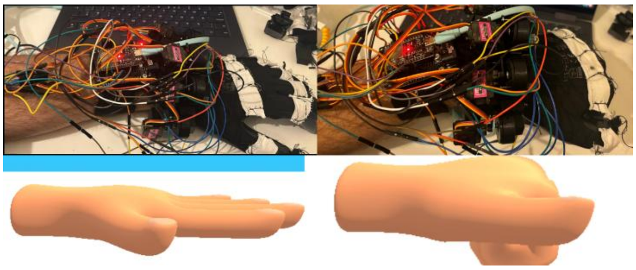

Figure 5: picture of the final glove vs the Unity simulation.

The calibration procedure, although tedious and a bit long, ensures accuracy of tracking across a multitude of hand sizes. While the overall system performed reliably within the multiple tests and scenarios where it was used. The overall system worked smoothly without any noticeable issues. The robustness of the system was tested by continuous usage, where it maintained performance without any significant loss of tracking accuracy.

Table 1: finger position tracking results.

finger	Angle measured	Simulation angle	Deviation
Index	79	72	7
middle	46	40	6
ring	53	52	1
pinky	33	30	3

B. Force Feedback effect

The force feedback system that was implemented using the servos has proved to be robust and able to provide realistic resistance when interacting with virtual objects. The tests conducted to test the accuracy of the force feedback yielded positive results. As can be seen by the time difference, haptic feedback offers greater efficiency. Greater accuracy can be achieved with more calibration, but any big improvements would require the use of a different technology.

Use indicates that the force feedback yielded improvement in the interaction with a lower time overall due to the help of feedback in the tasks. This suggests that it's helpful in a professional training environment.

Table 2: Force feedback Effect results.

task	Time without feedback	Time with feedback	Difference (seconds)
Number 1	12.3 s	10.8	1.5
Number 2	10.9 s	9.9	1
Number 3	11.2 s	10.5	0.7
Number 4	15.6 s	14.1	1.5

C. Integration with Unity

Due to the C# script in unity and the code in the ESP32 the integration is seamless, where both exchange data effectively without encountering any errors or issues. The unity script picks up on the real time data transmitted from the ESP32 with minimal latency, while the ESP32 turn on servo motors in the correct time with minimal delay. The synchronization between the hand movement and the hand movement in unity was highly accurate with no perceivable lag.

D. Durability testing

The durability testing involves the continuous use of the glove for a continuous period of time, and testing the tracking accuracy of the glove. The testing procedure involved wearing the glove for about forty minutes where the index was moved to the 45 degree position according to the simulation and the actual finger angle being recorded.

The testing has shown that although the glove maintains relative accuracy, it still drifts losing a certain amount of accuracy in the process.

Table 3: durability testing.

time	10 min	20 min	30 min	40 min
Simulation angle	45	45	45	45
Actual angle	43	42	39	38
variation	2	3	6	7

V. Discussion

A. Result Analysis

1) Critical Evaluation of System Performance

The data glove that was developed in this project performed as expected in terms of real time tracking of finger angle and hand position and rotation, as well as haptic feedback. The system performed with low latency which ensured a smooth user experience. The potentiometer provides precise finger movement data, although some finger movements created inconsistencies dues to the nature of the mechanism, calibration improved on the issue but for further accuracy an improvement or change in technology is required. The MPU also performed excellently offering accurate tracking, some minor inconsistencies were noticed in prolonged testing, likely due to sensor drift, but they were so minor that they didn't affect the accuracy of tracking or the user experience.

2) Discussion of achievements Relative to Project Objectives

The projects objectives have been achieved as shown below:

1. The project has successfully developed a data glove that functions properly.
2. The pulley system successfully implements control finger positioning and applies haptic feedback.
3. Successfully used an imu to track hand position and orientation.
4. Successfully implemented ESP32 communication with computer.
5. Successfully integrated C# code for unity control
6. Implemented an appropriated code that controls the components of the ESP32
7. Successfully calibrated and tested the glove
8. And finally conducted an appropriate analysis for cost and feasibility

B. Challenges and Limitations

1) Challenges Faced During Development

A multitude of challenges have been faced during the development of this globe. One significant issue was getting the pulley system to work with force feedback, it took multiple design and iterations of the mechanism before landing on a successful design. Another big challenge is to get Unity to interface with the serial bus as it's not supported by Unity anymore, the solution to this was to use old DLL files with custom C# code to allow the ESP32 to interface with Unity. Additionally, unity, although versatile, has a lot of bugs that turned the development process tedious, such as random crashes, systems not working and interactions not registering.

2) Limitations of Current Design

Acknowledging limitations with the current design Is important as it offer space for future improvement. The biggest drawback of this is the potentiometers, each one tracks three joints in one access limiting the possible finger poses. Another issue with the current design is its DIY nature, specifically the 3D printed parts, for future scalability these parts need to be Mold injected to drive cost down significantly while adding covers to the different exposed mechanical components.

C. Comparison with Existing Solutions

Compared to existing commercial solutions, this project offers a more cost-effective solution, without compromising on any of the essential functionality that other products on the market offer. Products such as the cyber-glove offer more sophisticated tracking and haptic feedback but at a significantly higher cost, making them less accessible to most business and potential user bases, limiting the potential of widespread adoption. On the other end of the spectrum, cheaper gloves lack necessary feedback mechanisms or the necessary precision, which this project successfully addresses. By striking a balance between sophistication and cost, the developed glove offers a viable alternative to the market.

D. Implications for Professional Training

The development of this project has a large and meaningful impact on professional training along a multitude of fields. By providing good haptic feedback and accurate finger and hand tracking, at a relatively affordable price, it offers a solution that is a lot easier to adopt on a large scale compared to existing solutions. This in part could not only lead to future development but could lead to the creation of even better technologies at an even lower cost.

E. Future Work

1) Development Directions That Were Not Explored Further

Due to budget and time constraints multiple directions and technologies could not be explored further. For instance, the design of components specified for this application such as potentiometers and servo motors that could drastically increase accuracy and compatibility, unfortunately such development requires a bigger budget, more specialized equipment and a much longer development cycle. Similarly, the addition of more sensors, for example to measure grips strength, could provide better feedback to the user. Overall, although the project presents impressive results, there is a lot left on the table to be improved and researched.

2) Possible Expansions of Functionality and Applications

The gloves that are developed in this project offers limitless possibilities when it comes to the development of expansion of functionality and applications. A specific one would be the development of specialized gloves for specialized training applications such as applications that require heat, that require precise force measurement among others. Another possibility is using the glove as a controller of a robotic limb in applications that are dangerous to humans but require human dexterity. Another source of future development is the expansion of integrations beyond unity to other VR platforms.

VI. Financial Viability

A. Cost Breakdown

1) Hardware Cost

The total cost of the hardware used in the gloves development and prototyping is as follows:

- The ESP32 development board costs: £8.69
- The potentiometers cost: £9.49
- The servo motors cost: £14.05
- The MPU costs: £2.86
- The jumper cables cost: £6.99
- The glove costs: £1.09
- The badge reals cost: £6.99
- 3D printing total cost: £82.12
- The Velcro straps cost: £3.25

Total hardware cost is: £135.53

2) Production Cost

When it comes to mass production, the cost of 3D printing is removed as the plastic parts will be made using traditional production methods such as injection molding. This, along with sourcing parts directly from manufacturers in bulk, would drop the cost of production per glove down to around £60-£80. This almost half the cost of the original glove allowing for even better pricing of the technology

B. Development Costs

1) Labor and time Cost

The development of the actual glove took approximately 200 hours of labor, this includes design, calibration, and manufacturing. Assuming an hourly rate of an average engineer of £25, the labor cost is £5,000 [27].

2) Firmware Development Cost

Another big expense is the firmware development for both the ESP32 and Unity, this took another 100 hours, which adds up to £2,500.

C. Scalability Costs

Scaling production, which would involve contracting a manufacturer for the gloves production, assembly, along with the procuration of Molds for the injection molding. The initial cost would be substantial, estimated to be around £10,000, but the per-unit cost of the glove would drop drastically as shown above [28].

D. Cost-Benefit Analysis

1) Analysis of Financial Viability

Studying the low cost of the hardware and the potential reduction of cost through traditional manufacturing methods, the glove represents a viable financial opportunity for the professional training market. The initial development and setup cost can easily be offset by the lower per-unit costs in mass production, making the glove an affordable widespread option.

2) Return On Investment (ROI)

Assuming the glove can be sold at a price point of £150 and a production cost of around £90. The break-even point will be reached after selling approximately 292 gloves, this is accounting for initial setup cost, labor and cost of parts and production. Not only is the potential of the glove in a professional training market substantial, but it also offers a very strong ROI over time.

E. Funding considerations

Potential funding source would include:

- Private funding: this includes individuals and organizations; they would offer support for either a percentage of profits or of the company.
- Educational institutions: these include universities such as Queen Mary where they would request a share of the profits to fund other university programs.
- Government programs: government contracts and initiatives would be great source of funding where they would pay for a bulk order upfront, giving both capital and a strong customer.

VII. Conclusion

A. Summary of Findings

The project successfully developed what can be considered functional and effective data glove for VR training applications. The glove provides accurate finger and hand tracking, realistic haptic feedback and finally seamless integration with unity. Making it a viable option for its intended purpose which is professional training.

B. Implications of The Study

1) Implications of the Research in a Broader VR and Haptic Feedback Landscape

This research contributed to the broader Field of VR and Haptic Feedback by demonstrating that high quality, immersive solution for professional training can be developed at a lower cost making them accessible to a wider audience.

2) Implications of the Research in Professional Training

This data glove has the potential to greatly improve the quality of professional training for a lot more people. Offering not only more data on the subject but also creating subsequently more research on how to improve existing technologies.

VIII. References

[1] J. K. Gibbs, M. Gillies, and X. Pan, “A comparison of the effects of haptic and visual feedback on presence in virtual reality,” International Journal of Human-Computer Studies, vol. 157, p. 102717, Jan. 2022, doi: https://doi.org/10.1016/j.ijhcs.2021.102717.

[2] W. Dangxiao, G. Yuan, L. Shiyi, Z. Yuru, X. Weiliang, and X. Jing, “Haptic display for virtual reality: progress and challenges,” Virtual Reality & Intelligent Hardware, vol. 1, no. 2, p. 136, 2019, doi: https://doi.org/10.3724/sp.j.2096-5796.2019.0008.

[3] A. Chapman, C. Headleand, and P. Dickinson, “Haptic Feedback in Virtual Reality: An Investigation Into The Next Step of First-Person Perspective Presence,” 2019. Available: https://core.ac.uk/download/pdf/237700199.pdf

[4] Y. Shi and G. Shen, “Haptic Sensing and Feedback Techniques towards Virtual Reality,” Research, Feb. 2024, doi: https://doi.org/10.34133/research.0333.

[5] G. Burdea, “Haptic Feedback for Virtual Reality,” ResearchGate, May 1999. https://www.researchgate.net/publication/2356993_Haptic_Feedback_for_Virtual_Reality

[6] V. Chheang et al., “Advanced liver surgery training in collaborative VR environments,” Computers & Graphics, Feb. 2024, doi: https://doi.org/10.1016/j.cag.2024.01.006.

[7] D. Howell, “A Haptic Future: Sensing the Virtual | Silicon UK Tech News,” Silicon UK, Aug. 21, 2023. https://www.silicon.co.uk/digital-transformation/a-haptic-future-sensing-the-virtual-525988

[8] “Haptic feedback for VR training in healthcare | Strivr Blog,” Strivr.com, 2022. https://www.strivr.com/blog/haptic-feedback-immersive-training-scenarios (accessed Aug. 09, 2024).

[9] K. Kovanur Sampath, A. Arumugam, E. Yaghi, K. Chidambaranathan, and P. Andersen, “The role of virtual reality (VR) with haptic feedback in enhancing physical examination skills of health care students – A systematic review protocol,” International Journal of Osteopathic Medicine, vol. 46, pp. 51–54, Dec. 2022, doi: https://doi.org/10.1016/j.ijosm.2022.10.008.

[10]D. Barnard, “History of VR - Timeline of Events and Tech Development,” Virtualspeech.com, Jun. 14, 2023. https://virtualspeech.com/blog/history-of-vr

[11]P. I. Corp, “Plexus / High-performance VR/AR Gloves,” plexus.im. http://plexus.im/

[12]L. De Bonet, “lucidgloves- Firmware and 3D Print Files,” GitHub, Jan. 11, 2022. https://github.com/LucidVR/lucidgloves

[13]DextaRobotics, “Dexta Robotics - Touch the Untouchable-岱仕科技 - 触 摸 虚 实 的 边 界 ,” www.dextarobotics.com, 2023. https://www.dextarobotics.com/en-us

[14] M. Eswaran and M. V. A. R. Bahubalendruni, “Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state-of-the-art review,” Journal of Manufacturing Systems, vol. 65, pp. 260–278, Oct. 2022, doi: https://doi.org/10.1016/j.jmsy.2022.09.016.

[15]H. Fang, J. Guo, and H. Wu, “Wearable triboelectric devices for haptic perception and VR/AR applications,” Nano Energy, vol. 96, p. 107112, Jun. 2022, doi: https://doi.org/10.1016/j.nanoen.2022.107112.

[16]A. Gani, O. Pickering, C. Ellis, O. Sabri, and P. Pucher, “Impact of haptic feedback on surgical training outcomes: A Randomised Controlled Trial of haptic versus non-haptic immersive virtual reality training,” Annals of Medicine and Surgery, p. 104734, Sep. 2022, doi: https://doi.org/10.1016/j.amsu.2022.104734.

[17]J. K. Gibbs, M. Gillies, and X. Pan, “A comparison of the effects of haptic and visual feedback on presence in virtual reality,” International Journal of Human-Computer Studies, vol. 157, p. 102717, Jan. 2022, doi: https://doi.org/10.1016/j.ijhcs.2021.102717.

[18]HaptX, “Haptic Gloves G1 - Gloves for virtual reality and robotics | HaptX Pre-Order,” g1.haptx.com, 2023. https://g1.haptx.com/learnabout

[19]H. Khosravi, K. Etemad, and F. F. Samavati, “Mass simulation in VR using vibrotactile feedback and a co-located physically-based virtual hand,” Computers & Graphics, vol. 102, pp. 120–132, Feb. 2022, doi: https://doi.org/10.1016/j.cag.2021.12.002.

[20]W. Kim and S. Xiong, “Pseudo-haptic button for improving user experience of mid-air interaction in VR,” International Journal of Human-Computer Studies, vol. 168, p. 102907, Dec. 2022, doi: https://doi.org/10.1016/j.ijhcs.2022.102907.

[23]Mechatech, “How do common virtual reality tracking systems work?,” www.mechatech.co.uk, 2022. https://www.mechatech.co.uk/journal/how-do-common-virtual-reality-tracking-systems-work

[24]R. Monica and J. Aleotti, “Improving virtual reality navigation tasks using a haptic vest and upper body tracking,” Displays, vol. 78, p. 102417, Jul. 2023, doi: https://doi.org/10.1016/j.displa.2023.102417.

[25]I. Patringenaru, “A glove powered by soft robotics to interact with virtual reality environments,” Ucsd.edu, 2017. https://jacobsschool.ucsd.edu/news/release/2225?id=2225

[26]M. Yu et al., “A self-sensing soft pneumatic actuator with closed-Loop control for haptic feedback wearable devices,” Materials & Design, vol. 223, p. 111149, Nov. 2022, doi: https://doi.org/10.1016/j.matdes.2022.111149.

[27]“Unit labour costs,” OECD, 2024. https://www.oecd.org/en/data/indicators/unit-labour-costs.html (accessed Aug. 19, 2024).

[28]Market Data Forecast, “Smart Glove Market | Size, Trends, Forecast | 2024 to 2029.,” Market Data Forecast, 2024. https://www.marketdataforecast.com/market-reports/smart-glove-market (accessed Aug. 19, 2024).

IX. Appendices

A. Appendix A Technical Schematics

All 3D models can be found in the GitHub link bellow, along with STL files, alternated designs and final 3D printed models: https://github.com/yaz-gear/final-project/tree/main/3D

B. Appendix B Code Listings

The following GitHub link leads to the code for the ESP32: https://github.com/yaz-gear/final-project/blob/main/code/Esp32_code/Esp32_code.ino

The following GitHub link leads to the code for Unity: https://github.com/yaz-gear/final-project/blob/main/code/HandController.cs

C. Appendix C component source

All the components, their sources and costs are in the GitHub link bellow: https://github.com/yaz-gear/final-project/tree/main/cost%20and%20data

D. Appendix D DATA

The GitHub link bellow has the video showcasing the finger tracking using the potentiometers: https://github.com/yaz-gear/final-project/blob/main/Results/Video_showcasing_finger_tracking.mp4

The GitHub link bellow has the video showcasing the hand tracking using the MPU: https://github.com/yaz-gear/final-project/blob/main/Results/Video_showcasing_hand_tracking.mp4

The GitHub link bellow has the video showcasing the haptic force feedback using the servo motors: https://github.com/yaz-gear/final-project/blob/main/Results/Video_showcasing_haptic_feedback.mp4

the following link is a YouTube video link in case the videos are not displayed correctly in GitHub: https://www.youtube.com/watch?v=QZUjNw43ylE&list=PLMDzgYoAarGEzdUJmHpmiIwPcnGIEnsN9
The following GitHub link includes any other pictures or data: https://github.com/yaz-gear/final-project/tree/main/Results