Virtual Reality Force Feedback and Safety Device

Good Good Boys:

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February 4, 2019

Executive Summary

Virtual reality (VR) is a set of technologies that are rapidly evolving into a prominent and mainstream feature of the video game and entertainment industries. The Facebook-backed company Oculus is one of the most prominent companies innovating in this field. Their first consumer headset, the Oculus Rift, with its fully tracked headset and controllers allows for near-limitless creative uses for both consumers and developers. However, the Oculus Rift and all the other systems on the market suffer from glaring safety omissions that make their use hazardous for even the most experienced of users. A VR head-mounted display (HMD) fully obscures the user's vision and immerses them in a virtual world, blinding them to the outside world and often causing them to completely forget about their physical surrounding. Although "virtual fence" software implementations exist for these systems to alert the user when they are in danger of exiting their safe VR play area, these systems are often ineffective with smaller play spaces, rapid in-game movements, and less experienced users. Consequently, a user can accidentally strike walls, objects, and even other people while immersed in their simulated world. This can easily result in injuries and physical damage to their surroundings.

To alleviate some of the safety deficits of current virtual reality products, we propose developing a hardware and software solution that is able to physically prevent the user from extending their arms outside of their established play area. This will include a wearable vest system and cable-attached wrist guards that are able to engage variable levels of resistance to outward arm movement. The full capabilities of this system will be showcased in a virtual reality demonstration program featuring a variety of virtual objects and an enforced play space boundary. This program will run on the same PC that will power the Oculus Rift virtual reality headset.

1) Problem Statement

Virtual reality (VR) technology has reached mainstream audiences in recent years. The most prominent examples of VR head-mounted displays (HMD) include the Oculus Rift, HTC Vive, and PlayStation VR. These three systems are all examples of the most advanced form of consumer VR currently available that includes full tracking for the headset and two controllers, one for each hand. However, since a HMD fully obscures the user's vision, it is very easy for them to become immersed in the virtual reality program and lose sense of their physical surroundings. This can result in the user accidentally striking an object or person, losing their balance, or stepping out of the designated VR play area. The primary way of mitigating these dangers is to completely clear out the VR play area and mark a virtual boundary. As an example, the Oculus Guardian System requests that the user mark out a boundary during the initial setup phase. This boundary is ordinarily invisible to the user, but it appears as a visible mesh boundary when the user's headset or controller comes too close to the boundary of the play area [1]. Although this sort of system is effective in many low-velocity scenarios, it is heavily dependent on the user being properly conditioned to react quickly and appropriately. Conversely, this system is far less effective with rapid in-game movements, smaller play spaces, and less experienced users.

Although this nascent VR industry has not yet been studied scientifically from a physical safety standpoint, there are multitudes of publicly available videos that demonstrate the types of common accidents that can occur. Some common accidents include colliding with walls and ceilings, striking individuals that are near the play space, and shattering nearby monitors and TVs. The currently available controllers protect your hands to a certain degree, but hand injuries still often accompany these types of accidents. In a worst-case scenario, at least one individual has died in a VR-related accident after he fell on a glass coffee table while immersed in a VR game [2].

The most direct way to address the issue of accidentally striking objects and people outside of the play space is to physically restrict outward arm movement once it is determined that the user is likely to cross the play space boundary. This, effectively, requires a force feedback mechanism. Although force feedback is being actively explored in the area of virtual reality, almost all of the current research is being done in regard to force feedback for individual fingers in order to simulate touch [3]. There are some whole-body force feedback systems being researched, but they usually include incredibly bulky exoskeleton contraptions that are nowhere near commercial viability standards [4].

2) Design Objectives

1. A force feedback system will be produced that is able to restrict outward arm extensions of the virtual reality system user. This force feedback will be able to fully arrest outward arm extensions before the user is able to cross the boundary of the VR play space. Each arm will be independently restricted, dependent on the positioning of the respective controller. The forces generated by this system will only be able to reactively pull against the user's attempt to push their hands outward, but it will not be capable of actively pulling in their arms. This mechanism minimizes the safety risks as compared to comparable exoskeleton contraptions.

2. The software controlling the hardware implementation of the force feedback mechanism will be capable of a variable level of resistance to outward arm extension. This will allow both a full-stop arrestment of outward motion as well as gentler resistance increments. This opens the possibility to more comfortable decelerations of the arms as well as a multitude of gaming-related applications involving the simulation of physical interactions with virtual objects. These more comfortable decelerations are also intended to increase user comfort and reduce the risk of injury.

3. The system will demonstrably decrease the risk of the user accidentally moving their

hands to a zone outside of their established VR play area boundary. The pre-established play area boundary will serve as a hard spatial limit, and the system will fully counteract arm movements that attempt to cross this boundary. This will dramatically reduce the risk of injury that can occur when a user's hands exit the play area and could come into contact with walls, ceilings, objects, and people.

4. A virtual reality demonstration program will be created to showcase the full functionality of the force feedback system. This will include a demonstration of the play space boundary enforcement in the horizontal and vertical directions. Additionally, in-game virtual objects will be created to highlight the variable levels of force feedback that are possible with the system.

5. The hardware system will be less complex and less physically intrusive than many of the other force feedback systems currently being researched [3][4][5], allowing it to be both more affordable to build and more practical to use for many dedicated VR enthusiasts.

3) Major System Requirements and Constraints

a) Major Functional Requirements

1. A passively powered cord retraction mechanism must be implemented. This will ensure that the cord extending from the chest-mounted hardware to the wrist guard does not ever experience an excessive amount of slack that could interfere with the normal operation of the system. The retraction mechanism should be passively powered by a mechanism such as a spring so that the device is optimally quiet and energy-efficient.

2. The force feedback system must be able to resist at least 100 pounds of force applied to the retractable cords on each side of the device. The goal is that this measurement of force, applied over some distance, should be sufficient to stop a full-force punch from most adults before their arm is fully extended and potentially in an unsafe area outside of the establish play area boundaries.

3. The force feedback system should be able to prevent the user's hands from exiting the play area when an arm movement begins with the hand initially 2 feet or more within the outer boundaries of the VR play area. This includes the vertical restriction in the play area's height. This requirement does not address situations where the user is moving their entire body outside of the play area (i.e. walking/running/leaning) since that is outside of the scope of this project.

4. The variable force feedback must include at least 4 distinct levels of resistance to an outward movement of the user's arms. These 4 levels of resistance include the maximum resistance setting, but they are independent of the negligible tension introduced into the cord by the passively powered retraction mechanism. Although 4 levels of resistance are the minimum requirement, a near-continuous range of resistances is preferable.

5. The virtual reality demonstration program must include elements that guide the user through a full experience of the hardware capabilities. This includes educating them about how the VR play area boundaries are enforced and encouraging them to *carefully* test these boundaries.

6. A set of at least 4 distinct virtual objects will be created that are able to activate the entire range of resistances that are possible with the force feedback system when the user interacts with them appropriately.

7. Since the force feedback system is intended as a backup mechanism to protect the user from having their hands accidentally exit their safe play space, the system must activate the vibrational motors in the Oculus Rift controllers as a complementary alert mechanism. This mechanism complements the existing virtual wall mesh that will appear in their field of view in a normal Oculus VR environment. Additionally, this vibrational haptic feedback is meant to precede the mechanical activation of the force feedback mechanism so that the user can stop or retract their hands before the force feedback system would need to intervene.

8. The system must have a togglable "boundary control"-only mode that intervenes only when the user is moving your hands outside of the safe play space (and is not activated by interactions with in-game objects). This mode will extend battery life and allow the user to experience only minimally intrusive force feedback. It will additionally reduce the physical strain that the device could have on the user during prolonged use.

b) Major System Constraints

1. The force feedback must be fully compatible with the Oculus Rift CV1 virtual reality system running on a VR-capable Windows 10 PC.

2. The end-to-end latency between the virtual reality program issuing a command for full-force resistance and the hardware device applying this resistance level should be less than 0.5 seconds. This constraint is independent of other system requirements.

3. The total weight of the chest-mounted system, including the vest, must be less than 30 pounds.

4. The chest-mounted system cannot protrude out more than 6 inches from chest level.

5. The system must be powered by an appropriate rechargeable battery pack (or system of battery packs). The battery pack must be of a size that can reasonably be integrated into a vest-mounted system.

6. The vest containing the majority of the hardware must be size-adjustable to snugly fit adults of different sizes. There is not a hard requirement on how small or large of an individual it must fit since the design should be modifiable to accommodate an individual of smaller or larger stature, if necessary.

7. For safety reasons, the vest containing electrical components of the system must be able to be easily removed within 10 seconds.

8. The chest-mounted hardware must contain a prominent central button (or pair of buttons) that resets the servos to a neutral position (to disengage the disc brake system) and powers down the system. This button should be able to be reached by either one of the user's hands when the cords are fully retracted.

9. The rigid mounting surface on the chest needs to be backed by an electrically insulating material that is at least one-eighth inch thick to minimize the risk of electrostatic discharge to the user.

10. All electrical components and rotating mechanical components must be covered by an enclosure for safety reasons. This enclosure cannot contain any sharp edges that could pose a safety risk to the user during usage. Ventilation holes and slits should be narrow and not be located on the upper part of the enclosure where long hair would otherwise present a safety hazard for the user.

11. The exit points of the two nylon cords on the chest-mounted hardware must be within 8 inches of the center of the nearest shoulder joint (closer is better). This will ensure that the line tension roughly mimics the force vector that an object would naturally exert when the user pushes against it with their hand. This constraint is meant to minimize the risk of user injury.

12. The PC-based VR software and accompanying documentation must make it abundantly clear that the device is a prototype that is absolutely not for use by children or those with relevant health risk factors. Therefore, the VR software must present a disclosure clearly explaining this before the user may proceed in the demonstration program.

13. The force feedback system must default to a low-resistance cap of approximately 20 pounds of resistance to outward arm movement. The user may elect to remove this restriction through a further opt-in step that reemphasizes the risks and safety precautions. This constraint is meant to protect novice users that are not yet used to the force feedback system.

14. The PC-based VR software should have a warning pop up after 10 minutes of use to remind the user of the possible health risks involved with the overuse of the product. This prototype is intended as more of a technology demonstration, so extended studies would need to be conducted before precautionary messages such as these should be lifted.

c) Standards

Over the course of the project we will be taking compliance to standards and regulations into account when we are sourcing and purchasing parts:

- We will source wireless antennas that comply with FCC Section 15.247 for RF emissions. This regulation pertains to wearable devices to ensure the specific absorption rate of RF signals remains in a safe range.

- Our batteries will be sourced from a manufacturer that fulfills ISO 9001 (ensures the organization meets statutory and regulatory requirements related to its products) and ISO 14001 (certifies that the organization has an effective environmental management system).

- The end product will make use of network standards for data transmission such as

UDP. This will provide us a standard datagram encoding so that the packets can be composed and read by separate programs, even if these programs use a different programming language.

- Our wireless communication will occur with standard IEEE 802.11ac Wi-Fi transmission frequencies and protocols to simplify implementation and regulatory compliance.
- The Raspberry Pi will use the I2C serial protocol to interface with the Adafruit 16-channel servo HAT.
- The desktop application will use the standard Windows .NET framework baked into C# for interfacing with the Unity engine and the transmission of packets to the Raspberry Pi.
- The Raspberry Pi will very likely run on Raspbian Lite, a well-supported distribution of Linux that is adherent to Linux's standard features.
- The software running on the Raspberry Pi will very likely be written entirely in Python and will conform to either Python 2.7 or Python 3.7 programming language conventions.
- Our product will be licensed under the MIT open source license for fair use by whoever wishes to responsibly use or reimplement our designs.
- This project will not result in a consumer-ready product that will ever be manufactured or shipped to consumers by our team, so we will not need to seek regulatory oversight or compliance for the final protype device.

d) Societal Factors

<u>Public Health, Safety, and Welfare:</u>

In recent years, virtual reality has been transforming the realm of medicine and public health. Virtual reality can be used for therapeutic and educational benefits. For example, one VR game, SnowWorld, designed by Professor David Patterson of University of Washington Medicine and fellow researcher Hunter Hoffman has been used to try and mitigate pain from people suffering from severe burn injuries. This unique software simulates icy terrains for the participants to explore, allows them to toss and get hit by snowballs, and experience many other sensations in this winter wonderland. Brain scans of people who have played the game have been used to show and relate the perception of pain. Other virtual reality experiences are used to relieve pain and anxiety in cancer patients and those who have undergone traumatic experiences acquiring PTSD.

Our project contains multiple moving parts, including a servo motor and rotating disc. As all of this is worn on the chest, there is a possibility of the forces created by the rotation of the disc or the brake may cause the device to malfunction or possibly break. To reduce possible injury, we are working our product is as safe as possible. This includes making the base chest piece out of a high-density plastic or similarly strong material that is capable of handling the forces created by the servos and braking system. The chest-mounted electrical components also present the possibility of electrical shock or collision. To combat this, every part will be held in by an enclosure, most likely 3D printed, and the mounting plate will be backed by an electrically insulating material. Additionally, since this is a device that forcibly interacts with the user's body during normal operation, we are integrating a multitude of disclosures, safety instructions, and additional user opt-ins. By default, the device will have a force limit of approximately 20 pounds that it can use to restrict outward arm movement. Only after an extra layer of instructions, disclaimers, and user opt-in will this restriction be able to be lifted. Lastly, our instructional material will warn against the prolonged usage of the device due to the risk of repetitive strain injuries that exists for almost any form of repetitive movement.

Global Factors:

When VR first came out it, it was either a poor experience, incredibly niche, or both. Now, this technology is quickly surrounding us and is much more affordable than it was as few as 5 years ago. Nowadays, virtual reality headsets are being utilized not just for gaming, but also for educational purposes, health issues, and countless other projects. Usage of VR headsets and systems ranges widely from all ages and is used for leisure time at home as well as education and newfound projects for big companies and beyond.

Social and Cultural Factors:

VR can be used to simulate many sorts unimaginable experiences. We can simulate ancient cities and architectures to explore. One could travel to a cultural festival and experience it from the other side of the world. This can be used to open the possibility of experiencing such things first hand. If people have the chance to virtually travel to other cities, they could get a feel for the culture and experience a connection that they might have never imagined.

Most people tend to know a singular lifestyle. They know a singular religion, background, or certain wealth. They'll only know the specific places they've been to. Using virtual reality, people have a chance to simulate other experiences and to expose themselves to things they've never known. People can connect online through social media already. Now imagine taking this a step further and being able to meet others in person through virtual reality, traveling to exotic locales, and seeing a whole new world.

What VR lacks is a physical response to movement. Our product is sure to increase immersion and user satisfaction. Over time, our product could be expanded and/or combined with other products to create a full force feedback system to create fully immersed VR experiences including not just the arms, but also the legs, the head, individual fingers, and more. After this layer of immersion is reached, the world of online interactions is sure to become much more similar to in-person socialization. The worldwide accessibility of this type of socialization is sure to help bridge cultural and societal divides that would otherwise fuel cultural biases and other societal discord.

Environmental Factors:

Environmental agencies could potentially simulate certain terrains for training and educational purposes. For instance, they could simulate best practices for performing work in protected natural habitats. VR can also be used for mapping out terrains, scoping out certain weather patterns, and simulating daily things like traffic or population density.

Our prototype product will be fully disassemblable, so any broken parts will be able to be replaced without discarding the entire system. Additionally, many of the materials (such as the plastics and steel components) can be safely recycled. The NiMH battery pack will be removeable so that once it is at its end of life it can easily be sent to a responsible disposal drop-off point for rechargeable batteries. There are also recycling programs available for electrical components such as the Raspberry Pi board. However, not all materials are recycled into other products (even when they sent to a recycling center), so the product cannot avoid contributing a small amount of material to a landfill at the end of its life.

Economic Factors:

Our prototype development is targeting a total budget of approximately $450-750. So individually produced units of our product can be considered expensive. However, when you consider the high startup cost of using VR including a high-end computer, peripherals, and the headset itself, our product is much less expensive than that total buy-in cost of perhaps several thousand dollars. VR enthusiasts tend to have the recreational money necessary for expanded setups like this. However, this price point would likely be a non-starter in a competitive global hardware economy. Luckily, the hardware design we have proposed is mechanically rather simple with no single component costing even $100. Therefore, after further hardware refinements and a move to mass-produced and custom-made parts, the unit price would surely drop precipitously at scale. We do not intend our original prototype design to be as cheap as possible since we will be purposefully overengineering it to ensure reliability, but we are open sourcing the hardware and software deliverables so that a team interested in bringing a similar product to mass market would be able to benefit from our experiences and design ideas.

4) Design Concept

a) *Research and investigation*

1. Our team has looked into the Unity game engine and decided that it will be a powerful and developer-friendly game engine to develop the PC-based software component of the VR force feedback system [6]. Unity Personal is free for any user or organization with less than $100,000 in annual gross revenue, so we will be able to use this version of the game engine for free [7]. Advanced features of the paid version of the software should not be necessary. Also, Unity programs are written in C#, so several members of our team should be able to code within this game engine.

2. We investigated the best way for the chest-mounted computing device to communicate with the PC-based Unity software. Any sort of hardwired connection seemed like it would be very complicated and possibly require a custom plug-in that would require the rather expensive paid tier of Unity. However, users in their forums encouraged the use of UDP packets as an easy way to communicate with custom hardware devices that are capable of that standard. Since so much of the latency of the system is going to be built into the physically moving components, any additional latency resulting from a Wi-Fi packet transmission is relatively insignificant.

3. We investigated how accessible the Oculus Guardian System boundary information is to a developer. Luckily, Oculus has made this information readily available with the ability to access the boundary's dimensions, geometry, the closest distance to the outer boundary

surface, and much more [1].

4. We have bought a mechanical disc brake set originally intended for a bicycle and investigated how feasible it would be to adapt for the purposes of this project. When measured with a luggage scale, the force that needs to be applied to the actuating arm does not appear more than around 20 pounds, although this number will need to be properly verified once the hardware is mounted. Based on this number, it appears as though a standard 20 kg-cm RC servo should be sufficient without the need for any sort of lever system modifications. Lastly, the travel distance of the actuating arm appears to be less than 1 cm with only a couple millimeters of this travel including contact between the brake pad and rotor, so extra care will have to be taken with how we deal with this mechanism.

5. We investigated an appropriate servo model for the purposes of actuating the mechanical disc brake system, and the FT5121M digital servo distributed by Pololu appears to be a good fit. This model is rated for 20.5 kg-cm of torque and can rotate 60° in 0.12 seconds. They each cost approximately $50, they but have performance advantages over similarly sized servos in Pololu's catalog that cost less. It can run on 6.0 to 7.4 volts, so we should be able to directly use RC hobbyist-grade batteries with voltages in this range. This particular model draws burst current of up to 5 amps, so we will need to considerate of this if we utilize it in our design. We currently have one of these servos on-hand, pending further testing.

6. In order to address the possible "short travel distance problem" of engaging the disc brakes, we have looked into the use of springs to help to prevent the stalling the servos and provide additional resolution in the amount of resistance that can be engaged by the disc brake system. A variety pack of appropriately sized springs of varying spring constants can be bought for under $20, and we have already purchase such a set of springs.

7. After surveying the available products, we purchased a lawnmower recoil starter to serve as a strong candidate to provide the nylon cord and retraction mechanism for the force feedback system. This product includes a steel coil spring, strong plastic spool, and a very durable metal shell. It has 3 mounting holes that appear to be sufficiently durable for our purposes. We have two of these units on hand, with one already mounted on our first hardware prototype.

8. To gain a better appreciation for how comfortable it would be to have an arm abruptly stopped by a cord attached to the forearm in some way, we rigged up a retractable dog leash to a weight lifting glove via some Velcro loops. Even when punching with full force and abruptly stopping the cord's extension, the experience was not painful or even unpleasant. Of course, no injuries occurred, and it appears as though using a similar attachment mechanism will work fine for the purposes of this project, although we will proceed carefully.

b) *Selection of Design Concept*

Current Design Choices:

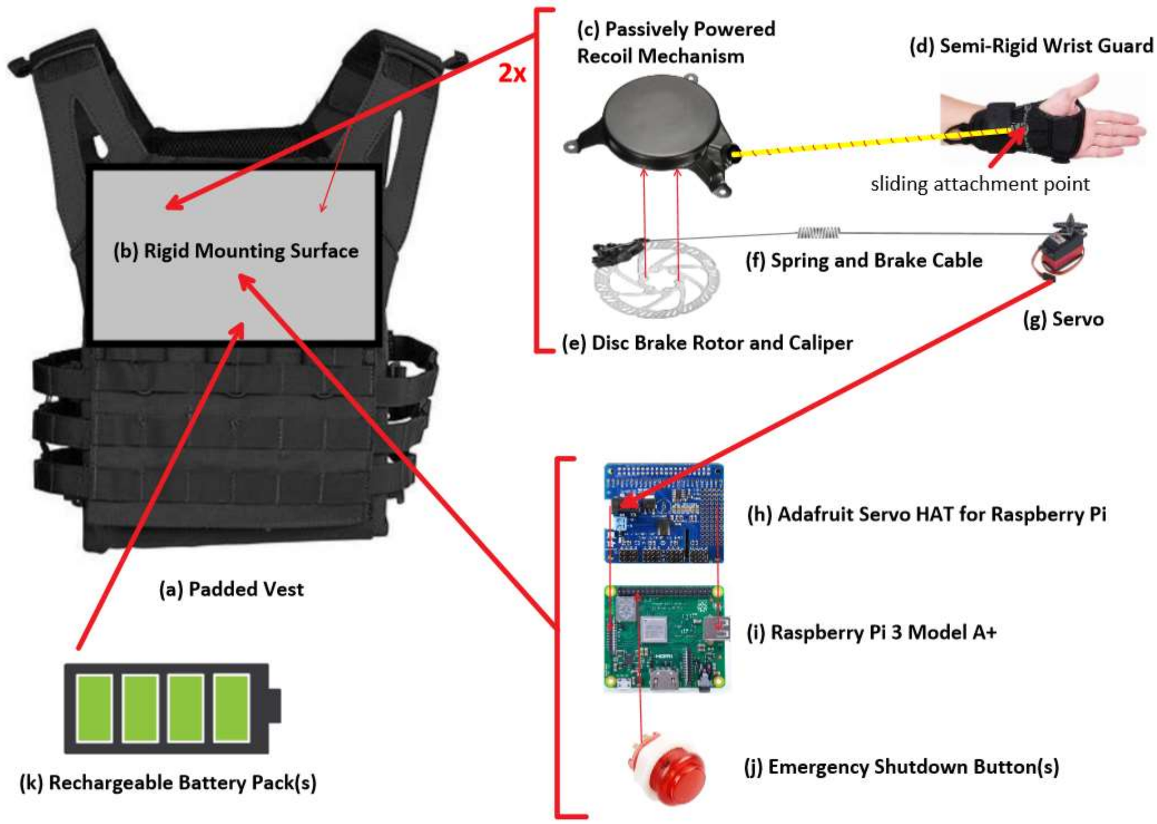

Figure 1: Chest-Mounted Hardware Overview (product photos from [8][9][10][11][12][13][14])

The various components of Figure 1 are expanded on below and referenced by same letters as used in the figure.

a) **Padded Vest:**
A Velcro-adjustable padded vest will securely hold a rigid mounting surface to the chest. Overall, this vest will serve as an attachment point for the main hardware components of the system and distribute any forces applied to the mounting plate across the upper torso. The vest itself will be derived from modifications made to a padded vest, likely a vest originally manufactured for paintball or airsoft hobbyists. This vest will likely have Velcro attachments both above the shoulders and around the torso, making it very simple to remove.

b) **Rigid Mounting Surface:**
Hardware components for both sides of the device, the Raspberry Pi, and the battery compartment will all be mounted on this rigid surface. It will be completely covered with an enclosure to prevent the underlying components from becoming a safety hazard. Additionally, it will be backed by at least one-eighth inch of insulating material such as a

hard plastic or foam to ensure that the components mounted on it will not be an electrical shock hazard for the user.

c) **Passively powered recoil mechanism:**
The nylon cord that attaches to the wrist guard originates from a spool mounted to the chest plate. A ribbon spring at the core causes the cable to retract with a light tension when there is any slack in the cord. This mechanism is derived from an off-the-shelf retractable lawn mower recoil starter.

d) **Semi-Rigid Wrist Guard:**
A pair of semi-rigid wrist guards will be modified to include a small braided steel cable mounted below the inner wrist. These steel cables will allow the attachment of a strong nylon cord to hook in with an attachment point that can freely move across the steel cable. This sliding attachment point will help to minimize the amount of torque that can be applied to the forearm in regular ranges of motion.

e) **Disc Brake Rotor and Caliper:**
Attaches to cable spool and resists outward extension of cable when engaged by the servo.

f) **Spring and Brake Cable:**
Allows the smooth conversion of servo rotation into tension applied to the brake cable. The spring (or a similar mechanism) is critical to obtaining a smooth gradient of resistances that the system can apply to resist outward arm movement.

g) **Servos:**
The disc brake calipers will each be engaged via a brake line and spring to a sufficiently powerful pair of servos. The current model of interest is the FT5121M 20.5 kg-cm digital servo. These servos will engage variable disc brake resistance based on calibrated forces. The servos accept a pulse-width modulated (PWM) signal to control their rotational positioning.

h) **Adafruit Servo HAT for Raspberry Pi:**
The Adafruit servo HAT (Hardware Attached on Top) generates the PWM signal necessary to control the two attached servos. This ensures reliable PWM signal generation and reduces the burden on the CPU of the Raspberry Pi.

i) **Raspberry Pi 3 Model A+:**
The two servos will ultimately be controlled by a Raspberry Pi 3 Model A+. The Raspberry Pi will use its included Wi-Fi radio in order to communicate the desktop-based VR software via UDP packets over the local network. The Raspberry Pi will be running software that continually monitors for incoming UDP packets that will contain instructions on how it is supposed to move the servos that control the disc brakes. The local software will contain built-in safety precautions such as network timeout and forced shutdown protocols.

We are currently leaning towards using Raspbian Lite for the operating system since it will be fully compatible with the Raspberry Pi and a great variety of compatible libraries.

Additionally, we believe we will have the software for the Raspberry Pi written in Python for full compatibility with libraries such as the one that controls the Adafruit servo HAT.

j) **Emergency Shutdown Button:**
This button (or pair of buttons) will be mounted on the exterior of the chest-mounted unit. It will be reachable by either hand, even when the nylon cables are fully retracted. When pressed, this button will cause the Raspberry Pi to reset the servos to their neutral position and cause the system to power down.

k) **Rechargeable Battery Pack(s):**
The servos will be powered by a larger 7.2V nickel-metal hydride (NiMH) battery pack. We will attempt to power the Raspberry Pi by this same battery pack by stepping down the voltage to 5V, but the risk of brownouts during heavy servo activation may necessitate an auxiliary battery pack for the Raspberry Pi.

The following components were not visualized in Figure 1, but they are very important to the design:

- **Chest-Mounted Hardware Cover:**

  All the electronics and mechanisms mounted on the chest plate will be protected by a cover with integrated ventilation (passive or active, as needed). This cover will protect the user from most of the moving parts and electrical parts of the system. If feasible, it may be 3D printed, but its relatively large dimensions may necessitate building it using a different method.

- **PC-Based VR Demonstration Program:**

  The force feedback hardware solution will be showcased with a demonstration program that will be coded in C# using the Unity game engine. The 3D asset will consist primarily of the built-in assets provided by Unity, although we may elect to include custom-made 3D assets as well. This program will demonstrate the ability of the device to apply variable resistance to outward arm movement through the interaction with various objects that your virtual hands can collide with. Additionally, the outer boundaries of the play space will also engage the restriction mechanism in order to demonstrate the potential of the system as a safety device. If the headset falls below a certain height or the acceleration profile resembles a fall, then a safety mechanism will disengage the servos and allow the user to move freely. This safety mechanism can also be triggered by pressing a physical button on the chest.

- **Oculus Rift CV1 Headset, Controllers, and Tracking System:**

  The PC virtual reality demonstration program will use the VR play area boundaries provided by the Oculus Guardian System. Of course, this means the VR headset will be an Oculus Rift CV1 headset. The headset will be paired with Oculus Touch controllers as well a 3-sensor infrared camera sensor array to provide the precise tracking necessary for the PC software component of the force feedback system. This tracking system is already fully integrated into the Unity game engine by Oculus.

- **Window 10 PC with VR-Capable Hardware:**

  Our PC-Based VR demonstration program will be tested on a Windows 10 PC with an NVIDIA GeForce GTX 1080 Ti, a high-end graphics card. We will have two of these PCs, one from a team member and one provided by Prof. Tyler Bell, the project sponsor.

An artistic rendition of the conceptual design for the final prototype is shown below in Figure 2.

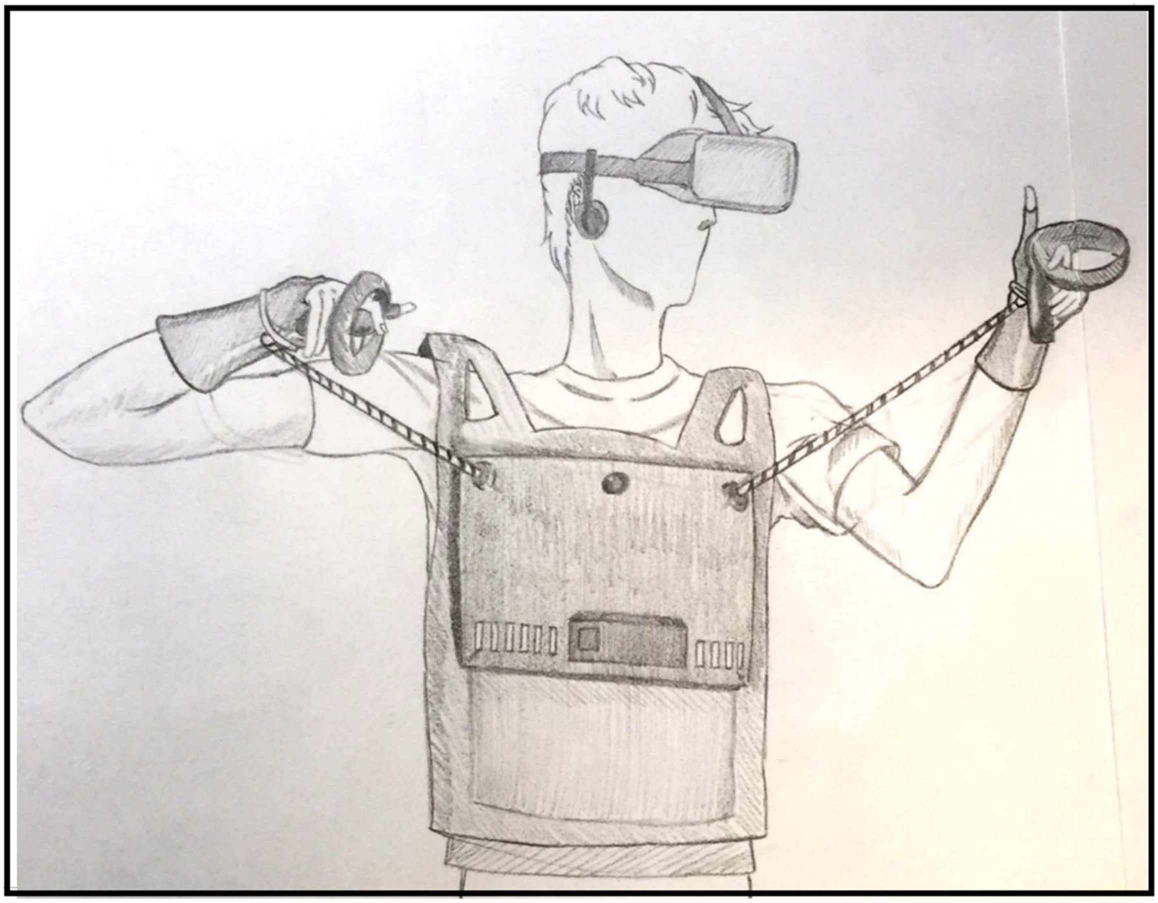

Figure 2: Artistic Rendition of Final Prototype in Use

Design Decisions in the Pipeline:

- We still need to determine if a separate battery pack will be necessary to power the Raspberry Pi. Since the servos can each draw a significant amount of current, they may occasionally cause voltage drops in our NiMH battery pack that could cause the Raspberry Pi to malfunction (i.e. a brownout). After we conclude testing with both servos running concurrently later in February, we should be able to determine if a separate battery system will be needed for the Raspberry Pi. If this extra battery is necessary, it will likely be a relatively small lithium-ion battery solution made specifically for the Raspberry Pi.

- We still need to think of what the best off-the-shelf wrist guard for our system will be. It is possible this may be of an orthopedic wrist guard or perhaps a protective roller skating wrist guard. We will also need to give more consideration as to how we will attach a steel cable to this component so that the nylon cord can hook into it as desired in our design specification. Final decisions regarding this component will occur in early March when we begin constructing our V3 protype.
- We have not yet made a final decision on the material and construction method of the cover and rigid mounting surface for the chest-mounted hardware. Preferably, we would like to 3D print the cover. However, since the dimensions are rather large for most of the available 3D printers, we may elect for a different material and construction method. This decision will occur in early March when we begin constructing our V3 protype. The rigid mounting surface will likely be made out of a high-density plastic such as HDPE, but we may need to add a metal such as aluminum to increase its structural strength.

Previously Considered Design Elements:

- The group had originally thought to use the innards of a retractable dog leash to serve as the passive recoil mechanism. This mechanism seemed sturdy enough and had a button that could abruptly stop the leash from extending, so it appeared like a good place to start. However, we later elected to use a lawn mower recoil starter assembly instead. The recoil starter assembly is made of much more robust materials (including a metal enclosure with built-in mounting holes). Additionally, a recoil starter assembly is large enough to accommodate a standard 160 mm disc brake rotor underneath, and the disc brake is very easy to attach securely to the underside.
- We had originally intended have the Raspberry Pi directly generate the PWM signals that are needed to control the servos. However, it became clear during our investigations that since the Raspberry Pi does support multiple hardware-driven PWM signals, it would need to generate these signals in software. Software-driven PWM signals are not as reliable as those created by dedicated hardware and they create considerable CPU overhead. Therefore, we elected to buy an Adafruit 16-channel servo HAT. This device sits directly on top of the Raspberry Pi and can generate the PWM signaling necessary to drive up to 16 independent servos. Additionally, this servo HAT came with an easy-to-use Python library and good support documentation.
- We were originally on the fence on whether we should use a battery to power the chest-mounted hardware or simply power it via an external outlet-connected power supply. Ultimately, we decided to commit to powering the whole system via rechargeable battery packs due to the affordability and performance characteristics of the batteries aimed at RC hobbyist. A 7.2V NiMH battery pack only costs in the neighborhood of $20 and should be plenty to power the 2 servos we will be using. Additionally, an external power supply that could handle the amperage spikes that we are anticipating would be quite costly and limit the mobility of the system.
- We had originally had our hearts set on a lithium polymer battery pack due to its spectacular capacity-to-weight ratio. However, it soon became clear that large lithium

polymer batteries are prone to rupture and can cause fires when overcharged (something that can occur when a malfunction occurs during charging). Thus, we elected for the much safer NiMH (nickel-metal hydride) battery chemistry. These batteries are far less prone to rupture and fire.

5) Deliverables and Milestones

a) *Project Deliverables*

The following deliverables will be provided for inspection for the ECE:4890 instructors and the project sponsor, Prof. Tyler Bell.

1. Proof-of-concept hardware prototype:

   This prototype will include a chest-mounted system that contains a Raspberry Pi or a similar computing device along with all the electrical and mechanical components necessary to independently resist the extension of two cords. These cords will be separately attached to two wrist guards that will be worn by the user. The chest-mounted system will be integrated into an adjustable vest form factor.

2. Virtual reality demonstration program:

   The virtual reality program will be programmed with Unity or another VR-capable game engine to be ran on an Oculus Rift headset. Its source code will be provided as a ZIP file. This program will continually monitor the positioning of the user's controllers and headset using the virtual reality system's tracking hardware. When it detects that the user's controller is at a high risk of exiting the pre-established play area, it will send appropriate instructions to the computing device controlling the force feedback system. These instructions will be specific to each of the two controllers' positionings. If the pre-defined VR play area boundary does not include a height boundary, this program will instruct the user to specify a height limit by raising one of their controllers and clicking a button to lock in a height limit to be enforced by the force feedback system. Additionally, the virtual reality program will include a small sampling of virtual objects for the user to interact with. These objects will allow the user to enjoy the full range of variable force feedback capable with the system. These objects will complement the boundaries of the play area and allow the user to experience the force feedback system without risking constantly approaching the boundaries of their play space.

3. Software for the computing device contained within the chest-mounted system:

   This software will directly control the force feedback system's hardware, but its operation will be slave to the virtual reality demonstration program running on the user's PC. However, it will include local safety override features such as an emergency disable button and connection timeout precautions. This software will also be delivered as a ZIP file containing its source code.

4. Operational user manual:

   A user manual will be provided that instructs the user on how to compile, install, and use the provided software. First, this will include instructions for the compilation and installation of the software used on the computing device controlling the force feedback hardware. Second, this will specify how the user can compile and run the files provided for the virtual reality demonstration program. Instructions for this software component will include a general explanation of how the user can interact with the virtual environment to fully experience the force feedback of the system.

5. Hardware prototype construction instructions:

   The hardware prototype is only intended as a proof-of-concept prototype, so it is expected that the end user will construct their own hardware device with similar components as were used in the original prototype design. The provided assembly instructions, in combination with other design documentation, will be sufficient for a similarly capable individual or team to create a functional prototype. These instructions will also include details on how to calibrate the system's force feedback.

6. Assembly drawings of the various components of the physical device and how they fit together.

7. Schematics of any custom circuits in the final design, including appropriate manufacturer part numbers.

8. Top-level parts list:

   This will include all mechanical parts, materials, screws/bolts, connectors, and other off-the-shelf components that were used in the final design.

9. Extra files relevant to the hardware design:

   These will include any applicable 3D printing files and PCB layout files, along with any other files used during the design of the project that may be helpful to include alongside the other hardware deliverables.

10. Final report briefly detailing the overall successes and failures of the project:

    This document will be a few pages indicating, overall, how well our final product deliverables matched the original goals and expectations of the project. This will include a general timeline of how this work progressed over the months.

b) Timeline

Our team has collectively decided on a 3-stage prototyping process consisting of 3 distinct prototypes for the chest-mounted hardware. We are terming these prototypes Version 1 (V1), Version 2 (V2), and Version 3 (V3). The milestones that we plan to reach with each of the hardware protypes are summarized below:

V1 Prototype (1/21/2019 – 2/15/2019):

- This prototype will use a wooden board for mounting hardware components.
- Begin prototyping and testing of individual components.
- Mount the disc brake system, recoil mechanism, and servo on a *single side* of the mounting surface. The other system components (including the Raspberry Pi and components for the other side of the device) will be mounted on later prototypes.
- Measure forces applied to and resisted by the braking mechanism. Determine if any modifications need to be made to obtain the desired performance characteristics.
- Gauge the system's mechanical stability and effectiveness, then make the modifications that are necessary to improve its performance and reliability.
- Establish basic wireless communication between the PC system's game engine and the Raspberry Pi. This will be in the form of a barebones Unity program that will allow us to verify the effectiveness of the Oculus tracking system and the end-to-end system lag that we can expect between the PC software and the mechanical engagement of resistance on the chest-mounted hardware controlled by the Raspberry Pi.

V2 Prototype (2/15/2019 – 3/4/2019):

- This prototype is intended to help us plan how to arrange the components in the final prototype without working with the more expensive materials that will be present in the V3 prototype.
- This prototype will be mounted using a wooden board (the same material as V1), but it will have almost all of the hardware components we anticipate using mounted to it. This includes hardware components for *both sides* of the device along with all of the electrical components such as the Raspberry Pi and battery system.
- This prototype will be wearable, but it will not yet be optimized for comfort or be attached to a vest. Instead it will contain a couple of straps so that we can wear it occasionally while testing the hardware and software systems.
- Implement a regular shut off switch and an emergency safety shutdown button. The emergency shutdown button will include a software routine that first resets the servos to their neutral positions to disengage the brakes, after which the system will shut down.
- With both servos fully wired up, we will be able to determine if a separate battery will be necessary to power the Raspberry Pi to avoid system brownout issues that could possibly occur during moments of high servo activation.
- The software components of the system will continue to be developed alongside this hardware prototype.

V3 Prototype (3/4/2019 – 4/7/2019):

- This prototype will be made with our final building materials, including a padded vest to attach the rigid mounting surface onto. Unlike the V1 and V2 prototypes, the rigid mounting surface will very likely be made of a material other than wood in order to create a thinner, lighter, and more aesthetically pleasing surface.
- This prototype will be the first prototype to have an enclosure constructed for it after all of the components have been mounted. This enclosure will include ventilation at the bottom, a battery compartment, holes for the two nylon cords to exit, and an emergency safety shutdown button or two.
- A pair of wrist guards will be modified so that we can use them to attach to the two nylon cords originating from the chest-mounted hardware. A clip mechanism of some sort will be used so that the nylon cords can be easily detached from the wrist guards.
- More in-depth components will be added to the Unity program during the time we are working on the V3 prototype. These in-game elements will demonstrate a range of variable resistance settings through the interaction with various 3D digital objects.
- We are aiming to more or less finalize this prototype by April 7 so that the first draft of the design documentation turned in will remain accurate and not require heavy modifications.
- Final system calibration and testing will occur on this prototype in the final week of April.
- Public demonstrations in late April and early May will use this hardware prototype.

A complete project timeline in Figure 3 on the next page will summarize the timing of various tasks in our pipeline.

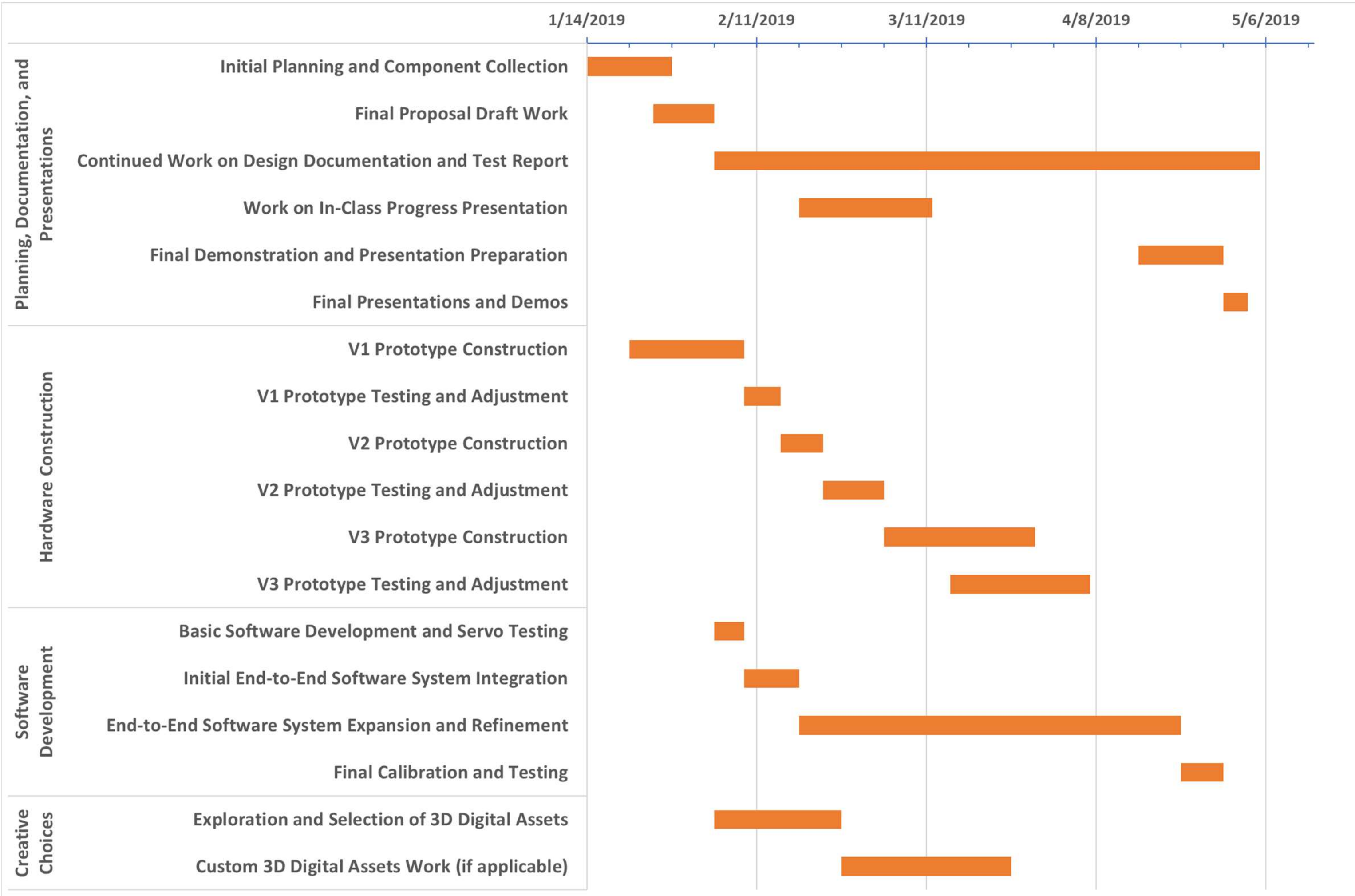

Figure 3: Anticipated Project Timeline

Important Timeline Dates:

- February 4: Final Project Proposal Draft Turned In
- February 26, March 5, or March 12: In-Class Progress Presentation (~5 minutes)
- April 7: First Draft of Design Documentation Due
- Week of April 29: Final Project Presentations and Demonstrations
- May 3: Modern Marvels Event (2:00-3:00 pm)
- May 5: Final Design Documentation and Test Report Due

In addition to turning in final deliverables to the course instructors and our project advisor, we will also be making all of the documentation and source code publicly available on GitHub under an open source license.

Currently, Stephen Siemonsma and Kevin Mattes have been assigned to all software related tasks in the timeline and will collaborate very closely on those items. Sam Hisel, due to his experience and access to restricted machine shop equipment will be responsible for the majority of the prototype hardware construction and iteration. George Drivas has been assigned to exploring the available 3D assets and (if the group elects to do so) design custom 3D assets for the final VR demonstration program. George will also be involved with the hardware iteration with responsibilities for some wiring, soldering, and tasks that do not involve specialized machining equipment.

6) Risk Management

a) *Primary Risks to Project Success*

1. Power demands of the system could be too much for the form factor:

    Since the servos can require large bursts of energy when rotating into position, their power draws are often quite high. And, since there will be two servos, they may be making these power demands simultaneously. Additionally, the servos will continue to draw significant current while they hold their position during periods where they are being instructed to maintain disc brake engagement. This may cause considerable strain on the battery system.

2. Variable resistance curve could be too steep:

    Due to the small actuation distance of the disc brakes being used in this system, it is possible that it may be difficult to obtain a nice gradient of resistances. This would cause the variable resistance goal of the project to be in jeopardy.

3. The wearable system may be uncomfortable:

    Since a considerable amount of hardware must be mounted on a rigid plate on the user's chest in order to function as designed, making this system sufficiently comfortable may be a challenge for the team. Additionally, the wrist guards may cause their own comfort and usability challenges due to the tugging of the retractable nylon cords that will be attached.

4. Calibration and reproducibility issues:

    In order for the variable force feedback system to work correctly, a calibrated force feedback curve must be able to be reliably produced every time that the product is used. Any inconsistencies in the servos or the braking hardware could cause significant deviations from the calibration curve and affect the user experience.

5. Higher than expected learning curve in Unity:

    Unity, the game engine we are currently using in this project, seems to have adequate online tutorials and resources available to accomplish the goals of our VR software experience. However, it is possible that we will have to use more sophisticated software methods than expected to accomplish the performance standards we have set for ourselves. This may require a deeper time commitment than originally expected, possibly jeopardizing our timeline.

6. Unanticipated team member loss:

    It is possible that our 4-member team could lose a team member during critical junctures in the project, or possibly for an extended period. This could be caused by factors such as sickness, academic complications in which they drop out of the course, family emergencies, or other overriding priorities that could affect our project timeline.

7. Project delays due to part availability and shipping speed:

    Throughout the system design and implementation, we may encounter bottlenecks due to integral components being out-of-stock or taking longer than desired to ship. We already encountered a small delay such as this when the first servo took longer to arrive than originally estimated. It is also possible that changes in our design may require the ordering of unanticipated parts that were not originally factored into our timeline.

b) Risk Management Plan

The primary risks to a successful project are addressed here in the same order they were presented previously:

1. Power demands of the system could be too much for the form factor:
    We will attempt to compensate for larger than predicted power demands with a combination of a larger battery pack (or combination of battery packs), a better ventilated battery enclosure, and larger capacitors to smooth out the power demands of the system. It is quite possible that computer controlling the chest-mounted hardware will need to be powered by a separate battery to avoid brownouts and ensure system stability.

2. Variable resistance curve could be too steep:
    We are currently planning to test a variety of different springs to see which one will perform the best to give the system fast and reliable performance over a range of disc brake resistances. If we are not able to obtain a sufficiently smooth force feedback calibration curve, we will explore other options for the braking system, including hydraulic disc brakes, a type of brake that is more common on modern bicycles than the mechanical disc brakes being used in the current design proposal.

3. The wearable system may be uncomfortable:
    We will make sure that the rigid chest plate is backed by sufficient padding so that this part of the design should not be a primary concern. Additionally, we will investigate the fabrics used in interior of the wrist guards, if they appear to cause any comfort issues in regard to skin chaffing. Since we are using relatively inexpensive off-the-shelf components for a lot of the force feedback system, many of these components could easily be discarded in exchange for a similar product that may be more comfortable. In our preliminary investigations, the sudden stopping motion of the system was not uncomfortable in and of itself, but extended play sessions may end up presenting user comfort issues which are hard to anticipate in advance. We will need to address these issues as we continue to develop and iterate our design.

4. Calibration and reproducibility issues:

    We will ensure that we only integrate reliable servos into the final design. They will be independently tested to ensure they are not a source of calibration issues. The braking system may also need to be broken in before it becomes optimally reliable, so we do this if it seems necessary for reliable operation. Lastly, due to the mechanical nature of the components, the system may need to be occasionally recalibrated in order to maintain reliable performance. We plan to regularly recalibrate the system as needed, including a final calibration near the conclusion of the project.

5. Higher than expected learning curve in Unity:

    To add insurance against delays related to Unity's learning curve, we are beginning to use and implement it as soon as possible. Once we have verified that the servo and braking system are functioning properly, we are going to immediately attempt to integrate the earliest hardware protype with a very rudimentary VR interface in Unity. This early end-to-end system integration will help us test the waters for what is possible with the Oculus Rift's tracking system and Unity's collision physics. It should also give us a crash course on the areas of Unity and the Oculus SDK where we should focus our time in the coming weeks and months, hopefully giving us enough time to adapt and plan around the learning curve. Additionally, if we run into software issues which we are unable to resolve ourselves due to inexperience with the particularities of Unity, we plan on seeking consultation on developer forums as needed.

6. Unanticipated team member loss:

    Our group should be well situated for the temporary or permanent loss of one of our team members. We communicate often and in detail, and we often collaborate closely on the same portions of the project. Therefore, we will never too unfamiliar with each other's work and should be able accommodate the loss of a team member without completely jeopardizing the project. For instance, Stephen and Kevin are closely collaborating on the software components of the project and have similar skillsets, so losing one of these team members would not result in the inability to continue progress on the software components. Additionally, Sam and George have similar assignments and qualifications on the hardware side of the team, so they should be able to cover for one another as needed. For instance, even though George has been assigned to work on any custom 3D assets that we may need for our VR software experience, Sam also has worked with 3D models (for 3D printing) and could easily contribute to that area as well.

    However, if we were to simultaneously lose 2 or more team members during the course of this project, it would indeed be very difficult to maintain the desired timeline and project scope. If something catastrophic like that occurred, we would likely need to rethink our project scope in consultation with the course instructors to accommodate the lack of manpower.

7. Project delays due to part availability and shipping speed:

    So far, we have been mitigating delays due to part shipping times by leveraging 2-day Amazon Prime shipping on several components, even if this may cost slightly more than ordering from a slower supplier. We additionally plan to buy some future electrical and hardware components locally to avoid shipping delays altogether. Since many of our off-the-shelf components could be ordered from any number of distributors and brands, we do not anticipate any delays from out-of-stock components. The one component that we need to be careful of is the second servo, which we have not yet ordered but would like to be an identical model to the one we already have on-hand. We plan to immediately order this second servo as soon as we fully verify the performance of the first servo that we are currently testing. Since the chest-mounted hardware contains identical components on the left and right sides, slight delays on the second servo should not affect the project timeline since our software work can simply focus on the side of the device that we get working first. Lastly, since we have already ordered most of our parts and know the general pricing on remaining components, we do not anticipate any issues surrounding remaining components such as the vest and wrist guards, which we will order well in advance of needing to work with them.

7) Budget

Estimated Budget		
Raspberry Pi 3 Model A+	$	28.95
Adafruit 16-Channel Servo HAT	$	19.05
Samsung EVO Select 64GB MicroSD Card	$	11.65
Recoil Starter Assembly (2x)	$	40.26
160 mm Mechanical Disc Brake Set (1 pair)	$	19.00
High-Voltage Digital Servo (FT5121M) (x2)	$	115.00
Servo Mounting Bracket (x2)	$	5.00
Misc. Hardware (e.g. screws/bolts)	$	20.00
Raspberry Pi Standoff Kit	$	12.00
Assorted Spring Kit	$	20.13
7.2V NiMH Rechargeable Battery (x1 - x3)	$	18.00-54.00
6V-12V Battery Charger	$	19.07
Adjustable Voltage Regulator	$	9.53
Tactical Protective Vest	$	30.00-60.00
Luggage Scale (to measure force)	$	9.48
Lithium-Ion Battery for Raspberry Pi (only if necessary)	$	0.00-60.00
Wrist Guards (1 pair)	$	15.00-30.00
Steel Bicycle Cables Set	$	11.00
IC Components, Wiring, and Adapters	$	30.00-60.00
12"x36" Wooden Protyping Board	$	6.34
Rigid Mounting Plate for Final Prototype (material TBD)	$	15.00-50.00
Cover for Final Hardware Prototype (material TBD)	$	20.00-100.00
Total	$	474.46-760.46

Please note that certain components of the VR force feedback system are not included in this budget since they were previous purchases that were originally unrelated to this project. These components include: an Oculus Rift CV1 headset, a pair of Oculus Touch controllers, three Oculus tracking sensors, and a Windows PC with an NVIDIA GTX 1080 Ti graphics card. A very similar set of VR and computer resources are being made available by Professor Bell, the project sponsor. However, this project will be independently funded by a member of the student group and will not require any outside funding.

8) Team Considerations

a) Knowledge and Skills

All our team members have at the very least a basic knowledge of both software programming and circuit design/construction since we have all taken Engineering Problem Solving II, Computers in Engineering, and Electrical Circuits at the University of Iowa. Furthermore, this is not a strictly 2 hardware, 2 software person team as both sides of the group have more advanced experience working in both software and hardware. For further hardware design and construction, both Sam and George have both taken Electronic Circuits and George has taken Advanced Circuit Techniques. On the software side, Sam, Stephen, and Kevin have all taken Introduction to Software Design, a course focused on Java programming fundamentals. Stephen has experience in Professor Mathews Jacob's research lab where he often develops software solutions to research problems, and he has interned at IDx as an R&D intern. Kevin has also taken Compiler Design and Software Exploration, Languages, and Tools. Kevin is also currently taking an Internet of Things course, and he has co-op experience at Rockwell Collins. Additionally, three members of the team have taken Embedded Systems, and Stephen is currently enrolled in this course. Regarding the mechanical design and manufacturing, Sam has experience in CNC machining, CAD, and 3D printing. Sam has full access to a machine shop on campus for whenever specialized equipment may be required when constructing device prototypes.

b) Team Organization and Function

For the most part, the hardware will be worked on by Sam Hisel and George Drivas. This includes the battery system, implementing the servos, and all of the mechanical components. These two team members will also be responsible for the accompanying hardware files and documentation deliverables. Since the electrical hardware is not anticipated to include a large amount of custom design and construction, George will also be involved in the selection of 3D game assets and quite possibly the creation of custom 3D models.

The software will be written by Stephen Siemonsma and Kevin Mattes. Software components include the PC virtual reality demonstration program as well as the software that will run on the Raspberry Pi to control the servos and connected hardware components. The software will be collaboratively developed on GitHub repositories.

Both the hardware and software sides of the team will closely collaborate and assist each other as needed. We will all attend biweekly Monday meetings with our project sponsor, Professor Bell to discuss project progress, planning, and testing. Additionally, we will meet with the ECE:4890 professors biweekly to discuss our progress on the project. Lastly, the team will communicate often in-person outside of scheduled meetings as well as via email, text messaging, phone calls, and video conferences. Non-software files will be shared within the group via a shared OneDrive folder.

c) Interaction with Sponsor

Professor Tyler Bell, a researcher with a strong interest in virtual reality technologies, will serve as the role of project sponsor. He has agreed to biweekly Monday meetings with the design team for the duration of the spring 2019 semester. During these meetings, we will primarily discuss recent progress on the project as well as difficulties we are encountering. Professor Bell will make his virtual reality lab equipment and space available for product testing and development. Professor Bell will continue to be included in important emails and decisions relevant to the project that occur outside of our regularly scheduled meetings. Professor Bell will give final approval of design decisions and accept the final software and documentation deliverables. He will also serve as an important evaluator at the termination of the project.

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