Team C5 - Fruit Ninja AR

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***Abstract* —The use of Virtual and Augmented Reality systems has become exponentially popular in recent years. The human-environment interaction methods have become increasingly expensive and existing controllers are clunky objects that need to be held. In this paper we propose a wearable glove system with haptic feedback, which produces different vibrations. Our design consists of Infrared LEDs, image processing, a RaspberryPi, an Inertial Measurement Unit, a wearable Arduino, and Infrared Cameras.**

***Index Terms* — Haptic Feedback, Motion Tracking, Infrared Tracking, Inertial Measurement Unit (IMU), Wearable Technology, Game Controller, Bluetooth LE, Unity, Arduino, Raspberry Pi**

I. Introduction

THE first mainstream application of motion-tracking technology for video games was the Wii Remote, developed by Nintendo for the Wii game console. Since then, motion tracking has also been explored in the Xbox Kinect and most recently, various virtual reality (VR) controllers. The main drawback to the Wii Remote was its bulk, which made it non-intuitive to use for some games that required abrupt motion. The Xbox Kinect solved this problem by removing the need for a controller altogether by using an array of sensors to detect motion from a single device sitting in front of the television. However, the Kinect was not without its own drawbacks. The Kinect required a significant amount of space to function, and lacked the ability to provide haptic feedback to the user, causing a less immersive experience [1]. These drawbacks as well as the expensive price of the Kinect led to its eventual discontinuation. The market currently lacks a device that combines the strengths of these two technologies. A motion-sensing glove can allow for haptic feedback and high-quality motion detection while removing the need to grip a bulky device and can work in a small space.

A successful implementation of this design should achieve a number of quantitative goals that are intended to provide a seamless user experience. The glove must output positional data at a rate greater than or equal to 30Hz, which roughly equates to the frame rate of most video games. The resolution must be capable of detecting motion of as little as 1 inch from a distance of 13ft from the sensor. Latency must be minimized, and cannot exceed 100ms, so as to maintain a smooth user experience. This latency applies to both motion detection as well as the delay for haptic feedback from in-game events. Finally, these goals will be demonstrated in a Fruit Ninja-style arcade game. Fruit Ninja was chosen as it is a familiar game to many people, with over 1 billion downloads, and requires a very quick swiping action [2]. This swiping action works best without having to hold a bulky controller, and any implementation that falls short of our design goals will lead to a rocky gameplay experience.

II. Design Requirements

The main goal of the project is to create a smooth user experience that would be comparable to other products on the market. Breaking this down further, the glove needs to meet the goals specified earlier in the introduction, in addition to other qualitative specifications. The haptic feedback motor on the glove must be calibrated to provide a vibration effect as strong as the rumble feature in typical game controllers. The quantitative metrics described earlier will be sufficient to design a game that runs smoothly, however, the game has to effectively take advantage of the positional data to offer a high quality experience. As such, there will be a calibration step at the beginning of the game where a user can mark each of the four corners that they wish to use to bound the motion area. All of these setup steps must be simple and quick so as to not cause unnecessary friction for the user before the game can be played. Finally, to achieve our goal of providing a lightweight and comfortable experience, the glove must not have a bulky microcontroller or too much excess weight.

III. Architecture and/or Principle of Operation

The main component of the glove controller (Fig 1.) is the wearable FLORA Arduino. There is an Infrared LED on the glove which we use for positional tracking (more details in the next paragraph). There is also a Bluetooth module which is connected to the FLORA in order to receive haptic feedback from the Unity game. Depending on what this feedback value is, the Arduino has a script to turn on the appropriate Haptic Motor Controller (with the use of a Multiplexer), which itself controls a Vibrating Mini Motor Disc. In this manner, the player will receive different vibrations depending on the current game state. Finally, the Arduino is powered by a battery holder so that it can be wireless. This is critical for convenience and usability since we want this controller to replace the current Augmented and Virtual Reality controllers that exist at the moment.

In between the Hardware glove controller and the Unity Software (Fig 2.), the IR LED on the glove will be tracked by the IR Camera Module which is attached to a RaspberryPi. The RaspberryPi can then transmit this positional data to Unity with Serial Communication. It can also receive haptic feedback from the game and send this back to the FLORA on the glove via the Bluetooth Module that is connected to the Arduino. In our final design, we propped up the IR camera just above the laptop, so that the player can simply look at the screen to play the game while this camera tracks the IR LED on the glove. The player could point this camera anywhere they desire to play Augmented Reality Fruit Ninja on the background that they choose.

The Software diagram (Fig. 3) shows an arrow coming into the block on the left. This is the positional data being sent from the glove controller. Since Unity has Bluetooth communication, it is able to send and receive data to/from the Arduino's Bluetooth module on the glove. This positional data needs to be interpreted and converted into a mouse on the screen. From there, Unity can simply assume that the mouse is the input for the Fruit Ninja game. We can then do some Collision detection with the mouse and the other objects in the game (fruits, bombs, special fruits/bombs). For both Fruit and Bomb objects, we can keep track of their position, their name or type of fruit/bomb, the number of points that they are worth, and whether they have been cut or not. The game keeps track of an array of fruits and bombs that are on-screen and have not been cut. The game physics in Fruit Ninja are relatively simple: the fruits and bombs spawn at the bottom of the screen and then travel in an arc motion, first up to the top of the screen and then back down. The game timer is in charge of actually spawning these objects and will spawn more over time as the game progresses. Finally, our game will also have a Main Menu.

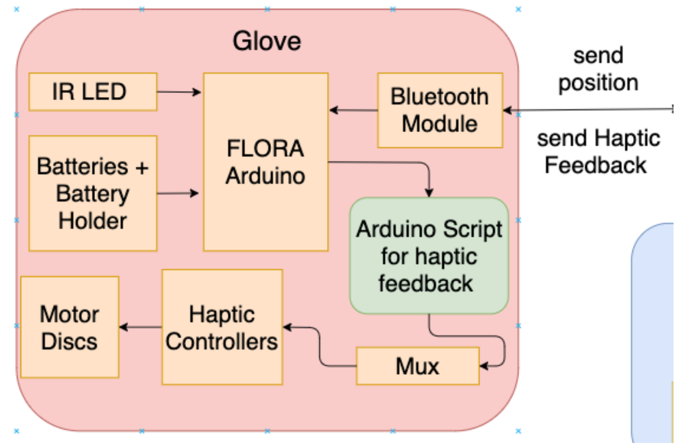


Fig. 1. Zoomed-In Glove Schematic.

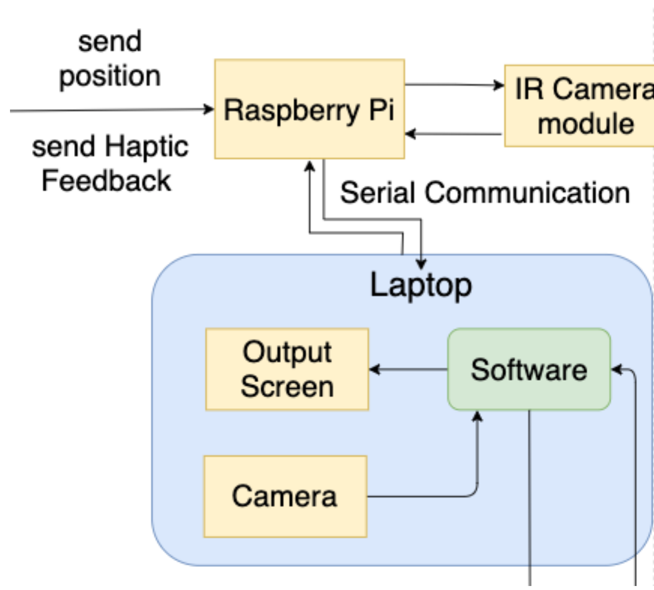


Fig. 2. Zoomed-In RaspberryPi + Laptop Schematic

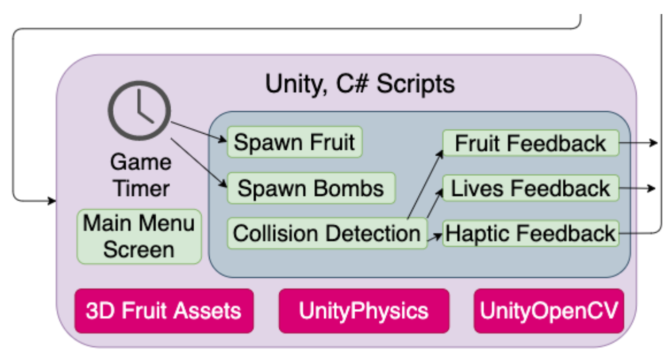


Fig. 3. Zoomed-in Software Schematic

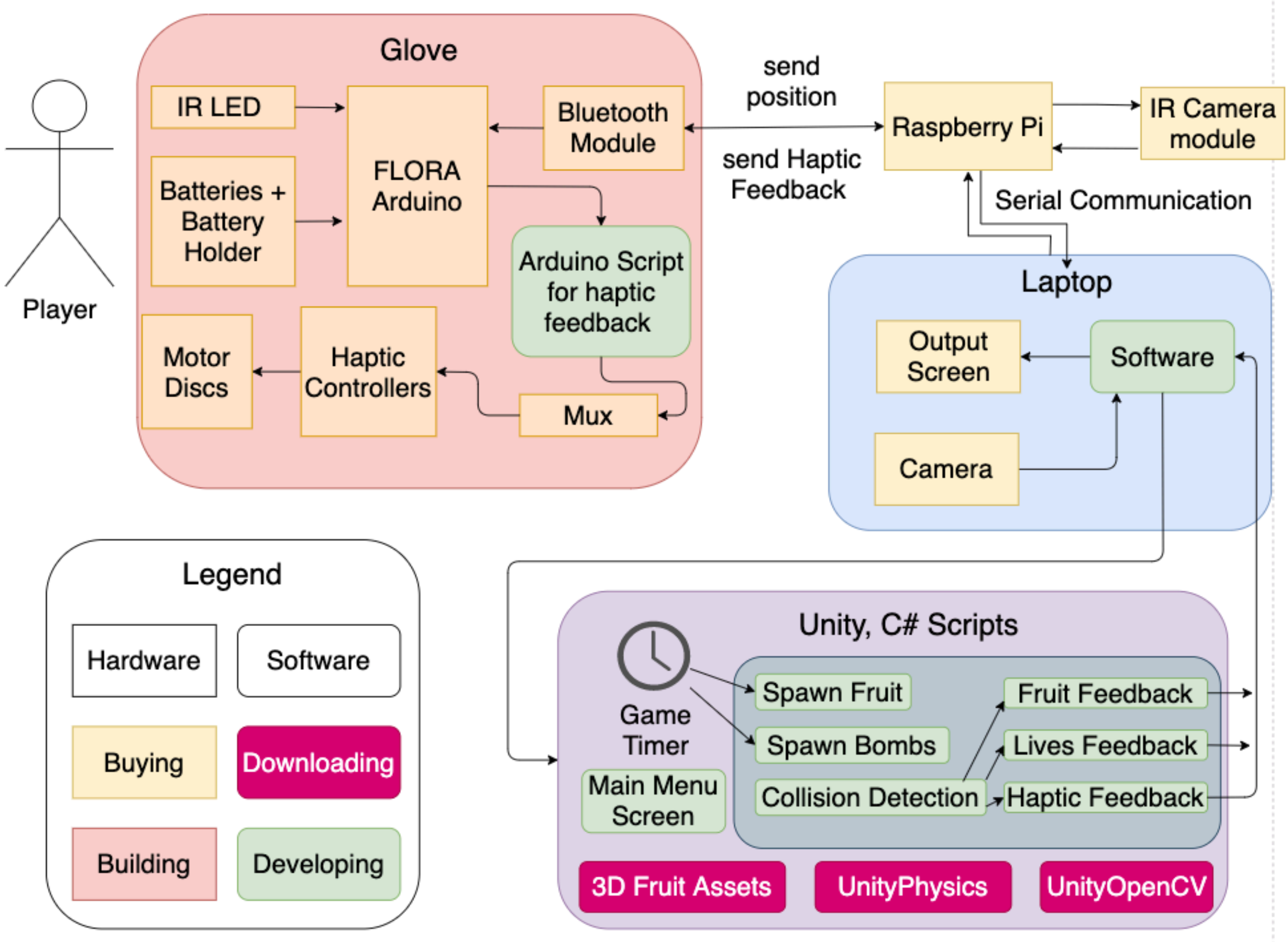


Fig. 4. Complete Block Diagram

The figure above (Fig 4.) shows the Block Diagram as whole, which is a combination of Figures 1, 2, and 3: the glove controller, the RaspberryPi and cameras, and the Unity Fruit Ninja Game.

IV. Interfaces

A. LED-Laptop Interface

The Laptop camera will capture video of the surrounding environment and OpenCV computations will track the position of the LED.

B. Arduino-RaspberryPi Interface

The bluetooth serial module connected to the arduino periodically sends the IMU accelerometer readings to the Raspberry Pi.

The Raspberry Pi sends the haptic feedback signal to the arduino when the motors need to be triggered.

C. IR LED – RaspberryPi Interface

Infrared Cameras connected to the Raspberry Pi will track the IR LED position in real time.

D. RaspberryPi – Laptop Interface

The RaspberryPi sends the following data to the laptop:

1. Processed IMU positional data
2. Processed IR LED positional data

The laptop sends the following data to the RaspberryPi:

1. Haptic feedback signal to trigger Arduino Motor Controllers

E. Unity – Laptop Interface

The laptop provides Unity with the processed glove position. Unity sends the haptic feedback signal to the laptop.

V. Design Trade Studies

In order to ensure an ergonomic system, the glove tracking should have a high accuracy and minimal latency. In order to achieve this requirement, the following approaches were considered.

A. Using colored LEDs with OpenCV:

This approach consisted of tracking the specific color of the LED and involved resizing each frame, blurring it, converting it to HSV and then applying a mask for the specific LED color. The accuracy of this approach depends on the field of view of the camera, and number of pixels used per feature. In order to verify if this solution would meet our accuracy requirements we used the following figure:

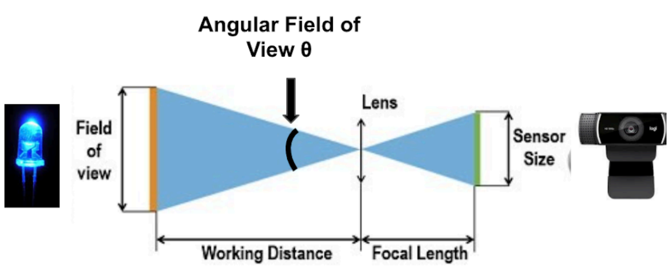


Fig. 5. Camera Field of View

Based on the figure, the following equations were derived to calculate the minimum required sensor resolution:

$$Linear\ Field\ of\ View = 2 * Working\ Distance * \tan(Angular\ Field\ of\ View/2) \quad (1)$$

$$Sensor\ Resolution \geqslant Pixels\ Per\ feature * (Linear\ Field\ of\ View\ /\ Size\ of\ Object) \quad (2)$$

The following values were used (assuming the system was used on a MacBook 2020 Laptop):

Variable	**Value**
Minimum Working Distance (meters) [3]	0.5
Maximum Working Distance (meters) [3]	2.5
Sensor Resolution (pixels x pixels) [4]	1280x720=928,800
Sensor Angular Field of View	54°
Pixels per feature	2
Size of LED to track (millimeters) [5]	5

Using the following fixed values, the table below demonstrates the minimum sensor resolution required to accurately track a 5mm LED based on variable working distance.

Working Distance (meters)	Linear Field of View (meters)	Minimum Sensor Resolution (pixels)
0.5	0.5095255779	203.8102312
1	1.019051156	407.6204623
1.5	1.528576734	611.4306935
2	2.038102312	815.2409247
2.5	2.54762789	1019.051156
5	5.095255779	2038.102312

Since the camera provides us with 1280x720 pixels all measurements up to a working distance of 1.5 meters would be possible, however, the accuracy along the y-axis would reduce when working distance $\geqslant$ 1.5 meters. This approach also involved 3 OpenCV operations on every frame which would take $O(Width * Height)$ runtime and lead to poor latency.

B. Inertial Measurement Unit (IMU)

The IMU consists of an accelerometer and gyroscope unit that can be used to track the glove position in 3-D. The accelerometer can provide 3-D acceleration measurements, acceleration due to motion $\mathbf{a_m}$, a gravitational acceleration component $\mathbf{a_g}$ and error $\boldsymbol{\varepsilon}$ [6]. This provides us with the following equations:

$$acceleration = (ax + ay + az) \quad (3)$$

$$acceleration = am + ag + \varepsilon \quad (4)$$

Assuming initial glove velocity is $\mathbf{v(t_1)}$, the glove velocity at an instant of time $\mathbf{t_2}$ can be calculated by accumulating acceleration changes [6].

$$velocity(t2) = v(t1) + \sum_{t=0}^{t2} am(t) * (t2 - t1) \quad (5)$$

Similarly, the displacements s(t), can be estimated by accumulating changes in velocity.

$$s(t2) = s(t1) + \sum_{t=0}^{t2} vm(t) * (t2 - t1) \quad (6)$$

After testing the IMU on our subsystem we found poor accuracy as compared to the LED due to the following reasons:

- Double integration of acceleration to find new positions. This implies that any errors in acceleration measurements will increase quadratically.
- Position error accumulates because the new position depends on the initial position.
- Errors associated with IMU hardware itself.

C. Infrared LED and Receiver

These components help accurately track the position of the glove in the x,y,z planes using the setup outlined in Figure 6 (below):

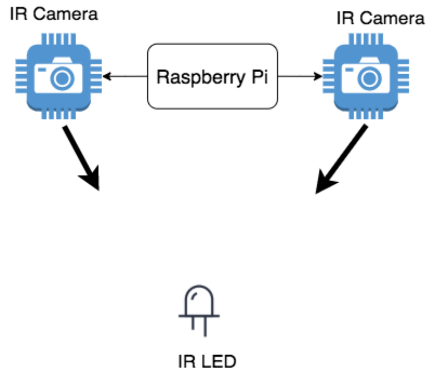


Fig. 6. Infrared LED – Camera Setup

The IR LEDs provide a radiometric power of 530MW, wavelength of 850nm. The receiver resolution of 1080x720 pixels for video provides accuracy similar to using a laptop camera for color detection. Using IR tracking provides the following benefits over the previously discussed approaches:

- Optical tracking is less susceptible to background noise.
- Since the input frames will only consist of the Infrared signal there will be 1 filter applied to every frame. A reduction in computation requirements will ultimately lead to a reduction in latency.

Comparison of Proposed Solutions

Metric	OpenCV + LED	IMU	IR LED + Receiver
Resolution	1280x720	-	1080x720
Accuracy	Can provide required accuracy up to 1.5 meters from camera	Poor accuracy, needs to be recalibrated often	Can provide required accuracy up to 1.5 meters from camera
2-D Tracking	Yes	Yes	Yes
3-D Tracking	No	Yes	Possible with two receivers
Input Signal Noise	If background consists of colors similar to glove LED	High	Low
Latency	High latency, 3 filters applied to each frame	Low latency, minimal computation	Low latency, 1 filter applied to each frame

VI. System Description

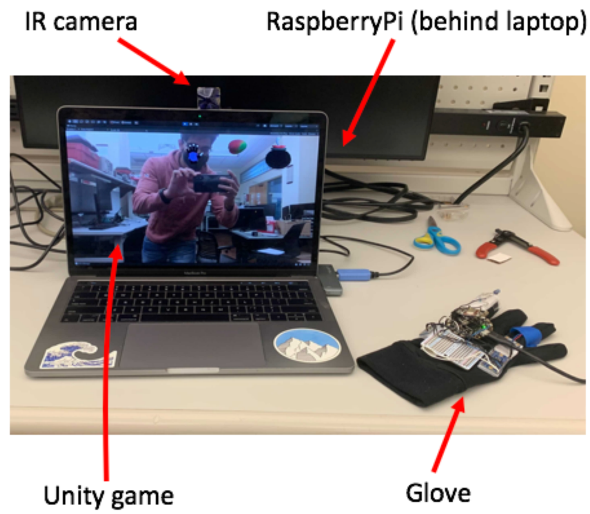


Fig. 7. Overall system

The overall system is composed of a Unity Game, IR Camera, Raspberry Pi and Glove. Each of these components are used to run the following 5 subsystems.

- Bluetooth Communication Module (on Glove)
- Serial Communication Module (Glove to Laptop)
- Infrared Position Module (on Glove and RaspberryPi)
- Game Module (Unity game run on Laptop)
- Haptic Feedback Module (on Glove)

These subsystems combine to allow for the project to achieve the desired goals and a smooth gameplay experience.

A. Bluetooth Communication Module

Haptic feedback will be achieved via a Bluetooth Low-Energy (BLE) connection to the Raspberry Pi. The Raspberry Pi is the communication bridge between the computer running the game and the glove itself. The data flows in the following manner for the haptic feedback event - the Unity game encounters a fruit or bomb slash, the game then calls a function which invokes a script to send a serial message (see Section VI.B) to the Raspberry Pi, which triggers the Raspberry Pi to send a Bluetooth signal to the Arduino FLORA, which receives it and triggers the rumble effect. The Adafruit BLE library is used to handle Bluetooth communication on the Arduino Flora. Adafruit provides drivers which are used to interface with the FLORA Bluetooth module [7]. On the Raspberry Pi, the standard socket library is used to interface over Bluetooth. The protocol that drives the Bluetooth communication defines the following messages:

- "init" – sent by the RaspberryPi, and necessitates a response of "init:true" within 2.5 seconds if the FLORA is in working order
- "rumble" – sent by the RaspberryPi, and expects the FLORA to trigger a rumble effect on the glove

B. Serial Communication Module

The Raspberry Pi communicates via a serial connection with the computer. The communication protocol is as follows: For both sides of the communication, a message is defined as a sequence of bytes followed by a line separator. A message is a loosely-defined and extensible sequence of bytes that controls an effect on the receiving end of the message. One such message is the "init\n" message sent by the PC to the Raspberry Pi. It expects a response of "init:true\n" or "init:false\n" within 5 seconds, where a timeout implies a failure to connect. A value of true denotes that the Raspberry Pi was successfully able to communicate with the Arduino FLORA, and a value of false means that the communication check failed. After initialization has succeeded, the PC can send a message of the form "rumble\n" to the Raspberry Pi at any time in order to cause a rumble effect. The Raspberry Pi outputs the calculated positional data via messages of the form "x:3, y:7, z:-9\n". The pySerial Python library is used to handle the sending and receiving of these messages on both the Raspberry Pi and host machine [8]. To facilitate communication between the game environment and the Python script managing the serial connection, a simple library is provided for the Unity game. This library exposes a function Init() which starts the Python script and connects to its socket. An event handler is registered during the Init() process which is invoked when new position data is available. A Rumble() method is also exposed which sends data over the Python socket to trigger the rumble effect on the glove.

C. *Infrared Position Module*

Infrared Position tracking is the main module responsible for determining the glove's position. It performs this via an infrared camera on the Raspberry Pi which follows an Infrared LED mounted on the tip of the glove. The Raspberry Pi handles the image processing and transformation of raw image data into x, y, and z position mappings. The calculation for mapping coordinates from the infrared camera to game coordinates will be performed by this module on the Raspberry Pi. This allows for the data which is transmitted over serial to the PC to be pure positional coordinates that can be accessed with no calculation. The design intentionally leaves open the potential to add an additional Raspberry Pi and camera module which tracks the IR LED from a different perspective, allowing for 3D depth sensing. Absent of this upgrade, the z coordinate will always remain constant at 0.

D. *Game Module*

We intentionally designed our system such that it is not tightly integrated into the game code. The game is merely treating the glove system in a black-box way, where it does not deal with the data processing itself. It simply expects the positional data to arrive over a socket connection, and displays the game objects accordingly. Therefore, a different game could make use of our glove without re-engineering the underlying components. The Fruit Ninja game is intended to be a demonstration of using the glove system, and as such is intentionally designed to not be tightly integrated. It has full access to the glove system via the scripts and socket connection, but the details for how position is sensed and tracked are irrelevant to the game developer. This is crucial for portability of the glove system. For the Fruit Ninja game implementation specifically, the game begins by performing a setup process as defined by our Unity API, which confirms all components are connected. During the initialization, the player will be asked to move their hand to draw the corners that define the border of where they will be playing. An on-screen prompt explains this process. After initialization has been completed, the game begins, and motions of the player's hand will swipe and slice fruit which float into the screen. The game uses the Unity 2D Colliders, Unity Rigid Bodies and Collision detection to simulate the effect of fruit being tossed onto the screen and sliced when the glove interacts with them [9].

E. *Haptic Feedback Module*

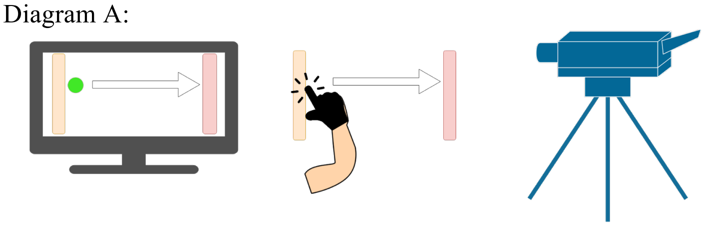
The haptic feedback module depends on the previous modules for communication, and builds upon them to provide a rumble effect on the glove. The rumble effect is achieved via a simple vibrational motor disk. This motor disk is controlled by the Adafruit haptic motor controller, which communicates with the FLORA over I2C [10]. When the FLORA receives a Bluetooth message to trigger a rumble, it sends an initialization sequence followed by a simple rumble code as documented on the Adafruit website. The power for the motor controller is connected in parallel with the 3.3V power supply for the Arduino FLORA.

VII. Test and Validation

To test our system, we used three primary specifications: Latency should be minimized and should not be larger than 100ms. Precision should be maximized such that small movements within our interaction area are accurately detected and tracked by the system. Motion of 10mm should be detectable within our interaction area. And finally, the tracking rate should be maximized, so that data is output with a rate of at least 30Hz.

A. *Results for Latency*

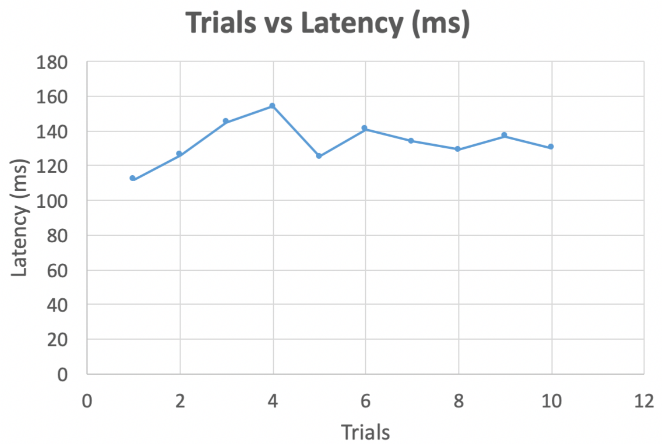
To measure latency, we describe the following apparatus in Diagram A:



As shown in the diagram, we have a user ("tester") wear the glove and wave their hand between two visible barriers. Meanwhile, a camera is configured to record both the hand motion as well as the screen with the cursor's motion. Afterwards, the film is manually examined frame-by-frame to count the number of frames between the physical motion reaching the barrier, and the frame in which the cursor completes it's motion. This number of frames is then used to compute the latency in the following equation, where n represents the number of frames and k is the camera's framerate in frames per second (FPS):

Latency (ms) = 1000 * n / k

We performed 10 trials of this test, and charted the results in Diagram B:

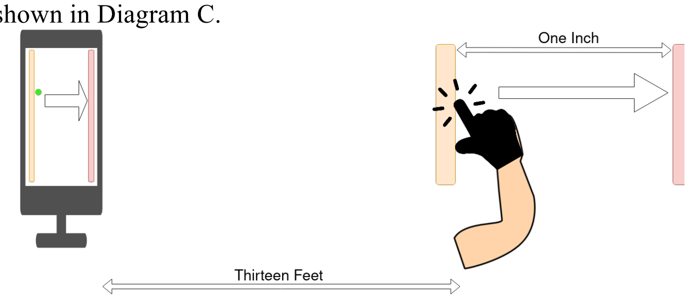


The average latency we achieved was 133ms. At 133ms, we are exceeding our theoretical goal of 100ms by 33ms. We chose 100ms because it seemed to be a reasonable standard compared to other video games. Ping latency for online video games is under 100ms on average, which is why we chose it [11]. Although we did not achieve 100ms, our qualitative experience suggests that 133ms is still reasonable for playing our system, although future iterations could use this as an aspect for improvement.

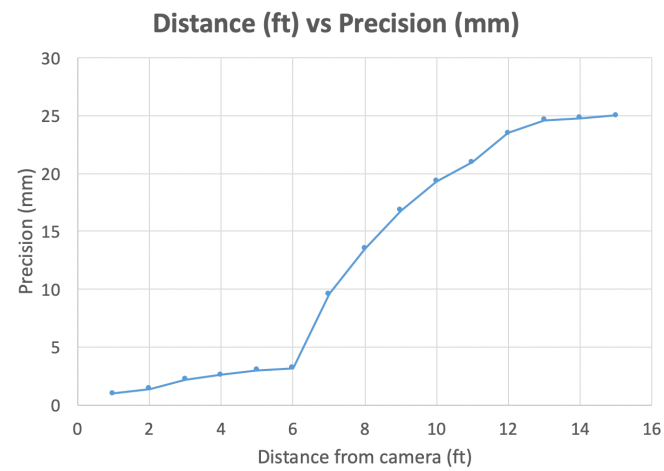
Major factors limiting latency appear to be software-related. The script computing the location of the LED is fast but adds small latency. Serial communication adds minimal latency. The Python script running on the computer that moves the cursor appears to add some latency, because the library used for controlling the cursor is not instant.

B. *Results for Precision*

We used a similar testing apparatus to test precision, as shown in Diagram C.



In the precision test, the tester waves their hand like last time, but now only a small distance. Also, the distance from the sensor is recorded. The tester continues to do smaller and smaller motions until the system becomes unable to detect the motion (outputs the same coordinates before and after motion). This value is recorded, and then the tester steps back a step, and repeats the trial. Our results are documented in Diagram D.



We suggest that the reason precision was roughly stable before a distance of 6 ft was due to the inherent difficulty of trying to consistently move the glove small distances of <5 mm. A future improvement to the testing setup could perform this test with a mechanical apparatus, instead of relying on a human hand and a ruler. Regardless, we see that within the range of 6ft to 13ft, the precision is bounded between 5 and 20 mm, which was acceptable for playing the game. We reach our original goal of 10mm at distances < 7ft from the sensor.

The main factor limiting precision is the resolution of our infrared sensor, which we discuss further in Results Section C.

C. *Results for Tracking Rate*

Our tracking rate was determined by the number of data points received by the client laptop per second. Our goal from the outset was 30Hz, which was chosen because 30 frames per second is standard for most computer displays. Our infrared sensor attached to the Raspberry Pi offered different configurations that traded framerate for resolution. We chose the option that maximized resolution, leaving the framerate at 30Hz. To verify that the framerate of the camera was the limiting factor for tracking rate, we wrote a script on the client laptop to count the number of data points per second, which averaged to 30Hz. With this configuration, we were able to reach our goal tracking rate, while maximizing the resolution of our system.

VIII. PROJECT MANAGEMENT

A. *Schedule*

It is important to reiterate the primary focus of our project: the glove controller. Thus the first half of the project, and of the semester, is dedicated to building the glove and testing it. We need to make sure that the Bluetooth communication between the Arduino and the RaspberryPi works. To test this, the Arduino must be able to send the positional data (from the IMU and the IR LED) to Unity and receive the feedback that it sends back based on the game state. Once all parts on the glove have been tested and we are sure that the back and forth communication functions correctly, then we can move onto the Software side of the project. This includes the base game engine, collision detection between the fruit/bomb objects and the mouse, game physics, and any other functionalities for the Fruit Ninja game.

B. Team Member Responsibilities

Due to the circumstances that arise from this global pandemic, this course is being taught remotely. For this reason, it makes sense to have one member of our group in charge of assembling the Hardware so that we don't need to each build a glove. So, all of the parts have been ordered to Arthur's house, but the three of us will meet on campus to build it. Then, all three of us will be focused on the back-and-forth communication between the glove and Unity (positional data and haptic feedback). While Arthur is testing the functionality of the glove, Ishaan and Logan will test the Bluetooth Communication between Unity and the FLORA Arduino. Then, Ishaan and Arthur will write Collision Detection algorithms in Unity while Logan builds the basic game engine for Fruit Ninja. Once we have the skeleton of the game, the three of us will focus on the game physics and some last details for certain game functionalities.

C. Budget

To date, we have purchased all of the components outlined in our design, and almost all components have arrived. There are a number of components that have been ordered and arrived, but may not make it into the final system. This was a conscious decision, however, since the total cost for our components was always expected to be relatively low, so wasted budget was not a large concern. The breakdown of components and budget is appended in a table at the end of this report (Figure 8).

D. Risk Management

Already this project has faced a number of unexpected deviations from the initial idea. Some strategies we have made to reduce risk are inherent to the modular design of the system, and our plan to frontload work on the physical aspects of the project, while leaving software finishing touches to the end. With our initial design, we wanted to track position via a laptop webcam and an RGB LED. We then explored swapping this method for an IMU sensor, however, preliminary research showed that since IMUs can only detect acceleration, position is achieved by a double integration. This means that any error would be squared, so drift would be quadratic, and unsuitable for our purposes. Therefore, our current plan is to use an infrared LED and camera for position tracking. For another layer of risk mitigation, if the IR system does not achieve our required benchmarks for precision, we can add the IMU module back on the glove to assist with position tracking, while using the IR system to gain a reference point. We are capable of making this pivot if necessary because the Bluetooth module is designed to be extensible and transmit data as needed to the Raspberry Pi receiver box.

IX. Ethical Issues

At first glance, a wearable video game controller may seem benign to most ethical issues that are prevalent in other engineering projects, however, there are still important potential ramifications of the project to consider.

Perhaps most obviously, the issue of accessibility certainly pertains to our glove. Currently, it is only designed for right-hand-dominant people and would be awkward to use by left-hand-dominant people, thereby putting them at a disadvantage. This could be easily solved by future work to mirror the glove design on a left-hand glove. Ensuring that both models are readily accessible would be important if the design were ever brought to market. Additionally, it would also be ideal to have a left-handed glove so that more interactive games can be made, which potentially use both hands. It is also important to consider that some people lack arms or suffer from diseases that make motion of the arms and hands difficult, such as Parkinson's Disease or Tourette Syndrome. These people would also be put at a severe disadvantage if using these gloves for interaction became commonplace. A potential solution for accessibility would be to allow for traditional ergonomic computer mice and other accessible computer interaction devices to be compatible with the system and future games.

Another ethical consideration is the potential for the glove to be used for other applications than video game interaction. For example, the CyberGlove by CyberGlove systems is a similar device that tracks hand movement via a glove, and their haptic feedback glove system is marketed for, "industrial engineering, military, and academic research applications" [12]. Should a future iteration of our glove be used in other applications, the ethical considerations for potential uses would need to be discussed. Any military or government usage of the glove would inherently incur political aspects to consider. Additionally, as it stands, a system failure in the glove does not have any negative externalities, however, if the glove were used in a mission-critical application in the military, a system failure could be catastrophic. Therefore, any future applications and development for our glove should be framed such that these ethical considerations are acknowledged and reflected in future designs.

X. Related Work

The main commercial product that relates to our system is the CyberGlove by CyberGlove Systems, which is a company with over 20 years of work in building motion and finger tracking gloves. As such, their products are $30,000 per glove and incorporate advanced sensors [12]. Researchers such as Johnny Lee have successfully used the infrared camera bundled in the Wii remote to track infrared-emitting objects in a room [13]. This approach is similar to our plan to use an IR tracking system. One academic approach that makes use of an IMU system for finger tracking was explored by The Control Systems Group in Berlin [14]. By using high quality 9DOF IMU sensors, the researchers were able to track finger movements within an error of +/- 3% over a 15-minute period. The advantage of IMU approaches is the lack of a dependency of line of sight. This is not a design constraint of our project, but past work on stabilizing IMU position data via point of reference dead reckoning could allow us to achieve higher quality data.

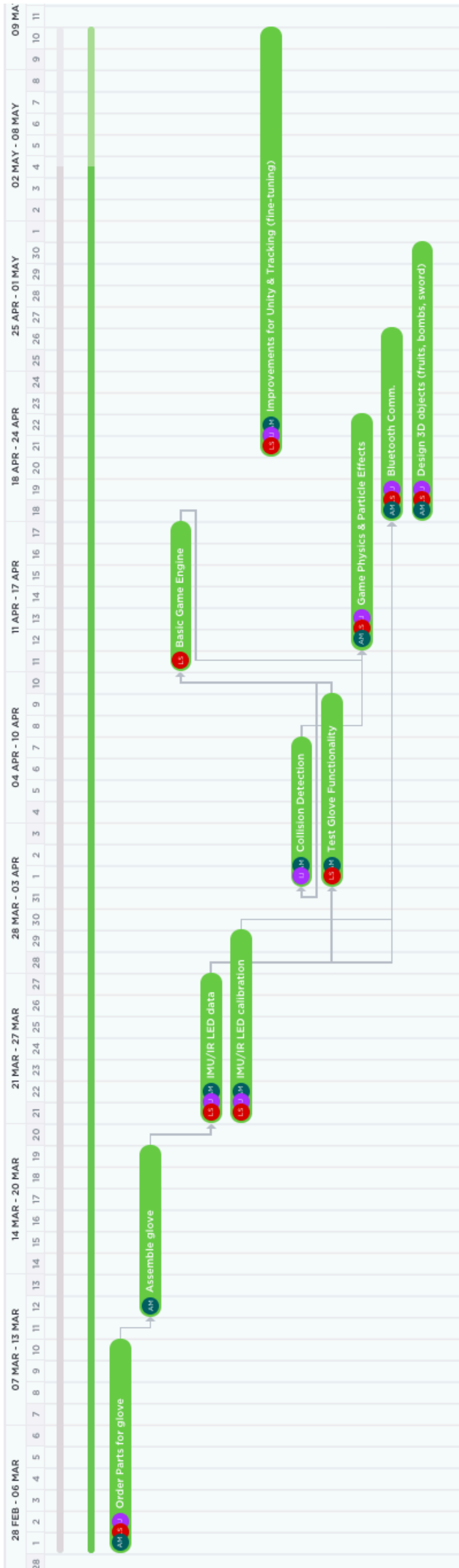


Fig. 8. Final Schedule

XI. Summary

Our system was able to achieve an average latency of 133ms and minimum precision of 25mm when played from distances up to 15 feet from the sensors. FruitNinja AR can detect movement along the x, y axes and can be improved by tracking movement along the z axis (distance from the glove to the IR sensor).

Through working on this project our group learned the importance of planning work on large projects and parallelizing tasks. Initially we made limited progress when the entire team worked on the glove tracking subsystem but found it most effective to divide work into the following – Haptic feedback system, Tracking system and Unity environment. We also learned to effectively account for deviations from our original plan, and to leave appropriate time to test and validate our decisions.

XII. References

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Part	Ordered?	Arrived?	Assembled?	included in Prototype?	Price	Supplier
FLORA	yes	yes		yes	$14.95	Adafruit
Basic glove (that we attach parts to	yes	yes		yes	$9.95	Amazon
Velcro Strips	yes	yes		yes	$2.98	VELCRO
Vibrating Mini motor disc	yes	yes		yes	$7.80	Adafruit
Adafruit Haptic motor controller	yes	yes		yes	$31.80	Adafruit
FLORA Bluetooth LE module	yes	yes		yes	$9.89	Amazon
Battery Holder	yes	yes		yes	$2.95	Adafruit
Quarter Size Breadboard	yes	yes		yes	$2.95	Adafruit
Arduino Starter Kit	yes	yes		yes	$34.99	Amazon
IR LEDS	yes	yes		yes	$7.95	Adafruit
Raspberry Pi Kit	yes	no		yes	$99.99	Amazon
Raspberry PI NoIR	yes	no		yes	$29.95	Adafruit
Serial communication for Pi	yes	no		yes	$9.95	Adafruit
10 DOF IMU Sensor (C) Inertial Measurement Unit	yes	no		no	21.99	
			total:		$266.10	

Fig. 9. List of Parts for Budget