Robot Controller through Gestures

ECE 445 Design Document

Eric Zhou(yirui2), Guang Yin(guangy2), Haoduo Yan(haoduoy2)

Group 41- Spring 2022

TA: Hanyin Shao

1. Introduction

1.1 Problem and Solution Overview

Traditionally, different robots are controlled by their specialized controllers from different companies, and it takes time to learn how to use them smoothly and naturally. We propose a gesture control system that builds upon the system, making the process of controlling a robot simple and fun. We plan to design a robot controller which can recognize human gestures and send corresponding commands to robots. The system will have three high-level requirements.

1.2 Visual Aid

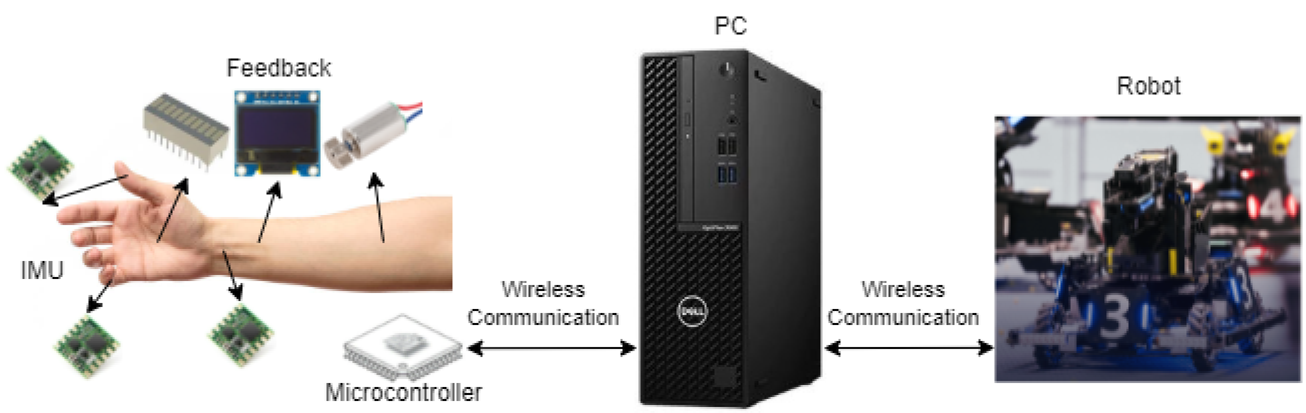

Fig1. Visual aid

1.3 High-level requirements list

- The position and orientation of the user's fingers and arms can be collected through IMUs mounted on the user.
- User's body movements and gestures can be translated to robot control actions respectively.
- Users can get feedback from the user through a feedback system mounted on the user.

2. Design

2.1 Block Diagram

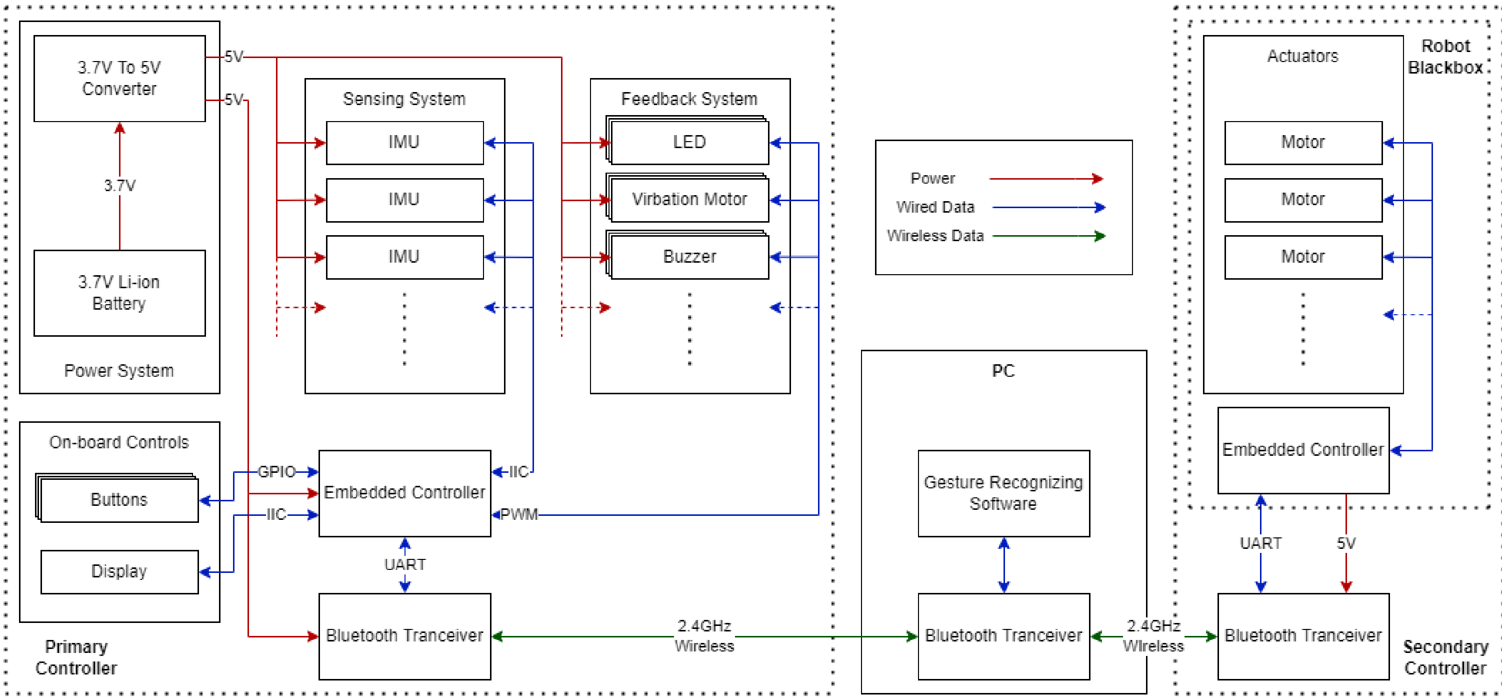

Fig2. Block Diagram

2.1.1 Subsystem overview

2.1.1.1 Human Positioning System

The system is mainly used to measure the position and orientation of the fingers and arms of the user using several IMUs placed on the user's fingers and arm. It will then report these readings to a PC through a Bluetooth wireless connection.

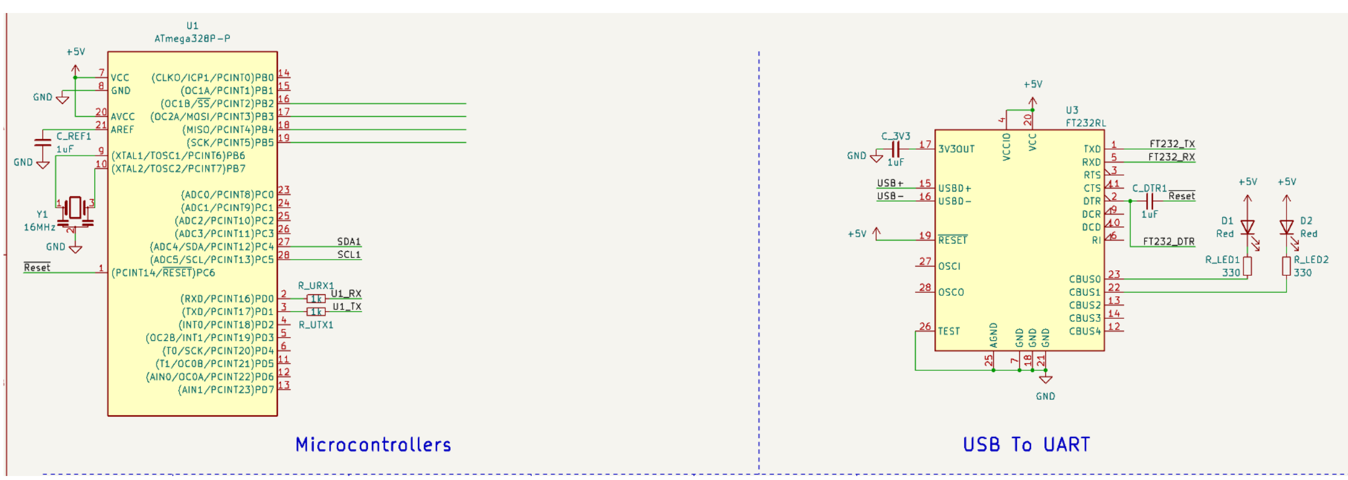

Fig3. Schematics of Human Positioning System

2.1.1.2 Gesture Control System

This system is a software that will recognize the gestures of the user using the data retrieved by the Human Positioning System. It will then translate these readings into robot commands and command the robot via Bluetooth accordingly.

2.1.1.3 Robot Feedback System

The system will read the warning messages from the robot's own controller and translate these warnings to actions of the feedback system. It will then command the feedback systems on the user to respond accordingly.

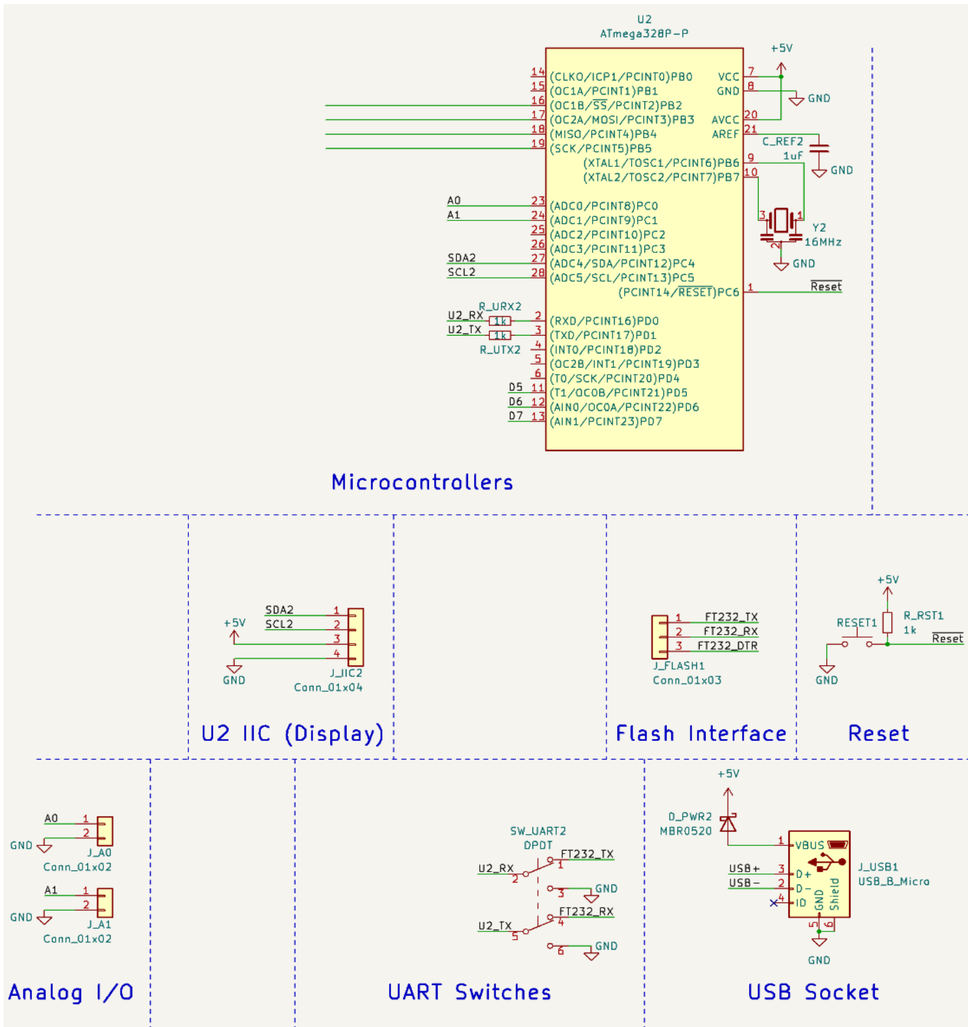

Fig4. Schematics of Robot Feedback System

2.2 Subsystem in Details

2.2.1 Primary Controller

The primary controller consists of a power source, an embedded processor, multiple IMUs, multiple actuators, and a transceiver.

The power source will be using a 3.7V Li-ion battery and a 3.7V to 5V voltage converter to power the whole system.

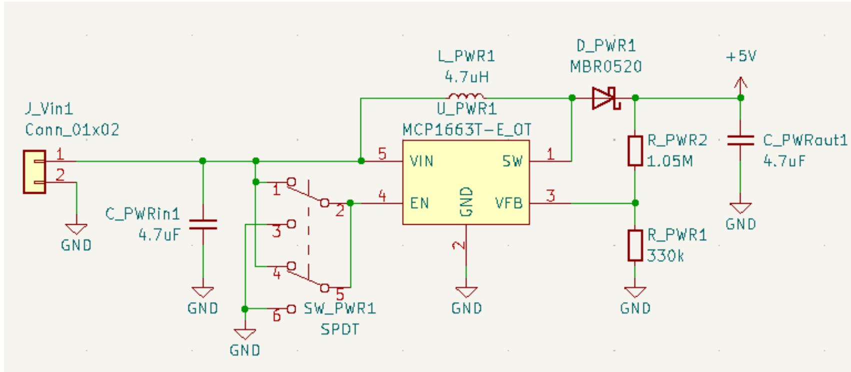

Fig5. 3.7V to 5V Step-Up Circuit

The sensing system will have multiple (at least 4 and at most 8) IMUs connected to the embedded controller through IIC communication. The data of the IMUs should be read from the IMUs at least 47Hz (detailed calculations are included in the 2.4.2 IIC communication bandwidth section).

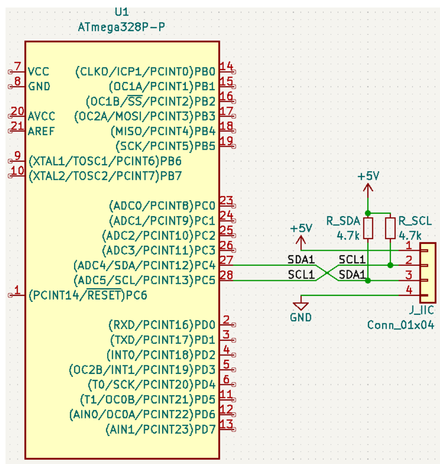

Fig6. IIC Communication Socket

The feedback system will have multiple components that help to display messages in some ways. It includes visual feedback (LED and display), hearing feedback (buzzer), and body feedback (vibration motor). These commands are sent to the display using IIC protocol, and to other devices with PWM or analog output pin.

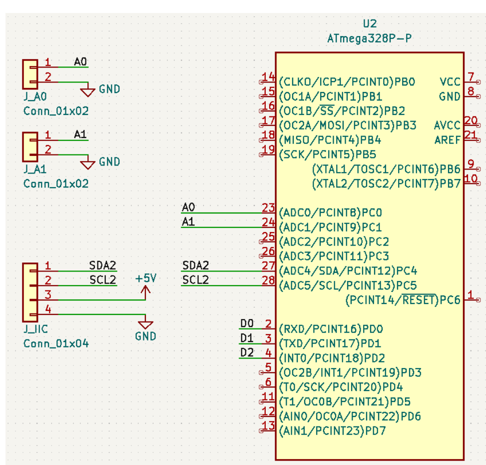

Fig7. Feedback System

The system should also be able to send the angles read/calculated via a 2.4GHz Bluetooth link. It can help identify the position and orientation of the fingers and arm of the user.

2.2.2 Intermediate PC

2.2.2.1 Gesture Recognizing Software

The program will take in the raw data transferred by the transceiver of the primary controller and detect gestures using those data. Ideally, it can recognize many gestures such as the motion of hand and arm, including making a fist, waving arms, shaking hands, etc., depending on the positions of the IMUs placed on the user. Then the system will generate controls based on these gestures and send them to the robot using a 2.4GHz Bluetooth datalink.

2.2.2.2 Warning Translation Software

The program will take in the warning singles transferred by the transceiver of the secondary controller and translate these warning signals into actions of the feedback system, including flashing LED, running vibration motors, and playing sounds through buzzers. Then the system will send them to the primary controller using a 2.4GHz Bluetooth datalink.

2.2.3 Secondary Controller

The controller will be powered through the batteries on the robot.

The controller will receive the control commands from the PC via a 2.4GHz Bluetooth data-link and communicate with the robot's own controller through a wire to let it execute the commands.

The controller will also be used to read the warnings from the robot's own controller using wired connections, then send out these warnings to the PC via a 2.4GHz Bluetooth datalink.

2.3 Requirements & Verification Tables

2.3.1 Primary Controller

Requirements	Verifications
1) After using 4.7kΩ resistors to pull up the IIC communication line, the voltage at the power side of the pull-up resistor should be at least 3.7V to make the IIC correctly functioning. 2) After a prolonged running of the microcontroller, the microcontroller, IMUs, and the feedback systems should not exceed the temperature of 40 degrees Celsius to prevent injuries to the human body. 3) After sensor fusion, the output angle of the user should be a valid configuration, and the deviation of the measured angle from the true angle should not exceed 5 degrees.	1) After powering up the microcontroller, use a multimeter to probe the voltage between the power side of the resistor and the ground. Make sure that the voltage is at least 3.7V. 2) Run the whole system normally without actually wearing the equipment, let the device run for about an hour, then measure the temperature of the whole system through an infrared thermometer, make sure the temperature is below 40 degrees Celsius. 3) Take an individual IMU, place it on surfaces of the known slope, and read the values output from the program for testing pitch and roll. For yaw testing, place a compass along with it to check if the readings deviate at most 5 degrees.

2.3.2 Gesture Recognition Software

Requirements	Verifications
1) The half-duplex communication between the embedded processor on the user and PC is fluent and without any error present.	1) Use a wired connection along with a wireless connection, run the whole system and place the IMUs in arbitrary positions. Make sure readings from the processor and readings from the PC are the same. Then send feedback system specified commands, observing if the commands sent out are expected.
2) The software is able to recognize some gestures that are essential for the whole system to run.	2) Wear the system and calibrate it first by pressing the calibration button on board while making a fist. Make sure the software is displaying that the user is making a fist. Then extend the fingers and make sure the software recognizes that behavior.
3) The half-duplex communication between the PC and robot are fluent and without any error present.	3) Using the same method as 1), attaching wire connection between these devices, make sure the data transmitted is the same.

2.3.3 Secondary Controller

Requirements	Verifications
1) The system can successfully communicate with the robot's own controller, including sending commands to the controller and receiving warnings from the controller.	1) When a Bluetooth connection is established between PC and secondary controller, test via Bluetooth, using a wired connection otherwise. It should be able to send commands to the secondary controller to command the robot to move, turn, rotate its gimbal, making sure the robot works as expected. Try to bump into walls or make the robot overload, see if any warning message is recognized by the secondary controller.

2.4 Tolerance Analysis

2.4.1 Accelerator Range

According to K. M. DeGoede et al.[1], the fasted motion that can be produced by human hands and arms are about moving $33 \pm 3\ cm$ in 226ms average when intercepting incoming objects. When an object starts at rest, the distance traveled by any object under constant acceleration is

$$d = v_{init}t + \frac{1}{2}at^2 = \frac{1}{2}at^2$$

If we consider the process of accelerating and decelerating having the same acceleration, then the maximum speed happens when the total distance is half-traveled, and when reaching that point, the time used is exactly half of the total time. Then

$$d = \frac{1}{2}at^2 = \frac{1}{2}a(\frac{t_{total}}{2})^2 = \frac{1}{8}at_{total}^2$$

$$\Rightarrow a = \frac{8d}{t_{total^2}} = \frac{8\times(33+3)\times10^{-2}m}{(226\times10^{-3}s)^2} = 56.39ms^{-1}$$

According to the datasheet of the WT901[2], its accelerometer can measure up to ±16g maximum, about $156.8m/s$, which is more than two times larger than the maximum velocity that a human can reach. So its accelerometer can read all user inputs correctly.

To project the motions of human fingers, the data output frequency is set to 60HZ. We plan to set three distinguishable bending angles (30°, 60°, and 90°). The angle accuracy is X, Y-axis: 0.05° (Static), X, Y-axis: 0.1° (Dynamic), which is enough for recognition. In the modeling, the middle and the index finger are the most frequently used fingers, so we choose a finger size of 60mm[5].

2.4.2 IIC Communication Bandwidth

According to NXP Semiconductors[3], “when using serial, 8-bit oriented, bidirectional data transfers can make at up to 100kbit/s in the standard mode.” Since the standard mode is the slowest mode, the bandwidth of IIC communication is at least 100kbit/s. According to the datasheet of WT901[2], one query to one of the IMUs will need the controller to send out 3 bytes (24bits) first to select the IMU using the IIC address, then the IMU will respond with a data packet of 8 bytes (64bits) for each set of parameters queried. So one query will have

$$24\ bits + 64bits = 88\ bits$$

And the readings that the controller needs to figure out the position and orientation of the IMUs are accelerometer readings, gyroscope readings, and magnetometer readings. Combined together, for each query, one IMU needs

$$88bits \times 3 = 264bits$$

Then the minimum querying frequency IIC protocol will allow is

$$floor(\frac{100kbit/s}{264bits}) = floor(378.78Hz) = 378Hz$$

Considering that we have at most 8 IMUs to query, in the worst case, each one of them will have a minimum querying frequency of 47Hz. According to the WT901 datasheet, the sampling frequency can be anywhere between 0.5Hz to 200Hz for each sensor, and 47Hz falls in the range.

2.4.3 IMU Sampling Frequency

For the 47Hz worse-case querying frequency, the maximum angular velocity that the sensor can detect defined by Nyquist sampling frequency is

$$\frac{47Hz}{2} \times 2\pi = 147.65rad/s = 23.5\ revolution/s$$

This would be more than sufficient for detecting the motion of the human body because humans cannot exceed this range under normal conditions.

Addon to that, the gyroscope of the WT901[2] can accept readings up to $\pm\ 2000\ deg/s$. So the motions can be captured by the IMU successfully even in situations where the IMUs are not mounted on the user.

2.4.4 Bluetooth Communication Bandwidth

According to the datasheet provided by ITead Studio [4], the HC-05 Bluetooth module that we plan to use has a transmission rate up to 3Mbps.

For the angle data that is sent by the primary controller, in our design, up to eight angles are sent from the primary controller to the PC. Each of the angles can be encoded as a 2-byte integer by using the formula below

$$angle_{encoded} = int(angle_{raw,radian}/2\pi \times 32768)$$

Using this formula will cause the precision of the data to drop to $1.92 \times 10^{-4} rad = 0.011 deg$, which is negligible. Then eight angles are encoded in 16 bytes, which means the HC-05 can send the data up to

$$\frac{3Mbps}{16\ byte \times 8\ bit/byte} = 24576Hz$$

The frequency is more than enough compared to the potential query frequency of 47Hz.

For control data sent to the robot, this theoretical speed is also high enough that the data transmission would also use less than 1% of the total capacity.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor Costs

According to the average annual salary of an electrical engineer, the hourly salary for each team member is $36/hour. And we expect to work 8 hours per week on this project. The total labor cost would be:

$36/hr × 2.5 × 8 weeks × 8hrs/week = $5,760 per partner. The total cost of our team would be $17,280.

3.1.2 Component Costs

1. IMU: WT901
   - We need a minimum number of 4 IMUs to make recognizing user gestures possible, 6 IMUs to make the tracking system more reliable, and 8 IMUs to make the design have advanced functionalities. Each IMU will cost about $32. So it will cost $128 minimum, $192 intermediate, and $256 maximum.
2. Bluetooth Transceivers: HM-19
   - Two pairs of Bluetooth transceivers are required for wireless communication in between these three devices. Each one costs about $10, so $40 together.
3. LCD Display: SSD1306
   - For backup, we plan to buy two. Each one costs about $7 on Amazon, so $14 together.
4. Power sources: 3.7V Li-ion battery 500mAh
   - One battery is listed at $12 on Amazon. To prevent Li-ion battery damage, a backup is required. Together they will cost about $24.
5. PCB board:
   - ATMega328, listed on Digikey as $2.46
   - CSTNE16M0VH3L000R0 resonator, listed on Digikey as $0.4
   - FT232RL-TUBE USB-UART converter, listed on Digikey as $4.70
   - Comidox 3.7V to 5V DC-DC Step Up Power Module, $7.00 on Amazon for 5 packs
   - Several resistors, capacitors, LEDs, and triodes, estimated to be less than $5
   - Manufacturing cost estimated to be less than $5
   - Together they cost about $17.92

6. Feedback system: LED, OLED, vibration motor, buttons
    - Because a group member has those components at hand, no extra costs are added

In total, the components and manufacturing cost together will be about at least $183.85, and at most $311.85 (before tax).

BOM table

Part #	Manufacturer	Description	Price	Qty	Total
WT901	WitMotion	X, Y-axis: 0.05° (Static) , X, Y-axis: 0.1° (Dynamic)	$31.90	6	$191.4
HM-19	DSD TECH	Bluetooth 5.0 BLE	$9.99	4	$39.96
SSD1306	HiLetgo	0.96" 128X64 LCD Display with I2C	$7.19	2	$14.38
1578	Adafruit	3.7v 500mAh	$11.69	2	$23.38
ATmega328	Microchip Technology	ATMEGA328P-PU	$2.46	3	$7.38
CSTNE16M0VH3L000R0	Murata Electronics	16 MHz Resonator	$0.4	3	$1.2
FT232RL-TUBE	FTDI	USB to UART	$4.7	3	$14.1
Regulator	Weewooday	Voltage Boost Converter	$6.99	1	$6.99
Other	N/A	resistors, capacitors, LEDs, and triodes Manufacture cost	$10	1	$10
Total					$308.79

3.2 Schedule

Some details are broken into three parts, where each of the team members will choose one to complete.

Week	Eric	Haoduo	Guang
2/21	Finish PCB design and select component	Order parts and revise design document	Finish PCB design and estimate costs
2/28	Collect data from IMUs with Arduino Nano (ATmega328)	Revise design document Design an algorithm to recognize gestures	Implement Bluetooth, i2c, and UART communications on an Arduino Nano board
3/7	Test Robot Bluetooth communication and demo program	Build user interface and improve the accuracy of the algorithm Submit PCB board to order	Build gesture database and training dataset, test Bluetooth on the PC
3/14	Catch up on delayed work and refine PCB design in spring break		
3/21	Submit second round PCB order Individual progress report	Design user interface for the program Individual progress report	Solder PCB board Combine and test the whole program Individual progress report
3/28	Build and solder circuits in the open lab, test power and other subsystems Test software compatibility and feedback mechanism		
4/4	Perform numerical analysis on the project, determine key features and characterizations Make outlines for the final review		
4/11	Design demo program and functionalities		
4/18	Mock demo, solve potential problems in procedure		
4/25	Complete presentation and final report		

4. Discussion of Ethics and Safety

4.1 User Safety

1. Since our product will directly contact human skin, it is important to separate the skin from electricity and make sure that no hazardous components will put users in danger. The wearable component in our design does not pose a threat to the user, and we will keep it operating under a low voltage that reduces energy consumption.
2. When battery power is lower than 10%, the product should notify the user. If it is lower than 5%, the device should shut down the system automatically to prevent the battery from starvation. Also, if the system is not in use for a long time, it should also shut down itself.
3. Our product utilizes Bluetooth protocol for wireless communication between the controller and the robot, and user body data is collected to analyze and recognize user gestures and body movements. We commit to protect and respect user privacy, complying with section 7.8.I-1 of IEEE's guidelines [6].

4.2 Producer Safety

1. In the lab, always power off the battery before any hardware changes. Rubber gloves are required before touching any electronic components that may cause potential electrical injury.
2. Used batteries and broken electronic units should be disposed of in specialized bins instead of throwing away casually. For specific steps, please consult the disposal procedure in the lab safety training.
3. We will treat all persons fairly and with respect and not engage in discrimination based on characteristics such as race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression. We will also not engage in harassment of any form, including sexual harassment or bullying behavior

4.3 Procedures to Mitigate Concerns

1. All members must complete the soldering assignment before entering the lab.
2. We would make laboratory safety a topic on every group meeting agenda. In the group meeting, we will review new experimental procedures and discuss all safety concerns.
3. For specific tasks, we require the use of personal protective equipment. We guarantee to take our professional responsibilities to pursue high standards on our project. Specifically, we refer to the Division of Research Safety at the University of Illinois [7].

5. Citations

[1] K. M. DeGoede, J. A. Ashton-Miller, J. M. Liao, N. B. Alexander, "How quickly can healthy adults move their hands to intercept an approaching object? Age and gender effects, " The Journals of Gerontology: Series A, vol. 56, no. 9, 2001.

[2] Wit Motion, "WT901 datasheet". Available: https://github.com/WITMOTION/WT901/blob/26527441cfbc71e1ffd86c9e0fe0ef500a31a767/WT901%20Datasheet.pdf [Accessed: 23-Feb-2022]

[3] NXP Semiconductors, "IIC-bus specification and user manual." Available: https://www.nxp.com/docs/en/user-guide/UM10204.pdf [Accessed:23-Feb-2022]

[4] ITead Studio, "HC-05 bluetooth to serial port module datasheet". Available: https://components101.com/sites/default/files/component_datasheet/HC-05%20Datasheet.pdf [Accessed:23-Feb-2022]

[5] M. Zhu, Z. Sun, Z. Zhang, Q. Shi, T. He, H. Liu, T. Chen, and C. Lee, “Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications,” Science Advances, vol. 6, no. 19, 2020.

[6] “IEEE code of Ethics,” IEEE. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: 21-Feb-2022].

[7] Division of Research Safety, “Electrical Safety in the Research Laboratory”. Available: https://www.drs.illinois.edu/Page/SafetyLibrary/ElectricalSafetyInTheResearchLaboratory [Accessed:23-Feb-2022]