Digital Leg Tacker Utilizing Sensor Fusion

ECE 445 Design Document - Fall 2023

Project #15
Qing Wang, Diana Long, Joseph Cho
Professor: Fliflet, Arne
TA: Zicheng Ma

Contents:

1. Introduction
    a. Problem
    b. Solution
    c. Visual Aid
    d. High-Level Requirements
2. Design
    a. Block diagram
    b. Physical Design
    c. Subsystem Overview
    d. Subsystem Requirements
    e. Software design
    f. Tolerance Analysis
3. Cost and Schedule
    a. Cost Analysis
    b. Schedule
4. Ethics and Safety
5. Citations

Introduction

Problem:

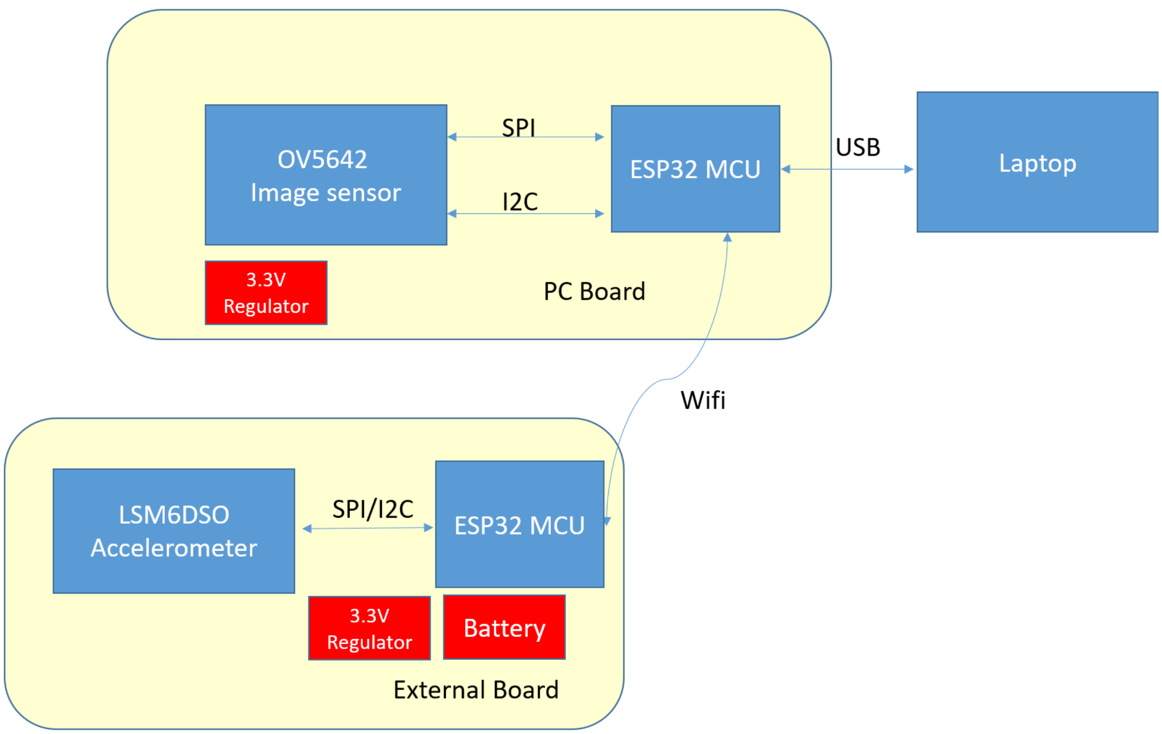
For many modern technologies, such as VR, hand gesture control is necessary for people to interact with the controller. The use of this space requires the user to be able to track a position and move in the physical plane to achieve any meaningful input; However, for people with disabilities, those actions may not be possible, thus limiting the potential of this technology. With the ever-growing use of these technologies in both commercial and business use, a solution to replace the need for hand gestures and allow these people to access these technologies is needed. Although motion tracking technology for other body parts, such as the leg, is already available in the market, they tend to use expensive cameras. This cost also hinders the growth of virtual reality and similar technologies, as the added fee to be able to access this equipment turns many consumers away. Without a middle ground between cost and efficiency, these new revolutionary technologies will not influence our world to the potential that they can.

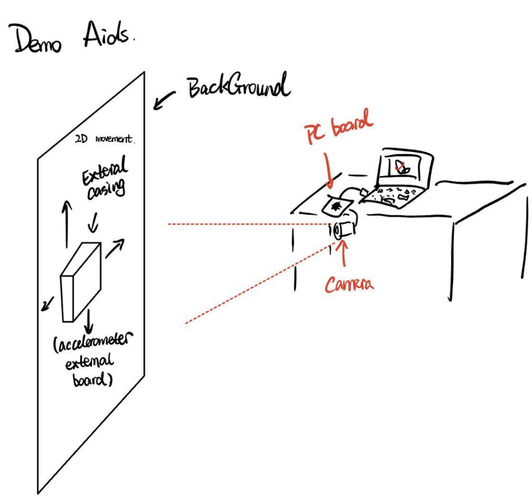
Solution:

By creating a device that can track your leg movement, we can replace the need for hand gestures to serve as inputs for controllers which can help those who are impaired in their arms. We will design a motion tracker that consists of lower frame rate cameras that will allow the user's leg to be registered as a motion digitally, allowing for more affordable controllers to exist using technology similar to the current controllers.

We will be using cameras to track the movement of the leg, as currently most motion tracking technology uses very high end cameras. We will be cutting costs by using cheaper cameras with a lower framerate but maximizing their usage. While the movement may seem choppy due to being a noticeable fps value, it will cut costs and make our product more affordable for manufacturing and for the user. We will also be using accelerometers that will be attached on the user's legs. Using these data, we can perform sensor fusion which will allow our device to track motion as if it was using a higher framerate camera.

Visual Aid:



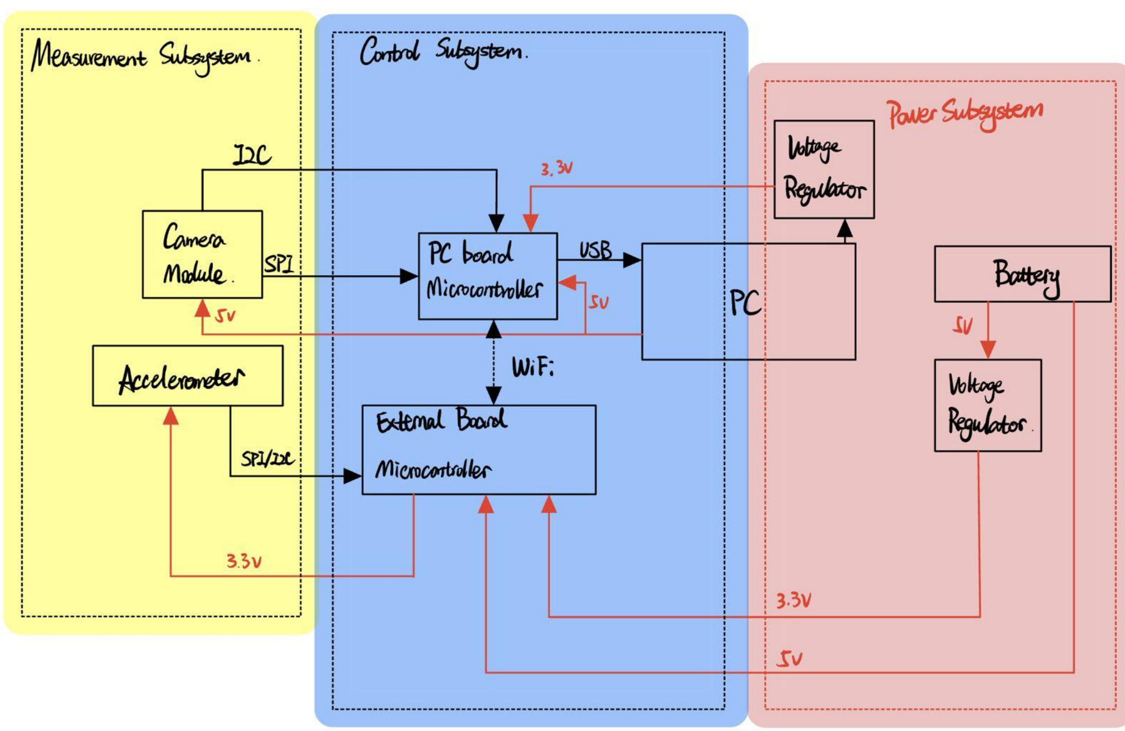


High-Level Requirements:
To consider this leg tracker a success, we have three main criteria:

1. The measured output of the leg is within 6 inches of absolute error of the actual position 80% of the time. This criteria exists so that our project is accurate in its function.
2. The minimum refresh rate of our output is 15 frames per second. This criteria is to ensure that sensor fusion is done properly, which should double the fps from the camera (7~9 fps) to 15 frames per second.
3. The response time of the data will be within each refresh rate of the camera module, which is 7 fps, since we must provide output data with new camera input at every interval of camera input.

Design

Block Diagram:



Physical Design:

The physical design of our device mostly consists of the casing. The casing will be a 3D printed case that houses a microcontroller, an accelerometer, and a battery. The casing will be large enough to fit the microcontroller, the accelerometer, the PCB that attaches them and the battery pack.

The rest of our physical design comes from connecting our camera module, a PCB board with a microcontroller, and our PC together. The camera module will simply sit on a table and connect to our microcontroller. We will be using I2C/SPI to retrieve the camera data, as that will make interpreting the data significantly easier. The external components inside the case will be connected to the microcontroller that's attached physically to the PC using wifi, allowing us to not have any long wires. This connection also allows data to be transferred in a reliable manner, as attempting other forms of wireless communication can be inconsistent.

Subsystem Overview:

We have three subsystems, a measurement subsystem, a control subsystem, and a power subsystem. These three subsystems will communicate with each other to create our final product. These are all separate systems due to the complexity of each part and the different code needed between them.

Our measurement subsystem consists of the accelerometer and the camera module. Accelerometer will connect and communicate with the external board (board inside the casing), which is part of our control subsystem. Appropriate power will be provided from the board and the output of the accelerometer will be transferred through SPI/I2C for our accelerometer. Camera module will be connected to the PC board (board connected physically with PC) which is a part of the control subsystem as well and will be discussed in the control subsystem section.

This subsystem will be powered by both PC and battery, which are both parts of the power subsystem.

Another subsystem we have is the control subsystem. This subsystem consists of both of our boards, equipped with our microcontroller (ESP32-S3-WROOM-1). The microcontroller of the external board will receive the data from the accelerometer and relay the data to the PC board through wireless communication. The microcontroller of the PC board will receive data from both components in the measurement subsystem. The camera module will communicate with the PC board through SPI/I2C communication and the accelerometer will communicate through wireless communication established between the PC board and the external board. Once the data is received, the PC board will perform sensor fusion to obtain the final output. The control subsystem will be powered by the two power sources of the power subsystem.

Our last subsystem is the power subsystem. This subsystem consists of the PC and the battery, which will provide power to the other 2 subsystems. A voltage regulator will be included for both components of this subsystem so that they're capable of providing both 5V and 3.3V voltage supply. Our battery will be providing power to the external board while the rest are powered by the PC.

Subsystem Requirements:

Our measurement subsystem consists of an accelerometer and a camera module. The accelerometer we plan on using (PN: LSM6DSOTR) is compatible for use in PCB design and it has SPI/I2C serial interface that allows us to enable this component to communicate with our board in control subsystem. This component requires a minimum of 1.7V and maximum of 3.6V supply voltage (Vdd) which means that a 3.3V supply of a board connected with a microcontroller can support it [6]. This part allows us to receive data on the acceleration of the object attached with it, which will be the casing in our case. As for our camera module, the part we're planning on using (Arducam OV2640 2MP Mini) which is compatible for use in PCB design as well and has I/O ports that are compatible with both 5V and 3.3V. PC is capable of providing both of these voltage supplies which makes our measurement subsystem compatible with our power subsystem.. This part has a SPI speed of 8 MHz, which is enough to transfer video images with limited fps, which will be calculated and discussed further in the tolerance analysis section. [4] Figure 1 below shows that the camera module has both SPI/I2C connection on the module. Figure 2 below also shows that the LSM6DSO accelerometer can be designed like the redboard to have SPI/I2C I/Os.

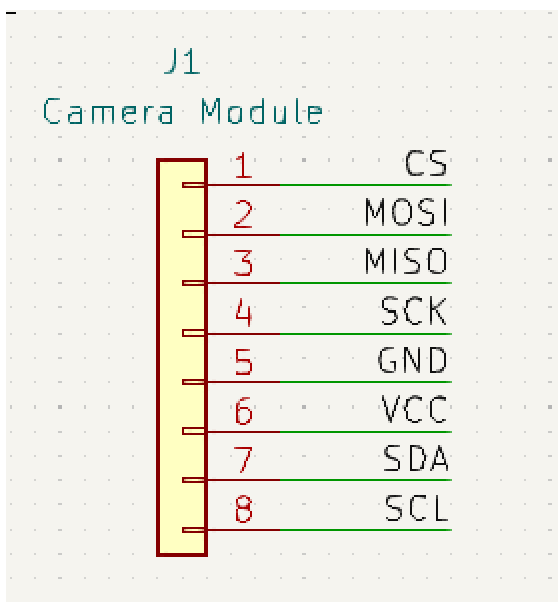


Figure1: Camera Module Pinout [4]

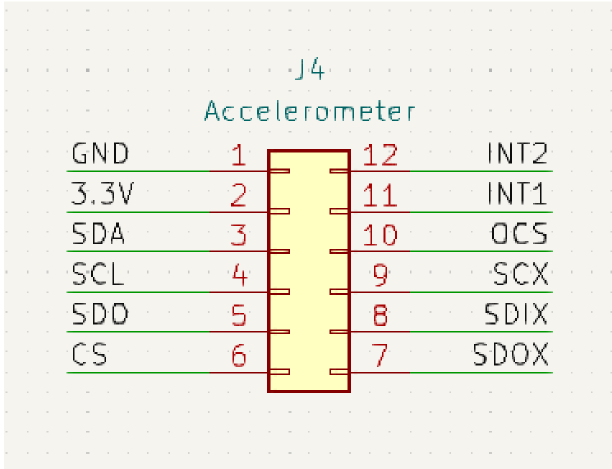


Figure 2: Accelerometer Pinout based on Redboard Design and IC Pinout [2]

Our control subsystem consists of our boards, which are each equipped with a ESP32 MCU (ESP32-S3-WROOM-1). As previously discussed in the measurement subsystem, our external board, which is inside the casing with the accelerometer, must be able to supply 3.3V at least for the accelerometer. This means that the 3.3V pin on our ESP32 MCU should have a male or female pin connected to it so that its output is available for us to use. Once the data from our accelerometer is transferred to the ESP32 MCU in the external board through either I2C or SPI interface, our external board will relay the data to the PC board through wireless communication. The PC board, which is the PCB that's physically attached to the PC, will contain the camera module, which will be connected to the PCB board through SPI/I2C connections [4], and it should also have a USB port on the board for connection with the PC. [10] The USB will then allow communication of the camera's data from the PC board to be analyzed and converted as numerical data. The numerical data will then be sent back to our PC board so that our PC board can perform sensor fusion with the data from the external board. Lastly, the outcome data from the sensor fusion will be transferred from the PC board to the PC to be viewed.

Our last subsystem is the power subsystem. This subsystem consists of 2 components, the battery and the PC. Our PC will be responsible for providing power for the parts that are physically connected to the PC while the battery will be responsible for powering the parts that are in the external casing. Both parts will be connected with a regulator so that they're capable of providing both 5V and 3.3V voltage supply since some of these components require a 5V voltage supply while some will malfunction with such a high voltage supply.

Subsystem Verification:

Requirements	**Verification**
1.All components must be connected to the appropriate power supply.	We can probe the pin that receives power for each component with a voltmeter and check that each component is receiving the appropriate voltage (5V or 3.3V).
2.The components of the accelerometer unit must not malfunction even if the user plugs in the battery backwards and corrects it afterwards.	The battery pack will make sure that power is not provided to the components of the accelerometer unit if the battery is in the wrong orientation. We can verify this functionality by having the battery placed in the wrong orientation while probing the power connections on the components with a power measurement tool such as a voltmeter. Power should not be provided.
3. Components of the accelerometer unit must not malfunction even if it's exposed to an environment that is hotter than room temperature since the components will be placed inside a case.	The accelerometer unit's functionality in a case can be tested individually by having it run for 10 minutes while checking the PC to make sure that the data from the accelerometer unit is being successfully communicated to the PC.
4. Our camera module should be capturing images at 7 fps and the data should be transferred to the PC and to the PC board for	If everything works well, we should be receiving image data of a 7 fps camera. If it doesn't work, we can first check the

sensor fusion.	connection between each component by probing the inputs and outputs to check that some sort of data is being transferred. If data is being transferred but the system is malfunctioning, we can check the data being received by the PC to see if it's either our SPI interface or I2C interface that's not working. If either isn't working properly, we can check the connection of the camera module, respective converter, and the USB to check where the problem occurs and address appropriately.
5. PC board and external board must be able to communicate with each other through wireless communication.	We can check that the wireless connection is established and that data is being transferred through it by having an simple arbitrary signal sent from one ESP32 MCU to the other, such as a button being pressed.

Tolerance Analysis:

One aspect of our design that could pose a risk to successful completion of the project would be the voltage regulator causing the hardware components to not receive enough voltage. If our Vin-Vout value is less than that of the dropout voltage of a voltage regulator, our system may end up functioning as if there isn't enough voltage being supplied to it. This can be solved by having high enough Vin relative to the required Vout of the system. Our minimum Vout is 3.3V since both of our components in our measurement subsystem, which are the accelerometer and our camera module, are compatible with 3.3V voltage supply. Our Vin value can be up to 5V since our board will be equipped with a microcontroller which makes our maximum dropout voltage of the voltage regulator 5-3.3=1.7V. This is enough for voltage regulators that regulate voltage to an output of 3.3V so this design should be feasible.

Power consumption of the external components which will be powered by the battery is an important factor as well since it would determine how long our system can run. Total power consumption is calculated by the total current consumption of I/O The maximum power consumption for each external component is (0.55mA+ 4.3mA) * 3.3V = 16.005 mW for the accelerometer [2], and (355+97)mA * 5V = 2.26W for the microcontroller [6]. 16.005mW + 2.26W = 2276.005mW = 2.276005W. A common AA battery has around 3~4 Wh of lifetime so placing multiple of these batteries would make the lifetime of our system last hours. Using a triple battery holder for example, our system's lifetime would be approximately 6 hours which is long enough to track motions for time consuming activities.

Heat in external components is also a factor to be considered. The operating temperature for both parts in the external casing is -40°C to 85°C [2][6]. Since the demo and operation of the system would normally be under room temperature which is around 20°C, our microcontroller would have to become extremely hot for it to pass the operating temperature. Since we're only using 2 connections, we wouldn't be generating heat anywhere near the maximum heat capacity and we can also make sure that we remain within this temperature range by adding some holes in the casing to allow heat dissipation. Energy required to heat up gas in certain sized volume is defined by the equation dry Energy = air specific heat * dry air density * volume * rise of temperature. The given values are air specific heat = 1 J/g K, and dry air density = 1204g/m^3. Assuming our casing is 100mm*100mm*40mm = 0.0004m^3, which is the maximum size of PCB board * height of 40mm, and rise of temperature is 65 (from 20, which is room temperature in celsius, to 85), we obtain approximately 31.304 which is far greater than the amount of heat energy created by the components.

Another aspect of our design that could pose a risk to successful completion of the project would be the framerate of the camera module and the process of transferring the data from the camera module to the PC. According to the datasheet of the camera module [4], the maximum SPI speed of the camera module is 8MHz = 8 Mbits/s. The minimum resolution of the camera module is 160x120 = 19200 bits per image. The value of available fps is given by the equation (bits/s) /(bits per image * total number of RGB bits) = fps. The total number of RGB bits is equal to 24 since each value consists of 8 bits and there are 3 colors (red, green and blue) with 8 bits each. Therefore, the theoretical maximum fps would be 17.3611111111 fps using the camera module. However, there are many factors to consider such as the fact that the camera module can't always be functioning at its maximum SPI speed which can delay the fps to about half of its maximum fps. Through experimentation, we obtained that the camera can obtain 7~10 fps of image data.

Cost and Schedule

Cost Analysis:

- **Labor**
  For each team member, we could expect a salary of (40$/hour) x 2.5 x 60 hours to complete(estimate) = $6000. Multiply with the number of team members in our team, $6000 x 3 = $18,000 total labor cost
- **Parts**
  - Accelerometer (PN: LSM6DSOTR): $5.88 (DigiKey) [1]
  - Camera Module (Arducam OV2640 2MP Mini Module): $25.99 (Amazon) [3]
  - 2x ESP32 MCU (PN: ESP32-S3-WROOM-1-N16): $6.96 (DigiKey) [5]
  - 6x Switching Diode (PN: BAV99-TP): $0.60 (DigiKey) [7]
  - 2x USB Connectors (PN: 10118193-0001LF): $0.92 (DigiKey) [9]
  - USB to UART Bridge (PN: CP2102N-A02-GQFN28): $4.07 (DigiKey) [11]
  - BJT Transistor (PN: UMH8NTR): $0.51 (Mouser) [13]
  - LDO (PN: AP7363-33D-13): $0.58 (DigiKey) [15]
  - Total Cost of Parts: $45.51
- **Total Cost: $18,045.51**

Schedule:

Week	Task	Person
Sept. 15 - Sept. 28	Ordering Parts for prototyping	Everyone
	Research on parts to use	Joseph Cho
	Compose design documnet	Everyone
Sept. 29 - Oct. 9	board assembly	Joseph Cho, Diana Long
	design review	Everyone
	start PCB design	Joseph Cho
	start software design	Qing Wang
Oct. 10 - Oct.25	Ordering PCBs	Joseph Cho
	Individual progress reports	Everyone
	continue on board assembly	Joseph Cho, Diana Long
Oct. 26 - Nov. 12	Individual Test on board	Joseph Cho
	Finalize hardware design	Joseph Cho, Diana Long
	Finalize software design	Qing Wang
Nov.13 - Nov. 17	mock demo	Everyone
Nov. 18 - Nov26	Debugging circuit(if any)	Joseph Cho
	Debugging software(if any)	Qing Wang
Nov. 27 - Dec. 7	Final Demo	Everyone
	Mock Presentation	Everyone
	Final Presentation	Everyone

Ethics and Safety

Following the IEEE code of Ethics [14] and the OSHA standards, we promise to keep the following code of Ethics and safety.

- Safety First
    - Safety is our top priority and we are committed to creating and maintaining a safe and healthy environment during the development process. Our external components will be cased properly so that the parts inside the casing do not pose danger of burn from heat or electric shock to the person moving the external components.
    - This is in accordance with IEEE Code of Ethics 1.
        - Code 1 states that all members must always prioritize and protect the safety of the public and the environment.
    - This is in accordance with OSHA standard 1910.137.
        - 1910.137 describes design requirements for protective electrical insulation equipment which is the insulation tape and cloth in our case.
- Compliance with safety regulations
    - We strictly adhere to the lab safety regulations and report any safety incidents or hazards.
    - This is in accordance with IEEE Code of Ethics 1 and 4.

        - Code 1 states that all members must always prioritize and protect the safety of the public and the environment.
        - Code 4 states that all members must refrain from participating in any activities that disobey the laws and regulations which include safety regulations.
    - This is in accordance with OSHA standard 1910 Subpart H.
        - Subpart H discusses hazardous materials and the safety procedures and equipment necessary for protection against different hazards.
- Privacy
    - We protect the privacy of sensitive information and data entrusted to us. We will only collect the minimum amount of data from the accelerometer and camera that are necessary for our project.
    - This is in accordance with IEEE Code of Ethics 4.
        - Code 4 states that all members must refrain from participating in any activities that disobeys the laws and regulations which include privacy regulations.
- Avoid Misuse
    - We will try our best to avoid accidental or intentional misuse of our project. For accidental misuse, we would compose a manual for the user to let them know how to use the product properly. In the case of intentional misuse, one possible scenario is to attach the sensor and camera to others without their acknowledgement. To avoid this situation, we would make the accelerometer part bright and obvious.
    - This is in accordance with IEEE Code of Ethics 1, 2, and 3.
        - Code 1 states that all members must always prioritize and protect the safety of the public and the environment.
        - Code 2 states that all members must work towards educating the public about new technologies.
        - Code 3 states that any professional project must refrain from creating and participating in a situation with conflicting interests and that the members must alert anyone who's affected by these situations if it occurs.
- Upholding the Code
    - We will always uphold these codes throughout the project regardless of the situation. We will report any and all cases of violation of these codes without the fear of retaliation.
    - This is in accordance with IEEE Code of Ethics 10.

- Code 10 states that all members must keep each other accountable to follow these codes and that retaliation towards members who report violation of these codes should not happen.

Citations

[1] DigiKey, "LSM6DSOTR", DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/stmicroelectronics/LSM6DSOTR/9586579, accessed October 2023

[2] STMicroelectronics, "iNEMO inertial module: always-on 3D accelerometer and 3D gyroscope" Revision 2, STMicroelectronics, 2019, https://www.st.com/resource/en/datasheet/lsm6dso.pdf, accessed October 2023

[3] Amazon, "Arducam Mini Module Camera Shield with OV2640 2 Megapixels Lens Compatible with Arduino UNO Mega2560 Board and Raspberry Pi Pico", https://www.amazon.com/Arducam-Module-Megapixels-Arduino-Mega2560/dp/B012UXNDOY/ref=sr_1_1_sspa?crid=FBU8UPTHI2YB&keywords=ov2640+camera+module&qid=1697851827&sprefix=ov2640%2Caps%2C121&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1, accessed October 2023

[4] OmniVision Technologies Inc, "ArduCAM-M-2MP Camera Shield" version 1.11, OmniVision Technologies Inc, 2015, https://www.uctronics.com/download/Amazon/ArduCAM_Mini_2MP_Camera_Shield_DS.pdf

[5] DigiKey, "ESP32-S3-WROOM-1-N16", DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/espressif-systems/ESP32-S3-WROOM-1-N16/16162647, accessed October 2023

[6] Espressif Systems, "ESP32-S3-WROOM-1ESP32-S3-WROOM-1UDatasheet", Datasheet v1.2, Espressif Systems, 2023, https://www.espressif.com/sites/default/files/documentation/esp32-s3-wroom-1_wroom-1u_datasheet_en.pdf, accessed October 2023

[7] Digikey, "BAV99-TP", DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/micro-commercial-co/BAV99-TP/717241, accessed October 2023

[8] Micro Commercial Components, " BAV999(SOT-23)", MCC, https://www.mccsemi.com/pdf/Products/BAV99(SOT-23).pdf, accessed October 2023

[9] Digikey, "10118193-0001LF", DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/amphenol-cs-fci/10118193-0001LF/2785388, accessed October 2023

[10] FCI Basics, " Micro USB 2.0 Connectors", amphenol-cs, https://cdn.amphenol-cs.com/media/wysiwyg/files/documentation/datasheet/inputoutput/io_usb_micro.pdf, accessed October 2023

[11] DigiKey, "CP2102N-A02-GQFN28", DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/silicon-labs/CP2102N-A02-GQFN28/9863477, accessed October 2023

[12] Silicon Labs, "CP2102N Data Sheet", Silicon Labs, Rev. 1.5, https://www.silabs.com/documents/public/data-sheets/cp2102n-datasheet.pdf, accessed October 2023

[13] Mouser Electronics, “ROHM Semiconductor UMH8NTR” Mouser Electronics Inc, 2023, https://www.mouser.com/ProductDetail/ROHM-Semiconductor/UMH8NTR?qs=4kLU8WoGk0vN3MRgK4FwQA%3D%3D, accessed October 2023
[14] Rohm Semiconductor, “UMH8N / IMH8A : Transistors”, Rev. C, 2014.10, https://fscdn.rohm.com/en/products/databook/datasheet/discrete/transistor/digital/umh8ntr-e.pdf, accessed October 2023
[15] DigiKey, “AP7363-33D-13”, DigiKey, 1995-2023, https://www.digikey.com/en/products/detail/diodes-incorporated/AP7363-33D-13/3829401, accessed October 2023
[16] Diodes Incorporated, “AP7363”, Diodes Incorporated, October 2021, https://www.diodes.com/assets/Datasheets/AP7363.pdf, accessed October 2023
[17] IEEE, “IEEE Code of Ethics,” Section 7, IEEE, 2023, https://www.ieee.org/about/corporate/governance/p7-8.html, accessed September 2023
[18] United States Department of Labor. “Regulations (Standards - 29 CFR) | Occupational Safety and Health Administration.” Osha.gov, 2019, www.osha.gov/laws-regs/regulations/standardnumber/1910.
[19] The Grainger College of Engineering, “Why ECE at Illinois? Salary Averages,” University of Illinois Urbana-Champaign, 2023, https://ece.illinois.edu/admissions/why-ece/salary-averages, accessed September 2023