



P.U.T.T.I.
Portable Unitary Throwable Target Interceptor
Department of Electrical Engineering and Computer Science

Group 18 Authors:

Alex Evison

*Electrical
Engineering*

Callum Fuller

*Electrical
Engineering*

Nathan Kimmel

*Electrical
Engineering*

Jake Tattersall

*Computer
Engineering*

Review Committee:

Dr. Sonali Das

Dr. Swaminathan

Rajaraman

Dr. Xun Gong

ECE

MSE

ECE

Lecturer

Associate Professor

Professor

Advisors:

Dr. Saleem Sahawneh

ECE

Lecturer

Table of Contents

Chapter 1 – Executive Summary	8
Chapter 2 – Project Description	9
2.1 Project Background and Motivation	9
2.2 Current Commercial Technologies and Existing Projects	9
2.3 Objective and Goals	11
2.3.1 Goals	11
2.3.2 Objectives	12
2.3.3 Hardware	12
2.3.4 Software	14
2.4 Required Specifications	15
2.4.1 Hardware Block Diagram	16
2.4.2 Software Diagram	17
2.4.3 Prototype illustration	18
2.5 House of Quality	19
2.6 Estimated Cost Table	19
Chapter 3 – Research	20
3.1 Hardware	20
3.1.1 Single-Board Computer	20
3.1.1.2 Single Board Computer Selection	23
3.1.2 Camera	23
3.1.2.3 Camera Selection	26
3.1.3 Laser	26
3.1.3.2 Laser Selection	30
3.1.4 Temperature Sensor	31
3.1.4.2 Temperature Sensor Selection	35
3.1.5 Humidity Sensor	35
3.1.5.2 Humidity Sensor Selection	39
3.1.6 Microwave Sensor	40
3.1.6.2 Microwave Sensor Selection	44
3.1.7 Microwave Sensor Housing	45
3.1.8 LCD	46
3.1.8.2 LCD Selection	50

3.1.9 3D Filament.....	50
3.1.9.1 3D Filament Selection.....	51
3.1.10 Microcontroller.....	52
3.1.10.2 Microcontroller Selection.....	54
3.1.11 Voltage Regulator	55
3.1.11.2 Voltage Regulator Selection	57
3.1.11.4 3.3V Switching Regulator Product Selection	61
3.1.11.5 5V Switching Regulator Selection	62
3.1.11.6 1.8V Linear Regulator Selection	62
3.1.12 Motors	62
3.1.12.2 Motor Type Selection.....	65
3.1.12.4 Motor Product Selection	67
3.1.13 Batteries.....	68
3.1.13.2 Battery Part Selection.....	71
3.1.13.3 Battery Production Selection.....	72
3.1.14 Buzzer	73
3.1.14.2 Buzzer Selection	75
3.2 Communication Protocols.....	76
3.2.1 SBC to Camera	76
3.2.1.2 SBC to Camera Selection	77
3.3 Software	77
3.3.1 Computer Vision Language	77
3.3.1.2 Computer Vision Language Selection	79
3.3.2 Detection Framework.....	79
3.3.2.2 Detection Framework Selection	80
Chapter 4 - Standards	81
4.1 I2C.....	81
4.2 UART	82
4.3 SPI	83
4.4 USB.....	84
4.5 MIPI CSI-2.....	84
4.6 GPIO	85
4.7 Python PEP 8.....	85
4.8 Git and GitHub	86

4.9 Docker	87
4.10 PWM	87
4.11 Power Constraints	88
4.12 Environmental Constraints	89
4.13 Economic Constraints	91
4.14 Health and Safety Constraints	91
4.15 Sustainability Constraints	92
4.16 Political Constraints	93
Chapter 5 – Application of ChatGPT and Other Similar Platforms	93
5.1 GitHub Copilot	93
5.2 ChatGPT	94
5.2.1 Case Study 1	94
5.2.2 Case Study 2	95
5.2.3 Case Study 3	96
5.2.4 Case Study 4	96
Chapter 6 – Hardware Design	97
6.1 MCU	97
6.2 Atmospheric Peripherals	98
6.3 Laser	100
6.4 Power Delivery/Electrical Power System	100
6.5 LCD	102
6.6 Motors	103
6.7 Buzzer	103
6.8 Radar Module	104
Chapter 7 – Software Design	105
7.1 Git and GitHub	106
7.2 Computer Vision Detection	106
7.3 Python Development	108
7.4 Interfacing with the Camera	109
7.5 Machine Learning Model Development	109
7.5.1 Data Collection	109
7.5.2 Model Training	110
7.5.3 Model Implementation	111
7.6 SBC Setup	111

7.6.1 MicroSD Card Flashing	111
7.6.2 Chromium	112
7.6.3 Docker Image	113
7.7 XM125 Radar Software	114
7.8 ESP32 Software	116
Chapter 8 – PCB Design	121
8.1 Board Layout	121
8.1.1 Main Board	121
8.1.2 Regulator Boards	123
8.2 Mechanical CAD Diagram	125
Chapter 9 – System Testing and Evaluation	127
9.1 NVIDIA Orin Nano	127
9.2 Camera	127
9.3 YOLO Model	128
9.4 Laser	129
9.5 Humidity Sensor	129
9.6 Temperature Sensor	130
9.7 Motors	130
9.8 Batteries	131
9.9 Buzzer	131
9.10 Radar Modules	131
Chapter 10 – Administrative Content	132
10.1 Budget	132
10.2 Bill of Materials	133
10.3 Distribution of Work	133
10.4 Senior Design Milestones	134
Chapter 11 – Conclusion	136
Appendices	137
Appendix A – Reference	137
Appendix B – Copyright permission	147
Appendix E – LLM Prompts and Outcomes	148

List of Tables

Table 1 - Overall System Specifications	15
Table 2 - Component Specifications.....	16
Table 3 - Estimated Cost Table	19
Table 4 - SBC Specifications.....	22
Table 5 - Camera Specifications.....	26
Table 6 - Laser Specifications	30
Table 7 - Temperature Sensor Specifications	34
Table 8 - Humidity Sensor Specifications	39
Table 9 - Microwave Sensor Specifications.....	44
Table 10 - LCD Specifications	49
Table 11 - Microcontroller Specifications.....	54
Table 12 - Power Table	55
Table 13 - Switching Regulator Specifications.....	60
Table 13 - LDO Regulator Specifications	61
Table 14 - Motor Type Specifications	65
Table 15 - Motor Specifications	67
Table 16 - Battery Type Specifications	70
Table 17 - Battery Specifications	72
Table 18 - Buzzer Specifications	75
Table 19 - SBC to Camera Protocol Specifications	77
Table 20 - Computer Vision Language Specifications.....	78
Table 21 - Detection Framework Specifications	80
Table 22 - Bill of Materials	133
Table 23 - Distribution of Work	134
Table 24 - Senior Design Milestones.....	135
Table 25 - Project Development Milestones	135

List of Figures

Figure 1 - Active Defense System (ADS) from Tom Clancy's Rainbow Six Siege	10
Figure 2 - Iron Fist Active Protection System.....	10
Figure 3 - Hardware Diagram	16
Figure 4 - Software Diagram.....	17
Figure 5 - Isometric view of final product includes space for camera and laser on barrel	18
Figure 6 - Front view of final product includes adequate space for components	18
Figure 7 - Bottom view of final product includes adhesive material to allow for multi-faced deployment	18
Figure 8 - House of Quality.....	19
Figure 9 - MCU Connections	98
Figure 10 - Humidity Sensor Schematic	99
Figure 11 - Temperature Sensor Schematic.....	99
Figure 12 - Laser System Schematic.....	100
Figure 13 - 3.3V Switching Regulator Schematic	101
Figure 14 - 5.0V Switching Regulator Schematic.	101
Figure 15 - 1.8V Linear Regulator Schematic.....	102
Figure 16 - LCD Schematic	102
Figure 17 - Motors Schematic.....	103
Figure 18 - Buzzer Schematic.	104
Figure 19 - Radar Module Schematic.....	104
Figure 20 - Data Transfer Diagram.....	105
Figure 21 - Use Case Diagram	105
Figure 22 - A GitHub repository created for this Senior Design project.	106
Figure 23 - Single-board Computer Flowchart.....	107
Figure 24 - The VSCode IDE being used to develop Python scripts.	108
Figure 25 - balenaEtcher, a program used to flash the MicroSD card.	112
Figure 26 - The Home screen of the Orin Nano after successfully booting up.	113
Figure 27 - Docker and the Ultralytics image on the Orin Nano.	114
Figure 28 – XM125 Radar Software Flowchart.....	116
Figure 29 - Arduino IDE	119
Figure 30 - ESP32 Software Flowchart	120
Figure 31 - Main PCB Board 2D View	122
Figure 32 - Main PCB Board 3D View	122
Figure 33 - 3.3V/5V Regulator Board 2D View	123
Figure 34 - 3.3V/5V Regulator Board 2D View	123
Figure 35 - 1.8V Regulator Board 2D View	124
Figure 36 - 1.8V Regulator Board 3D View	124
Figure 37 - Isometric view of CAD rendering.....	125
Figure 38 - Front view of CAD rendering.....	125
Figure 39 - Bottom view of CAD rendering.....	126
Figure 40 - Technical drawing of CAD rendering.....	126
Figure 41 - The YOLO model detecting a football on the Orin Nano. FPS hits 19-20 at peak.....	129

Chapter 1 – Executive Summary

The P.U.T.T.I. is meant to perform just as the acronym describes it to be. The device should be portable for easy transfer, should be one unitary object with as few detachments as possible, and should be able to target and intercept specific throwable targets. It is meant to be autonomous so that any user who switches it on can place it in the desired location and forget about the device, trusting in its capabilities.

The purpose of the P.U.T.T.I. is to ensure the safety of military personnel in close quarters combat situations. Multiple people packed into a room can provide the perfect target for dangerous explosives, so having the capability to neutralize these threats before they reach the servicemen will help ensure their safe arrival home.

While it would be ideal to find a way to successfully neutralize these threats, working with explosives is dangerous and not necessary for creating a prototype. Moreover, creating the neutralization tool would prove just as dangerous. Under no circumstances would these be allowed during a live demonstration. To compensate, pre-determined targets of similar estimated sizes have been chosen to serve as demonstration targets, and a simple laser will be implemented to provide proof-of-concept for neutralization and tracking. In theory, a reader could use similar methods described in this report to implement real neutralization methods by simply swapping in and out parts.

The project will require a dedicated AI model and a computer which can run said model. The model will be trained in the pre-determined targets and allow the computer to detect these objects through a camera. The camera will have a wide field of vision to increase the visibility of the device. After an object has been detected, a microcontroller unit will be required to control motors to align the laser, as well as microwave modules to aid in keeping track of the target's location if it has changed. It is important that the personnel be alerted if a target has been neutralized, so a buzzer will be implemented to warn the servicemen of an incoming or neutralized threat. Additionally, temperature and humidity sensors will be present to aid with determining the details of the environment should those factors be detrimental, and an LCD screen will be used to display these statistics.

There are plans that can be made and discussed about the future development of the P.U.T.T.I. that can be worked on in the future past the prototyping and designing of the device however the purpose of senior design and the development of this device is to create a working, reliable prototype and demonstrate its effectiveness. We want to ensure that the project has a solid foundation of research and understanding to guarantee that the device will function at maximum capacity and is meets all the guidelines provided to us for this course, but we also want to make sure that the device is interesting and challenges us in ways that we haven't been challenged before in many of our other courses.

Chapter 2 – Project Description

2.1 Project Background and Motivation

From early fortifications to the development of missile defense systems, humans and the societies they reside within have always designed and built protection technologies to protect themselves from outside threats. In today's day and age, war makes use of small drones, UAVs, and other improvised aerial projectiles. These hazards pose threats to not only soldiers on the frontlines but also to civilian infrastructure, where defenses such as missiles are too costly or rifles which are too impractical to hit and stop their target. Active defense technology has seen major processes in recent decades from large-scale missile interceptors to vehicle mounted active protection systems, yet these solutions remain inaccessible outside of military use due to their high costs, large footprints, and complexity. This makes a gap for smaller, more adaptable systems that can quickly respond to threats.

This is where the P.U.T.T.I. comes in, the Portable Unitary Throwable Target Interceptor. The P.U.T.T.I. is a compact, deployable defense device unit equipped with sensors to detect any threats such as UAVs or grenades. Once a target is identified, the unit deploys countermeasures to neutralize or disable the object before impact. The P.U.T.T.I. balances effectiveness with practicality, showing that a defense solution can be lightweight and cost efficient while also being reliable.

In addition to its practicality, this project allows our team a unique challenge. It requires us to use what we have learnt up to this point to create something to help solve an existing problem with our own take on the subject.

2.2 Current Commercial Technologies and Existing Projects

This project takes inspiration from the *Tom Clancy's Rainbow Six Siege* video game character Jäger, who can deploy an "Active Defense System" (ADS) which automatically detect and intercept incoming projectiles such as grenades or flashbangs. While fictional, this concept provided the initial motivation for our design, though our implementation will serve as a non-destructive proof-of-concept¹.

¹ "Tom Clancy's Rainbow Six Siege X: Ubisoft (US)," Ubisoft, <https://www.ubisoft.com/en-us/game/rainbow-six/siege>.



2

Figure 1 - Active Defense System (ADS) from Tom Clancy's Rainbow Six Siege

Real world parallels to this gadget already exist in the real world in the form of Active Protection Systems (APS), like the Russian Arena. These systems detect and neutralize large incoming projectiles like rockets and anti-tank missiles, typically using Doppler radar. A drawback to this type of detection system is susceptibility to clutter from terrain reflections, but these military systems are still a good demonstration for the feasibility of quick time automated threat detection and response. However, these systems are expensive, destructive, and too large to be suitable for small-scale applications.



3

Figure 2 - Iron Fist Active Protection System

² "Gadgets," gadget · Rainbow Six Siege · Rainbow Six Bootcamp, <http://rainbowsixbootcamp.com/tags/gadget/>²

³ "Iron Fist Active Protection System - detect, track, neutralize," General Dynamics Ordnance and Tactical Systems, <https://www.gdots.com/protection-systems/active-protection-systems/iron-fist-active-protection-system/>.

A related field is anti-drone and counter-UAV technology, where systems deploy RF sensors, radar, and/or cameras to detect aerial vehicles. These systems are also capable of taking down said vehicles with high precision from long distances, often through high powered lasers or net deployment. This technology highlights the effectiveness of combining multiple sensors for automated targeting and demonstrates practical ways to intercept flying objects.

By contrast, our project aims to create a compact variant of these types of systems, focusing on safe, low-cost devices capable of removing the threat of thrown weapons. Instead of intercepting targets with destructive force, our system will emphasize detection speed, accuracy, and response time using commercially available components. This approach attempts to tie together the inspiration of Jäger's ADS with principles seen in real life technologies. Making a device that is easily transportable, deployable, and useable in real world scenarios.

2.3 Objective and Goals

It is important to establish goals and objectives that we plan to achieve through the entire process of designing and developing the P.U.T.T.I. For both the goals and objectives there will be aspects that are essential to the success of the project that will be required for it to function effectively. Additionally, there will be stretch which may be difficult to achieve within the scope of the project but will add extra functionality and complexity to the design.

2.3.1 Goals

Basic Goals:

- Create a compact defense system capable of detecting and targeting stationary targets
- Allow for quick deployment and moving
- Be able to target within a 150-degree field of view around the center of the device

Advanced Goals:

- Target and track moving projectiles consistently without significant delay
- Align a laser to the target to simulate interception

Stretch Goals:

- Decrease the power consumption of the device to allow it to last longer, especially in combat zones where the device may have to be deployed for a significant number of times without access to new batteries.
- Increase the durability of the frame, making it more resistant to a vast number of harsh conditions, including sandstorms, rain, snow, etc.
- Allow for the product to attach to different faces including walls and ceilings without a loss of function to allow for more stealth

2.3.2 Objectives

Basic Objectives:

- Use cameras and sensors in combination with one another to detect targets around the device and send this information to a laser to be able to pinpoint stationary targets.
- All the hardware will be placed inside the shell of the device which will be 3D printed.
- Use a Single-board Computer to control the camera and to communicate to the Microcontroller Unit to move the motors and laser.
- Use a camera to gain a full 150-degree field of view around the center of the device.

Advanced Objectives:

- Using the Single-board Computer and FPGA board map out the entire surrounding area and calculate the trajectory of moving projectiles with a latency of less than 100 ms to ensure that the target can be hit.

Stretch Objectives:

- Use aluminum to create the frame of the device allowing for a more durable but slightly costlier design for the device whilst still being less than five pounds in weight.
- Add suction cups to the base of the device whilst still allowing for the device to be deployed in less than one minute.
- Create an easily detachable section of the device where batteries can easily be changed or the device can be charged to increase the battery life past one hour.
- Using a small projectile powered by pressurized gas hit the moving projectile with a success rate greater than or equal to 80% of the time

2.3.3 Hardware

P.U.T.T.I. will need to be portable and unitary to maximize ease of use. It is a poor assumption to assume there will be time to prepare and set aside the time to deploy the system. To ensure easiest portability, there are a couple of options, but further research is necessary. The device could be adhesive to surfaces with an easy manner to adhere and detach from surfaces. Options like suction cups could make the system easily adhere and detach from indoor floors but may have difficulty in outdoor areas. Another option is to use weights or a heavy body to reduce movement from external forces or air bursts. The downside would be that carrying the system would be more difficult. Although less portable, one final option is to use screws to be able to drill the system into any malleable surface. This would have significant setup time and would be improper for certain floors, but it would help guarantee stability.

To ensure that P.U.T.T.I. remains unitary, there should be no detachable objects or objects separated from the main body. The cameras and air mechanisms should all remain on the main body. While detachable cameras would be ideal to create

three-dimensional view of targets or to isolate the target detection zone, this will severely increase preparation time. Cameras should remain on the main body. Details on camera options are further explored in the software section.

To improve on the target detection, microwave sensor modules may be ideal for detecting moving objects. The sensors could check for moving objects as a primary targeting method, then move to the camera and image processing for secondary targeting to confirm object shape and size and to avoid humans.

While it would be ideal to both intercept and neutralize targets, for safety purposes, the neutralization aspect shall be discarded. Interception can remain for proof of concept, and the interception method should be replaceable with a future neutralization method. Using a laser pointer to show that the target was acquired is one option. While less optimal, it would suffice for proof-of-concept and may reduce the mass and size of the targeting system to aid in response time with improved physical movement.

A motor system would be required to rotate the laser module up and down as well as left and right. To do this, a pan-and-tilt method would be most appropriate. Some motor options include stepper, servos, and brushless⁴. Stepper motors have specific angles that it can align to and are fast to move between angles. Servos require a position feedback sensor and manual tuning for the inertial load but may prove to be a valid option. Brushless motors have lower duty cycles but can last longer than other motors. More research is required.

A Microcontroller will be necessary to control these components. While there are many options, a Microcontroller with the capabilities of high speeds and multiple communication protocols is required. Microcontrollers from the Arduino brand are always a valid option to get started but may suffer from lack of RAM or too slow of speed needed for real-time performance. A Microcontroller such as the ESP32 may be useful due to its small size and fast speeds as well as possible wireless communications, but these extra components may prove unnecessary.

A Single-board Computer is needed to perform image processing in real time. The Single-board Computer will have improved processing power compared to the Microcontroller, and will be able to interface with the camera, allowing for quick calculations in the moment with little communication latency. The Raspberry Pi is a cheap starting point to consider. It has significant performance with a high-speed CPU and large RAM. The Jetson boards from Nvidia may also be significant, since these boards are equipped with GPUs and are designed to perform AI activities such as image processing.

With extra time and resources, there are some better alternatives to achieve goals. While the previous neutralization options would be sufficient to provide the proof of concept, the ideal situation would be to simulate the neutralization of targets. Launching a projectile like a small foam ball or a net towards targets could fulfill this. To intercept thrown objects, one option would be implementing an air system to shoot a short burst of air at targets. Initial research shows that an air compressor,

⁴ TWPe-jpc, "Servo vs. Stepper vs. Brushless DC Motors," Elinco International, Inc. Japanese Products Corp., <https://www.e-jpc.com/servo-stepper-brushless-dc-motors>.

air tank, and linear actuator with solenoid will be sufficient to achieve this objective⁵. A PSI of approximately 20-40 PSI will suffice to affect targets within a 10-20 ft radius but may have poor results. A 12V linear actuator with a solenoid should also suffice for releasing air. Further research is required. The air system may be replaced with another projectile method, or the projectile may be added on top of the air system so that the existing air system will launch it.

2.3.4 Software

P.U.T.T.I.'s main goal is to target thrown objects and intercept them. To be able to do this, P.U.T.T.I. will need to use image detection to identify these thrown objects. Live capture of the surroundings will need to be captured via camera, and to fulfill the unitary description of P.U.T.T.I., the camera(s) should be located on the system rather than be detachable or located away from the system.

Two main options prevail with image capture. The first option is to use a fisheye camera⁶. This will give P.U.T.T.I. a wide field of vision while making calculations easier since images from multiple cameras will not need to be stitched together; however, there will be some distortion from the shape of the lens, so calculations to trajectory may be more difficult. The fisheye camera will need to be placed in a manner that the barrel and camera do not obstruct each other. The ability to target objects that are rolled or very low may be nonexistent. The second option is to use multi-camera adapter to connect four different cameras, each pointing in a cardinal direction⁷. The resulting images would need to be stitched together or track objects between them.

One option for image detection is to use the open-source software library OpenCV. OpenCV specialized in computer vision and machine learning, has numerous algorithms to detect objects and track movements, and has a large community with open forums for easy question and answer. It is also under an Apache 2 license, so OpenCV is a solid choice for an image detection library⁸.

While the methods mentioned above will provide a solution to the goals and objectives, there are some drawbacks. The camera options may prevent low to the ground objects from being targeted. One solution to this would be to use additional cameras pointed downward to detect those objects. Object range will not be able to be determined, so only the apparent size will be useable. A solution to this would be to attach a sensor, such as an ultrasonic sensor, to the targeting barrel. When a target is determined, the barrel can align to the target and activate the ultrasonic sensor to determine range before intercepting, but this will increase response time. Bright lights or dark rooms may make object detection difficult. This may warrant looking into infrared cameras or night vision cameras.

⁵ ChatGPT, <https://chatgpt.com/>

⁶ "Arducam 5mp OV5647 ultra wide angle fisheye camera for Raspberry Pi," Arducam, <https://www.arducam.com/arducam-ultra-wide-angle-fisheye-5mp-ov5647-camera-for-raspberry-pi.html>

⁷ "Mini Multi-Camera Adapter Board for Arduino-Arducam," Arducam, <https://www.arducam.com/mini-multi-camera-adapter-board-for-arduino-arducam-b0074.html>

⁸ OpenCV Team, "About - OpenCV," *OpenCV*, Jul. 18, 2025. <https://opencv.org/about/>

2.4 Required Specifications

Table 1 - Overall System Specifications

Overall System Specifications		
Parameter	Description	Target Values
Detection Latency	Time from projectile entering field of view to detection.	≤ 100 ms
Targeting Response Time	End-to-end delay from detection to targeting.	≤ 500 ms
Range	Maximum distance at which projectiles can be detected and tracked.	1 ft -> 5+ ft
Field of View	Angular coverage.	$\geq 120^\circ$ H $\times$ 60° V
Targeting Success Rate	Probability of successfully detecting and targeting projectiles.	80% -> 100%
Target Size	Approximate size of targets to be detected.	6 in -> 18+ in
Operational Lifespan	Minimum continuous operation time.	≥ 1 Hour
Weight	Total system weight.	2 – 5 kg
Device Dimensions	Overall size of device.	≤ 0.5 m $\times$ 0.5 m $\times$ 0.5 m

Table 2 - Component Specifications.

Component Specifications		
Components	Parameters	Target Values
Laser Module	Wavelength	630 nm – 680 nm
	Output Power	$\leq 5 \text{ mW}$
Motors	Angular speed	$\geq 150^\circ/\text{s}$
	Resolution	$\leq 1^\circ$
Camera	Frame Rate	$\geq 60 \text{ fps}$
Microwave Sensor	Detection Range	$\geq 5 \text{ m}$
Microcontroller	Communication	UART/I2C Interface

2.4.1 Hardware Block Diagram

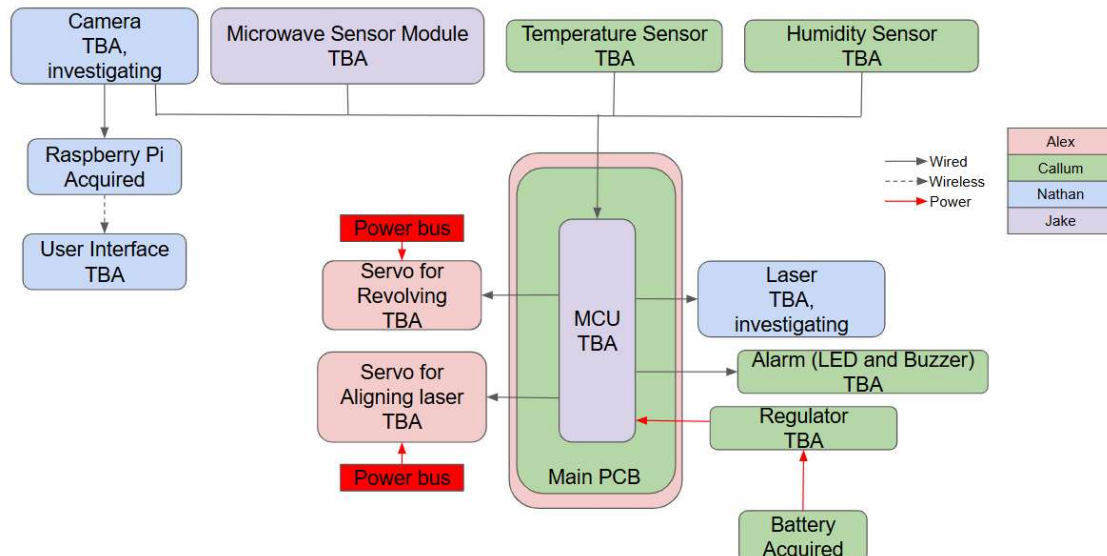


Figure 3 - Hardware Diagram

2.4.2 Software Diagram

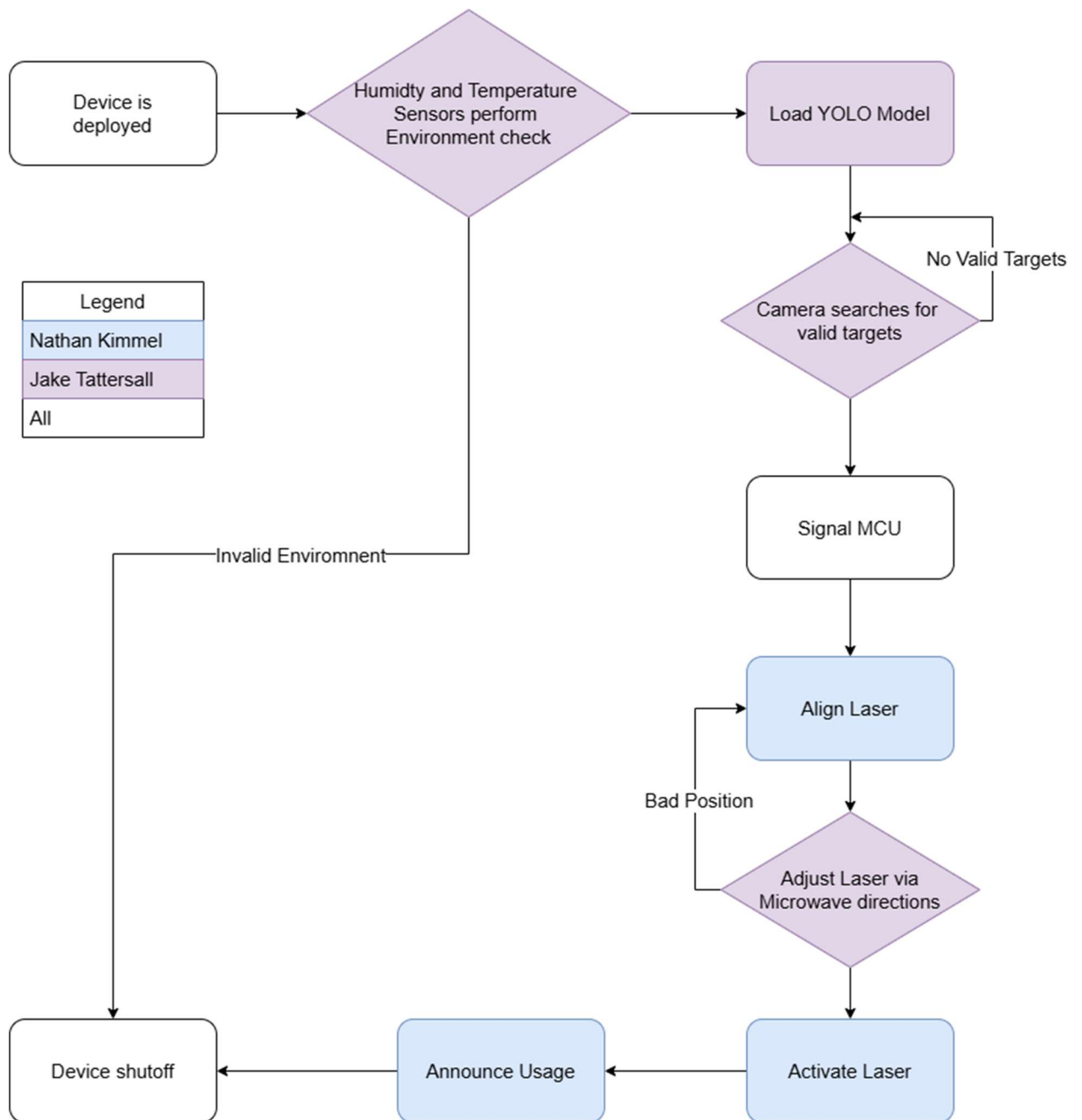


Figure 4 - Software Diagram

2.4.3 Prototype illustration

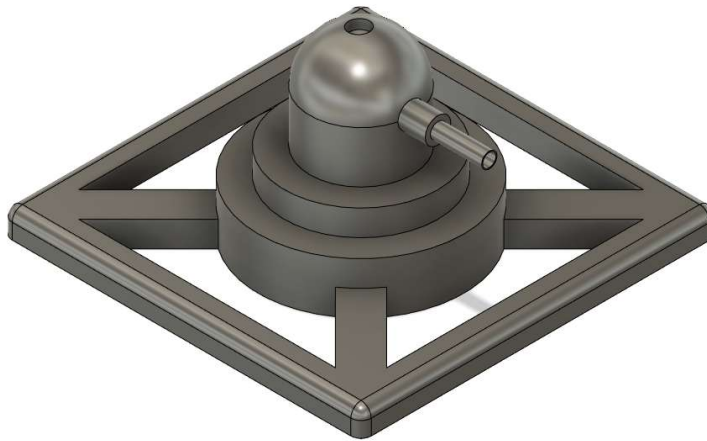


Figure 5 - Isometric view of final product includes space for camera and laser on barrel



Figure 6 - Front view of final product includes adequate space for components

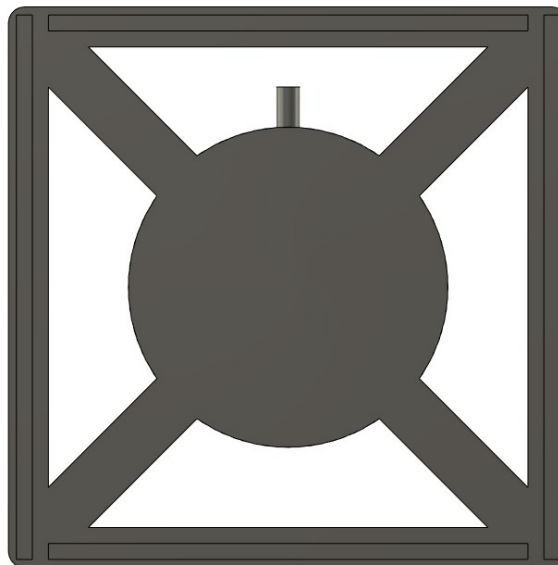


Figure 7 - Bottom view of final product includes adhesive material to allow for multi-faced deployment

2.5 House of Quality

Legend		Parameters	Detection Latency	Targeting Time Response	Range	Field of View	Targeting Success Rate	Operational Lifespan	Weight	Device Dimensions
+	Positive Correlation									
-	Negative Correlation									
^	Positive Relationship									
v	Negative Relationship									
o	No Relationship									
Marketing Needs	Response Time	-	^^	^^	v	vv	^	o	o	o
	Accurate Targeting	+	^	^	v	v	^^	o	o	o
	Coverage	+	o	o	^^	^^	o	o	o	o
	Portability	+	o	o	o	o	o	^	^^	^^
	Safety	+	^	^^	o	o	^^	^	o	o
	Battery Life	+	o	o	v	v	o	^^	v	v
	Cost	-	v	v	vv	v	vv	v	v	v

Figure 8 - House of Quality

2.6 Estimated Cost Table

Table 3 - Estimated Cost Table

Item	Cost per Item	Quantity	Total Cost
Raspberry Pi 4B	\$35.00	1	\$35.00
Fisheye Camera	\$20.00	1	\$20.00
Laser Module	\$7.00	1	\$7.00
Radar Module	\$10.00	3	\$30.00
Battery Pack	\$49.00	1	\$49.00
3D Print Filament	\$20.00	2	\$40.00
PCB	\$40.00	1	\$40.00
Motors	\$35.00	2	\$70.00
Etc. Components	\$30.00	1	\$30.00
			\$321.00

Chapter 3 – Research

3.1 Hardware

3.1.1 Single-Board Computer

For image processing, attention focuses on single-board computers (SBCs). Single-board computers are as the name suggests: powerful computers equipped with similar items of a standard home desktop, but on a single small board. The options for these may prove to be a better decision than MCU's. A single-board computer is a System-on-Chip (SoC) device which can appear similar to a microcontroller. Single-board computers have a CPU, memory, and input/output ports, but they can also have storage and an operating system. Additionally, single-board computers could contain USB or HDMI ports, Ethernet, Wi-Fi, Bluetooth, and a microSD card slot⁹.

The Raspberry Pi 4B would be the optimal choice from the Raspberry Pi family. Priced at around ~\$35-\$75, it is cheaper than the other options by a comparable amount. The 64-bit quad-core ARM CPU can achieve speeds up to 1.8 GHz. Versions of the board can have 1, 2, 4, or 8 GB LPDDR4 SDRAM, which cause the variation in price. It has access to Wi-Fi, ethernet, and Bluetooth, and it has 2x USB 3.0 and 2x USB 2.0 ports for additional connections. 40 input/output pins will be enough to control all peripherals. Power should be supplied at 5 V. It also has one MIPI CSI-2 camera port. There are concerns with the processing power for running a sophisticated computer vision model. The model may only reach three to four frames per second, which would not be sufficient for real-time detection. While this may be a fair option for image capture, it may not be best for this project¹⁰.

The Coral Dev Board is a single-board computer with a preference with machine learning. In fact, it is advertised for custom PCB hardware and for embedded system prototypes. The Edge TPU coprocessor has the capability to hit 4 trillion operations per second (TOPS) and will perform 0.5 Watts per TOPS. The CPU is a NXP i.MX 8M SoC quad Cortex-A53, Cortex-M4F. It also has an integrated GC7000 Lite Graphics GPU, as well as a Google Edge TPU coprocessor capable of 4 TOPS. The RAM depends on the model purchased, which comes in either 1 or 4 GB LPDDR4 variants. The flash memory is 8 GB eMMC as well as a MicroSD card. It contains Wi-Fi and Bluetooth 4.2 capabilities and Ethernet. The GPIO has a 3.3V power rail with multiple pins. Power is supplied as 5V DC via USB Type-C. For the camera, it does have a MIPI CSI2 camera slot as well as a MIPI DSI slot. The board is also 56 mm x 85 mm, so well within a reasonable size. While this device is very promising and the advertised price of \$129 is well within budget, it is rarely available. When it is on Amazon, it is double the price, so it may be worth picking another more-powerful board that is priced similarly to the double price¹¹.

⁹ P. Gupta, "Embedded tech: How sbcs are Shaping the future (2025)," Logic Fruit Technologies, https://www.logic-fruit.com/blog/embedded/sbcs-shaping-embedded-future/?srsltid=AfmBOopJilHYdLanky4oWRweTfJk2vtFEAR4RdkV5INIU89Dv_kov2vI.

¹⁰ Raspberry pi 4 model B specifications – raspberry pi, <https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/>.

¹¹ "Dev Board datasheet," Coral, <https://gweb-coral-full.uc.r.appspot.com/docs/dev-board/datasheet/>.

If another product is chosen, the Coral USB Accelerator can be useful for the machine learning capabilities. The USB Accelerator uses a Google Edge TPU coprocessor with 4 TOPS and connects via USB 3.0 Type-C. The Dimensions of this USB are 65 mm x 30 mm, so very reasonable to store nearby. This could be a useful addition to another SBC, however this also faces the same cost and availability problem as the Dev Board¹².

The Nvidia Jetson Nano comes in priced at >\$200, all concerns previously brought up with CPU and memory issues disappear. The 64-bit CPU is a quad-core ARM processor with speeds up to 1.43 GHz. The memory is 4 GB LPDDR4 with speeds up to 25.6 GB/s. It has enough MIPI CSI-2 ports to sustain 4 cameras. Power should be supplied between 5 – 10 W. The Jetson Nano additionally has a built in GPU with max frequency of 921 MHz, which could aid in image processing. This is certainly a good choice for P.U.T.T.I.; however, the cost may become a deciding factor¹³.

The Nvidia Orin Nano Super Development Kit (DevKit), or further referenced as Orin Nano, is another board provided from Nvidia, priced around ~\$250. This devkit is advertised to “seamlessly run the most popular generative AI models, like vision transformers, large language models, vision-language models, and more”¹⁴. The AI performance is estimated to produce 67 trillions of operations per second (TOPS), which could certainly perform real-time vision. The memory bandwidth is up to 102 GB per second, which could handle several images per second. The CPU frequency is 1.7 GHz, which could also support fast runtime. The CPU is a 6-core Arm Cortex-A78AE 64-bit CPU with up to L3 cache. The memory is 8 GB 128-bit LPDDR5, and the storage is either an SD card or external NVMe. The power of this devkit is between 7-25 W of power, so it does have a high draw¹⁵. It does support 2 MIPI CSI-2 22-pin camera ports and has 4 x USB 3.2 and a USB Type-C connection, as well as 40 GPIO featuring UART, SPI, and I2C. It also has a designated GPU of Ampere architecture with 1024 CUDA cores and 32 tensor cores. The board dimensions in mm are 103 x 90.5 x 34.77¹⁶. This device could certainly handle all image processing that needs to be performed and at near real-time speeds, but the price may be discouraging.

The Firefly ROC-RK3588S single board computer comes in priced between \$170-230. The Firefly contains a “new generation flagship AIoT chip”, an 8-core 64-bit CPU with speeds up to 2.4 GHz. It also contains an on-board GPU, the quad-core ARM Mali-G610 MP4, providing 6 OPS. The RAM available are 4, 8, 16, and 32 GB, but the 4-8 options would be best. The board takes in 12 V DC power, and it has one USB 3.0 and three USB 2.0 ports, as well as one USB Type-C port. There is one MIPI-CSI camera slot to support the fisheye camera. It does support Wi-Fi

¹² “Coral: google for developers,” Google for Developers, <https://coral.ai/products/accelerator>.

¹³ “Nvidia Jetson Nano,” NVIDIA, <https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-nano/product-development/>.

¹⁴ “Jetson Orin Nano Super Developer Kit,” NVIDIA, <https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-orin/nano-super-developer-kit/>.

¹⁵ “Jetson-Orin-datasheet-Nano-developer-kit-3575392-R2.PDF,” File Not Found, <https://nvdam.widen.net/s/zkfqjmtds2/jetson-orin-datasheet-nano-developer-kit-3575392-r2>.

¹⁶ “Jetson Orin Nano developer KIT User Guide - Hardware Specs,” NVIDIA Developer, https://developer.nvidia.com/embedded/learn/jetson-orin-nano-devkit-user-guide/hardware_spec.html.

and Bluetooth and has HDMI ports. This board only has 20 GPIO pins, containing UART, SPI, GPIO, ADC, and VCC¹⁷. This board can be a strong contender.

Table 4 - SBC Specifications

Feature	Raspberry Pi	Coral Dev Board	NVIDIA Jetson Nano	Nvidia Orin Nano Super	Firefly ROC-RK3588S
# GPIO	40	40	40	40	20
Bluetooth	Bluetooth 5.0	Bluetooth 4.2	No	No	Bluetooth 4.2
Clock Speed (GHz)	1.8	1.5	1.43	1.7	2.4
CSI	1xMIPI CSI-2	1xMIPI CSI-2	1xMIPI CSI-2	2xMIPI CSI-2	2xMIPI CSI-2
Flash memory	microSD	8-16 GB	microSD	microSD	4-8 GB
GPU	Broadcom VideoCore VI	GC7000 Lite	128 Core NVIDIA Maxwell	Ampere	Mali-G610
Operating System	Linux	Mendel/Linux	Ubuntu	Linux	Linux
Operating Voltage (V)	5	5	5	5+	5
Power Consumption (W)	~7	~2	~10	~7-25	~7
Price	~\$60	~\$130	~\$130	~\$250	~\$200
Processor	Quad-core ARM Cortex-A72	Quad-core Cortex A-53	Quad-core ARM Cortex-A57 MPCore	6-core Arm Cortex-A78AE	Quad-core ARM Mali-G610
Size (mm)	85.6 x 56.5	56 x 85	100 x 80	103 x 90.5 x 34.77	90 x 60
USB	2 x USB 2.0, 2 x USB 3.0	1 x USB 3.0, 1x USB Type C, 1x USB 2.0	4 x USB 3.0	1 x USB 3.2, 1 x USB Type C	1 x USB 3.0, 2 x USB 2.0, 1 x USB Type C
Weight (g)	~70	~50	~46	~176	~50
Wi-Fi	Dual-band 802.11ac	Dual-band 802.11 ac	Dongle required	GbE Connector	Dual-band 2.4 / 5 GHz

¹⁷ "ROC-RK3588S-PC Arm Single Board Computer: Firefly RK3588 SBC," Firefly Store, <https://www.firefly.store/products/roc-rk3588s-pc-8-core-8k-ai-mainboard>.

3.1.1.2 Single Board Computer Selection

After much review, it would appear that the Nvidia Orin Nano Super DevKit is the best choice for this project. The Orin Nano will be able to perform well with small computer vision models, performing up to 67 TOPS. The specialization in machine learning will be extremely beneficial in producing near-real-time speeds. While expensive, it is within budget and will ensure that the image detection performs at high quality. Moreover, the Nvidia community is expansive and support for any problems or errors should be able to be addressed.

3.1.2 Camera

The camera is a significant requirement for this project. The camera will be the deciding factor of whether or not a target is truly a target or not. The camera needs to have a wide view of the area and should clearly capture any target within a few feet. There are many different types of communication protocols used by the cameras explored, but the most relevant types were GPIO, USB, and CSI. These protocols are explored further below, so for now, the individual cameras for each can be considered.

The first idea produced was to have one camera in each of the cardinal directions. This led to the discovery of the Arducam Mini Multi-Camera Adapter Board. This board would allow four cameras to be used simultaneously, so long as it is connected to I2C and SPI¹⁸. This would also require the additional purchase of 4 cameras of approximately 90 degree field of visions (FOVs). Additionally, it appears that the compatible cameras for this board do not reach 90 degrees. A different option may be more sufficient¹⁹. It would be more optimal to have one camera to see the entire range, and it could make use of the MIPI CSI-2 port or USB port.

The fisheye camera presents itself as a solution. Featuring a wide angle lens, these cameras can reach large angles around the 180 degrees mark. Using one camera will reduce the complexity of wiring and remove the need for image stitching or cross referencing.

Additionally, the fisheye cameras explored below all make use of other standard connections like USB and CSI, and due to the following of these standards, a common library can be used between all cameras. The IFWATER USB camera module used USB 2.0 and is priced at about ~\$50. Using the Aptina AR0144 sensor, this camera is advertised to capture video at 720p at up to 60 frames per second. The lens has an adjustable focal length and can feature up to 170 degrees field of vision, which is very close to the desired 180 degrees. The plug-and-play nature of the camera is advertised to work well on the SBC without any need to install extra drivers. It is also advertised to have a global shutter, preventing images from appearing blurred. While this device has nice

¹⁸ Mini Multi-Camera Adapter Board for Arduino-Arducam, <https://www.arducam.com/mini-multi-camera-adapter-board-for-arduino-arducam-b0074.html>.

¹⁹ Arducam mini 2MP plus - OV2640 SPI camera module for Arduino Uno MEGA2560 Board & Raspberry Pi Pico, <https://www.arducam.com/arducam-2mp-spi-camera-b0067-arduino.html>.

specifications, the maximum resolution of 1280x720 pixels may be too small to accurately capture images of targets²⁰.

The ELP OV2710 camera is another USB camera which could prove useful. This camera uses the USB 2.0 port and is priced at about ~\$43. Using the OV2710 sensor, this camera is advertised to capture video at 1280x720 resolution at up to 60 frames per second. The field of vision is 170 degrees which is plenty of range for this project. It is advertised to work on many different operating systems including Linux and Raspberry Pi, which are good signs. The camera is advertised to reach even 100 frames per second at some resolutions²¹. This camera seems to be very promising, but CSI port cameras should be considered for a moment.

For the cameras using a CSI port, there are only two sensors supported by the Nvidia Orin Nano: the Sony IMX219 sensor and the Sony IMX477 sensor. Official documentation suggests that no other sensors, such as the OV5647 sensor, will function properly with the Orin Nano²².

The Sony IMX219 sensor is a 4.60 mm CMOS active pixel image sensor. The chip contains 8.08 million effective pixels, and can operate on three different power supplies: analogue 2.8 V, digital 1.2 V, or IF 1.7 V. It is advertised with low power consumption, high sensitivity, low dark current, and no smear on the image. The shutter speed is variable, and the maximum frames per second is approximately 30 in all-pixel scan mode. With 4-lane CSI ports, it can send up to 755 Mbps per lane, while a 2-lane CSI port results in 912 Mbps per lane. The dimensions of the active pixels to be used by the software will be 3280 x 2464, or the approximate 8.08 million pixels. The resolution and frames per second are well within the expected values for this project²³.

The Sony IMX477 sensor is a 7.857 mm CMOS active pixel stacked image sensor. This 12.3 Mega-pixel chip achieves high-speed image capture using A/D converter circuits with high sensitivity and low noise. This sensor also operates with three power supply voltages: analog 2.8 V, digital 1.05 V, or 1.8 V for input/output. This sensor is advertised with low power consumption and a high signal-to-noise ratio. The normal mode results in up to 60 frames per second. For 2-lane and 4-lane CSI ports, it can achieve up to 2.1 Gbps per lane. The number of active pixels is 4056

²⁰ "Amazon.com: IFWATER 60FPS global shutter USB camera module with 170° fisheye lens,high speed 720p aptina AR0144 camera for industrial applications with Jetson Nano,laptop,Raspberry Pi : Electronics," Amazon.com: IFWATER 60fps Global Shutter USB Camera Module with 170° Fisheye Lens,High Speed 720P Aptina AR0144 Camera for Industrial Applications with Jetson Nano,Laptop,Raspberry Pi : Electronics, <https://a.co/d/5KiHAUx>.

²¹ "Amazon.com : ELP 170degree Fisheye Lens USB camera with 1080p HD resolution, OV2710 CMOS USB camera module 2 megapixel high speed 100fps wide angle mini camera module USB2.0 for robot,ATM,Kiosk,Eye Tracking Device : Electronics," Amazon.com : ELP 170degree Fisheye Lens USB Camera with 1080p Hd Resolution, OV2710 CMOS USB Camera Module 2 Megapixel High Speed 100fps Wide angle Mini Camera Module USB2.0 for Robot,ATM,Kiosk,Eye Tracking Device : Electronics, <https://a.co/d/enpHHCu>.

²² Nvidia Jetson Orin NXOrin Nano compatible CSI camera ..., <https://files.seeedstudio.com/products/NVIDIA/NVIDIA-Jetson-Orin-NX-Orin-Nano-Compatible-CSI-Camera-Comparison.pdf>.

²³ 1, <https://www.opensourceinstruments.com/Electronics/Data/IMX219PQ.pdf>.

x 3040, or approximately 12.33 million pixels. This chip's specs are also within the project's requirements²⁴.

When deciding which CMOS chip to use, the IMX219 sensor may be better for this project. Very few cameras are available on the IMX477 camera, most being directly advertised as for Raspberry Pi. The frames per second are also hard to find for many of these cameras. As a result, products using the IMX219 sensor were explored below.

One option advertising a wider angle of view is the Arducam IMX219 camera of 220 degrees field of vision. While it does advertise out-of-the-box usage with the Orin Nano, the description does mention that a specific kernel driver is needed to function. Using a lens with part number M32076M20, the camera uses a fixed focus type as well as an integrated infrared filter to help produce better quality images. At maximum quality, the highest frames per second achieved was 21, while lower qualities such as 1280x720 resulted in 60 frames per second. The board itself is only 25 x 24 mm large. Four screw holes are located on the board to secure it. While this camera seems promising, one concern arises about the large field of vision. While it could be beneficial to see below the horizontal, this is an extreme edge case which could be developed with a more-refined prototype. Seeking this extra angle could be scope creep. This camera is priced at approximately \$26²⁵.

Another option also advertising a wider angle of view is the Arducam IMX219 camera of 175 degrees. This camera also advertises out-of-the-box usage with Nvidia Orin Nano as well as the disclaimer about the correct drivers. In fact, this camera is nearly identical to the previous Arducam camera with the exception of the lens, which is the reason for the 175 degree field of vision. This camera seems to be a better fit in terms of field of vision compared to the previous camera, and would be more likely to be selected to achieve better object detection. The camera is priced at approximately \$36²⁶.

One final fisheye option is the Waveshare IMX219 camera of 160 degrees. As with the previous two cameras, this camera will have similar statistics due to the IMX219 CMOS. While this is true, the websites used to gain information on this camera revealed some extra information, which may apply to the previous cameras as well. The camera receives 3.3 V through pin 15 of the CSI ribbon. The operating temperature for a stable image is between 0 and 50 degrees Celsius. The lens size is 6.5 mm x 6.5 mm, and has a focal length of 3.15 mm. It also advertises <14.3% distortion, which is fairly minimal and can be helpful since

²⁴ IMX477-AACK | Sony Semiconductor Solutions, https://www.sony-semicon.com/files/62/pdf/p-13_IMX477-AACK_Flyer.pdf.

²⁵ Arducam IMX219 camera module with fisheye lens for Jetson Nano and raspberry pi compute module, <https://www.arducam.com/product/arducam-imx219-wide-angle-camera-module-for-nvidia-jetson-nano-raspberry-pi-compute-module-4-3-3-b0287/>.

²⁶ Arducam IMX219 Wide Angle Camera Module for NVIDIA® Jetson AGX Orin/Orin Nano/orin NX, <https://www.arducam.com/b0179-arducam-imx219-wide-angle-camera-module-for-nvidia-jetson-board.html>.

objects may not be near the edge of the frame regardless²⁷. The camera is priced at approximately \$22²⁸.

Table 5 - Camera Specifications

Feature	IFWATER AR0144	ELP OV2710	Arducam 222	Arducam 175	Coolwell 160
FOV (degrees)	170	170	222	175	160
FPS @ Max Quality	20	30	21	21	21
Size (mm x mm)	38 x 38	38 x 38	25 x 24	25 x 24	25 x 24
Price	\$49	\$43	\$26	\$36	\$21
Connection	USB	USB	CSI	CSI	CSI

3.1.2.3 Camera Selection

After much review, the ELP USB camera is the best choice for this project. The 170-degree field of vision would be perfect for getting a valid view of the area above the P.U.T.T.I. It will interface well with the USB port to provide fast imaging at high qualities. The USB interface will be easily accessible via code, making integration simple. The long and protected USB cord will also allow for safe movement.

3.1.3 Laser

There are five different types of lasers that need to be first considered before deciding the individual part that will best suite our product, these five types of lasers are solid-state lasers, gas lasers, semiconductor lasers, fiber lasers, and dye lasers. Each of these types of lasers is used in a variety of different fields and circumstances and has different use cases and advantages but ultimately one of these types of lasers needs to be chosen as for the best fit for the P.U.T.T.I.

Solid-state lasers are lasers that use a solid medium to produce light. They are used in a multitude of industries and are used for delivering high powered and precise lasers. Whilst useful in a different context the high power of these lasers is likely too dangerous for this project. Additionally, they are quite expensive, meaning they are likely outside of the budget for this project due to the strict budget of \$1000.²⁹

²⁷ "IMX219-160 8MP camera with 160° FOV - compatible with Nvidia Jetson Nano/ Xavier NX," Seeed Studio, <https://www.seeedstudio.com/IMX219-160-Camera-160-FOV-Applicable-for-Jetson-Nano-p-4603.html>.

²⁸ "Amazon.com: Compatible with Nvidia Jetson Nano Camera IMX219-160 8-megapixels camera module 3280 × 2464 resolution 160 degree wide angle of view with IMX219 sensor : Electronics," Amazon.com: Compatible with NVIDIA Jetson Nano Camera IMX219-160 8-Megapixels Camera Module 3280 × 2464 Resolution 160 Degree Wide Angle of View with IMX219 Sensor : Electronics, <https://a.co/d/3dgm12k>.

²⁹Dr. R. Paschotta, "Solid-state lasers," RP Photonics, https://www.rp-photonics.com/solid_state_lasers.html.

Gas lasers are generated by passing a current through a gas that is contained within some sort of tube. This type of laser will be ineffective for the system due to the requirement that gas be contained in a tube, the system needs to have a laser that has a range of at least five meters and gas lasers are not able to do that effectively since the system will be small and not even capable of supporting a tube of that distance. It would also be a hazard as the constant movement of the system could cause the tube to hit objects, resulting in the tube breaking.³⁰

Semiconductor lasers work by passing a current through the p-n junction of a semiconductor. These lasers are small compared to many other lasers, inexpensive, and easily obtainable making them ideal for a project of this size. These types of lasers are commonly used in laser pointers which are not very strong lasers, ideal for a system that needs to be safe but still able to track objects in the air. Additionally, these lasers are easy to connect and compact making them suitable for a system that needs to be easily moved.³¹

Fiber lasers are high powered lasers that are often used for high precision cutting in material processing. They are very precise and have a very good beam quality however they must be used in enclosed mediums which makes them difficult to use in a system like the P.U.T.T.I. Additionally even if they were able to implement in the design, they are incredibly expensive with even the cheapest options being around \$500 which would be around half of our budget.³²

Dye lasers use liquid or solid dyes as the medium for producing light. Much like the other lasers discussed dye lasers have many of the same problems. They are large, expensive, and difficult to practically mount and apply to the design. It is not feasible to create a liquid medium that is at least five meters that can freely move around without the medium becoming damaged and as soon as the container becomes damaged the laser becomes completely inoperable. Whilst the quality of the laser is good, and it offers a lot of customization, the factors previously outlined make this type of laser completely unusable for a project of this size with the budget that has been outlined.³³

After looking at the advantages and disadvantages of each of the types of lasers it was decided that semiconductor lasers would be the best suited for our project. This decision was decided by a few important factors that set the semiconductor lasers apart from the other lasers. Mainly the size and cost since many of the other types of lasers require a large frame or medium for the light to travel through that is not easily mountable to a product the size of the P.U.T.T.I. Additionally, semiconductor lasers are the most readily available types of lasers making them easy to purchase, connect, and prototype without having much background knowledge in photonics or lasers. With it now decided that the type of laser we want to use is a semiconductor laser it is now necessary to look at a variety of

³⁰ Dr. R. Paschotta, "Gas lasers," RP Photonics, https://www.rp-photonics.com/gas_lasers.html.

³¹ Dr. R. Paschotta, "Semiconductor lasers," RP Photonics, https://www.rp-photonics.com/semiconductor_lasers.html.

³² G. Haas, What is a Fiber Laser and how do they work?, <https://haaslti.com/blog/what-is-a-fiber-laser-how-it-works>.

³³ Dye laser - an overview | sciencedirect topics, <https://www.sciencedirect.com/topics/physics-and-astronomy/dye-laser>

different semiconductor lasers and compare them to see which is the best for the project and which meet the criteria that was outlined previously.

The 1054 by Adafruit Industries LLC is a basic laser diode that produces a laser with a wavelength of 650nm, well within the range of 630nm to 680nm that we are targeting. It runs on a voltage between 2.8 volts to 5.2 volts which is perfect given that the microcontroller will be able to provide a voltage of 3.3 volts, and it can handle a current of around 25 milliamperes. The diameter of the cylinder that holds the laser is on the slightly larger end when compared to some of the other lasers which could be a concern given the tight size constraints of the P.U.T.T.I. however the 1054 is on the cheaper end of available lasers having a unit price of \$5.95 on DigiKey.³⁴

The PLT5 520DB_P by ams-OSRAM USA INC comes as a radial 3 lead laser rather than a cylinder like half of the lasers that will be compared which means the laser is much smaller than the cylinder lasers but also means it is more restrictive on how far away from the main PCB it can be and also making it more fragile. The PLT5 520DB_P is also expensive with a unit price of \$14.73 on DigiKey and unfortunately the voltage required for the input is 5.8 volts meaning that power from the microcontroller will not be sufficient to power the laser. On top of this the wavelength of the laser is 515nm which is over 100nm lower than what we want, producing a green laser rather than the desired red laser.³⁵

The VLM-650-04 LPA by Quarton Inc is a cylinder packaged semiconductor laser that is very similar to the 1054 mentioned earlier and the VLM-650-01 LPT which will be mentioned next. It has a wavelength of 650nm which is in the middle of the range that we want for our product and it is the smallest cylinder packaged laser of the three that will be compared having a cylinder diameter of 6.55mm however despite this smaller size it is more expensive than the 1054 with a unit price of \$22.99 on DigiKey. The current rating is slightly higher than the 1054 however the power produced is half that of the 1054 and the lowest bound for the input voltage is slightly lower by 0.2 volts at 2.6 volts compared to 2.8 volts for the 1054. Despite the price increase, the size of the VLM-650-04 LPA is appealing and given that size is one of the more important factors for us in choosing a laser it is an option to consider.³⁶

The VLM-650-01 LPT is another semiconductor laser produced by Quarton Inc. This laser is incredibly like the VLM-650-04 LPA having the same input voltage, wavelength, and current rating. Where the VLM-650-01 LPT differs from the VLM-650-04 LPA is the size and power of the laser. This laser only produces a single milli-watt of power making it produce the least amount of power of all the lasers, both cylinder and radial. The laser is the largest of the lasers however having a cylinder diameter of 10.4 mm making it potentially too big for the P.U.T.T.I.

³⁴ 1054 Adafruit Industries LLC | optoelectronics | DigiKey,

<https://www.digikey.com/en/products/detail/adafruit-industries-llc/1054/5629439>.

³⁵ PLT5 520DB_P AMS-Osram USA Inc. | Optoelectronics | DigiKey, HYPERLINK

"[https://www.digikey.com/en/products/detail/ams-osram-usa-inc/PLT5-520DB-](https://www.digikey.com/en/products/detail/ams-osram-usa-inc/PLT5-520DB-P/20534484)

[P/20534484](https://www.digikey.com/en/products/detail/ams-osram-usa-inc/PLT5-520DB-P/20534484)." <https://www.digikey.com/en/products/detail/ams-osram-usa-inc/PLT5-520DB-P/20534484>.

³⁶ VLM-650-04 LPA Quarton Inc. | optoelectronics | DigiKey,

<https://www.digikey.com/en/products/detail/quarton-inc/VLM-650-04-LPA/1010455>.

especially given that this laser is more expensive than the VLM-650-04 LPA having a unit price of \$32.20 on DigiKey. Comparing just the VLM-650-01 LPT and VLM-650-04 LPA it seems that the latter is the better option out of the two given their similarities to one another with the 04 LPA narrowly meeting the requirements of our project better.³⁷

The D405-120 by US-Lasers Inc is another radial laser. This laser differs drastically from the PLT5 520DB_P however in most aspects. Like the other radial lasers this type of laser is much smaller than the cylinder packaged lasers however it also comes with the same downsides as mentioned regarding the PLT5 520DB_P as it is more difficult to attach to the device where we want to place it. Specifically related to the D405-120 it has a wavelength of 405nm which would result in a purple laser which is well below the wavelength of the laser that we would want however it does run on 4.8 volts and produce 120mW of power meaning that it would have excellent range given that there is nothing in the atmosphere blocking the laser. The laser however is very expensive having a unit price of \$80.43 on DigiKey. Whilst the wavelength is not the most important aspect of the laser, and the size of the laser is favorable; the high power of the laser does not justify us spending the additional money on it given that we only require a range of at least five meters. This laser would be overkill for a project of this scope and there are simply better and cheaper options available.³⁸

The final laser that needs to be analyzed is the RLD85NZJ4-00A by Rohm Semiconductor. This is another radial 3 lead semiconductor laser. Due to this laser not being a cylinder packaged laser it comes with the same concerns as mentioned for both the PLT5 520DB_P and D405-120. This laser is interesting however since it is cheaper than the D405-120 at a unit price of \$53.76 according to DigiKey whilst having almost double the power at 220mW. The wavelength for this laser is much higher than we originally planned, having a wavelength of 852nm meaning that the laser would not actually be visible to the human eye as it produced infrared light. This could be appealing in different circumstances or future iterations of the P.U.T.T.I but for the current scope of the project this is not necessary as we do not need a huge amount of power and being able to see the laser is more important than the laser having a large range. Additionally, the input voltage for this laser is very specific at 2.8 volts making it more difficult to connect to the main circuit given that our MCU will run on 3.3 volts so we would have to create an entirely new power source just for the laser which is not something that we plan to do.³⁹

³⁷ VLM-650-01 LPT Quarton Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/quarton-inc/VLM-650-01-LPT/1010451>.

³⁸ D405-120 US-Lasers Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/us-lasers-inc/D405-120/3438595>.

³⁹ RLD85NZJ4-00A rohm semiconductor | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/rohm-semiconductor/RLD85NZJ4-00A/12336426>.

Table 6 - Laser Specifications

	1054	PLT5 520DB_P	VLM-650- 04 LPA	VLM-650- 01-LPT-ND	D405-120	RLD85NZJ 4-00A
Manufacturer	Adafruit Industries LLC	ams- OSRAM USA INC.	Quarton Inc.	Quarton Inc.	US-Lasers Inc.	Rohm Semicondu ctor
Wavelength	650nm	515nm	650nm	650nm	405nm	852nm
Voltage - Input	2.8V ~ 5.2V	5.8V	2.6V ~ 5V	2.6V ~ 5V	4.8V	2.8V
Current Rating	25mA	60mA	40mA	40mA	150mA	350mA
Power	5mW	10mW	2.5mW	1mW	120mW	220mW
Package/Case	Cylinder (10mm Dia)	Radial, Can – 3 Lead	Cylinder (6.55mm Dia)	Cylinder (10.4mm Dia)	Radial, Can, 3 Lead (5.6mm, TO-18)	Radial, Can – 3 Lead

3.1.3.2 Laser Selection

From all the lasers that were analyzed a chart comparing their wavelengths, input voltage, current rating, power, and size can be generated and used for selecting the specific laser that we want to use. The main lasers that will be considered are the 1054, VLM-650-04 LPA, and VLM-650-01 LPT since these are cylinder packages making them easier to interface and in general much cheaper than the radial 3 lead lasers. All three of these lasers are quite similar producing the same wavelength, all requiring an input voltage well within the range for it to run on our MCU and having a similar size. Considering all these aspects and minor differences however we decided on choosing the 1054 laser by Adafruit Industries LLC. The main reason for choosing this laser over the other lasers is the price, with very little separating the three lasers the 1054 is much cheaper than the other two lasers and very available on multiple vendors. This means that if there are any issues with the laser and we need to buy a replacement we will not be set that far back. Even though the smaller size of the VLM-650-04 LPA was rather tempting the price difference simply could not justify us choosing this specific laser. The 1054 laser will work remarkably well for the P.U.T.T.I and fits all the constraints and requirements that were previously outlined all for a cheap price.

3.1.4 Temperature Sensor

Temperature sensors used for measuring temperature of the atmosphere primarily come in four different types. These are thermistors, resistance temperature detectors, thermocouples, and integrated circuit sensors. Each type of temperature sensor has its specific use cases and different ways of measuring temperature. It is important to analyze each of these types of sensors to determine which ones require further research and which one's best suite the product.

Thermistors are resistors that detect the ambient temperature based on the change in the resistance. There are two types of thermistors, negative temperature coefficient (NTC) thermistors which work by lowering the resistance when the temperature increases and positive temperature coefficient (PTC) thermistors which work the opposite where an increase in the temperature causes the thermistors resistance to increase. These types of temperature sensors are often low cost and have a fast response time but are often less accurate over a small temperature range. Since the P.U.T.T.I do not need the most accurate measurements as the sensor serves the purpose of measuring the ambient air temperature this could be a suitable type of temperature sensor that can be used in our design. The most important aspect for the temperature sensor is for it to be small and cheap.

Resistance temperature detectors (RTD) are often made from platinum which allows or the temperature to be measured due to the predictable nature of platinum. RTDs are very accurate and have a larger range of temperatures that they can measure than thermistors, but this causes them to be more expensive than most other temperature resistors. They can be quite large as well, making it difficult for them to meet the size criteria for our design since they often come with lots of additional wire due to their use in HVAC systems.

Thermocouple temperature sensors generate a voltage that is based on the difference between the temperature of the two junctions of the device. There are different types of thermocouples with varying temperature ranges, however they all have quite a large temperature range which is much too large for this design since there are no environments that will reach anywhere near to these temperatures. These devices are also often quite lengthy, much like the RTDs, and whilst they are typically less expensive than RTDs they are also less accurate.

Integrated circuit (IC) sensors measure the voltage across two diodes to measure the change in temperature in the environment. IC sensors can have both analog and digital outputs which make them quite versatile and since they are integrated circuits they are very compact. They are not as accurate as some of the other types of sensors mentioned and have a much narrow range, but this works much better for the system since the temperature ranges are much more realistic for the types of environments that the system will be deployed in. Additionally, IC sensors are very easy to interface which will make them ideal for the system.⁴⁰

Looking at what each of the temperature sensors excels in and falls in we have decided to go with NTC thermistors as the type of temperature sensor that will best

⁴⁰ Sensors | DigiKey, <https://www.digikey.com/en/application-technology/sensors>.

suite the P.U.T.T.I due to the relatively small size, cheap price, and ease of installation. There are over 10,000 different NTC thermistors available on DigiKey so now it is important to narrow this down to just a few and then determine which specific NTC thermistor will be the best choice for our project keeping into account the size, cost, and operating temperature as the most important aspects. Whilst the actual temperature sensor should be small it is important to note that a longer lead wire may be more suitable since the temperature sensor will need to be further away from the main PCB to ensure the atmospheric temperature is most accurately sensed.

The B57869S0103F140 is manufactured by TDK Electronics (formerly EPCOS) and is a simple NTC thermistor with a resistance of 10,000 ohms. This is an ideal resistance since it is relatively small when compared to some other thermistors and as a result has a very small resistance tolerance of 0.2%, but the operating temperature range is also slimmer to compensate. For the P.U.T.T.I however this is not important since the sensor will only be measuring atmospheric temperature which should never get close to the lower or upper limit of -55°C and 155°C respectively. This thermistor does not come with a lead wire making it potentially difficult to attach it far away from the main body of the device however this can be overcome by extending the wire by soldering additional wire to the end. The B57869S0103F140 is quite cheap as well having a unit price of \$2.97 according to DigiKey which is well within our budget and would allow us to purchase multiple in the case that some of the sensors encounter issues or if we want to use multiple sensors to increase the accuracy of the reading.⁴¹

The PANE103395410 is a thermistor manufactured by Vishay Ametherm that like the B57869S0103F140 has a resistance of 10,000 ohms however it has a resistance tolerance ten times greater than the B57869S0103F140 potentially causing issues with the readings however if the system is calibrated correctly and the resistance is checked thoroughly this should not be a major issue. This thermistor has a very similar operating temperature to the previously mentioned B57869S0103F140 with just a slightly narrower range by 10°C having a lower operating temperature of -50°C and an upper operating temperature of 150°C . As mentioned previously this is not that impactful on the decision that will have to be made since the range is still well within a reasonable range for what we will require of it. Unlike the B57869S0103F140 this thermistor has a sizable lead wire with a length of 150.00 mm or 5.91 inches, this will make the sensor easy to connect to the main PCB of the device likely with additional length so we will not need to make any additions to the sensor which are more difficult to make than removing some excess wire. According to DigiKey this sensor is \$2.96 which is a very similar price to the previously mentioned thermistor however due to the extra lead wire it is unlikely that we would be able to fit as many sensors in the device as we could for the B57869S0103F140.⁴²

⁴¹ B57869s0103f140 epcos - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epcos-tdk/B57869S103F140/3500481>.

⁴² Pane103395410 Vishay Ametherm | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/ametherm/PANE-103395-410/1765764>

The AL03006-535K-145-G1 is a very powerful and strong thermistor manufactured by Amphenol Advanced Sensors. This thermistor has a resistance of one million ohms and as a result has quite a big resistance tolerance of 10%. One million ohms is the largest resistance out of all the thermistors that will be discussed and has the largest operating temperature range of all the thermistors as a result, having a range of -50°C and 204°C. These values are simply just much more than what the project requires, and the short lead wire, at 29.20 mm or 1.15 inches, also makes this thermistor difficult to easily attach to the main PCB. Even though the AL03006-535K-145-G1 is very cheap at a unit price of \$2.10 on DigiKey there is not a reason why we would need a thermistor with such a high resistance and operating range.⁴³

The B57540G1103F000 is another thermistor developed and manufactured by TDK Electronics. It is very similar to the previously mentioned B57869S0103F140 with the main differences coming from the operating temperature and lead wire length. The B57540G1103F000 has the same resistance but with a resistance tolerance five times greater than the B57869S0103F140 at +/- 1.0%. This small difference does not make a huge impact, and it is also half of the resistance tolerance of the PANE103395410. This thermistor however does have a shorter lead wire at 65.00 mm or 2.56 inches compared to the PANE103395410 which could make it more difficult to connect to the system however this is still sizeable wire that should function well in the system. With the most similar thermistor to this one being the other thermistor manufactured by TDK Electronics the price is also important with the B57540G1103F000 being significantly cheaper than the B57869S0103F140 at a unit price of \$2.76 on DigiKey yet having a greater operating temperature range at -55°C to 200°C. With all these differences between the two we think that the B57540G1103F000 is clearly the better choice out of the two TDK Electronics manufactured thermistors however further comparison and considerations will need to be made to determine if it is the most suitable when compared to the rest of the thermistors.⁴⁴

The NRCE105K4400B1KS is a very small thermistor manufactured by Eaton. It is also the thermistor with the second highest resistance at 100,000 ohms yet despite this resistance being ten times smaller than the next highest resistance of the AL03006-535K-145-G1 at one million ohms the resistance tolerance is still +/- 10% which could cause issues with the accuracy of the readings. This could likely be solved by ensuring that the system is calibrated correctly however it is still a concern than needs to be considered. The operating temperature range is the narrowest for the NRCE105K4400B1KS having a range of -40°C to 125°C which is still perfectly suitable for this project and an advantage since we would prefer a narrow range. It was already mentioned that this thermistor is incredibly small having a lead wire length of only 6.50 mm or 0.26 inches which will make it very difficult to attach to the main component of the system and the small lead wire makes it hard to solder additional wiring to the thermistor which is a big

⁴³ AL03006-535K-145-G1 amphenol thermometrics | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/AL03006-535K-145-G1/136421>.

⁴⁴ B57540g1103f000 epcoS - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epcoS-tdk-electronics/B57540G1103F000/3500367>.

disadvantage due to the importance of length of the thermistor. Even though the length of the NRCE105K4400B1KS is a big downside, perhaps its greatest upside is the cost with it being the most inexpensive option of all the thermistors at a unit price of \$0.21 on DigiKey. Whether or not the inexpensiveness of the NRCE105K4400B1KS makes up for some of the other troubles it has will need to have significant discussion since the other thermistors are still well within the budget for this project even if they are over ten times more expensive.⁴⁵

The 192-103LET-A01 is the final thermistor that will be discussed. This thermistor is manufactured by Honeywell; it is remarkably like TDK Electronics' B57540G1103F000 having the same resistance at 10,000 ohms and a resistance tolerance of only 0.3% greater at +/- 1.3%. The three biggest differences between the 192-103LET-A01 and the B5740G1103F000 are the operating temperature, length of the lead wire, and price. The 192-103LET-A01 has a smaller operating temperature range at -60°C to 150°C which does not affect the outlook on the thermistor much unless it is the only meaningful substantial difference between the two. This thermistor is much shorter than the B57540G1103F000 having a lead wire length of 38.00 mm or 1.50 inches which is almost half of the length of the B57540G1103F000 which is substantially shorter and could make connecting the thermistor to the rest of the device difficult however this is a fix that can simply be achieved by soldering additional wire to the sensor. Perhaps the most important difference between this thermistor and the rest of them however is the price. The unit price for the 192-103LET-A01 is \$3.35 according to DigiKey, which is significantly more expensive than some of the other options however it is also one of the most available options with there being over 15,000 of them in stock at DigiKey alone.⁴⁶

Table 7 - Temperature Sensor Specifications

	B57869S01 03F140	PANE1033 954	AL03006- 535K-145- G1	B57540G1 103F000	NRCE105K 4400B1KS	192- 103KET- A01
Manufacturer	EPCOS - TDK Electronics	Vishay Ametherm	Amphenol Advanced Sensors	EPCOS - TDK Electronics	Eaton - Electronics Division	Honeywell Sensing and Productivity Solutions
Resistance in Ohms @ 25°C	10k	10k	1M	10k	100k	10k
Resistance Tolerance	±0.2%	±2.0%	±10.0%	±1.0%	±10.0%	±1.3%

⁴⁵ Eaton-Electronics Division distributor | DigiKey, <https://www.digikey.com/en/supplier-centers/eaton-electronics-division>.

⁴⁶ 192-103LET-A01 Honeywell Sensing and productivity solutions | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/honeywell-sensing-and-productivity-solutions/192-103LET-A01/1886044>.

Operating Temperature	-55°C ~ 155°C	-50°C ~ 150°C	-50°C ~ 204°C	-55°C ~ 200°C	-40°C ~ 125°C	-60°C ~ 150°C
Max Power	60mW	125mW	-	18mW	450mW	-
Length - Lead Wire	-	150.00mm	29.20mm	65.00mm	6.50mm	38.00mm

3.1.4.2 Temperature Sensor Selection

Looking at all the thermistors, a simple chart comparing the resistance, resistance tolerance, operating temperature, max power, and length of the lead wire can be made and found below. From this a thermistor must be selected that will best suite the P.U.T.T.I for measuring atmospheric temperature. Considering not only these factors but also additional factors such as cost and availability the decision was made to use the B57540G1103F000 by TDK Electronics. Whilst this thermistor did not have the longest lead wire which was incredibly important it was one of the cheapest thermistors and readily available at many retailers making it easy to obtain additional sensors in the case that we have issues that need to be fixed. Additionally, the maximum power of this thermistor was very small which is not the most important part of the thermistor however when we are using small voltages like 3.3 volts and 5.0 volts having a small maximum power can be important and when many of the thermistors had similar aspects between one another this was an additional variable that was considered. The B57540G1103F000 will be the perfect choice for the P.U.T.T.I to measure the atmospheric temperature.

3.1.5 Humidity Sensor

Humidity sensors will be used to detect the humidity in the surrounding atmosphere of the P.U.T.T.I to ensure the device will be fully operational and if the humidity of the atmosphere is not acceptable then the device will shut down. There are three major types of humidity sensors that first need to be discussed before choosing the exact part that we need to use for our project. These humidity sensors differ mostly on how they read or what type of humidity they read, relative humidity or absolute humidity.

Capacitive humidity sensors are used to measure relative humidity. Relative humidity is the ratio of the water vapor content to the temperature. These types of humidity sensors work by using a polymer that absorbs moisture placed between two electrodes, this allows for the humidity to be read based on the amount of water that the dielectric material absorbs as the dielectric constant will be changed based on the amount of water that is in the atmosphere and therefore absorbed. These sensors are quite small, and cheap, however they do offer some accuracy concerns as there is often a 2-3% error in the accuracy of the reading, additionally they are more susceptible to degrading over time than other sensors.

Resistive humidity sensors, like capacitive humidity sensors, are used to measure relative humidity. Resistive humidity sensors measure the humidity in a very similar way to capacitive humidity sensors, however there are some minor differences. These types of sensors are also made from moisture absorbing material but the mechanism behind how they work is slightly different as in a resistive humidity sensor a conductive polymer is placed between the two electrodes and as the material absorbs water the electrical conductivity increases resulting in a decrease in resistance, from this a humidity reading can be generated. The pros and cons of resistive humidity sensors are essentially the same as the capacitive humidity sensors; they are also quite small and cheap and suffer from the same accuracy issues.

Thermal conductivity sensors measure absolute humidity instead of relative humidity which means that the sensor is measuring the actual amount of water vapor mass within the volume of air rather than measuring the ratio of the water vapor to the temperature. These sensors measure humidity by calculating the difference in the thermal conductivity of dry air and the ambient air. Since thermal conductivity sensors measure absolute humidity they are often much more accurate than relative humidity sensors but this also means that they are more expensive and larger which is more of a concern for the design of the P.U.T.T.I than accuracy of the humidity since there is a rather large range that the system will work on and we only need to measure the ambient humidity.⁴⁷

The most important part of the humidity sensor that we use for the P.U.T.T.I device is that it measured relative humidity, this immediately eliminates the thermal conductivity sensors from being used in our project. This means that we want to use either capacitive humidity sensors or resistive humidity sensors. There isn't much that separates the two other than the way that the humidity is sensed and the output type of the sensor, because of this we will compare both types of sensors equally and determine which is the most appropriate type for the design.

The HS12SP is a resistive humidity sensor with a resistive output that is manufactured by Amphenol Advanced Sensors. It has a humidity range of 30% to 90% which is a bit narrow since we want to ensure that the P.U.T.T.I can function in a variety of different areas that could have humidity as low as 10% or higher than 90% so making sure we can accurately read the relative humidity in those regions is necessary to ensure proper functionality. Additionally, the accuracy of the relative humidity is +/- 5% which is quite substantial especially compared to some of the other humidity sensors that will be analyzed. It also has a very slow response time at 120 seconds, whilst the humidity sensor does not need to be constantly reading since humidity does not typically change that frequently having a two-minute response time could make it difficult to coordinate the readings with the temperature sensor and microcontroller. The supply voltage is also only one volt which means we would need an additional regulator for the sensor to function

⁴⁷ P. Mueller, "Humidity sensor questions and answers," Dickson Data, <https://dicksondata.com/humidity-sensor-faq>.

which would occur additional costs on top of the \$5.60 that the sensor costs through DigiKey.⁴⁸

The HPP801A031 is a capacitive humidity sensor with a capacitive output manufactured by TE Connectivity. This sensor has a very big range of 1% to 99% relative humidity which will cover any region that the device could be deployed in, it is also very accurate only having a 2% error either way which means the reading will be very accurate so we can read the humidity very accurately in a variety of different regions and environments. Additionally the HPP801A031 has a very quick response time at three seconds which means that we can constantly measure the relative humidity of the atmosphere to ensure that the device will always be functionally, whilst the humidity does not change rapidly as mentioned previously this fast response time will be useful when programming the P.U.T.T.I. The biggest downside to the HP801A031 is the supply voltage needed to run the sensor as it needs a 10-voltage supply meaning we would need to have an additional regulator and likely need to increase the base voltage of the power supply. Having to include a regulator or change the power supply could result in massive changes to the device or functionality which could be difficult to make. The sensor is also quite expensive at \$8.62 on DigiKey so we must decide whether the upsides of the sensor outweigh the voltage supply and cost issues associated with it.⁴⁹

The HIH-4021-003 is a capacitive humidity sensor that outputs a voltage and is manufactured by Honeywell. This sensor can measure relative humidity at every humidity having a range from 0% to 100% which will be incredibly useful given that some environments can reach upwards of 100% humidity, and we want the device to be functional in any possible environment which could include tropical climates. The sensor is also quite accurate having an accuracy of +/- 3.5% which should ensure an accurate reading however could have some impact on the readings. The response time is also quite quick at five seconds which is a perfectly acceptable response time. The biggest issue with the HIH-4021-003 is the cost. Whilst it is the most available sensor of all the humidity sensors it is also the most expensive having a unit price of \$23.41 on DigiKey. This cost could make it difficult to purchase multiple in case there are issues with the humidity sensor or if we want to include multiple sensors to compare and get a more accurate reading of the relative humidity in the atmosphere.⁵⁰

The 3721 is a capacitive humidity sensor that outputs the humidity as a digital output through I2C. This sensor is manufactured by Adafruit Industries LLC much like the laser that was chosen previously. This has a large range that it can measure the relative humidity of 0% to 99% which should be large enough, whilst having a range with an upper bound of 100% would be preferred many of the sensors that can reach that are much more expensive. It is also very accurate having an accuracy of +/- 3% which is around the middle range of all the sensors.

⁴⁸ HS12SP amphenol Telair | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/HS12SP/4780894>.

⁴⁹ HPP801A031 TE connectivity measurement specialties | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/te-connectivity-measurement-specialties/HPP801A031/697731>.

⁵⁰ HIH-4021-003 - digikey, <https://www.digikey.com/en/products/detail/honeywell-sensing-and-productivity-solutions/HIH-4021-003/2503904>.

One of the biggest upsides of this sensor compared to many of the other sensors is that the sensor only requires a minimum 3.3-volt supply and maximum 5.5 volts which works perfectly with the microcontroller which will work on 3.3 volts and 5 volts meaning that no additional regulators should be required to power the sensor. The sensor is also incredibly cheap compared to the other sensors at a unit price of \$3.95 on DigiKey however it is also not super readily available with there being less than 100 in stock so it could be difficult to find any on a tight schedule if we have issues with them later requiring replacement. The best thing about the 3721 is that because the sensor outputs a digital signal, we can easily interface the sensor and tell exactly what the humidity is without having to convert capacity, resistance, or voltage to humidity which could make it easier for the user to tell exactly what the humidity is reading and whether they need to be concerned that the device may not function correctly. Additionally, this sensor can also read temperature so we can use it as an extra temperature sensor to compare the values read by the temperature sensor and make sure the readings are accurate between all the sensors.⁵¹

The HUMIDITY-SENS-E is a capacitive humidity sensor with a capacitive output manufactured by Vishay Beyschlag, Draloric, and BC Components. This sensor has a slightly restrictive humidity range having a lower range of 10% and upper range of 90%, the lower range is not as important as the upper bound since there are likely more environments that device will be deployed in that can reach this high of a humidity. This sensor also has the longest response time at 180 seconds which means this sensor could suffer from some of the issues outlined when analyzing the HS12SP sensor. Having a three second response time will not necessarily impact the accuracy of the reading however it could cause issues with communication. This sensor also has the largest power requirements needing a voltage supply of 15 volts which as explained when analyzing the HPP801A031 is likely a factor that is just easily avoided by selecting one of the other sensors. The cost of this sensor, whilst not as expensive as the HIH-4021-003, is quite expensive having a unit price of \$13.70 on DigiKey which on top of the other issues discussed means that this sensor likely isn't the best equipped for a device like the P.U.T.T.I.⁵²

The CHS-MSS is a capacitive humidity sensor that outputs a voltage and is manufactured by TDK Corporation. The humidity range for this sensor is the most narrow of the six sensors having a range of 20% to 85% which would mean the sensor would be unable to measure the humidity in a variety of different environments including tropical and dessert environments which are regions where the P.U.T.T.I is likely to be deployed. Additionally, the sensor has quite a bit of inaccuracy with an accuracy of +/- 5% much like the HS12SP which had the second most narrow humidity range. These two factors means that the CHS-MSS might find it difficult to accurately measure the humidity and ensure that the system

⁵¹ 3721 Adafruit Industries LLC | Sensors, transducers | DigiKey, <https://www.digikey.com/product-detail/en/adafruit-industries-llc/3721/1528-2564-ND/8558266>.

⁵² Humidity-sens-e Vishay Beyschlag/draloric/BC components | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/HUMIDITY-SENS-E/769433>.

can remain functional. The response time is 60 seconds which is much longer than some of the other sensors with single digit response times however it is a response time that would likely still suit the system and would still be able to communicate with all parts of the device without much degradation or difficulty. The voltage supply range is 4.75 volts to 5.25 volts which means it could be powered by the 5.0 volts of the microcontroller making it easy to connect however it is one of the more expensive sensors having a unit price of \$19.31 on DigiKey.⁵³

Table 8 - Humidity Sensor Specifications

	HS12SP	HPP801A031	HIH-4021-003	3721	HUMIDITY-SENSE-E	CHS-MSS
Manufacturer	Amphenol Advanced Sensors	TE Connectivity Measurement Specialties	Honeywell Sensing and Productivity Solutions	Adafruit Industries LLC	Vishay Beyschlag/Draloric/BC Components	TDK Corporation
Humidity Range	30 ~ 90% RH	1 ~ 99% RH	0 ~ 100% RH	0 ~ 99% RH	10 ~ 90% RH	20 ~ 85% RH
Output	60k @ 50% RH	180pF @ 55% RH	3.268V @ 75.3% RH	I2C Output	122pF @ 43% RH	500mV @ 50% RH
Accuracy	±5.0% RH	±2.0% RH	±3.5%	±3.0%	-	±5.0%
Response Time	120s	3s	5s	5s	180s	60s
Voltage - Supply	1V	10V	5V ~ 5.8V	3.1V ~ 5.5V	15V	4.75V ~ 5.25V
Operating Temperature	0°C ~ 50°C	-40°C ~ 140°C	-40°C ~ 85°C	-40°C ~ 80°C	0°C ~ 85°C	0°C ~ 50°C

3.1.5.2 Humidity Sensor Selection

Compiling and analyzing all these sensors, we can see that the two best sensors are the HIH-4021-003 and 3721. Both sensors will function exactly how we want them to in the device however the preferred sensor of the 3721 is more difficult to obtain. The HIH-4021-003 is much more expensive than the 3721 but it is also much more available which means if we have any issues with the sensor, we can easily get a replacement. Considering this and all the aspects of the sensors, which

⁵³ CHS-MSS TDK Corporation | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/tdk-corporation/CHS-MSS/931222>.

can be seen in the table below, we believe that the 3721 by Adafruit Industries LLC is the best sensor for the P.U.T.T.I, mostly due to the cheap cost and easy interfacing. If there are issues with the availability of the sensor then we may have to change to another sensor such as the HH-4021-003 however as it currently stands there are available 3721 sensors and we should be able to obtain them.

3.1.6 Microwave Sensor

To meet the project's goal of fast and reliable detection of thrown projectiles, a sensing method is required that performs well for high-speed motion under a variety of conditions. While the project will include a camera with a wide field of view for object recognition and initial detection, this visual tracking alone is limited by frame rate, motion blur, lighting conditions, and computational latency. The speed of a thrown object can allow it to cover several meters in a very short amount of time, meaning delays in image processing can directly limit the available reaction time of the system.

To overcome these limitations, several different sensing technologies were considered. The three most prominent sensors considered were ultrasonic sensors, infrared sensors, and microwave sensing. Ultrasonic sensors are commonly used for low-cost distance detection but come with a variety of issues. The distance for most ultrasonic sensors is too low for reliable tracking, and most ultrasonic sensors have too small of a field of view. However, the biggest issue is that the refresh rate for ultrasonic sensors is far too low for effective projectile tracking. Infrared sensors were also considered, which can be separated into two types. Passive infrared sensors do not give out EM waves and only detect heat signatures, meaning they cannot sense nonthermal fast moving objects. Active infrared sensors would be much more effective since they emit their own EM waves, providing directional distance measuring. However, they are highly sensitive to surface irregularities and angles, making them more inconsistent with rotating projectiles. Additionally, both ultrasonic and infrared sensors are usually not used for velocity measurements, which is critical for our project's purposes⁵⁴.

Microwave radar sensors offer a strong solution to these limitations because of their ability to detect motion through doppler frequency shifts. They emit EM waves and measure the changes in the reflected signal, allowing the sensor to directly calculate the velocity and direction of a thrown projectile rather than just inferring it from multiple distance measurements. This allows motion to be detected within a few milliseconds, which is ideal for the types of projectiles we wish to track. Microwave sensors are also robust to the types of environmental challenges that can limit camera-based tracking and infrared sensing. This is because they are not significantly impacted by lighting conditions, smoke, or glare, which is crucial for the conditions that our project should work under. Through this comparison, microwave sensors clearly stood out as the sensor type most capable of supporting the project's reliability and responsiveness requirements.

⁵⁴ Admin, "Microwave vs infrared sensors: Understanding the differences," Rotech Automation, <https://rotech.com.au/microwave-vs-infrared-activation-sensors-whats-the-difference/>

With this sensing method justified and selected, the next step is determining the appropriate requirements for the microwave radar sensors. The most critical factor is detection latency. Since thrown projectiles can travel several meters in less than a second, the sensor must provide updates very frequently such that velocity and direction can be determined within milliseconds of detection.

Range is another essential specification. The project requires a minimum detection/targeting range of 5 meters. This means that the minimum range for the microwave sensor should be 5 meters or greater, allowing for incoming threats to be identified early enough in flight to adequately calculate trajectory. While a large range of detection is preferred for this sensor, the maximum detection range of the P.U.T.T.I. depends primarily on the camera detection range.

Field of view requirements mainly depend on the architecture of the project. Since multiple microwave sensors will be situated about the device to cover different sectors, each sensor must have a wide enough angular detection area to ensure full coverage when combined. An adequate field of view should allow the system to activate only the sensor monitoring the sector where the camera first detects the projectile, which will reduce unnecessary power consumption and reduce signal interference between sensors. In total, the sensor array should have an angular coverage greater than or equal to 120 degrees H × 60 degrees V.

The final two parameters that should be considered are detection reliability and power efficiency. Detection reliability concerns the sensor's ability to provide continuous, accurate readings when active and its effective lifespan. Since the system will be battery powered, the microwave sensor should draw minimal current when active and should ideally enter a low-power state when idle, conserving power.

With these performance considerations, including short detection latency, adequate tracking range, appropriate field of view, high detection accuracy, and lifespan, the specific microwave sensor can now be chosen. The next section will compare numerous commercially available microwave sensors and justify the final selection based on these specifications.

One radar module considered for this project is the A121 Pulsed Coherent Radar from Acconeer AB. While it does not technically classify itself as a microwave sensor, it still uses microwaves to take the same radar measurements. This is a compact 60 GHz pulse sensor designed for precise motion and distance tracking, which aligns well with the system's rapid projectile detection requirement. The sensor supports microcontroller communication using an SPI interface (up to 50 MHz). It allows for direct velocity measurement and provides high resolution, in the order of millimeters for absolute distance and micrometers for relative distance, which is great for precise tracking of fast-moving projectiles. Its typical detection range is 7 meters for human targets and up to 23 meters for nonhuman targets, exceeding the 5-meter range requirement for the system. For the field of view, the A121 has a typical half-power beamwidth of about 65 degrees in the H-plane and 53 degrees in the E-plane. This means that using an array of three of these sensors, each separated by 60 degrees, will more than satisfy the project's 120 degrees by 60 degrees minimum angular coverage goal. This device is also

suitable for low-power consumption, supporting both interrupt-driven wake functionality and power-saving modes (like sleep and deep-sleep). It operates using either a 1.8V or 3.3V supply for VIO and 1.8V for everything else with a maximum current draw of 100 mA during active use for any power supply. It has a fast start up time, typically 2 ms, but this depends on the power supply and decoupling capacitors selected. The sensor has a moisture sensitivity level of 3 (MSL 3), meaning that it must be protected in a sealed enclosure and will likely need to be baked before encasing in plastic or glass. The sensor has a price of \$16.74 on Digikey, meaning that the A121 is a capable, cost-effective option for the P.U.T.T.I. system. The two primary concerns regarding this sensor are that the humidity requirements may create issues with device longevity, and that there is no front-end processing of the raw radar data, which will add more computational stress on the central microcontroller and will require more knowledge about data processing⁵⁵.

The second radar sensor evaluated is the IWR6843AOP from Texas Instruments. This device is a 60 – 64 GHz sensor that includes its own microcontroller, digital signal processing hardware, and internal memory for storing measurements. It has mm resolution detection, similar to the previous sensor discussed. This sensor supports multiple communication pathways, including SPI, UART, and I2C (though there's no high speed I2C support), which allows for easy MCU compatibility. Additionally, this sensor has an onboard DSP module, which would make data processing very easy. However, there are several drawbacks when it comes to this device that make it a poor fit for the P.U.T.T.I. system. The datasheet does not specify a typical detection/measuring range nor does it provide any angular coverage values, making it difficult to predict coverage capabilities and its ability to fulfill the project's requirements. This device's design is intended to be the primary computational platform for industrial systems, meaning it is not intended for low-power applications. The power supply design is also much more complex than required, requiring multiple supply rails including 1.2V, 1.3V, 1.8V, and 3.3V (if using the 3.3V input for IO pins), with maximum input currents varying rail to rail. This complexity would add unneeded cost and design time to creating the PCB that would conflict with many of the project's goals. Regarding the moisture level, it has the same issue as the previous radar sensor. Lastly, the sensor costs \$32.87, making it nearly twice as expensive as the previous sensor, which would be even more considering multiple sensors would be needed to cover our intended field of view. Overall, the IWR6843AOP is very complex and has incomplete specifications for our required parameters⁵⁶.

The third radar sensor evaluated is the IWR6432AOP from Texas Instruments. This device is a 57 – 63.5 GHz sensor and features an integrated antenna array consisting of two transmitters and three receivers, which allows for velocity measurements with millimeter resolution. A notable aspect of this sensor is that it supports UART, I2C (not high speed), and SPI communication protocols, with SPI

⁵⁵ A121-001-T&R acconeer ab | sensors, transducers | DigiKey,

<https://www.digikey.com/en/products/detail/acconeer-ab/A121-001-T-R/17883300>

⁵⁶ "IWR6843ARQGALP active," IWR6843AOP | Buy TI Parts | TI.com,

<https://www.ti.com/product/IWR6843AOP/part-details/IWR6843ARQGALP>.

allowing for the most optimal communication for the peripheral mode using an external microcontroller. The power requirements are much simpler than that of the previous TI sensor, with the device operating using a 1.8V rail (and a 3.3V rail for IO if desired). Additionally, this sensor has both an idle mode and deep-sleep mode, which would help reduce power consumption when inactive. Like the previous microwave module, this one has an onboard MCU (M4F) with internal memory for measurement recording but does not contain a digital signal processing unit. While the datasheet does not provide explicit half-power beamwidth values, it does provide radiation pattern graphs relating receiver gain to azimuth and elevation angles which, while making it harder to pinpoint values, allows for more specific values to be predicted based off operational frequency. With a specified detection range of 20 meters and a price of \$11.19 on TI's website, this sensor appears to be a capable and cost-effective option. However, there are several concerns limiting its suitability for the P.U.T.T.I. system. The absence of a DSP module would add a greater processing load on the primary microcontroller. The power draw for this device is also an issue. The maximum current draw is upwards of 1360 mA for the 1.8V rail and 90 mA for the 3.3V rail, meaning this sensor consumes significantly more power than simpler microwave sensors. Regardless, this device is sold out at this time⁵⁷.

The final radar module evaluated is Acconeer's Entry+ XM125 module. This module contains a dedicated 32-bit ARM Cortex-M4 processor along with the previously discussed A121 radar sensor. Where the lone A121 requires significant firmware development, the onboard MCU of this module can run Acconeer's radar system software, which will handle lower-level signal processing. This can reduce the computational workload on the P.U.T.T.I. system's main microcontroller and simplify the need for complex data processing knowledge. The XM125 supports both UART and I2C communication protocols, allowing for high-speed data transfer. This module also includes power-management features like a wake-up pin and idle/off power modes, which will allow for more efficient power consumption. The module costs \$21.21 per unit on Digikey and is in stock. Overall, the XM125 provides suitable coverage for our project's goals and basic signal processing capabilities⁵⁸.

⁵⁷ "IWR6432AOP," IWR6432AOP data sheet, product information and support | TI.com, HYPERLINK "https://www.ti.com/product/IWR6432AOP?keyMatch=iwrl6432aop&tisearch=universal_search"https://www.ti.com/product/IWR6432AOP?keyMatch=iwrl6432aop&tisearch=universal_search.

⁵⁸ XM125 Acconeer ab | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/acconeer-ab/XM125/17883267>.

Table 9 - Microwave Sensor Specifications

Parameter	A121	XM125	IWRL6432AOP	IWR6843AOP
Manufacturer	Acconeer	Acconeer	Texas Instruments	Texas Instruments
Frequency Band	60 GHz	60 GHz	57 – 63.5 GHz	60 –64 GHz
Processing Capabilities	None	Cortex-M4	Cortex-M4F	Cortex-M4F + C674x (DPS)
Communication Interface	SPI	UART, I2C	UART, I2C, SPI	UART, I2C, SPI
Detection Range	23 meters (target-dependent)	Same as A121	20 meters	Not specified
Field of View (per unit)	About 65 H × 53 V	Same as A121	Detailed pattern plots (no explicit values)	Not specified
Supply Voltage	1.8V, 3.3V-optional	1.8V, 3.3V-optional	1.8V, 3.3V-optional	1.2V, 1.3V, 1.8V, 3.3V-optional
Moisture Sensitivity	MSL 3	MSL 3	MSL 3	MSL 3
Price (per unit)	\$16.74	\$21.21	\$11.19	\$32.87

3.1.6.2 Microwave Sensor Selection

When comparing these four devices, they were each ranked based on alignment with the performance requirements of the P.U.T.T.I system. Texas Instruments IWR6843AOP provides extensive processing capabilities but lacks important specification data, introduces both power and architectural complexity into the system that isn't necessary, and provides no low-power modes. The IWRL6432AOP offers improved efficiency and a lower price but is out of stock and still has a relatively high current draw when active, which opposes the need for a low-power microwave sensor. In contrast, Acconeers A121 directly supports the sensing needs of the system without adding unnecessary power supply complexity. It provides millimeter level accuracy, appropriate tracking range, low power consumption, interrupt-based activation, and an angular coverage that can meet the desired field of view requirements using an array. Its relatively low cost is also beneficial. The bare sensor lacks any sort of signal processing, which is why the XM125 should be considered in its place. The XM125 combines the

sensing performance of the A121 with onboard, low-level signal processing with simple communication interface support. Due to its balance of capability and efficiency, the Entry+ XM125 module is the most practical and effective choice for the P.U.T.T.I. system.

3.1.7 Microwave Sensor Housing

The previously discussed XM125 radar module, which uses the A121 PCR and an STM32L431 microcontroller, is actually fully capable of operating without an additional casing. The module is capable of operating in standard indoor conditions and can perform all necessary sensing and processing functions without external protection. Initially, an outer casing for the radar module was believed to be required due to its MSL3 rating (moisture sensitivity level 3), but upon further research into these levels it was deemed unnecessary.

Moisture sensitivity level ratings are strictly related to the manufacturing process, not the overall longevity of the module. Specifically, it relates to components that undergo reflow soldering. During reflow soldering, the high temperatures can expand accumulated moisture, which can crack and damage the components. Since this project will not require reflow soldering, the radar module's MSL3 rating will have no bearing on the longevity of the component. This means that the radar modules will not require a casing to shield it from humidity. While a casing is not required for radar function, it may still be beneficial for the project's overall life. Over an extended period of time, protection from environmental factors such as ambient humidity and dust may still help the radar modules to live longer.

Even though no enclosure is required, decent environmental protection can still be beneficial over the long term. The XM125 is a small, exposed PCB with small components and a sensitive radar sensor. In almost any real environment or storage space, dust accumulation will become an issue. Dust is not immediately harmful, but over time it can aid in water accumulation directly on the device that can cause issues for data collection. One research paper from Kang et al. found that water content found in dust contaminants significantly affects signal attenuation and transmission for radar sensors. Across all tests, object detection capabilities and signal attenuation got worse with increased levels of water content⁵⁹. These effects develop very slowly and often don't matter for short term projects, but they are valid concerns if the system should work a long time from now.

Although a case is not needed for normal operation and testing, it's still useful to consider potential enclosure methods so that if long term storage protection becomes desired later on, it can be implemented easier. Since the module consists of a small pcb with a radar chip on top, the only portion that requires real protection is the radar sensor itself. This means that the design should not interfere with the

⁵⁹ J. Kang *et al.*, "Effects of dust and moisture surface contaminants on automotive radar sensor frequencies," *Sensors*, vol. 25, no. 7, p. 2192, Mar. 2025. doi:10.3390/s25072192

radar's field of view while still preventing dust build-up on and around the radar sensor.

One of the most straight forward methods is to 3D print a small housing unit that can fit around the module. Filaments such as PLA, ABS, and PETG could all be used since the A121 PCR can pass through common plastics and glass with minimal signal attenuation. All three can act as a basic dust and moisture barrier, but each provides different advantages, though a greater analysis of each can be found in the 3D print material research section. ABS requires an enclosed printer, which is already more effort than it is worth. PLA is easiest to print but tends to absorb moisture more readily. PETG has better moisture resistance and impact resistance, though it is slightly more expensive. Any of these could be used to print the enclosure, but PETG would offer the best balance of printability and durability without needing a specialized printer.

While the outer casing can be made of PETG, the region above the radar sensor should be made of something else. If it is, then it must be printed thinly and uniformly enough to mitigate any signal direction changes. So, the most practical approach would be to leave an opening in the case above the radar sensor and to attach a flat panel on top of it. Two simple choices for this would be acrylic or polycarbonate sheets cut to match the opening. Acrylic is rigid, easy to cut, and is generally cheaper to buy. Polycarbonate is much more impact resistant but is harder to cut into shape and is generally more expensive⁶⁰. Both allow the radar signals to pass through with minimal distortion. For the enclosure, the acrylic would be best since it's cheaper and would be much easier to cut to fit the opening. Attaching the acrylic to the opening with screws would disrupt the signals from the radar, which means that it would be best to just glue it. This apparatus would provide a clear barrier to prevent dust from settling directly on the radar chip while still preserving accurate readings.

Another layer of optional protection for the radar module is placing a moisture absorbing silica packet inside the housing. Even though the overall humidity of the room and inside the container should not interfere with normal operations after soldering, a small packet could still reduce local moisture buildup over long periods of time.

Overall, since the XM125 can operate normally without any protective casing, an enclosure should remain a stretch goal and future consideration rather than a required element of the initial project. With that being said, a PETG outer casing with an acrylic window will be the best option if desired.

3.1.8 LCD

While the overall project is designed to be mainly autonomous, a way to display information is still necessary for convenience and verification. The system will

⁶⁰ "Polycarbonate vs acrylic - learn about the difference between acrylic & polycarbonate material: A&C plastics," Polycarbonate vs Acrylic - Learn about the Difference Between Acrylic & Polycarbonate Material | A&C Plastics, HYPERLINK "<https://www.acplasticsinc.com/informationcenter/r/acrylic-vs-polycarbonate>"

monitor both temperature and humidity levels, but without a display, users would be required to access the microcontroller via an external connection to a computer. This would reduce ease of use and would slow down device testing significantly. So, adding a display would increase testing efficiency and ensure that the sensors are working correctly during device operation.

When determining what type of display would work best for the P.U.T.T.I. system, several screen technologies were considered. These considerations included OLED displays, TFT displays, and LCD displays.

OLED (also known as organic light-emitting diode) displays are known for their great contrast ratios, viewing angles, and thin width. Each pixel in an OLED display emits its own light, meaning that there's no need for a backlight. This allows for much true blacks and more vivid colors to be displayed. While this type of display offers great visual performance, it also has many drawbacks for the current project. OLED displays generally have a higher power consumption than simpler types of displays even while displaying continuously. They also generally have shorter lifespans relative to other display types, making them less reliable. Lastly, they are fairly expensive on average and usually require greater setup time. For a system that only needs a display for humidity and temperature readings, the enhanced visual quality of an OLED display wouldn't justify the added cost⁶¹.

TFT (also known as thin-film transistor) displays are a type of liquid crystal display, using transistors to achieve a full color graphical screen. These are commonly used in devices with high quality user interfaces and many things to display, including mobile phones, monitors, dashboards, etc. These displays can present complex elements like icons and animations, which makes them ideal for devices with dynamic graphics. However, this technology comes with various drawbacks. TFT displays are known for having a high-power demand and much larger data transferring requirements. Using this type of display would require significantly more resources from the microcontroller than necessary, which could interfere with some of its more important tasks. Their additional cost and physical size are also drawbacks. Since the system needs to only display non-complex sensor readings, most of the TFT display's capabilities would go mainly unutilized. Because of this, a TFT display would not fit the scope of the project⁶².

LCD (also known as liquid crystal display) technology provides a much more practical and balanced solution for the P.U.T.T.I. system. Character LCDs have dedicated sections to display one character from a predefined list of characters. They can display simple information efficiently with relatively low power consumption. They are, on average, much less expensive than other display types and are reliable long-term. They interface with almost any microcontroller using common communication protocols, such as I2C. While they lack color and complex graphical capabilities, their simplicity avoids many of the pitfalls of the other display

⁶¹ N. Staff, "OLED vs LCD," Newhaven Display, <https://newhavendisplays.com/blog/oled-vs-lcd/>.

⁶² "TFT LCD," Wikipedia, https://en.wikipedia.org/wiki/TFT_LCD.

types discussed. For these reasons, an LCD display would be the most appropriate choice for presenting information for the P.U.T.T.I. system⁶³.

When selecting a sufficient LCD display for the system, the main specifications of interest are readability, ease of communication, and power efficiency. The display should be big enough and contain enough characters to present both humidity and temperature readings from the sensors. A standard 16x2 character LCD display should be more than enough to accomplish this, though the word “temperature” may need to be abbreviated. The readability is influenced by backlight brightness and contrast, so the display should have a contrast pin and potentiometer to adjust these properties. Since the system is primarily intended for indoor use, an LED backlit LCD with adjustable brightness is preferred.

For communication with the microcontroller, the LCD module should use a simple, well-known interface for data transfer. I2C and SPI are good options that can simplify wiring and reduce pin usage on the microcontroller, though these are not as common and require their own libraries. An LCD module that uses a standard controller would work great too since it allows the microcontroller to write directly to the display, which allows for predictable timing and easier debugging during testing. Given the current design for the P.U.T.T.I. system, the microcontroller should have sufficient I/O pins available, meaning that the additional pin usage and wiring complexity of this type of LCD should not be a major drawback. The display should operate using either 5V or 3.3V (or something close), increasing electrical compatibility with other components, and allowing for easy implementation into the system. Lastly, the module should be low power and cost-effective. Overall, a standard 16x2 LCD module, with a preference for SPI support, that meets the specifications above will provide a balance between efficiency, complexity, and cost.

The first LCD module evaluated is the NHD-0216K1Z-NSW-BBW-L by Newhaven. It's a 16x2 character display that uses a standard parallel interface. It operates on a 5V input supply and, because it's parallel interfacing, it requires 11 pins from the microcontroller. It uses a ST7066U controller and provides a detailed instruction and character table in the datasheet, which would make programming significantly easier. The device's typical input current is about 1 mA, and it includes a 5V LED backlight, which makes providing power easy since it's the same voltage as the input. The module costs \$7.45 on Digikey. So, this LCD is reliable, well-documented, and cost effective, but it requires a high amount of available pins from the microcontroller⁶⁴.

The second LCD module evaluated is the CN0295D by SunFounder. It's a 16x2 character display that uses the I2C protocol. This reduces the number of pins required significantly since only two will be needed for communication. The module uses a 5V input, and its datasheet provides instructions for Arduino and Raspberry Pi control but does not provide an instruction or character table. Since the project

⁶³ “TFT, LCD, and OLED displays: What's the difference, and when does it matter?,” Arkco, <https://www.arkco-sales.com/articles/hmi-tft-lcd-oled>.

⁶⁴ NHD-0216K1Z-NSW-BBW-L Newhaven display intl | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/newhaven-display-intl/NHD-0216K1Z-NSW-BBW-L/1701179>.

will be using a lone microcontroller, this lack of documentation may prove difficult for integration. The CN0295D is priced at \$8.95 on Digikey⁶⁵.

The third LCD module evaluated is the NHD-0216SZ-NSW-BBW-33V3 by Newhaven. This module is identical to the first Newhaven module discussed in every property besides power. It operates using a 3.3V supply and typically draws 1.5 mA of current. The lower voltage provides more efficient power management, but the excessive pin requirement is still the same. This unit is \$14.04 on Digikey, making it about twice as expensive as the first Newhaven module⁶⁶.

The fourth and final LCD module evaluated is the AMC1602AR-B-B6WTDW-SPI by Orient Display. It's a 16x2 character display that uses an AC780S controller. It communicates via a four wire SPI interface, which consists of a serial clock line, serial data line, chip select line, and register select line. This interface is significantly more efficient when it comes to pin usage, using only 4 pins as opposed to the usual 11 pins that a parallel interface uses. This display uses a 5V input with a typical input current of about 1.2 mA, making it a very power efficient option. The datasheet includes both an instruction table and character table, which will make programming very easy. The datasheet also provides a detailed reliability table showing robustness to extreme temperatures, high humidity, and sudden vibrations. This module's price is \$11.21 on Digikey⁶⁷.

Table 10 - LCD Specifications

Parameter	NHD-0216K1Z-NSW-BBW-L	CN0295D	NHD-0216SZ-NSW-BBW-33V3	AMC1602AR-B-B6WTDW-SPI
Manufacturer	Newhaven	SunFounder	Newhaven	Orient Display
Communication interface	Parallel	I2C	Parallel	SPI
Supply voltage	5V	5V	3.3V	5V
Current draw	1 mA	Not given	1.5 mA	1.2 mA
Pin requirement	11 pins	2 pins	11 pins	4 pins
Cost (Digikey)	\$7.45	\$8.95	\$14.04	\$11.21

⁶⁵ CN0295D sunfounder | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/sunfounder/CN0295D/18668612>.

⁶⁶ NHD-0216SZ-NSW-BBW-33V3 Newhaven display intl | optoelectronics | DigiKey, <https://www.digikey.co.uk/en/products/detail/newhaven-display-intl/NHD-0216SZ-NSW-BBW-33V3/2773590>.

⁶⁷ "AMC1602AR-B-B6WTDW-SPI (16X2 character LCD module - SPI interface): Store," Orient Display, <https://www.orientdisplay.com/products/amc1602ar-b-b6wdw-spi-16x2-character-lcd-module-spi-interface/>.

3.1.8.2 LCD Selection

Of the four options evaluated, Orient Display's AMC1602AR-B-B6WTDW-SPI seems to be the most practical choice. While the Newhaven displays are very well-documented and relatively cheap, the high number of pins required would be a waste of important system resources. The SunFounder display is great pin-wise but has poor documentation, making it a poor fit. By contrast, the Orient Display LCD module offers efficient communication via the SPI interface, clear well-written documentation, and has very low power consumption. While its price is slightly higher than some other options, it is the best fit for the scope and requirements of the P.U.T.T.I. system.

3.1.9 3D Filament

The body serves as the main structure of the P.U.T.T.I. system, which will house the SCB and many of the internal components. It needs to be lightweight, rigid, and well suited for different environments, primarily indoors. The main parameter affected by this part is the weight of the project, which should be between two and five kilograms. To meet these requirements, 3D printing was chosen as the primary fabrication technique. 3D printing allows for custom shaping of the body, which is good for unique features like venting heat and cable management. Alternatives were briefly considered, such as laser cutting, but they lack design flexibility, are generally heavier, and more expensive. Additionally, using 3D printing allows for easier redesigning and more iterations if necessary.

Several 3D printing materials were evaluated to determine which would be the best fit for the body, focusing on weight, fabrication ease, and structural integrity. These materials include resin, ABS filament, PLA filament, and PETG filament.

PLA (polylactic acid) is one of the most common 3D printing filaments. It's lightweight and known for its ease of use. It prints at a relatively low temperature (180 – 220 Celsius) and does not tend to warp. PLA is generally one of the cheaper options and is environmentally friendly, which doesn't matter much, but is worth noting. Its primary drawback is its reduced heat resistance compared to other options, but this is not a concern since the project is designed to operate in a room temperature environment and none of the components should generate enough heat to be an issue. This filament is low cost and is a practical choice for early prototype creation.

ABS (acrylonitrile butadiene styrene) is another 3D printing filament. It prints at a higher temperature (230 – 250 Celsius) and is prone to warping. Warping can be avoided by using an enclosed printer, but this makes printing harder since an external printing service would have to be used. This filament is known to be resistant to high temperatures and for higher durability and is mostly used for industrial and mechanical parts. ABS is more expensive than PLA, but it may be worth it for the higher durability, making it a decent choice of filament⁶⁸.

⁶⁸ "Pla vs Abs Filament: Understanding abs vs PLA filament performance," ANYCUBIC, https://store.anycubic.com/blogs/3d-printing-guides/pla-vs-abs-filament?tm=tt&ap=gads&aaid=adaSU7wmdvATJ&utm_source=google&utm_medium=cpc_pmax&ut

PETG (polyethylene terephthalate glycol) was also evaluated as an intermediate between PLA and ABS. It offers high flexibility, resistance to impacts, and high temperature tolerance over PLA while avoiding the warping issues of ABS. Printing with PETG will be slightly heavier than PLA but, depending on the weight of other components, this could work be beneficial to distribute weight. It prints at around the same temperature as ABS (230 – 250 Celsius), but can print without an enclosure and doesn't emit fumes like ABS. PETG has a similar price to ABS, so it's still a little more expensive than PLA. Overall, this filament is a good choice for an end product but may not be the best choice for prototyping⁶⁹⁷⁰.

The final material evaluated was resin, which uses resin printing. Resin printing is capable of a very high level of detail and is usually used for miniatures or model replicas. This method of printing requires additional curing and post-printing chemical use, which makes it even more expensive and time consuming than any other 3D printing material. The resin alone is more expensive than the previous filaments discussed. Also, resin printers are less common and would require a service. So, resin printing would not be the best fit for the project⁷¹.

3.1.9.1 3D Filament Selection

After evaluating the different printing options, PLA stands out as the best choice for prototyping the body of the system. Its low cost and ease of printability make it ideal for prototyping designs. Once the design has been finalized, the filament can be switched to PETG. It offers much higher durability, impact resistance, and temperature resistance while maintaining the ease of printing that PLA exhibits. While PETG is slightly more expensive, the benefits listed above justify its use once the design has been finalized. Overall, using PLA for the project's initial development and PETG for the finished product will provide the best balance between cost and structural integrity.

[m_campaign=us_sales_pmax_k3series_0522&gad_source=1&gad_campaignid=20978953137&gbraid=0AAAAAqsGgB_R84-QMOEeZ7DwHWqhsBHlR&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkQnphRIwoZ3vQLoYrtpXgT1SVkMVPWBuYk9w0P-aOyN4JLZZJS329YaAnOTEALw_wcB](https://www.sliceengineering.com/blogs/news/the-3d-printing-holy-trinity?srsltid=AfmBOorVS0PTX7FLGp3wibpYSXdP-fPAMAJeBDcbOw8vYUtHCRyH8ZsN).

⁶⁹ "The 3D printing holy trinity: Pla, ABS, and petg," Slice Engineering, <https://www.sliceengineering.com/blogs/news/the-3d-printing-holy-trinity?srsltid=AfmBOorVS0PTX7FLGp3wibpYSXdP-fPAMAJeBDcbOw8vYUtHCRyH8ZsN>.

⁷⁰ C. Lim, "Choosing the right filament: PETG, Pla, or ABS?," SOVOL, https://www.sovol3d.com/blogs/news/choosing-the-right-filament-petg-pla-or-abs?source=kang-zero&utm_source=google&utm_medium=search&utm_campaign=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_content=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_matchtype=&utm_network=x&gad_source=1&gad_campaignid=22688845864&gbraid=0AAAAACRod-Oj_mZuqOhYNQg9mrBsyA-R&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRIhDf9ab-SvHjshEhipPMrYt59yy4sNuOE6YTrrglGZq8TaTdsEd8aAIDIEALw_wcB.

⁷¹ A. Alder, "3D printing resin vs filament: Strength, quality & cost," 3D Printing Resin vs Filament: Strength, Quality & Cost, https://4dfiltration.com/resources/3d/resin-vs-filament-strength-quality-cost?gad_source=1&gad_campaignid=15858854285&gbraid=0AAAAAB3Y0gmSAFB4PTyWwThy_5hIZbsgu&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRa4mYjfd7Pv9sTA6ADkgW8T_fNB4PrhKCW7r0zFY7CLFex5N2ERt0aAj3JEALw_wcB.

3.1.10 Microcontroller

The microcontroller acts as the central control element of the P.U.T.T.I. system and is responsible for coordination between all hardware components. It will take readings from the sensors, data from Raspberry PI, process said information, and output to the display, motors, and laser. Since the system is intended for autonomous high-speed tracking, it requires a dependable microcontroller that can process large amounts of data quickly.

One of the most important aspects of the microcontroller is the communication protocols available. The current system design has components that rely on SPI, I2C, UART, and I/O architecture, meaning that the chosen microcontroller must support each of these. Additionally, there should be enough pins which can support each protocol independently such that they can all be used at the same time. Power efficiency is another big consideration, especially since the system will be battery powered. The microcontroller should have high control over the power it requires, remaining low-power and consuming minimal current during idle periods. This will allow the system to run off the battery much longer, working towards the system's long operational lifespan goal. It should also operate using a power supply of either 3.3V or 5V, which would make it electrically compatible with other components, simplifying PCB wiring.

Memory capacity (Flash memory and RAM) was also considered. The microcontroller should have enough memory to store any necessary firmware and also any required data history from the camera and radar subsystems, which may be required for projectile tracking. Another important aspect to consider is the clock speed of the microcontroller. The P.U.T.T.I. system's purpose is to track thrown projectiles which can vary in speed, but could reach up to a few meters in less than a second. This speed requires a microcontroller with a high enough clock speed to take data from the camera subsystem, activate the sectors respective radar, take the radar data, process that data, and provide the projectile pathing to the motors in order to track it with the laser. Not to mention that the temperature and humidity readings from the sensors need to be checked at the same time.

The final aspect to take into account when choosing a microcontroller is connectivity features such as Wi-Fi and Bluetooth. These features could speed up testing and updating by allowing us to remotely access data and code without physically hooking up a computer to the microcontroller. However, this is not required for the system to operate, so the inclusion of these features should be viewed more as an added benefit instead of a requirement. Overall, the ideal microcontroller for the project should have sufficient computational capability and speed, be power efficient, and allow for the simultaneous use of SPI, I2C, UART, and I/O pins.

The first microcontroller evaluated is the PIC18F46K22 by Microchip. It operates between 2.3V and 5.5V, which allows it to interface at 3.3V or 5V. It supports SPI, I2C, has two USART channels, and allows for easy PWM implementation, making it compatible with all other components used in the system. It has upwards of 35 I/O pins. The microcontroller has 64 kB of flash memory and 3.8 kB of SRAM, meaning it can handle large code bases but might struggle with high amounts of

real-time data. With an internal 16 MHz clock (which can be boosted to 64 MHz using a PLL) this microcontroller provides a solid speed for the project's purpose. Additionally, the microchip has an idle mode in which the CPU shuts down while peripherals are still monitored, which allows for power efficiency when no projectiles are detected. This microcontroller costs \$4.34 on Digikey⁷².

The second microcontroller evaluated is the ATmega328P by Microchip. This chip is what the Arduino Uno uses and represents a robust 8-bit option. It supports I2C, SPI, and one USART channel, with up to 23 I/O pins, meeting all of the communication goals. It operates on a supply between 2.7V and 5.5V and has six different sleep modes. The most notable one is the idle mode, which works similarly to the previous microcontroller, turning off the CPU while monitoring inputs from the peripherals. It can run up to 16 MHz using the internal clock, offers 32 kB of flash memory, and 2 kB of SRAM, which allows for simple control systems that don't require too much data storage. While it's known for its reliability, its processing and memory capabilities are relatively limited. This microchip can be found on Digikey at \$2.89 per unit⁷³.

The third microcontroller evaluated was the STM32F103C8T6 from STMicroelectronics. This chip is the most powerful chip evaluated using a 32-bit ARM Cortex-M4 core. It has a flash memory of 64 kB and 20 kB of SRAM, allowing for a large amount of code and significantly more storage than the previous two microcontrollers discussed. It operates at 3.3V, contains a 16 MHz oscillator, and it supports multiple communication protocols, including two I2C routes, three USART channels, two SPI ports, and up to 37 I/O pins. This allows for a lot of flexibility when it comes to connecting multiple peripherals simultaneously, but would be overkill when it comes to the component requirements of the P.U.T.T.I. system. Like the other microcontrollers, this one has a sleep mode function that will improve power efficiency. This microcontroller is \$6.08 on Digikey, representing the most expensive option per unit⁷⁴.

The fourth and final microcontroller evaluated was ESP32-WROOM-32 developer module by Espressif Systems. It operates at 3.3V, has 520 kB of SRAM (with 8 kB in RTC memory), and has 4 MB of flash memory. Because of this, the ESP32 has significantly better storage capabilities than that of the other three previously discussed, which would benefit the project. The module contains a dual processor with a 40 MHz crystal oscillator, which is more than fast enough for the goals of the P.U.T.T.I. system. It supports SPI, I2C, 2 USART channels, up to 32 general purpose I/O pins, and allows for easy implementation of PWM communication. The microcontroller also has a low power mode that works the same as the other three chips, which will improve power efficiency. Additionally, this module comes with built-in Wi-Fi and Bluetooth, which would allow for wireless access to the system's

⁷² PIC18F46K22-I/P microchip technology | integrated circuits (ICS) | digikey,
<https://www.digikey.com/en/products/detail/microchip-technology/PIC18F46K22-I-P/2480375?msocid=2c71e9962a8d6eb016a8fe32bd46f5a>.

⁷³ ATMEGA328P-pu Microchip Technology | Integrated Circuits (ICS) | digikey,
<https://www.digikey.com/en/products/detail/microchip-technology/ATMEGA328P-PU/1914589>.

⁷⁴ STM32F103C8T6 stmicroelectronics | integrated circuits (ICS) | digikey,
<https://www.digikey.com/en/products/detail/stmicroelectronics/STM32F103C8T6/1646338>.

code and data, saving time when testing. Even without using the wireless options, this module comes with a simple USB-C port, allowing for direct connection from a computer to the chip. The ESP32 module can be found on Amazon for \$15.99 for three (so \$5.33 per unit)⁷⁵.

Table 11 - Microcontroller Specifications

Parameter	PIC18F46K22	ATmega328P	STM32F103C8T6	ESP32-WROOM-32
Clock Speed	16 MHz (64 MHz with PLL)	16 MHz	16 MHz	40 MHz
SRAM	3.8 kB	2 kB	20 kB	520 kB (8 kB RTC)
Flash Memory	64 kB	32 kB	64 kB	4 MB
Operating Voltage	2.3V - 5.5V	2.7V - 5.5V	3.3V	3.3V
GPIO Pins	Up to 35	Up to 23	Up to 37	Up to 32
Interfaces	2 UART, I2C, SPI	UART, I2C, SPI	3 UART, 2 I2C, 2 SPI	2 UART, I2C, SPI
Price (Digikey)	4.34	2.89	6.08	5.33

3.1.10.2 Microcontroller Selection

While the PIC18F46K22, ATmega328P, and STM32F103C8T6 each have solid capabilities, the ESP32 stands out as the best choice of microcontroller. The PIC18F46K22 is very similar to the ESP32 with its communication protocol support, but it lacks the ease of code modification since it's missing the USB-C port and wireless features. It also has significantly less SRAM, making it less suited for data collection and processing. The ATmega328P has similar issues to the PIC18F46K22, but has even less SRAM. The STM32F103C8T6 offers better performance using a 32-bit core processor and greater memory than the other two options, but it still lacks the computer connection ease of the ESP32 and may be overqualified. Knowing the design requirements of the project and how many pins/protocols are needed, many of the qualities of this microcontroller would go un-utilized if chosen. In contrast to these three controllers, the ESP32 provides a good balance of processing power, memory, and communication protocol support, all with built-in Wi-Fi and Bluetooth. When compared to the requirements of the system, 1 – 2 UART channels, SPI, I2C, and at least ten open general purpose I/O

⁷⁵ ESPRESSIF documentation, https://documentation.espressif.com/esp32-wroom-32_datasheet_en.pdf?utm_source.

pins, it matches well, even providing easy PWM implementation for controlling the motors. Overall, the ESP32 module is the best choice for the central microcontroller of the P.U.T.T.I. system.

3.1.11 Voltage Regulator

The P.U.T.T.I has many devices with varying different required input voltages, and as such voltage regulation will be needed for this project. Voltage regulation means the ability to maintain a stable and constant voltage for the various components that exist for our project. This is important for multiple reasons, but there are at least three worthy to note. The first is to make sure that every component is receiving the correct amount of voltage that is required, and the second is to ensure that components aren't damaged because of too much voltage being applied. Finally, one last reason is to assure that there aren't as many fluctuations as possible in voltage for some devices that may be more sensitive to changes in the value of the voltage being applied to them. Voltage regulation basically acts as a safety net for the voltage in the project, ensuring a constant stream of voltage is being supplied where it needs to be. Below is a table that has a list of the components required for our project, and what voltage values are needed for them to work properly.

Table 12 - Power Table

Component	Supply Voltage Needed	Maximum Current Draw	Maximum Power Required
MCU	3.3V	300mA	1.2W
Motors	4.8V ~ 8.4V	5A	25W
Microwave Module	1.8V	10mA	3.12mW
SBC	5V	2.37A	25W
LCD	5V	1.2mA	8.25mW
Camera	3.3V	250mA	1W
Humidity Sensor	3.1V ~ 5.5V	1.5mA	4.75mW
Temperature Sensor	3.0V ~ 5.5V	1.34mA	18mW
Buzzer	2.0V ~ 5.0V	30mA	90mW
Laser	2.8V ~ 5.2V	25mA	5mW

From the table it's easy to see that there are two different supply voltages needed for our project. First, we need 5V being supplied to the LCD and SBC. Then, 3.3V is needed for the microwave module, camera, humidity sensor, and MCU. To properly supply the voltage needed for each of these components, we should look at the different types of regulators that exist and compare their differences to see which one best suit the need for our project. There are two known voltage

regulators, that being the linear and switching regulators which is further discussed below⁷⁶..

First, there is the linear regulator, which is one of the voltage regulator types which could help ensure that the voltage being supplied to our components on the PCB. Linear regulators, for the most part, are step-down converters which produce a lower output voltage compared to the input. They are known for being simple, cost-efficient, and reliable, which makes them a great candidate for our project. The other big upside to using a linear regulator is they provide very low-noise power, which could be important for components that are sensitive to noise. There are some downsides to using the linear regulator. The first is the inefficiencies that tend to arise by using them, as to get rid of excess voltage what the regulator will do is dissipate it as heat, which is very unideal when dealing with input and output voltages that have a wide gap between them as a lot of heat would then be generated. This excess heat and power consumption could lead to issues in our system if power efficiency is ever a concern. Also, because they are for the most part step-down converters, that means they cannot step up voltage as that goes against their design. Finally, for the sake of PCB design linear regulators tend to be bigger than switching regulators which is of course a down side as it is ideal to take up the least amount of space on the board to allow for more components on the board and to give them space for the sake of if noise ever ends up being an issue (as well as it could be an issue depending on the physical size of our project). As previously mentioned, they are great at providing stable power which still makes them a worthy candidate.

Lastly, it's important to note the different forms of linear regulators, being the series and shunt regulators. A series regulator does as its name suggests, placing the variable element (such as a transistor) in series with the load. The constant output voltage is therefore achieved by varying the resistance of the series element. Then, there is the shunt regulator, which has its variable element (again such as a transistor) connected in parallel with the load. Additionally, the shunt resistor has a limiting resistor connected in series with the load, which is important as to maintain the constant voltage across the load, the current must be drawn through the resistor in series. The series regulator is more efficient than the shunt voltage regulator, however, has a more complicated design than the shunt regulator. Shunt regulators tend to be used in very low-powered circuits where wasted current is small (such as a voltage reference circuit), while series regulators are typically used in power supply applications. Additionally, one very common type of series regulator is the low dropout (LDO). The LDO is a DC linear regulator which regulates the voltage even when the supplied voltage is very close to the output voltage, which makes it valuable for the sake of battery life for our P.U.T.T.I⁷⁷.

⁷⁶ "What Are the Types of Voltage Regulators and How Do They Work?" *EP Power*. Available: <https://ep-power.com/what-are-the-types-of-voltage-regulators-and-how-do-they-work>

⁷⁷ "Linear Voltage Regulator: Circuit, Types & Applications," *How2Electronics*. Available: <https://how2electronics.com/linear-voltage-regulator-circuit-types-applications>

The other main type of voltage regulator is the switching regulator which also ensures the stability and efficiency of the PCB for the components which require varying input voltages. The switching regulator works by rapidly switching the series element (usually a field effect transistor, or FET for short), on and off by a switching controller IC which will monitor the output of the switching regulator in a feedback control loop. This ensures that the output is constant under normal operating conditions. This gets into one of the main advantages of the switching regulator compared to the linear regulator, which is the efficiency is much better with these kinds of regulators, especially when dealing with input and output voltages that have a wide gap between them. Next, because less energy is lost in the transfer, this also means less heat is produced from the component. Finally, unlike a linear regulator which can only be step down, the switching regulator can also be a step up in addition to also being step down. There are some downsides to these regulators with the first being that they tend to be noisy compared to their linear regulator counterpart, but this could of course be mitigated by using proper PCB layout techniques and filters, but this leads to the second downfall of the switching regulator which is it is much more complicated than the linear regulator, requiring more complex PCB designs to get it to work properly. With that being said, the upside of being much more efficient and having the flexibility of being step up or down is not to be overlooked, and would be a good choice for the P.U.T.T.I to ensure all components receive the correct amount of voltage whilst optimizing power usage⁷⁸.

Next, similar to the linear regulator, there are a few different types of switching regulators, those being the buck, boost, buck-boost, and inverting regulators. A buck converter steps down the input voltage like a linear regulator but does so using the switching method described above. The boost converter, in contrast, steps up the input voltage. Then, there's the buck-boost converter which can both step up and step down the voltage (depending on what is needed). Finally, there's the inverting regulator which as the name suggests inverts the voltage turning the positive voltage into a negative one. Each converter has a purpose, and it's important to keep in mind what we want the converter to do in our circuit⁷⁹.

3.1.11.2 Voltage Regulator Selection

Since there are multiple different input voltages required for our project, there will be multiple different regulators required for our project. Since our two main input voltages are 5V and 3.3V, it would make sense to go for the switching regulator for both options as they will be highly efficient when stepping down high input voltages, they will generate low heat, and will minimize our power loss which could be important for other components within our project. We will also need a 1.8V regulator as there is one component that requires that voltage, and for that

⁷⁸ "Switching Regulator Definition," *Analog Devices*. Available:

https://www.analog.com/en/resources/glossary/switching_regulator.html

⁷⁹ "Buck, Boost, and Other DC-DC Converters Explained," *TDK Lambda Americas*. Available:

<https://www.us.lambda.tdk.com/resources/blogs/20200731.html>

regulator we will go with a linear regulator as they provide very stable power, which is important for smaller components like our microwave module. From the research that was conducted these regulators are ideal for dealing with power critical systems such as our own as there are many components that require power including the camera, microwave module, and various other sensors within the P.U.T.T.I. Below we will now discuss picking out different switching regulators for both the 3.3V and 5V inputs that are required for our project to function⁸⁰..

First, we have the AP64502SP-13, which is an efficient, synchronous buck converter, which will be able to provide the 3.3V output to the varying components mentioned above. The input voltage ranges from 3.8V to 40V, which should make it compatible with our power source. The varying inputs it can receive is desirable as the power requirements could change due to what is available, and whatever is in stock. The regulator delivers up to 5A of continuous current which will be important for powering all of our different devices. Additionally, this device has a very efficiency of the range between 90-95%, which will help tremendously reduce power loss and letting the P.U.T.T.I operate for long periods of time which is important for keeping military personnel safe. Operating at a 500 kHz switching frequency, the AP64502SP-13 provides a fast transient response and low output voltage ripple, ensuring consistent and clean power for sensitive electronics. It also integrates key protection features such as overcurrent, short-circuit, over-temperature, and undervoltage protection, safeguarding both the converter and connected devices under demanding conditions. Furthermore, the soft-start function mitigates high inrush currents during power-up, protecting the overall power system. Finally, its compact 8-SO-EP package makes it ideal for weight- and space-sensitive designs, perfectly aligning with the needs of our P.U.T.T.I platform⁸¹.

The TPS54531DDAR is also a high-performance, synchronous buck converter designed to deliver a stable 3.3 V output for our P.U.T.T.I's electronics. With an input voltage that can range from 3.5 V up to 28 V, it'll be able to support a wide variety of battery configurations and ensure our PCB design remains constant even as the supply or component set-up increases. This IC supports up to 5 A continuous output current, which gives ample headroom for powering multiple subsystems such as the camera, sensors, and motors. It operates at a fixed switching frequency of ~570 kHz, allowing a fast transient response and low output ripple which is essential for noise-sensitive logic and camera electronics. Key protection features include cycle-by-cycle current limiting, frequency fold-back, thermal shutdown, and over-voltage transient protection, enhancing robustness in aerial applications. A soft-start capability allows controlled ramp-up and mitigates inrush current on startup. The compact SO-8 Power PAD package facilitates efficient thermal dissipation and suits the space- and weight-sensitive environment

⁸⁰ "Linear vs. Switching Regulators," *Renesas Electronics*. Available:

<https://www.renesas.com/en/products/power-management/linear-vs-switching-regulators>

⁸¹ "AP64502SP-13 – Diodes Incorporated," *Digi-Key Electronics*. Available:

<https://www.digikey.com/en/products/detail/diodes-incorporated/AP64502SP-13/15286693>

of our P.U.T.T.I.'s design. Compared with the earlier AP64501SP-13 you considered, while both support flexible battery input ranges and high output current, the TPS54531DDAR is optimized for somewhat lower maximum input voltage (28 V vs up to 40 V) but still meets the continuous 5 A requirement making it a strong fit if your battery rail remains under that 28 V threshold⁸².

The RT6285GSP is a versatile, asynchronous step-down (buck) converter from Richtek Technology Corporation. engineered to deliver a stable 3.3 V output for our P.U.T.T.I.'s logic and sensor subsystems. It accepts an input voltage range from 5.5 V to 30 V, making it compatible with common LiPo battery configurations (such as 2S through 6S) and ensuring that our PCB architecture remains consistent even if the battery pack or supporting electronics change as we need more components for the project. The device supports up to 5 A of continuous output current, which provides strong headroom for powering multiple subsystems simultaneously. Operating at a fixed switching frequency of 500 kHz, it delivers a fast transient response and low output ripple which is important for maintaining reliable performance of sensitive electronics. Some key protection features include cycle-by-cycle over-current limiting, thermal shutdown, undervoltage lock-out, and an internal soft-start mechanism to limit inrush current on startup. It comes in an SOP-8 package with an exposed pad, facilitating effective thermal dissipation while keeping size minimal which is ideal for our weight and space sensitive P.U.T.T.I. Compared to the earlier converter we looked at (for example the AP64502SP-13), while both support 5 A output and are suitable for 3.3 V or 5 V rails, the RT6285GSP uses an asynchronous (diode-based) approach rather than fully synchronous MOSFETs, and its input upper limit is 30 V (versus some others reaching 40 V) — making it slightly less flexible for very high-voltage battery configurations but still extremely well suited for typical robotics⁸³.

The S-13D1B1218-M6T1U3 is a very efficient low-dropout (LDO) linear voltage regulator, designed to provide a precise and stable 1.2 V or 1.8 V output for sensitive components in the P.U.T.T.I.'s microwave module. This LDO is able to support an input voltage range up to 5.5V. Unlike switching converters, the S-13D1B1218-M6T1U3 operates quietly, producing minimal electromagnetic interference, which is an important advantage when dealing with sensitive components where noise matters. The LDO can deliver up to 150 mA of output current, and with features including its optimization for efficiency and thermal stability under moderate loads, built-in overcurrent protection, thermal shutdown, and output short-circuit safeguards, all of which will ensure nothing bad happens to the microwave module. Thanks to its compact SOT-23-6 package, the regulator offers an easy-to-mount, thermally capable solution for PCB designs that prioritize simplicity and reliability⁸⁴.

⁸² "TPS54531DDAR – Texas Instruments," *Digi-Key Electronics*. Available:

<https://www.digikey.com/en/products/detail/texas-instruments/TPS54531DDAR/4162425>

⁸³ "RT6285GSP – Richtek USA Inc.," *Digi-Key Electronics*. Available:

<https://www.digikey.com/en/products/detail/richtek-usa-inc/RT6285GSP/16376754>

⁸⁴ Digi-Key Electronics, "S-13D1B1218-M6T1U3 – ABLIC Inc.," Available:

<https://www.digikey.com/en/products/detail/ablic-inc/S-13D1B1218-M6T1U3/6117298>

Next, we have the NCP1117IST18T3G, which is another reliable low-dropout (LDO) linear voltage regulator, designed to provide a consistent and regulated 1.8V output for the P.U.T.T.I.'s microwave module. This LDO is capable of supporting a wide input voltage range of up to 20 V, allowing it to easily regulate higher supply voltages down to the required 1.8 V level. Like the S-13D1B1218-M6T1U3, the NCP1117IST18T3G functions as a linear regulator, meaning it operates quietly and produces very little electrical noise, making it particularly useful in environments where sensitive electronic signals must remain clean and undistorted. The device can deliver up to 1 A of output current, which makes it suitable for powering more demanding sections of the system. In addition, the LDO has a built-in current limiting and thermal shutdown protection which helps prevent overheating or damage caused by excessive current draw. Additionally, this LDO offers improved heat dissipation and a mechanically stable design that supports reliable long-term operation on a printed circuit board whilst being housed in a SOT-223 package⁸⁵.

Finally, there is the TLV1117-18, which is a very stable low-dropout (LDO) linear voltage regulator, developed to supply a steady 1.8 V output to the microwave module on the P.U.T.T.I. This regulator can accept input voltages of up to 15 V, and like the other LDOs used in the system, it provides smooth, low-noise voltage regulation that is ideal for sensitive circuitry found within the microwave module. The TLV1117-18 is capable of delivering up to 1 A of output current, ensuring that even components with higher current requirements are able to receive sufficient, consistent power (like that of the NCP1117IST18T3G). Some of its features are it has built-in overcurrent protection, thermal shutdown, and short-circuit protection which all play an important part in maintaining the overall safety and reliability of the system. Also like the NCP1117IST18T3G, it is store in a SOT-223 form factor, making it have a strong thermal performance and easy integration into compact PCB layouts where space and stability are key design considerations⁸⁶.

Table 13 - Switching Regulator Specifications

Criteria	AP64502SP-13	TPS54531DDAR	RT6285GSP
Input Voltage Range	3.8V to 40V	3.5V to 28V	5.5V to 30V
Output Voltage	0.8V to 40V	0.8V to 26.04V	0.8V to 24V

⁸⁵ "Brushless vs. Brushed DC Motors," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors>

⁸⁶ "Brushless vs. Brushed DC Motors," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors>

Max Output Current	5A	5A	5A
Efficiency	Up to 90%	Up to 92%	Up to 90%
Switching Frequency	100 kHz to 2.2 Mhz (typically 500 kHz)	570 kHz	500 kHz
Protection Features	UVLO, OVP, cycle-by-cycle current limit, thermal shutdown	UVLO, OVP, thermal shutdown, current limit	Cycle-by-cycle over-current limit, thermal shutdown, soft-start
Cost	\$2.09	\$2.04	\$0.84

Table 14 - LDO Regulator Specifications

Criteria	S-13D1B1218-M6T1U3	NCP1117IST18T3G	TLV1117-18IDCYRG3
Input Voltage Range	1.5V to 5.5V	20V	2.7V to 15V
Output Voltage	1.2V to 1.8V	1.8V	1.8V
Max Output Current	150mA	1A	1A
Protection Features	Output current protection, thermal shutdown	Current limiting, thermal shutdown protection	Thermal shutdown, current limit, undervoltage lockout (UVLO) in some versions
Cost	\$0.72	\$0.46	\$0.67

3.1.11.4 3.3V Switching Regulator Product Selection

We carefully considered several voltage regulator options before deciding on the AP64502SP-13 for our P.U.T.T.I. project. This was done as the AP64502SP-13 matches the requirements that we want for our project. The AP64502SP-13 offers

the best balance of flexibility, protection, and efficiency, even though other regulators have their own benefits. Although regulators with smaller input voltage ranges might work well, future flexibility and battery choice are constrained by their incapacity to manage higher input voltages. In contrast, applications using up to 12S LiPo batteries are best suited for the AP64502SP-13's broad 3.8 V–40 V input range, which allows for future design changes or power system enhancements. Additionally, its integrated protection features, which include but are not limited to overcurrent, short-circuit, and thermal shutdown ensure reliable and safe operation even under demanding or high-temperature environments, contributing to the overall robustness and longevity of the system.

3.1.11.5 5V Switching Regulator Selection

Since the AP64502SP-13 can also function for higher input voltages, we have also decided to use the same switching regulator for the 5V inputs as well. By using the same regulator, we can simplify our design, ensuring that there is a uniform voltage regulation which will help reduce the risk of component incompatibility. This will save us time as well as we won't have to spend more time testing multiple different regulators and instead, we can just test the one. The voltage input range which can vary up to 40V and reliability for 3.3V and 5V outputs will make for an efficient choice of delivering power.

3.1.11.6 1.8V Linear Regulator Selection

Of these linear voltage regulator options, we decided to go with the NCP1117 for our LDO for the P.U.T.T.I. project. This decision was made because the NCP1117 gives us all the things we would want from our LDO, in particular its high input voltage range and low cost, as compared to the other linear regulators. Whilst the other regulators offer certain advantages, the NCP1117 provides the most practical combination of voltage tolerance, availability, and ease of implementation. Devices with more limited input voltage ratings may perform adequately in lower-voltage systems; however, their restricted operating range would significantly limit future design flexibility. In comparison, the NCP1117 is well-suited for systems operating from a 14 V supply, as it can safely accept input voltages of up to 20 V without risk of failure. Furthermore, its internal protection mechanisms, including current limiting and thermal shutdown, contribute to a safer and more dependable operation under varying loads and temperature conditions, ultimately supporting the overall durability and reliability of the system.

3.1.12 Motors

Motors will be used in this project to provide the P.U.T.T.I with the pan-and-tilt range necessary to both observe and engage any projectile that enters its field of view. Since our objective is to be accurate and be able to track and intercept objects in real-time, the selected motors must deliver sufficient torque, low backlash, and fine positional resolution to maintain a stable aim under motion and vibration. Reliable stability and precise closed-loop control ensure the camera stays locked on fast-moving targets and that the countermeasure (e.g.,

compressed-air interceptor or targeting laser) is aligned now of deployment, minimizing the risk of a missed engagement.

Our first motor option is brushed DC motors. The motor windings, which generate torque and power the rotor and propellers, receive electricity from brushes. Brushed DC motors' primary benefit is their ease of use. These motors are great for our P.U.T.T.I because they are well-known and simple to construct. The ease of use would free us up to focus on other crucial aspects of the P.U.T.T.I, such as the YOLO algorithm or radar, rather than motor design. Furthermore, brushed DC motors are easily customizable to the limitations of our project because they are widely available in a range of sizes and power ratings, meaning finding the one we would need for our project should be simple. These motors do have a few drawbacks, though. The brushes can experience wear and tear over time, reducing efficiency and potentially needing replacing after short periods of time. Additionally, since there is a physical contact, electrical noise is introduced which can further limit the motors lifespan. However, since in our project we are only using the motor to pan and tilt our camera, this remains as a great budget option.

Our second motor option is brushless DC motors (abbreviated to BLDC). These motors work on the same principle of magnetic attraction and repulsion as brushed DC motors, but instead of using physical brushes and a commutator, they use electronic commutation to send current through the stator windings. This design gets rid of the mechanical contacts that brushed DC motors have, which makes them run more smoothly and quietly and last much longer. Brushless DC motors are great for our P.U.T.T.I because they are reliable and precise. This is very important to us because we need to make sure that the laser can line up with anything that is thrown into the camera's field of view. Since they do not suffer from brush wear, they require little to no maintenance, making them a dependable option for accurate and consistent camera movement. Better tracking and aiming accuracy when detecting and targeting projectiles is made possible by the motor's ability to react more smoothly to commands from our control system due to its increased efficiency and decreased electrical noise. Brushless DC motors do have certain disadvantages, though. To manage motor commutation, they need extra electronic components, which complicates the design and raises costs. This is important because we want to use our money for more crucial items like the camera and SBC. To get the best performance, the control circuitry also needs to be precisely adjusted. Despite these challenges, the performance benefits of brushless DC motors, such as their speed, accuracy, and longevity, make them a strong candidate for future iterations of our P.U.T.T.I system where precision and reliability will be critical⁸⁷.

Coreless DC motors are our third motor choice. Despite not having an iron core in the rotor, these motors function similarly to conventional brushed DC motors. The motor can accelerate and decelerate nearly instantaneously because of its

⁸⁷ "Brushless vs. Brushed DC Motors," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors>

extremely low rotational inertia. The coreless motors can provide smooth and precise control, which is ideal for the quick, fine adjustments needed to track fast-moving projectiles, making them a great choice for our P.U.T.T.I. Additionally, by lowering the total load on the servo assembly, their lightweight design would enhance responsiveness and lower power usage. They are generally more expensive to produce and can be more fragile due to their delicate winding structure. Additionally, they tend to generate more heat under heavy loads, which could potentially limit their use in high-power applications. Despite these limitations, their speed, precision, and low inertia make coreless DC motors a compelling option for camera movement and target tracking, where fine motion control is a priority⁸⁸.

As the name implies, the primary characteristic of a stepper motor is that its shaft rotates in predetermined "steps." This precise movement is made possible by the internal structure of the motor, which eliminates the need for an external sensor or feedback mechanism by enabling the precise angular position to be ascertained by counting the number of steps completed. Since stepper motors are inherently precise and repeatable, they are ideal for our P.U.T.T.I. The camera can be precisely positioned to track or scan regions of interest because it can move in controlled, incremental steps. When spotting or interacting with moving projectiles, this degree of positional control is useful for preserving steady aim and scanning patterns. They can make noise at certain higher operating speeds due to their step-based motion, and they typically lose torque as rotational speed increases. Additionally, they are not as energy efficient as brushless motors during continuous movement. With that being said, the accuracy, simplicity, and sensor-free position control of stepper motors make them a strong and reliable option for controlled camera movement in our P.U.T.T.I.⁸⁹.

There are many important factors to consider when selecting a motor for the P.U.T.T.I. system, as these motors are responsible for panning and tilting both the camera and laser assembly. The weight of the motor must be carefully considered, since heavier motors could add unnecessary strain to the mounting mechanism and reduce responsiveness during operation. Power consumption is also crucial, as lower power consumption helps maintain overall system stability and ensures longer operational time without excessive energy draw. In addition, the torque output and control precision determine how smoothly and accurately the camera can move, directly impacting the system's tracking and targeting performance. The motor's speed control is equally important, as it will allow for quick and accurate adjustments when following a moving subject or repositioning the laser. Durability and maintenance requirements must also be considered, since the motors will be in frequent motion and need to perform reliably over extended periods of use in the field. Finally, cost and availability are practical considerations, as the chosen

⁸⁸ "Stepper Motors: Basics, Types, and Uses," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/stepper-motors-basics-types-uses>

⁸⁹ "What is a Coreless DC Motor and How Does It Work?" *Telco Intercon*. Available: <https://www.telcointercon.com/blog/what-is-a-coreless-dc-motor-and-how-dose-it-work>

motor should balance performance, reliability, and affordability to align with the overall goals and constraints of the P.U.T.T.I project.

Table 15 - Motor Type Specifications

Criteria	Brushed	Brushless	Coreless	Stepper
Weight	Moderate	Moderate	Low	High
Power Consumption	High	Low	Low	Moderate
Torque Output	Moderate	High	Moderate	Very High
Speed Control	Moderate	Very High	High	High
Smoothness of Motion	Moderate	High	High	Low
Precision	Moderate	High	High	Very High
Durability	Moderate	Very High	Moderate	High
Maintenance	High	Low	Moderate	Low
Cost	Low	High	High	Moderate

3.1.12.2 Motor Type Selection

From the table, after considering what we value most in a motor, we have decided to go for the BLDC for the P.U.T.T.I. For our project, one of the most important aspects is that the motor has a high level of precision alongside a high level of movement to ensure that whatever the P.U.T.T.I is trying to track is being tracked accurately so that way the camera and laser are always hitting the target (or at the very least much more likely too). Additionally, being able to quickly and efficiently pan over to the target is also ideal. If we compare those three standards to the rest of the motors that we have looked at, it's easy to eliminate the other options. Brushed motors overall just don't compete with brushless motors besides their costs, otherwise having downside. Coreless, while being very close in terms of

performance to brushless, just fall short in comparison to the BLDC as their maintenance and durability fall short of the BLDC. Finally, stepper motors due to their design in moving in short bursts wouldn't be ideal as we want the motor motion to be smooth and fluid, not rigid. The brushless DC motors give us almost everything we would want from a motor: they have a high or very high level of torque, speed control, precision, and smoothness of motion all of which are crucial to making sure the laser and camera can accurately get to its target. The BLDC has low maintenance alongside a high level of durability which is also necessary for ensuring that the P.U.T.T.I is functional for long periods of time outside keeping its operatives safe. While the BLDC may have a higher cost, this cost can be justified by how valuable the other aspects of the project are.

The INJORA INJS235 35 KG Waterproof BLDC Servo is a servo that's rated at up to 35 kg·cm stall torque at 8.4 V, meaning it delivers a strong mechanical output that's well suited for heavy-duty actuation tasks. It uses a BLDC motor paired with full metal gears and dual ball bearings, which translates to smoother operation, longer life, and less maintenance compared to brushed alternatives. The servo supports a voltage range of 4.8 V to 8.4 V, meaning it's compatible with typical robotic power systems and gives some headroom for higher voltages. The servo comes with a waterproof casing that improves durability in field conditions, making this component robust for outdoor deployment. This motor weighs the most and is the largest out of all the motors, weighing in at 85 g and coming in a size of 63 x 38 x 54. However, it makes up for this weight gain by having a greater stall torque and speed, the torque being significantly greater than the other two motors. Altogether, it offers a strong mix of torque, build quality, and durability which makes it a solid candidate for mounting the P.U.T.T.I's camera giving it the ability to pan and tilt while being accurate and being on target⁹⁰.

The MEUS Racing Brushless High-Torque Micro Servo provides a compact but surprisingly strong solution for our P.U.T.T.I system actuators. It runs from about 4.8 V up to 8.4 V, just like the INJORA. At the higher end of that voltage range, it can deliver up to 12.5 kg·cm of torque, which is less than that of the INJORA. However, it would still likely be enough to support both the weight of the camera and laser. The brushless motor and metal gear train mean smoother, quieter, and more durable operation, which will be necessary if the P.U.T.T.I is to function properly as precision is a must. At only 21.6 g and being approximately 23 × 12 × 27 mm, it's lightweight enough not to upset the balance or add excessive mass to our system. Its 180°+10° travel angle gives us good flexibility in how we mount it. The biggest tradeoff here is since it's a compact micro servo, for very large loads we'd still check the torque/gear ratios carefully—but for the targeting and sensor adjustments in P.U.T.T.I it's a smart, efficient choice⁹¹.

⁹⁰ "INJORA INJS235 35KG Waterproof Brushless Servo Large Torque Digital Servo," *INJORA*. Available: <https://www.injora.com/products/injora-injs235-35kg-waterproof-brushless-servo-large-torque-digital-servo>

⁹¹ "Brushless High Torque Micro Servo," *MEUS Racing*. Available: <https://www.meusracing.com/products/brushless-high-torque-micro-servo-us-warehouse>

The Power HD M8 brushless servo offers a compact and capable solution for our P.U.T.T.I system's panning and tilting. It has an operating voltage range from 4.8 V to 8.4 V like the other two motors, and a stall torque of approximately 8.5 kg·cm at 8.4 V, this being the lowest stall torque of the motors. It provides enough force for precise movement of the small camera and laser without being oversized. The unit weighs just 28.6 g and measures about 28.5 × 13.4 × 29.0 mm, which means it won't add much to our system's weight or bulk. It also features high-quality gears and a BLDC motor core, contributing to quieter, smoother, and more reliable operation over time. While this servo may not have advanced I/O feedback features, its combination of torque, low weight, compact form factor, and affordability make it a strong candidate for a movement module in P.U.T.T.I where precision and minimal weight are key⁹².

Table 16 - Motor Specifications

Criteria	INJORA	MEUS	M8 Brushless Servo
Voltage (V)	4.8 - 8.4	4.8 - 8.4	4.8 - 8.4
Torque	35	8.5 - 12.5	8.5
(kg*cm @8.4V)			
Speed (s/60°)	0.07	0.058	0.058
Size (mm)	63 x 38 x 54	23 x 12 x 27	28.5 x 13.4 x 29.0
Weight (g)	85	22.1	28.6
Waterproof Rating	Yes (IP67 rated)	Partial (splash-resistant)	Likely splash-resistant
Cost	\$35.00	\$61.00	\$60.00

3.1.12.4 Motor Product Selection

Looking at the table, it's clear to see who our winner is. Although it may be bulkier than the other two motors, the INJORA more than makes up for that fact with its cost, torque, and speed which makes it an easy pick. In addition to it being superior in terms of strength, it also has the added upside of being completely waterproof, which could be a big deal if the P.U.T.T.I were to be ever deployed outdoors. If we

⁹² "Power HD M8 Brushless Servo 0.068sec/7.6kg," *Dollar Hobbyz*. Available: <https://www.dollarhobbyz.com/products/m8-brushless-servo-0-68sec-7-6kg>

look past the numbers in the table above, the INJORA stands out for its overall reliability and build quality as it's designed to handle stress without sacrificing precision. Its brushless design gives it a smoother motion over long periods of use. This combination of power, durability, and affordability makes the INJORA not just the most practical choice on paper, but also the most dependable option for consistent performance in real-world conditions.

3.1.13 Batteries

Batteries will be used to power all the various components of our project. A battery is a device that stores electrical energy and then releases it in a chemical reaction. This power that is generated will be used for mostly everything in our project, including our motors, sensors, and the MCU.

There are two things we will be looking for when it is in regard to the battery. The first being how much voltage the battery can output and the weight of the battery. Both of these are extremely important as all components need to get their desired voltage, but also the P.U.T.T.I needs to still be light as field operatives will have to be able to carry around the P.U.T.T.I so having it be light is crucial. There are other smaller things that are important, such as the thermal stability of the battery. If the battery overheats, then that could burn the whole system down. We also must make sure the battery will fit within the project as there are the motors and sensors that need to be on the P.U.T.T.I so making sure the battery is small would of course be ideal.

The first type of battery we will look at is lithium-ion (Li-ion). The Li-ion is a rechargeable battery, made with a lithium-based cathode, a graphite anode, and an electrolyte solution consisting of lithium salts which allows for the lithium ions to between the cathode and anode. They are used in many commonly seen devices such as smartphones and electric vehicles. Some of the advantages that Li-ion batteries have is a high energy density, which means they can store a lot of energy in a relatively small package. They have a long cycle life, meaning they last a long time (up to several years with proper maintenance), which makes them a cost-efficient choice. Additionally, they charge very fast which is ideal for devices that need to be on the go just like our P.U.T.T.I. Finally, they come in many different shapes and sizes so finding one for our project that would fit wouldn't be an issue. They also come with some downsides, such as being sensitive to extreme temperatures, which may not be ideal if the P.U.T.T.I needs to be used in something like the desert or arctic. While they may have a good cycle life, their overall lifespan tends to be limited as they can degrade by as much as 20% after 500 or so charge and discharge cycles. With that all being said, the Li-ion still remains a contender due to its lightweight construction, runtime, and efficiency for our project⁹³.

Very similar to the Lithium-Ion battery is the polymer (LiPo) battery. These batteries are a type of rechargeable battery that is composed of a lithium-based cathode

⁹³ "The Pros and Cons of Lithium-Ion Batteries: A Deep Dive," *Bioenno Power*. Available: <https://www.bioennopower.com/blogs/news/the-pros-and-cons-of-lithium-ion-batteries-a-deep-dive>

and anode which is separated by a liquid electrolyte, where inside of the liquid electrolyte consists of a polymer electrolyte. This polymer electrolyte causes the differences between the two different types of lithium batteries, as this polymer electrolyte allows for an even higher specific energy compared to traditional lithium-ion cells, resulting in a greater lightweight design. This makes them particularly useful in portable systems where weight and power delivery are critical. This is in addition to the same upsides as the Li-ion battery, where they come in a variety of different sizes and shapes, as well as having a quick discharge rate and strong current output capabilities. However, there are also some new downsides alongside their upsides. LiPo batteries are much more prone to overcharge, over-discharge, and overall damage if not handled properly which could lead to some safety hazards. They also tend to have a shorter lifespan if not maintained correctly and require careful charging and monitoring to prevent swelling or failure. As long as safety measures are taken to ensure the battery doesn't become damaged, they remain as a top contender for our P.U.T.T.I project, offering a great balance between performance, weight, and energy density needed to keep the system running effectively for extended periods⁹⁴.

The nickel-metal hydride (NiMH) is also a type of rechargeable battery. However, unlike the other two this battery uses a hydrogen-absorbing alloy as the anode, and the nickel oxyhydroxide as the cathode. This combination allows for a higher specific energy compared to their older nickel-cadmium (NiCd) counterpart, which it does so in a smaller package then compared to the NiCd. Another great feature is that they use a reduced number of toxic metals compared to other batteries, making them a more environmentally friendly option. The last standout feature that they have is that they have a great cycle life, even better than that of the lithium-based batteries. For the P.U.T.T.I project, NiMH batteries present a safe and reliable option for powering the camera, motors, MCU, and onboard sensors during long-term operation. Their inherent stability and resilience to temperature variations make them dependable for maintaining system uptime and ensuring continuous targeting functionality. Additionally, NiMH batteries are more environmentally friendly than older chemistries like Nickel-Cadmium, and they can endure hundreds of charge-discharge cycles before significant degradation. Their main downside is that compared to other batteries such as lithium ion, they have a lower high energy density, as well as per cell the voltage is lower compared to that of the lithium batteries. Additionally, overall, they are heavier than that of the Li-ion and LiPo batteries which of course is important for whoever is carrying the battery. Despite these trade-offs, their simple charging requirements, long lifespan, and resistance to overcharging make NiMH batteries a practical and dependable power solution for the P.U.T.T.I system, especially in situations where reliability and safety are prioritized over weight and compactness⁹⁵.

⁹⁴ "Difference Between Lithium-Ion and Lithium-Polymer Batteries (FAQ)," *Battery Power Tips*. Available: <https://www.batterypowertips.com/difference-between-lithium-ion-lithium-polymer-batteries-faq>

⁹⁵ "What Are Nickel Metal Hydride (NiMH) Batteries?" *R&D Batteries*. Available: <https://www.rdbatteries.com/blog/post/what-are-nickel-metal-hydride-nimh-batteries-.html>

Table 17 - Battery Type Specifications

Criteria	Li-Ion	LiPo	NiMH
Density (Wh/kg)	110-160	100-130	60-120
Cycle Life	150 to 250 (7.2V)	200-300 (7.2V)	300 to 500 (6V)
Charge Time	2-4 hours	2-4 hours	2-4 hours
Over Charge Tolerance	Very Low	Low	Low
Cell Voltage	3.6V	3.6V	1.25V
Operating Temperature	-20 to 60 Celcius	0 to 60 Celcius	-20 to 60 Celcius
Maintenance Requirement	Not req.	Not req.	60 to 90 Days
Weight	200-300 Grams	250-400 Grams	500-800 Grams

We have decided to go with the LiPo batteries as the best choice for our P.U.T.T.I project. Although the energy density is higher on average for the Li-ion batteries, the Li-ion falls short in other aspects such as the weight and cost. Additionally, we didn't go with the NiMH for similar reasons, but also because the voltage is much lower per cell than that of the LiPo or Li-ion batteries. For the P.U.T.T.I project, the LiPo batteries present the most balanced option for powering the motors, camera, MCU, and sensors while keeping the overall system lightweight and efficient. Their high discharge rate ensures that sudden power demands can be met without voltage drops, maintaining stable performance for the targeting system. The LiPo batteries are the best combination of being energy dense alongside being small, compact, and with a low enough weight to justify having a group of batteries in series. This is of course wanted as people who are carrying around the P.U.T.T.I need it to not be so cumbersome so they can still move efficiently. Additionally, their flexibility in form factor and fast recharge capability makes them ideal for

portable systems that require consistent and reliable power delivery during extended missions⁹⁶.

3.1.13.2 Battery Part Selection

The Nihewo 4S 4500 mAh 80C LiPo battery is an affordable option for powering our P.U.T.T.I system. It runs at 14.8 V, which fits perfectly for our setup, and the 80C discharge rating means it can deliver strong bursts of current when needed which can be useful for keeping the motors, camera, MCU, and sensors running smoothly. Even though the 4500 mAh capacity isn't huge, it offers a good balance between weight and runtime, keeping the P.U.T.T.I light enough to carry easily while still lasting a reasonable amount of time before needing a recharge. The battery itself is fairly compact, around 136 × 43 × 34 mm, and weighs just over 400 grams, so it won't add much bulk to the system. The main trade-off with the Nihewo pack is that, since it's cheaper, the claimed 80C rating might be a little optimistic, meaning it might not handle extremely high current as well as more expensive brands. Still, for the price, it's a practical and capable choice that should meet our needs as long as we handle charging and monitoring properly⁹⁷.

The Spektrum 14.8V 5000mAh 4S 30C Smart LiPo Battery is another option for our project. It also provides 14.8 volts, which is perfect for powering our motors, sensors, and other components without any major drop in performance. With a capacity of 5000mAh, it should give us a good amount of runtime before needing a recharge. The 30C discharge rate is also more than enough for what we need as it can deliver power quickly when required without putting too much strain on the battery. One of the best parts about this battery is that it's part of Spektrum's "Smart" line, meaning it has built-in tech that keeps track of things like charge cycles, health, and capacity. This is desirable as it then makes it convenient to figure out how the battery is performing and if there are any issues with it. The IC5 connector is also a nice touch, providing a secure and stable connection. Weighing just over 480 grams, it's not too heavy and won't make the system bulky. The only real downside is the price, as it's definitely a bit more expensive compared to other LiPo options. With that being said, if we consider the reliability, added safety, and ease of use, it's a strong choice that we can count on for consistent performance and less battery-related hassle in the long run⁹⁸.

The Turnigy Rapid 6S LiPo battery is another strong option for our project. The battery has a total voltage of 22.2V and a large 5000mAh capacity, meaning it can handle demanding tasks for extended periods of time without quickly running out of charge. Its extremely high 100C discharge rate means it can deliver a lot of current when needed, which is potentially needed for driving motors, sensors, and onboard systems simultaneously without experiencing any power dips. Another

⁹⁶ "What's the Best Battery?" *Battery University*. Available: <https://batteryuniversity.com/article/whats-the-best-battery>

⁹⁷ "Nihewo 4S 4500mAh 80C LiPo Battery," *Amazon*. Available: <https://www.amazon.com/Nihewo-Battery-Compatible-Airplane-Helicopter/dp/B0BDRP6BKP>

⁹⁸ "Spektrum 14.8V 5000mAh 4S 30C Smart LiPo Battery: IC5, SPMX50004S30," *Amazon*. Available: <https://www.amazon.com/Spektrum-14-8V-5000mAh-Smart-SPMX50004S30/dp/B07W5VV899>

upside is even with this increased output, the Turnigy Rapid remains relatively compact and well-built, featuring an XT90 connector that ensures a secure, low-resistance connection. Its size and weight are reasonable for what it delivers, though it's about double the weight of the smaller-capacity 4S batteries. The tradeoff, however, may be worth it, as this battery provides excellent reliability and power consistency, which is something we may need to keep the P.U.T.T.I operational for long periods while maintaining stable performance across all its components⁹⁹.

Table 18 - Battery Specifications

Criteria	Nihewo	Spektrum	Turnigy Rapid
Voltage (V)	14.8	14.8	22.2
Capacity (mAh)	4500	5000	5000
Discharge Rate (C)	80	30	100
Connector	XT60	IC5	XT90
Weight (g)	430	486	713
Dimensions (mm)	136 × 35 × 45	143 × 36 × 42	136 x 44 x 64
Cost (\$)	25	105	49.43

3.1.13.3 Battery Production Selection

For our project, the Turnigy Rapid gives us the best of both worlds between being both affordable, whilst giving us more than enough power in case other components are added to our project later down the line. While it may be way more than the other two batteries, it's not even a pound heavier and having the extra power outweighs the extra weight that is added by having a 6s vs. a 4s. Even with its extra weight, it ends up being the same size approximately as the other two batteries despite being a 6s, which gives it another reason to be our pick for the P.U.T.T.I.

⁹⁹ "Turnigy Rapid 5000mAh 6S 22.2V 100C LiPo Battery Pack w/XT90 Connector," *HobbyKing*. Available: <https://hobbyking.com/en-us/turnigy-rapid-5000mah-6s-22-2v-100c-lipo-battery-pack-w-xt90-connector.html>

3.1.14 Buzzer

There are two types of buzzers that can be used in this project, these are active buzzers and passive buzzers. Active buzzers work by creating noise using a built-in oscillator and DC voltage whilst passive buzzers need an external AC input to create sound. Due to this distinction an active buzzer would be best for this design since the buzzer just needs to generate a sound to alarm the user that the object has been successfully targeted and intercepted. When comparing the types of active buzzers that we want to use the most important part is the input voltage that they run on, since the microcontroller will run on 3.3 volts it would be much better for the buzzer to also run on this voltage, if the buzzer does require a larger voltage like 5 volts it may still work however the noise may be weakened.

The KY-012 is an active buzzer manufactured by Joy-It. It has an input voltage of 3.5 volts to 5 volts which is slightly higher than 3.3 volts which would be the optimal input voltage given we are using a 3.3 volt switching regulator for our microcontroller. This buzzer produces 85dB at ten centimeters and has quite a small size. The size of the buzzers will not be too important given that almost all of the buzzers available commercially will be quite small and easily able to fit in the device. This buzzer was unavailable on DigiKey with us only managing to find a three-pack variety of them on Amazon coming out to \$2.33 per buzzer, being on the expensive end of buzzers. This buzzer is also a little bulkier than some of the other buzzers and whilst we mentioned that size wasn't the most important aspect of the buzzer when there are other buzzers that are very similar to one another this could be a deciding factor in which buzzer we decide to go with.¹⁰⁰

The CMI-1295-0585T is a buzzer produced by Same Sky. This buzzer has the highest minimum voltage range at 4.0 volts which is much more than the 3.3 volts that we would likely want to aim for however it is still within the range of 5 volts that is our maximum limit. This buzzer also has a sound pressure level of 85 dB at ten centimeters which is quite common in active buzzers since they are only able to produce a single sound. This buzzer, unlike the previously mentioned KY-012 is also only the buzzer and does not have a small board that comes with it meaning that it is much smaller and the placement of this buzzer will be much more flexible than the KY-012. This buzzer is available through DigiKey at a unit price of \$1.35 and is one of the most available having a stock of over 15,000 meaning that if we have any issues with the buzzer or if we want to have multiple we can easily purchase more.¹⁰¹

The WST-1203UX is a buzzer manufactured by Soberton Inc. This buzzer is the first one that has a minimum operating voltage of 3.0 volts meaning that it can easily function using the 3.3-volt regulator that will power the rest of the components. This is also the smallest buzzer that we have analyzed so far but as a result is also the quietest with a sound pressure level of 83dB at ten centimeters, this should not have a major impact on the sound however it is important that we

¹⁰⁰ ArduinoModules, "KY-012 active Buzzer module," ArduinoModulesInfo, <https://arduinomodules.info/ky-012-active-buzzer-module/>.

¹⁰¹ CMI-1295IC-0585T same sky (formerly CUI devices) | audio products | DigiKey, <https://www.digikey.com/en/products/detail/cui-devices/CMI-1295IC-0585T/11674150>

make sure that it can be heard from an adequate distance to alert the user when the target has been hit. This buzzer is slightly more expensive than the CMI-1295-0585T at a unit price of \$1.66 on DigiKey but the fact that it works with a 3.3-volt input voltage is very important.¹⁰²

The CMI-1275-03TH is another buzzer manufactured by Same Sky. Since they are manufactured by the same company, they have very similar statistics but there are also some huge differences that set it apart from the CMI-1295-0585T. The CMI-1275-03TH, unlike the CMI-1295-0585T operates at a 3.3-volt input since the operating voltage range is between 2 volts and 5 volts. This is incredibly important for the P.U.T.T.I since the microcontroller runs on a voltage directly between the upper and lower bound of the supply voltage. This buzzer also has an 85 dB sound pressure level at ten centimeters however it approaches this at a lesser voltage than the other buzzers earning that it requires less voltage to reach a higher sound level. The CMI-1275-03TH is also cheaper than the other Same Sky buzzer having a unit price of \$1.10 on DigiKey however having a worse stock. This buzzer should still be readily available and seems to be better than the CMI-1295-0585T in every way.¹⁰³

The IE330403-1 is a low frequency buzzer manufactured by DB Unlimited. This buzzer is different from the previously mentioned buzzers because it has lead wires and is a rectangular shape rather than a circular shape. Due to the low frequency of this buzzer, it does not reach the same sound levels as the other buzzers only having a sound pressure level of 70dB at ten centimeters however it does run on a supply voltage of 3.3 volts which many of the other buzzers don't. The biggest downside of this buzzer is its cost and availability; there are less than 60 IE330403-1 available through DigiKey and they have a unit price of \$5.20.¹⁰⁴

The RBE-4.000-3215-NS1 is the final buzzer that needs to be analyzed and is a buzzer manufactured by Raltron Electronics. This is the largest buzzer out of all the buzzers having a diameter of 32.00 mm, it is the buzzer that also has the largest voltage range, frequency, and sound pressure level. This could be useful however since the sound pressure level is 95dB at ten centimeters when the supply voltage is 5 volts then we can expect that for a 3.3 volt input the sound pressure level will be somewhere closer to the CMI-1275-03TH. Despite being the most powerful buzzer this buzzer is cheaper than the least powerful buzzer, the IE330430-1 coming in at a unit price of \$3.91 on DigiKey. Whilst the power of this buzzer is appealing the fact that it needs upwards of 20 volts to reach its maximum potential is not very feasible and it is likely that it will have diminished capacity if we try to force it into the P.U.T.T.I.¹⁰⁵

¹⁰² WST-1203UX Soberton Inc. | audio products | DigiKey, <https://www.digikey.com/en/products/detail/soberton-inc/WST-1203UX/1245301>.

¹⁰³ Same sky (formerly Cui Devices), <https://www.digikey.com/en/supplier-centers/cui-devices?msockid=0f2d84fc671b62cb37fd926f664a63a4>.

¹⁰⁴ IE330403-1 DB unlimited | DigiKey, <https://www.digikey.com/en/products/detail/db-unlimited/ie330403-1/9990502>.

¹⁰⁵ RBE-4.000-3215-NS1 raltron electronics | audio products | DigiKey, <https://www.digikey.co.uk/en/products/detail/raltron-electronics/RBE-4-000-3215-NS1/22320882>.

Table 19 - Buzzer Specifications

	KY-012	CMI-1295-0585T	WST-1203UX	CMI-1275-03TH	IE330403-1	RBE-4.000-3215-NS1
Manufacturer	Joy-It	Same Sky	Soberton Inc.	Same Sky	DB Unlimited	Raltron Electronics
Voltage Range	3.5V ~ 5.5V	4.0V ~ 7.0V	3.0V ~ 7.0V	2.0V ~ 5.0V	2.0V ~ 4.0V	3.0V ~ 20.0V
Current-Supply	30mA	30mA	30mA	30mA	3mA	10mA
Frequency	2500Hz ± 300Hz	2300Hz	2300Hz	2700Hz	400Hz	4000Hz
Sound Pressure Level	85dB @ 10cm	85dB @ 5V, 10cm	83dB @ 5V, 10cm	85dB @ 3V, 10cm	70dB @ 3V, 10cm	95dB @ 5V, 10cm
Operating Temperature	-20°C ~ 70°C	-40°C ~ 85°C	-20°C ~ 60°C	-20°C ~ 70°C	-10°C ~ 60°C	-20°C ~ 70°C
Size/Dimension	19mm x 15mm x 11mm	12.00mm Dia, 9.70mm H	12.00mm Dia, 7.70mm H	12.00mm Dia, 8.00mm H	15.50mm H	32.00mm Dia, 15.00mm H

3.1.14.2 Buzzer Selection

After looking at all the buzzers the two buzzers that are most feasible for our project are the CMI-1275-03TH by Same Sky and the IE330403-1 since they are the two buzzers where the input voltage range best suites our device. Comparing these two buzzers they have quite a few stark differences, the IE330403-1 has a narrower voltage range and much lower frequency but the CMI-1275-03TH has the greater sound pressure level and is much cheaper. Given these differences the clear choice for us is to go with the CMI-1275-03TH, it is almost 5 times cheaper and much more readily available. Additionally, the buzzer's sound pressure level is probably the second most important aspect of the buzzer and the CMI-1275-03TH has a much louder buzzer which is desired to ensure that anyone using the product can hear when it is being activated.

3.2 Communication Protocols

3.2.1 SBC to Camera

A critical communication protocol to consider is the connection between the Single-board Computer and the camera. The communication protocol between the processor and camera directly impacts image resolution, frame rate, and overall system responsiveness. A speedy connection is required to quickly send the image to the microcontroller and keep processing as real-time as possible.

One common communication protocol is I2C. I2C requires a data wire and a clock wire. The SBC, or controller, can have many peripherals attached to these singular inputs. Even though multiple peripherals share the same ports, the controller can still choose which peripherals to send commands to. Bits are sent one by one from the peripheral to the controller over the data wire, and the clock wire determines when actions are taken. Typically, the average clock speed is about 400 kHz, but some controllers can access speeds of up to 5 MHz. As previously mentioned, transfer speeds of 5 MHz may not be sufficient for the possible image sizes, so I2C may be a poor choice¹⁰⁶.

USB cameras can provide a much higher bandwidth for image transfer. USB allows for direct streaming of image data at higher resolutions and frame rates, and many available webcams support 1080p video or higher. USB cameras are typically plug-and-play, allowing for easy usage with the SBC. A typical USB 2.0 port can feature a speed up to 480 Mb/s, which would be sufficient for basic image processing needs. Typical USB devices can use up to 5V and up to 500 mA, meaning a maximum power usage of 2.5W. USB 3.0 has speeds up to 5 Gb/s, which is well above image processing needs. On most single-board computers, USB cameras are straightforward to implement and can achieve sufficient resolution and frame rates for real-time image analysis¹⁰⁷.

Introduced in 2005, MIPI CSI-2 has become one of the most widely used interfaces for cameras and imaging. The MIPI Alliance has defined it as the standard for mobile and embedded systems. It can support many different qualities of video and photographs, including 1080p, 4K, 8K, and more. The reason for its success comes from its high performance with lower power consumption and electromagnetic interference. CSI-2 interfaces can use up to 32 virtual channels to support many different image sensors across multiple data types. The interface also features low latency and transport efficiency, allowing the imaging to allow for real-time perception and decision making. Efficient transport also leads to a lower power consumption, and is handles with minimal number of wires. The differential pulse code modulation compression helps to avoid artifacts from being generated in images. Standardizing this interface is extremely beneficial to the project. Having a common interface standardized in the industry means that cameras can be easily swapped out should one perform better than another. Video formats and resolutions can be altered without any changes to the hardware, since the MIPI CSI-2 interface supports a wide variety of formats. The standard interface will also

¹⁰⁶ "I2C," I2C - SparkFun Learn, <https://learn.sparkfun.com/tutorials/i2c/all>.

¹⁰⁷ T. Agarwal, "USB protocol : Architecture, Working Specifications & Applications," EIProCus, <https://www.elprocus.com/usb-protocol/>.

minimize wiring complexity, turning the process of attaching the camera into a seamless process. One limitation is that the typical connecting cable length is small; however, this should not be an issue as there are extenders and the MCU can be located close to the camera location in the final product¹⁰⁸.

Table 20 - SBC to Camera Protocol Specifications

Feature	GPIO	USB	CSI
Max Resolution	Unsuitable	High	Very High
Speed	Slow	High	Very High
Power	Extremely Low	Low	Low
Complexity	2 Wires	USB Connection	Ribbon Connection
Reliability for Images	Poor	Great	Great

3.2.1.2 SBC to Camera Selection

After much review, it would appear that the USB port is the best choice for this project. The SBC can easily interact with it, and distance should not be a significant issue. Cameras that use USB are widely available and the USB port will have sufficient speed and resolution for image processing, and it features a low power usage.

3.3 Software

3.3.1 Computer Vision Language

For image processing, two languages prevail: C++ and Python. Both languages are available for use on the SBC and can interact with GPIO and other sensors. They are also both high-level programming languages commonly used in the software realm.

C++ is a high-level, object oriented, general purpose language created by Bjarne Stroustrup. It was made to be an extension of the programming language C and is common among low-level tasks. C++ is portable between platforms, ensuring that switching from one microcontroller to another will not cause an issue. Memory usage of programs written in C++ is minimal since the compiler helps to optimize usage. Since it does not have a garbage collection system, the user must be responsible for maintaining the memory. This can cause problems if unexpected errors arise in the code, but it can give the programmer better flexibility to fully control their memory. C++ is also highly scalable and has a large community to

¹⁰⁸ "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.

receive guidance and documentation from¹⁰⁹. C++ also features a faster speed than other languages since it is pre-compiled rather than interpreting line-by-line. As a result, C++ becomes a fast, flexible programming language capable of many tasks. Some downsides to C++ include security and user-friendliness. As mentioned before, the user must be fully aware of all memory being created and cannot let memory leaks occur. It is also easy to create errors while coding, and it can take many lines of code to perform some simple actions¹¹⁰.

Python is a high-level, object-oriented, interpreted language created by Guido Van Rossum, now maintained by the Python Software Foundation. It is widely accepted by many operating systems, and it will run on the Orin Nano. Python has a focus of creating a syntax that is as clear and short as possible. Python variables are also dynamically typed, so the user does not need to explicitly declare variables. Unlike C++, Python can be more user-friendly because of these properties. Python is very flexible and can take on tasks from many different fields, including computer vision and machine learning. Open source libraries exist for nearly every task, and the community for Python is similar in size and documentation as the C++ community. One downside of using Python is that the speed will be slower since it is interpreted line-by-line. Python may be better overall since the many activities of the P.U.T.T.I. can be better managed in fewer lines and memory management occurs automatically thanks to the built-in garbage collector¹¹¹.

Table 21 - Computer Vision Language Specifications

Feature	Python	C++
Speed	Slower	Faster
Compile Type	Interpreted	Pre-Compiled
Ease of Use	Easy	Difficult
Memory Management	Garbage Collector	User Managed
GPIO Access	Yes	Yes
Cross-platform Compatibility	Yes	Yes
Community and Documentation	High	High

¹⁰⁹ "Python vs. C++: Key differences and uses," IONOS Digital Guide, <https://www.ionos.com/digitalguide/websites/web-development/python-vs-c/>.

¹¹⁰ STX Next, "Python vs. C++: Which language wins for your project?," Software Development Services & Solutions Company – STX Next, <https://www.stxnext.com/blog/python-vs-c-plus-plus-comparison>.

¹¹¹ GeeksforGeeks, "Difference between python and C++," GeeksforGeeks, <https://www.geeksforgeeks.org/python/difference-between-python-and-c/>.

3.3.1.2 Computer Vision Language Selection

After much review, it would appear that Python is the best choice for this project. Coding in Python is an extremely popular choice for machine learning and image processing tasks. On the Orin Nano, the choice between Python and C++ may result in marginal differences. Using Python can allow for easy prototyping and implementation of computer vision, and will save time in development.

3.3.2 Detection Framework

In order to classify the object, a framework must be employed to understand the image taken by the camera. When an object is detected, the camera must identify the target and determine whether or not it is a valid target or not. One method is to use OpenCV to detect shapes or edges. Another method is to use CNN-based Deep Learning from trained data to recognize objects.

OpenCV (Open Source Computer Vision) is as the name suggests. This open source computer vision and machine learning software library is widely used across many different platforms with the goal of providing a common infrastructure for computer vision applications and accelerate the use of machine learning and perception. The library contains more than 2500 optimized algorithms to detect faces, objects, classify human actions, track movements, and more. Well-established companies like Google, Microsoft, IBM, Intel, and other automotive companies make use of the library as well as many startups, so this library is well known and highly regarded. The community is extremely large, the about page even points directly to forums and Q&A pages. This library could certainly be beneficial and well-employed for this project.

You Only Look Once (YOLO) is a deep learning method which involved partitioning the image into a grid. Using the YOLO detection system, YOLO examines each grid cell globally, viewing the entire image to make assumptions. While training, it can learn generalizable representations of objects to try and understand an object better. It is also extremely fast, meaning that real-time detection is maintainable. It performs one regression problem to predict bounding boxes and compute probabilities from one pass over the image. One downside of the YOLO method is that its accuracy can be low for smaller objects, even though its accuracy for larger objects can be high. Research must be performed to determine how to achieve fast speeds on an Embedded CPU, as it can be slower on Single-board computers, as well as how the targets may be viewed by the camera¹¹².

The Single Shot MultiBox Detector (SSD) is another single-stage object detection algorithm that prioritizes speed while maintaining moderate accuracy. SSD operates by applying a convolutional network to feature maps of different scales, allowing it to detect objects of varying sizes in a single forward pass. This multi-scale approach gives SSD an advantage in detecting small and large objects simultaneously, while maintaining real-time performance. SSD typically uses a

¹¹² You only look once: Unified, real-time object detection, https://www.cv-foundation.org/openaccess/content_cvpr_2016/papers/Redmon_You_Only_Look_CVPR_2016_paper.pdf.

base network such as VGG16 or MobileNet to extract features, followed by additional convolutional layers for detection. The use of multiple feature maps makes SSD more flexible than earlier YOLO versions, though it is generally slower than the most optimized YOLO architectures¹¹³.

Faster R-CNN represents a two-stage object detection approach that emphasizes accuracy and precise localization. The algorithm first generates candidate regions, known as *region proposals*, through a Region Proposal Network (RPN). These proposals are then refined and classified in a second stage using a convolutional neural network. This structure allows Faster R-CNN to achieve high detection accuracy, especially for complex scenes and small objects, since it analyzes each proposed region more thoroughly. However, the additional proposal stage introduces computational overhead, making it slower than single-stage detectors such as YOLO or SSD. Faster R-CNN is widely used in research and applications that prioritize detection quality over real-time performance¹¹⁴.

Table 22 - Detection Framework Specifications

Feature	OpenCV	YOLO	Single Shot MultiBox	Faster R-CNN
Stages	Depends	One	One	Two
Speed	Depends	Very Fast	Fast	Slow
Accuracy	Depends	Moderate	Moderate	High
Complexity	Low	Moderate	Moderate	High
Dataset?	No	Yes	Yes	Yes
Size	Small	Small/Moderate	Moderate	Large

3.3.2.2 Detection Framework Selection

After much review, it would appear that a YOLO model is the best choice for this project. On the Nvidia Orin Nano Super DevKit, the YOLO model is predicted to run at reliable frames per second, which the built-in components and machine learning specialized hardware of the SBC should assist. The targeted objects should also be large enough to be detected.

¹¹³ J. Hui, "SSD object detection: Single shot multibox detector for real-time processing," Medium, <https://jonathan-hui.medium.com/ssd-object-detection-single-shot-multibox-detector-for-real-time-processing-9bd8deac0e06>.

¹¹⁴ GeeksforGeeks, "Faster R-CNN: ML," GeeksforGeeks, <https://www.geeksforgeeks.org/machine-learning/faster-r-cnn-ml/>.

Chapter 4 - Standards

4.1 I2C

Inter-Integrated Circuit (I2C) was first released in 1982 and is a bidirectional 2-wire bus that allows for data communication between different devices connected via the I2C bus and has become the de facto world standard [1]. This I2C bus is composed of two bus lines, a serial data line (SDA) and a serial clock line (SCL) that allow for communication between integrated circuits on embedded systems. To send data through the SDA and SCL both lines must be set to high through a pull-up resistor, these resistors are set to low or high based on the input voltage rather than a fixed voltage. When the voltage is at 30% of the input reference voltage the bus is set to low and when at 70% the bus is set to high. To ensure that all data passed through the SDA bus is valid the SDA bus cannot change whilst the SCL bus is set to low meaning that for valid data communication to occur both lines must be set to high.

I2C supports four different modes, Standard-mode, Fast-mode, Fast-mode Plus, and High-speed mode all with different speeds of data transfer. The Standard-mode supports a data transfer rate of up to 100 kbits/s, the Fast-mode supports a data transfer rate of up to 400 kbits/s, the Fast-mode plus supports a data transfer rate of up to 1 Mbit/s, and the High-speed mode supports a data transfer rate of up to 3.4 Mbits/s.

I2C uses 10-bit addressing allowing for different devices with different bit addresses to connect to the same bus. Despite this 7-bit addressing is much more commonly used. These connected devices can also use any of the previously mentioned modes to control the bus speed. The first 7 bits of the address are reserved for the target address using the same format 11110XX where the XX are the Most-Significant Bits (MSB). The eighth bit is reserved for the R/W bit to determine the direction of data transmission.

There is a fifth mode that can be used, Ultra Fast-mode (UFm) that can send data at a rate of 5 Mbits/s however this mode is only able to transmit data in one direction. UFm uses two unidirectional lines USDA and USCL which have the same pull-up voltages to determine when the lines are high or low and like the other modes is also transferred with the MSB. The addressing also remains the same with 10-bit addressing possible but 7-bit addressing being the much more common method.

Every device connected to the I2C bus has its own unique address and simple controller/target relationships that always exist. A controller can either be a controller-transmitter or a controller-receiver. Additionally, there can be multiple controllers on the bus and there is software to prevent collisions and data corruption ensuring that multiple controllers can transfer data at the same time.

I2C has gone through many versions ever since the release of version 1 in 1992. The most impactful changes to I2C were the release of version 2 in 1998 where High-Speed mode was introduced, version 3, released in 2007, introduced Fast-Mode Plus whilst keeping downward compatibility with the other, slower modes, version 4 added the Ultra-Fast mode in 2013, all future versions up until version 7

which was released in 2021 have only made changes to the user manual with corrections and updated terminology to match with MIPI I3C and NXP's Inclusive Language Project.

I2C will be extensively used in this project to send data between the sensors and the microcontroller. Whilst I3C is the successor to I2C it has not become the standard used by the world and still has a long way to go before this will happen. I2C works perfectly for this project allowing for secure and fast data communication between the various components of the system.¹¹⁵

4.2 UART

The Universal Asynchronous Receiver/Transmitter (UART) standard is one of the earliest used methods of serial communication in embedded systems. It was initially designed by Gordon Bell in the 1960s and was first put on a single-chip in 1971. It provided a simple method for digital devices to communicate information without needing a shared clock signal. Now, it still holds the same purpose, being supported by almost all modern microcontrollers. Although most instances are actually known as USART (Universal Synchronous/Asynchronous Receiver/Transmitter), which add an optional clock synchronization ability.

UART communication works by using two primary lines, one being a transmit line (TX) and the other being a receive line (RX). These both connect directly from one device to the other. Since UART is asynchronous, both devices in the network need to be set to the same baud rate, which helps to time transmissions of data. Because this method doesn't require a shared clock, it's fairly simple to implement and is electrically efficient so long as the baud rates are set correctly. Usually, UART uses a baud rate in the range from 9600 to 115200 bits per second, with data framing issues occurring when mismatching rates are used.

There are different ways to use UART, with communication being possible in three modes. The first is simplex mode, in which data is sent in only one direction. The second is full duplex mode, in which both devices can send and receive data simultaneously. The last is half duplex mode, in which the two devices take turns sending and receiving information. Additionally, UART requires multiple settings to be configured the exact same on both devices: flow control, baud rate, if there's a parity bit, data bit size, stop bit size, and voltage (though it is possible to combine two UART modules at different voltage levels).

The data frames used in UART can be separated into five sections. The first part is when the line is set to idle, meaning the logic is set to high for an extended period of time. The second part is known as the starting bit, where the receiver is signaled that new data is coming in (this happens when the logic is set to low). The third part is the actual data bits, which contain the information (this is five to nine bits, depending on the settings). The next part is the parity bit, which tells the receiver if any information has changed, though this is not always used. The last part is the stop, which sets the logic back to high. The most common settings for a UART data frame have 8 bits and exclude the parity bit (known as 8N1), making the

¹¹⁵ NXP, <https://www.nxp.com/docs/en/user-guide/UM10204.pdf?fsrch=1&sr=1&pageNum=1>

protocols efficiency 80%, since two out of every ten bits is used for control instead of data¹¹⁶.

4.3 SPI

The Serial Peripheral Interface (SPI) standard is a de facto standard for synchronous serial communication. This was first created by Motorola in the early 1980s as a fast, synchronous alternative to UART. Since it was created, it has become standard in almost all modern microcontrollers.

SPI is a synchronous mode of communication, which means that all data transferring is coordinated by a clock signal generated by the master device (usually the MCU). This communication requires 4 main lines, including MOSI (master out slave in), MISO (master in slave out), SCLK (serial clock), and SS (slave select). The master device uses the clock and initiates communication, which allows the slave device to respond in sync with the clock signal. Due to this synchronization, SPI bypasses the timing issues of UART, which allows it to reach much higher data transfer rates in megahertz. Each device uses a shift register, which shifts data as it's sent between the master and slave devices. The use of an SS line for each slave device can be prevented by daisy chaining the slave devices together. This means that by connecting the output of a slave device to the subsequent slave device (then repeating for each device) all of the shift registers are merged, allowing data to move through each device only using one SS line.

SPI communication can operate in four possible modes, which are defined by clock polarity (CPOL) and clock phase (CPHA). The clock polarity determines which logic level is counted as the clock's idle, either logic high (1) or logic low (0). The clock phase determines which clock edge to transfer data by sampling and shifting. Both the master device and slave devices need to be set to the same mode to communicate properly. For each clock cycle one bit is shifted from the master device to the next slave device through the MOSI line, while another bit is shifted back from the slave device to the master device through the MISO line. This feature is what allows SPI to be significantly faster than asynchronous modes of communication.

SPI data frames do not work like the data frames of UART. Communication is initiated by the master device when the SS line is pulled low and it ends when the SS line is set back to high. While the SS line is low, a continuous stream of data bits are sampled and shifted through the devices, with each clock cycle shifting one bit. One primary drawback of SPI communication is the lack of error checking that the parity bit does for UART, but this can be accounted for using software methods.

SPI is used in all sorts of devices which require high-speed communication between peripherals and the central microcontroller. For the P.U.T.T.I. system, SPI can be used for fast, reliable data transferring between the ESP32 and various peripherals. While it may require more connections/pins than UART, its quick

¹¹⁶ "Universal asynchronous receiver-transmitter," Wikipedia,
https://en.wikipedia.org/wiki/Universal_asynchronous_receiver-transmitter.

speed and flexibility via daisy chaining make it a necessary communication protocol for many devices¹¹⁷.

4.4 USB

USB, or universal serial bus, is a popular method for connecting peripherals to computers. They are very simple to use and are often plug-and-play, meaning that the machine can begin using it as soon as the device is plugged in. USB devices are connected to a single bus and assigned an address, allowing for multiple connections to be made.

USB 2.0 was released in April 2000 and supports speeds in the Megabits, a popular method of attaching low-bandwidth peripherals like keyboards and mice or attaching high-bandwidth peripherals like cameras and printers. Replacement parts using USB connections are easily accessible due to the widespread use of the USB standard, and the plug-and-play nature of such devices allow for them to be usable on many different devices. The USB connection also reduces the need for complex circuitry and wiring, allowing for a simple connection¹¹⁸.

4.5 MIPI CSI-2

Introduced in 2005, MIPI CSI-2 has become one of the most widely used interfaces for cameras and imaging. The MIPI Alliance has defined it as the standard for mobile and embedded systems. It can support many different qualities of video and photographs, including 1080p, 4K, 8K, and more. The reason for its success comes from its high performance with lower power consumption and electromagnetic interference. CSI-2 interfaces can use up to 32 virtual channels to support many different image sensors across multiple data types. The interface also features low latency and transport efficiency, allowing the imaging to allow for real-time perception and decision making. Efficient transport also leads to a lower power consumption and is handles with minimal number of wires. The differential pulse code modulation compression helps to avoid artifacts from being generated in images. Standardizing this interface is extremely beneficial to the project. Having a common interface standardized in the industry means that cameras can be easily swapped out should one perform better than another. Video formats and resolutions can be altered without any changes to the hardware, since the MIPI CSI-2 interface supports a wide variety of formats. The standard interface will also minimize wiring complexity, turning the process of attaching the camera into a seamless process. One limitation is that the typical connecting cable length is small; however, this should not be an issue as there are extenders and the MCU can be located close to the camera location in the final product¹¹⁹.

¹¹⁷ "Serial peripheral interface," Wikipedia, https://en.wikipedia.org/wiki/Serial_Peripheral_Interface.

¹¹⁸ M. Brain, "Understanding USB types and the flexible USB system," HowStuffWorks, <https://computer.howstuffworks.com/usb.htm>.

¹¹⁹ "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.

4.6 GPIO

The SBC contains 40 GPIO pins. GPIO has become a standard method of connecting peripherals to an MCU. These digital pins can be configured to serve as either input or output. Pull-up or pull-down resistors can typically be enabled for every pin. Present in GPIO setups are designated 3.3V and 5V outputs as well as grounds. For input/output pins, a 3.3V reading is approximated to be logical one, while closer to 0V than 3.3V is logical zero. The GPIO pins should avoid more than 50 mA current. Select pins can be configured to perform standardized communications such as I2C, SPI, UART, and PWM. GPIO pins are an extremely important standard for most, if not all, embedded systems. They allow easy access to controlling components and connecting peripherals to the microcontroller. For the project, using GPIO pins will allow successful and easy connection between the SBC and the many peripherals, including peripherals that may use specific communication protocols rather than producing a digital signal. The standardized pinout common across all SBC's means that the SBC can be swapped out efficiently if needed.

4.7 Python PEP 8

As with all programming languages, there are many ways to manage the contents of Python code. Whitespace, variables, and functions can all be written and read differently at the programmer's preference. Because of this variability between programmers, some coding conventions needed to be installed to improve readability of code and to ensure that it is consistent and transferable between different programmers. An important saying for programming is "Readability counts"¹²⁰. PEP 8, the official Python style guide, is an outline of a comprehensive set of recommendations to ensure clarity between codebases.

There are times when the guidelines can be broken, but they are not often. Some examples include when the guideline would actually result in less readable code, to be consistent with pre-existing code, the pre-existing code predates these guidelines and the code does not need to be altered, and to keep the code compatible with older versions of Python which may not support features in the guidelines. However, when these scenarios or similar scenarios do not apply, then the guidelines should be followed.

One of PEP 8's most emphasized principles is consistent indentation. The standard specifies using four spaces per indentation level, avoiding the use of tab characters entirely to prevent alignment issues between editors. Proper indentation is critical not only for readability but also because Python uses whitespace to define code blocks rather than braces or keywords.

Another key guideline involves line length, which should generally not exceed 79 characters for code and 72 characters for comments or documentation strings (docstrings). This recommendation helps maintain readability across different

¹²⁰ "PEP 8 – style guide for python code," Python Enhancement Proposals (PEPs), <https://peps.python.org/pep-0008/>.

devices and editors, especially when viewing code in side-by-side comparisons or documentation generators.

Naming conventions are also an important aspect of PEP 8. Variable and function names should use “lowercase_with_underscores”, while class names should follow the “CapWords” (PascalCase) convention. Constants are written in “ALL_CAPS_WITH_UNDERSCORES”, and private variables or methods should begin with a single underscore to indicate limited internal use.

PEP 8 also stresses the importance of blank lines and spacing to visually separate logical sections of code. For instance, top-level function and class definitions should be surrounded by two blank lines, while methods within a class should be separated by a single blank line. Additionally, unnecessary spaces such as those inside parentheses, brackets, or before commas should be avoided to keep code visually clean.

When it comes to imports, PEP 8 recommends placing them at the top of the file, grouped by standard library imports, third-party imports, and local application imports, each separated by a blank line. This organization improves clarity and avoids confusion about dependencies.

Lastly, comments and documentation strings are strongly encouraged. Comments should explain why code exists rather than restating what the code already expresses. Docstrings, enclosed in triple quotes, should be used for all public modules, classes, methods, and functions to describe their purpose and usage.

4.8 Git and GitHub

Git is a free, open-source software used to provide version control to projects. Using Git, a user can track their changes and manage their history to quickly update projects or revert changes. It stores a full copy of the user’s project on their local machine to allow for easy access to all branches and commits. When a user wants to test a change, they can create a branch where their changes will not affect the main branch. The user can upload changes in the form of commits to their project. After changes and testing have been completed, the user can merge their branch into the main branch¹²¹.

One of the biggest sites that uses Git is GitHub. GitHub is a remote repository store which allows for users to use Git to store their codebase and commits on a remote server. This can make it easy for users to share their code with other developers. It also make it easy to package and ship software to anyone that needs it. GitHub enforces security with repositories, ensuring that users are properly documented with SSH keys and accounts before allowing them to push to a repository¹²².

¹²¹ “About git,” Git, <https://git-scm.com/about>.

¹²² “GitHub · change is constant. github keeps you ahead.,” GitHub, <https://github.com/>.

4.9 Docker

Docker is a widely used containerization platform that allows applications to run in lightweight, isolated environments called containers. Docker allows developers to share consistent packages and environments to avoid the problem of “It worked in my environment but not yours.” Packaging software and dependencies into a single standard image significantly simplifies deployment as well. Containers are different from Virtual Machines in that they run on the host operating system’s kernel rather than emulating a different environment. Docker also provides a location for storing and retrieving pre-made images called Docker Hub. Through Docker Hub, a user can quickly build an image from a pre-existing image, allowing them to avoid some of the process of installing many dependencies and simply needing to install dependencies specific to their project. By standardizing software deployment through containerization, Docker enhances reliability, portability, and maintainability throughout the entire development lifecycle¹²³.

4.10 PWM

PWM (Pulse Width Modulation) is a modulation technique commonly used in embedded systems, motor control, and power management applications. It works by varying the width of digital pulses to mimic analog signal levels, which in turn controls the amount of power that is delivered to the load. PWM is used in many applications, including microcontrollers, servomotor drivers, and switching power supplies (to name a few) because of how efficient, precise, and easy it is to implement due to it being a digital signal.

When setting up PWM, the microcontroller generates a continuous series of high and low pulses through a dedicated output pin. The connected device interprets the average voltage from this signal to control behavior, such as the speed of a motor or the brightness of an LED. For example, a 0% duty cycle means the signal is high for none of its period, delivering effectively grounding the signal and thus sending no power, while a 100% duty cycle means full power delivery. By rapidly toggling between on and off states at high frequency, PWM provides smooth and stable control that approximates analog output without requiring a digital-to-analog converter (DAC).

PWM has a few defining behaviors. Firstly, it has a duty cycle which is just the percentage that the signal remains high (also known as on time) over the whole length of the signal, determining the output voltage to the delivered load. Then, you have the frequency which is how often the PWM cycle will repeat itself (measured in hertz). Finally, there is the resolution, which is the number of discrete duty cycle steps the controller can produce. The higher the resolution, the finer the control, which is important for precise applications such as servo positioning.

PWM’s efficiency and simplicity make it a cornerstone of digital control in embedded systems. By using digital hardware, PWM enables precise analog-like control of voltage and current without the usual downside of complexity and sometimes inefficiency that analog circuits may give. Its applications range from

¹²³ “Accelerated Container Application Development,” Docker, <https://www.docker.com/>.

controlling servomotors and actuators in robotics to regulating voltage in DC-DC converters and generating audio signals in communication systems. The versatility, efficiency, and ease of implementation have made PWM an indispensable technique in both industrial and consumer electronics.

Overall, PWM is one of the most fundamental and efficient methods for controlling digital signals. Its adaptability across various applications, such as in lighting, sound, and voltage regulation, showcases how important it is in modern embedded design. Through carefully considering the required duty cycle, frequency, and waveform alignment, PWM allows precise and reliable control across many electronic systems¹²⁴.

4.11 Power Constraints

The P.U.T.T.I will be mostly powered by batteries except from the Single-Board Computer which has its own adapter. Since many different parts of the project require different voltages, we will be using both switching and linear regulators to control the voltage for each of the components. The switching regulators will be used to set voltages of 3.3 volts and 5 volts whilst the linear regulator is used to set the voltage to 1.8 volts for the microwave sensor. We need to make sure that the system can be powered for a reliable amount of time given that the system will be deployed in combat zones where it cannot be easily recharged. Given all the different components there will be substantial power drain on the system so making sure we can lower this and ensure that the system is able to run efficiently and effectively is an incredibly important priority.

The component that has the biggest power drain will be the Single-Board computer since it requires a voltage of 19 volts and will be processing the images, however this is somewhat mediated by the system having its own power supply meaning it will not drain the batteries supply voltage to the rest of the system. All the other components all need a constant power supply to them as they communicate to the microcontroller. In particular, the motors and laser need a steady stream of power to ensure that they line up perfectly with the tracked image and that the laser is of an adequate power. If there is a major change in the supply voltage, then the system could not be able to track the objects correctly and the laser could receive a voltage that makes the laser more dangerous than we intend.

There will be countless amounts of data being transferred through UART, SPI, and I2C. All these protocols require a steady power source to prevent data from being corrupted or lost. Much like the motors, if this data is lost or corrupt then the accuracy of the readings or the targeting system could be lost resulting in catastrophic failure for the system. The regulators should be able to ensure that we are able to supply a constant voltage is supplied to all the components that will transfer data such as the humidity sensor, LCD, microwave sensor module, and Single-Board Computer. Even though the single-board computer has its own

¹²⁴ "Pulse Width Modulation (PWM): How It Works and Why It's Essential in Electronics," *SameSky Devices*. Available: <https://www.sameskydevices.com/blog/pulse-width-modulation-pwm-how-it-works-and-why-its-essential-in-electronics>

voltage supply this is not regulated so we may have to take additional measures to guarantee the information sent from the single-board computer to the microcontroller are valid.

Given the variety of different input voltages of the components it will be a challenge to make sure that all of them receive a stable connection and that they can run all the time. We may have to add functionality to turn off certain sensors when they are not needed or run them less frequently. This could not only make keeping a stable voltage easier for the whole system but could cut down on unnecessary power consumption, allowing for the system to run longer. Some of the components like the laser should be able to save a lot of power since they only need to be turned on when there is a valid object to track. Since the laser is one of the components that runs on a 3.3 volt supply it will be very beneficial to try and limit the amount of time that the laser is turned on as many other components will also be attached to the 3.3 volt switching regulator. Most of the other components will likely need to run constantly or at least to a higher degree than the laser so trying to limit them will not be as efficient as limiting the lasers time turned on however we should still make as much of an effort as possible to limit all the remaining components from using power constantly.

Making sure that the power consumption of the P.U.T.T.I is limited is incredibly important. We need to make sure that not only is the amount of power the system consumes limited but also that all the voltage supplied to the various components is efficiently delegated and regulated to be stable. Managing the power consumption is one of the most important parts due to the environments that the P.U.T.T.I will be deployed in and running out of power in these warzone areas could result in a significant loss of life and put people at serious risk of injury.

4.12 Environmental Constraints

Another constraint that will impact the P.U.T.T.I substantially will be the environment. Since the P.U.T.T.I will be employed in a variety of different environments there will be a significant amount of interference that could affect the functionality of the system. Since the system is based on a microwave sensor and camera the environment can significantly impair the device from being able to accurately detect objects in the surrounding environment. It is difficult to test how the system will function at every type of lighting, temperature, or humidity but it is still a constraint that needs to be considered when designing the P.U.T.T.I, not just to ensure that the tracking system works but also to ensure that there are no issues with other environmental phenomena.

The lighting in different environments can change drastically and these fluctuations in the lighting can cause issues with the camera's detection software. Additionally specific areas such as desert environments are likely to have much more glare than other environments which can also significantly impact the camera. It is important that we take this into consideration when designing the system to track the images. Some ways that we can try to counteract this are by using specific filters on the lens or using a lens hood however this may not be practical for the P.U.T.T.I, depending on the size of the hood. It is very difficult to create a system

that works in every type of environment so another way that we can deal with this is by making the systems software easily adjustable to fit the specific environment that it is being deployed in however this would mean that additional personnel would likely be needed to deploy the device which has a big impact on the ease of use for the device, we want to make sure that the device is easily deployed and accessible however to ensure proper functionality we may have to make a change that makes it slightly harder to deploy.

Another significant environmental constraint is interference with the cameras in the atmosphere that obscure the camera such as fog, rain, snow, sandstorms, etc. These types of obscuration can have a huge impact on the cameras ability to track moving objects. One of the ways that we have decided to combat this issue is by also employing a microwave sensor module which can work much better in these environments however it may impact the accuracy of the system. Unfortunately, because of the high dependence on electrical components we may not be able to make a system completely immune to these effects however we can do our best to make sure that the system does not experience a catastrophic failure.

Whilst fog mostly affects the cameras' ability to detect and track objects rain, snow, and sandstorms can also have a significant impact on the actual components on themselves as they can cause damage to the electrical components or the chassis of the P.U.T.T.I. This is a very likely problem that the device will run into so we need to make sure that we take all the necessary precautions to ensure that the system can always work in all these situations due to the unpredictable nature of these natural occurrences. We can make sure that all the electrical devices are properly sealed in waterproof materials to ensure that snow and rain cannot reach the electrical components of the device short circuiting the system and causing catastrophic failure. We can also make sure that the material that the chassis is made from is durable whilst still being lightweight, this can help with sand from eroding the exterior which whilst not immediately an issue could become more of an issue the longer that the device is exposed and deployed.

The humidity and temperature of the atmosphere is also incredibly important. We can expect the device to be employed in environments that frequently reach freezing or below freezing temperatures as well as environments that experience intense heat. We can also expect to see areas where the humidity can reach upwards of 90% to 100% and as low as 10%. Temperature and humidity can have a huge impact on the electrical components of the device. We want to make sure that the device does not overheat which could cause excessive power loss or decreased functionality and we also want to make sure that the electrical components do not get too cold which could cause them to contract resulting in cracks or damage to the components. The humidity can also have similar effects on the electrical components of the system. If we expose the system to a high humidity environment, then there could be excessive condensation which could result in the system short circuiting and ceasing functionality. If the device is exposed to a low humidity environment, then there could be electrostatic discharge (ESD) that can damage the electrical components. The main way that we are handling these issues is to monitor the humidity and temperature of the

environment using humidity and temperature sensors so that we can automatically turn off the system in the case that the humidity or temperature reaches a point where the system may become damaged or have diminished functionality.

The environment will have a significant impact on the design of the P.U.T.T.I due to the various ways that it can cause damage to the system or the ways that it can result in decreased functionality. We want to make sure that the device can function at its best in all the different types of environments that warzones typically occur in. If these constraints are not considered, then we could see the P.U.T.T.I have poor performance in specific environments.

4.13 Economic Constraints

One constraint that we need to take into consideration is how much the design process for the P.U.T.T.I is going to cost. Our project is not sponsored meaning all the costs for the project are coming directly from our own funds, so we want to try to make sure we are not making unnecessary purchases throughout the whole design process. From the individual part costs to the manufacturing costs for the PCB.

Likely the most expensive aspect of the design process will be ordering the PCBs. Due to recent political events this has become an even bigger issue due to tariffs and other taxes that have caused the cost of PCBs from many vendors such as JLCPCB to skyrocket. To prevent us from spending too much money on these PCBs it is imperative that we conduct extensive testing on the PCBs before ordering and get approval from other sources and professors so that we can order these PCBs without having to worry about them having any catastrophic failures.

The second most expensive part of the project is the single-board computer. Due to the requirements for image processing, we were forced to spend additional money on a more powerful single-board computer. To make sure we do not spend too much of our budget on a single part we need to do extensive research and should consult our committee members as well as our advisor before committing to such an expensive component.

Overall, the rest of the components should not be too expensive, but we still need to be careful that we do not incur additional spending due to errors we make. We must make sure that all components we purchase are handled with care and we try to find vendors with the best possible deals. We have quite a high budget given that the project is individually funded by the four group members but ensuring that we can progress through the design process in the most inexpensive way possible is of the utmost importance.

4.14 Health and Safety Constraints

A very important constraint in the design process of the P.U.T.T.I is health and safety. We want to create a device that is used to prevent loss of life or injury, so we need to make sure that the device does not cause any damage to users or combatants alike.

Since we are using electrical components, there is always a slight risk of combustion and fires, so we need to ensure that we mitigate this risk as much as possible to ensure that the device does not malfunction and causes injury to those around. Another component that we are using has the potential to cause injury is the laser. We need to make sure that the laser we use is strong enough to be easily seen, however it will not cause significant damage to those around us. The best way to achieve this is to make sure that the camera detection is incredibly accurate and never accidentally detects a human, particularly a human face, as an object to target. Whilst we will only be using a low powered laser for the purpose of this course it is important to understand that it can still cause damage if directed into the eyes of those around them and we want to make sure that even with a high powered laser we would not have to worry about causing injury to people.

In addition to trying to limit the components of the device from causing health and safety concerns, we will also need to take measures to shut down the device. We should try a way to shut down the device as a precaution remotely in case the device malfunctions. The temperature and humidity sensor will act as an automatic way to disable the device in the case where the temperature or humidity are too high for the device to function however, we should still implement a way to shut down the device if an unforeseen issue arises.

As the core premise of the P.U.T.T.I is to prevent the loss of life making sure that the device is reliable and can always operate without fear that it could cause damage to its users is of incredible importance. If we do not take the necessary precautions to prevent such issues from occurring, we could end up doing more bad than good.

4.15 Sustainability Constraints

Our device will be deployed in very volatile situations that can lead the device to being destroyed. This means that we need to make sure that the device will not have a major impact in the environment, not just through the materials we use but also the power consumption, and the environmental damages from the processes of making the device.

The biggest consideration that we must make about sustainability is the environmental impact that the device could have if it were destroyed or damaged. We expect that the device may leave parts of it scattered in the environment in the case that it is damaged so we must consider if any of the parts of the system could cause environmental damage. One of the biggest fears is that electrical fires could cause brush fires and other similar fires in areas if sparks are created by electrical components.

Another major sustainability constraint that we need to take into consideration is the amount of power the system consumes. We don't want the system to consume massive amounts of energy as we want to limit the amount of energy that the system needs to use that could be used in other areas. Ensuring that the system has a long and sustainable battery life is incredibly important given the environmental effects that the production and charging of batteries can have.

The final sustainability constraint that we need to consider is the processes that go into the manufacturing process for the P.U.T.T.I. Since we are using 3D printed chassis in the prototyping, we need to consider the environmental impacts and footprint that these materials have, and we should investigate alternatives for a fully-fledged design. The electrical components and PCB production also are incredibly damaging to the environment so ensuring that we can limit the amount of PCB orders and the PCB size we make is necessary to lower our environmental footprint.

4.16 Political Constraints

The P.U.T.T.I is a device intended to be used in warzone environments, meaning that for eventual approval and use we would need to cut through a lot of red tape for the project to get approval for use. It is important that we consider all the potential challenges that could be made against using the device and incorporate these challenges into the design process and ensure that the device can be approved. This may come down to making the user interface easier for human handlers to understand or ensure that the device is easily able to be demonstrated and accurate to what we set forth with the proposal of the device. Additionally, we will need to ensure that the device does not push against any existing laws both within the United States across all states but also internationally.

Chapter 5 – Application of ChatGPT and Other Similar Platforms

5.1 GitHub Copilot

GitHub Copilot, or may be referred to below as GHC, is the powerful AI created by GitHub. GitHub Copilot has several features, including the ability to be assigned to issues. When done so, GitHub Copilot will plan out solutions, write code and create test, then verify that the correct results are produced, finally generating a pull request with the solution. It can also review your own pull requests, determining bugs before letting another reviewer examine your code¹²⁵

While the above features are important, one of the more powerful and used features is the built-in VSCode extension. Because the AI has been trained on public code repositories, it has the ability to suggest edits and generate new code in almost any language. Inline code suggestions can provide solutions to one line or an entire function. Additionally, prompting the AI in the extension panel can let the AI examine and explain current code, answer questions, or act like a basic LLM and respond to prompts. The AI can also receive a prompt through the side panel rather than the inline editor to edit multiple files or large sections at a time based on the user's prompt¹²⁶.

¹²⁵ "GitHub copilot · your AI pair programmer," GitHub, <https://github.com/features/copilot>.

¹²⁶ Microsoft, "GitHub copilot in vs code," RSS, <https://code.visualstudio.com/docs/copilot/overview>.

The GitHub Copilot AI can be incredibly useful when writing code, especially when multiple files are involved. Instead of having to copy and paste contents of the files into another LLM, they can be designated in the side panel as context so that the AI knows what code to draw inspiration from or what code to edit. The ability to both ask questions to the AI and ask for edits to code makes it incredibly versatile at writing, developing, and reviewing code. One downside to the AI is the limited prompting ability. While available in a free state, it comes with limited messages per month. A purchasable upgraded plan is required to have more prompts.

The AI will make some hidden benefits and flaws visible when put to use. Please refer to Appendix E for the Case Studies of GitHub Copilot and the outcomes of these prompts.

5.2 ChatGPT

ChatGPT, is a very well-known AI created by OpenAI. ChatGPT is best used for asking questions and trying to further your understanding of certain topics. When asking ChatGPT a question, it will answer in a variety of ways either giving full on paragraphs or bullet points, and almost always ending its response with a question along the lines of asking for if you require more assistance.

In addition to being able to ask questions, you can also ask ChatGPT for coding questions and when doing so the AI will give you a code that you can try to fix your problem. This is incredibly useful for quickly generating a skeleton code that you can work with to get started with whatever you are trying to do¹²⁷.

5.2.1 Case Study 1

This first case study [GHC Case Study 1] was meant to showcase the power of the Ask feature of the GitHub Copilot AI. The prompt intended to allow analysis of the AI's ability to describe a successful YOLO training. In short, it did an excellent job at explaining the whole process. The process would involve most of the steps explained by the AI. One successful training would start by collecting images for the dataset and creating labels for each image. The class for the image would need to be specified as labels are created for each image. It even gave a common example of how the dataset should be structured and some common sites which allow for easy labeling using a GUI.

Beyond getting a detailed description of the setup for the dataset, the AI also provided a correct method of training the data using Ultralytics. It provided a valid data.yaml file to use to specify the directories of the training data and labels as well as the classes in the model. It also specified how to install and use the Ultralytics python package with valid pip install and commands. Furthermore, it went beyond and provided verification commands to ensure that the model was correctly trained and could detect objects. The useful tips provided were an added bonus which revealed further hidden details about the process and will be very useful in putting

¹²⁷ "A Brief History of AI and the Rise of ChatGPT," *GaussAlgo*. Available: <https://www.gaussalgo.com/knowledge-base/a-brief-history-of-ai-and-the-rise-of-chatgpt>

Ultralytics to use. Overall, the Ask feature provided a well-structured and detailed response which will provide for a successful start to training the dataset.

We can take Copilot's response and compare it to ChatGPT's response, a more commonly used LLM. Both ChatGPT and Copilot had the same format when it came to answering the prompt, first stating how they'll give a walkthrough of how to train a yolo model, then giving steps on how to train the yolo model, and finally both offered tips as to how to best train the model.

However, this is where the responses started to differ. While both explained the steps as to how to train the yolo model, they explained their steps in a different order. Copilot gives the recommended folder layout in step four, while ChatGPT gives it in step two. It's also worth noting the way ChatGPT showed the layout of the folder was different than that of Copilot, where it showed the file path by utilizing dashes to show the overall structure of the file giving a better understanding of where all the different folders go. Going further into the different steps comparing the steps where they talk about the data.yaml file, again they basically give the same information, but this time Copilot also adds another way you can implement the names. Another difference between the two appears in step six of the Copilot's instructions, where it says to make sure at this point to install Ultralytics and train, something that ChatGPT assumed the user had already done. Additionally, ChatGPT gave way fewer tips than did Copilot, which is less than ideal for someone who is just using a yolo model for the first time. Finally, they differ in terms of their final statement: ChatGPT asks if it could show me an example to see a YAML in practice while Copilot gives three options, one being to generate a data.yaml file, create a script, or to produce a valid script. The difference here is that ChatGPT wants to only provide an example so that the user can learn on their own while Copilot asks if the user would want it to just make the files for them.

5.2.2 Case Study 2

This second case study [GHC Case Study 2] was meant to showcase the power of the Edit feature of the GitHub Copilot AI. To capture many images, a script was needed to record the targets in motion as they pass the camera on the SBC. Rather than taking individual pictures, capturing many from a live feed only when motion is detected would provide better results and image collection.

Overall, the Edit feature did a solid job creating a Python script to capture the images. It followed all of the instructions provided by the prompt. It used OpenCV to capture images from the camera and to store the image whenever motion is detected. The algorithms appear to be correct, but one issue arose since the code only captured frames every five seconds. While the unique ID's present in the filenames would ensure no file got overwritten, it would not matter much since the script would be no better than capturing the images by hand. A change needed to be made for this, but the remaining parts of the code seemed correct.

Again, asking the same prompt but now putting it into ChatGPT gives a rather similar response, where ChatGPT states what the code is supposed to accomplish and then gives the code. Unlike Copilot though, ChatGPT also gives a brief

explanation as to how the code works and instead of stating the end to make sure that opencv-python is installed, it instead states so at the beginning before showing us the code.

Now comparing the actual codes that were provided, ChatGPT gave a much more commented code, explaining what each of the little sections of the code did, as well as what should be changed to fit our project's needs unlike Copilot which only gave a few comments throughout the whole code.

5.2.3 Case Study 3

This third case study [GHC Case Study 3] was meant to showcase the power of the Edit feature's correcting capabilities of the GitHub Copilot AI. To fix the previous prompt from GHC Case Study 2, the Edit feature was employed again to alter the file.

This time, the Edit feature provided ideal solutions to the script. While only removing six lines and adding six lines, the changes yielded a valid script which would serve the purpose of gathering numerous images for the dataset. Now, the script could be employed to gather images for the dataset to train the YOLO model using Ultralytics. After employing the script, data would be randomly sorted into the directories specified from GHC Case Study 1 and the methods described would be followed. Overall, the Edit feature can provide a great place to start with writing code but may be prone to making small failures, especially if prompts are not specific or if poor wording is present; however, it can perform changes afterwards successfully.

Comparing what ChatGPT wrote in comparison to Copilot, these answers ended up being very different in terms of format. ChatGPT went through the original code it came up with and edited bits and pieces of it to match what prompt we had asked for. ChatGPT changed the `SAVE_DIR = "captures"` line to a much more specified file that is referred to as `captures`. Beyond that, the code is still mostly the same, but at the end ChatGPT gave the features of the new code explaining what the code now will do and where it'll be saved to. In addition, like always ChatGPT asked to further modify the code so that it would run better on a raspberry pi.

5.2.4 Case Study 4

This fourth case study was done to just ask both artificial intelligences a non-coding question about our project, specifically about the way we would be powering our project so we could see what possible solutions exist. For this one we used the microsoft copilot as the github one is more coding oriented.

Copilot gave some battery suggestions right off the bat, recommending we use Li-ion or LiPo at 11.1 or 14.8 volts, as well as what components would need for the amount of voltage. It later went and estimated how much power our project could potentially use (which it found to be about 5000 mAh). Finally, it gave us some suggestions how to set up the batteries and how to ensure that they were safely implemented so no harm would come to us or our system.

Comparing this to ChatGPT, ChatGPT also gave some different battery types, but instead of just stating them it went ahead and gave the pros and cons of the different battery types and when might be more preferred than the other. ChatGPT then went along and gave two options for how we could possibly setup our battery pack system and then gave many of the same suggestions as Copilot however at no point did it mention how it arrived at the power budget of our project, it just stated an example. The last big difference between the two was ChatGPT had everything labelled in sections from A-E while Copilot had just listed out what it recommended for our project.

Overall, both Copilot and ChatGPT gave good initial responses to the prompts that we asked them. ChatGPT gave more information to responses, as well as further recommendations or suggestions for what the user could do to further their understanding while Copilot was more straight to the point. It's important to note that there would be gaps in knowledge if we had not used both artificial intelligences. This was seen in case study one, where both Copilot and ChatGPT gave roughly the same response, but in slightly different orders and different tips and tricks that could be used to create what we wanted to make. ChatGPT overall is best for when you just need information as quickly as possible, while Copilot is better for learning the material yourself which again was seen in the case studies where ChatGPT would just give you the code, while Copilot gave pointers as to how to edit it.

Chapter 6 – Hardware Design

6.1 MCU

The microcontroller schematic we created uses the ESP32-WROOM-32. Using the datasheet for this, we were able to create a schematic that fits into our project's design, utilizing the necessary pins to connect the peripheral components to the microcontroller. We utilize multiple pins for different uses, for ADC, SCL, SDA, and I/O.

This schematic uses a couple of capacitors connected to the 3.3V input to filter any unwanted noise. Per the datasheet for the ESP32-WROOM-32 we used one capacitor of 10uF and another capacitor of 0.1uF connected in parallel and connected to the 3.3V input pin. The value of the 10uF capacitor could be changed to filter out more noise. However, since these capacitors are used elsewhere, we believed it was best when considering how many capacitors we would have to acquire.

There is also a 10,000-ohm pull-up resistor to enable the microcontroller so that it functions correctly. This means that less current flows through the EN pin, without it there could be some very serious issues with the microcontroller preventing it from working. There is also another 0.1uF capacitor connected to the EN pin to make the line more stable and reliable.

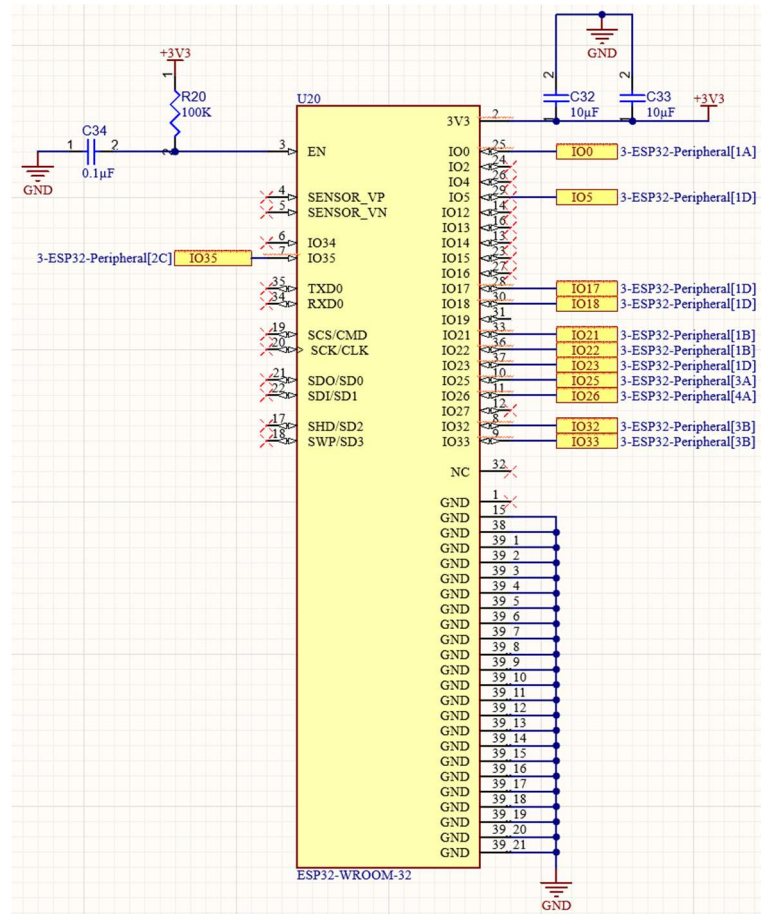


Figure 9 - MCU Connections

6.2 Atmospheric Peripherals

The 3721 humidity sensor by Adafruit is a four-pin device that transfers data via I2C. This device is powered by the 3.3V regulator and will be connected to the microcontroller by pins 2 and 4 which are the SDA and SCL pins of the 3721 respectively. Since the 3721 does not come with pull-up resistors, we needed to include one on both the SDA and SCL lines. We decided to use 10,000-ohm resistors, even though the standard is often 4,700-ohm resistors. We are already using the 10,000-ohm resistors in the microcontroller connections, so we felt it was better to continue to use similar parts when able. Additionally, there is another 0.1uF capacitor connected between the 3.3 V pin and ground pin which acts as a decoupling capacitor to ensure stability. The SDA pin will be connected to pin 33, or GPIO pin 21, of the microcontroller, and the SCL pin will be connected to pin 36, or GPIO pin 22, of the microcontroller.

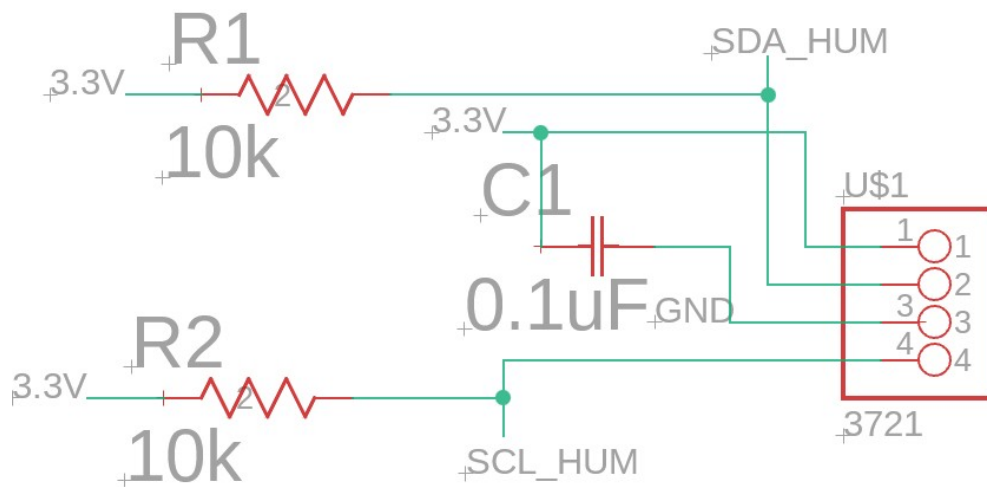


Figure 10 - Humidity Sensor Schematic

The temperature sensor is quite simple and schematic since we are using a thermistor, so we just need to connect the thermistor to the 3.3 V supply voltage and to the ADC1 channel of the microcontroller. There are some important parts of the schematic however, most notable for the 10,000-ohm pull-up resistor that we connect between the 3.3 V supply and the thermistor. We chose this value because the thermistor has a value of 10,000 ohms at room temperature so using the same resistance in series, we can make sure that room temperature corresponds to half of the input voltage, which should be around 1.65 volts making translating the readings of the thermistor easier. There is also another capacitor used for decoupling; however, this time we opted to use a 10nF capacitor. The thermistor is connected to a pin that has ADC1 support which for us was pin 6.

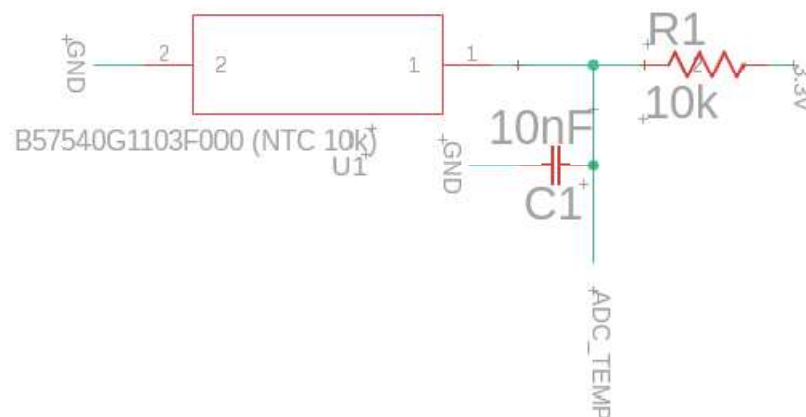


Figure 11 - Temperature Sensor Schematic

6.3 Laser

The laser system functions on an I/O pin, meaning that it is either on or off. Despite this, there are some intricacies to the design of the laser module. The main component of note is the MOSFET; we need to use this because the amount of current needed to power the laser is too much for the ESP32 to produce. This allows us to have much safer control over the powering of the laser. The 100-ohm resistor is used to protect the ESP32 from having too much voltage input, and the 100,000-ohm pull-up resistor guarantees that the laser will always be turned off when the system first turns on. The laser module is connected to the microcontroller via pin 25.

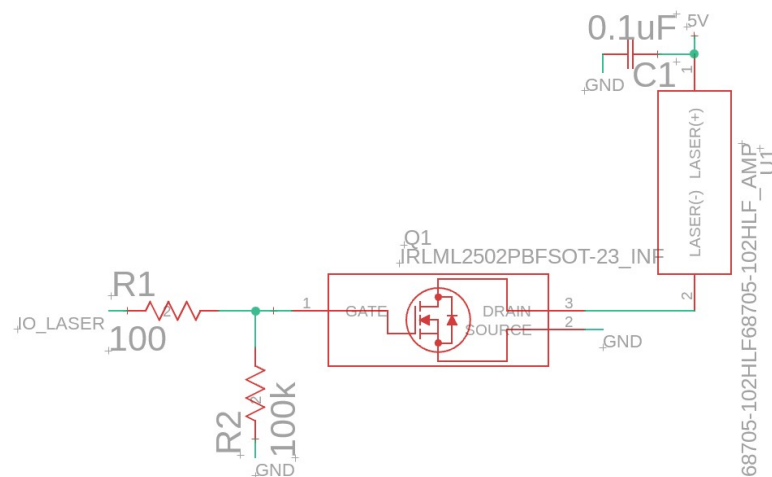


Figure 12 - Laser System Schematic

6.4 Power Delivery/Electrical Power System

The power system of our project consists of a power supply which uses a six cell 5000 mAh 22.2-volt battery. The battery and overall power system are important for this project as without it regardless of how good our tracking software is, it won't turn on and won't work as a result. It's important that we have other systems in place to protect our circuit and keep it from providing too much voltage to any given component.

Since most of the power for the system is generated by batteries, we need to make sure that the input voltage for the various components and microcontrollers that we are using does not exceed the amount that they can handle. Most of the components and the microcontroller will take a 3.3-volt input, meaning that we need to create a voltage regulator that can create a stable 3.3-volt output. This regulator will be on the main PCB board with the rest of the components. The 3.3-volt buck regulator schematic is below.

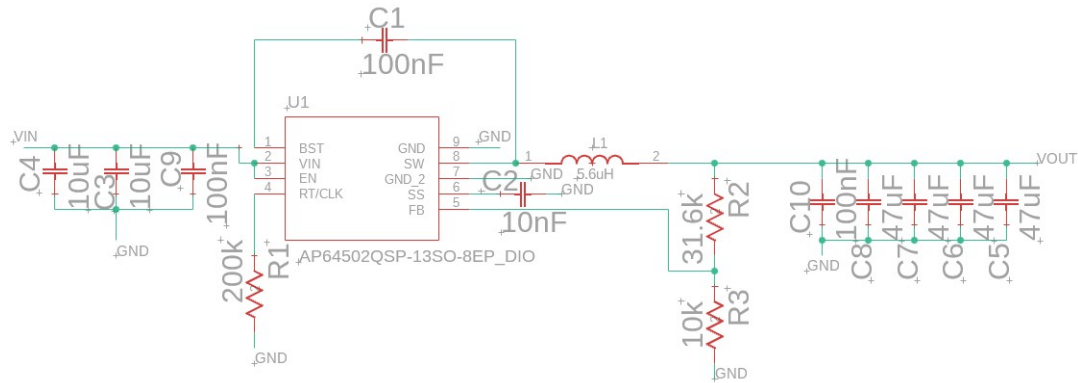


Figure 13 - 3.3V Switching Regulator Schematic

A few of the components in the device will also need to be powered by a 5V regulator. Since we are using the same regulator, we can also keep most of the circuit the same as there being some minor tweaks to ensure a proper output of 5V. The most notable changes are the 31.6k ohm resistor being swapped for a 52.3k ohm resistor and the inductor being changed from 5.6uH to 6.8uH. With these minor changes we can guarantee that the output will be 5V. However, we will still need to test the regulators to make sure they are built correctly and provide the correct output.

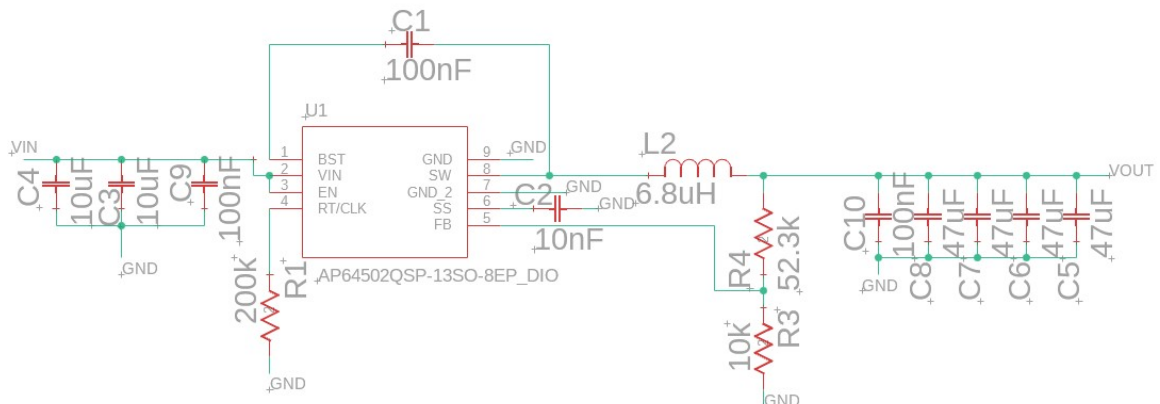


Figure 14 - 5.0V Switching Regulator Schematic.

In addition to the switching regulators, our project also requires a 1.8V linear regulator to regulate the voltage of the microwave module. The NCP1117IST18T3G is the fixed LDO voltage regulator for our project. Current draw shouldn't be an issue since it's only powering the microwave module, so 1A should be more than enough.

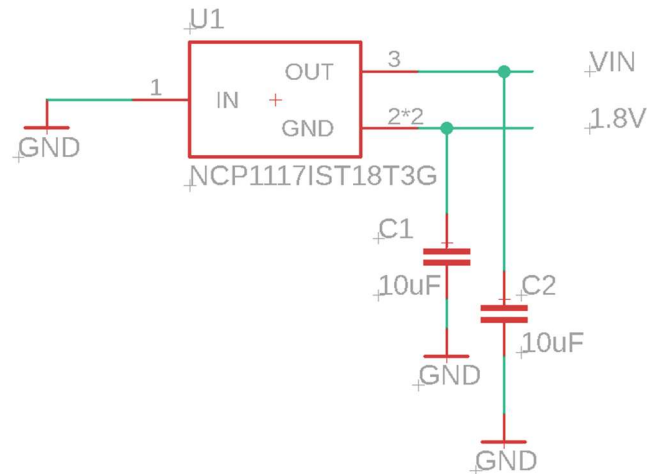


Figure 15 - 1.8V Linear Regulator Schematic

6.5 LCD

The LCD module connects to the ESP32 through the SPI interface. This setup uses four main signal lines, those being the CSB (chip select, GPIO5), SCLK (clock, GPIO 18), SID (data input, GPIO23), and RS (register select, GPIO17) which sends data and commands to the screen. The VSS and VDD pins provide ground and power, respectively, while the V0 pin is connected to a variable resistor (potentiometer) that adjusts the contrast of the display for better visibility under different lighting conditions. Additionally, the LED+ and LED- pins control the backlight of the screen, ensuring it's easy to read. A 100Ω current-limiting resistor can be added to the backlight circuit to prevent overcurrent. Altogether, this configuration allows the ESP32 to display data efficiently and clearly, making the LCD a key component for real-time feedback and system monitoring on the P.U.T.T.I.

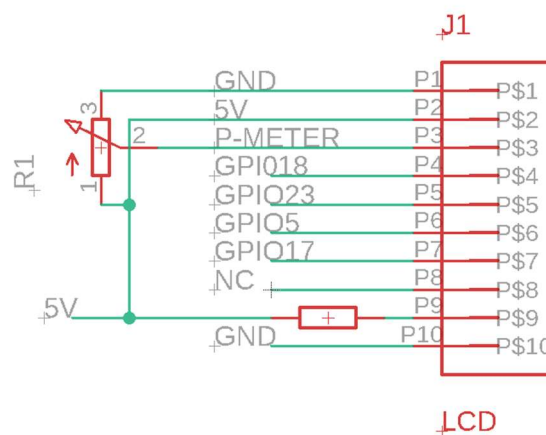


Figure 16 - LCD Schematic

6.6 Motors

The servo motors are connected to GPIO pins 25 and 26 on the ESP32, which are both capable of sending PWM signals to control their movement. These pins let us adjust the position of each motor by changing how long the signal stays on and off, giving us smooth and precise control. The signal from each pin goes to the servos control line, while the power and ground are supplied separately from a steady 5 V source to make sure the motors have enough strength and don't draw too much from the ESP32. This setup lets each servo move independently, so we can fine-tune their motion and get consistent, responsive control as the system runs.

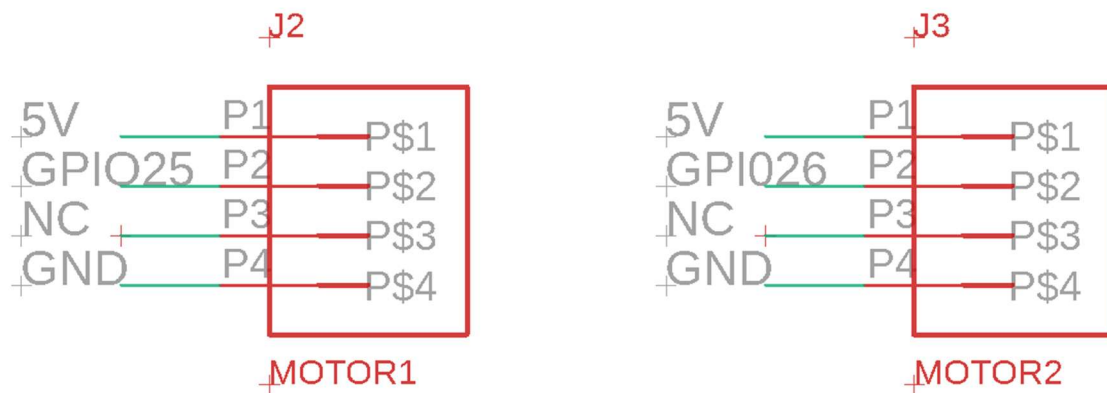


Figure 17 - Motors Schematic

6.7 Buzzer

The CMI-1275-03TH active buzzer is connected to the ESP32 through a GPIO pin. The circuit for the buzzer is quite simple and can be found below, it consists of a NPN transistor which helps provide a steady current to the buzzer and gives us the opportunity to switch the buzzer to a 5 volt input if we want to increase the volume of the buzzer at a later point, a 100k ohm resistor which acts as the pull-down resistor, the 1,000 ohm resistor which guarantees that the transistor will switch cleanly, the 100nF capacitor which is used for decoupling, and the actual buzzer itself which will produce the sound and create the holes needed to solder the buzzer into the PCB.

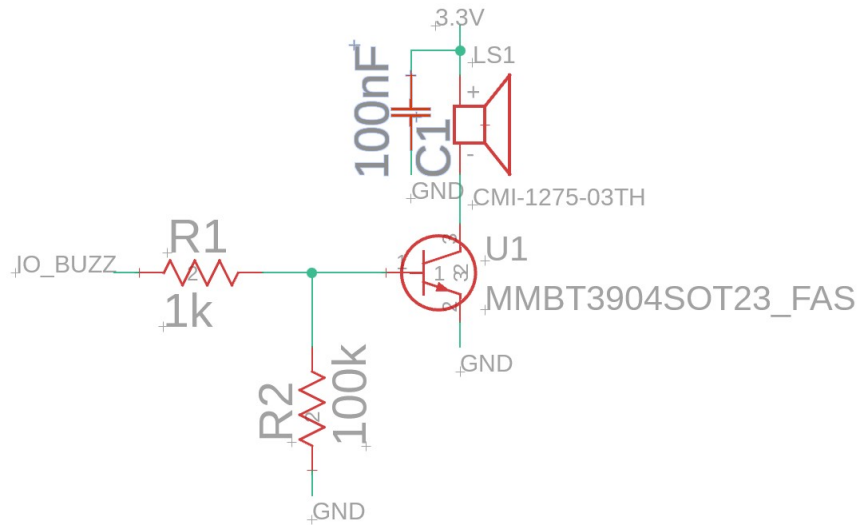


Figure 18 - Buzzer Schematic.

6.8 Radar Module

The XM125 is one of three microwave modules that will be connected to the I2C of our ESP32 in addition to ground. This will be accomplished by having male and female connectors on the board so that way we can test each microwave module individually.

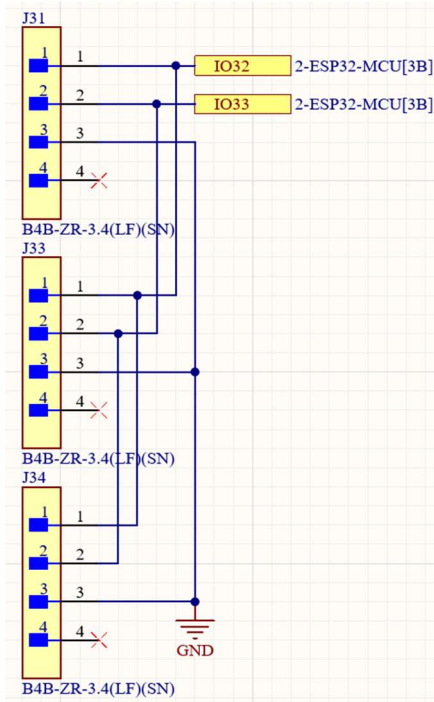


Figure 19 - Radar Module Schematic

Chapter 7 – Software Design

This project requires three major software components, uploaded directly to the SBC, XM125, and MCU, respectively. The software on the SBC will consist of computer vision detection, and the software on the MCU will consist of motor and laser control and extraneous component control. These different components will be essential to ensuring the project's success.

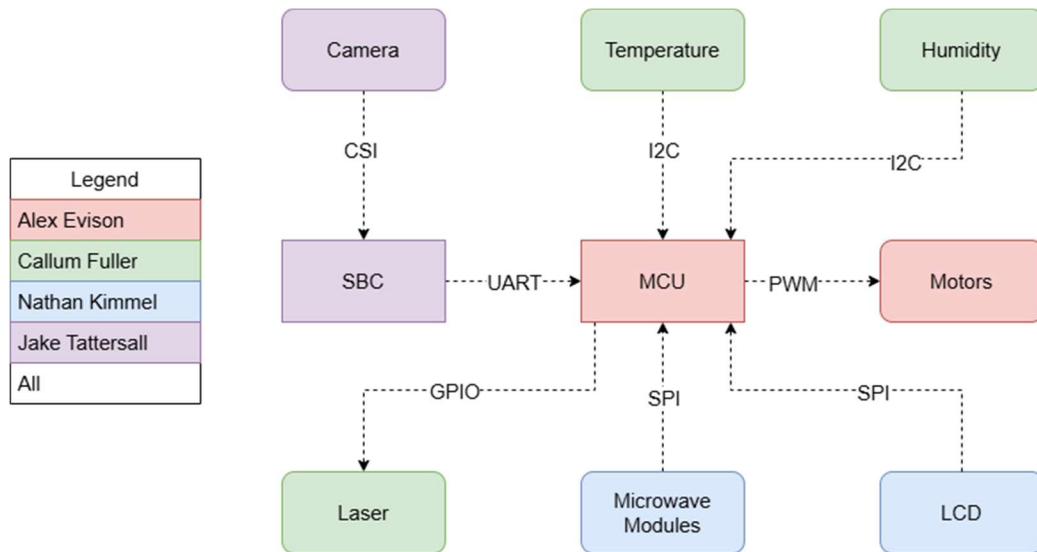


Figure 20 - Data Transfer Diagram

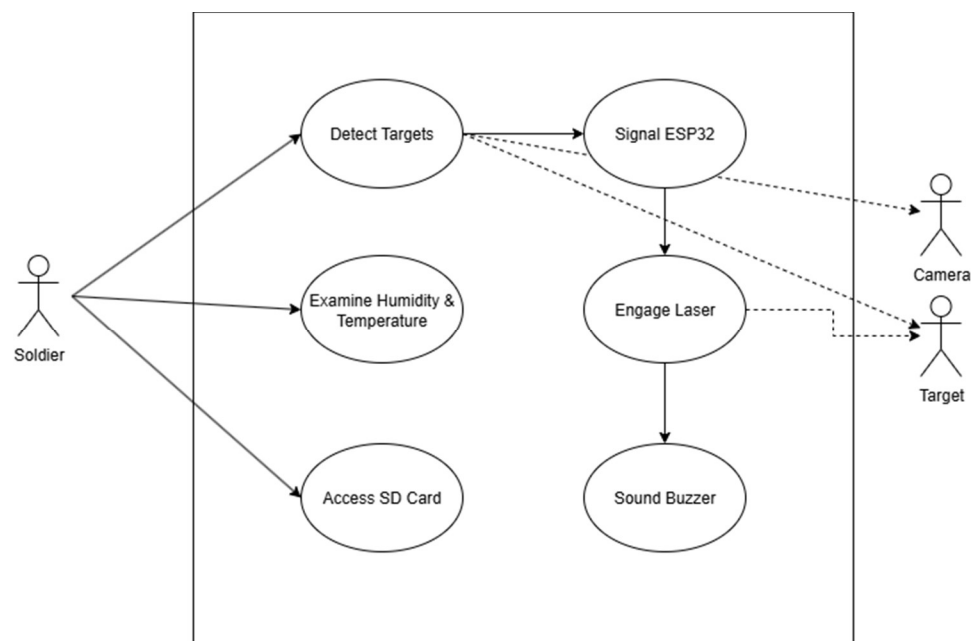


Figure 21 - Use Case Diagram

7.1 Git and GitHub

All software written for this project will be stored on GitHub. GitHub is an online repository platform that uses Git, a distributed version control system, to track and manage changes across a codebase. With Git, every contributor maintains a full local copy of the repository, including its entire history, enabling fast operations and full offline access. Users can easily clone a repository to begin development on their local machine, make incremental changes, and use Git to commit those changes with descriptive messages. These commits can then be pushed back to the online repository, ensuring that updates are backed up, synchronized across collaborators, and integrated into the project's official history.

GitHub also provides additional features that standardize collaboration and improve software quality. Branching allows developers to work on new features or experiments in isolation without affecting the main codebase, while pull requests create a formal process for reviewing proposed changes before merging them. This encourages thorough documentation, peer review, and adherence to coding standards. GitHub's issue tracking, project boards, and integrated CI/CD pipelines further support development by organizing tasks, automating testing, and catching errors early. By using GitHub as the central development hub, the project ensures traceability, reduces integration conflicts, and maintains a structured and transparent development workflow that aligns with industry-standard version control practices.

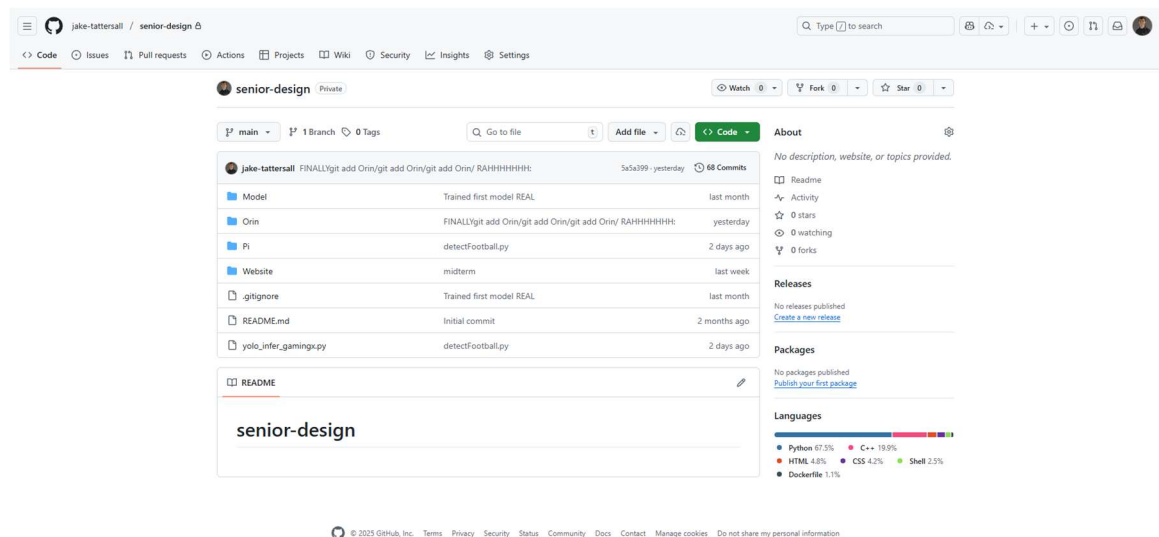


Figure 22 - A GitHub repository created for this Senior Design project.

7.2 Computer Vision Detection

The currently proposed method of image detection is to use a YOLO model to detect valid targets. Using this model, the camera and Single-board Computer will detect valid targets and relay the relative position to the MCU. The YOLO model will be implemented using Ultralytics, a company devoted to making AI open

source and available to the public. The procedure to train and implement the model is well-documented and straightforward. While performing the image detection, motion detection may be occasionally implemented so that the YOLO predictions are not needlessly evaluated every frame. This gating method can lead to faster runtime, while making sure that immobile targets are still captured¹²⁸.

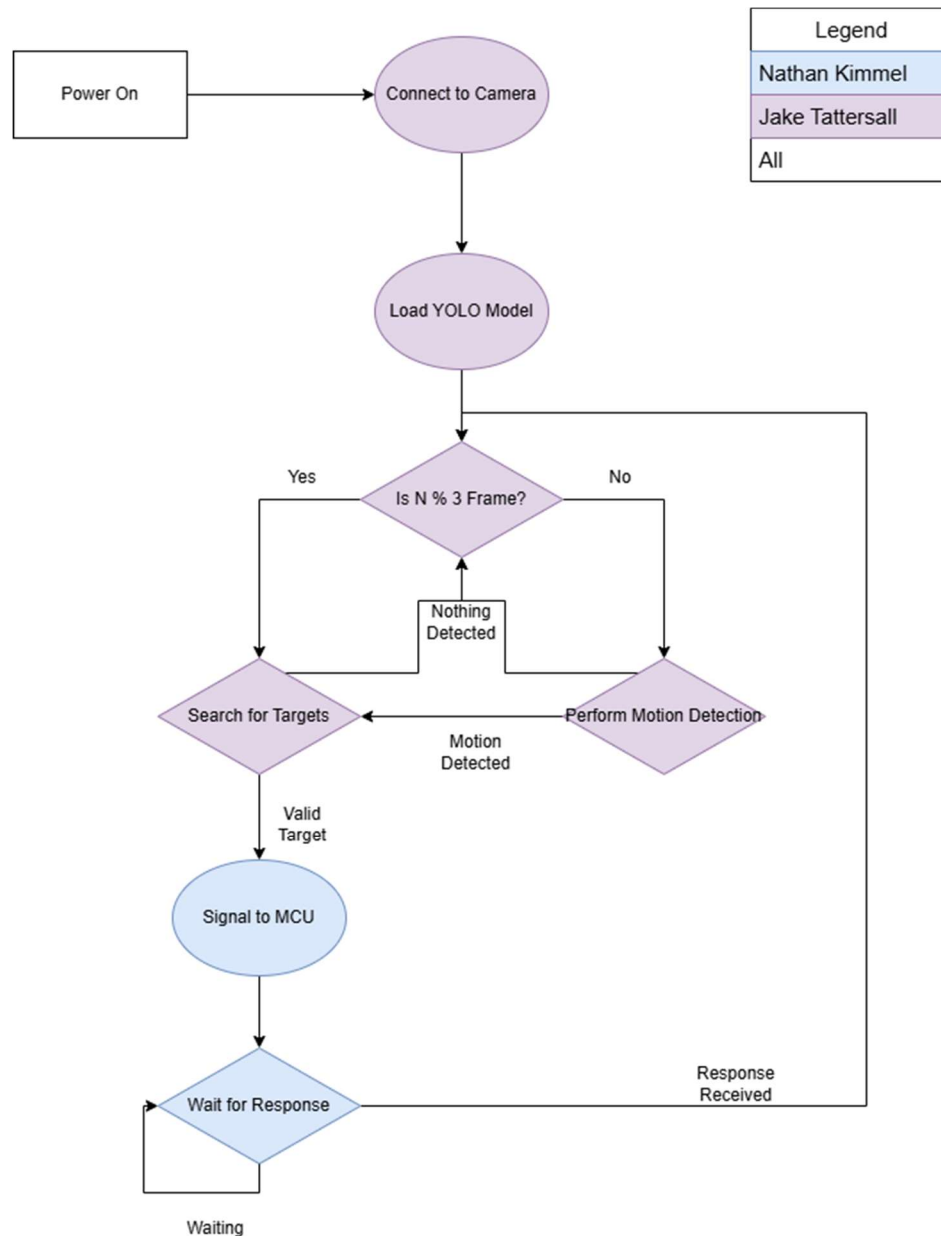


Figure 23 - Single-board Computer Flowchart

¹²⁸ Ultralytics, "Home," Ultralytics YOLO Docs, <https://docs.ultralytics.com/>.

7.3 Python Development

Programming for the Orin Nano will take place using Visual Studio Code (VSCode) and PyCharm. Visual Studio Code is an open source code editor which supports almost every language. For most common activities, an extension exists to implement it in the IDE. For example, a Git extension can be implemented to simplify the process of pushing and pulling commits as well as viewing previous commit history. Built into VSCode is a Copilot extension to aid in writing code or answering questions about how code may work¹²⁹.

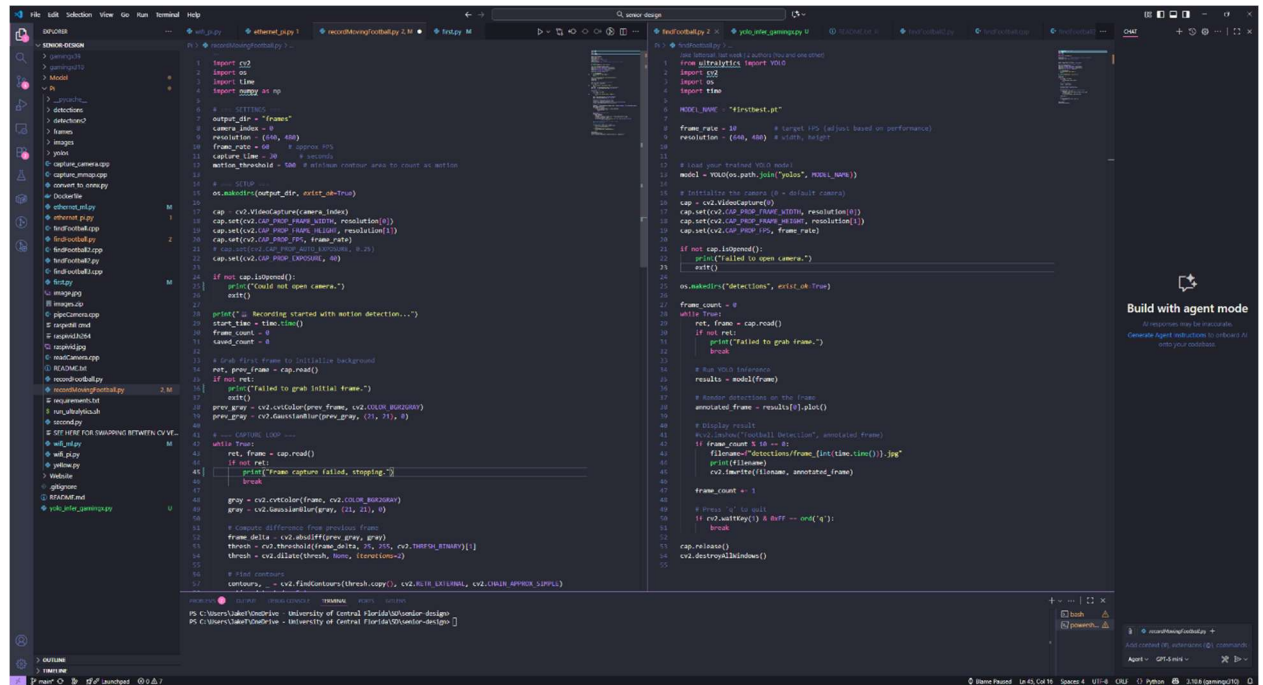


Figure 24 - The VSCode IDE being used to develop Python scripts.

PyCharm is a Python-specific IDE used to develop Python projects. While the PyCharm version on the Orin Nano may not have the flexibility of VSCode, it is still a powerful tool for editing Python scripts. It has built-in capabilities of detecting references and declarations of functions and variables to allow for easy support when seeking code explanations. It also advertises auto-code completion for mundane tasks to assist with the parts the user does not need to worry about. It is an extremely powerful IDE which will provide a much better alternative to a standard text editor¹³⁰.

¹²⁹ Microsoft, "Visual studio code - the open source AI code editor," RSS, <https://code.visualstudio.com/>.

¹³⁰ JetBrains, "PyCharm: The only python ide you need," JetBrains, <https://www.jetbrains.com/pycharm/>.

7.4 Interfacing with the Camera

To interface with the camera, the OpenCV library will be used to detect the primary video device. The OpenCV library provides quick and efficient methods for capturing images and setting resolution and frames per second, while ensuring that the runtime speed is not hindered. Using the results of the OpenCV library function calls will allow for fast image post-processing in an easy manner with little-to-none setup. The camera will likely be usable on connection, so image capture should be quick and easy.

7.5 Machine Learning Model Development

In order to detect objects, the Nvidia Orin Nano Super DevKit will use a YOLO (You Only Look Once) model, manually trained to detect desired objects. First, data had to be collected to train the model, followed by performing the training then finally implementing it on the Single-Board Computer.

7.5.1 Data Collection

The first step of using the YOLO model is to collect data for the model to train from. This means that select targets needed to be pre-identified and used to train the model. A python script was implemented to capture images. These images should be captures from the camera being used so that the model can detect objects how they will actually be viewed by the programs being run.

To capture images from the camera, the OpenCV library was used to read frames and store them. OpenCV, short for Open Source Computer Vision Library, is a widely adopted open-source library designed for computer vision and image processing tasks. Primarily supported in C++, Python, and Java, it provides a wide range of tools for capturing, manipulating, and analyzing images and videos. Its main goal is to offer a common infrastructure for computer vision applications and to accelerate the adoption of machine learning and perception technologies. The library includes over 2,500 optimized algorithms for tasks such as face detection, object recognition, human action classification, motion tracking, and more. OpenCV is used by well-established companies like Google, Microsoft, IBM, Intel, and various automotive manufacturers, as well as many startups, making it a highly regarded and widely known tool. The community is extensive, with forums and Q&A resources directly linked on the official website.

After the images were captured using the fisheye camera and OpenCV, they needed to be labeled to prepare them for model training. Labeling is a critical step in supervised learning, as it allows the model to understand which parts of an image correspond to the objects of interest. In the YOLO (You Only Look Once) framework, each labeled object is represented by five numerical values that define its class and bounding box coordinates, enabling the model to learn both what the object is and where it appears within the frame. To generate these labels, the Make Sense AI (makesense.ai) tool was used. Make Sense AI is a browser-based platform that simplifies the labeling process by allowing users to upload images directly and annotate them through an intuitive graphical interface. Its design

makes it especially convenient for quick dataset preparation, as all processing occurs locally in the browser, ensuring that uploaded images are not stored on external servers and that data privacy is maintained throughout the process¹³¹.

7.5.2 Model Training

The process to train the YOLO (You Only Look Once) model has simplified significantly thanks to the help of Ultralytics. Ultralytics is the organization responsible for developing and maintaining the modern implementations of the YOLO family of models. Their open-source framework provides an accessible and efficient way to train, validate, and deploy object detection and image segmentation models. The Ultralytics Python package simplifies the training process by offering a high-level API that automates tasks such as dataset handling, augmentation, model configuration, and performance tracking. It supports multiple YOLO architectures, including YOLOv5, YOLOv8, and custom-trained variants, allowing users to fine-tune models on their own datasets with minimal setup. In addition to local training, Ultralytics integrates seamlessly with popular machine learning tools and hardware accelerators, enabling rapid experimentation and deployment on platforms ranging from desktop PCs to embedded systems.

With the dataset fully prepared and labeled, the next step was to configure and train the YOLO model using the Ultralytics framework. The labeled images were divided into training and validation sets to allow the model to learn from one subset while being evaluated on another to measure its performance and prevent overfitting. Each image and its corresponding label file were organized according to the YOLO directory structure, which separates data into train, val, and optionally test folders, each containing images and their annotation files. A YAML configuration file was then created to define the dataset paths, the number of object classes, and their respective names.

Once the dataset configuration was complete, training was initiated through the Ultralytics command-line interface. Using a command such as “yolo task=detect mode=train model=yolov8n.pt data=data.yaml epochs=100 imgsz=640”, the model began iteratively adjusting its internal parameters to minimize detection errors. During training, the framework automatically handled data augmentation—such as random scaling, cropping, and flipping—to improve the model’s robustness under varying conditions. Real-time progress and accuracy metrics were displayed throughout the training process, including loss values, precision, recall, and mean average precision (mAP)¹³².

After training completed, the model’s performance was evaluated on the validation dataset to verify its accuracy and consistency. The best-performing weights were saved automatically by the framework, representing the model state that achieved the highest validation accuracy. These trained weights were later exported and deployed to the Single-Board Computer for real-time object detection.

¹³¹ “Make sense,” Make Sense, <https://www.makesense.ai/>.

¹³² Ultralytics, “Train,” Ultralytics YOLO Docs, <https://docs.ultralytics.com/modes/train/>.

7.5.3 Model Implementation

Once the YOLO model was successfully trained, the next step was to implement it on the Single-Board Computer (SBC) for real-time object detection. The trained model weights, exported from the Ultralytics environment, were transferred to the SBC for deployment. Python was used as the primary programming language due to its strong compatibility with both Ultralytics and OpenCV, as well as its broad support for machine learning and image processing libraries.

To perform inference, the Python environment on the SBC was configured with the necessary dependencies, including Ultralytics, OpenCV, and NumPy. The connected camera was accessed using OpenCV's video capture functionality, enabling the SBC to continuously read image frames in real time. Each captured frame was then passed to the YOLO model for inference, where the trained network analyzed the image and returned predictions indicating the presence, class, and position of any detected objects.

To visualize results, bounding boxes and class labels were drawn directly onto the video feed, allowing for immediate feedback of detections. Performance optimization was considered throughout this process, with emphasis on maintaining an acceptable frame rate and minimizing latency. This involved selecting an appropriate input image size, utilizing hardware acceleration when available, and reducing unnecessary processing overhead.

The final implementation allowed the SBC to act as a self-contained detection system by capturing video input, performing inference locally, and displaying or recording detection results in real time. This approach demonstrated the feasibility of deploying advanced computer vision models on compact, power-efficient hardware suitable for embedded applications.

7.6 SBC Setup

In order to correctly set up the NVIDIA Orin Nano, several steps were necessary to ensure that the device could be fully operational and could serve as a proper development platform. Fortunately, NVIDIA provided a comprehensive first-time setup document to explain how to get to the home screen for the first time¹³³. While following this guide did not perform all of the required steps, the next steps afterwards were easily found through forums or official pages.

7.6.1 MicroSD Card Flashing

The first step was to flash the MicroSD card with an NVIDIA JetPack image. The official guide provided a link to the JetPack image on their website as well as a supported software, balenaEtcher, to flash the MicroSD card with the image. The software made the flashing process quick and easy. Simply booting up the application allows the user to select the image to flash and the drive, and the

¹³³ "Jetson Orin Nano Developer Kit Getting Started Guide," NVIDIA Developer, <https://developer.nvidia.com/embedded/learn/get-started-jetson-orin-nano-devkit>.

software handles the rest. The whole process first flashes then verifies a valid installation, and the process took about 10 minutes per flash. After a successful flash, the MicroSD card could be inserted, and the Orin Nano could be successfully accessed when booted up.

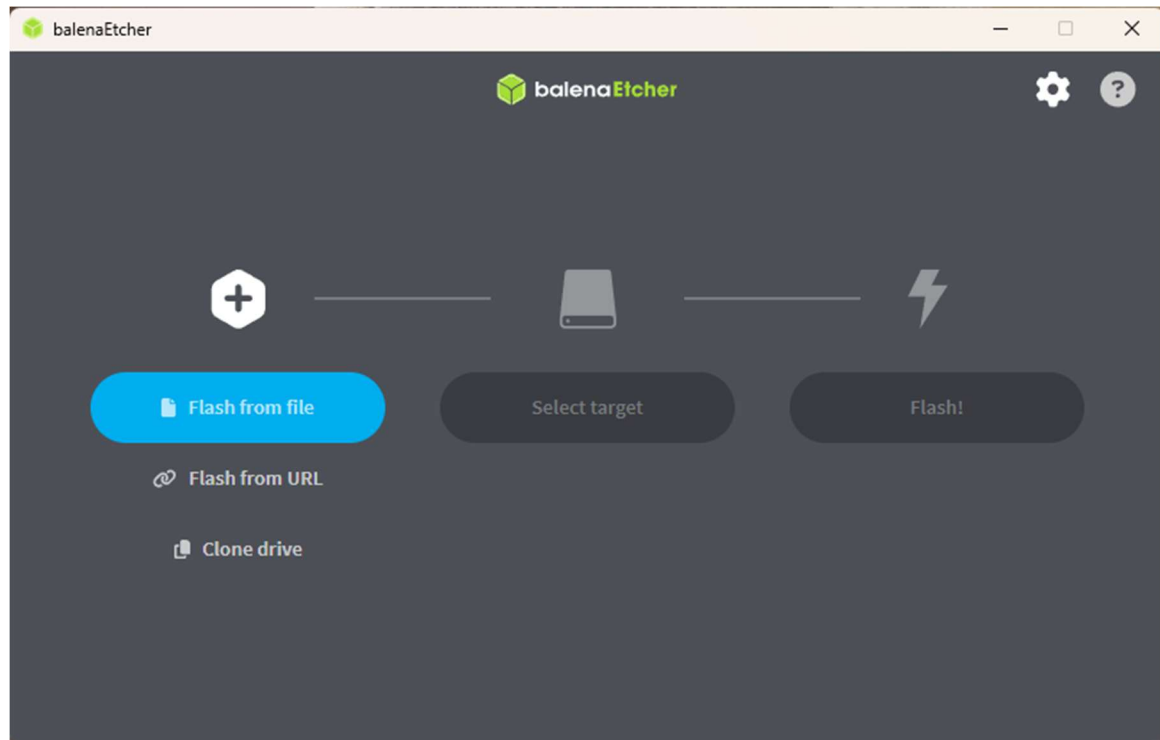


Figure 25 - balenaEtcher, a program used to flash the MicroSD card¹³⁴.

7.6.2 Chromium

Once on the home screen, the device could be used freely. The software center or command line could be used to download extra software if they were not already installed. PyCharm was installed in this manner, as well as Chromium, but there were known issues with Chromium on the provided JetPack version. As a result, the below lines were required to be run in a command shell, as provided by user Kangalow¹³⁵:

```
snap download snapd --revision=24724
sudo snap ack snapd_24724.assert
sudo snap install snapd_24724.snap
sudo sudo snap refresh --hold snapd
```

¹³⁴ "Balenaetcher - Flash OS images to SD Cards & USB drives," balenaEtcher - Flash OS images to SD cards & USB drives, <https://etcher.balena.io/>.

¹³⁵ Kangalow, "Chromium, other browsers not working after flashing or updating - here's why and Quick Fix," NVIDIA Developer Forums, <https://forums.developer.nvidia.com/t/chromium-other-browsers-not-working-after-flashing-or-updating-heres-why-and-quick-fix/338891>.

From here, GitHub could be accessed through the browser as well as any other website which were crucial to completing the setup process. SSH keys could be generated and assigned, and internet searches could be completed faster.

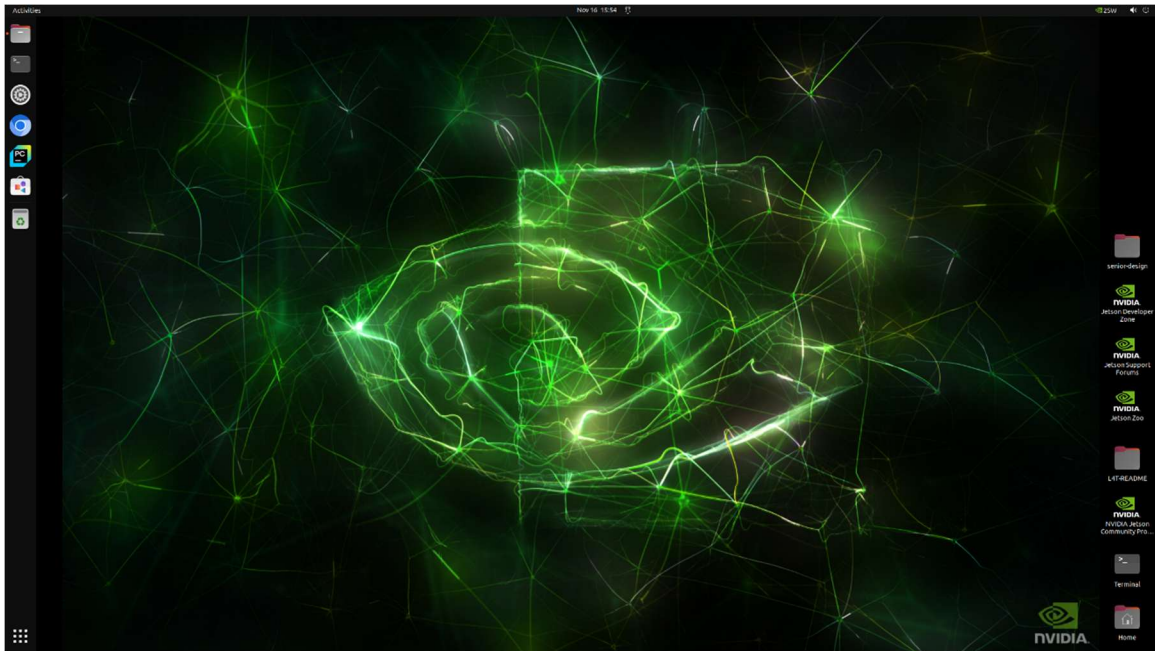


Figure 26 - The Home screen of the Orin Nano after successfully booting up.

7.6.3 Docker Image

Finally, development could occur after setting up all of the required components and software. To successfully install and use the necessary packages, one would need to override the provided OpenCV package as it does not make use of the GPU. The process to perform this action on the Orin Nano was a lengthy and questionable process, where mistakes could be irreversible. As such, a better method of installing the packages was required. One very simple option was made present: using a Docker image.

The Ultralytics team had thankfully created a comprehensive guide to installing their image on a Jetson machine¹³⁶. This image contained OpenCV with access to the GPU as well as the Ultralytics package to perform YOLO model detections. Slight modification had to be done to correctly be able to interface with the container as well as mounting drives to ensure changes in or out of the container persisted, but these changes were minor.

¹³⁶ Ultralytics, "Nvidia Jetson," Home - Ultralytics YOLO Docs, <https://docs.ultralytics.com/guides/nvidia-jetson/>.

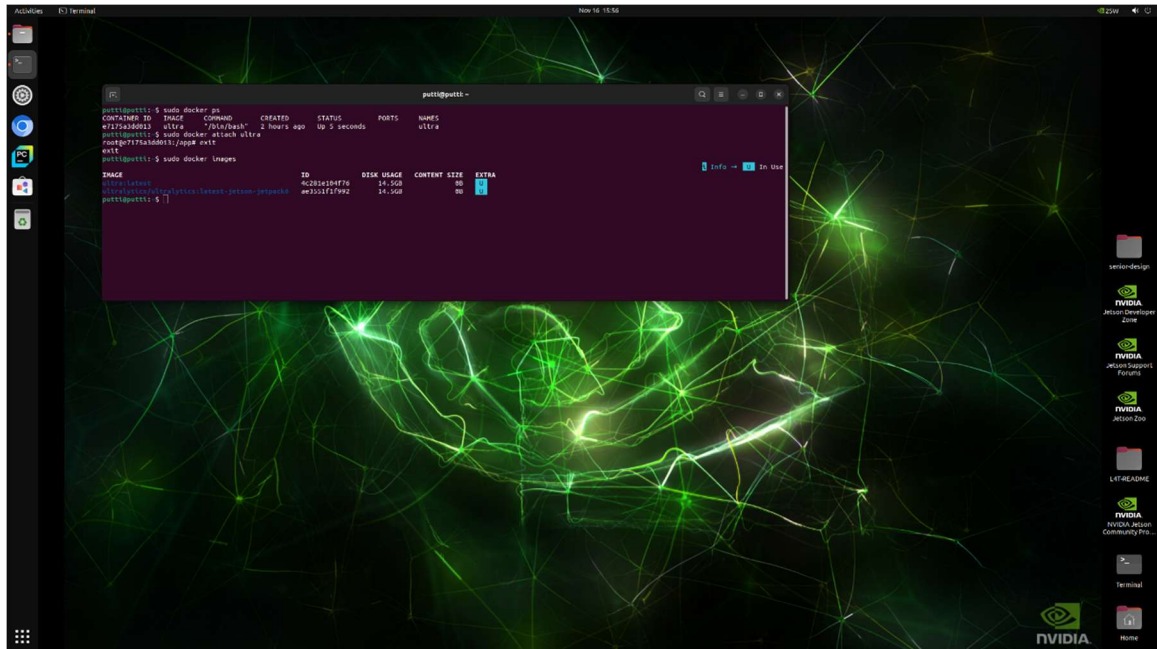


Figure 27 - Docker and the Ultralytics image on the Orin Nano.

7.7 XM125 Radar Software

The Acconeer XM125 radar module will serve as the project's primary sensor for measuring the velocity of a detected projectile. The module integrates a STM32L431 microcontroller, which uses a 32-bit ARM Cortex-M4 processor, with the A121 Pulsed Coherent Radar (PCR). This enables real time signal processing of the radar data directly on the module. To use this module for the project, the Acconeer Software Development Kit will be used for configuring and creating the custom radar firmware for object detection and measuring.

The SDK provides access to the XM125 A121 radar sensor, peripheral interfaces, and radar computational resources. It contains many example applications, including presence detection, distance measuring, and level measurements, which will serve as good resources for creating custom code. For the P.U.T.T.I. system, the Sparse IQ Service provided by Acconeer will be the most relevant since it shows how complete radar data can be used to measure the velocity of objects using doppler analysis. The IQ service is specifically designed for detecting motion (not stationary objects) by sampling the radar signal reflections at wide spaced intervals. This sampling technique enables the service to create compact and robust measurements over a short period of time, which can then be used to determine the motion of a target and its speed¹³⁷.

On a more technical level, the Sparse IQ Service uses the radar to output sequences of sweeps which are organized into data frames, with each sweep representing a measure of the reflected radar wave. The usual sweep rates range

¹³⁷ XM125 software user guide, https://docs.sparkfun.com/SparkFun_Qwiic_Pulsed_Radar_Sensor_XM125/assets/component_documentation/XM125%20Software%20User%20Guide.pdf.

from 1 kHz to 50 kHz and frame rates range from 1 Hz to 200 Hz. As opposed to some applications, this service improves signal to noise ratio using more specific radar outputs. For measuring an object's velocity, the sweeps can be processed through applying a fast fourier transform. This processing will identify doppler frequency shifts, which are directly proportional to the velocity of the object being measured. Since the Sparse IQ Service is already optimized to do almost all of this on the onboard microcontroller, it will reduce the need for heavy computation, lightening the load for the ESP32¹³⁸.

Developing this firmware for the XM125 will be done using STM32CubeIDE, which is recommended by Acconeer's software document. The previously mentioned SDK includes a project file that's compatible with this IDE, which will make development with it easy. First, the XM125 SDK will be implemented into STM32CubeIDE and the libraries for communication and radar data gathering will be enabled. Next, the parameters for velocity measuring using the Sparse IQ Service will be set, including sweep rate, the range interval, and the frame rate. Last, once the radar is proven functional, logic will be implemented to finally apply the doppler measurement calculations to yield velocity values.

So, in total, the XM125 handles gathering radar readings and signal processing onboard, which eliminates heavy computation for the ESP32. The A121 generates IQ sweeps, which then get processed by the STM32L431 microcontroller using Sparse IQ Service algorithms, or code adjacent. Then the velocity and distance data are extracted and sent to the ESP32 using UART (or if higher speeds are required then I2C will be used). This software structure allows the system to have high speed measurements of the surroundings without overloading the ESP32 with data processing tasks.

¹³⁸ "Sparse," Sparse - Acconeer docs,
https://docs.acconeer.com/en/latest/a111/radar_data_and_control/services/sparse.html.



Figure 28 – XM125 Radar Software Flowchart.

7.8 ESP32 Software

The ESP32 serves as the central controller for the entire P.U.T.T.I. system since it is responsible for coordinating sensor inputs, some internal processing, motor and lcd outputs, power efficiency, and overall system behavior. While the XM125 radar modules perform their own internal signal processing, they rely on the ESP32 to activate them, gather their results, and determine the system's response. Because of this, the ESP32's software will act as the primary module that binds all subsystems together into one cohesive projectile tracking system. Since the code will be tested and finalized later in the project, the focus for this portion is to establish the software structure, expected flow, tasks, subsystem interactions, and reasoning behind design choices. This provides an easy-to-follow roadmap for the microprocessor programming phase.

At a high level, the ESP32 will be responsible for monitoring environmental conditions, communicating with the correct radar module, interpreting radar measurements, controlling pan-tilt motor motion, and activating the laser. The system will remain in a low power state for most operation until the camera signals that an approaching object has entered a specific sector of the system's field of view. This detection through UART serves to wake up the ESP32, prompting it to initiate the finer tracking sequence and activating the buzzer through I2C. Upon receiving this signal, the ESP32 will determine which radar module corresponds to the sector in which the object was detected and issue a command over I2C to begin radar measurements. As radar frames become available, the ESP32 will process the returned values (velocity, distance, and direction) to determine the object's apparent trajectory. Since the XM125 handles most internal signal processing, these computations are lightweight and relate to estimating the angular motion and the path that the laser should track. As tracking values are updated, the ESP32 adjusts the pan/tilt platform through PWM so that the attached laser follows the previously described predicted path. During all of this, the ESP32 also manages readings from the temperature sensor and humidity sensor, ensuring the system is in the operational range and updating the LCD through SPI. Once the radar no longer detects the projectile, the ESP32 disables the laser, resets the motors, shuts down the radar and buzzer, and returns to an idle low power state.

The ESP32 code will be divided into clear parts that each handle specific categories of the system's functions. This allows the code to be broken down into more digestible parts and provides easy mapping between subsystems.

The first portion will handle communication with the camera and interpret the activation signal. This section must rely on an interrupt that wakes the ESP32 from low power mode, identifies the detected section, and takes any usable data from the camera while ignoring any additional activation signals during active tracking. This will ensure that the system reacts instantly without being overwhelmed by redundant signals.

The second portion of the software will handle radar communication. This involves sending the start measurement command via I2C, waiting for valid data, smoothing velocity values, estimating projectile motion, interpreting any direction changes, and calculating the angles required to maintain laser alignment with the projectile. While these are not computationally heavy calculations, this is the largest math-based segment of the code.

The next portion of the code will be dedicated to motor control. It will be responsible for translating the continuously computed target angles into accurate PWM signals to control the pan/tilt motors. To reliably do this, there are a few things that the code needs to handle. It must ensure smooth transitions between angles to prevent any jittering, avoid signaling for angles that are not possible for the pan/tilt system, and maintain consistent signal updates to allow for continuous motion. This portion is the key component behind the performance of the system's tracking function.

Another portion is responsible for the laser control and buzzer system. This will operate in parallel with the tracking logic part. It is responsible for activating the laser only when the tracking system is operating and the pan/tilt motors are properly aligned with the projectile. When data no longer shows a detected projectile, the laser will be shut off. Doing this accurately will prevent the laser from hitting anything other than the intended object, providing safety for anyone around the P.U.T.T.I. system. Additionally, when the tracking system is enabled, the buzzer will also be sounded to alert anyone nearby.

The final portion is dedicated to environmental monitoring. It will run continuously alongside the rest of the code. This part takes temperature and humidity readings from the respective sensors passively in the background via I2C. Then, it prints these readings to the LCD screen using SPI. If the temperature, humidity, or a mix of both reach ranges that affect data collection for the tracking system, then adjustments can be made to the calculations, or the system will shut down to prevent misfires.

While not technically its own separate part of the code, power management is a critical factor that will be utilized throughout the software. The ESP32 will typically operate in a low power mode, with motors and radar modules disabled. When the signal from the camera is received through UART, it must wake up with minimum latency and begin the tracking and alerting processes. Once the projectile leaves both the camera and respective radars' field of view, the microcontroller will return to a low power mode. For consistently reading from the environmental sensors and updating the LCD, the ESP32 will have to wake up periodically while conserving power. Properly coding the transitions from active and passive modes will ensure power efficiency and improved lifetime for components and the project as a whole.

The ESP32 will be programmed using the Arduino IDE. This option provides a straightforward environment to develop and test the microcontroller software. It also makes it easy to implement UART, I2C, SPI, PWM, and interrupts without any complex set up. Since the final code will not be written until senior design 2, establishing that the Arduino IDE is what will be used to program easily defines the future trajectory of the project. This choice will keep the software accessible from anywhere and will keep it modular as previously described. The IDE window can be seen below.

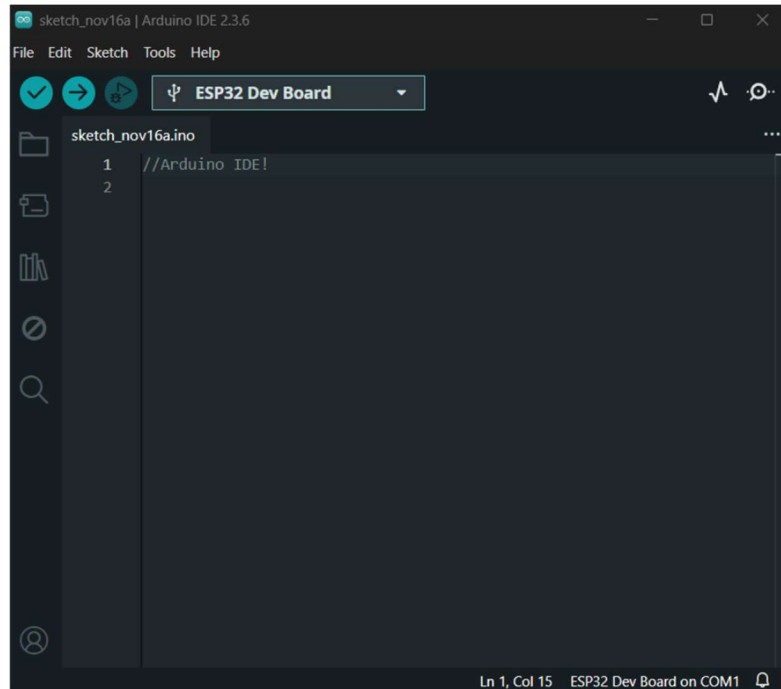


Figure 29 - Arduino IDE

Overall, the ESP32 software serves as the coordinator that brings every function of the P.U.T.T.I. system together. While the exact implementation of the code will be finalized later in the project, specifically senior design 2, outlining the structure of the code now ensures that each subsystem of the project has a clear place in the flow of the code and that the interactions between each is defined. Mapping how the ESP32 interacts with the radar modules, motors, camera system, environmental sensors, and laser/buzzer will provide a quick and easy framework to use in senior design 2. A flowchart summarizing everything can be seen below.

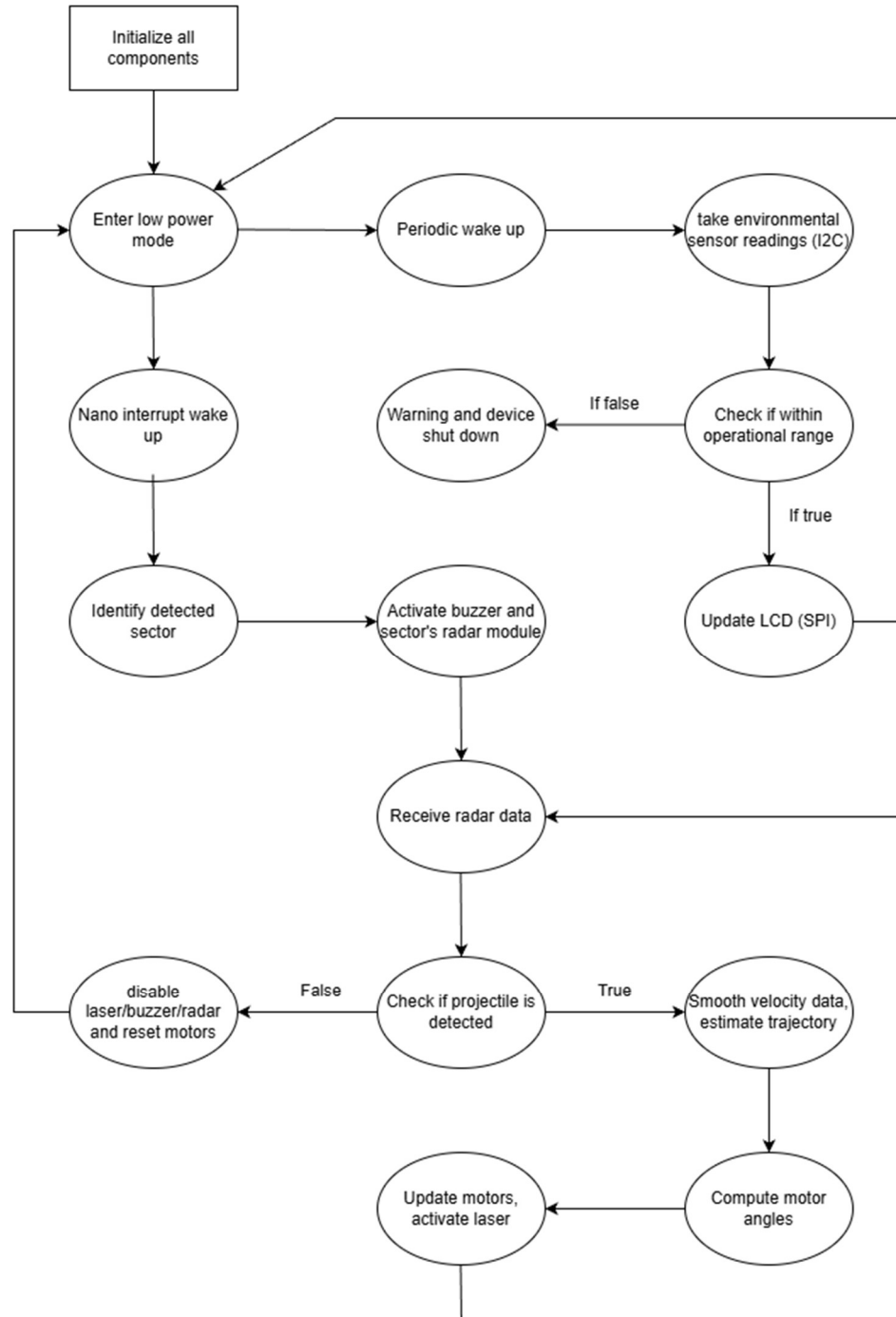


Figure 30 - ESP32 Software Flowchart

Chapter 8 – PCB Design

8.1 Board Layout

8.1.1 Main Board

The main PCB for the P.U.T.T.I. system houses the ESP32-WROOM-32, the voltage regulation circuitry, environmental and motion sensors, radar modules, communication interfaces, and motor control connections. This board functions as the central hub of the entire system, and its performance is critical to the successful operation of the project. For the P.U.T.T.I. to operate as designed, the PCB must satisfy the following requirements. First, the board must support programming and debugging the ESP32 over USB-C (even when power isn't being supplied). This is accomplished by implementing the required USB-to-serial interface and auto-programming circuitry, allowing our code to be uploaded without the need for external programming tools. The 3.3 V switching regulator ensures that the ESP32 can operate when powered from the USB alone during development and testing. Second, since the system includes sensitive components such as sensors, switching regulators, and communication modules, the PCB must minimize electrical noise. This is done through a variety of different ways, including using multiple layers, proper grounding techniques, the use of decoupling capacitors at each regulator and IC, and wide power traces for current-heavy components such as motors. When possible, components such as the linear regulator were intentionally selected over switching regulators in some areas to reduce electromagnetic interference. Third, the PCB must provide reliable connections to external devices including the radar modules, camera (via the Jetson Nano), and motor assemblies. This is accomplished through male and female connectors on the PCB which are then connected to designated pins such as UART, I2C communication, PWM motor control, and power distribution. These connectors were chosen to allow easy for easy integration and testing. Finally, the PCB must be capable of providing enough voltage to all onboard components. This is achieved through the integration of multiple linear voltage regulators, including the dedicated 5 V and 3.3 V switching regulators, and the 1.8 V LDO regulator. These regulators step down the primary battery voltage to safe operating levels required by the ESP32, sensors, radar modules, and other peripherals. The regulators that were chosen were picked based on their efficiency, thermal stability, low-noise performance, and suitable input voltage range to ensure consistent and safe operation under varying load conditions.

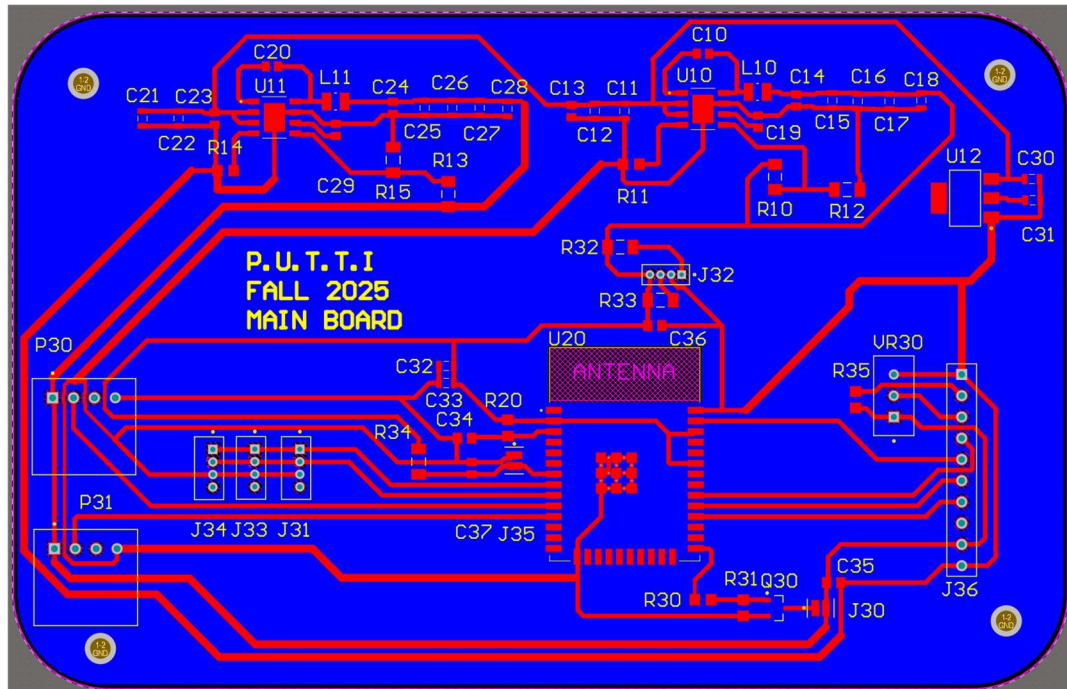


Figure 31 - Main PCB Board 2D View

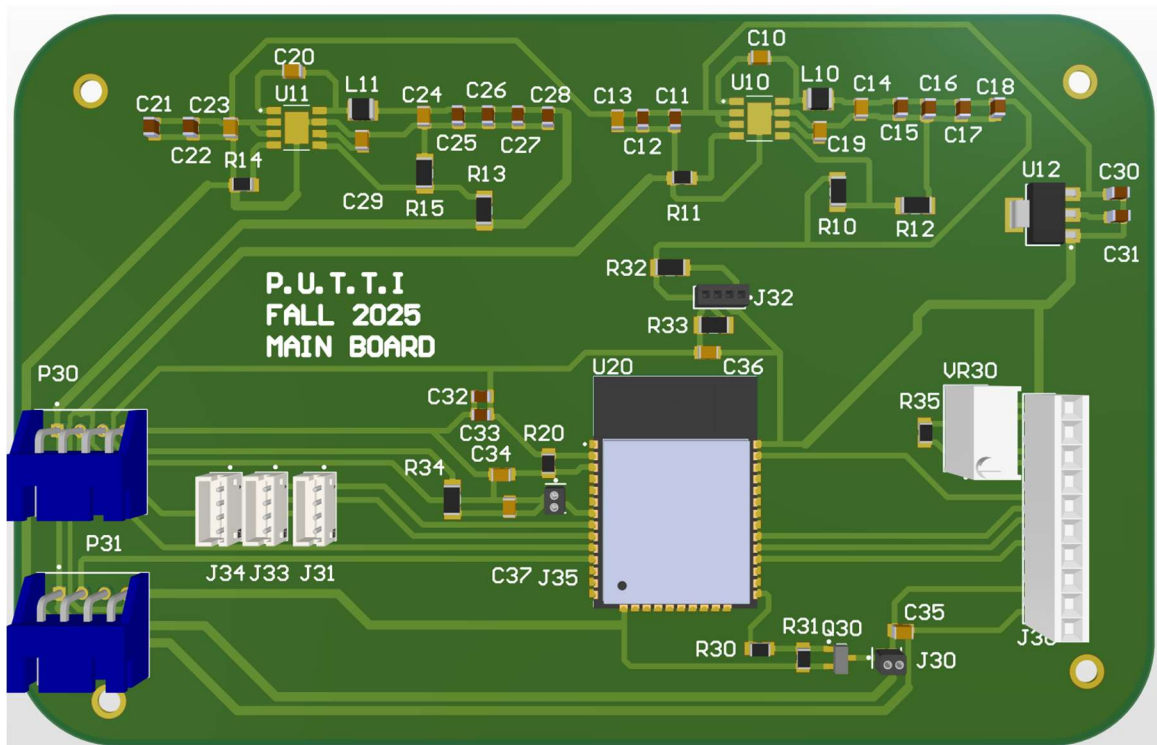


Figure 32 - Main PCB Board 3D View

8.1.2 Regulator Boards

In addition to our main board, although there are the regulators on the board, we had thought of instead implementing some regulator boards that aren't on the same board as all other components. To accomplish this we would have two identical breakout boards being the switching regulator 3.3 V and 5 V boards as well as the 1.8V linear regulator board. This was done for many reasons including to reduce electrical noise, have an easier time debugging, as well as to have less heat on the main board. To elaborate on what else the regulators must achieve besides providing power to our project, they must also deliver an adequate level of current through their rails that way each component can be properly powered. Additionally, the switching regulators to ensure maximum efficiency components such as the inductor and capacitors were placed as close to the IC as possible.

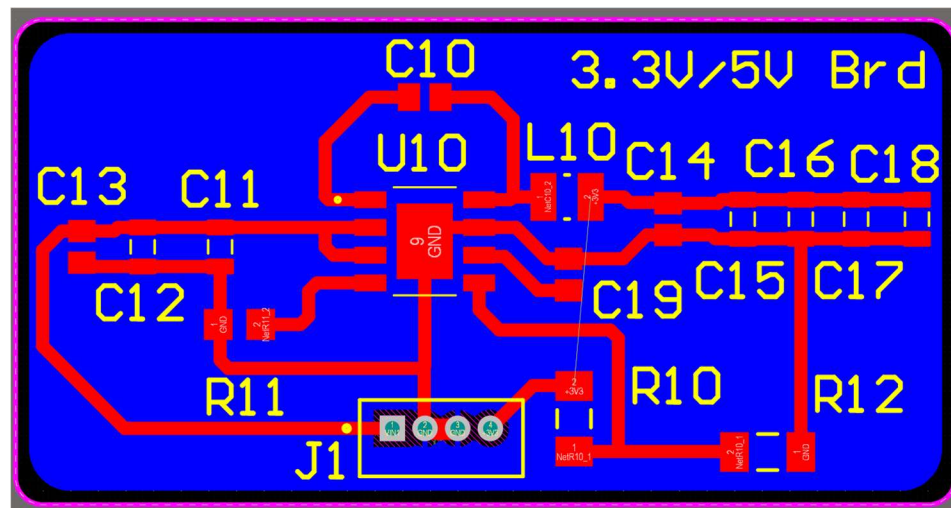


Figure 33 - 3.3V/5V Regulator Board 2D View

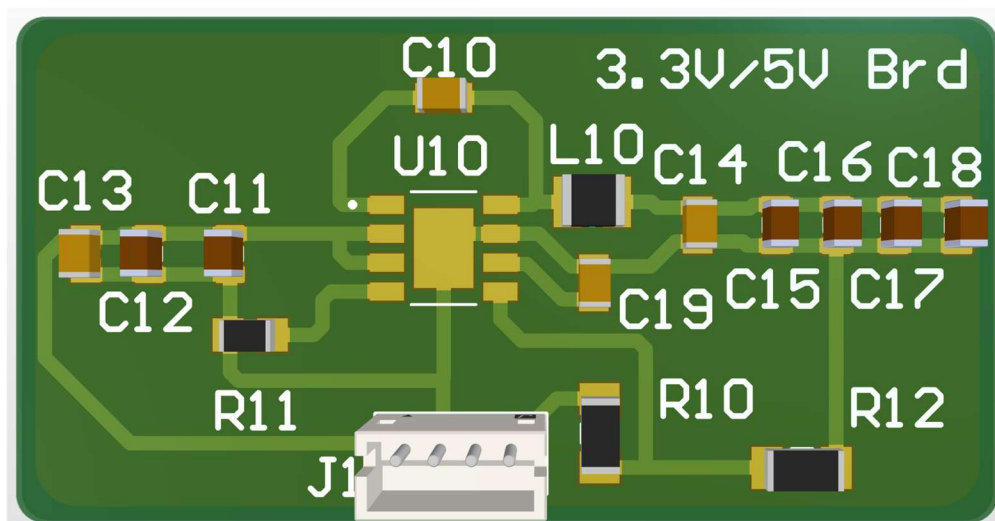


Figure 34 - 3.3V/5V Regulator Board 2D View

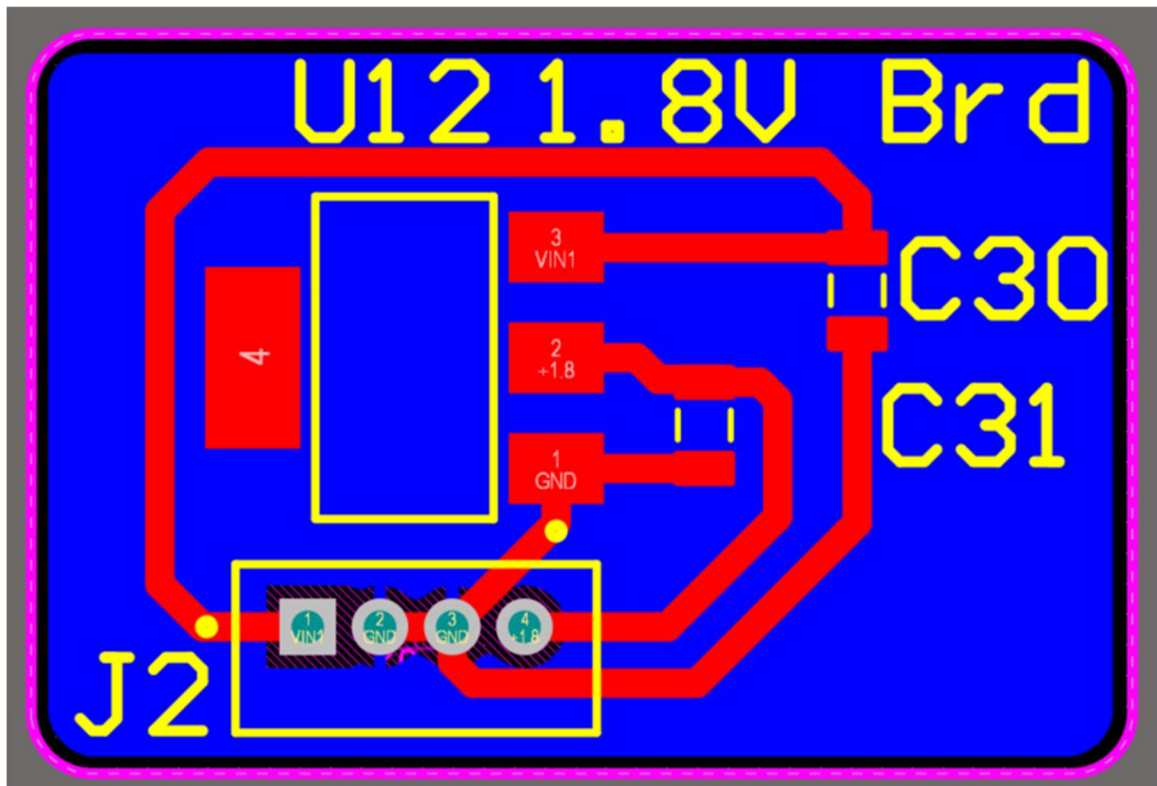


Figure 35 - 1.8V Regulator Board 2D View

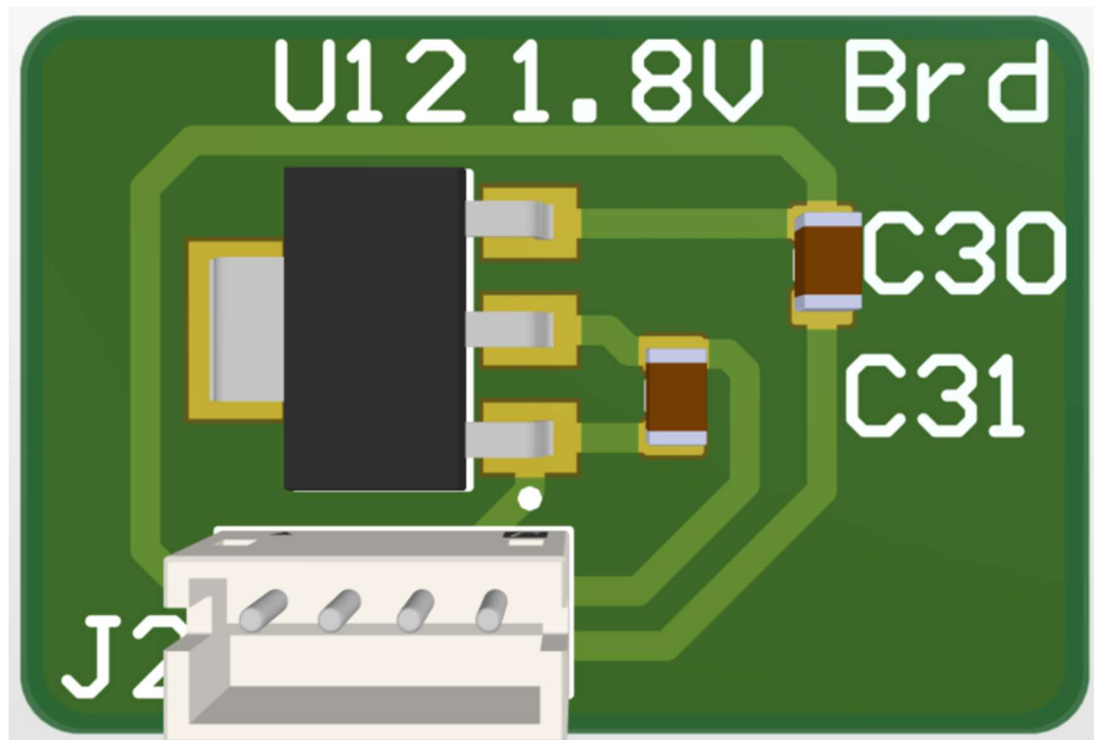


Figure 36 - 1.8V Regulator Board 3D View

8.2 Mechanical CAD Diagram

From the initial proposal of the P.U.T.T.I, we have made many changes to the design and foundations of what the device will look like. These may even change in the future during Senior Design 2 however we have created a CAD rendering of the updated P.U.T.T.I now taking into consideration the dimensions of many of the components as well as adapting to the different functionalities of the device from what we initially proposed. The major differences from the initial rendering and now are the shorter barrel with specific measurements to accommodate the lasers length and diameter, the shorter, wider body to guarantee that the SBC will be able to fit in the device, the smaller frame on the bottom of the device to still provide support but decrease the size of the overall device, and the three openings in the side of the device will help with airflow and allow the radar sensors better detection. The different views and technical drawings of the updated P.U.T.T.I rendering are below.



Figure 37 - Isometric view of CAD rendering.



Figure 38 - Front view of CAD rendering.

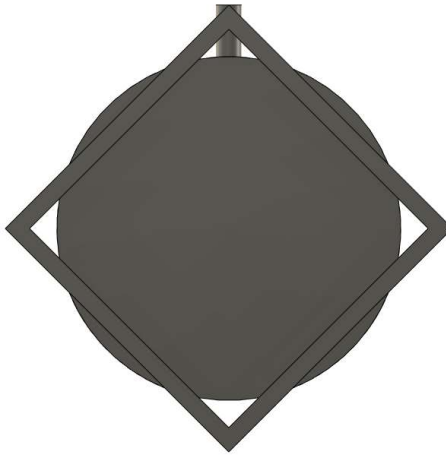


Figure 39 - Bottom view of CAD rendering.

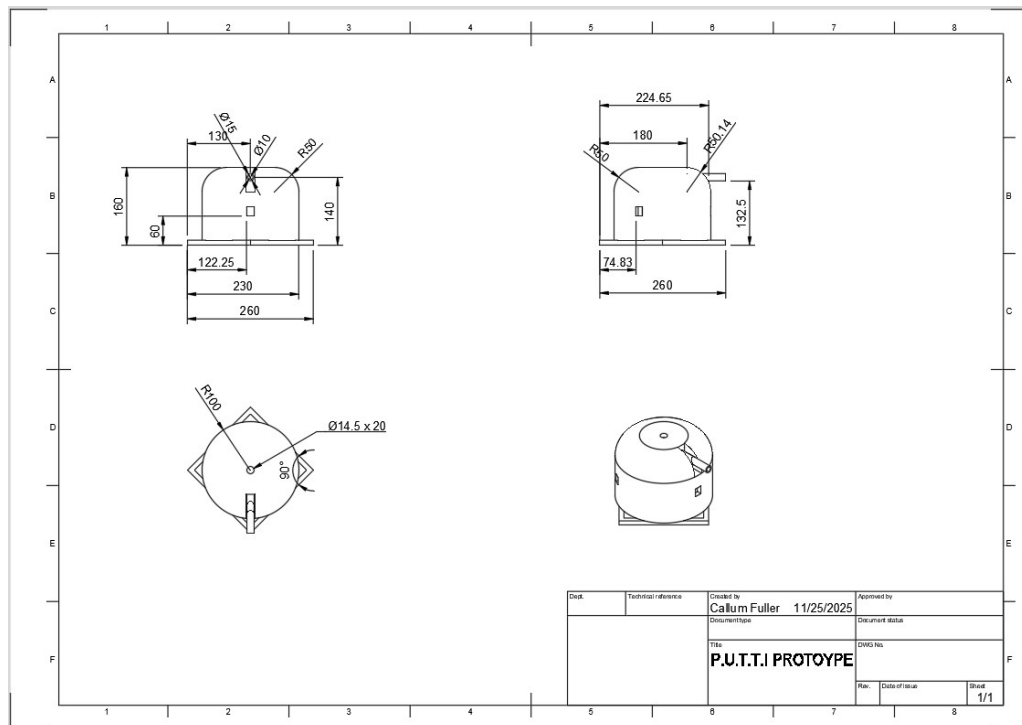


Figure 40 - Technical drawing of CAD rendering.

Chapter 9 – System Testing and Evaluation

In this chapter, methods for testing the hardware and software will be explored as tests to complete before or during Senior Design 2.

9.1 NVIDIA Orin Nano

The NVIDIA Orin Nano had a pre-made comprehensive setup guide, which was explored in Chapter 7. In order to ensure that the device works as needed, the MicroSD card should successfully be flashed, the device should be able to power on after having the card inserted, the device should be able to complete the account setup process, the Docker image containing Ultralytics should be able to be downloaded and a container should be created using the image, and the YOLO model should be able to run at relatively-real-time speeds.

The MicroSD card faced some challenges while being flashed. The USB stick placed into the external computer which downloaded the image faced a minor complication. The initial flash completed and was in the verification process, but failed near the 94% completion point. However, a second flash completed successfully. Future flashes will need to be examined closely.

Thankfully, after the MicroSD card was flashed, the device went through little to no complications once the MicroSD card was inserted. The main page was successfully reached, bug fixes from the JetPack image were easily solved, and software could be successfully installed or accessed.

The Docker image was easily retrieved since the JetPack image had Docker pre-installed. However, the command to create and access a container with the image was changed to fit the needs of the project. The given command did not use the GPU nor did it allow external persistent files to be shared between the device and container.

The Docker container will be sufficient for the needs of the project. The one minor stipulation is that the OpenCV version is headless, meaning that it does not permit GUIs to be shown. As a result, any debugging must be done by saving the images to disk, which is a slow operation. However, the final code will not need to show anything to a GUI so this can be overlooked for now. Once the code was inserted not the container, the code worked as expected and at relatively great frames per second, reaching about 19-20 frames per second while saving frames to disk, meaning that the code will actually have a higher frame rate. This is also without the gating mechanism, so the frame rate will be even higher.

To conclude, the Orin Nano was tested successfully and it passed with flying colors. The YOLO model ran successfully and the camera was accessed, with some notes as explored in the next section.

9.2 Camera

The camera initially faced some problems. No guides existed to aid with image capture on the Orin Nano, so forum posts were needed to piece together possible solutions, but these alone were not sufficient. A CSI camera and USB camera were

on hand when testing the functionality. The CSI camera was tested first, since CSI would have a slighter upper hand over USB but could be harder to implement. In fact, this is what was discovered.

The CSI camera could not be accessed through normal means. A specific command had to be called to access the camera, with several arguments bloating the command call. The command could easily be used from the command line, but implementing it through the Python code was extremely difficult. This complication compounded on itself when the Docker image was found to not support this command, and installing a version of OpenCV which could support both the camera command and the GPU was not likely to succeed.

The USB camera was then implemented. This camera was severely easier to implement than the CSI camera. In fact, the code required only one or two lines of code to change from a default camera capture code. Rather than expecting a command to be pipelined into the OpenCV program, the camera could be accessed through normal means of accessing video capture device 0.

To conclude, the USB camera was tested successfully and it passed with flying colors, contrary to the CSI camera which failed miserably. Attempts may be made in the future to implement the CSI camera, but the USB camera is much more enticing, especially because the quality of the images will be compressed for calculations regardless so the difference will not be highly noticeable.

9.3 YOLO Model

The YOLO model so far has not been completed. Following the steps explained in Chapter 7, a small YOLO model has been created from a small dataset of approximately 500 footballs. Ideally, a dataset should be at least 2000 images. The current model was created to simply test the speed of the SBC and to ensure that the Ultralytics package could actually be implemented on it.

As discussed in previous sections and chapters, the Ultralytics package was employed through the use of a provided Docker image. A simple script was created to use the SBC camera to capture images, then to store the image to the disk, recording the frames per second and if any targets were found.

The model has a very low accuracy, but this is to be expected. The model is not trained very well and does not have an extensive set of images to learn from, so the football was not always detected. However, the collection of images for the dataset will be a process which occurs before or near the beginning of Senior Design 2. For now, the current demo model will suffice for demo purposes.

To conclude, the YOLO model was tested successfully and passed with some remarks. The continual training of the model until it can very accurately detect a football will continue throughout the process of Senior Design to ensure that the device will work anywhere. Different backgrounds, details in the scene, and positions of the ball will be used to give variety to what the model can learn from to ensure a successful training.

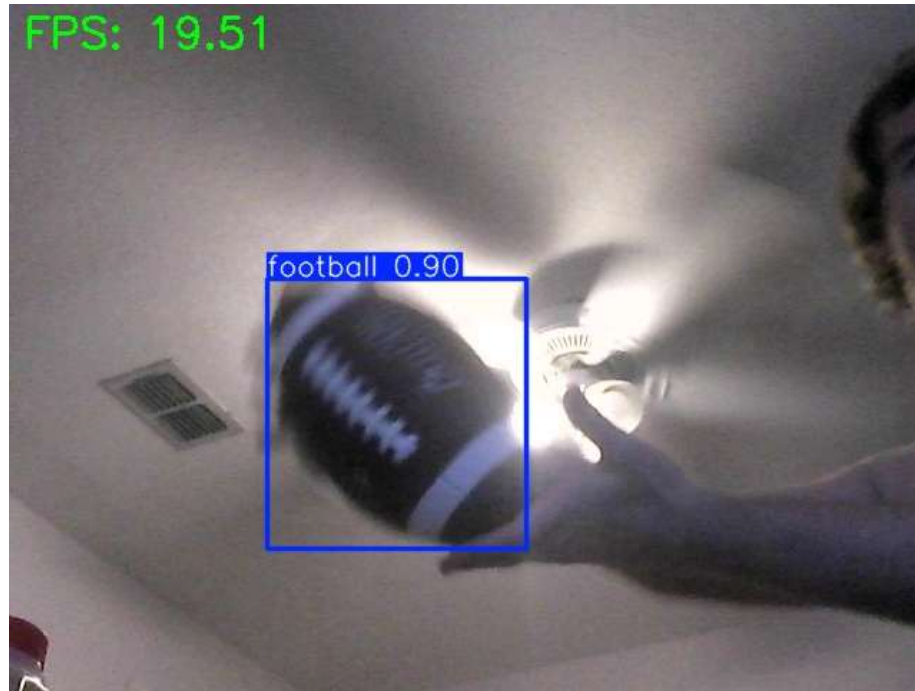


Figure 41 - The YOLO model detecting a football on the Orin Nano. FPS hits 19-20 at peak.

9.4 Laser

The most important part of testing the laser is testing the output power to ensure that the power is accurate to what the product description is and that the power is consistent when connected to the regulator and when the regulator receives different input voltages. To practically test the laser, we will use LIV testing and connect the laser to the device and have the device sweep the voltage from 0 to an open circuit voltage. Then, with all the information collected we can create a graph of the voltage and current which can be used to determine the power of the laser. From this we will be able to see if the laser is accurate to what the product description was and if the power is consistent or what voltage level would be best for setting the laser at in the final device. This method of testing the laser and any future testing of the laser in tandem with the other components of the device will be tested during the following semester in Senior Design 2.

9.5 Humidity Sensor

To test the humidity sensor, we will connect the humidity sensor to the circuit described in the hardware section of the paper and perform various readings in different settings to ensure that the humidity sensor is reading correctly and can be used to measure a humidity in as many different environments as possible. Additionally, we will make sure to test the sensor in the same environment over many readings so we can see the general variance with the readings so we can account for this in our final design when incorporating all the components. Additional testing of the humidity sensor will need to happen during Senior Design

2 to ensure that the sensor works when all the other components are connected and the voltage the sensor reads is accurate. We will also need to test the I2C connection of the sensor and the ESP32 to guarantee that the data from the sensor is sent accurately and timely.

9.6 Temperature Sensor

The temperature sensor will be tested similarly to how the previously mentioned humidity sensor was. We will connect the temperature sensor with the circuit and then test it at different temperature readings to make sure we have a full understanding and proof that the sensor reads temperatures across the full range and then we will gather multiple readings of the temperature sensor at the same temperature to see the error with the temperature sensors readings. We expect there to be some error, but we want to make sure that this is completely down to the hardware limitations of the sensor and not related to any of the connections that we make in the circuit. Like with the humidity sensors I2C connection we also need to make sure that the temperature sensor is connected correctly to the ESP32 and the correct information is being sent, a calculation will need to be made to translate the raw readings of the sensor into readings that we can understand however this testing and any additional testing will occur in Senior Design 2.

9.7 Motors

The motors will have two main stages of testing to verify they will do what we need them to do for our project. In the first stage, each motor will be individually, then together to confirm that they are able to rotate through their intended ranges of motion, specifically achieving smooth and controlled panning and tilting without obstruction or signal interruption. A simple mounting bracket will be used to hold the motors in a fixed position during this phase in order to isolate motor performance from any external mechanical variables. The response time, stability, and repeatability of each motor movement will be observed to ensure consistent operation when commanded by the ESP32.

The second phase of testing will involve them being fully implemented with the system, including the camera and laser modules mounted directly onto the motor-driven platform. This will be done by using visual data processed by the NVIDIA Jetson Nano, after which commands will be sent to the ESP32 to adjust the motors' angles in real time, causing the system to sweep left and right in search of a designated target. Once the target is detected, the motors will reposition to center the object within the camera's field of view. Finally, the laser will be activated and programmed to track the target's movement, allowing for continuous alignment. This phase will validate the performance of the motors, as well as the accuracy of the vision-based control system. Upon successfully completing this stage of testing, we will demonstrate that the P.U.T.T.I. system is functioning as intended in a real-world operating environment.

9.8 Batteries

The batteries for the P.U.T.T.I. system will be tested to ensure that they send enough power to all voltage regulators and components. This testing will consist of connecting the batteries to the 5-volt and 3.3-volt switching regulators, and the 1.8-volt low-dropout regulator, verifying that each output provides the correct voltage when it is receiving power. Then, we will see if each component within our system is receiving enough voltage and current to operate properly. Additionally, the stability of each voltage rail will be observed to check for any significant drops or fluctuations when multiple components are powered simultaneously which would be a problem if this were to be true because we want each component to be receiving the power it needs. Finally, we will have the batteries continuously powering the system for an hour to meet our operational lifespan requirement. This will all be done to ensure that the batteries can reliably support the full system, providing us confidence that the P.U.T.T.I. can operate as designed without power interruptions.

9.9 Buzzer

The active buzzer is a relatively simple component to test. We mostly need to ensure that the buzzer is activated correctly when ESP32 toggles the buzzer, and we need to test the sound pressure level at different input voltages and ranges. This can be tested with any device that measures decibels and we can further test the buzzer making sure to increase the range from the buzzer of the reading device and the input voltage of the buzzer to see what voltage works best for the distance that we want the buzzer to be able to be heard from.

9.10 Radar Modules

Testing the radar modules will consist of evaluating both the software running on the XM125 and the hardware performance of the A121 sensor, which will be done during senior design 2. The first stage of radar module testing will focus on the software portion and confirming the software that will be created using the Acconeer SDK operates like we expect it to. Once the code is flashed onto the XM125, the main goal will be to ensure that the Sparse IQ Service is configured correctly according to the web resources. This involves the sweep rate, frame rate, and range settings that determine how the radar actually collects and processes data. The initial tests will be waving in front of the radar module and observing if the collected frames are processed correctly. This waving should create data that the code processes and turns into tangible values such as velocity and direction. These tests should help determine whether the radar module's custom software can successfully create meaningful data before any integration with the ESP32 occurs. Since this section is software based, this only needs to be tested with one of the three radar modules, as opposed to testing all three.

After confirming that the software can create stable values and data, the next step will be to evaluate the communication methods possible between the radar module and the ESP32. The XM125 supports communication with the ESP32 through

either UART or I2C. So, both should be tested in senior design 2 to determine which of these will yield the greatest balance of factors, which include speed, reliability, and ease of implementation for the final system. The current plan is to use I2C since it can easily include all three radar modules, as opposed to UART which would require a way to use one Tx and Rx for all three modules, but it should be tested to ensure it is the most efficient option. UART will be examined to determine transmission speeds of data and how different sample rates can affect it. I2C will also be tested because, although it will be easier to connect all three modules, the additional connections from different sensors may reduce the speed of the connection. During this phase, the ESP32 will run basic test scripts to read incoming values from the radar module and determining if the speed of each connection can keep up with projectile tracking. This portion will also only need to be tested with only one of the modules. The goal of this stage is just to ensure that the ESP32 can reliably receive the radar's processed outputs before assembling the complete system.

Once the communication method is confirmed, more in-depth hardware performance testing will need to be done. This stage involves evaluating the accuracy of the radar module. Specifically, the accuracy of distance measurements and velocity measurements under standard indoor conditions will be tested. Since the radar module uses FFT/doppler analysis to determine speed, tests can be done by using objects moving at known speeds and distances to measure the accuracy of the module's processed readings. For example, one method for doing this would be to roll a ball across the floor along a meter stick in front of the radar. This would allow for the true velocity to be determined from the distance along the meter stick and the time it was rolling and for it to be compared against the measurements of the radar. Similar simple tests should be repeated at different distances from the module to test how well its accuracy is maintained as the range gets larger. For each distance, multiple tests should be done to create data sets. Then, these data sets can be analyzed to determine how stable and reliable readings are from the same distance, which may require the software to be further fine-tuned. This process should be repeated for each radar module since their fine-tuning characteristics may differ.

Chapter 10 – Administrative Content

10.1 Budget

The budget for our project is \$1000. This value was decided on all members of the group to ensure that there is an adequate amount of funds for the initial design as well as any revisions that need to be made after testing. It is likely that the project will not reach this budget; however, having a cushion will ensure that the best possible design can be created to fully achieve the desired goals and objectives of this project.

10.2 Bill of Materials

The actual amount of money spent on the major components of the project can be found below. From this we are clearly below the budget we provided ourselves of \$1000. The bill of materials may change throughout Senior Design 2 in the case that we run into any major issues with the parts selected or if parts break, however at this moment in time we are well within our budget.

Table 23 - Bill of Materials

Item	Unit Cost	Quantity	Total Cost
Nvidia Orin Nano Super	\$ 249.99	1	\$ 249.99
ELP OV2710	\$ 20.99	1	\$ 42.99
1054 Laser Diode	\$ 5.95	1	\$ 5.95
B57540G1103F000 Thermistor	\$ 2.76	1	\$ 2.76
3721 Humidity Sensor	\$ 3.95	1	\$ 3.95
XM125 Radar Sensor Module	\$ 21.21	3	\$ 63.63
LCD	\$ 11.21	1	\$ 11.21
Microcontroller	\$ 5.33	3	\$ 15.99
Buck Regulator	\$ 1.55	10	\$ 15.45
Brushless Servo	\$ 33.99	2	\$ 67.98
Buzzer	\$ 1.10	1	\$ 1.10
Total			\$ 481.00

10.3 Distribution of Work

A table of the assigned roles to each group member can be found below. We want to ensure that everyone is contributing adequately to the project, so it is important to establish roles and responsibilities to each member based on their strengths or interests in particular fields. Knowing what each group member is working on is integral for our group to function and for the project to be completed effectively and on time. With this we can put our trust into one another and focus on our own responsibilities rather than having to worry about what one another is working on.

Table 24 - Distribution of Work

Name/Major	Primary Responsibilities	Secondary Responsibilities
Alex Evison Electrical Engineering	PCB Design	Peripheral Integration
	Motors and Motor Control	Testing
	Project Lead	MCU Implementation
Callum Fuller Electrical Engineering	Peripheral Integration	Chassis Design
	PCB Design	Safety Constraints
	Administrative Documentation	Soldering/Component Installation
Nathan Kimmel Electrical Engineering	Microwave Sensor Implementation	PCB Design
	MCU Implementation	Detection System Design
	User Interfacing	Testing
Jake Tattersall Computer Engineering	Detection System Design	Website Design
	Camera Setup	User Interfacing
	Administrative Documentation	MCU Implementation

10.4 Senior Design Milestones

It is important to have a plan for Senior Design to ensure that the group stays on track and all the future deadlines are known and achieved on time. There needs to be separate milestones for the documentation side of the project and the hardware and design side of the project since they will overlap, and both sides of the project are important to map out.

Table 25 - Senior Design Milestones

Task	Start Date	Anticipated End Date	Description
Brainstorming	8/24/2025	8/31/2025	Discussing project ideas that are feasible and meet all design requirements
D&C Document	9/1/2025	9/5/2025	Complete 10+ pages for Divide and Conquer document to discuss with advisor
D&C Meeting	9/9/2025 11:00 am	9/9/2025 11:30 am	Discuss Divide and Conquer document with advisor and get approval
Midterm Report	9/30/2025	10/31/2025	Complete the first 60+ pages of the document
Final Report	10/20/2025	11/25/2025	Finish the document by the end of SD1.
Mini Demo Video	10/20/2025	11/25/2025	Record demonstration of project

Table 26 - Project Development Milestones

Task	Start Date	Anticipated End Date	Description
Basic Model of Project	8/31/2025	9/5/2025	Creating a model of the basic design of the planned look for the project
Selection of Materials and Components	8/31/2025	9/14/2025	Choosing and purchasing the necessary components required for the project
Designing the System	9/14/2025	10/24/2025	Coding the system, creating the system on a breadboard, and testing its functionality.
PCB Design	10/24/2025	11/17/2025	Design the PCB using Fusion/Altium.
Create Prototype	11/17/2025	11/25/2025	Combine all components together to create and demo a prototype of the project.
PCB Testing	TBD	TBD	Solder all components and test functionality of PCB
Testing	TBD	TBD	Test the prototype to see if any changes or revisions need to be made
Revisions	TBD	TBD	Make changes to the project or add additional functionalities.
Final Project	TBD	TBD	Create final version of the project and submit it for review.

Chapter 11 – Conclusion

In conclusion, this report contains the complete technical work for the Portable Unitary Throwable Target Interceptor (P.U.T.T.I.) system and has defined all of the functions expected of the fully constructed design in senior design 2. Modern small airborne threats such as drones and thrown explosives still pose a significant risk to military personnel, which shows the need for a compact defensive system that can react quickly and safely. The P.U.T.T.I. system aims to fill this need by focusing on portability, reliability, and autonomy so that soldiers can quickly deploy it and not have to worry about thrown projectiles. Though, for safety requirements and proof of concept only a laser will be used to show projectile tracking.

For this first design phase, each subsystem of the project was researched, each part was selected to fit certain criteria, and everything has been designed to be integrated into one complete system. The detection system, which begins with a trained object recognition model, identifies the projectile and its general location. Once detection occurs, the ESP32 takes over, and the report fully outlines the pathway and loops from camera output to radar selection and activation, pan/tilt motor movement, and laser alignment and activation. Since real interceptors were out of the scope of this project and could raise safety concerns, the laser serves as an effective proof of concept showing how the system would accurately track and neutralize a projectile threat.

Overall, this report demonstrates how an initial idea has been turned into a complete engineering plan, mapping how every part connects, contributes, and interacts. As of now, some portions of the project have already been tested including the camera software, laser, buzzer, and motors, which can be seen in the demo video. Senior design 2 will focus on assembling the rest of the project, writing and debugging the microcontroller and radar software, fine-tuning accuracy, and finally demonstrating the full capabilities of the system.

Appendices

Appendix A – Reference

- [1] “Tom Clancy’s Rainbow Six Siege X: Ubisoft (US),” Ubisoft, <https://www.ubisoft.com/en-us/game/rainbow-six/siege>.
- [2] “Gadgets,” gadget · Rainbow Six Siege · Rainbow Six Bootcamp, <http://rainbowsixbootcamp.com/tags/gadget/>.
- [3] “Iron Fist Active Protection System - detect, track, neutralize,” General Dynamics Ordnance and Tactical Systems, <https://www.gdots.com/protection-systems/active-protection-systems/iron-fist-active-protection-system/>.
- [4] TWPe-jpc, “Servo vs. Stepper vs. Brushless DC Motors,” Elinco International, Inc. Japanese Products Corp., <https://www.e-jpc.com/servo-stepper-brushless-dc-motors>.
- [5] ChatGPT, <https://chatgpt.com/>.
- [6] “Arducam 5mp OV5647 ultra wide angle fisheye camera for Raspberry Pi,” Arducam, <https://www.arducam.com/arducam-ultra-wide-angle-fisheye-5mp-ov5647-camera-for-raspberry-pi.html>.
- [7] “Mini Multi-Camera Adapter Board for Arduino-Arducam,” Arducam, <https://www.arducam.com/mini-multi-camera-adapter-board-for-arduino-arducam-b0074.html>.
- [8] OpenCV Team, “About - OpenCV,” *OpenCV*, Jul. 18, 2025. <https://opencv.org/about/>.
- [9] P. Gupta, “Embedded tech: How sbcs are Shaping the future (2025),” Logic Fruit Technologies, https://www.logic-fruit.com/blog/embedded/sbcs-shaping-embedded-future/?srsltid=AfmBOopJilHYdLanky4oWRweTfJk2vtFEAR4RdkV5INIU89Dv_kov2vl.
- [10] Raspberry pi 4 model B specifications – raspberry pi, <https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/>.
- [11] “Dev Board datasheet,” Coral, <https://gweb-coral-full.uc.r.appspot.com/docs/dev-board/datasheet/>.
- [12] “Coral: google for developers,” Google for Developers, <https://coral.ai/products/accelerator>.
- [13] “Jetson Orin Nano developer KIT User Guide - Hardware Specs,” NVIDIA Developer, https://developer.nvidia.com/embedded/learn/jetson-orin-nano-devkit-user-guide/hardware_spec.html. Coral: google for developers,” Google for Developers, <https://coral.ai/products/accelerator>.
- [14] “Nvidia Jetson Nano,” NVIDIA, <https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-nano/product-development/>.
- [15] “Jetson Orin Nano Super Developer Kit,” NVIDIA, <https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-orin/nano-super-developer-kit/>.

- [16] "Jetson-Orin-datasheet-Nano-developer-kit-3575392-R2.PDF," File Not Found, <https://nvdam.widen.net/s/zkfqjmt2s2/jetson-orin-datasheet-nano-developer-kit-3575392-r2>.
- [17] "ROC-RK3588S-PC Arm Single Board Computer: Firefly RK3588 SBC," Firefly Store, <https://www.firefly.store/products/roc-rk3588s-pc-8-core-8k-ai-mainboard>.
- [18] Mini Multi-Camera Adapter Board for Arduino-Arducam, <https://www.arducam.com/mini-multi-camera-adapter-board-for-arduino-arducam-b0074.html>.
- [19] Arducam mini 2MP plus - OV2640 SPI camera module for Arduino Uno MEGA2560 Board & Raspberry Pi Pico, <https://www.arducam.com/arducam-2mp-spi-camera-b0067-arduino.html>.
- [20] "Amazon.com: IFWATER 60FPS global shutter USB camera module with 170° fisheye lens,high speed 720p aptina AR0144 camera for industrial applications with Jetson Nano,laptop,Raspberry Pi : Electronics," Amazon.com: IFWATER 60fps Global Shutter USB Camera Module with 170° Fisheye Lens,High Speed 720P Aptina AR0144 Camera for Industrial Applications with Jetson Nano,Laptop,Raspberry Pi : Electronics, <https://a.co/d/5KiHAUx>.
- [21] "Amazon.com : ELP 170degree Fisheye Lens USB camera with 1080p HD resolution, OV2710 CMOS USB camera module 2 megapixel high speed 100fps wide angle mini camera module USB2.0 for robot,ATM,Kiosk,Eye Tracking Device : Electronics," Amazon.com : ELP 170degree Fisheye Lens USB Camera with 1080p Hd Resolution, OV2710 CMOS USB Camera Module 2 Megapixel High Speed 100fps Wide angle Mini Camera Module USB2.0 for Robot,ATM,Kiosk,Eye Tracking Device : Electronics, <https://a.co/d/enpHHCu>.
- [22] Nvidia Jetson Orin NXOrin Nano compatible CSI camera ..., <https://files.seeedstudio.com/products/NVIDIA/NVIDIA-Jetson-Orin-NX-Orin-Nano-Compatible-CSI-Camera-Comparison.pdf>.
- [23] 1, <https://www.opensourceinstruments.com/Electronics/Data/IMX219PQ.pdf>.
- [24] IMX477-AACK | Sony Semiconductor Solutions, https://www.sony-semicon.com/files/62/pdf/p-13_IMX477-AACK_Flyer.pdf.
- [25] Arducam IMX219 camera module with fisheye lens for Jeson Nano and raspberry pi compute module, <https://www.arducam.com/product/arducam-imx219-wide-angle-camera-module-for-nvidia-jetson-nano-raspberry-pi-compute-module-4-3-3-b0287/>.
- [26] Arducam IMX219 Wide Angle Camera Module for NVIDIA® Jetson AGX Orin/Orin Nano/orin NX, <https://www.arducam.com/b0179-arducam-imx219-wide-angle-camera-module-for-nvidia-jetson-board.html>.
- [27] "IMX219-160 8MP camera with 160° FOV - compatible with Nvidia Jetson Nano/ Xavier NX," Seeed Studio, <https://www.seeedstudio.com/IMX219-160-Camera-160-FOV-Applicable-for-Jetson-Nano-p-4603.html>.

- [28] "Amazon.com: Compatible with Nvidia Jetson Nano Camera IMX219-160 8-megapixels camera module 3280 × 2464 resolution 160 degree wide angle of view with IMX219 sensor : Electronics," Amazon.com: Compatible with NVIDIA Jetson Nano Camera IMX219-160 8-Megapixels Camera Module 3280 × 2464 Resolution 160 Degree Wide Angle of View with IMX219 Sensor : Electronics, <https://a.co/d/3dgm12k>.
- [29] Dr. R. Paschotta, "Solid-state lasers," RP Photonics, https://www.rp-photonics.com/solid_state_lasers.html.
- [30] Dr. R. Paschotta, "Gas lasers," RP Photonics, https://www.rp-photonics.com/gas_lasers.html.
- [31] Dr. R. Paschotta, "Semiconductor lasers," RP Photonics, https://www.rp-photonics.com/semiconductor_lasers.html.
- [32] G. Haas, What is a Fiber Laser and how do they work?, <https://haaslti.com/blog/what-is-a-fiber-laser-how-it-works>.
- [33] Dye laser - an overview | sciencedirect topics, <https://www.sciencedirect.com/topics/physics-and-astronomy/dye-laser>.
- [34] 1054 Adafruit Industries LLC | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/adafruit-industries-llc/1054/5629439>.
- [35] PLT5 520DB_P AMS-Osram USA Inc. | Optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/ams-osram-usa-inc/PLT5-520DB-P/20534484>.
- [36] VLM-650-04 LPA Quarton Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/quarton-inc/VLM-650-04-LPA/1010455>.
- [37] VLM-650-01 LPT Quarton Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/quarton-inc/VLM-650-01-LPT/1010451>.
- [38] D405-120 US-Lasers Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/us-lasers-inc/D405-120/3438595>.
- [39] RLD85NZJ4-00A rohm semiconductor | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/rohm-semiconductor/RLD85NZJ4-00A/12336426>.
- [40] Sensors | DigiKey, <https://www.digikey.com/en/application-technology/sensors>.
- [41] B57869s0103f140 epcos - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epcos-tdk/B57869S103F140/3500481>.
- [42] Pane103395410 Vishay Ametherm | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/ametherm/PANE-103395-410/1765764>.
- [43] AL03006-535K-145-G1 amphenol thermometrics | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/AL03006-535K-145-G1/136421>.

- [44] B57540g1103f000 epcoS - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epcoS-tdk-electronics/B57540G1103F000/3500367>.
- [45] Eaton-Electronics Division distributor | DigiKey, <https://www.digikey.com/en/supplier-centers/eaton-electronics-division>.
- [46] 192-103LET-A01 Honeywell Sensing and productivity solutions | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/honeywell-sensing-and-productivity-solutions/192-103LET-A01/1886044>.
- [47] P. Mueller, "Humidity sensor questions and answers," Dickson Data, <https://dicksondata.com/humidity-sensor-faq>.
- [48] HS12SP amphenol Tellaire | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/HS12SP/4780894>.
- [49] HPP801A031 TE connectivity measurement specialties | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/te-connectivity-measurement-specialties/HPP801A031/697731>.
- [50] HIH-4021-003 - digikey, <https://www.digikey.com/en/products/detail/honeywell-sensing-and-productivity-solutions/HIH-4021-003/2503904>.
- [51] 3721 Adafruit Industries LLC | Sensors, transducers | DigiKey, <https://www.digikey.com/product-detail/en/adafruit-industries-llc/3721/1528-2564-ND/8558266>.
- [52] Humidity-sens-e Vishay Beyschlag/draloric/BC components | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/HUMIDITY-SENS-E/769433>.
- [53] CHS-MSS TDK Corporation | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/tdk-corporation/CHS-MSS/931222>.
- [54] Admin, "Microwave vs infrared sensors: Understanding the differences," Rotech Automation, <https://rotech.com.au/microwave-vs-infrared-activation-sensors-whats-the-difference/>.
- [55] A121-001-T&R acconeer ab | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/acconeer-ab/A121-001-T-R/17883300>.
- [56] "IWR6843ARQGALP active," IWR6843AOP | Buy TI Parts | TI.com, <https://www.ti.com/product/IWR6843AOP/part-details/IWR6843ARQGALP>.
- [57] "IWR6432AOP," IWR6432AOP data sheet, product information and support | TI.com, https://www.ti.com/product/IWR6432AOP?keyMatch=iwrl6432aop&tisearch=universal_search.
- [58] XM125 Acconeer ab | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/acconeer-ab/XM125/17883267>.

- [59] J. Kang *et al.*, "Effects of dust and moisture surface contaminants on automotive radar sensor frequencies," *Sensors*, vol. 25, no. 7, p. 2192, Mar. 2025. doi:10.3390/s25072192
- [60] "Polycarbonate vs acrylic - learn about the difference between acrylic & polycarbonate material: A&C plastics," Polycarbonate vs Acrylic - Learn about the Difference Between Acrylic & Polycarbonate Material | A&C Plastics, <https://www.acplasticsinc.com/informationcenter/r/acrylic-vs-polycarbonate>
- [61] N. Staff, "OLED vs LCD," Newhaven Display, <https://newhavendisplay.com/blog/oled-vs-lcd/>.
- [62] "TFT LCD," Wikipedia, https://en.wikipedia.org/wiki/TFT_LCD.
- [63] "TFT, LCD, and OLED displays: What's the difference, and when does it matter?," Arkco, <https://www.arkco-sales.com/articles/hmi-tft-lcd-oled>.
- [64] NHD-0216K1Z-NSW-BBW-L Newhaven display intl | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/newhaven-display-intl/NHD-0216K1Z-NSW-BBW-L/1701179>.
- [65] CN0295D sunfounder | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/sunfounder/CN0295D/18668612>.
- [66] NHD-0216SZ-NSW-BBW-33V3 Newhaven display intl | optoelectronics | DigiKey, <https://www.digikey.co.uk/en/products/detail/newhaven-display-intl/NHD-0216SZ-NSW-BBW-33V3/2773590>.
- [67] "AMC1602AR-B-B6WTDW-SPI (16X2 character LCD module - SPI interface): Store," Orient Display, <https://www.orientdisplay.com/products/amc1602ar-b-b6wtdw-spi-16x2-character-lcd-module-spi-interface/>.
- [68] "Pla vs Abs Filament: Understanding abs vs PLA filament performance," ANYCUBIC, https://store.anycubic.com/blogs/3d-printing-guides/pla-vs-abs-filament?tm=tt&ap=gads&aaid=adaSU7wmdvATJ&utm_source=google&utm_medium=cpc_pmax&utm_campaign=us_sales_pmax_k3series_0522&gad_source=1&gad_campaignid=20978953137&gbraid=0AAAAAqsGgBR84-QMOEeZ7DwHWqhsBHLR&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkQnphRIwoZ3vQLoYrtpXgT1SVkMVPWBuyk9w0PaOyN4JLZZJS329YaAnOTEALw_wcB.
- [69] "The 3D printing holy trinity: Pla, ABS, and petg," Slice Engineering, <https://www.sliceengineering.com/blogs/news/the-3d-printing-holy-trinity?srsId=AfmBOorVS0PTX7FLGp3wibpYSXdP-fPAMAJeBDcbOw8vYUtHCRyH8ZsN>.
- [70] C. Lim, "Choosing the right filament: PETG, Pla, or ABS?," SOVOL, <https://www.sovol3d.com/blogs/news/choosing-the-right-filament-petg-pla-or-abs?source=kang->

[zero&utm_source=google&utm_medium=search&utm_campaign=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_content=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_matchtype=&utm_network=x&qad_source=1&qad_campaignid=22688845864&qbraid=0AAAAACRod - Oj_mZuqOhYNQg9mrBsyA-R&qclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRlhDf9ab-SvHjshEhipPMrYt59yy4sNuOE6YTrrglGZq8TaTdsEd8aAIDIEALw_wcB.](https://www.digikey.com/en/resources/articles/3d-printing-resin-vs-filament-strength-quality-cost?utm_source=google&utm_medium=search&utm_campaign=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_content=%E8%87%AA%E5%AE%9A%E4%B9%89&utm_matchtype=&utm_network=x&qad_source=1&qad_campaignid=22688845864&qbraid=0AAAAACRod-Oj_mZuqOhYNQg9mrBsyA-R&qclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRlhDf9ab-SvHjshEhipPMrYt59yy4sNuOE6YTrrglGZq8TaTdsEd8aAIDIEALw_wcB)

- [71] A. Alder, "3D printing resin vs filament: Strength, quality & cost," 3D Printing Resin vs Filament: Strength, Quality & Cost, https://4dfiltration.com/resources/3d/resin-vs-filament-strength-quality-cost?qad_source=1&qad_campaignid=15858854285&qbraid=0AAAAAB3Y0gmSAFB4PTyWwThy_5hlZbsgu&qclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRa4mYjfD7Pv9sTA6ADkgW8T_fNB4PrhKCW7r0zFY7CLFex5N2ERt0aAj3JEALw_wcB.
- [72] PIC18F46K22-I/P microchip technology | integrated circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/microchip-technology/PIC18F46K22-I-P/2480375?msockid=2c71e9962a8d6eb016a8ffe32bd46f5a>.
- [73] ATMEGA328P-pu Microchip Technology | Integrated Circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/microchip-technology/ATMEGA328P-PU/1914589>.
- [74] STM32F103C8T6 stmicroelectronics | integrated circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/stmicroelectronics/STM32F103C8T6/1646338>.
- [75] ESPRESSIF documentation, https://documentation.espressif.com/esp32-wroom-32_datasheet_en.pdf?utm_source.
- [76] "What Are the Types of Voltage Regulators and How Do They Work?" *EP Power*. Available: <https://ep-power.com/what-are-the-types-of-voltage-regulators-and-how-do-they-work>
- [77] "Linear Voltage Regulator: Circuit, Types & Applications," *How2Electronics*. Available: <https://how2electronics.com/linear-voltage-regulator-circuit-types-applications>
- [78] "Switching Regulator Definition," *Analog Devices*. Available: https://www.analog.com/en/resources/glossary/switching_regulator.html
- [79] "Buck, Boost, and Other DC-DC Converters Explained," *TDK Lambda Americas*. Available: <https://www.us.lambda.tdk.com/resources/blogs/20200731.html>
- [80] "Linear vs. Switching Regulators," *Renesas Electronics*. Available: <https://www.renesas.com/en/products/power-management/linear-vs-switching-regulators>
- [81] "AP64502SP-13 – Diodes Incorporated," *Digi-Key Electronics*. Available: <https://www.digikey.com/en/products/detail/diodes-incorporated/AP64502SP-13/15286693>

- [82] "TPS54531DDAR – Texas Instruments," *Digi-Key Electronics*. Available: <https://www.digikey.com/en/products/detail/texas-instruments/TPS54531DDAR/4162425>
- [83] "RT6285GSP – Richtek USA Inc.," *Digi-Key Electronics*. Available: <https://www.digikey.com/en/products/detail/richtek-usa-inc/RT6285GSP/16376754>
- [84] Digi-Key Electronics, "S-13D1B1218-M6T1U3 – ABLIC Inc.," Available: <https://www.digikey.com/en/products/detail/ablic-inc/S-13D1B1218-M6T1U3/6117298>
- [85] onsemi, "NCP1117IST18T3G – IC REG LIN 1.8 V 1A SOT-223," Digi-Key Electronics, www.digikey.com/en/products/detail/onsemi/NCP1117IST18T3G/14545343
- [86] Texas Instruments, "TLV1117-18IDCYRG3 – IC REG LIN 1.8 V 800 mA SOT-223-4," Digi-Key Electronics, www.digikey.com/en/products/detail/texas-instruments/TLV1117-18IDCYRG3/1677110
- [87] "Brushless vs. Brushed DC Motors," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors>
- [88] "Stepper Motors: Basics, Types, and Uses," *Monolithic Power Systems*. Available: <https://www.monolithicpower.com/en/learning/resources/stepper-motors-basics-types-uses>
- [89] "What is a Coreless DC Motor and How Does It Work?" *Telco Intercon*. Available: <https://www.telcointercon.com/blog/what-is-a-coreless-dc-motor-and-how-dose-it-work>
- [90] "INJORA INJS235 35KG Waterproof Brushless Servo Large Torque Digital Servo," *INJORA*. Available: <https://www.injora.com/products/injora-injs235-35kg-waterproof-brushless-servo-large-torque-digital-servo>
- [91] "Brushless High Torque Micro Servo," *MEUS Racing*. Available: <https://www.meusracing.com/products/brushless-high-torque-micro-servo-us-warehouse>
- [92] "Power HD M8 Brushless Servo 0.068sec/7.6kg," *Dollar Hobbyz*. Available: <https://www.dollarhobbyz.com/products/m8-brushless-servo-0-68sec-7-6kg>
- [93] "The Pros and Cons of Lithium-Ion Batteries: A Deep Dive," *Bioenno Power*. Available: <https://www.bioennopower.com/blogs/news/the-pros-and-cons-of-lithium-ion-batteries-a-deep-dive>
- [94] "Difference Between Lithium-Ion and Lithium-Polymer Batteries (FAQ)," *Battery Power Tips*. Available: <https://www.batterypowertips.com/difference-between-lithium-ion-lithium-polymer-batteries-faq>

- [95] "What Are Nickel Metal Hydride (NiMH) Batteries?" *R&D Batteries*. Available: <https://www.rdbatteries.com/blog/post/what-are-nickel-metal-hydride-nimh-batteries-.html>
- [96] "What's the Best Battery?" *Battery University*. Available: <https://batteryuniversity.com/article/whats-the-best-battery>
- [97] "Nihewo 4S 4500mAh 80C LiPo Battery," *Amazon*. Available: <https://www.amazon.com/Nihewo-Battery-Compatible-Airplane-Helicopter/dp/B0BDRP6BKP>
- [98] "Spektrum 14.8V 5000mAh 4S 30C Smart LiPo Battery: IC5, SPMX50004S30," *Amazon*. Available: <https://www.amazon.com/Spektrum-14-8V-5000mAh-Smart-SPMX50004S30/dp/B07W5VV899>
- [99] "Turnigy Rapid 5000mAh 6S 22.2V 100C LiPo Battery Pack w/XT90 Connector," *HobbyKing*. Available: https://hobbyking.com/en_us/turnigy-rapid-5000mah-6s-22-2v-100c-lipo-battery-pack-w-xt90-connector.html
- [100] ArduinoModules, "KY-012 active Buzzer module," ArduinoModulesInfo, <https://arduinomodules.info/ky-012-active-buzzer-module/>.
- [101] CMI-1295IC-0585T same sky (formerly CUI devices) | audio products | DigiKey, <https://www.digikey.com/en/products/detail/cui-devices/CMI-1295IC-0585T/11674150>.
- [102] WST-1203UX Soberton Inc. | audio products | DigiKey, <https://www.digikey.com/en/products/detail/soberton-inc/WST-1203UX/1245301>.
- [103] Same sky (formerly Cui Devices), <https://www.digikey.com/en/supplier-centers/cui-devices?msockid=0f2d84fc671b62cb37fd926f664a63a4>.
- [104] IE330403-1 DB unlimited | DigiKey, <https://www.digikey.com/en/products/detail/db-unlimited/ie330403-1/9990502>.
- [105] RBE-4.000-3215-NS1 raltron electronics | audio products | DigiKey, <https://www.digikey.co.uk/en/products/detail/raltron-electronics/RBE-4-000-3215-NS1/22320882> (accessed Oct. 31, 2025).
- [106] "I2C," I2C - SparkFun Learn, <https://learn.sparkfun.com/tutorials/i2c/all>.
- [107] T. Agarwal, "USB protocol : Architecture, Working Specifications & Applications," ElProCus, <https://www.elprocus.com/usb-protocol/>.
- [108] "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.
- [109] "Python vs. C++: Key differences and uses," IONOS Digital Guide, <https://www.ionos.com/digitalguide/websites/web-development/python-vs-c/>.
- [110] STX Next, "Python vs. C++: Which language wins for your project?," Software Development Services & Solutions Company – STX Next, <https://www.stxnext.com/blog/python-vs-c-plus-plus-comparison>.

- [111] GeeksforGeeks, "Difference between python and C++," GeeksforGeeks, <https://www.geeksforgeeks.org/python/difference-between-python-and-c/>.
- [112] You only look once: Unified, real-time object detection, https://www.cv-foundation.org/openaccess/content_cvpr_2016/papers/Redmon_You_Only_Look_CVPR_2016_paper.pdf.
- [113] J. Hui, "SSD object detection: Single shot multibox detector for real-time processing," Medium, <https://jonathan-hui.medium.com/ssd-object-detection-single-shot-multibox-detector-for-real-time-processing-9bd8deac0e06>.
- [114] GeeksforGeeks, "Faster R-CNN: ML," GeeksforGeeks, <https://www.geeksforgeeks.org/machine-learning/faster-r-cnn-ml/>.
- [115] NXP, <https://www.nxp.com/docs/en/user-guide/UM10204.pdf?fsrch=1&sr=1&pageNum=1>.
- [116] "Universal asynchronous receiver-transmitter," Wikipedia, https://en.wikipedia.org/wiki/Universal_asynchronous_receiver-transmitter.
- [117] "Serial peripheral interface," Wikipedia, https://en.wikipedia.org/wiki/Serial_Peripheral_Interface.
- [118] M. Brain, "Understanding USB types and the flexible USB system," HowStuffWorks, <https://computer.howstuffworks.com/usb.htm>.
- [119] "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.
- [120] "PEP 8 – style guide for python code," Python Enhancement Proposals (PEPs), <https://peps.python.org/pep-0008/>.
- [121] "About git," Git, <https://git-scm.com/about>.
- [122] "GitHub · change is constant. github keeps you ahead.," GitHub, <https://github.com/>.
- [123] "Accelerated Container Application Development," Docker, <https://www.docker.com/>.
- [124] "Pulse Width Modulation (PWM): How It Works and Why It's Essential in Electronics," SameSky Devices. Available: <https://www.sameskydevices.com/blog/pulse-width-modulation-pwm-how-it-works-and-why-its-essential-in-electronics>
- [125] "GitHub copilot · your AI pair programmer," GitHub, <https://github.com/features/copilot>.
- [126] Microsoft, "GitHub copilot in vs code," RSS, <https://code.visualstudio.com/docs/copilot/overview>.
- [127] "A Brief History of AI and the Rise of ChatGPT," GaussAlgo. Available: <https://www.gaussalgo.com/knowledge-base/a-brief-history-of-ai-and-the-rise-of-chatgpt>
- [128] Ultralytics, "Home," Ultralytics YOLO Docs, <https://docs.ultralytics.com/>.
- [129] Microsoft, "Visual studio code - the open source AI code editor," RSS, <https://code.visualstudio.com/>.
- [130] JetBrains, "PyCharm: The only python ide you need," JetBrains, <https://www.jetbrains.com/pycharm/>.

- [131] "Make sense," Make Sense, <https://www.makesense.ai/>.
- [132] Ultralytics, "Train," Ultralytics YOLO Docs, <https://docs.ultralytics.com/modes/train/>.
- [133] "Jetson Orin Nano Developer Kit Getting Started Guide," NVIDIA Developer, <https://developer.nvidia.com/embedded/learn/get-started-jetson-orin-nano-devkit>.
- [134] "Balenaetcher - Flash OS images to SD Cards & USB drives," balenaEtcher - Flash OS images to SD cards & USB drives, <https://etcher.balena.io/>.
- [135] Kangalow, "Chromium, other browsers not working after flashing or updating - here's why and Quick Fix," NVIDIA Developer Forums, <https://forums.developer.nvidia.com/t/chromium-other-browsers-not-working-after-flashing-or-updating-heres-why-and-quick-fix/338891>.
- [136] Ultralytics, "Nvidia Jetson," Home - Ultralytics YOLO Docs, <https://docs.ultralytics.com/guides/nvidia-jetson/>.
- [137] XM125 software user guide, https://docs.sparkfun.com/SparkFun_Qwiic_Pulsed_Radar_Sensor_XM125/assets/component_documentation/XM125%20Software%20User%20Guide.pdf.
- [138] "Sparse," Sparse - Acconeer docs, https://docs.acconeer.com/en/latest/a111/radar_data_and_control/services/sparse.html.

Appendix B – Copyright permission

No copyright permission was needed.

Appendix E – LLM Prompts and Outcomes

[Q1] What about shooting pressurized air? how would the tracking and shooting be safely implemented?

[A1] 1. Choosing an Actuator

For a safe, classroom- or lab-friendly deployable:

Option	Pros	Cons
Compressed air via solenoid valve	Quick response, adjustable pressure, simple to control via GPIO	Need regulator for safe pressure, requires tubing and reservoir
Mini air blaster / air cannon (low pressure)	Can use canned air or small air pump, safe if low velocity	Limited range, small distance for detection
Foam projectile launcher	Safe, visible projectile, easy to aim	Slightly more complex mechanics

Recommendation: Use a **low-pressure solenoid valve with regulated air or foam ball launcher** for proof-of-concept.

- **Pressure:** 20–30 PSI max is plenty for 10–20 ft distances and is generally safe.
- **Components:**
 - Solenoid valve (12V or 5V)
 - Air tubing & small reservoir
 - Pressure regulator
 - Relay or MOSFET to switch the valve from Raspberry Pi

[GHC Case Study 1 Prompt] How would I create a dataset to train an ultralytics yolo model?

[GHC Case Study 1 Copilot Outcome] Here's a concise, practical checklist and examples to create a dataset for training an Ultralytics YOLO model (YOLOv8+). Use the Windows paths shown or adapt to your workspace.

1. Plan
 - Define classes and task (detection / segmentation / keypoint).
 - Aim for diverse images (lighting, scale, backgrounds). More data per class => better results.
2. Collect images
 - Gather JPG/PNG images into a single folder before splitting.
 - Recommended: at least hundreds of images per class (more for real-world robustness).
3. Annotate in YOLO format
 - YOLO detection: one .txt per image, same base filename.
 - Each line: class_id x_center_norm y_center_norm width_norm height_norm
 - Example (center and sizes normalized to [0,1]):
0 0.48125 0.35250 0.11406 0.20312
 - Tools: Labellmg (save as YOLO), CVAT, Roboflow (export YOLO), MakeSense.ai.

4. Folder layout (required by ultralytics)
 - Preferred structure:


```
c:\Users\JakeT\OneDrive - University of Central Florida\SD\senior-design\dataset
images\train*.jpg
images\val*.jpg
images\test*.jpg
labels\train*.txt
labels\val*.txt
labels\test*.txt
```
 5. Create data YAML file
 - Example data.yaml (place in dataset root). Update paths to absolute or relative:


```
train: c:/Users/JakeT/OneDrive - University of Central
Florida/SD/senior-design/dataset/images/train
val:  c:/Users/JakeT/OneDrive - University of Central
Florida/SD/senior-design/dataset/images/val
test: c:/Users/JakeT/OneDrive - University of Central
Florida/SD/senior-design/dataset/images/test

nc: 3
names: ['class0','class1','class2']
```

(You can use forward slashes on Windows; ultralytics handles them.)
 6. Install Ultralytics and train (Windows PowerShell / cmd)
 - Install:


```
pip install ultralytics
```
 - Train using a prebuilt model (example):


```
yolo train model=yolov8n.pt data=" c:\Users\JakeT\OneDrive -
University of Central Florida\SD\senior-design\dataset \data.yaml"
epochs=50 imgsz=640 batch=16
```
 - Evaluate / predict:


```
yolo val data=... model=runs/detect/train/weights/best.pt
yolo predict model=runs/detect/train/weights/best.pt
source="c:/path/to/images" conf=0.25
```
 7. Useful tips
 - Verify annotations visually before training.
 - Use augmentation (Ultralytics has built-in augmentations).
 - If classes imbalanced, use sampling/augmentation or class weights.
 - Start from a small model (yolov8n) for quick experiments, then scale up.
 - Monitor mAP, precision, recall; use early stopping if overfitting.
 - For COCO/other formats: convert to YOLO using scripts or Roboflow export.
 8. Converting COCO -> YOLO quick pointer
 - Use pycocotools + conversion script to create labels folder and data.yaml.
- If you want, I can:
- generate a ready data.yaml for your workspace path,

- create a small script to split images into train/val/test,
- or produce a validation script to visualize labels. Which would you like?

[GHC Case Study 1 ChatGPT Outcome]

Excellent question — creating a dataset for **Ultralytics YOLO (v8/v9)** training is one of the most important (and sometimes confusing) steps. Let's go step-by-step so you know **exactly** how to structure, label, and prepare your data.

✂ 1. What YOLO Needs

Ultralytics YOLO expects your dataset to have:

- **Images** (e.g., .jpg, .png)
- **Labels** (text files with bounding box info)
- **Dataset configuration file** (data.yaml)

🖼 2. Folder Structure

Here's the *recommended* structure (for example, my_dataset):

```
my_dataset/
├── images/
│   ├── train/
│   │   ├── img001.jpg
│   │   ├── img002.jpg
│   │   └── ...
│   ├── val/
│   │   ├── img101.jpg
│   │   └── ...
│   └── test/      # optional
│       └── img201.jpg
├── labels/
│   ├── train/
│   │   ├── img001.txt
│   │   ├── img002.txt
│   │   └── ...
│   ├── val/
│   │   ├── img101.txt
│   │   └── ...
│   └── test/      # optional
│       └── img201.txt
```

└─ data.yaml

Each **image** must have a **label file** with the **same name**, e.g.:

images/train/img001.jpg
labels/train/img001.txt

👉 3. Label File Format (.txt)

Each line in a YOLO label file represents **one object**:

<class_id> <x_center> <y_center> <width> <height>

All coordinates are **normalized** (values between 0 and 1).

Example:

0 0.52 0.45 0.20 0.30
1 0.75 0.40 0.10 0.15

This means:

- Object 1: class 0, centered at (52%, 45%) of the image, width 20%, height 30%.
- Object 2: class 1, centered at (75%, 40%)...

🧰 4. Labeling the Images

You'll want a labeling tool that exports in YOLO format:

Tool	Notes
Labellmg	Simple GUI, supports YOLO directly.
Roboflow	Web-based; can preprocess, augment, and export to YOLO.
CVAT	Industrial-strength, team-based labeling.
Label Studio	Flexible, also supports segmentation tasks.

👉 When done labeling, export as **YOLO format** — it will create .txt files for each image.

5. The data.yaml File

This file tells YOLO where to find your data and what classes exist.

Example:

```
train: ./my_dataset/images/train
val: ./my_dataset/images/val
test: ./my_dataset/images/test # optional
```

```
nc: 3 # number of classes
names: ['cat', 'dog', 'bird']
```

6. Verifying Your Dataset

You can check the dataset before training:

```
yolo detect train data=my_dataset/data.yaml model=yolov8n.pt imgsz=640
```

YOLO will automatically check that:

- image and label counts match,
- label values are valid,
- all paths are correct.

7. Train Command

Once ready:

```
yolo detect train data=my_dataset/data.yaml model=yolov8n.pt epochs=50
imgsz=640
```

You can replace:

- yolov8n.pt → with other model sizes like yolov8s.pt, yolov8m.pt, etc.
- epochs → number of training iterations.

Optional Tips

- Use **Roboflow** or **FiftyOne** to inspect and balance datasets.
- Keep at least:
 - 70–80% training

- 10–20% validation
- 5–10% test (optional)
- Data augmentation helps (YOLO has built-in augmentations).

Would you like me to show an **example of generating a small YOLO dataset** (e.g. for detecting Lego bricks or motors) so you can see what the label files and YAML look like in practice?

[GHC Case Study 2 Prompt] Please create a Python script with uses a camera to detect for moving objects. when found, it saves the image using a unique value so that when run again no image is overwritten

[GHC Case Study 2 Copilot Outcome] Solution (step-by-step)

1. Capture frames from the default camera with OpenCV.
2. Convert frames to grayscale and blur to reduce noise.
3. Maintain a running background model (accumulateWeighted).
4. Compute absolute difference, threshold and find contours to detect motion.
5. When motion with sufficient area is found and cooldown has passed, save the current color frame to a captures folder using a filename containing a timestamp and a UUID so it will never be overwritten.
6. Show live preview; press 'q' to exit.

Create a new script that captures video, detects moving objects, and saves uniquely named images.

```
import cv2
import os
import time
import uuid
from datetime import datetime

# Configuration
OUTPUT_DIR = r"c:\Users\JakeT\OneDrive - University of Central
Florida\SD\senior-design\captures"
MIN_CONTOUR_AREA = 2000    # ignore small movements
BACKGROUND_ACCUM_WEIGHT = 0.02
THRESHOLD = 25
COOLDOWN_SECONDS = 5      # avoid saving many frames for same event

os.makedirs(OUTPUT_DIR, exist_ok=True)

cap = cv2.VideoCapture(0)
if not cap.isOpened():
    raise RuntimeError("Cannot open camera")
```

```

bg = None
last_saved = 0

try:
    while True:
        ret, frame = cap.read()
        if not ret:
            break

        gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
        gray = cv2.GaussianBlur(gray, (21, 21), 0)

        if bg is None:
            bg = gray.copy().astype("float")
            continue

        # update running background model
        cv2.accumulateWeighted(gray, bg, BACKGROUND_ACCUM_WEIGHT)
        frameDelta = cv2.absdiff(gray, cv2.convertScaleAbs(bg))
        _, thresh = cv2.threshold(frameDelta, THRESHOLD, 255,
cv2.THRESH_BINARY)
        thresh = cv2.dilate(thresh, None, iterations=2)

        contours, _ = cv2.findContours(thresh.copy(), cv2.RETR_EXTERNAL,
cv2.CHAIN_APPROX_SIMPLE)
        motion_detected = False

        for c in contours:
            if cv2.contourArea(c) < MIN_CONTOUR_AREA:
                continue
            (x, y, w, h) = cv2.boundingRect(c)
            cv2.rectangle(frame, (x, y), (x + w, y + h), (0, 255, 0), 2)
            motion_detected = True

        # save if motion detected and cooldown elapsed
        if motion_detected and (time.time() - last_saved) >
COOLDOWN_SECONDS:
            ts = datetime.now().strftime("%Y%m%d_%H%M%S_%f")
            unique = uuid.uuid4().hex
            filename = f"{ts}_{unique}.jpg"
            path = os.path.join(OUTPUT_DIR, filename)
            cv2.imwrite(path, frame)
            print("Saved:", path)
            last_saved = time.time()

        cv2.imshow("Frame", frame)

```

```

cv2.imshow("Thresh", thresh)

if cv2.waitKey(1) & 0xFF == ord('q'):
    break
finally:
    cap.release()
    cv2.destroyAllWindows()

```

Usage: install OpenCV (pip install opencv-python), run the script. Images are saved into the captures folder with timestamp + UUID filenames so they won't be overwritten.

[GHC Case Study 2 ChatGPT Outcome]

Perfect — that's a classic **motion detection script** problem.
Below is a clean and working **Python + OpenCV** script that:

1. Uses your webcam to watch for motion,
2. Captures frames where motion is detected, and
3. Saves them with **unique filenames** (using timestamps or UUIDs, so no overwriting happens).

Requirements

Make sure you have these installed first:

pip install opencv-python

Python Script — motion_capture.py

```

import cv2
import uuid
import os
from datetime import datetime

# === Configuration ===
SAVE_DIR = "captures"
MIN_AREA = 5000 # Minimum contour area to be considered motion (tweak this)
CAMERA_INDEX = 0 # 0 = default webcam

# Create output directory if it doesn't exist
os.makedirs(SAVE_DIR, exist_ok=True)

# Initialize camera

```

```

cap = cv2.VideoCapture(CAMERA_INDEX)
if not cap.isOpened():
    print("❌ Error: Could not open camera.")
    exit()

# Read the first frame
ret, frame1 = cap.read()
ret, frame2 = cap.read()

print("📹 Motion detection started. Press 'q' to quit.")

while cap.isOpened():
    # Compute difference between frames
    diff = cv2.absdiff(frame1, frame2)
    gray = cv2.cvtColor(diff, cv2.COLOR_BGR2GRAY)
    blur = cv2.GaussianBlur(gray, (5, 5), 0)
    _, thresh = cv2.threshold(blur, 20, 255, cv2.THRESH_BINARY)
    dilated = cv2.dilate(thresh, None, iterations=3)

    # Find contours (regions of motion)
    contours, _ = cv2.findContours(dilated, cv2.RETR_TREE,
    cv2.CHAIN_APPROX_SIMPLE)

    motion_detected = False

    for contour in contours:
        if cv2.contourArea(contour) < MIN_AREA:
            continue
        motion_detected = True

    # Draw rectangle on motion area
    (x, y, w, h) = cv2.boundingRect(contour)
    cv2.rectangle(frame1, (x, y), (x + w, y + h), (0, 255, 0), 2)

    # If motion detected, save frame
    if motion_detected:
        unique_name =
f'{datetime.now().strftime('%Y%m%d_%H%M%S')}__{uuid.uuid4().hex[:8]}.jpg'
        filepath = os.path.join(SAVE_DIR, unique_name)
        cv2.imwrite(filepath, frame1)
        print(f"📁 Motion detected! Saved: {filepath}")

    # Show live video feed
    cv2.imshow("Motion Detection", frame1)

    # Update frames

```

```

frame1 = frame2
ret, frame2 = cap.read()
if not ret:
    break

# Quit with 'q'
if cv2.waitKey(10) & 0xFF == ord('q'):
    break

# Cleanup
cap.release()
cv2.destroyAllWindows()
print("✅ Motion detection stopped.")

```

Output

- All motion snapshots are saved in a folder named captures/
- Each image has a **unique filename**, e.g.:

```

captures/20251030_014833_a1b2c3d4.jpg
captures/20251030_014900_9f8e7d6c.jpg

```

How it Works

- The script continuously compares the **current frame** vs. the **previous frame**.
- If enough pixels change (based on contour area), it flags **motion**.
- The frame is saved with a unique name built from:
 - Current date/time (%Y%m%d_%H%M%S)
 - A short random UUID for guaranteed uniqueness.

Would you like me to modify it so it **runs headless** (no OpenCV window — just detects and saves quietly), e.g. for running on a Raspberry Pi or server setup?

[GHC Case Study 3 Prompt] I would like the code to save an image anytime motion is detected. there should be no cooldown time. also, ensure that the OUTPUT_DIR is correct

[GHC Case Study 3 Copilot Outcome] Solution (step-by-step)

1. Make OUTPUT_DIR use a path relative to the script so it's always correct for this project.

2. Remove the cooldown logic and related variables so an image is saved every time motion is detected.
3. Keep the existing motion-detection logic and saving filename format (timestamp + UUID) so files never overwrite.

c:\Users\JakeT\OneDrive - University of Central Florida\SD\senior-design\Orin\motion_detector.py

Change summary:

- Use a script-relative captures folder for OUTPUT_DIR.
- Remove COOLDOWN_SECONDS and last_saved; save immediately when motion_detected.

Ensure OUTPUT_DIR is inside the project and relative to this script

OUTPUT_DIR = os.path.join(os.path.dirname(__file__), "captures")

...

save if motion detected (no cooldown) — every detection results in a saved image

if motion_detected:

...

Removed lines

[GHC Case Study ChatGPT 3 Outcome]

Perfect — you want **continuous motion capture** (no cooldown), saving **every time** motion is detected, and ensuring the output directory always works no matter where you run it.

Here's the improved version that does exactly that 

📁 Final Python Script — motion_capture.py

import cv2

import uuid

import os

from datetime import datetime

=== Configuration ===

OUTPUT_DIR = os.path.join(os.getcwd(), "captures") # Always valid regardless of where script runs

MIN_AREA = 5000 # Minimum contour area for motion detection

CAMERA_INDEX = 0 # 0 = default webcam

Create output directory if it doesn't exist

os.makedirs(OUTPUT_DIR, exist_ok=True)

Initialize camera

cap = cv2.VideoCapture(CAMERA_INDEX)

if not cap.isOpened():

```

print(" ❌ Error: Could not access camera.")
exit()

# Capture initial frames
ret, frame1 = cap.read()
ret, frame2 = cap.read()

print(f" 📹 Motion detection started. Saving images to: {OUTPUT_DIR}")
print("Press 'q' to quit.")

while cap.isOpened():
    # Compute absolute difference between frames
    diff = cv2.absdiff(frame1, frame2)
    gray = cv2.cvtColor(diff, cv2.COLOR_BGR2GRAY)
    blur = cv2.GaussianBlur(gray, (5, 5), 0)
    _, thresh = cv2.threshold(blur, 25, 255, cv2.THRESH_BINARY)
    dilated = cv2.dilate(thresh, None, iterations=3)
    contours, _ = cv2.findContours(dilated, cv2.RETR_EXTERNAL,
    cv2.CHAIN_APPROX_SIMPLE)

    motion_detected = False

    for contour in contours:
        if cv2.contourArea(contour) < MIN_AREA:
            continue
        motion_detected = True

    # Draw bounding box
    (x, y, w, h) = cv2.boundingRect(contour)
    cv2.rectangle(frame1, (x, y), (x + w, y + h), (0, 255, 0), 2)

    # === Save frame immediately when motion is detected ===
    if motion_detected:
        unique_name =
        f"{datetime.now().strftime('%Y%m%d_%H%M%S_%f')}_ {uuid.uuid4().hex[:8]}.jpg
        "
        filepath = os.path.join(OUTPUT_DIR, unique_name)
        cv2.imwrite(filepath, frame1)
        print(f" 📁 Motion detected! Saved image: {filepath}")

    # Display live video
    cv2.imshow("Motion Detection", frame1)

    # Prepare for next iteration
    frame1 = frame2
    ret, frame2 = cap.read()

```

```

if not ret:
    break

# Exit on 'q'
if cv2.waitKey(10) & 0xFF == ord('q'):
    break

# Cleanup
cap.release()
cv2.destroyAllWindows()
print("✅ Motion detection stopped.")

```

✅ Key Features

- **No cooldown** → Every motion-triggered frame is saved instantly.
- **Unique filenames** → Uses both timestamp (with microseconds) and a UUID suffix:

captures/20251030_012340_567890_ab12cd34.jpg

- **Safe output directory** → OUTPUT_DIR automatically resolves to:

[wherever you run script]/captures

If the folder doesn't exist, it's created.

- **Live preview** → You'll see bounding boxes highlighting motion in a preview window.
Press **Q** to quit safely.

Would you like me to modify this so it **runs headless** (no preview window) and logs to a file — ideal for background or Raspberry Pi use?

[GHC Case Study 4 Prompt]

Hey (AI)! Im trying to power some motors, an MCU, an SBC, an LCD screen (small), and a camera and of course I need some voltage regulators and batteries to power and regulate the voltage, what would you recommend to me?

[GHC Case Study Copilot 4 Outcome]

Multi-rail power for motors, MCU, SBC, LCD, and camera

You've got mixed loads with very different needs. The cleanest approach is one battery "backbone" feeding dedicated rails: a high-current rail for motors, a 5 V rail for the SBC, and a clean 3.3 V rail for the MCU/sensors—with isolated or filtered branches for the LCD and camera. This keeps motor noise away from compute and sensitive imaging.

Recommended system architecture

Battery backbone: Use a single pack sized to your motors, then regulate down for everything else. For most hobby/robotics builds: 3S–4S Li-ion/LiPo (11.1–14.8 V nominal) gives headroom for efficient buck conversion to 5 V and 3.3 V; go higher only if your motors require it. Larger SLA or tool-pack batteries work too if weight isn't a concern.

High-current motor rail: Feed motor drivers directly from the battery (with bulk capacitance and protection). Don't run compute rails from the motor driver's VS pin. Add inline fusing per driver and a TVS diode near connectors to tame transients.

5 V compute rail (SBC, camera, LCD logic): A synchronous buck DC-DC converter from battery to a tight 5.1 V rail. Keep this rail physically and electrically separate from motor wiring. Use LC input and output filters for ripple and EMI control.

3.3 V MCU/sensors rail: Derive 3.3 V from the 5 V rail with a low-noise regulator. Prefer a small buck for efficiency if current >300 mA; otherwise a low-dropout (LDO) for best noise performance. Give the MCU its own local decoupling and ground star point.

LCD backlight/camera aux rails: Some small LCDs need a boosted LED backlight rail (e.g., 8–12 V). Generate this with a tiny boost converter from 5 V and keep return currents away from the MCU ground. Cameras typically sit fine on 5 V with good filtering.

Tip: Automotive design notes stress segmentation, transient protection, and solid grounding to survive harsh loads—those habits pay off in motorized projects too.

Specific regulator and part recommendations

Battery to 5 V (SBC/camera/LCD logic):

Converter type: Synchronous buck, 10–20 A class for headroom and low ripple.

Examples: TI LM2596 modules are common but dated; look for modern synchronous bucks with low EMI and soft-start from reputable module vendors. Target <50 mV ripple under load.

5 V to 3.3 V (MCU/sensors):

If low current/noise sensitive: Quiet LDOs (PSRR >60 dB at 100 kHz). Place near MCU with multiple 0.1 μ F decouplers and a 10 μ F bulk cap.

If higher current/heat matters: Small synchronous buck (efficiency >90%) followed by an RC or ferrite bead filter into the MCU rail.

LCD backlight boost (if required):

Converter type: Compact boost with LED current limiting. Keep switching node short; separate ground return to avoid injecting noise into 3.3 V.

Community-proven pick for modest boosts: MT3608 modules are popular for simple 9–12 V boosts at sub-amp currents.

Motor drivers:

Driver choice: Match battery voltage and stall current. Add big low-ESR bulk caps at each driver (e.g., 470–1000 μF) and a fast fuse per channel. Use flyback diodes for brushed motors if driver lacks them.

All-in-one (automotive-style) option: A System Basis Chip (SBC/PMIC) can integrate regulators, watchdogs, and transceivers for MCU domains; still pair with a separate high-current motor supply. Useful if you want CAN/LIN, brownout supervision, and safety features in one device.

Power budget and battery sizing

Estimate max and average: Sum each rail's current, then add 30–50% headroom for transients.

Energy sizing: Pick capacity by runtime target.

Power: $P = V \cdot I$

Energy: $E = P \cdot t$

Example: If motors peak at 10 A on 12 V and compute averages 1.5 A on 5 V, you're around 120 W peak. For 1 hour at half duty, budget ~60 Wh; a 3S 5000 mAh LiPo (~55 Wh) is in range.

Voltage headroom: Ensure the battery's minimum voltage under load stays above your buck's dropout plus required 5 V—another reason 3S–4S packs are forgiving.

Noise, grounding, and protection

Segregation: Route motor power and grounds separately from compute. Star-connect grounds at a single point near the battery shunt/fuse.

Input protection: Use reverse-polarity protection (ideal diode or MOSFET), a main fuse, and a TVS diode sized to the battery bus. Add soft-start/NTC to limit inrush to big caps.

Filtering: LC filters on buck inputs/outputs; ferrite beads feeding sensitive rails (MCU/camera). Keep switching loops tight and away from signals.

Monitoring: If your SBC supports it, supervise rails and implement brownout resets; automotive PMIC/SBCs provide watchdogs and wake features if you need robust control.

Thermal: Heatsink high-current bucks; place them where airflow is decent. Measure ripple and temperature under load to validate margins.

What I'd pick to start

Battery: 3S 5000–8000 mAh LiPo/Li-ion for compact builds; 4S if motors like higher voltage. Add a proper BMS if using bare cells.

5 V rail: 10 A synchronous buck module with soft-start, low ripple, and EMI shielding feeding SBC, camera, and LCD logic.

3.3 V rail: Low-noise LDO (up to 300 mA) near MCU; upgrade to a small buck if sensors/MCU exceed that.

LCD backlight: MT3608 or similar boost set to required LED voltage/current, isolated ground return.

Protection: Main fuse, per-motor fusing, TVS at battery, reverse-polarity MOSFET, bulk caps at each driver, star ground, ferrite beads into MCU/camera rails.

If you share your motor voltage/current, the SBC model, and the LCD/camera specs, I can size each rail, suggest exact buck/LDO part numbers, and draw a simple power tree you can build confidently.

[GHC Case Study ChatGPT 4 Outcome]

Nice — let's build a practical, safe power plan you can actually wire up. I'll give: (A) battery-chemistry options, (B) two realistic architecture choices (one unified-pack, one "separate rails" approach), (C) specific regulator / motor-driver module recommendations, (D) a short worked sizing example, and (E) safety / wiring tips. I didn't ask for specs (motor voltage/current, exact SBC model), so I'll make conservative assumptions and give choices that cover most hobby/robotics setups.

A — Battery chemistry: quick guidance

LiPo / Li-ion (higher energy density) — lighter and smaller (good if weight/size matters). They require careful charging, BMS, and more cautious mechanical handling. [Grepow](#)

LiFePO₄ (LFP) — heavier but far safer, longer cycle life, more stable (great for fixed/long-lived projects). Good where safety and longevity beat absolute energy density. [Grepow](#)

Pick LiPo if you need compact/very light (drones / small robots). Pick LiFePO₄ if you want a robust pack that's less likely to catch fire and will last thousands of cycles.

B — Two practical architectures

**Option 1 — Single battery pack + switching
(recommended for efficiency)**

Use a single battery pack (e.g., 2S/3S/4S LiPo or appropriate LFP) sized for your motor voltage range.

Use **high-efficiency buck (DC-DC) converters** to make the 5V rail(s) for SBC, MCU, camera and to 3.3V if needed. Buck converters keep heat down and preserve runtime versus linear regulators. [Altium](#)

Motors can either run directly from the battery (typical) or from a dedicated motor rail derived from the same pack (if motors require a different voltage). Use a motor driver/H-bridge sized to the stall/peak current.

Why this is good: fewer packs, lighter, efficient conversion for the SBC (which often needs several amps at 5V).

Option 2 — Separate power bricks (simpler / modular)

Use a dedicated 5V power supply (power bank or 5V buck) for the SBC (especially if it needs stable 5V at 3A+), a smaller battery for motors, and a tiny LiPo + LDO/buck for the MCU if desired.

Simpler wiring and isolation (a stalled motor won't drag down the SBC), but heavier and more components.

C — Specific regulator & motor driver recommendations (practical modules)

Buck / 5V supply (for SBC/camera)

For a 5V rail capable of multiple amps you can use compact, proven step-down modules. Example: **Pololu S13V30F5** (5V output, up to ≈ 3 A continuous depending on input/thermal conditions), and Pololu offers other 5V buck options. These are robust and include protections. [Pololu Robotics and Electronics](#)

If your SBC wants 5V @ 3–5A (e.g., Pi 4/5 with peripherals), choose a buck rated for the full continuous current plus margin (e.g., 4–5 A) or use a dedicated 5V PSU/USB-PD solution.

Buck vs LDO

Use **switching buck regulators** for any supply $> \sim 0.5\text{--}1$ A or where $V_{in} \gg V_{out}$ (they're 80–95% efficient). Use **LDOs** only for low-current, low-dropout needs or noise-sensitive analog rails (but expect heat). [Altium](#)

Motor drivers

For medium/high-current brushed DC motors: ST VN5019 carrier (Pololu / Pololu-style carriers) — handles continuous tens of amps (e.g., 12 A cont, 30 A peak) and runs from $\sim 5.5\text{--}24$ V — great general-purpose motor driver for hobby robots. [Pololu Robotics and Electronics](#)

For small brushed DC motors (single ~ 4 A peaks): DRV8871 (TI) breakout — simpler, can handle a few amps and has OCP/thermal protections. Good when each motor is lower power. [TI](#)

D — Sizing example (worked example so you can scale)

Assume:

SBC (e.g., Raspberry Pi class) — 5 V @ 2.5–3 A peak

MCU — 3.3 V @ 0.05–0.2 A

LCD small — 5 V @ 0.1–0.3 A

Camera — 5 V @ 0.3–0.6 A

Motors combined — **peak** 8–12 A (stall/acceleration); **nominal** maybe 2–4 A average

Total continuous draw (conservative): SBC 3 A + peripherals 1 A + motors 3 A = ~ 7 A at their rails.

Battery sizing (simple method)

Battery runtime (hours) $\approx$ Capacity (Ah) / Load (A). Example: a **3S 5000 mAh (5 Ah)** pack supplying the system (after converters) with average 7 A draw:

Runtime $\approx 5 \text{ Ah} / 7 \text{ A} \approx 0.71 \text{ h} \approx$ **43 minutes** (real world lower because of converter inefficiencies and motor peak bursts). For motors with significant peak current you need a battery with suitable **C-rating** and headroom. (*This is the basic capacity formula — useful for quick sizing.*) [Pololu Robotics and Electronics+1](#)

Practical notes:

Allow 20–30% margin for converter inefficiency and headroom.

For a Pi-like SBC that wants steady 5V@3A, either use a buck regulator rated $>3\text{A}$ or a 5V power module/USB-PD supply.

Choose battery capacity and **C-rating** so the battery can provide motor peak current without excessive voltage sag.

E — Safety and wiring checklist (don't skip these)

BMS / balance charging for multi-cell Li-packs (mandatory). Don't charge unprotected packs.

Fuses on each major rail (motors especially). Use slow-blow/autos where appropriate.

Decoupling caps at motors and regulator outputs; motor kickback suppression and TVS diodes for noisy rails.

Common ground / star grounding: connect grounds at a single point to avoid ground loops and voltage offsets.

Wiring gauge: use thick wires for high-current paths (motor battery-to-driver; battery-to-buck). Short leads to reduce losses.

Thermal management: buck converters and motor drivers can need heatsinking or airflow.

Test first with a bench power supply or current-limited source when debugging.

Quick shopping-ish parts list (examples to search for)

- Battery: 3S LiPo 5000 mAh 30C (or LiFePO₄ equivalent if safety/long life prioritized). (choose pack voltage to match motor requirements) [Grepow](#)
- 5V buck regulator (3–5 A rating): Pololu S13V30F5 or similar high-current buck. [Pololu Robotics and Electronics](#)
- Motor driver(s): Pololu VNH5019 carrier (for high-power motors) or TI DRV8871 breakout (for small motors). [Pololu Robotics and Electronics+1](#)
- BMS/charger: matched to cell count (3S/4S) and charge current you want.
- Fuses, Schottky diodes, decoupling caps, XT60 / Anderson connectors for battery, banana/servo connectors for regulator outputs.

If you want, I can **do one of the following next, right away** (pick one — I'll produce it now):

1. a tailored parts list with exact product SKUs and shopping links for a **3S LiPo** system sized to X runtime (tell me roughly how long you want to run and the motor's nominal voltage/current if you can),
2. a wiring diagram (ASCII or simple schematic) showing battery → BMS → main switch → motor drivers and buck converters → SBC/MCU, or
3. a short BOM for a **LiFePO₄**-based build (safer long-term) and recommended charger/BMS.

Which would you like me to produce immediately?