



P.U.T.T.I.
Portable Unitary Throwable Target Interceptor
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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 until 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>.



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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.

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



Figure 2 - 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 arial 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.

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

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/>.

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 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 50 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

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>.

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, 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

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>

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.

2.4 Required Specifications

Table 2.4.1 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.	≥ 120° H × 60° V
Targeting Success Rate	Probability of successfully detecting and targeting projectiles.	80% -> 100%

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/>

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 × 0.5 m × 0.5 m

Table 2.4.2 *Component Specifications*

Component Specifications		
Components	Parameters	Target Values
Laser Module	Wavelength	630 nm – 680 nm
	Output Power	≤ 5 mW
Motors	Angular speed	≥ 150°/s
	Resolution	≤ 1°
Camera	Frame Rate	≥ 60 fps
Microwave Sensor	Detection Range	≥ 5 m
Microcontroller	Communication	UART/I2C Interface

2.4.1 Hardware Block Diagram

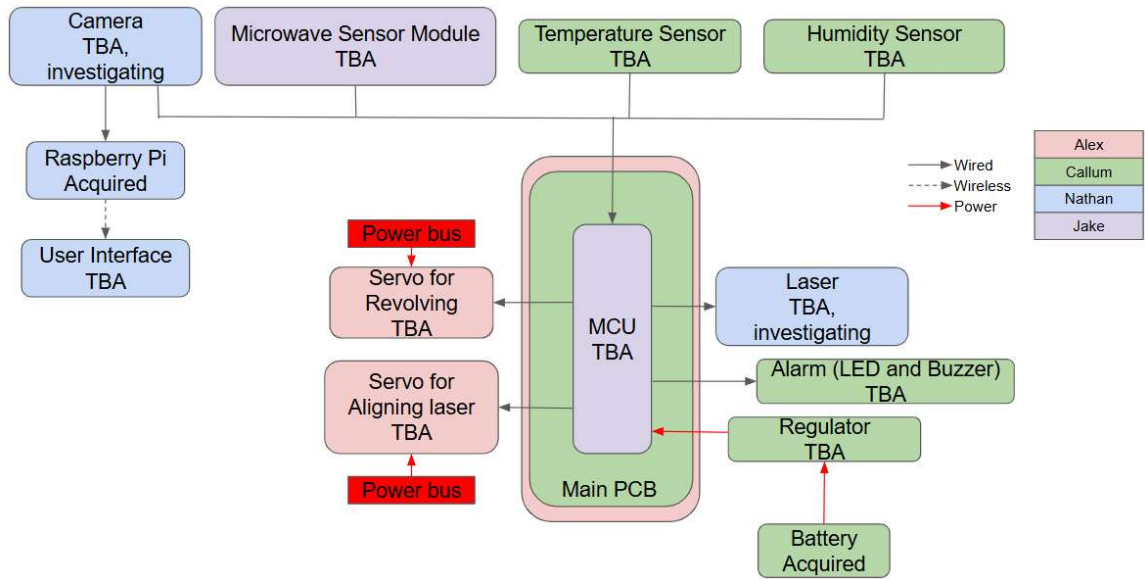


Figure 3 - Hardware Diagram

2.4.2 Software Diagram

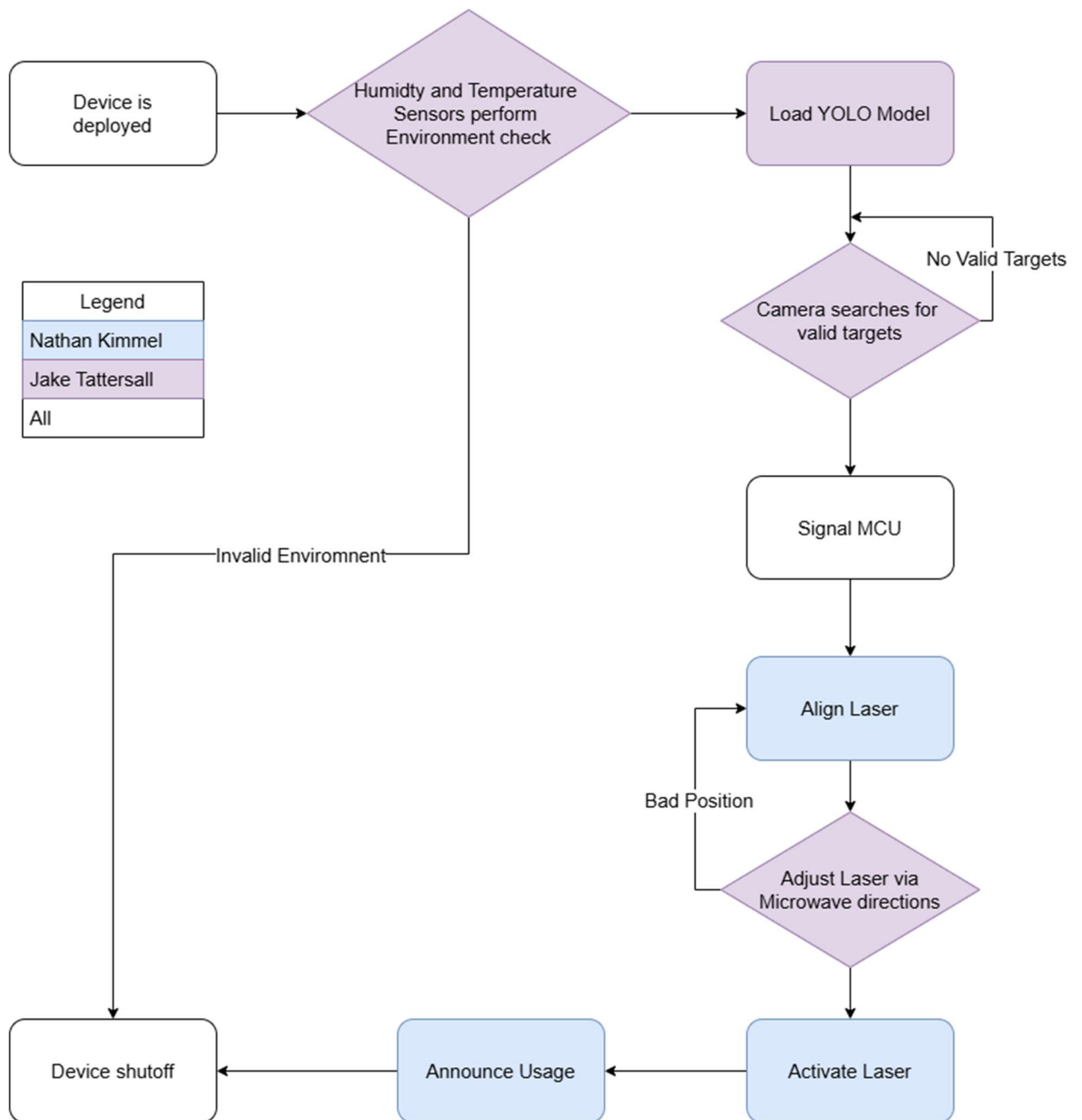


Figure 4 - Software Diagram

2.4.3 Prototype illustration

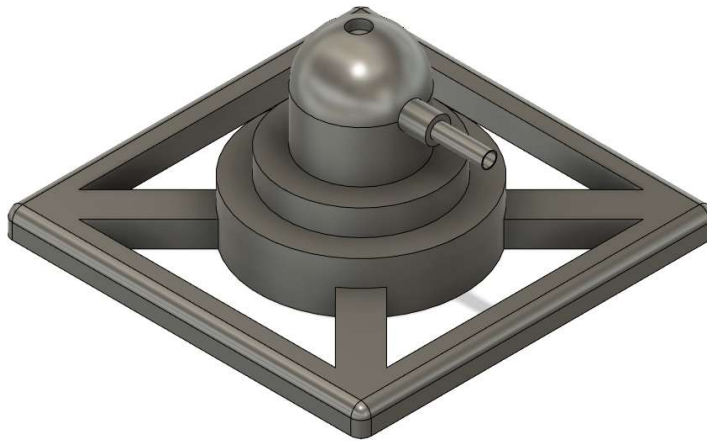


Figure 5 - Isometric view of final product includes space for camera and laser on barrel



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

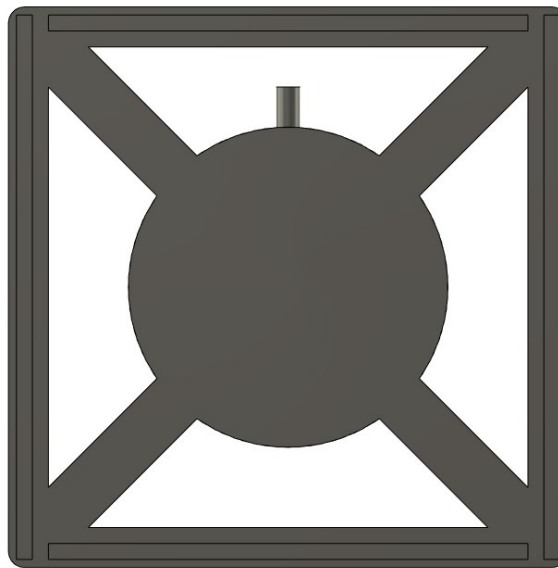


Figure 7 - Bottom view of final product includes adhesive material to allow for multi-faced deployment

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

2.6 Estimated Cost Table

Table 2.6.1 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
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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 3.1.1.1 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

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

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>.

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.

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 specifications, the maximum resolution of 1280x720 pixels may be too small to accurately capture images of targets²⁰. This device could remain a valuable option, but the MIPI CSI-2 port offers better use cases for this project.

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,"

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 Nano²¹.

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 project²².

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 x 3040, or approximately 12.33 million pixels. This chip's specs are also within the project's requirements²³.

Table 3.1.2.1 Camera Sensor Specifications

Feature	IMX219	IMX477
Resolution	3,280 x 2,464	4,056 x 3,040
Active Pixels	8.08 M	12.33 M
Diagonal	4.60 mm	7.857 mm
Interface	CSI	CSI
Input Voltage	2.8 Analog, 1.2 Digital, 1.7 IF	2.8 Analog, 1.05 Digital, 1.8 IF

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

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

²³ IMX477-AACK | Sony Semiconductor Solutions, https://www.sony-semicon.com/files/62/pdf/p-13_IMX477-AACK_Flyer.pdf.

Max FPS at highest quality	30	60
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3.1.2.2 Camera Type Selection

After much review, it would appear that the CSI cameras would work best for this project. Achieving both high frames per second and resolution capabilities, even if not used, will be very beneficial to the project. 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 \$26²⁴.

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 \$36²⁵.

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

²⁴ 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/>.

²⁵ 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>.

advertises <14.3% distortion, which is fairly minimal and can be helpful since objects may not be near the edge of the frame regardless²⁶. The camera is priced at approximately \$22²⁷.

Table 3.1.2.2 Camera Specifications

Feature	Arducam 222	Arducam 175	Coolwell 160
FOV (degrees)	222	175	160
FPS @ Max Quality	21	21	21
Size	25 x 24	25 x 24	25 x 24
Price	\$26	\$36	\$21

3.1.2.3 Camera Selection

After much review, the Waveshare camera is the best choice for this project. The 160-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 CSI port to provide fast imaging at high qualities. The extra details about the component are also useful in selecting which exact product to purchase.

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 \$1000.²⁸

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

²⁶ "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>.

²⁷ "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>.

²⁸ Dr. R. Paschotta, "Solid-state lasers," RP Photonics, https://www.rp-photonics.com/solid_state_lasers.html.

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.²⁹

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.³⁰

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.³¹

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.³²

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

29Dr. R. Paschotta, "Gas lasers," RP Photonics, https://www.rp-photonics.com/gas_lasers.html.

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

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

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

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.³³

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.³⁴

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.³⁵

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. 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-

³³ 1054 Adafruit Industries LLC | optoelectronics | DigiKey,

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

³⁴ PLT5 520DB_P AMS-Osram USA Inc. | Optoelectronics | DigiKey, HYPERLINK

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

³⁵ VLM-650-04 LPA Quarton Inc. | optoelectronics | DigiKey,

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

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.³⁶

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.³⁷

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.³⁸

Table 3.1.3.1 Laser Specifications

	1054	PLT5 520DB_P	VLM-650-04 LPA	VLM-650-01-LPT-ND	D405-120	RLD85NZJ4-00A
Manufacturer	Adafruit Industries LLC	ams-OSRAM USA INC.	Quarton Inc.	Quarton Inc.	US-Lasers Inc.	Rohm Semiconductor

³⁶ VLM-650-01 LPT Quarton Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/quarton-inc/VLM-650-01-LPT/1010451>.

³⁷ D405-120 US-Lasers Inc. | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/us-lasers-inc/D405-120/3438595>.

³⁸ RLD85NZJ4-00A rohm semiconductor | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/rohm-semiconductor/RLD85NZJ4-00A/12336426>.

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 for 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 narrower 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.³⁹

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 suit 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

³⁹ Sensors | DigiKey, <https://www.digikey.com/en/application-technology/sensors>.

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.⁴⁰

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 B57869S0103F140.⁴¹

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

⁴⁰ B57869s0103f140 epcos - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epcos-tdk/B57869S103F140/3500481>.

⁴¹ Pane103395410 Vishay Ametherm | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/ametherm/PANE-103395-410/1765764>

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.⁴²

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.⁴³

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 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

⁴² AL03006-535K-145-G1 amphenol thermometrics | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/AL03006-535K-145-G1/136421>.

⁴³ B57540g1103f000 epco - TDK Electronics | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/epco-tdk-electronics/B57540G1103F000/3500367>.

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.⁴⁴

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.⁴⁵

Table 3.1.4.1 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%
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	-

⁴⁴ Eaton-Electronics Division distributor | DigiKey, <https://www.digikey.com/en/supplier-centers/eaton-electronics-division>.

⁴⁵ 192-103LET-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>.

Length - Lead Wire	-	150.00mm	29.20mm	65.00mm	6.50mm	38.00mm
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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.⁴⁶

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 which would occur additional costs on top of the \$5.60 that the sensor costs through DigiKey.⁴⁷

The HPP801A031 is capacitive humidity sensor with a capacitive output manufactured by TE Connectivity. This sensor has a very big range of 1% to 99% relative humidity with 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

⁴⁶ P. Mueller, "Humidity sensor questions and answers," Dickson Data, <https://dicksondata.com/humidity-sensor-faq>.

⁴⁷ HS12SP amphenol Telaire | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/amphenol-advanced-sensors/HS12SP/4780894>.

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.⁴⁸

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 incase 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.⁴⁹

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. 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

⁴⁸ HPP801A031 TE connectivity measurement specialties | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/te-connectivity-measurement-specialties/HPP801A031/697731>.

⁴⁹ HIH-4021-003 - digikey, <https://www.digikey.com/en/products/detail/honeywell-sensing-and-productivity-solutions/HIH-4021-003/2503904>.

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.⁵⁰

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.⁵¹

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 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.⁵²

⁵⁰ 3721 Adafruit Industries LLC | Sensors, transducers | DigiKey, <https://www.digikey.com/product-detail/en/adafruit-industries-llc/3721/1528-2564-ND/8558266>.

⁵¹ 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>.

⁵² CHS-MSS TDK Corporation | Sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/tdk-corporation/CHS-MSS/931222>.

Table 3.1.5.1 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 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 HIH-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 purposes⁵³.

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.

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.I. depends primarily on the camera detection range.

⁵³ Admin, "Microwave vs infrared sensors: Understanding the differences," Rotech Automation, <https://rotech.com.au/microwave-vs-infrared-activation-sensors-whats-the-difference/>

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 processing⁵⁴.

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 parameters⁵⁵.

The third radar sensor evaluated is the IWR6843AOP 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 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,

⁵⁴ A121-001-T&R acconeer ab | sensors, transducers | DigiKey,

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

⁵⁵ "IWR6843ARQGALP active," IWR6843AOP | Buy TI Parts | TI.com,

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

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 time⁵⁶.

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 capabilities⁵⁷.

Table 3.1.6.1 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

⁵⁶ "IWRL6432AOP," IWRL6432AOP data sheet, product information and support | TI.com, HYPERLINK "https://www.ti.com/product/IWRL6432AOP?keyMatch=iwrl6432aop&tisearch=universal_search"https://www.ti.com/product/IWRL6432AOP?keyMatch=iwrl6432aop&tisearch=universal_search.

⁵⁷ XM125 Acconeer ab | sensors, transducers | DigiKey, <https://www.digikey.com/en/products/detail/acconeer-ab/XM125/17883267>.

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 IWR6843AOP 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, Acconeer 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 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 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 cost⁵⁸.

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 project⁵⁹.

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 types discussed. For these reasons, an LCD display would be the most appropriate choice for presenting information for the P.U.T.T.I. system⁶⁰.

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

⁵⁸ N. Staff, "OLED vs LCD," Newhaven Display, <https://newhavendisplay.com/blog/oled-vs-lcd/>.

⁵⁹ "TFT LCD," Wikipedia, https://en.wikipedia.org/wiki/TFT_LCD.

⁶⁰ "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>.

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 microcontroller⁶¹.

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 will be using a lone microcontroller, this lack of documentation may prove difficult for integration. The CN0295D is priced at \$8.95 on Digikey⁶².

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 module⁶³.

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

⁶¹ 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>.

⁶² CN0295D sunfounder | optoelectronics | DigiKey, <https://www.digikey.com/en/products/detail/sunfounder/CN0295D/18668612>.

⁶³ 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>.

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 Digikey⁶⁴.

Table 3.1.7.1 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

3.1.7.2 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.

3.1.8 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

⁶⁴ "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/>.

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 filament⁶⁵.

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 prototyping^{66,67}.

⁶⁵ "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&qad_source=1&qad_campaignid=20978953137&qbraid=0AAAAAqsGqB_R84-QMOEeZ7DwHWqhsBHLR&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkQnphRIwoZ3vQLoYrtpXgT1SVkMVPWBuyk9w0P-aOyN4JLZZJS329YaAnOTEALw_wcB.

⁶⁶ "The 3D printing holy trinity: Pla, ABS, and petg," Slice Engineering, <https://www.sliceengineering.com/blogs/news/the-3d-printing-holy-trinity?srltid=AfmBOorVS0PTX7FLGp3wibpYSXdP-fPAMAJeBDcbOw8vYUtHCRyH8ZsN>.

⁶⁷ 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_-

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 project⁶⁸.

3.1.8.1 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.

3.1.9 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.

[Oj_mZuqOhYNQg9mrBsyA-R&qclid=Cj0KCQjwmYzlBhC6ARIsAHA3IkRlhDf9ab-SvHjshEhipPMrYt59yy4sNuOE6YTrrglGZq8TaTdsEd8aAIDIEALw_wcB](https://www.researchgate.net/publication/351111111/Oj_mZuqOhYNQg9mrBsyA-R&qclid=Cj0KCQjwmYzlBhC6ARIsAHA3IkRlhDf9ab-SvHjshEhipPMrYt59yy4sNuOE6YTrrglGZq8TaTdsEd8aAIDIEALw_wcB).

⁶⁸ 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_5hlZbsqu&qclid=Cj0KCQjwmYzlBhC6ARIsAHA3IkRa4mYjfD7Pv9sTA6ADkgW8T_fNB4PrhKCW7r0zFY7CLFex5N2ERt0aAj3JEALw_wcB.

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 Digikey⁶⁹.

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

⁶⁹ PIC18F46K22-I/P microchip technology | integrated circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/microchip-technology/PIC18F46K22-I-P/2480375?msocid=2c71e9962a8d6eb016a8ffe32bd46f5a>.

processing and memory capabilities are relatively limited. This microchip can be found on Digikey at \$2.89 per unit⁷⁰.

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 unit⁷¹.

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 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)⁷².

Table 3.1.9.1 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)

⁷⁰ ATMEGA328P-pu Microchip Technology | Integrated Circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/microchip-technology/ATMEGA328P-PU/1914589>.

⁷¹ STM32F103C8T6 stmicroelectronics | integrated circuits (ICS) | digikey, <https://www.digikey.com/en/products/detail/stmicroelectronics/STM32F103C8T6/1646338>.

⁷² ESPRESSIF documentation, https://documentation.espressif.com/esp32-wroom-32_datasheet_en.pdf?utm_source.

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

3.1.9.2 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 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.

3.1.10 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 3.1.10.1 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 below.

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.I.

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 usage.

Next, similarly 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 is able to

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 circuit.

3.1.10.2 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 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 function.

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 in reducing 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 platform.

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 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 threshold.

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 robotics.

Table 3.1.10.3 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

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

3.1.10.4 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.

3.1.10.5 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 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.

3.1.10.6 1.8V Linear Regulator Selection

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 reliability.

3.1.11 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 critical. 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 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 priority.

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.

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

Table 3.1.11.1 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

3.1.11.2 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 target.

The MEUS Racing Brushless High-Torque Micro Servo provides a compact but surprisingly strong solution for our P.U.T.T.I system's 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 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 choice.

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 key.

Table 3.1.11.3 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

3.1.11.4 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 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.

3.1.12 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 actually 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 a 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 project.

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 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 periods.

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 compactness.

Table 3.1.12.1 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 missions.

3.1.12.2 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 properly.

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 run.

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 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 components.

Table 3.1.12.2 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

3.1.12.3 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.

3.1.13 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.⁷³

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.⁷⁴

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 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.⁷⁵

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

⁷³ ArduinoModules, "KY-012 active Buzzer module," ArduinoModulesInfo, <https://arduinomodules.info/ky-012-active-buzzer-module/>.

⁷⁴ CMI-1295IC-0585T same sky (formerly CUI devices) | audio products | DigiKey, <https://www.digikey.com/en/products/detail/cui-devices/CMI-1295IC-0585T/11674150>

⁷⁵ WST-1203UX Soberton Inc. | audio products | DigiKey, <https://www.digikey.com/en/products/detail/soberton-inc/WST-1203UX/1245301>.

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.⁷⁶

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 \$5.20.⁷⁷

The RBE-4.000-3215-NS1 is the final buzzer than 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.⁷⁸

Table 3.1.13.1 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

⁷⁶ Same sky (formerly Cui Devices), <https://www.digikey.com/en/supplier-centers/cui-devices?msockid=0f2d84fc671b62cb37fd926f664a63a4>.

⁷⁷ IE330403-1 DB unlimited | DigiKey, <https://www.digikey.com/en/products/detail/db-unlimited/ie330403-1/9990502>.

⁷⁸ 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>.

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

3.1.13.2 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 choice⁷⁹.

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. For SPCs, USB cameras are often limited by the availability of host controllers, driver support, and the processing power required to handle streaming data. 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 analysis⁸⁰.

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

⁷⁹ "I2C," I2C - SparkFun Learn, <https://learn.sparkfun.com/tutorials/i2c/all>.

⁸⁰ T. Agarwal, "USB protocol : Architecture, Working Specifications & Applications," ElProCus, <https://www.elprocus.com/usb-protocol/>.

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 product⁸¹.

Table 3.2.1.1 SBC to Camera Protocol Specifications

Feature	GPIO	USB	CSI
Max Resolution	Unsuitable	High	Very High
Speed	Slow	High	Very High
Power	Extremely Low	Moderate	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 MIPI CSI-2 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 CSI are widely available, and they often advertise direct use with our SBC. The CSI port will have sufficient speed and resolution for image processing, and it features a low power usage.

⁸¹ "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.

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 receive guidance and documentation from⁸². 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 actions⁸³.

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 collector⁸⁴.

Table 3.3.1.1 Computer Vision Language Specifications

Feature	Python	C++
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⁸² "Python vs. C++: Key differences and uses," IONOS Digital Guide, <https://www.ionos.com/digitalguide/websites/web-development/python-vs-c/>.

⁸³ 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>.

⁸⁴ GeeksforGeeks, "Difference between python and C++," GeeksforGeeks, <https://www.geeksforgeeks.org/python/difference-between-python-and-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

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 camera⁸⁵.

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 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 architectures⁸⁶.

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 performance⁸⁷.

Table 3.3.2.1 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

⁸⁵ 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.

⁸⁶ 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>.

⁸⁷ GeeksforGeeks, "Faster R-CNN: ML," GeeksforGeeks, <https://www.geeksforgeeks.org/machine-learning/faster-r-cnn-ml/>.

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.

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.⁸⁸

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

⁸⁸ 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 data⁸⁹.

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

⁸⁹ "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 devices⁹⁰.

4.4 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 product⁹¹.

4.5 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.

⁹⁰ "Serial peripheral interface," Wikipedia, https://en.wikipedia.org/wiki/Serial_Peripheral_Interface.

⁹¹ "Camera serial interface 2 (MIPI CSI-2)," MIPI, <https://www.mipi.org/specifications/csi-2>.

4.6 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"⁹². 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 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.

⁹² "PEP 8 – style guide for python code," Python Enhancement Proposals (PEPs), <https://peps.python.org/pep-0008/>.

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.

4.7 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 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 systems.

4.8 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 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.

4.9 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 and 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.

4.10 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.

4.11 Health and Safety Constraints

The P.U.T.T.I is designed to only target inanimate objects but due to the use of a laser there is potential for the device to cause damage to people. We need to ensure that the system works reliably and does not accidentally target human life, even with a low powered laser the device could still cause damage and imposing additional safety constraints can protect users from device malfunctions.

The use of batteries and the fact that the P.U.T.T.I will be deployed in very volatile situations leaves it open to combustion issues. It is very important we take into consideration these issues so that the device does not have electrical failures that might result in catastrophic failure leading to surrounding people or infrastructure being unnecessarily injured.

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.

4.12 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 damages. One of the biggest fears is that electrical fires could cause brush fires or other similar fires in areas if sparks are created by the 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.

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 code⁹³

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 prompt⁹⁴.

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 asks 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

⁹³ "GitHub copilot · your AI pair programmer," GitHub, <https://github.com/features/copilot>.

⁹⁴ Microsoft, "GitHub copilot in vs code," RSS, <https://code.visualstudio.com/docs/copilot/overview>.

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 do.

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 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 GitHub Copilot 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 GitHub Copilot 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 at the very least 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 that we had asked for. ChatGPT changed the `SAVE_DIR = "captures"` line to being 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.

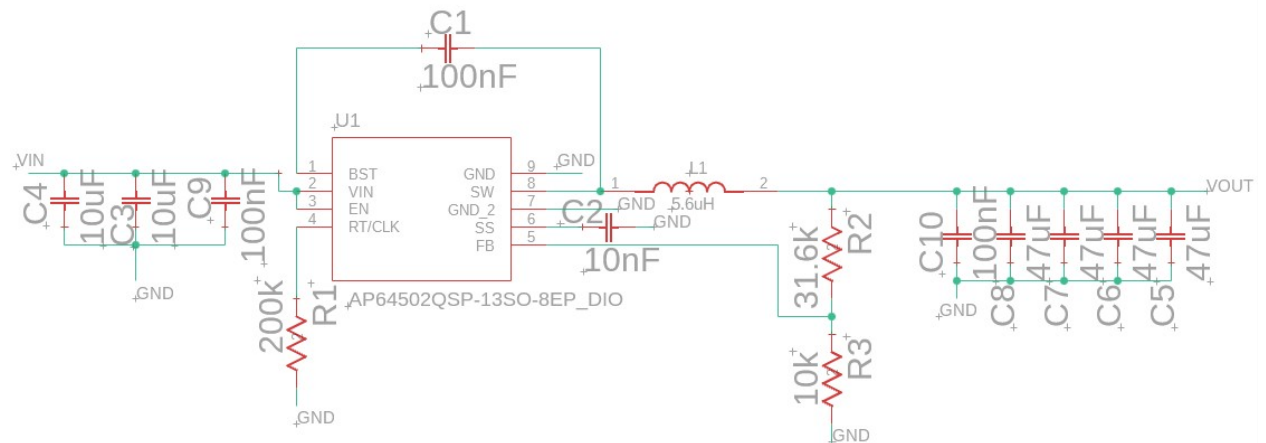
Overall, both Copilot and ChatGPT gave good initial responses to the prompts that we asked them. ChatGPT gave more information to responses, as well as further recommendations or suggestions for what the user could do to further their understanding while Copilot was more straight to the point. It's important to note that there would be gaps in knowledge had we 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 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 being generated by batteries, we need to make sure that the input voltage for the various components and microcontroller 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 switching regulator schematic is below.



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 the 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.

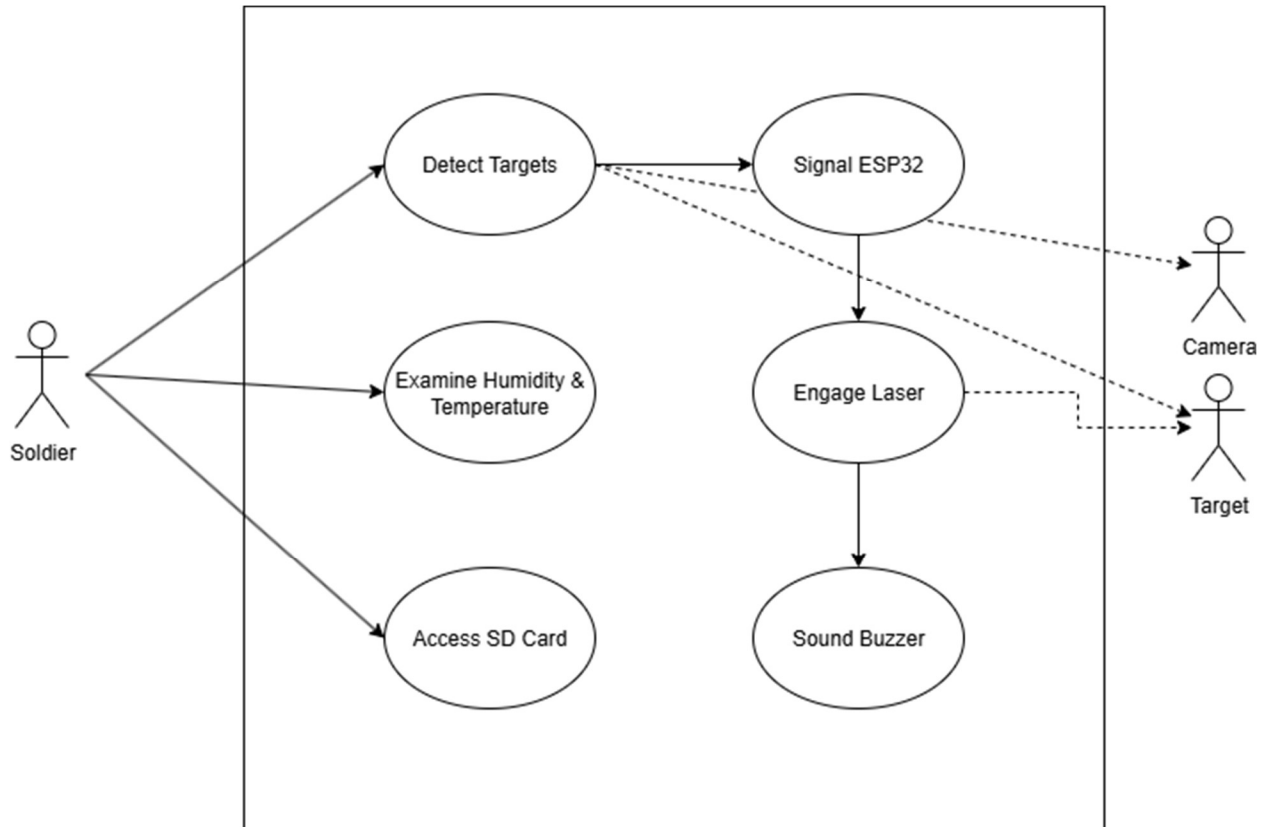


Figure 8 - Use Case Diagram

7.1 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 captured⁹⁵.

⁹⁵ Ultralytics, "Home," Ultralytics YOLO Docs, <https://docs.ultralytics.com/>.

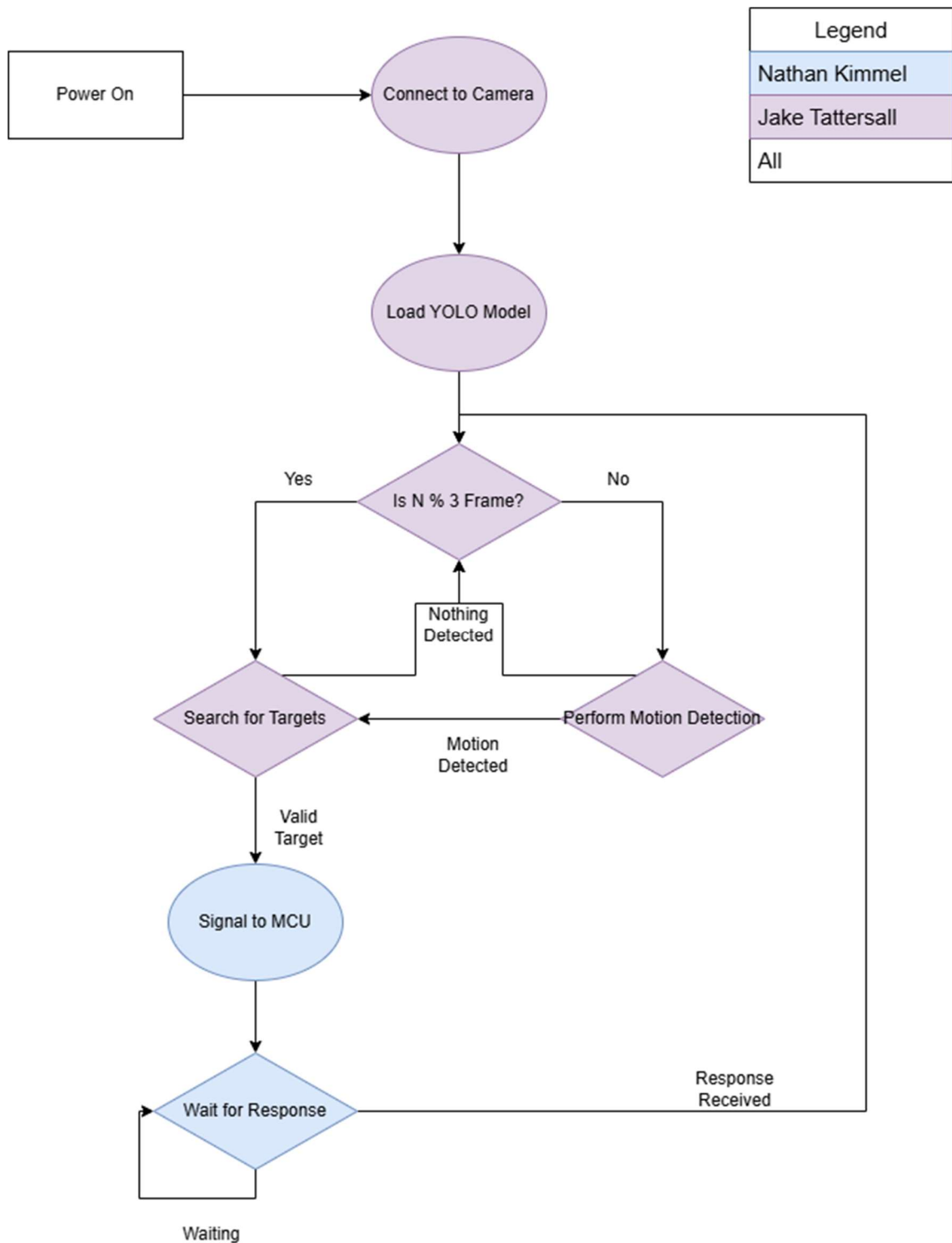


Figure 9 - Single-board Computer Flowchart

7.2 Python Development

Programming for the Orin Nano will take place using Visual Studio Code (VSCode). 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 in to VSCode is a Copilot extension to aid in writing code or answering questions about how code may work⁹⁶.

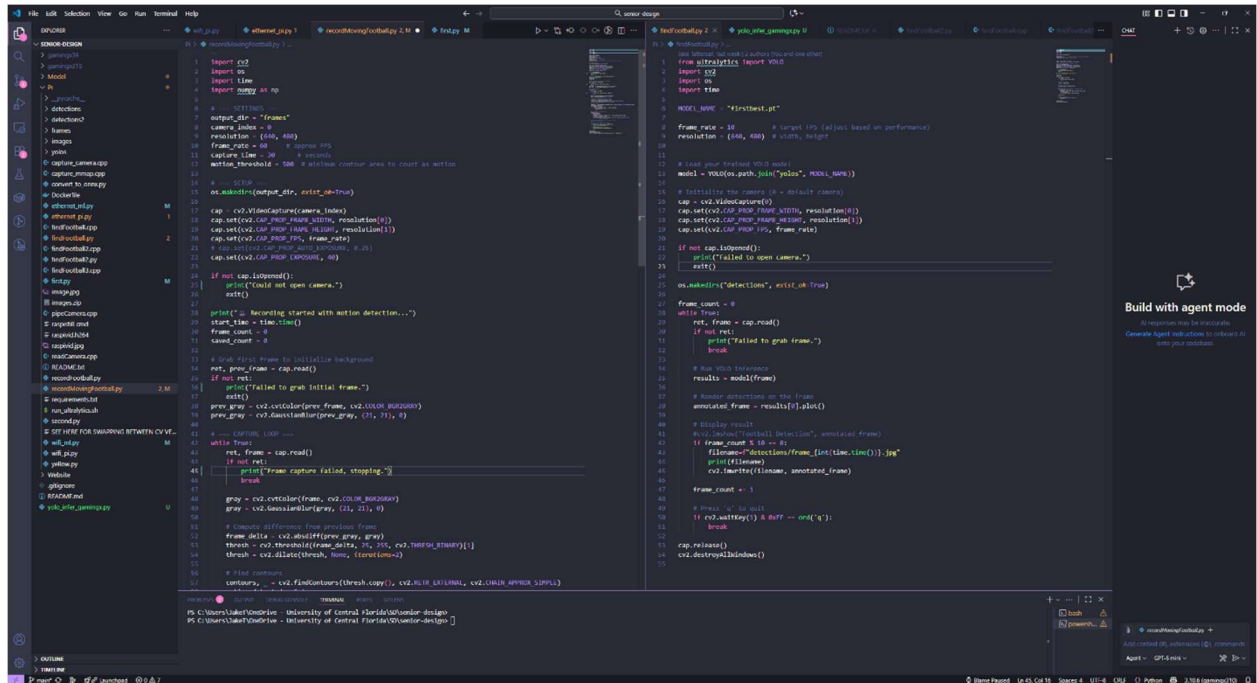


Figure 10 - The VSCode IDE being used to develop Python scripts.

7.3 Interfacing with the CSI Port

To interface with the CSI port, 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.

7.4 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.

7.4.1 Data Collection

⁹⁶ Microsoft, "Visual studio code - the open source AI code editor," RSS, <https://code.visualstudio.com/>.

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](https://www.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 process⁹⁷.

7.4.2 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

⁹⁷ "Make sense," Make Sense, <https://www.makesense.ai/>.

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)⁹⁸.

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.

7.4.2 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.

⁹⁸ Ultralytics, “Train,” Ultralytics YOLO Docs, <https://docs.ultralytics.com/modes/train/>.

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.

7.5 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 speed⁹⁹.

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 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

⁹⁹ XM125 software user guide,

https://docs.sparkfun.com/SparkFun_Qwiic_Pulsed_Radar_Sensor_XM125/assets/component_documentation/XM125%20Software%20User%20Guide.pdf.

on the onboard microcontroller, it will reduce the need for heavy computation, lightening the load for the ESP32¹⁰⁰.

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.

7.6 ESP32 Software

The microcontroller portion of the software section will be added once ESP32 programming begins.

¹⁰⁰ "Sparse," Sparse - Acconeer docs,
https://docs.acconeer.com/en/latest/a111/radar_data_and_control/services/sparse.html.

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

To be completed after Revision meeting to ensure all components are viable.

10.3 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 10.1 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 10.2 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	11/7/2025	Design the PCB using Fusion.
PCB Testing	11/7/2025	11/17/2025	Solder all components and test functionality of PCB
Create Prototype	11/17/2025	11/25/2025	Combine all components together to create and demo a prototype of the project.
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.

Appendices

Appendix A – Reference

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Appendix B – Copyright permission

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

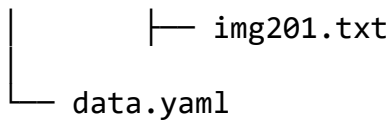
Ultralytics YOLO expects your dataset to have:

- **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
```



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?