Mini-AWACS
Airborne Warning and Control System
Small UAS Airspace Domain Awareness RADAR Payload

Sponsored by U.S. Southern Command (SouthCom)

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CHAPTER 1:

1. PROJECT NARRATIVE

BACKGROUND AND MOTIVATION

The military application of unmanned aircraft systems (UAS) has evolved since the initiation of their use by the US military. Although, larger UAS systems have the payload and cost to justify the integration of sophisticated sensor and radar systems. Smaller lower cost UAS do not. A long term goal expressed by our sponsor from US Southern Command (SouthCom) was to be able to deploy these UAS as functional drone swarms and to test other applications for these platforms. However, due to the size and cost of these smaller UAS platforms a full sensor and radar package is too costly and not feasible. This is a current barrier to the development of future capabilities as these UAS will have no collision avoidance systems to prevent accidents with each other or with other aerial assets. The only military asset that can provide the necessary radar information to solve this problem is the Airborne Warning and Control System (AWACS) which is a large plane with a long range radar system. However, AWACS are extremely costly and limited, thus they are not a viable solution for this problem. As a result the military requires a cheap, reliable, and easily deployable system that solves this issue so that the US military can continue to perform experiments and broaden the uses of UAS on the battlefield.

PROJECT FUNCTION

The overall function of this system is to be a deployable 100lbs sensor payload that can provide the necessary information to allow these smaller UAS systems to be used safely in environments where the necessary information for safe operation is not available. This will be done via radar and IR imaging which will provide the data needed for these UAS to operate safely. The end goal is for the product to function as a mini-AWACS. This system will be comprised of the following components:

Marine Radar: To keep the project cost low and develop a prototype for testing, a marine radar system will be repurposed to capture necessary radar information for the UAS to operate safely. The motion of the radar system will have to be modified to scan from a top down position. The radar system will provide long range spatial information to the UAS. The marine radar will also consist of a software development kit that will allow us to use the signal as desired with the reconfigured radar scanning pattern. This data will be fed into our central PC in order to communicate with the UAS via the Starlink System.

Starlink® Hardware: Starlink® module will be utilized to transmit the radar and IR imaging system information from the mini-AWACS via Starlink to a cell phone on the UAS to provide the UAS with the desired radar and IR information. This will allow the UAS to operate safely with other aerial assets allowing for further testing and research to develop the capabilities of these UAS.

Microcontroller: The microcontroller in the system will control the movement of the radar piston and the infrared camera motor. The microcontroller will operate partially as a feedback system for the IR motor, as the positional information from the motor will be used to determine the IR imaging in relation to the vehicle's position. The radar piston will operate on command only, cycling its whole range at a continuous speed.

Radar Angle Piston: The angle of the radar will be controlled by a piston-wheel system which will be calculated to move exactly ±30° from the neutral downwards position. The piston movement will be constant to facilitate the radar's clean and accurate sweep of the skies beneath it, so that it can be ensured the UAS training does not disrupt the airspace.

CHAPTER 2:

2. PROJECT OBJECTIVE, GOALS AND REQUIREMENTS

The overall objective of this project is to create a cost effective mini-AWACS which can be deployed on an aircraft to provide the US military's UAS the necessary radar and visual information required for safe operation. In order to meet this objective the mini-AWACS has to be able to gather Radar and IR information and provide this data to the UAS via Starlink® to a cellphone on the UAS as a proof of concept. If successful this will allow for continued development of the product. The final objective of this project is to provide the US military with a system that gives them the ability to safely test and develop its UAS capabilities.

Basic goals:

- Design and build the new motion platform for the marine radar so the radar field of view meets the specifications of the sponsor
- Have radar system operate properly on new motion platform
- Successfully transmit data from the mini-AWACS to the designated cellphone via Starlink®
- Total system must meet payload max weight of 100 lbs

Advanced goals:

- Deploy mini-AWACS on small aircraft to test prototype at 10,000ft for proof of concept (Sponsor goals)

Stretch goal

- Full prototype testing at high altitude "stratosphere" to determine if commercialization is feasible. (Sponsor goals)
- Full length test of the prototype for extended time at altitude on an unmanned air balloon. (Sponsor goals)

Objectives:

- Determine the necessary mechanical components and configuration to allow the radar to move in the desired top/down 60 degree arc of motion.
- Utilize the software development kit to program the radar to provide useable data in its new physical configuration
- Connect Starlink Mini Terminal to transmit data from mini-AWACS to cellphone

REQUIREMENTS

Specifications for each subsystem are listed below:

Radar system
- Modify Raymarine Cyclone 6 ft Open Array Radar Pack to operate in a top down laterally sweeping pattern vs. it's original rotational scanning pattern
    - Design mechanical component which will provide new scanning motion of radar with desired scanning field of view of 60 degrees
- Able to operate for 1 week in a powered environment on an air balloon at high altitude

System Shell
- Able to withstand low pressures of about 8 psi
- Able to maintain functionality and structural integrity while traveling through up to 180 mph of air resistance
- Able to maintain functionality in regular weather (-20° C to 40° C)
- Should be at most 30 lbs

Radar Rotation System
- Able to move the Raymarine Cyclone radar 60° about its center, 30° each to the left and right from the neutral downwards facing position
- Able to accurately rotate in up to 30 mph winds at operational altitude
- Operates on a feedback system from the operating program to determine the angle at which the radar produces each of its signal responses
- Able to rotate the radar matching normal marine operating speeds, at the lowest around 72° per second or one direction in 0.8 seconds.
- Able to rotate the 30+ lb radar array smoothly

Starlink® Connection
- Accurately transmits information from the radar detection program through starlink to cell phone connections on drones
- Utilizes a standard (23,4 in x 15.07 in) Starlink® antenna mounted within the system shell

3. DESCRIPTION OF FEATURES AND FUNCTIONALITIES

The main and arguably most important feature in our project is the Raymarine Cyclone 6 ft Open Array Radar Pack which will be modified to scan in a top down sweeping mode instead of its original rotational scanning pattern. The radar will be converted into a top down sweeping radar to provide precise, real time coverage of the airspace below the host aircraft. This coverage ensures that the unmanned aircraft systems avoid potential air collisions.

Another feature of our project is the ability to send the scan data from the radar to the unmanned aircraft systems below. This is done using Starlink's high speed, low latency communication. Each unmanned aircraft will be equipped with a mobile phone that will receive the radar's data via Starlink. This data will allow the unmanned aircraft systems to track their surroundings and will act as a virtual radar for the small aircraft.

The system shell is another feature of our project that is required in order for the mounted radar to operate as intended. Its functionalities include but are not limited to the following. The system shell will be able to withstand low pressures of about 8 psi and will be able to maintain functionality and structural integrity while traveling through up to 180 mph of air resistance. It will also be able to maintain functionality in regular weather conditions (-20° C to 40° C).

Regarding the radar rotation system, it must be able to move the Raymarine Cyclone radar 60° about its center, 30° each to the left and right from the neutral downwards facing position. It must be able to accurately rotate in up to 30 mph winds at operational altitude. Lastly, it must be able to rotate the radar matching normal marine operating speeds, at the lowest around 72° per second or one direction in 0.8 seconds.

4. EXISTING PRODUCT, PAST PRODUCT, OR RELATED WORK

Although there is an existing product that can perform similar functions as the product we are designing, like the Airborne Warning and Control System (AWACS), our product will be significantly less expensive and more easily deployable. The AWACS, and other aircrafts that function similar to it, are extremely costly and not meant to be mass deployed. Our product will be the first of its kind that will be affordable, mass deployable, and in contrast to aircrafts mentioned earlier, it will be mounted to the bottom of private aircrafts which will allow for a large number of radars to be in the sky simultaneously.

Throughout the years there have been multiple planes with radars on them, for example the Lockheed EC-121 Warning Star and then the Airborne Warning and Control System (AWACS) after it. These systems are not directly comparable to our product, however they provide a background on how our product should work but on a smaller scale. A few other planes that incorporated the use of radars are the Boeing E-7 Wedgetail, the Grumman E-2 Hawkeye, and the Beriev A-50.

There is very little to no related work to our product as it has been assigned to us by the US Southern Command (SouthCom) to address an ongoing need to enable unmanned aircraft systems (UAS) to operate without the fear of an air collision during peacetime training. Existing air virtual radar systems have been designed mainly to be used for larger scale operations relative to what our product is aimed to do.

5. ENGINEERING SPECIFICATIONS

Table 1: Engineering requirements specification for the performance of the envisioned system

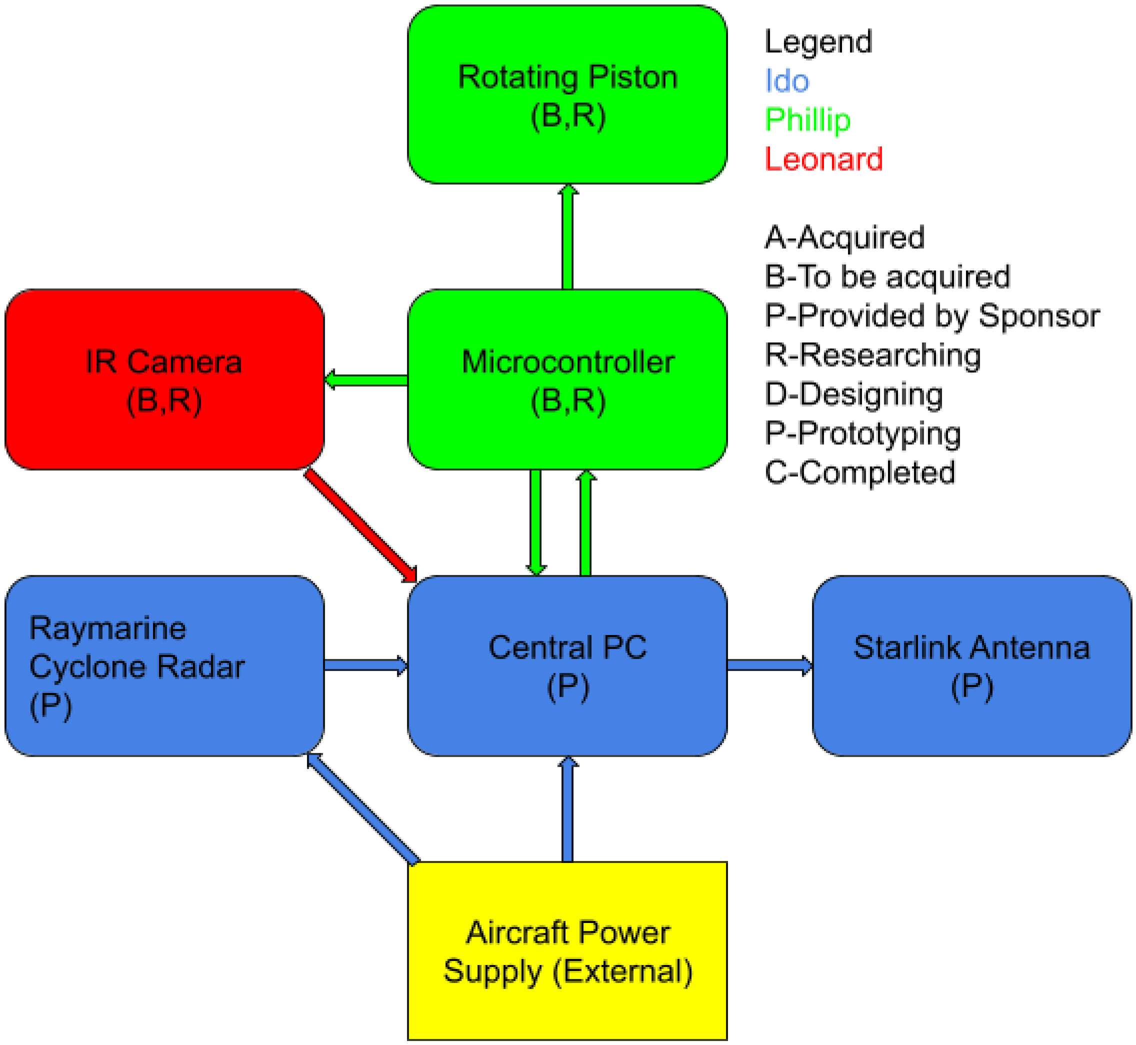
Specifications	
Parameter	Specification
Rotating wheel's rotation angle	60° range of motion, centered downwards
Piston's Rotation Speed	Should complete one 60° cycle in 5 seconds Seconds, at least 12°/s
Starlink connection communication time with UAS	Less than 3000 ms
Temperature resistance	-20° C to 40° C
Wind Resistance	Up to 180 mph from the front, up to 40 across the rotating axis
Length of continuous operation	1 week
Dimensions	No more than 2 ft x 2 ft x 6 ft

The highlighted specifications on the table are the specifications to be demonstrated during the demo of the project prototype.

Table 2: Engineering requirements specification for the components that will be used in this project to build the stereoscopic camera detection and ranging system

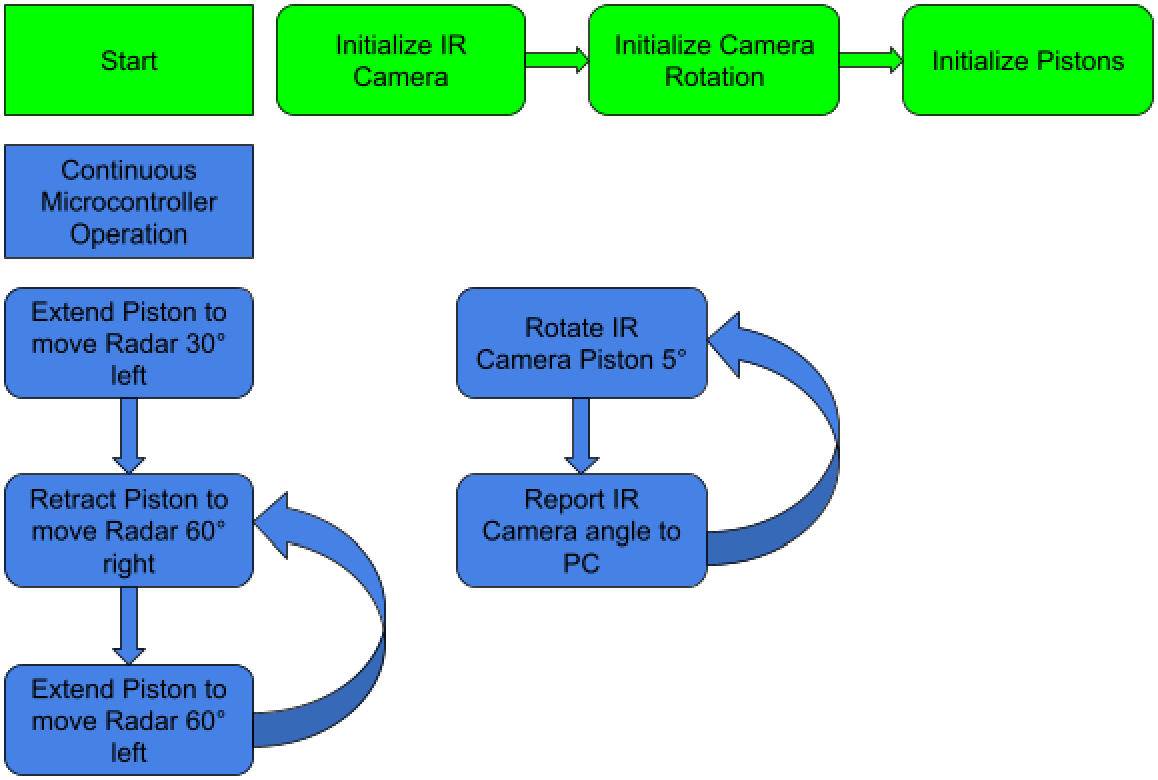
6. DETAILED HARDWARE DIAGRAMS

RADAR SYSTEM BLOCK DIAGRAM



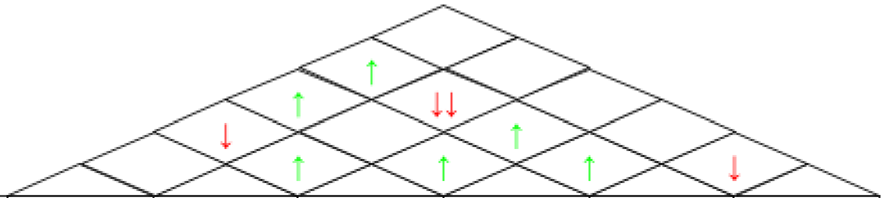
7. SOFTWARE DIAGRAM/FLOWCHART

The microcontroller software is going to be a continuous loop after initialization with one feedback process on the IR camera motor to report the position for the computer to recognize the plane's relative position.



8. HOUSE OF QUALITY

The house of quality is a speculative estimate of the tradeoffs for our engineering goals within the project versus other engineering goals and the marketing goals for our potential customers alongside desirable traits for the project for our sponsor.



	Engineering Requirements	Weight	Rotation Speed	Cost	Temperature Resistance	Operation Time	Rotation Angle
Marketing Requirements		-	+	-	+	+	+
Weight	-	↑↑		↑	↓		
Power Draw	-		↑↑			↓	
Cost	-		↓	↑↑	↓	↓↓	
Durability	+	↑	↓	↓	↑	↑	↓
Maintainability	+		↓	↓	↑		↓
Target		<100 lbs	>60°/s	<$10000	-20° C - 40° C	>1 week	60°

2A. Optical Parallel Project:

To accomplish the same goal as the mini-AWACS system from an elevation of 10000 ft or higher altitude the optical components required are inaccessible for a senior design project due to the custom nature and cost of the components. This is further complicated by the need for infrared imaging for night and poor weather conditions. However, the objective of this project is to create an optical system that can perform the same goal of identifying an object in the airspace and provide a position and vector for the object. The advantage of radar is that it is a ubiquitous technology which is used in numerous applications, is well understood and commercially available to consumers. Despite these advantages, radar has low resolution compared to systems that use higher frequency electromagnetic waves and thus cannot always identify and provide information related to the object detected. Optical systems have the advantage of being able to detect and identify what an object is or at a minimum capture an image of the object. Because of these advantages we will try to demonstrate the potential for an optical system to meet the overarching objective of this project using stereoscopic imaging to determine the range and position of an object and if possible, also get vector information. This will be done via a paired camera system with a paired telephoto lens design to acquire resolvable images at longer distances to create a 3D depth map and provide position and range information of the desired object. If successful this can demonstrate the potential for stereo imaging to provide position, vector and visual information of a detected object. Like a Radar system the system will need the capability to scan the environment. Due to the limited time and number of students working on both projects the scope of the scanning will be limited. Although it would make sense for a final product to follow a similar sweeping pattern as the radar, the system we are building will not have the necessary field of view for this to make sense. As a result, the camera system will sweep in a rotational pattern to demonstrate the system's ability to scan an environment and will be user controlled vs. automated. These decisions are being made due to the constraints of the project and the shortened timeline for completion due to the necessary design changes.

Optical Goals:

Optical basic goals:

1. Acquire stereo images with adequate resolution to provide range information with less than 20% error at 100ft

Advanced goals:

1. Acquire stereo images with adequate resolution to provide range information with less than 15% error at 200ft
2. Acquire 3D depth map from stereo images to determine position of object in relation to other objects within the imaged scene

Stretch goals:

1. Acquire image with adequate resolution to provide range information with less than 10% error at 300ft
2. Provide vector information regarding motion of object in relation to its initial position

Optical Objectives:

Basic objectives:

1. Use Zemax to design the necessary optical system using available off the shelf lenses including an achromatic lens with the appropriate focal length to allow the system to capture images with adequate resolution to range an object at 300 ft.
2. Design housing for lens system to attach to camera
3. Determine distance between cameras that will allow for accuracy within 10% when ranging an object between 250ft-300ft away.

Advanced objectives:

1. Improve accuracy of ranging at distances 300< ft by making necessary adjustments to system baseline to reduce ranging error at longer distances
2. Make necessary adjustments to image processing program to provide distance and object position in cartesian coordinates relative to the system

Optical stretch objectives:

1. Use Zemax to model optimized/ideal lens system with increased lens count and customization to improve magnification of optical system to improve image resolution to meet requirements to range at 300< ft. (This goal is unlikely to be achieved unless off the shelf optical elements can accomplish this goal at the advanced goal stage as custom optics of the required size and design are likely to be cost and time prohibitive)
2. Attempt to develop an image processing program that can track an object's movement to provide a motion vector.

Table 1. Engineering requirements specification for the components that will be used in this project to build the envisioned system.

Component	Parameter	Specification	Unit
ELP Global Shutter USB Camera	Sensor size Sensor type Speed Shutter	1/2.6” CMOS 90 Global	mm CMOS vs. CCD Frames per second Global vs. Rolling
Planoconcave Lens	Diameter Effective focal length Coating	20 -100 425-675	mm mm nm
Achromatic Doublet	Diameter Effective focal length Coating	50 350 425-675	mm mm nm

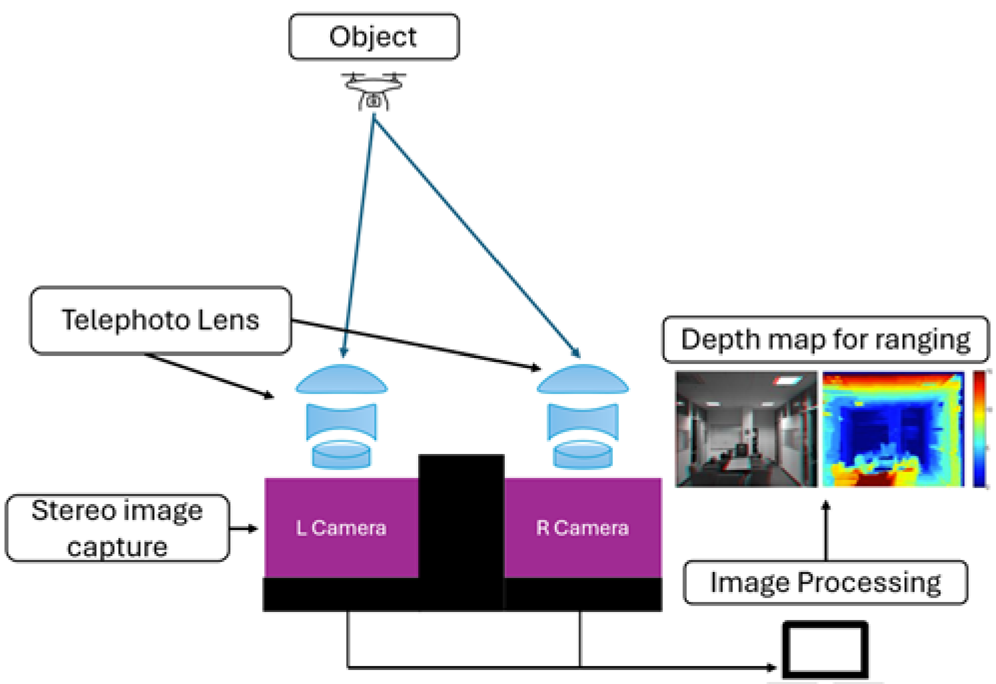
The above proposed components will be used to build the stereoscopic camera system we will use for depth mapping and ranging. Cameras will be connected to the laptop via a USB Hub and all image processing will be performed on the laptop. Rough estimates were performed using the thin lens equation to determine potential lenses which can be used for a telephoto lens of desired focal length and image magnification.

Table 2. Engineering requirements specification for the performance and physical features of the envisioned system.

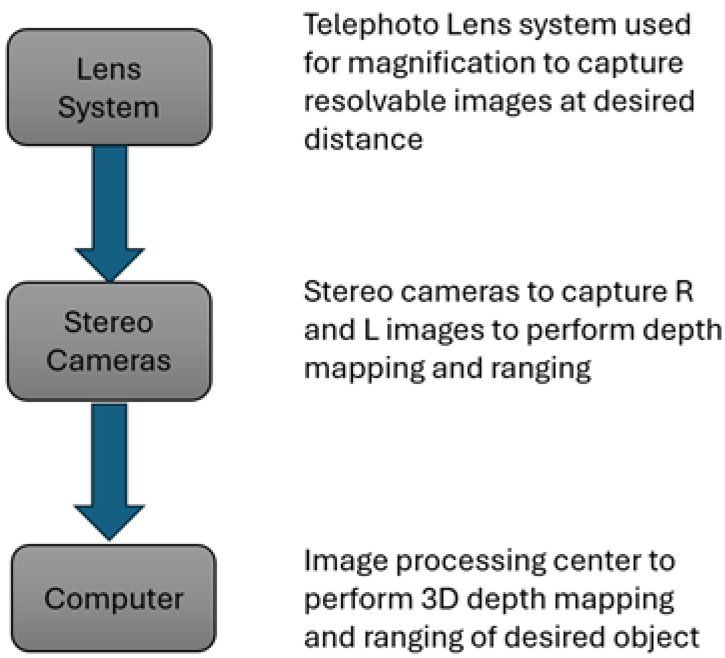
Engineering Requirement	Requirement Specification	Unit
Capture stereo images of a scene	< 1	Seconds

Complete depth map of scene captured by stereo images	< 3	Seconds
Provide range of desired object	< 5	Seconds
Stepper motor will respond to commands to rotate system	<1	Seconds
Complete depth map of scene captured in stereo video (stretch)	<10	Seconds
Provide range of objects in video (stretch)	<15	Seconds

OPTICAL SCHEMATIC



OPTICAL BLOCK DIAGRAM



CHAPTER 3:

RESEARCH AND INVESTIGATION

The first, and most important part for our design project was which radar we were using to create the payload and deliver sufficient aerial information to the drone swarm. The most desirable traits for the radar are sufficient scanning distance so the scan can be performed at high altitudes and as low power draw as we can facilitate. We specifically will be looking at open array radars because they enable the repurposing of the radar for different scanning modes that we are looking for for the project.

Below are some of the options that we were considering to use as a radar for our project.

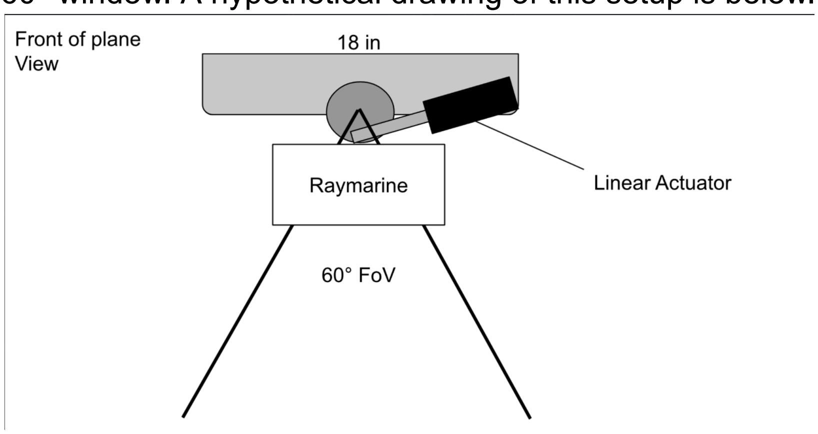
Radar Model	Manufacturer	Scanning Range	Typical Power Consumption	Array Weight	Price
GMR Fantom™ 56	Garmin	72 nautical miles	65 W	16 lbs	$6699.99

DRS6A XN13A	Furuno	72 nautical miles	96 W	23 lbs	$6370.00
Cyclone 6 ft Open Array Radar Pack	Raymarine	72 nautical miles	55 W	15.4 lbs	$8249.99

Among the different radar options, they all have similar array weight and similar scanning range for the low power options from Garmin, Furuno, and Raymarine. However, the Raymarine has the lowest typical power consumption making it the primary choice for the purposes of our project. The lowest power consumption possible lessens the load we need for both the aircraft carrying the package and expands the constraints of the power supply system we need. The cyclone also having lower weight than other options at the 6 ft radar size helps in another way as it lessens the mechanical demand on our rotation system.

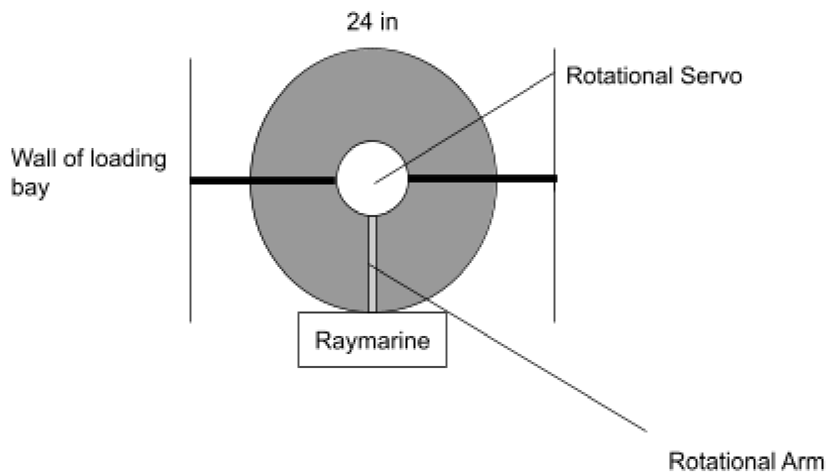
Our project has several options to approach the selective goals we have established at the broader scale, within the size constraints of the 2 foot by 8 foot holding bay for our deliverable radar package.

The first option was utilizing a piston wheel setup which utilized a linear actuator on a piston wheel to provide the rotational motion that drives the radar mounting within the 60° window. A hypothetical drawing of this setup is below.



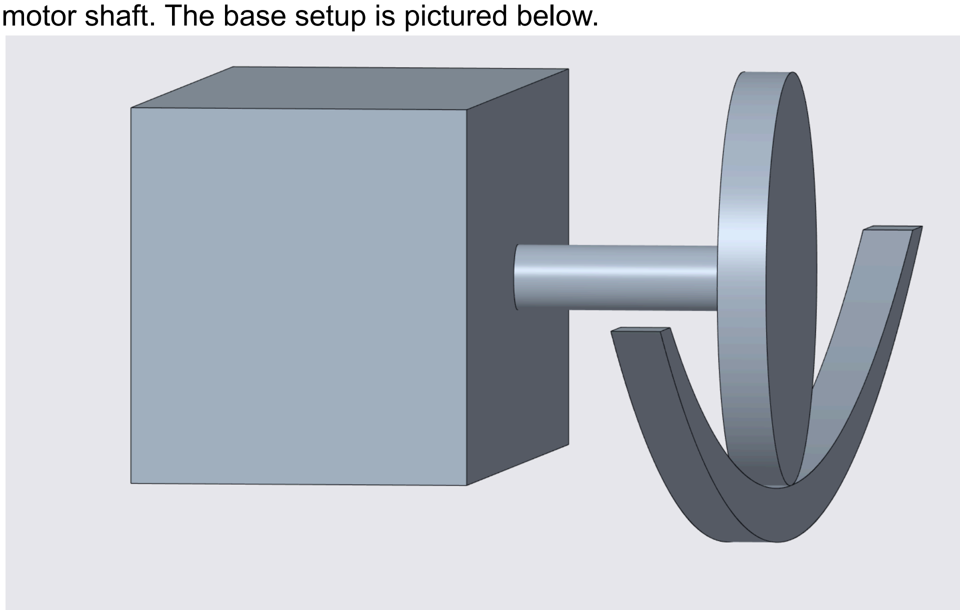
This was our first solution, which was dropped in favor of mechanically simpler solutions after the complexity of the dynamics equations was discovered in this mechanical solution. The linear actuator in this model was also more expensive than some other options, but the probability of incorrect math with the piston model was the largest reason this solution was eventually discarded.

The second mechanical solution we considered was direct servo operation of the cylindrical payload, where the rotation motor sits at the center of the payload and rotates the cylinder using its own torque. This solution was discussed early, and seemed very promising initially in its simplicity. A hypothetical drawing is shown below.

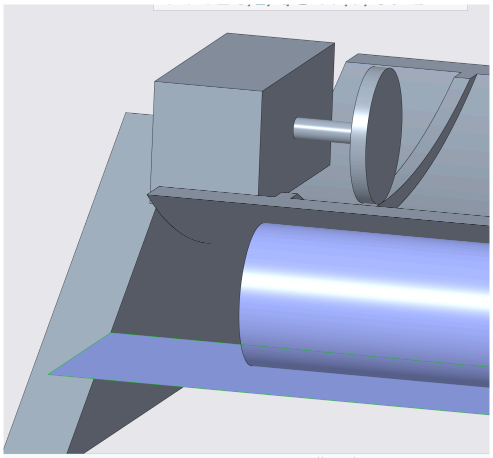


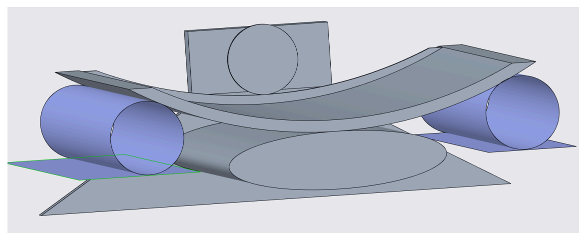
The solution in its elegant simplicity lacked fine control over the motors actions as well as really high torque requirements for both holding torque and operating torque, which increases the cost significantly. In comparison to our current mechanical solution, the servo motors operation is completely dependent on its current moving speed, which is affected by degradation and opposes the constraint of long operation time independent of maintenance. While this solution could use our mechanical encoder to feedback into the servos operating controller, it is a far more complex feedback system than our final system which has greater fine control over the motor's operation.

Our third mechanical solution entails the use of a stepper motor in a rack and pinion system, which utilizes a gear to rotate our payload in specific degree amounts, which gives us great control of how far the payload rotates. Each step of the stepper motor can relate to any size step of the payload through different gear ratios of our choice, giving great discretion in both hardware and software design that we are looking for. Also, the rack and pinion system decreases the holding torque by decreasing the rotational force on the gear and therefore the motor shaft. The base setup is pictured below.



We plan to implement this setup using an arc of a cylinder mounted on rollers held in place by gravity, as sketched below. The blue tubes would be the rollers and the surface under them would either be part of the plane or part of a greater assembly. The rack and pinion method still powers the motion of the whole system, the rolling arc simply lets us cut massively on material costs.





The rack and pinion method also lets us implement the mechanical encoder the simplest, as we can extend the size of the rack to accommodate a second gear which will feed into the encoder. This encoder should feed into the microcontroller which should then transmit into the starlink, which the computer science team can use to determine the orientation of the radar.

The motors between the three systems vary somewhat in cost, but all would need similar motor drivers to supply sufficient voltage, and redesigning a voltage signal system is not cost or time efficient. The greater cost difference is the mechanical motors themselves, which need vastly different mechanical specifications per solution. After surveying the robotics manufacturer Applied Motion's website and Polulu, we arrived at this cost comparison for each system.

System	Part	Model	Listing Price
Piston Wheel	Linear Actuator	Glideforce LACT2-12V-05 Light-Duty Linear Actuator	$132.65
Direct Servo Rotation	Continuous Rotation Servo	SpringRC SM-S4303R Continuous	$14.95

		Rotation Servo	
Rack and Pinion	Stepper Motor	#1204 (SY20STH30-0604A)	$28.95

While these are all the base price of each part, massive price discrepancy between the three motors can be observed. At this point, we discarded the piston wheel solution because the price was double that of the rack and pinion system and the dynamics equations provided a fail point that we did not want to run into. Here, we also considered just going with the cheapest option of the servo control, however the servo motor would be put under far more strain since it is directly rotating the large radar, and upgrading the servo or somehow implementing more servos to overcome that torque would easily make the servo solution both more volatile and more expensive than the rack and pinion solution.

So, knowing we were pursuing the rack and pinion solution we looked into the options for different stepper motors available to us, and the peripheral materials necessary to operate them.

Stepper motors come in different sizes for different amounts of torque and come in single shaft and double shaft motors. Because our design utilizes the rack and pinion system, the motor does not need much strength as its torque will be converted alongside our chosen gear ratio to massively upscale the effective torque, with the drawback of affecting rotation speed, which is not a large concern given we can change the radar scanning system control. The double shaft design is also not too useful to us because the design does not apply other directions of force onto the motor, that would necessitate the use of a double shaft motor.

The first selection to be made with the motor was the size, ranging from NEMA 6 to NEMA 52. Because of the unrestrictive nature of our mechanical design, as the gear just needs to fit on the end of the flange of the motor, we can utilize the cheapest option in this regard. Also notably, the pilot diameter can be a variety of sizes as to fit other specifications, as long as it is not so big as to disrupt placement of other non-rotating parts that need to fit inside the loading bay with the motor mount. So, we will avoid going for NEMA 23 and above motors in our design, as the rest should have better volume constraints.

Below we have a table of a couple of options from Applied Motion that offer different NEMA standardized motors.

Motor Model Name	Holding torque	Frame Size	Cost

HT08-230D NEMA 8 High Torque Stepper Motor w/ double shaft	2.69 oz-in	NEMA 08	$53.00
HT11-020 NEMA 11 High Torque Stepper Motor	7.08 oz-in	NEMA 11	$58.00
HT17-268 NEMA 17 High Torque Stepper Motor	32.1 oz-in	NEMA 17	$48.00
HT17-268D-FBA NEMA 17 High Torque Stepper Motor with Double Shaft and FBA encoder	32.1 oz-in	NEMA 17	$102.00

Given the above comparison in motor cost, size and holding torque, we went with the HT17- 268 NEMA 17 motor without the encoder. It has both the lowest cost while fitting within our size constraint for the place we are looking to implement the radar. Notably, while our design does include an encoder feeding into our microcontroller to hand off radar position information to the radar algorithm, we elected not to utilize the inbuilt encoder as we wanted to use our encoder directly on our rack in our rack and pinion system to get the most accurate representation of where the radar is sitting in its current placement.

The next consideration was the power supply, of which the main concern was supplying either 12 volts or 24 volts of DC to the voltage modulator with sufficient current for the Raymarine cyclone radar and lasting a long length of time in the air. This narrowed our options to portable rechargeable DC power supplies designed largely for recreational outdoor activities or car batteries. Ideally the power supply would have multiple connection points to separate the connection to the voltage modulator and the connection to the rest of the system, as the rest of the system will be operating below 12 volts and the modulator needs direct line in connections from the power source for its input power. Another constraint we were looking to fulfill was as low a weight as possible, leaving more weight for the physical package and giving us more leeway in its construction.

A model comparison of some of the power supplies of both the recreation type and the car batteries is in the table below, cited from multiple sellers.

Model	DC output	Current from DC output	Watt hours or Reserve Capacity	Seller	Cost	Weight

WestingHouse iGen160s	12 V	10 A	155	Westinghouse Store	$155.00	5 lbs
MARBERO Portable Power Station 88Wh	12 V	10-13 A	80	MARBERO	$99.21	7.4 lbs
EnginStar Portable Power Station 300W 296Wh Battery Bank	12 v or 24 v	8 A for 12 V or 3 A for 24 V	296	EnginStar	$199.99	6.5 lbs
EverStart Platinum AGM Automotive Battery, Group Size 24F 12 Volt, 710 CCA	12 V	760 A	120 minutes	Walmart	$179.84	45.3 lbs

It became clear early into research that if we could avoid utilizing a car battery, we should. Between the far more extreme safety concerns, the weight of the battery itself, and the low independent runtime of car batteries, if we do not need the amperage then we should pursue other sources for our DC power source. Of the other options we looked through, the Westinghouse DC power supply had the lowest weight with a reasonable price tag for the scope of the project. The Westinghouse also had decent service time without charging. While it is likely we will need another power source in the week long air tests in future designs, for the test runs where we have the package within a small plane for several hours of sweeping the sky the Westinghouse power supply should work. The Westinghouse power supply also had several DC output plugs, enabling our desire for independent source circuits between the payload rotation system and the radar power system, furthering the cause for our choice of the Westinghouse power system.

Model 755A Size 15 Accu-Coder®

As we began exploring options for tracking the angular position of our sweeping radar system, one of the most promising components we came across was the Model 755A Size 15 Accu-Coder® from Encoder Products Company. This is a high-resolution incremental shaft encoder that's often used in motion feedback systems, and its small size, combined with its performance capabilities, makes it a strong candidate for our Mini-AWACS project. Since our radar system is designed to sweep across a range of angles rather than rotate continuously, we need extremely accurate feedback on position and motion throughout each sweep. Encoders like the 755A are commonly used in many different aerospace applications for this reason.

The encoder measures only about 1.5 inches in diameter and length, which is an important measurement for us since we are to be mounting our project onto a small aircraft, such as a Cessna. Our radar assembly can't be bulky or heavy, so a compact encoder that still delivers high performance is very beneficial. The all metal shielded ABEC ball bearings make it a durable component as well which is something we need for any part that will be exposed to vibration or movement during flight.

One of the biggest reasons we're considering this model is its high resolution capability—up to 30,000 cycles per revolution. That high of a level of precision would allow us to track the radar's exact angle throughout its sweeping motion with minimal error. With that kind of feedback, we could improve our systems accuracy and reliability by taking into account the radar's data and where the radar really is at that point in time. The encoder also supports output frequencies of up to 1 MHz, which is especially important for applications that involve rapid movement or quick changes in direction. If our radar system sweeps faster than we expect it to in certain scenarios, we don't want the encoder to fall behind or miss steps.

Another key reason the Model 755A stood out to us is that our project sponsor, Roy, specifically recommended it. He has worked with this exact encoder on multiple projects in the past and emphasized its reliability, signal clarity, and ease of integration. Getting a recommendation like that from someone who has hands on experience with the part goes a long way in making us feel more confident about using it for our project.
From an electrical standpoint, the encoder supports multiple output types. This gives us flexibility in terms of interfacing it with whatever microcontroller we end up using. However, it also means we need to be careful when selecting our signal interpretation

hardware, since each output type comes with its own power considerations. We'll also need to verify compatibility between the encoder output and the controller input so that we don't run into signal issues during data acquisition.
Mechanically, the 755A is built for demanding environments. It's rated for up to 7500 RPM, although in our case, the radar isn't rotating, it's sweeping. However, even in a sweeping configuration, we must be able to transmit data even when the radar has directional changes, and the data must be consistent with the radar's position. That is why the 755A could prove to be extremely important for the success of our project. It also offers a few different mounting styles, including standard servo and square flange, which might make it easier for us to experiment with different bracket designs during prototyping.

With all that being said, we still have to take into consideration a few of the potential downsides. we're going to need to test how well the 755A integrates with our microcontroller and flight computer. Depending on how quickly the radar ends up sweeping and what resolution we choose for the encoder, there's a chance it could generate many pulses in a really short amount of time, which is something we will need to further test. Also, even though the encoder has its own protection systems like reverse voltage and short circuit safeguards, we still want to make sure it holds up well under actual operating conditions.

Lastly, the encoder draws up to 100 mA at 28V, which is fairly low power, but we still need to factor it into our overall power budget. We have multiple components drawing current simultaneously, and we want to avoid any potential issues that could damage sensitive electronics.

Overall, the Model 755A seems like a strong match for what we're building. Its compact size, resolution capabilities, durability, and positive feedback from our sponsor make it one of the leading candidates for the radar sweep feedback system. We still plan to prototype it and test it under flight-simulated conditions, but at this point, it's high on our list of potential components.

Piezoelectric Devices
As part of our research into possible components for the Mini-AWACS system, we were once again told by our sponsor, Roy, to look into piezoelectric devices. These devices are made from materials like quartz or ceramics that generate an electrical charge when physically stressed. Additionally the reverse is also true, they can produce small movements or vibrations when you apply a voltage to them.

Right away, we realized that piezoelectric devices could be useful in a few different ways for our radar payload, which will be mounted on a small aircraft, like a Cessna. For example, one potential use is as a vibration sensor. Since the radar will be sweeping and the aircraft will experience some vibration during flight, using the piezoelectric sensor could allow us to see the real time effects of the vibrations. Piezoelectric devices are also used in ultrasonic systems. They are used in systems like rangefinders and many acoustic sensors

These devices are super lightweight and compact, which is extremely important when working with a small plane where space and weight are limited. They also don't require a lot of power since they actually generate their own voltage just from being moved or stressed.

That said, there are definitely some downsides we'd need to think about. For one, piezo materials can be pretty fragile. They could crack if they're mounted poorly. Also, the electrical signal they produce is usually really small, so we'd probably need to build or buy some kind of amplifier to make the signal usable in our system.

We also have to keep in mind that temperature might affect performance. Since the radar system will be flying at different altitudes, it could be exposed to very low temperatures, and some piezo materials don't respond well to extreme cold temperatures

Overall, though, piezoelectric devices seem like a really promising option. They're already used in a lot of aerospace applications, so we know the technology is solid. At this stage, we haven't committed to using one yet, but it's definitely something we want to test further to see how well it integrates with our system.

Microcontroller Comparison

The microcontroller selection is a major part of the research for our project. Since we must reliably track the radar position during each sweep we need a microcontroller that is able to handle the signal input and develop a software that reads it and passes it on to our software team on the computer science side. The microcontroller will essentially be the middleman between the hardware components and the software being able to interpret the data. The microcontrollers that our team researched and are considering are the STM32, the Teensy 4.1, the Arduino Due, and the MSP430.

The STM32 is heavily used in many embedded systems and is excellent for real time system performance. The STM32 is also able to use all of the different communication protocols. Lastly, the STM32 is also on the low end in terms of power consumption, which is ideal for a system that requires low power consumption but great accuracy and consistency.

The Teensy 4.1 is a great option that we are considering as well. The Teensy 4.1, like the STM32, is also heavily relied on for many timing critical applications. It also does not use a lot of power making it another ideal candidate for us to use in our Mini-AWACS senior design project. Our main concern with the Teensy 4.1 is that it is limited to 3.3V logic. Although that is not a deal breaker in the decision of our microcontroller, it is something that we need to look deeper into.

The Arduino Due is another microcontroller that our group has done extensive research on in order to ensure that we get the best microcontroller for the job. We found that although the Arduino Due does offer more RAM, faster clock speeds, and also supports all the communication protocols, its performance would not be as good as the STM32 or the Teensy 4.1's would be.

The last microcontroller we have looked into is the MSP430. The MSP430 is a low power microcontroller and is one that our entire group has familiarity with as we have used it in a few of our classes thus far. The MSP430 is a widely used microcontroller and is very power efficient. The issue with the MSP430 is that like the Arduino Due, it does not offer speeds as fast as those of the STM32 and the Teensy 4.1.

Whichever microcontroller our group chooses to use must be able to handle interrupts, track the radars sweeping motion, and reliably send the data it collects to our CS team through one of the communication protocols.

Microcontroller	**Pros**	**Cons**
STM32	Performs well in timing critical conditions. Supports multiple Communication Protocols. Widely used in embedded/aerospace projects Power efficient	More complex IDE Tough to learn
Teensy 4.1	Faster than the STM32 Performs well in timing critical conditions. Supports multiple Communication Protocols. Power efficient	More expensive Limited in its logic
Arduino Due	Very Simple to use Supports multiple Communication Protocols.	Slower than STM32 & Teensy 4.1 Not as accurate on timing critical applications
MSP430	Extremely low power	Slower than STM32 &

	consumption	Teensy 4.1 Not as accurate on timing critical applications Lower clock speed

Communications Protocols Comparison

Once we collect the radar's data, our next step is sending the data we collect to the software team in order for them to be able to send that data out to its final destination. To send the data to the software team, our group will need to use one of the 3 main communication protocols, ideally the one with the best speed and reliability. The three protocols our team has researched and is evaluating are I2C, UART, and SPI.

UART or Universal Asynchronous Receiver Transmitter is a simple point to point serial communication protocol that is easy to implement and works very well when sending moderate amounts of data. UART only uses two wires and is widely supported by almost all microcontrollers. An issue with UART that we have found is that since it does not include a clock line, it may not be perfectly synchronized with the device that is receiving the data.

I2C or Inter Integrated Circuit is another communication protocol that also only uses two wires. The difference is that I2C has a data line, SDA, and a clock line, SCL, which help with timing accuracy. The issue with I2C is that its maximum data rate is not as high as we would want it to be.

SPI or Serial Peripheral Interface is the fastest of the three protocols we have been researching. SPI uses four wires and its major advantages are its speed and its reliability. Its downside is that it may be more complex to set up, however that is not a concern of ours.

Communication Protocol	**Pros**	**Cons**
UART	Ease of implementation Widely supported by all microcontrollers	No clock line so timing can give us a critical issue Slower when passing large data at high speeds
I2C	Has built in clock which provides more timing accuracy	Slower when passing large data at high speeds

SPI	Very Fast Stable and Reliable Good for high frequency data Good for time sensitive data	More complex setup More wiring (space issue)

3A. OPTICAL PARALLEL PROJECT RESEARCH AND INVESTIGATION

Optical glass comparison:

The optical glass used for the lens system on the stereoscopic imaging system must be able to effectively transmit light in the visual spectrum. There are numerous choices of glass that can be used to accomplish this goal. The options available vary significantly in price and have different use case purposes but due to the nature of the project a cheap, easily sourced and ubiquitous glass type will be used for most of the lens system and will be coupled with an achromatic doublet. N-BK7 is a common glass type that is commercially available and meets the cost parameters of the project. It has the necessary transmission spectra and off the shelf lenses can be purchased with an anti-reflective coating that will improve the performance of the lenses in the visible spectrum. The lower cost also provides for the possibility of using a higher number of lenses in the lens system to reduce aberrations via optical design techniques allowing for better image resolution. Table 4 is a comparison of commercially available lenses with the same design but using different glasses.

Table 3.1: Optical glass comparison of a 50mm diameter lens with an effective focal length of 100mm with desired transmission spectrum.

	Fused Silica	N-BK7
Transmission Spectrum 90%< (nm)	200-2200	350-2200
Cost:	$292	$55
Available AR coating (nm)	400-700	400-700

In addition to N-BK7 glass, an achromatic doublet will also need to be incorporated into the lens system to address chromatic aberrations. Chromatic aberrations resulting from the dispersive nature of glass causes different wavelengths of light to refract at very slightly different angles when transmitting through the glass due to each wavelength of light having its own unique refractive index. The dispersion causes different wavelengths of light originating from the object to come to focus on different image planes. This can cause color fringing around the edges of objects in the captured image which will affect the system's ability to properly compare the images from each camera to range the object in the image. To address this aberration a common solution is to use an achromatic lens which can consist of 2 or 3 different lens materials. An achromatic lens uses glasses with different Abbe numbers. The Abbe number describes the dispersion properties of the glass. The Abbe number is determined by the equation:

$$V = \frac{n_d - 1}{n_f - n_c}$$

By using two glasses with a high and low Abbe number respectively, the complementary dispersion characteristics of the glass can correct for chromatic aberrations. Table 5 shows a comparison of commercially available achromatic lenses that can be used for the imaging system.

Table 3.2: Achromatic lens comparison using lenses with effective focal length of 100 mm and diameter of 25 mm.

	N-BK7/N-SF5 (Edmund Optics)	N-BK7/N-SF5 (Thorlabs)
Abbe numbers	55.89/25.36	55.89/25.36
Transmission spectra 90%< (nm)	380-1970	380-1970
AR Coating (nm)	400-700	400-700
Cost	$109	$89.10

Both achromatic lenses have the desired transmission spectra, glass type, and AR coatings however the Thorlabs lens is most cost-effective.

Camera Comparison:

The cameras used for the stereoscopic system must be a matched pair to eliminate issues that can result from compensating for the characteristics of different cameras during image processing for triangulation. Digital cameras come in two sensor formats: a charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS). Both sensor formats have their advantages, but their use cases are suited better for specific applications. A basic comparison of the two sensors focuses on speed, image quality, power consumption and cost.

Table 3.3: CCD vs CMOS comparison

	CCD	CMOS
Image quality	Superior	Inferior
Speed	Inferior	Superior
Power consumption	Inferior	Superior
Cost	Inferior	Superior

Because of the system's stretch goal and need to keep cost low, a camera with a CMOS sensor will be used vs. a CCD. Although both sensor formats are available on cameras The style of electronic shutter must also be considered. The two primary shutter styles are the rolling shutter and global shutter. The rolling shutter is the cheaper option which captures an image line by line along the sensor. This can cause issues with capturing images of moving objects and can result in bending of the image. These shutters are still used commonly in consumer cameras. Global shutters capture an entire image at once. This shutter is useful in capturing images of moving objects and can eliminate many of the issues that result from using a rolling shutter. However, this shutter type typically increases the cost of the camera. Because the system’s primary function is to detect and range a moving object a global shutter is desirable.

Now that we have determined the type of sensor used in the camera, another consideration for the cameras that will be used in this system is the sensor size. There is a direct relationship between the sensor size and focal length of the lens system that gives the field of view (FOV) of the imaging system. The longer the focal length of the system the smaller the FOV. A smaller sensor will further reduce the FOV when paired with a longer focal length lens system. This can be seen via the equation:

$$FOV = 2 * \tan^{-1} \frac{sensor\ dimension}{2 * focal\ length}$$

Using this equation, we see that there is an inverse relationship between the focal length of the system and the size of the camera sensor. As a result, a long focal length which would allow the necessary magnification to resolve images adequately at longer distances will have a much smaller FOV. This could prevent the necessary overlap in left and right images which would prevent the system being able to create a depth map and provide the range of objects being imaged. In addition to the effect of focal length on FOV a small sensor further reduces the FOV of the system. Thus, a long focal length with a small sensor can prevent the system from taking a left and right image of the same scene. Thus, a balance between the sensor size and focal length of the system must be achieved to accomplish the goal of stereoscopic imaging. There are several standardized sizes for camera sensors. The most common sensors follow the convention for a 4:3 aspect ratio. The chart below lists some of the most common sensor sizes.

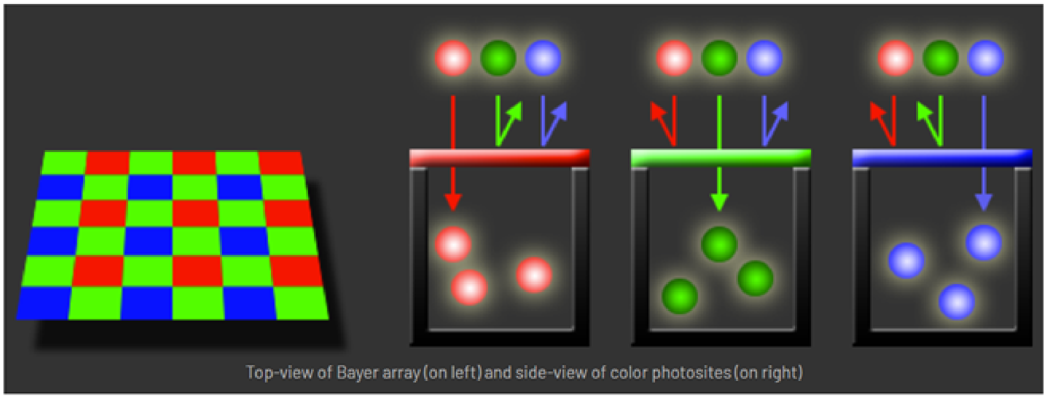
Table 3.4: Commercially available sensor sizes

Sensor	1/3 inch	1/2.5 inch	1/2 inch	1/1.8 inch	2/3 inch	1 inch	1.1 inch	4/3 inch	APS-C	APS-H	35 mm
Diagonal (mm)	6	7.2	8	9	11	16	17.6	21.6	27.9	35.5	43.3

As we can see from the chart above there is a significant range of sensor sizes that have a direct impact on the FOV of each camera system. In an ideal situation we would want the largest commercially available sensor format as this would allow for the longest usable focal length that can still maintain the necessary FOV to capture a long range left and right image of the same scene to accomplish the intended goal of the system.

The last consideration for the cameras is the number of megapixels (MP). A MP describes how many pixels are available on the sensor. For example, a 2 MP camera will have ~ 2 million pixels. A sensor with a higher number of MP will subsequently have a smaller pixel size improving the resolution of the camera assuming the lens system acquiring the image is well designed. In addition, a digital camera sensor does not sense color. To accomplish this a typical color sensor will have red, blue and green filters arranged in a 2x2 grid format. This method of sensing color is called Bayer filtering. The 2x2 grid usually consists of two green, one red and one blue filter as seen in the figure below taken from https://www.red.com/red-101/bayer-sensor-strategy.

Figure 3.1: Representation of common Bayer filter format with depiction of how each RGB filter allows only the transmission of the desired wavelength of light.



Once the sensor can capture the necessary light a process called interpolation is used to calculate the missing colors from the available data to recreate the desired image. Because we are attempting to capture images at long ranges the size of the object on the image plane will be relatively small. To accomplish this, we will need to be able to resolve these objects adequately to compare the left and right images to have enough disparity between to create the depth map needed for ranging. As a result, the ideal sensor will have a high number of MP to maximize the number of pixels available to resolve the images.

As we can see above there are several considerations when picking the cameras for this system. The ideal camera will have the largest sensor to allow for the largest FOV while maintaining the necessary focal length to resolve images at a distance, a global shutter and a high MP count with small pixel size. A commercially available camera that achieves these goals is likely to be too expensive for this project thus a compromise must be made. Priority will be placed on choosing a camera with a global shutter, medium sensor size and adequate MP count to achieve the goals of this project. Below is a comparison of budget appropriate cameras that can be used for the system. Although the sensor size is not ideal for the desired focal length of the lens system due to budget constraints a larger sensor size will 3x or more the cost of each camera. The table below is a comparison of several commercially available cameras that meet most of the criteria to accomplish the goal of this project.

Table 3.5: Comparison of three cameras that meet the criteria for a CMOS sensor with global shutter, necessary MP count and color sensing.

	ELP Web camera AR0234	See3CAM_37CUG	See3CAM_24CUG
Megapixels (MP)	2	3	2
Frame Rate (fps)	90	72	120

Sensor size	1/2.6”	1/2.6”	1920x1200
Pixel size	Not available	2.25 μm x 2.25 μm	3 μm x3 μm
Cost	$91.80	N/A	$199

Comparing the cameras above we can see that all of them share the same sensor size thus the focal length of the system will have the same effect on the FOV of the system thus the sensor size is not a factor in deciding which camera to use. All have an adequate frame rate for video to meet the stretch goal. What is not listed is the fact that the ELP camera comes with a C mount and zoom lens system. It is unclear from the manufacturer whether either See3CAM models have the ease of mounting a lens system. As a result, the ELP camera provides the easiest platform for modifications and the custom lens system. By having a C mount available on the camera housing, we can easily attach the custom designed lens system. The C mount is a standardized mounting system which is easy to fit. Also, it comes with a variable zoom lens which can be used for testing while the custom lens system is being designed and manufactured. This will allow the image processing code to be tested and debugged to ensure that the appropriate distance is calculated when completing a 3D depth map and ranging at variable zooms to ensure the code can be adjusted to the final specifications of the final lens system.

Telephoto Lens considerations:

For the system to achieve its stated goals the imaging system must have an effective lens system that can provide the necessary magnification to image objects at long distances. The lens system must also be able to address this need while minimizing aberrations that result from using a refractive lens system. Aberrations result from light rays not converging or diverging as expected as they travel through a lens or system of lenses. This causes images to be distorted, blurry or colored incorrectly. Aberrations can include but are not limited to spherical aberration, COMA, field curvature, chromatic aberration, astigmatism etc. Although light is not a ray nor does light travel in a perfectly straight path as a ray does, we can use geometric optics theory to simulate how a lens system will work using rays to model how light will travel in the optical system. The goal of our lens system will be to get the best magnification possible while maintaining necessary FOV for adequate overlap of the left and right images for depth mapping. There are several traditional lens systems that can provide magnification. For our purposes we will be using a telephoto lens design. The telephoto lens is a commonly used lens format that provides significant magnification while addressing aberrations. The telephoto lens system consists of a positive portion and a negative portion. Using the thin lens equation, we can find the focal length of the combined system assuming that the positive and negative lens portions are a thin lens:

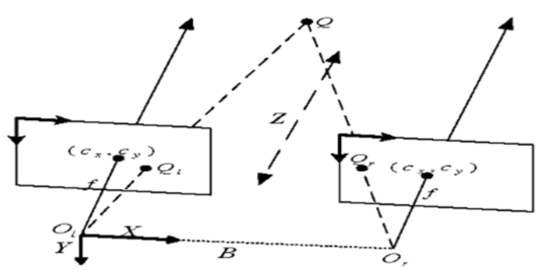
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

The telephoto lens has some advantages noting the ability to minimize all aberrations that can result from a refractive system. When considering field curvature and astigmatism, if we make the powers of the negative and positive portions of the lens system equal in magnitude, we end with a Petzval sum of zero which eliminates the previously mentioned aberrations. Best practice would suggest ensuring the positive and negative sections of the system are designed as aplanat systems. In doing so spherical aberrations and COMA will be addressed. This in theory will allow the lens system to control for all monochromatic aberrations. The challenge in accomplishing this is the need for several lenses to accomplish this goal. An ideal telephoto system will follow the above principles but to accomplish this, many commercially available telephoto lenses are constructed of several custom lenses in the positive and negative sections. This level of design is not feasible for this project thus we will attempt to magnify our image using the telephoto lens design principles but using fewer lenses with a simpler design incorporating a positive and negative lens with similar powers to accomplish the goals of this system.

Stereoscopic Vision (SV) for Ranging:

A stereoscopic vision system is an imaging system that works like the human visual system. It is composed of two cameras set on parallel optical axes that capture a left and right version of the same image. For our purposes two matching cameras with matching custom lens design will be used to acquire the images. For SV to be used for ranging we need to construct the model within which the system will function. Figure 3.2 from Mu, Wei et al. illustrates the framework within which the range of an object will be found.

Figure 3.2: Diagram of SV ranging framework



Each camera will be aligned on parallel optical axes. The left and right camera images will have their own coordinate plane. The baseline or distance between the center of the cameras will be fixed.   To determine the range of the object the disparity which is the difference in the position of the corresponding points in the left and right images related to the object must be determined. Disparity is defined by the following simplified equation:

$$Disparity = X_l - X_R$$

Which states that the disparity is the difference between the corresponding position of the object in the left image (X_l) compared to the position of the object in the right image

(X_R). Using the disparity (D), the focal length (f) of the camera systems and the baseline (B) can determine the range of the object (Z). This is defined by the equation:

$$Z = \frac{B * f}{D}$$

Considerations for the design include the baseline distance and the focal length of the cameras with the custom lens systems. If the baseline is too large there is a risk that the left and right images will not have adequate corresponding points to accomplish ranging. Increased focal length of the optical system will allow for better resolution of objects at further distances but will result in loss of field of view (FOV) which can also result in a loss of corresponding points on the left and right images or at a minimum result in the loss of ability to range at closer distances.

Image Processing:

Stereoscopic imaging applications rely on a significant amount of image processing. The image processing is what takes the two 2D images and creates a 3D mapping of the space captured in the images. To do this the images are rectified which makes it easier to find corresponding points in the stereo images. This is done by finding corresponding points in the left and right images and projecting the images onto a common image plane. This is done through epipolar geometry which places the corresponding points on epipolar lines. Rectification transforms the images, so the corresponding points are on the same vertical plane making the epipolar lines horizontal. This allows the disparity to be calculated resulting in the construction of a 3D depth map of the scene in the images. This depth map can be used to determine the range of the object as it can provide depth information of all objects within the scene being imaged. Considerations also must be made to the magnification of the lens system. When using imaging processing we have to incorporate the focal length of the system into the programming to properly range the object. To perform the necessary image processing a programming language that can perform the required task will have to be chosen. OpenCV and MATLAB both have a stereovision suite which includes the ability to perform image rectification and depth mapping with stereo images. OpenCV is an open access computer vision library which can be used for the purposes of this project. It is C++ based but is integrated into Python programming language. MATLAB is a stand-alone programming software package that has been used for years in engineering. It has a robust image processing toolbox as well as a computer vision toolbox which can complete the necessary image processing to complete the goals of the project. Below is a comparison of these programming languages:

Table 3.6: Comparison of MATLAB and OpenCV

Computer Vision	MATLAB	OpenCV
Expense	Upgrade cost	Open Access

Ease of Use	X	
Real time application		X
Visualization	X	

As we can see from the simple comparison of the computer vision options, they both have unique advantages and disadvantages and are best at serving slightly different purposes. Because this project will be a prototype and not an integrated system the need for real time processing is slightly less important. Additionally, MATLABs computer vision toolbox already has several functions that can accomplish the needs of the system, limiting the need for additional code. MATLAB comes with several complementary tool boxes and Apps that are designed specifically for camera vision applications. Last, MATLAB is a familiar platform and provides better visualization thus MATLAB will be used for the image processing required for the system to achieve its goals. MATLAB However, OpenCV is still a consideration if there are unforeseen issues using MATLAB's computer Vision toolbox.

Motor Comparison:
There are several types of electrical motors available including Servo, AC and DC motors. However due to the precise scanning needed for the system to be able to rotate the camera in small controlled increments to scan the environment a stepper motor will be used to rotate the platform the camera system is mounted to. The stepper motor moves in steps meaning with accuracies of 1.8° to 0.9° per step. This means the motor can rotate in very small increments allowing for high degrees of accuracy. This is particularly important when rotating a stereo camera system to capture the desired object within the FOV of both cameras. For our system we will be using the NEMA 23 stepper motor. This motor has the necessary torque to rotate the camera system and has a resolution of 1.8° per step allowing for very precise adjustments to the camera's position.

DEV Board Comparison:
There are several types of DEV boards on the market including the Arduino and ESP32 platforms which are commonly used. More powerful platforms for AI including the NVIDIA Jetson Nano development kit are also available on the market but have a significantly higher cost not warranted for this project. Although the NVIDIA development platform would be ideal for image processing, at this time we intend to use a laptop for the image processing that will be performed. As a result we will be using the Raspberry Pi 4 development board. This DEV board has far more processing speed 1.5 GHz compared to 240MHz when compared to the ESP32. Both have Wifi and Bluetooth connectivity which the Arduino does not have. The Raspberry Pi 4 also has two USB 3.0 ports which allows for camera connectivity if needed to manually trigger the cameras simultaneously. Although it is not clear whether or not this feature is needed, having the necessary hardware for this type of integration is potentially useful and the Arduino and ESP32 boards do not have this option. With these robust capabilities controlling the stepper motor will not be an issue. Due to the processing

speeds and flexibility integrating other components into the overall system the Raspberry Pi 4 is the best choice to meet all the requirements of the system without overreaching on the systems budget.

Stepper Motor Driver Comparison

The stepper motor requires a stepper motor driver to regulate the electrical current sent to the motor coils, making sure the motor operates efficiently without overheating, controls the direction of rotation of the motor and controls how the stepper motor rotates i.e full step, half step etc. This component is required to control the precise motion of the motor to control the camera system to image in the desired direction. There are several types of motor drivers available but for this system we will be using the TB6600. This driver has built in heat, under voltage and over current safety controls. Has the flexibility to handle a wide range of voltages 9V-42V and high current capacity of 4.0A. Other drivers of similar cost do not have these features. The high current capacity also allows the driver to work with the NEMA 23 motor that will be used to rotate the camera system.

CHAPTER 4:

STANDARDS AND CONSTRAINTS

Industrial Standards:

Our system utilizes the 12V DC standard power for almost all of its systems, coming from the 12V de facto standard for car and boat manufacturing. The 12 volt DC system requires no AC to DC converters, and only voltage step up and step down systems in high power use independent vehicles for their electrical systems, so all marine radar systems are built to utilize this power system.

Our system also utilizes the ethernet or j45 industrial standard for network communication. We are specifically using ethernet to create a sort of local area network consisting of the radar and the computer that communicate with the wide area network through the starlink system, which then communicate through the wide area network on drones. The ethernet standard was created to standardize local networking by the IEEE in 1985.

Our system also utilizes the universal serial bus standard which provides universal methods of communication and power transfer among devices. The universal serial bus was created to standardize communication between peripherals and host computers, as we are utilizing it in this project.

Constraints:

Weight:

Because our system is designed to be flown in a moving vehicle, the total weight is very important for the efficiency of the aircraft. The aircraft team working on this project will have a much easier job if the weight can be kept down to the lowest amount possible. This constraint controlled a lot of our selections during research, and will affect a lot of the materials for the physical assembly of the complete system. While there is not a hard limit on how heavy the whole project can be, the closer the system can be to 100 lbs or less the better.

Power usage:

Because of the weight constraint, the power usage and consumption of each component becomes a much greater constraint. Long lasting batteries supplying at the 12V standard become heavy very quickly, as seen with the car battery in comparison to the recreational batteries. Also, this means we have to work with far less wattage if we can, to keep our design for having to upgrade our power supply or have multiple power supplies. With the Westinghouse power supply, we will have to limit our current draw to 10 amps maximum per port, so we must find a way to power the whole system on 30 amps split among 3 ports.

Component Constraints:

The sponsor has supplied several of our components for us to use, such as the Raymarine Cyclone 6 ft radar (coming with the VCM100 voltage modulator), the Westinghouse power supply, the ASUS NUC, the Starlink terminal, and the 755A size 15 accu-coder encoder. These parts will all be included in the design unless the design cannot support them in any scenario.

Financial Constraint:

While the project is being sponsored by Southcom and enabling a much larger budget, the intent of the project is still to be a much cheaper replacement for existing technologies like the AWACS aerial radar system. Small financial inefficiencies can be overlooked in favor of other attributes, but keeping the overall cost of the project down is a goal of our team still.

Customer needs:

This project is ultimately going to fulfill the needs of defense contractors working to train drone swarms, and a large part of what our project is looking to do is provide information they need and want and incorporate it into the technologies we use in our design. While a lot of this is handled by our computer science team working on repurposing the radar software, this lead to the incorporation of the encoder to determine the position of the rack and pinion, and from there extrapolate the position of the radar and communicate that through the microcontroller onto the PC, which will utilize that information in its radar data algorithm which provides its signal to the starlink which passes onto the drones.

Knowledge constraint:

This constraint of our system is a little difficult to justify, but essentially some of the parts and systems we are using are going to be informed by what we know how to work with. A significant portion of our design problem is completely new territory for each member, such as the mechanical nature of our system. So, we are going to pursue solutions each of our members are more able to work with, while learning the integration between systems along the way. Especially with the degree spread of our small team, it is important to make some effort to stay within each team member's knowledge base for the project. Also, our sponsor's familiarity and their other resources will inform our decisions as more experienced engineers can help us identify shorter routes to our destination as well as prevent some of our mistakes from happening on the first place.

4A. OPTICAL PARALLEL PROJECT STANDARDS AND CONSTRAINTS

Industrial Standards:

Universal Serial Bus (USB) is an industry standard, developed by USB Implementers Forum (USB-IF), that allows data exchange and delivery of power between many types of electronics. It specifies its architecture, in particular its physical interface, and communication protocols for data transfer and power delivery to and from *hosts*, such as personal computers, to and from peripheral devices*.*

System Considerations:

USB will be used to power the cameras used in the stereo imaging system as well as perform data transfer from the camera to the computer for image processing.

ISO 18383:2015 identifies a set of features that describes digital still cameras (DSCs), and it specifies their definitions, measurement methods, and presentation methods.

System Considerations:

The characteristics used to determine which cameras will be used in the system are defined by this set of standards.

PRACTICAL CONSTRAINTS:

Time:

Due to this being a two semester course the time allotted to complete this system is limited to approximately 6 months. There is an additional loss of time since this project must be completed in the spring and summer semesters which decreases the length of time by 2 weeks due to the shorter summer semester. This time constraint is further exacerbated by the confusion regarding the "parallel optical" project which required a design change past the halfway point of the spring semester requiring a complete change in the goals, objectives, and function of the system.

Since this is the first time the students will be designing, building, testing and demonstrating their ability to engineer a functional system there will be many issues that will likely arise. The system will require testing, design changes, and debugging which will all require time to correct. As engineering students there will be issues that we may be able to anticipate but there will be many that we won't anticipate that will impact the time required to complete the project. Also, as a student there are limited resources available to the student body for such as 3D printers, lab equipment and access to instructors. These constraints ultimately have an impact on the time available to complete certain tasks and to trouble shoot. As a result, the best possible design to meet all the basic and stretch goals of the project may not be possible however there should be adequate time to create a functioning prototype that can demonstrate the system's ability to provide range information of an object at a distance.

Economic:

Because this is a senior design project which is to be completed by students, the budget for these projects is typically limited. However, for this groups primary project is sponsored there is some sponsorship assistance with this project it is limited as the optical parallel project is not the primary system design. Optical components of the size, number and quality required to meet all stretch goals of this project will be prohibitively expensive. For the optimal system custom lenses would be able to achieve the goals of the system best but are far too expensive for a student project. Also, commercial cameras with a 35mm sensor, global shutter and high enough frame rate to meet the stretch goals are also too expensive and beyond the budget for this system. As a result, the financial constraints of this project will be significantly limit the performance of the final system built for demo at the end of the two semester time period.

Environmental:

Environmental constraints will have the biggest impact on the development, testing and performance of the system. Most optical systems that can effectively operate during the day and night and in multiple environmental conditions will require the use of components that operate in the infrared spectrum or a combination of paired systems requiring components for the infrared and visible spectrums respectively. For the optical parallel system to successfully operate in the same manner as a mini-AWACS it needs to be able to operate in multiple weather conditions including rain, fog, snow, dust and anytime of day. It must also be able to operate at altitudes with below freezing temperatures. Thus, all components will need to have tolerances to operate at these temperatures.

A system that can accomplish these goals is unrealistic for this project. Thus, the system will only operate during daylight with good visibility. Conditions such as rain and fog will cause water to collect on the outer lens affecting the system's ability to collect light for imaging as the water will have refractive, reflective and dispersive effects on the incoming light that is not accounted for in the system. Low light or nighttime conditions will likely not have adequate light to capture resolvable images that can be used for the purpose of the system. Additional atypical environmental conditions such as smoke, sand or dust can also obstruct the ability for the system to view the intended object, preventing it from operating successfully. As a result, ideal daytime conditions will be necessary for all testing, troubleshooting, and demonstrations.

REMAINING CONSTRAINTS:

Manufacturability:

Manufacturing constraints are significant and limit the over performance of the system. Using a telephoto style lens system to increase the focal length of the camera systems while still maintaining a reasonable size usually requires manufacturing of custom lenses of varying diameters and radii of curvature. Additionally, these lenses can be made of different glasses. The customization of the lenses in the system are what will minimize aberrations in the system. However, lenses of this nature require custom ordering and must be manufactured by a third party. This type of manufacturing equipment is not available in the senior design lab and would be unrealistic for this project thus the lenses used for this system must be commercially available. Manufacturing of the custom lens housing will have to be done via 3D printing. This will require access to a 3D printer that will likely be shared by all the students participating in senior design so access will be limited. As a result, the design and manufacturing of the lens housing must be simple enough that it can be 3D printed in a short period of time to meet the availability of the necessary equipment. Furthermore, the same constraints apply to manufacturing the housing for the cameras. Manufacturing is an extremely important part of this project and requires a significant amount of optomechanical design for the system to operate properly; however this needs to be achievable within the constraints listed above.

Health and Safety:

Another constraint that must be considered is health and safety. Due to the outdoor space required to test the system safety considerations need to be made. The area required for testing will likely be a public shared space that includes pedestrians, animals and adjacent traffic. As a result, the testing must be done in a space that is far enough from traffic that reflections from the lens system do not impact drivers. Since images and video will be taken by the system an effort to keep passers by and others using the shared space out of the images due to privacy concerns. If people are recorded during the testing or demonstration, it would be appropriate to get written consent to publish their likeness as our demonstrating videos will be posted to Youtube.com which is a public distribution platform. Doing this would negatively impact the time required to complete the project and likely require approval of UCF. As a result, it will be best to avoid this issue and ensure the system is tested and demo performed without capturing images of people not involved in the project.

Due to the large public outdoor spaces required to complete testing and demonstrations of the system pets and wildlife need to be considered for safety. Although most small animals such as squirrels, birds or lizards are common to the central Florida area and are basically harmless. Pets such as dogs can get off leash and can be potentially dangerous, coyotes have also been seen recently in a few parks and open fields in central Florida. Although alligators are common throughout Florida testing will likely not be performed near bodies of water thus eliminating this safety risk. Although a dangerous encounter with one of these or similar animals is unlikely, we still need to be aware of the area around testing for any potential hazards. This could be considered an environmental constraint however these possibilities are more of a safety concern.

Political:

The mini-AWACS project is sponsored by Southern Command (SouthCOM) which is a branch of the department of defense (DOD). The end goal of this overarching project is to assist with military testing of drones. Thus, it is important to note that the goals of this project are governed by the needs of SouthCOM which can impact the course of the project and its potential end use.

CHAPTER 5:
ChatGPT Comparison

ChatGPT is an LLM that can be used as a resource to complete research related to any topic. ChatGPT can be used as an effective tool when initiating research on any subject however it is still being developed and currently on generation 4o and continues to improve. However, when using an LLM caution must be taken as the data provided is limited and may have some inaccuracies. Below we explore the use of ChatGPT compared to similar tools to assist in the completion of this project.

Optics Case study 1 prompt:

“What do I need to consider when designing a telephoto lens system?”

“Designing a telephoto lens system involves several steps and careful consideration of optical principles, materials, and manufacturing techniques. Here's an overview of the design process:
1. Determine the Specifications
- Focal Length: Telephoto lenses have long focal lengths, typically 85mm or higher. The first step is to decide the desired focal length for your telephoto lens.
- Aperture Size: Determine the aperture or the f-number (e.g., f/2.8, f/4) that affects how much light enters the lens. Larger apertures (lower f-number) are typically desired for better low-light performance.
- Field of View (FoV): This is related to the focal length and sensor size. A longer focal length results in a narrower field of view, allowing you to capture distant objects clearly.
- Image Quality: Consider factors like resolution, sharpness, and chromatic aberration control. You'll need to balance these with other factors like size and weight.

2. Choose a Lens Type and Configuration
A telephoto lens often uses multiple elements to manage aberrations and achieve the desired focal length:
- Prime vs. Zoom: A prime telephoto lens has a fixed focal length, while a zoom lens offers a variable focal length.
- Telephoto Elements: The design can include several lens elements like convex and concave lenses, achromatic doublets, or even aspherical elements to correct distortions and aberrations.
- Lens Groups: Group lenses into two main categories: positive (convex) and negative (concave) elements. Negative elements in telephoto lenses help in reducing the overall size and weight.

3. Correct for Aberrations
Telephoto lenses are prone to certain optical aberrations. These must be minimized:
- Chromatic Aberration: Use of achromatic doublets or special dispersion glass materials can reduce color fringing.
- Spherical Aberration: Correct with aspherical lens elements.
- Coma: Typically corrected by designing a combination of concave and convex lenses.
- Distortion: Telephoto lenses generally have lower distortion but should be evaluated in the design stage.

4. Lens Elements Layout
- Achromatize: Choose glass with different refractive indices (e.g., low dispersion glass) for different elements to reduce chromatic aberration.
- Telephoto Design: The telephoto design often incorporates a rear group (positive or negative) that shortens the physical length of the lens system. This helps in achieving a long focal length in a relatively compact form.
- Focus Mechanism: Decide between a focusing system that moves the lens elements or a group (internal focusing or external focusing). For high-end lenses, internal focusing is used to avoid changes in size during focusing.

5. Material Selection
- Lens Glass: Choose lens materials based on refractive index and dispersion properties. Modern telephoto lenses often use special glass types like ED (extra-low dispersion) or fluorite to improve performance.
- Coatings: Anti-reflective coatings help to reduce flare and ghosting. Multi-coatings are standard in high-performance telephoto lenses.
- Housing: Materials for the lens barrel are typically metal (like aluminum or magnesium alloy) for durability but could be plastic in less expensive models.

6. Mechanical Design
- Focus Mechanism: Choose whether the lens will have manual focus, autofocus, or both. Autofocus systems are often driven by stepper motors or ultrasonic motors (USM or STM).
- Zoom Mechanism: If it’s a zoom lens, design the zoom mechanism. This could be a push-pull system or a rotating ring.

- Stabilization: For longer focal lengths, image stabilization (IS) can be crucial to reduce camera shake at low shutter speeds. This can be achieved with either in-lens or sensor-shift stabilization.
- Mounting: The lens mount should be compatible with the camera body, ensuring proper communication for functions like aperture control and autofocus.

7. Test and Optimize

- Prototype and Testing: Once the design is complete, build a prototype and test for optical performance, focusing accuracy, and image quality. Simulate various conditions like flare, chromatic aberration, and distortion.
- Refinement: Based on the results of testing, refine the design. Adjust the lens elements' curvatures, positions, and materials to optimize performance.

8. Manufacturing and Final Design

- Precision Manufacturing: Lens elements must be ground and polished to very fine tolerances. The manufacturing process is crucial for the precision required for telephoto lenses.
- Assembly: Once elements are made, the lens must be assembled in a clean environment to avoid dust and debris.
- Quality Control: During assembly, the lens undergoes quality control tests, including optical tests to ensure that the final product meets the design specifications.

Key Considerations:

- Weight and Size: Telephoto lenses tend to be large and heavy. Using lightweight materials or designing for portability can improve the user experience.
- Cost: Higher-end telephoto lenses can be expensive due to the advanced materials and technologies used (such as fluorite, ED glass, and image stabilization).
- Compatibility: Make sure your lens design is compatible with various camera bodies, both in terms of mount and functionality.

Telephoto Lens Example Configurations:

- Double Gauss Design: A commonly used design for telephoto lenses with symmetrical configurations to minimize aberrations.
- Retrofocus Design: In a telephoto lens, this configuration uses a larger rear element to help create a short overall length.

Would you like help on any specific part of the design, such as focusing mechanisms, element arrangement, or material choice?"

ChatGPT (2025)

ChatGPT has covered many of the considerations of designing and building a telephoto lens system. It covers the specifications of the system such as FOV, focal length, sensor size, aperture size, and resolution which address the performance of the system. It mentions aberrations, choosing glass materials and the optomechanical considerations of the system. This is a good starting point and provides many of the considerations that need to be made when designing a telephoto lens system. Although the list of considerations is quite comprehensive it would be nice to have a list of the equations that are required to make the necessary calculations for producing the lens system. ChatGPT provides a good starting point, but more specific information is needed.

ECE ChatGPT Comparison

ChatGPT has been incredibly useful throughout the phases of this project thus far. It has been valuable for both the research and execution of some of our technical goals. ChatGPT accelerated our understanding, as well as our problem solving.

At the beginning of this project, We used ChatGPT to research many different things we were to use in this project. For each piece that we needed for this project we had ChatGPT list us things that do the same job as that piece and then we had ChatGPT compare the pieces to help us pick the best fit for our project. ChatGPT helped us initialize much of our research from that of the different microcontrollers, to the research between the different communication protocols that we could use for our project, to a refresher of some of the embedded systems that we will be using later in the project. ChatGPT helped jog our memory on foundational topics that we had much familiarity with but had not used recently.

After my initial research with ChatGPT, we went on to research each piece and topic separately; however, whenever we encountered topics that we were unfamiliar with or needed clarification, we were able to quickly ask. This accelerated the research time greatly.

One of the most valuable instances of the use of ChatGPT came after our group first received our Raymarine 6 ft cyclone radar and the Raymarine VCM100. We encountered multiple hardware issues that were not well documented online and ChatGPT was able to guide us in the right direction, giving us some potential causes and solutions. For example our VCM100 was not outputting the voltage that was necessary to power on the Raymarine 6 ft cyclone radar but we weren't sure if the issue was the VCM100. ChatGPT, along with the help of Raymarine technical support, suggested many different tests and explained how to safely test without further damaging the system. There were also instances where we needed to buy specific wires and fuses for further testing however we were not sure which wires and fuses would suffice for the Voltage and Amps needed and once again ChatGPT was used to answer those questions.

As the project progresses into the final implementation and testing stages, I expect to continue to use ChatGPT as a support tool. Whether it be for quick questions on the fly, troubleshooting questions, or general research questions, ChatGPT has been immensely helpful thus far into the project.

ECE Example ChatGPT prompt:

List me the 4 most used Microcontrollers and their pros and cons.

ECE Example ChatGPT Response:

Here’s a concise yet detailed breakdown of the **four most commonly used microcontrollers** and their **pros and cons**

Top 4 Most Used Microcontrollers

1. Arduino Uno (ATmega328P)

Pros:

- Extremely beginner-friendly with a huge user community
- Massive library and example code support
- Cheap and widely available
- Open-source and easily expandable

Cons:

- Slower clock speed (16 MHz)
- Limited memory and I/O (only 2 KB SRAM, 32 KB flash)
- Not ideal for complex or real-time systems
- No native USB support (requires serial adapter)

2. Teensy 4.1 (NXP i.MX RT1062)

Pros:

- Very fast (600 MHz ARM Cortex-M7)
- Lots of I/O pins and multiple serial interfaces (UART, I2C, SPI, USB, CAN)
- Supports audio, Ethernet, and advanced peripherals
- Compact and powerful for real-time tasks

Cons:

- Slightly steeper learning curve compared to Arduino
- Less beginner-friendly documentation
- More power-hungry
- Might be overkill for simple projects

3. STM32F4 Series (ARM Cortex-M4)

Pros:

- Used heavily in industrial and aerospace applications
- Very efficient (real-time capable)
- Great peripheral support: ADC, DAC, DMA, timers, communication protocols
- Multiple power modes and high integration

Cons:

- Requires knowledge of STM32CubeMX or low-level registers
- Development environment is more complex (e.g., STM32CubeIDE, Keil, etc.)
- Less beginner documentation compared to Arduino

4. Raspberry Pi Pico (RP2040)

Pros:

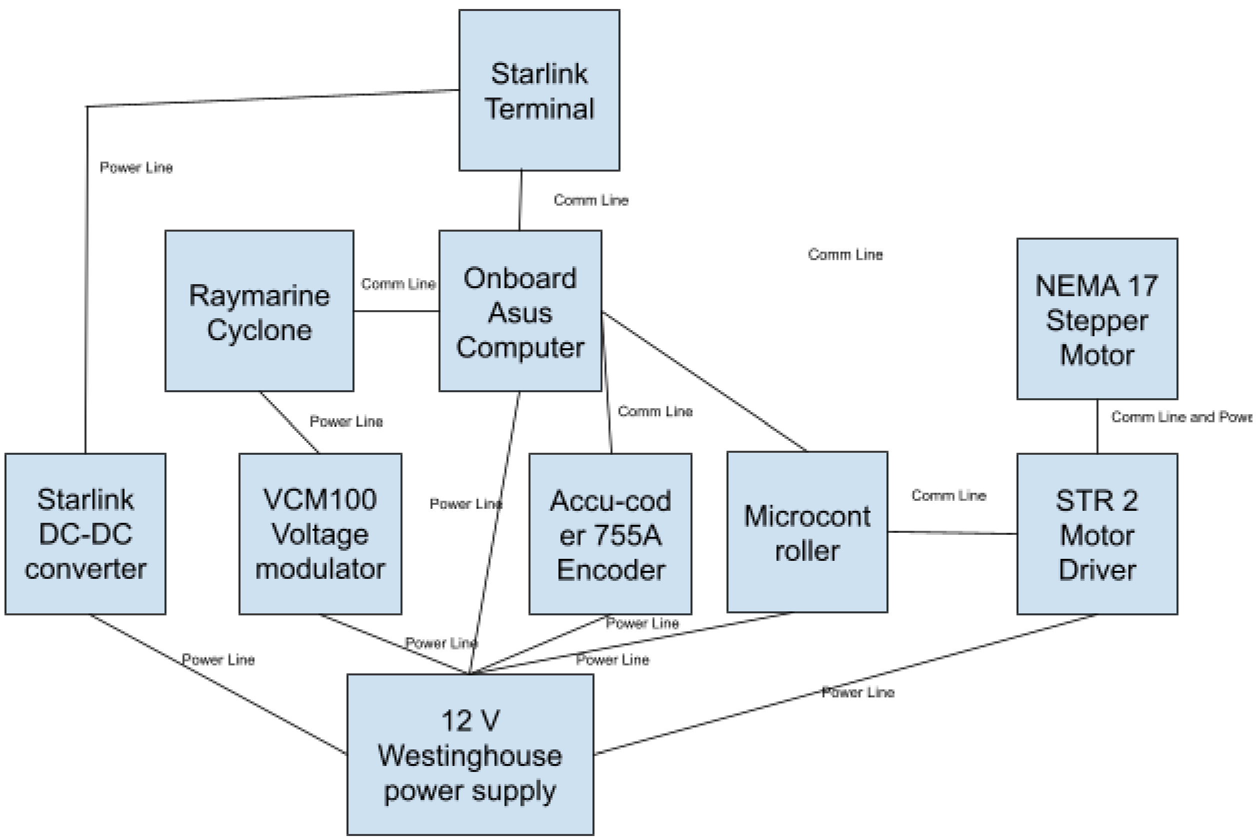
- Dual-core ARM Cortex-M0+
- Very affordable ($4)
- Supports C/C++ and MicroPython
- Good GPIO and analog support
- Fast I/O with programmable I/O (PIO) peripheral

Cons:

- No Wi-Fi or Bluetooth built-in (unlike ESP32)
- Relatively new; smaller community than Arduino
- Limited compared to more powerful MCUs like Teensy

Chapter 6 Hardware Design

The hardware design is built upon the given usage of the rack and pinion system discussed in the research section of this paper. For that mechanical system, we will need to have 5 distinct circuit loops created to provide power between subsystems and 4 devices need to communicate information between our system and the satellite network that communicates to the servers and then to the drone. A not to scale drawing of what our system must fulfill is shown below.

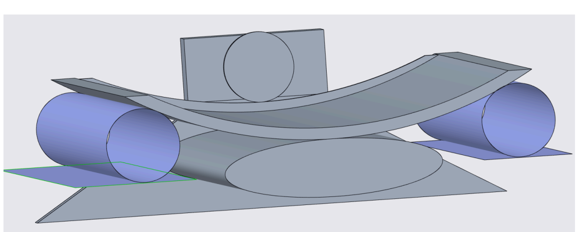


The connection pathways necessary for our complete design are the power supply to the Starlink Terminal, the Encoder, the computer, the microcontroller, and the stepper motor. The Starlink DC-DC converter, the Encoder, the VCM voltage modulator, and the STR2 stepper motor driver are all powered through a DC output signal of 12 V, enabling them to directly be powered by the power supply through its DC output. It is necessary we acquire a line splitter for this take as our DC supply has only three output ports, but the 10A current should be well sufficient to be split among all of the parts except the VCM100, who can get a separate port. The microcontroller operates on a 3V input signal, which can be supplied by the USB function of the Westinghouse power supply.

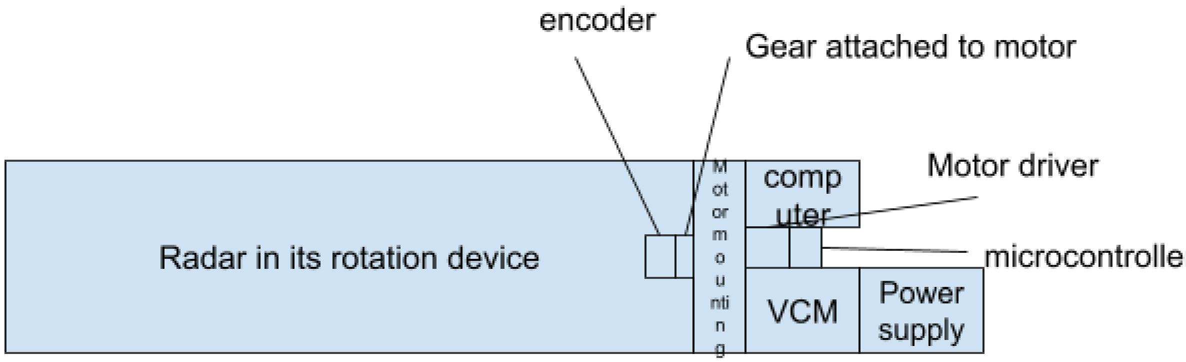
The VCM100 needs a direct pigtail connection with an inline 20A fuse, so that connection is going to be done by splicing together a DC to pigtail cable with the inline fuse spliced in the positive end of the signal. We will use CAT 14 cables to splice in the fuse here because of their ease of access and price point. The stepper motor driver also operates on a pigtail input line, so a similar connection will be used except without the fuse. The accu-coder connection is also wired similarly to the motor driver, using open ended cables. Here we can split the DC voltage of one of the 3 Westinghouse ports for both the encoder and motor driver. The starlink system will have its own DC plug, and will go directly from the Westinghouse supply to the converter into the starlink terminal. The onboard computer should run in a low power mode on its own battery life, however when the system is not engaged in sweep scanning the computer will have to be plugged into the system.

The communication methods between parts are a bit different. The radar connects to the computer through a raynet to j45 adapter, and the computer connects to the starling terminal through ethernet as well. It is possible later in design the computer is eliminated and there is a way to change our microcontroller to one with an inbuilt ethernet net port, and we somehow meld both ethernet signals together, but for now we are going to leave in the computer to communicate more simply over the starlink connection. So, the microcontroller will communicate with the PC over a usb 2.0 connection. And the encoder and motor driver will be connected directly to the pins of the microcontroller, allowing great code control over outputs and inputs into the microcontroller code. The stepper motor and the motor driver have an integrated system with which to both power and communicate the controls to the motor driver.

The physical setup of our hardware design has been somewhat described when talking about our rack and pinion system described in the research chapter, but how we plan to fit the periphery stuff is not. The radar, the motor, and the encoder will fit into the main rack and pinion assembly, the motor and the radar are pictured. The motor and the driver are in the back, and the radar is the cylindrical oval beneath the arc held in the pinion system. The encoder fits onto the rack on the side opposite of the motor.



The rack and pinion system will be on the outside edge of our system, with the triangular mount of the motor being the beginning of the rest of the payload.



Because of the larger size of our project, we will bolt all of the non moving parts of the assembly to a large board, providing a stable position for the radar mounting and a great place to route the lengthy cables to their respective locations. It should be noted that the starlink terminal will have to be connected to the top of the aircraft, because it needs direct access to the sky while our assembly will be hanging from inside a loading bay of the aircraft. The microcontroller will be moved onto a pcb for the final version of the project, so that completed solid connections can be locked in for long operation time. The power supply will likely be held by more temporary means, as it is charged by wall plugs, and taking the whole assembly and moving it towards a wall plug is far more impractical. For a similar reason, the computer will also use a more temporary solution to holding it into place. If velcro is sufficient in our physical design, it is the most likely attachment method for our project.

Failures of the Design

While testing the Raymarine 6' cyclone, we ran into several issues with powering the radar up with the Westinghouse power supply. The voltage modulator would not be in operation mode despite being provided the adequate 12 V power. In our testing, the "Fault" light indicator on the VCM100 was lit up, which through the manual and other resources described the issue as "electrical fault" and nothing else. So, it was incredibly difficult for us to determine the cause of the issue, even after contacting Raymarine support and trying several initial solutions to get the project running. So we had sent one radar and voltage modulator to a raymarine technician, while we worked with another team and powered their radar.

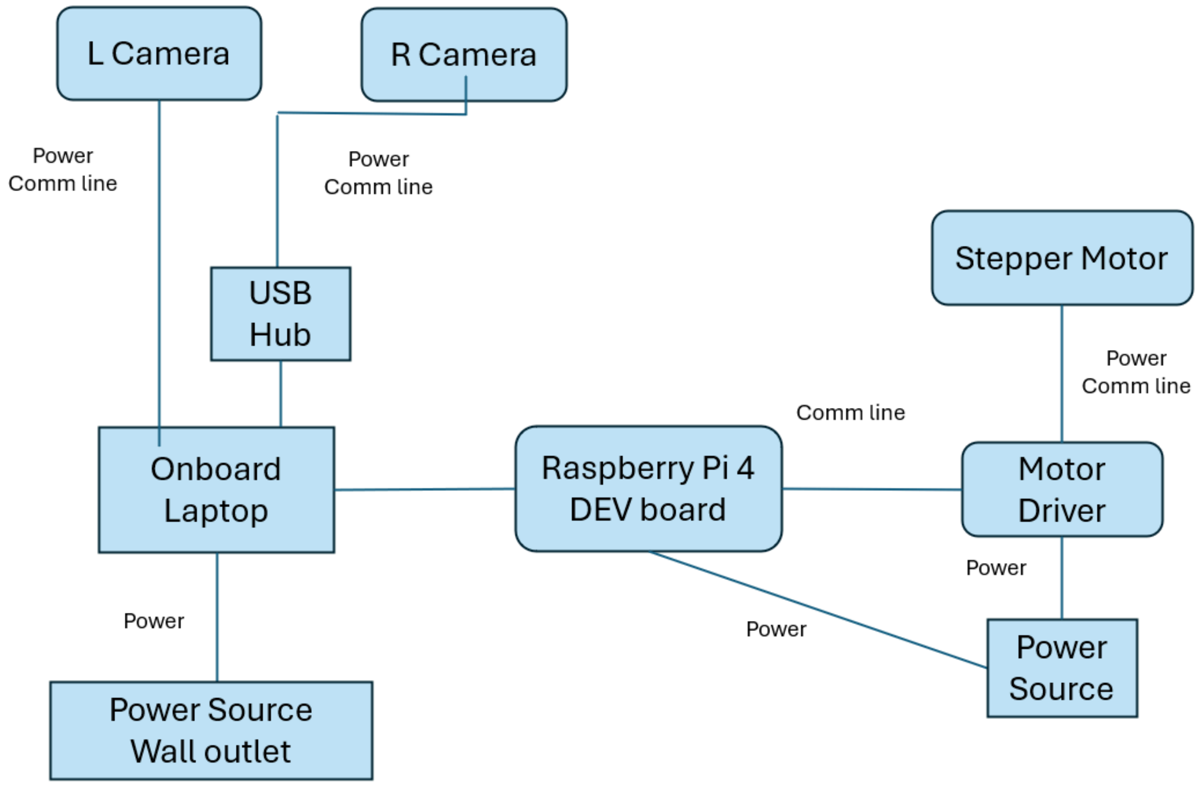
Through testing their radar, we did make headway in a few ways, firstly when powering their system we did it correctly the first time and got the VCM100 into sleep mode while connected to the radar. Several corrections in our initial connections we made, and among the embarrassing errors we made the first time were not recognizing which port of the VCM100 was AC and which was DC, and not incorporating the inline 20A fuse described in the manual under the assumption the Westinghouse supply had similar inbuilt fuses as described in the product summary. While working with the second team, they even found a solution to the connection and getting the radar out of sleep mode, because apparently the system takes longer than the battery's awake timer to power up.

So, a second device was used to draw power from the Westinghouse to keep it awake long enough to be able to turn on the radar from our PC interaction point.

Despite all of this progress, we received information, described in more detail towards the end of the paper, essentially saying our initial premise does not work, While we had made significant progress working while the radar was still in its rotational mechanism, we had not gotten to the point of disassembling the rotation assembly and incorporating it into our projects rotation element. We had planned to simply strip the signal connections from inside the base and use the adaptors to feed the signal connections into the isolated radar element. But, the radar itself cannot be separated from its rotational control signal, and the radar element cannot operate without the rotational feedback of the base. Making the radar element work in our design requires a hardware redesign of the raymarine cyclone itself, something we do not have the time or resources to do before the end of Senior Design 2. Such a project is industry level in scope, and taking far more than a few months to get going. We explore some potential solutions in chapter 11, which incorporate wholly new hardware design, rendering this section obsolete, but the information gained in testing is worthwhile, and the other team we are working with moved several steps forward in their project with our joint work.

6A. Optical Parallel Project Hardware Design

The hardware design of the optical design project is composed of two subsystems including the imaging and image processing section and the motorized platform the imaging system will be mounted to. The imaging subsystem uses a stereo camera setup with a pair of USB cameras with high magnification telephoto lens systems which are to be mounted on a rotating mount. The rotating mount will allow the imaging system to scan the environment and collect images and provide the range of objects in the respective images. The mechanical design of the rotating camera mount will integrate the stepper motor for motion of the stereo cameras and house the additional control components including the motor driver and Raspberry Pi 4 DEV board. The DEVboard will communicate with the Laptop so control of both subsystems will be done via the laptop. This is due to the fact that the Group 3 project consists of two separate projects limiting the time and resources allocated to the electrical engineering requirements for the optical project. Below is the hardware diagram for both subsystems.



We can see that the hardware design consists of two separate power sources This is due to the limited integration of the optical and motor components of the full system. In an ideal situation the entire system would share a single power source. However, due to the constraints placed on the group from having two parallel projects this compromise is necessary to allow bothe projects to be completed due to the limited time and resources available.

Chapter 7 Software Design

This project aims to create a lightweight airborne radar payload. One of the key systems of this project is the collection of real time positioning data of the radar as it performs its sweeping motion. Our group is responsible for implementing embedded system that collects the positional data and transmits this data to the computer science group, which will then take the radar data, filter it from ground cluttering, convert the data to JSON format, and then upload it to server which allows all the UAS to view the data through the use of Starlink. The software design includes the microcontroller hardware, data collection logic, encoder signal handling, and the communication strategy to transmit radar sweep data. The design ensures precise radar positioning is tracked during operation and relayed accurately to downstream systems.

A microcontroller with real time processing capabilities and high speed is required for this project. As of now we are between the STM32 microcontroller and the Teensy 4.1 microcontroller, both provide the following:

- Support for multiple communication protocols like UART, I2C, and SPI
- Compatibility with embedded C development environments
- High resolution hardware timers
- High communication speeds
- Reliability

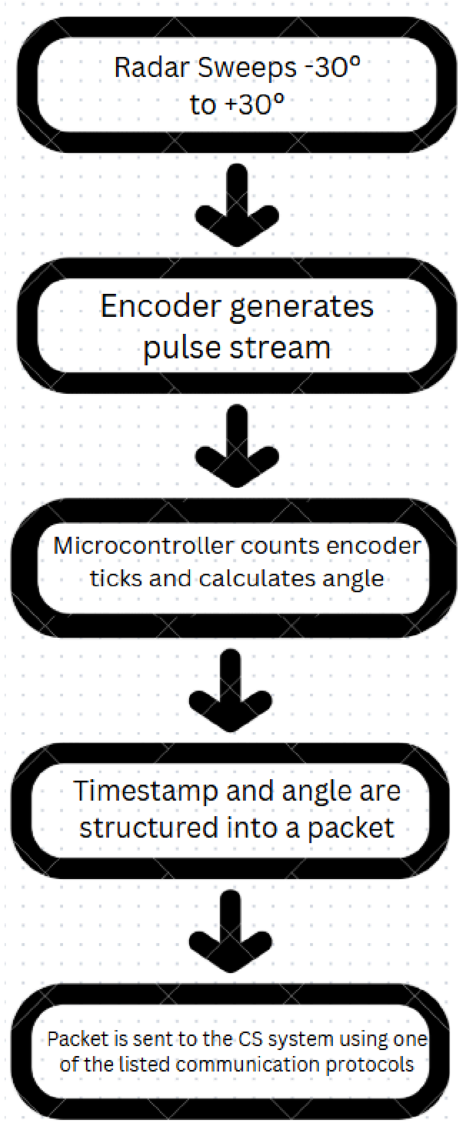
Alternative microcontrollers like the Arduino Due and the MSP430 were considered however the STM32 and the Teensy 4.1 proved to be more desirable.

The radar system moves in a sweeping motion using a stepper motor which has an encoder attached to it which sends signals which represent the radar's movement and direction. The microcontroller will read the encoder's data using interrupts. Each data packet will have a timestamp and the radars angle and potentially a few more variables.

To send that data packet over to the CS team one of the three communication protocols will be used, UART, I2C, or SPI.

- UART is very simplistic and would be supported by any microcontroller chosen.
- SPI is more complex, however, it provides higher throughput and would be used if high frequency data bursts are needed.
- I2C provides more timing accuracy however passes large data slower than SPI.

Software/Transmission Flowchart



This software module plays a major role in enabling the functionality of this entire project. Through the use of a high performance microcontroller and an efficient communication protocol, the system will provide the CS team with accurate, timestamped radar data.

7A. Optical Parallel Project Software Design

The goal of the optical project is to use stereo vision and triangulation to determine the distance an object is from the system via a stereo image pair and if possible be able to perform this function in real time via video stream. In order to complete this task the software design for this project is heavily based on the use of MATLAB's computer vision package to acquire the needed images and perform the image processing. There are several add-ons and toolboxes must be downloaded to allow MATLAB to use the USB cameras for image acquisition. Once completed stereo camera calibration parameters must be calculated with the system to create the rectified images and disparity map to be able to find the range of an object. These additional add-ons and toolboxes include:

MATLAB Support Package for USB Webcams

Image Acquisition Toolbox

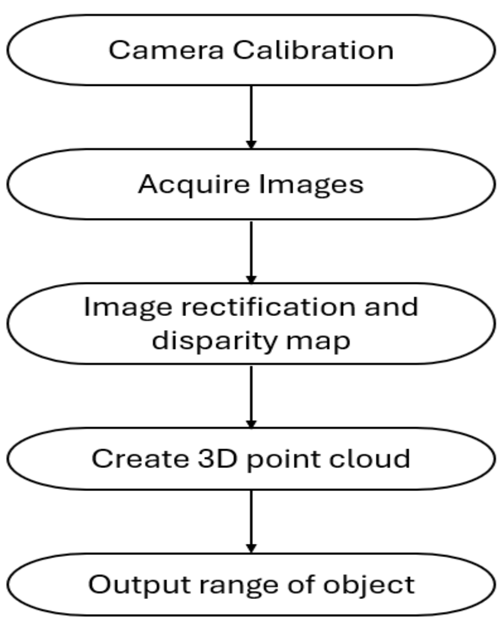
Image Acquisition Toolbox Support Package for OS Generic Video Interface

Image Processing Toolbox

Computer Vision Toolbox

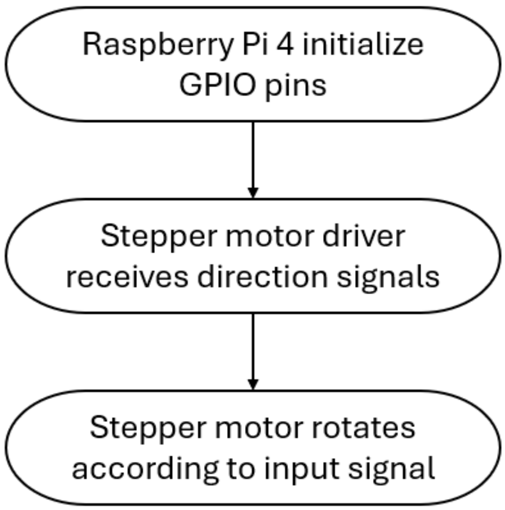
Using the above MATLAB add-ons and toolboxes the system will be able to acquire the desired images and perform the necessary image processing to achieve the stated goals. Before using the system the Computer Vision Toolbox must be used to calibrate the system. This is performed via the Stereo Camera Calibrator app. To complete this a geometric calibration pattern such as a checkerboard or CharuCo needs to be used. Several stereo images must be captured with the geometric pattern and processed in the calibrator app to create a .mat file with the necessary characteristics of the camera system to rectify stereo image pairs and create a disparity map. The software diagram below illustrates the needed calibration, image capture and processing flow.

Software transmission flowchart:



Additional software design is required to control the stepper motor which will move the stereo camera system to scan the environment. The software will use a python programming language library such as GPI zero to control the GPIO pins of the Raspberry Pi 4 Dev board. This will allow the Raspberry Pi 4 to control the stepper motor via the following process.

Software transmission flowchart:

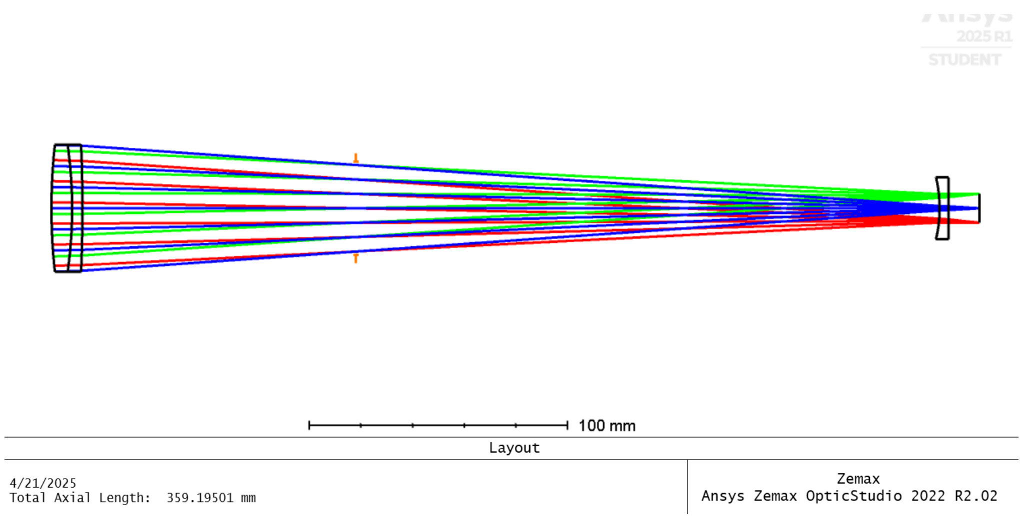


Chapter 8 System Fabrication/Prototype Construction

8A Optical Parallel Project Fabrication/Prototype Construction

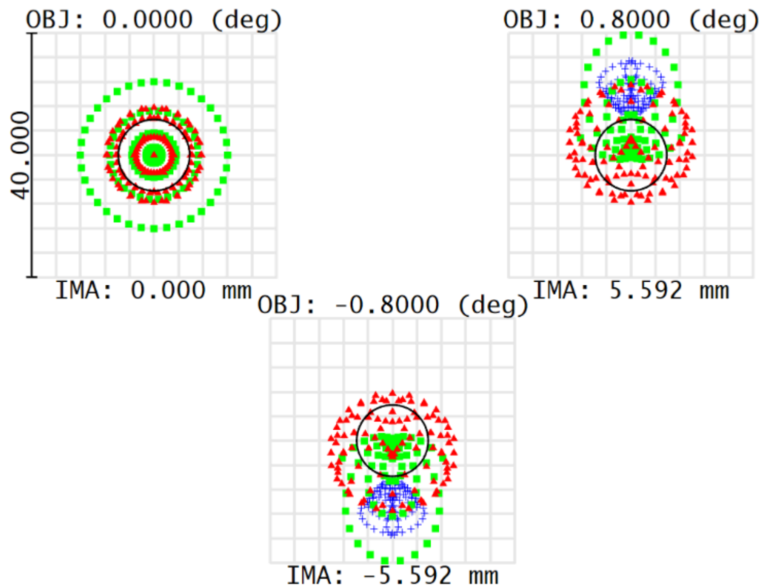
The optical project requires two specific components that will determine the performance of the system. The first is the lens system design that will be used on each camera to provide significant magnification to allow the system to visualize objects of ~ 1 meter in size at long distances adequately to determine the range of the object being imaged. In order to design this lens system Zemax was used to complete a lens design using commercially available lenses. The specific lenses for the system were chosen to address chromatic aberrations in addition to on and off axis monochromatic aberrations. A telephoto system consisting of a negative and positive lens were used to allow for a long effective focal length while preventing the system from becoming excessively long. Below we can see the diagram of the lens system.

Figure 8A.1: Zemax lens system layout with ray tracing using visual spectra, on axis and +/- 0.8 degree of axis rays



Parameters used to design the system include using red, green and blue wavelengths of light for ray tracing and off axis rays at 0.8° and -0.8°. The off axis rays correspond with the estimated field of view based on the sensor size of the chosen USB camera and estimated effective focal length of the system of 200mm. However, using the optimization tools in Zemax we were able to successfully increase the focal length of the system to 400mm while maintaining an image plane spot diameter that fit within the estimated 6.3mm diagonal of the camera sensor. This will ensure the image created at the image plane is not larger than the sensor. This effective focal length also allows for the smallest spot size on-axis and reduces COMA aberration which can be seen in the spot diagram in the figure below.

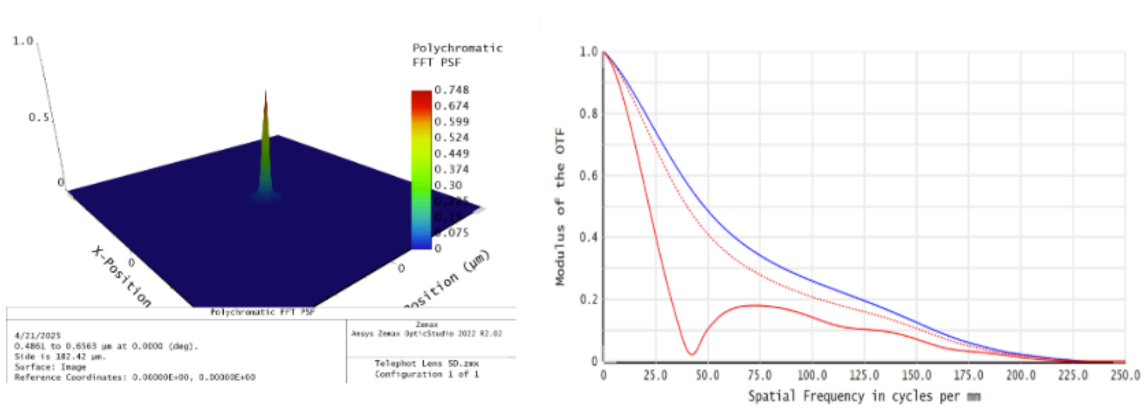
Figure 8A.2: Spot diagram of simulated lens system including spots for on axis and +/-0.8 degree off axis rays.




```
4/21/2025
Units are µm.        Airy Radius: 5.842µm. Legend items refer to Wavelengths
Field       :      1         2         3
RMS radius  :    5.533     8.731     8.731
GEO radius  :   12.042    19.708    19.708
Scale bar   :   40.000     Reference   : Chief Ray
```

Although there is some very mild spherical and COMA aberration in the spot diagram it is minimal, noting a nearly diffraction limited on-axis spot size and a small increase in the geometric radius of the spot off axis. Considering we are only using two commercially available lenses for the system the Zemax simulation demonstrates a high performing telephoto lens system. Additionally, the point spread function (PSF) is extremely narrow allowing for the potential to achieve high resolution at longer distances allowing the imaging system to create accurate disparity maps for subsequent image processing.

Figure 8A.3: PSF and MTF plots of the Zemax lens system simulation



However, the modular transfer function (MTF) of the optical system shows decreased performance at higher spatial frequencies which indicates potential for loss of contrast in the subsequent images which will affect the system from being able to accurately resolve items in the image which require a high level of contrast. As a result we see that the simulation of the lens system has performance trade-offs that need to be accounted for when assessing the performance of the actual system once it is built. Performance improvements are available but would require the fabrication of custom lenses which is not feasible.

The lens prescription data provides the following information related to the simulated telephoto lens:

System length	360 mm
Aperture Diameter	49 mm
Field Stop	Yes
F/#	8.5
NA	0.06

By using the telephoto design we have achieved an EFL of 400mm while keeping the lens system structure at 360mm. Additionally, the higher F/# indicates a large depth of focus allowing the fixed lens system to accurately image distances at various distances.

Additionally a lens tube needs to be constructed to house the lenses in the specific position required to acquire the desired images with adequate resolution. Creo Parametric was used to 3D CAD a lens tube that can be divided into three separate sections that can be bolted together to make the finalized lens tube. In figure 8A.4 we can see the full lens tube design. Inside the lens tube are retaining rings to assist with the exact position of the lenses in the tube In addition to providing the necessary spacing between the respective lenses and sensor there is adjustability designed into the lens tube including a cap section which can be screwed onto the lens tube to find the optimal position of the Achromatic lens at the front of the optical system. The adjustable cap can be seen in figure 8A.5.

Figure 8A.4: Lens tube 3D CAD design

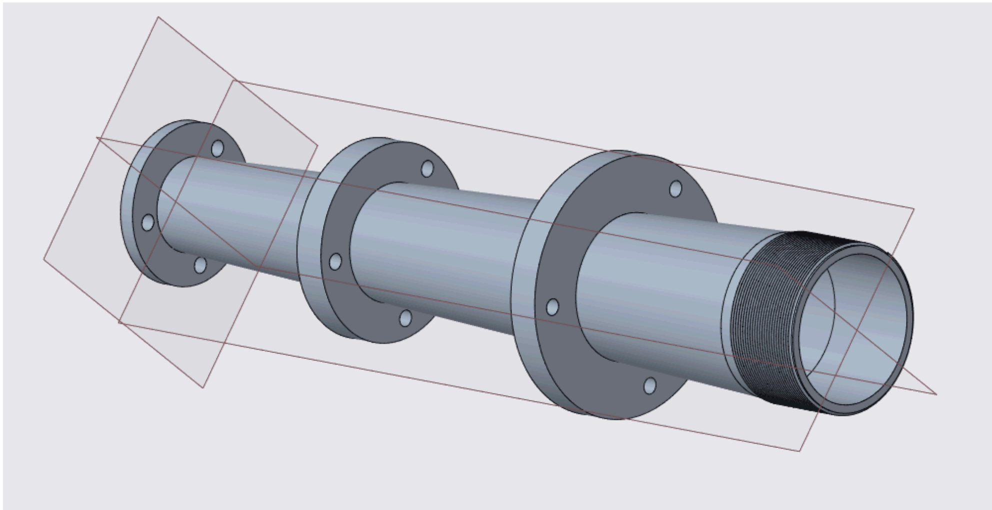
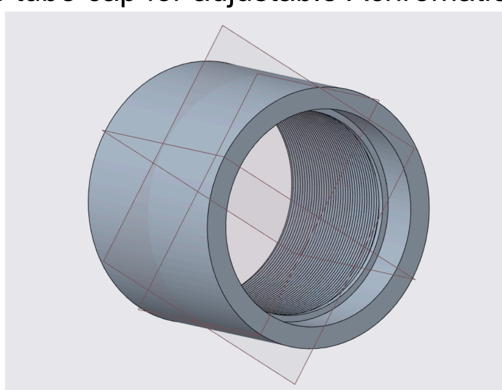


Figure 8A.5: Lens tube cap for adjustable Achromatic lens positioning



Additionally the lens tube will have to be mounted to the ELP cameras used in the system. These cameras come with a CS mount design that includes a 25.4mm diameter housing with a distance of

Chapter 9 System Testing and Evaluation

9A Optical Parallel Project System Testing and Evaluation

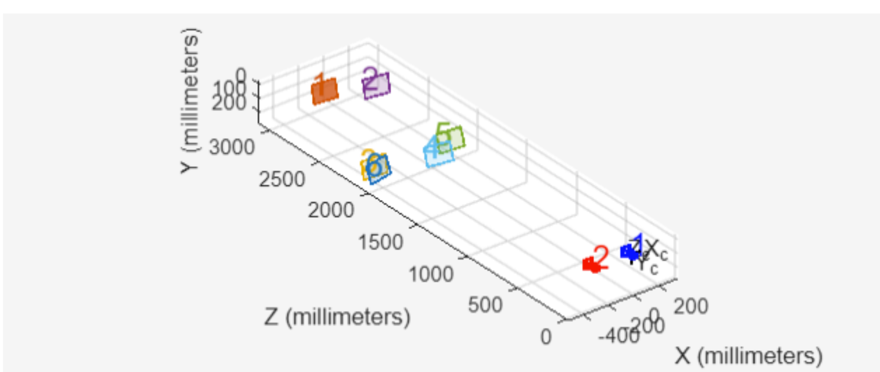
Testing was performed using a pair of USB cameras with the intent to determine if the image processing tools are sufficient to achieve the desired goal of the optical project.

In order to test this the paired cameras were set up with the intent to perform image acquisition, image rectification and make a disparity map. In order to perform this the cameras were set at a 16cm baseline with the goal of creating a camera calibration to create an accurate depth map via image rectification and disparity mapping. The calibration was performed using a checkerboard print out with 25mm squares. The checkerboard was placed in different areas of the scene and stereo images were captured as can be seen in the figure below.

Figure 9A.1: Stereo images used to complete camera system calibration in MATLAB

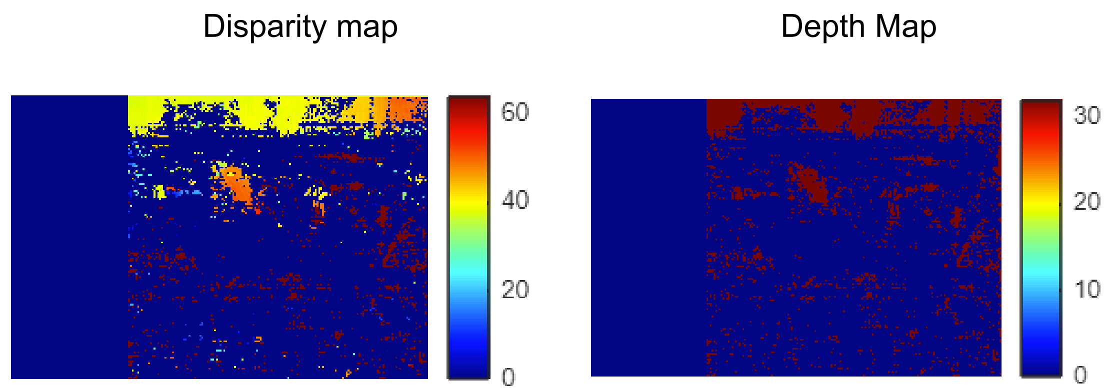
Using the stereo image pairs the MATLAB Stereo Camera Calibration App was used to create a .mat file which contains all of the necessary data required to perform image rectification and disparity mapping for the necessary image processing. The MATLAB Stereo Camera Calibration App was able to create an accurate 3D representation of the position of the checkerboard in all of the stereo image pairs and the baseline distance between the cameras as seen in the figure below.

Figure 9A.2: Camera system calibration in MATLAB noting accurate position of checkerboard and baseline distance between cameras



Using the testing camera setup and the calibration parameters test images were captured to determine the systems ability to accurately rectify the images and create a usable disparity map. As we can see in the following figure, stereo images captured were used to create a rectified pair and subsequent disparity map with the intent to use the disparity map and characteristics of the camera system to create a depth map.

Figure 9A.3: Disparity map and depth map of acquired images



Chapter 10 Administrative Content

Budgeting and Financial

Project to be sponsored and funded through SouthCom. Costs are estimates of key components of the project however additional items are likely to be added due to the custom nature of the mechanical and optical systems of this project.

Component	Name	Unit Cost	Quantity	Total
Radar System				
Radar	Raymarine Cyclone 6ft Open Array Radar Pack	$6699.99 (sponsor)	1	$6699.99
Radar software	Raymarine Software Dev Kit	$300 (sponsor)	1	$300
Data transmission	Starlink Mini Terminal	$450 (sponsor)	1	$450
Laptop PC	Provided by sponsor	$600 (sponsor)	1	$600
Computer	Intel NUC	$350 (sponsor)	1	$350

Portable power supply	Westinghouse portable power supply	$130 (sponsor)	1	$130
Mechanical System				
NEMA 17 Stepper Motor	HT17-268 NEMA 17 High Torque Stepper Motor	$48 + $20 shipping	1	$78
Motor Driver	STR 2 Motor Driver	$103 + $20 shipping	1	$123
Microcontroller	Raspberry Pi	$35	1	$35
Radar Housing	Custom	$200	1	$200
Encoder	Accu-coder 755A Size 15	$300	1	$300

GROUP 3 PROJECT MILESTONES FOR SD1 AND SD2

Senior Design 1 Project Milestones

TASK	START DATE	END DATE	DURATION
Project Brainstorming	1/6	1/10	1 Week
Sponsor Meeting	1/22	1/22	0 Weeks
Divide and Conquer Report	1/10	1/24	2 Weeks
Divide and Conquer Group Meeting	1/29	1/29	0 Weeks
Research Project Specifications	1/10	2/16	5 Weeks
Start System Design	2/17	4/15	8 Weeks
Midterm Report	1/10	4/4	13 Weeks
Midterm Report Group Meeting	4/7	4/9	0 Weeks
Finish System Design	2/17	4/15	8 Weeks

TASK	START DATE	END DATE	DURATION
SD1 Final Report & Mini Demo Video	4/22	4/22	0 Weeks

Senior Design 2 Project Milestones

TASK	START DATE	END DATE	DURATION
Update 90 Page Report	5/12	5/26	2 Weeks
Begin System Assembly	5/12	7/14	9 Weeks
Test and Fix Prototype	6/2	6/9	1 Week
Optimize Prototype	6/9	6/30	3 Weeks
Complete Prototype	6/30	6/30	0 Weeks
Presentation Practice	6/30	7/13	2 Weeks
Final Presentation	7/14	7/14	0 Weeks

11. Project Challenges and Proposed Solutions

Throughout the development of the Mini-AWACS senior design project, our team has run into a few critical challenges that we were unaware of going into this sponsored project. The issues that we have found emerged as we were trying to get our radar up and running, leading to a lengthy technical discussion with a Raymarine expert who confirmed that, because of the hardware chosen to complete this project and its limitations, our current implementation of this project would be physically impossible. This section will go over the challenges we are facing in this project, how it may affect our project trajectory, and the proposed solutions for each challenge that we are considering moving forward.

11.1 Radar Hardware Limitations

Our original design was based on the integration of the Raymarine Cyclone 6’ Radar paired with Starlink to distribute the data collected from the radar. The goal was to receive real time radar data and send it out to the multiple UAS through the use of Starlink. However, we recently learned that the way we intended to complete this project was not achievable due to the nature of the Raymarine Cyclone 6’ Radar.

According to a Raymarine radar specialist, who consulted with three of their most experienced engineers, it was confirmed that the Raymarine Cyclone 6’ Radar could not be repurposed as we initially intended to do. We also intended to recode the radar, which we were told was also not feasible. The implications of our recent findings are very significant. Without the ability to repurpose our radar, it becomes effectively unusable for our project.

11.2 Stopping Radar Rotation

Another major technical issue that was a core design of our project was that we were intending to modify the radars motion. Our intent was to change the radar from its original spinning motion and transform it into a sweeping radar motion instead. Unfortunately, the Raymarine specialist and engineers explained to us that the radar's rotation is imperative to its functionality. The radar transmits and receives in synchronization with its rotation. When the radar spins, it alternates between receiving signals and sending signals in its cycle. If we stop the radar from rotating, the radar will no longer be able to properly emit or detect signals.

11.3 Proposed Solution - Simrad Halo 24

After explaining to us all the findings, the Raymarine specialist strongly recommended that we switch to the Simrad Halo 24 Dome Radar, as it would be a better fit for our project and would allow us to complete the project, without trying to repurpose the radar itself. He explained to us that this radar appears to be the only viable solution if we were to keep this project's goals the same. To facilitate the integration of the new radar, he proposed that we speak directly to the group at Embry Riddle and get the dimensions of the bottom of the cessna they currently have that we plan on mounting the radar to. Then fabricate a fiberglass custom pod installed to the bottom of the Cessna that would allow the radar to be mounted right side up, tilted downward, so that it can scan the airspace below and in front of the Cessna.

11.4 Conclusion

Although our senior design project has faced some serious setbacks, the challenges our group has encountered so far have furthered our knowledge and understanding of radar systems that play a huge part in our project. The proposed switch to the Simrad Halo 24 Dome Radar has offered us a plan that would be feasible for our design and constraints. The issues we ran into were: an incompatible radar, the radar requiring a spinning motion, and loss of time to complete our project. However, with the help of the raymarine specialist and our sponsor we are able to look past these issues and get back on track with the new radar. Our last hurdle is getting our sponsor to approve the changes and purchase the new radar system.

Member Contributions

All subsection "A"s are done by Leonard, our photonics project manager.
Chapter 3 on Research and development was written by Phillip Jones up to the Accu-coder 755A which along with the rest was written by Ido Yaari

Chapter 4 on Standards and Constraints was written by Phillip Jones
Chapter 5 on LLM comparison was written by Ido Yaari and Leonard Mitchell
Chapter 6 on Hardware Design was written by Phillip Jones
Chapter 7 on Software Design was written by Ido Yaari
Chapter 10 was contributed to by all members of the project
Optoelectronics Feasibility was contributed by Leonard Mitchell

APPENDIX A:

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