Conceptual Design Document

RAPTR

Rapid Aerial Photographic Target Recognition

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Department of Aerospace Engineering Sciences
ASEN 4018

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1. Information

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2. Project Description

Personnel who deal with active problems, such as wildfires or enemies in a combat scenario, currently have limited means of rapidly gathering real time intelligence of zones of interest. The purpose of this project is to design, manufacture, and test a portable, user-deployable system that can image and identify ground targets of interest and provide real time threat location and classification of said targets to a ground station within three minutes of initial system deployment. The system will consist of three components: a vehicle system, a payload, and a ground station. The vehicle system shall deliver the imaging system payload to an altitude of 400 feet, while maintaining complete functionality of the payload. The imaging system must capture, compress, and downlink overlapping ground images at this altitude. The ground station will receive and process the data sent by the payload in order to identify the target and notify the user of stationary targets as small as 5'x5'x5' in size and located at least 2,000 foot laterally from the user. An interdisciplinary team made up of electrical and aerospace engineering students shall collaborate to design and build these systems; the electrical engineering team will specialize on the payload while the aerospace team will focus on the vehicle system. The ground system hardware will be designed by the electrical team, and the software will be jointly developed between the aerospace and electrical teams. Successfully developing this entire system will provide users with a quicker, safer, and more cost-efficient means of attaining real time intelligence of zones of interest.

2.1. Concept of Operations

The mission concept of operations is shown in Fig. 2.1. Once the target's presence is known, the user will set up and deploy the aerial vehicle. The vehicle will then climb to a cruising altitude of 400 feet and fly over the stationary 5'x5'x5' target. The vehicle's imaging payload will then take overlapping images of the area, and then compress said images. The compressed images, along with vehicle telemetry and payload pointing data, will be transmitted via a TBD ISM-band frequency to the ground station. Following payload transmission, the vehicle's mission will end, and it will proceed to land, independent of the remaining elements of the mission. The ground station, having received the transmission from a nominal range of 2000 feet in lateral distance and 400 feet in vertical distance, will decompress the data. The ground station will then utilize an image processing algorithm to identify the target in the images and associate the image and target location to the physical location of the target based off of the telemetry data. Using a user interface integrated into the ground station, the ground station will output target identification and location information to the user.

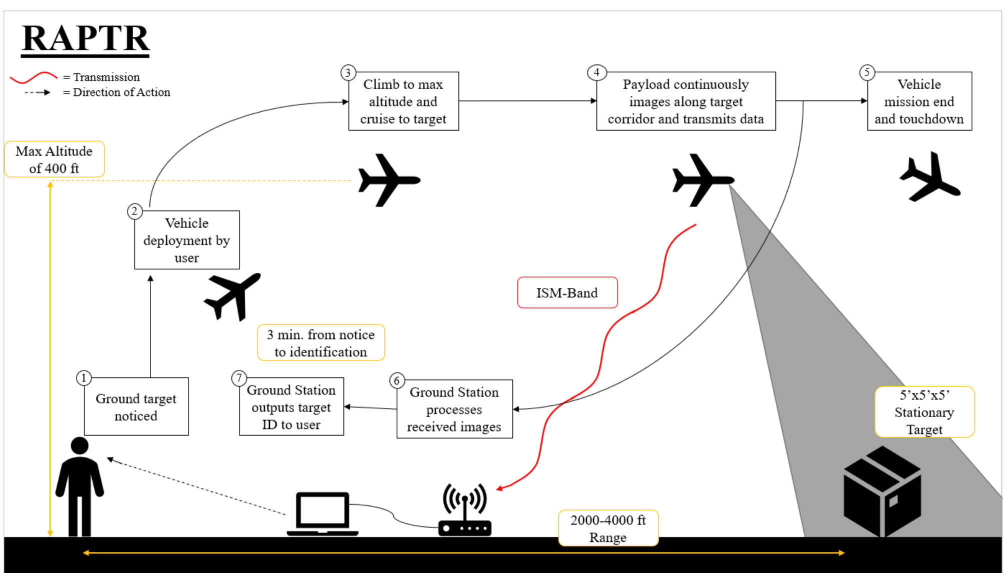

Figure 2.1. RAPTR CONOPs Diagram

2.2. Functional Block Diagram

RAPTR's Functional Block Diagram may be viewed in Fig. 2.2. RAPTR is composed of three primary components: the payload, the vehicle, and the ground station. The payload contains the imaging system, compression functionality, and the antenna for transmitting data back to the ground station. This component will be designed and tested by the electrical engineering team, with joint full system testing. The vehicle component, primarily designed by the aerospace engineering team, will include power, propulsion, ADCS/GNC sensors and controls. It will exchange telemetry data and power with the payload. Dependent on the vehicle solution, the vehicle will also feature RC functionality, in the event that any autopilot software does not perform nominally. The ground station component, developed jointly by both teams, contains a receiver antenna, power source, processing unit, and user interface for outputting target analysis to the user.

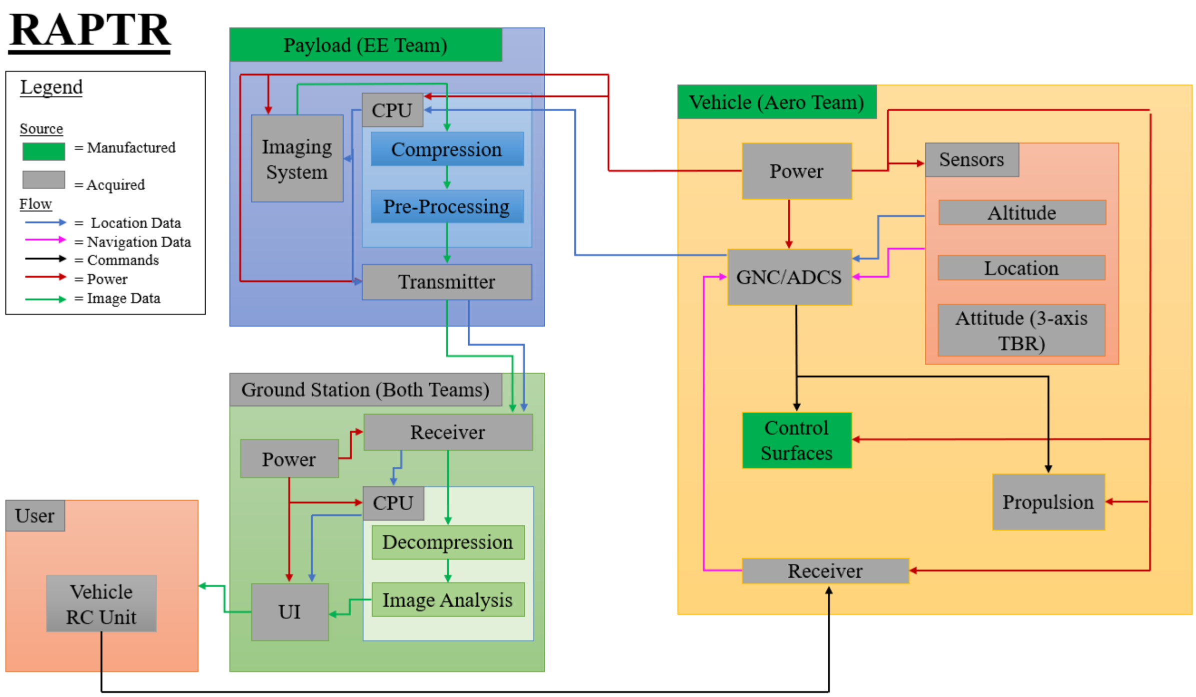

Figure 2.2. RAPTR Functional Block Diagram

2.3. Requirements Flow Down

The following functional requirements in Table 2.1 were established based on their necessity to properly fulfill the problem statement and concept of operations. These requirements are high-level, and each correlate to the proper function of a key aspect of the operation of RAPTR as a whole. To validate that each functional requirement is met, a set of lower-level derived requirements were constructed that must all be fulfilled for each functional requirement. These derived requirements may all be verified independently, and are designed to narrow down potential design solutions to a few feasible options. The derived requirements also feature lower level child requirements. These children requirements are generally non-essential to the fulfillment of the parent derived requirements nor the functional requirements, yet offer goals to work towards.

Requirement	Description	Validation
1	The system shall utilize image processing to detect a 5'x5'x5' stationary ground target that is 2000 feet downrange from the user and from an altitude of 400 feet.	Met if all derived requirements are met (Table 2.2)
2	The system shall be man portable and deployable on up to a 10 percent grade.	Show that launch mount can be set up on 10 percent grade (Testing)
3	The system shall transmit images to a ground station.	Payload and ground station testing
4	The system shall identify a distinctly colored target and determine the unique target shape and relay the target's latitude and longitude.	Ground station testing
5	The system shall complete its mission (deployment to processed images) within 3 minutes.	Timed functional test
6	The system shall comply with all federal and state laws regarding testing and functionality of the system.	Met if all derived requirements are met (Table 2.7)

Table 2.1. Functional Requirements

The first functional requirement necessitates that RAPTR be able to generate images from a certain altitude and distance from the user, which can be used to derive requirements for the imaging system listed in Table 2.2. The imaging resolution requirements are based on the Johnson Criteria for target detection, recognition, and identification, while the field of view and launch requirements are based on the imaging system size and capability. Detection is simply being able to tell that an object is there, recognition is being able to classify the kind of object (car, person, tank, etc.), and identification is being able to pinpoint more details about the target within its type (e.g. a sedan, the type of tank, a soldier).

Functional Requirement 1: The system shall utilize image processing to detect a 5'x5'x5' stationary ground target that is 2000 feet downrange from the user and from an altitude of 400 feet.		
Derived Requirement	**Description**	**Verification & Validation**
1.1	The vehicle shall be capable of imaging the target if launched within ±7.5° of the target relative to the user for a constant vehicle ground path	Flight tests of the integrated system shall be to verify vehicle trajectory. A quadcopter shall take test images on ±7.5° path to verify imaging
1.1.1	The imaging system shall be able to capture images at 0.1282 ft/pixel resolution with a max horizontal field of view of 540 ft and max vertical field of view of 400 ft	Computations on pixel resolution and field of view shall be done by taking images from the ground and measuring relevant parameters from the image.
1.2	The imaging system shall be able to resolve the target into 7 distinct pixels along each dimension for target detection	Computations on pixel resolution be done upon camera finalization. Tests using the camera on a quadcopter shall also be performed where the number of pixels on target are counted
1.3	The imaging system shall be able to resolve the target into 25 distinct pixels along each dimension for target recognition	See 1.2
1.4	The imaging system shall be able to resolve the target into 39 distinct pixels along each dimension for target identification	See 1.2

Table 2.2. Derived Requirements From Functional Requirement 1

The second functional requirement and it's derived requirements shown in Table 2.3 necessitate that RAPTR shall have a deployment method that is capable of launching the vehicle to the altitude and distance dictated in Functional Requirement 1. This functional requirement and it's derived requirements indicate the deployment method shall be able to accommodate changes in grade of terrain and be launch-able from varying terrain.

Functional Requirement 2: The system shall be man portable and deployable on up to a 10 percent grade.		
Derived Requirement	**Description**	**Verification & Validation**
2.1	The deployment system shall collapse to a fit within a 4'x2'x2' envelope and weigh no more than 10 pounds.	The deployment system shall provide a measurements and a demonstration to prove it fits within the size and weight requirements and can easily be carried by the user.
2.2	The system shall be able to accommodate changes in grade from level ground to a 10% grade in 1% grade increments.	The deployment system shall be tested in 1% grade increments to prove it is capable of launching the vehicle at a variety of angles.
2.3	The deployment system shall be able to launch from the following terrains: sandy, rocky, grassy.	The deployment capabilities will be tested on ground covered with one inch of sand, on solid rock ground, and on ground covered in grass.

Table 2.3. Derived Requirements From Functional Requirement 2

The third functional requirement and it's derived requirements shown in Table 2.4 necessitate that RAPTR can successfully transmit imaging data to the ground station during its mission. This RF communication between the payload and ground station must be done over a specific frequency channel and at a specified range. In order to achieve this range, the antenna must have an appropriate gain and transmission power. Values were determined assuming that the antenna will have a cable loss, approximately 3 dB. These requirements can be tested on the ground before being integrated into the vehicle.

Functional Requirement 3: The system shall transmit images to a ground station.		
Derived Requirement	**Description**	**Verification & Validation**
3.1	The system shall down-link data to the ground station over the ISM band frequency of 2.4 GHz	The transmitter frequency shall be tested and validated during ground tests
3.2	The system shall transmit data at least 2,100ft to the ground station	Test data will be transmitted across varying ranges to a receiver during ground tests
3.2.1	Transmitting antenna will have a gain of at least 10dB (TBR)	Ground test verification
3.2.2	Transmitting power will be at least 20 dBm (TBR)	Ground test verification
3.3	The vehicle system shall be radio transparent allowing for radio transmission of imaging data	If 3.3.1 is satisfied
3.3.1	No material on the vehicle shall inhibit the operation of the antenna	Ground tests of integrated vehicle and transmitter
3.4	The system shall down-link data to the ground station at a data rate of 2 mbps (TBR)	Ground tests of data rate

Table 2.4. Derived Requirements From Functional Requirement 3

The fourth functional requirement necessitates greater detail on target types, color schemes, and shapes for image detection purposes. These classifications are specified in Table 2.5 such that the image recognition software has a rough road map for its functionality.

Functional Requirement 4: The system shall identify a distinctly colored target and determine the unique target shape and relay the target's latitude and longitude.		
Derived Requirement	**Description**	**Verification & Validation**
4.1	The ground station shall correctly output the images value as ”target” or ”no target”	Feeding test images with targets into the ground station processing during a ground test to determine functionality and correct output
4.1.1	The algorithm shall output the status of the image to the user	See 4.1
4.2	The ground station shall output the location of the target relative to the ground station/user	Take images using a quadcopter of a target with a known location, then compare location computation to known value
4.2.1	The vehicle/payload shall use a sensor suite to quantify its location	Verify functionality of all location sensors during ground test
4.2.2	The vehicle shall collect payload look angle as telemetry	Test using different payload look angles on ground and compare to physical measurements
4.2.3	The ground station shall compute coordinates of center of the image within 150 ft TBR	See 4.2
4.3	The system shall be able to assign a classification to targets	See 4.1
4.3.2	The image processing algorithm must be able to identify target characteristics	See 4.1
4.3.2.1	The algorithm shall sort targets into bins associated with target classifications	See 4.1
4.3.3	The algorithm shall list characteristics associated with targets, such as shape	See 4.1

Table 2.5. Derived Requirements From Functional Requirement 4

The fifth functional requirement acts as a main driver for many of the design choices made. This requirement sets up the time requirements for the deployment and flight profile for the vehicle. Subsequently, the derived requirements in table 2.6 are able to set speed limits and transmission ranges for the vehicle along with a rough time window for image processing.

Functional Requirement 5: The system shall complete its mission (storage to processed images) within 3 minutes.		
Derived Requirement	**Description**	**Verification & Validation**
5.1	The vehicle shall go from storage to launch within 60 seconds.	Configure vehicle from storage to launch configuration and time.
5.2	The vehicle shall take less than 20 seconds to travel 2000 ft laterally and 400 ft vertically.	Record how long it takes the vehicle to get on site.
5.2.1	The vehicle shall achieve a vertical speed of at least 20 ft/s.	Flight Dynamics models, simulations, and calculations from test flight telemetry data.
5.2.2	The vehicle shall achieve a horizontal speed of at least 100 ft/s.	Flight Dynamics models, simulations, and calculations from test flight telemetry data.
5.3	The payload shall transmit steady stream of images until 4000 ft ground distance is reached.	Ground testing of image transmission from stationary source at 4000 ft and flight testing.
5.3.1	The vehicle shall be built to exhibit negligible electromagnetic interference.	Check material properties and test loss between antennas when material is placed between.
5.4	The ground station shall receive and process an image within 90 seconds of capture.	Record time for an image sent from a stationary source 4000ft away to be processed.

Table 2.6. Derived Requirements From Functional Requirement 5

Functional Requirement 6: The system shall comply with all federal and state laws regarding testing and functionality of the system.		
Derived Requirement	**Description**	**Verification & Validation**
6.1	Vehicle must comply with 14 CFR part 107.	
6.1.1	The vehicle must weigh less than 55 pounds.	Weigh Vehicle
6.1.2	The vehicle must be registered as a ”Small UAS” with the FAA.	FAA receipt of registration
6.2	Obtain a waiver for high altitude/ high speed testing	FAA receipt
6.2.1	Submit application for waiver more than 90 days in advance of test	
6.3	Obtain a Remote Pilot Certification	Certification and Receipts
6.3.1	Have a part 61 pilot certificate holder complete the ”Part 107 small Unmanned Aircraft Systems (sUAS) ALC-451” online training course	
6.3.2	Complete FAA Form 8710-13 (FAA Airman Certificate and/or Rating Application for a remote pilot certificate)	
6.3.2.1	have a CFI authenticate Remote Pilot appilcant’s identity and sign off on Form 8710-13	
6.4	The vehicle shall remain controlled until landing.	Controlled Landing Test

Table 2.7. Derived Requirements From Functional Requirement 6

3. Key Design Options Considered

3.1. Vehicle Design

The vehicle must be capable of carrying the payload 2000 feet laterally, 400 feet vertically, and position itself such that the payload will be able to image the intended target area. This requirement is outlined in more detail in **DR 1.1**, **DR 1.1.1**, and **DR 5.2**. To do this, the vehicle must provide enough lift to transport its own structure and the mass of the payload. The vehicle must also be compact and travel at a high velocity to fulfill **DR 2.1** and **FR 5**.The vehicle must comply with all Federal Aviation Administration rules and regulations as outlined in **FR 6**. After considering all of the requirements, the vehicle design has been narrowed down to four options. Those options are as follows:

- Rocket Powered Glider
- Electric Aircraft
- Traditional Rocket
- Quad-Copter

3.1.1. Rocket Powered Glider

The first vehicle design to consider is a rocket-assisted glider. This design integrates a nacelle with a solid rocket propulsive element with control surfaces such as wings, elevators, and a tail. The controls surfaces would be an integral part of this design to efficiently deliver a payload with enough stability to take quality images. A prototype design for a system such as this can be seen in Fig. 3.1, although for the purposes of RAPTR the concept would be considerably scaled down like the vehicle shown in Fig. 3.2 and Fig. **??**. This vehicle option would be provided thrust and lift with elements of rocket propulsion. This simplistic propulsive mechanism means the vehicle can be tested multiple times by simply adding more fuel to the propulsion system. The control surfaces would be designed, built, and tested to last multiple flights and would therefore be very durable. As the solid rocket fuel burns away the vehicle becomes lighter, allowing for increased glide distance.

Figure 3.1. USAF Rocket Powered Target Glider

Figure 3.2. Kit Rocket Glider, Isometric View

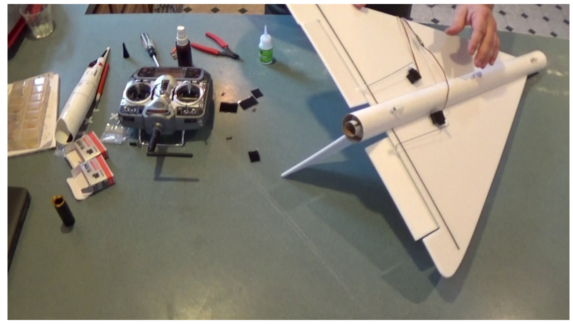

Figure 3.3. Kit Rocket Glider, Rear View

Description	Pro	Con
Solid Rocket Motors are relatively cheap, simple and durable	X	
Can be controlled by off the shelf hardware and software	X	
Can reach target area quickly while maintaining control	X	
No electrical power used to provide thrust	X	
Thrust mechanism can be easily jettisoned	X	
Increased regulations and flight rules when using rocket and UAV		X
Misuse of rocket motors can cause serious injury		X
Limited examples and previous work		X

Table 3.1. Pros and Cons of the Rocket Glider

3.1.2. Electric Aircraft

An electric aircraft is another possible vehicle design. An example of an electric aircraft is shown below in Fig. 3.4. As seen is this example, an electric motor is used to spin a prop which provides power for the aircraft. The prop and electric motor potentially create issues. Electric motors, and the batteries needed to power them, are relatively heavy. They would consequently reduce the payload capacity of the vehicle. However, electric aircraft are widely used. This means that there are many examples and references available, there are off the shelf hardware and software systems that can control the aircraft, and there are also off the shelf products that can be used to support the design of the aircraft. These design trade-offs are summarized in Table 3.2 below.

Figure 3.4. Example of an Electric Aircraft

Description	Pro	Con
Many examples and references	X	
Many off the shelf products available to support custom design	X	
Can be controlled by off the shelf hardware and software	X	
Electric motors and batteries required to power them are heavy		X
Props can be easily broken		X

Table 3.2. Pros and Cons of the Electric Aircraft

3.1.3. Traditional Rocket

A traditional rocket, like the ones shown in Fig. 3.5, provides a fast way to get a payload to altitude. The simplicity of a solid rocket motor also makes the rocket easy to transport and deploy. The traditional rocket design features small fins and control surfaces. This can cause issues with stabilization and control after launch. A traditional rocket is also designed to take a payload to a high altitude and not cover a great lateral distance. This may pose a problem in reaching the required lateral distance, particularly as the lateral distance is several times larger than the height ceiling. The characteristics of the traditional rocket vehicle are summarized below in Table 3.3.

Figure 3.5. Example of a Traditional Rocket

Description	Pro	Con
Easy to transport	X	
Easy to deploy	X	
Little control after launch		X
Hard to recover		X
Difficult to stabilize		X
Designed for vertical distance not horizontal distance		X

Table 3.3. Pros and Cons of the Traditional Rocket

3.1.4. Quad-Copter

The last design option to consider for the vehicle is a quad copter drone with a camera. (Figure 3.6) This option is one that is widely available to the average consumer today and is a popular off-the-shelf option for hobbyists. These cheap drones can be flown to low altitude and provide high quality video back to the user in almost real-time. A major drawback is that they can only generate a fraction of the lateral speed that a rocket or RC plane can. Also, they are extremely susceptible to high winds, and their stability relies entirely on the flight computer. This means that if the drone encounters too big of a disturbance it will lose stability and crash. Lastly, these drones are extremely fragile. If any of the four rotors take slightly too much damage, or are not fully operational, then the whole vehicle is essentially useless.

Figure 3.6. Example of COTS Quad-copter. (DJI Phantom 4)

Description	Pro	Con
Provides very stable platform for imaging	X	
Easy to deploy and recover	X	
High control after launch	X	
Very low maximum lateral velocity		X
Fragile elements make it difficult to transport		X
Susceptible to wind and other disturbances		X

Table 3.4. Pros and Cons of a quad-copter drone.

3.2. Payload Mounting

The integration of the payload into the vehicle must enable the payload to capture images of the target. This functionality is covered by **FR 1** and must specifically satisfy **DR 1.1**. Some form of pointing control must be present to assure that the payload can image the target; this will take the form of either vehicle attitude control, or a dynamic payload fixture. The three alternatives are as follows:

- Internal Nose with Aperture
- External Gimballed Dome
- Deployable Payload

3.2.1. Internal Nose with Aperture

This option is the simplest of the three. Figure 3.7 shows a diagram of the integration. The camera is fixed to the body of the vehicle and located in the nose cone. An aperture is present on the underside of the cone to allow the camera to image directly below the vehicle. In this alternative, the attitude control of the vehicle must be used to enable pointing. This pointing would be largely limited to rotations about the body x-axis with vehicle roll as pitch or yaw would alter the flight path too dramatically. The advantages and disadvantages to this alternative are detailed in Table 3.5.

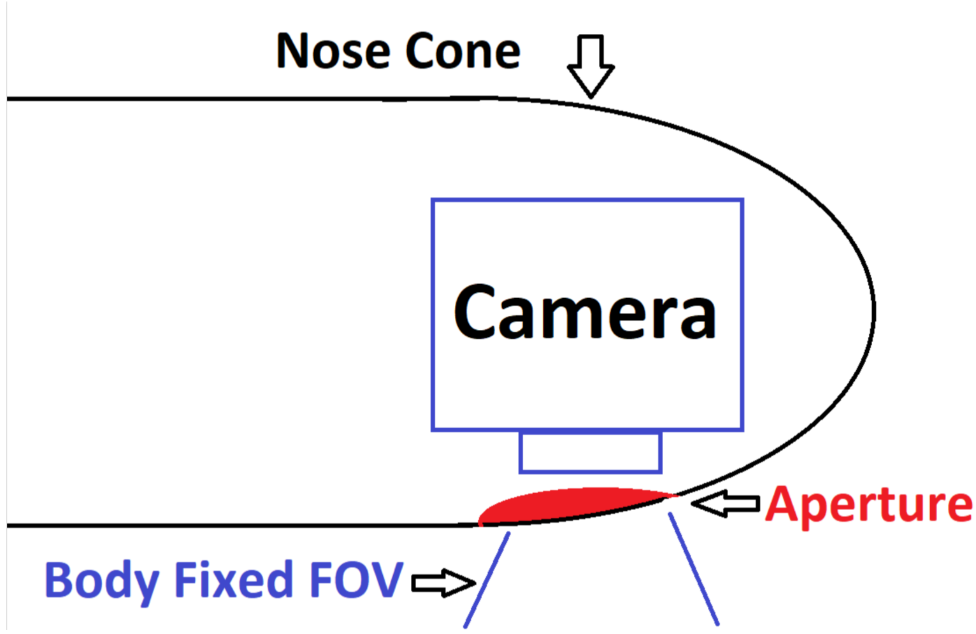

Figure 3.7. Diagram of body fixed nose aperture

Description	Pro	Con
No moving parts/ Simple to manufacture	X	
Pointing Location Easy to Quantify	X	
Limited (Body X) Pointing Rotations		X
Pointing requires Vehicle Attitude Changes		X

Table 3.5. Pros and Cons of the Internal Nose with Aperture

3.2.2. External Gimbaled Dome

The next alternative is to mount the camera externally in a rotating dome. A diagram of this setup is shown in Fig. 3.8. The camera is mounted within the dome on an actuated mount such that it can rotate up or down to change its looking azimuth. A rectangular window is placed along the dome to allow the camera to see all along its look range. This window is shaded in red in Fig. 3.8. The dome holding the camera is also free to rotate about the body z-axis of the vehicle. This rotation axis is shown as a dashed purple line in the diagram. With this combination of pointing control the camera could be pointed at any point on the ground visible from the vehicle's location. The vehicle would not need to adjust its attitude and also not need to fly directly over the target location. Achieving the greater pointing performance requires significant added complexity. The actuators for the two pointing directions must be controlled and quantifying the ground location of the image will require the two rotation angles to be reliably reported. The pros and cons of this alternative are detailed in Table 3.6.

Description	Pro	Con
Essentially Unlimited Pointing Rotations	X	
Required Vehicle Trajectory less Precise	X	
Added Control Complexity and Weight		X
Requires Rotation Angles to be Reported		X

Table 3.6. Pros and Cons of the External Gimbaled Dome

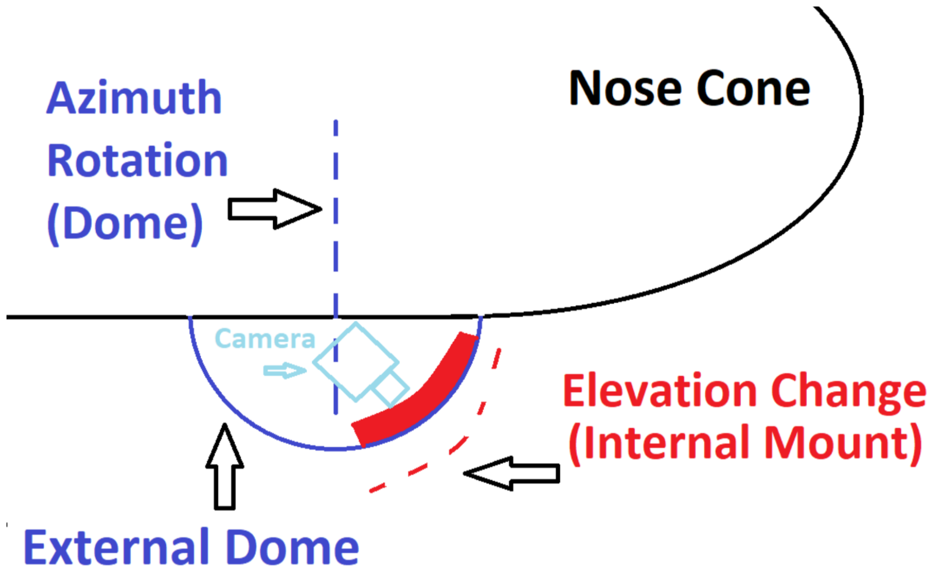

Figure 3.8. Diagram of External Gimbaled Dome

3.2.3. Deployable Payload

The final alternative is a deployable payload equipped with a parachute. For this setup, the payload is ejected from the vehicle once over the target zone. The camera is equipped with a wide field of view lens to allow room for error if the payload is not directly over the target. Images are captured and transmitted during the parachute descent. This is detailed in Fig. 3.9. This method requires stricter accuracy from the vehicle to assure that the payload is descending near the target. The system will also have to decide when to eject the payload with additional software and sensor considerations.

Allowing the camera to descend over the target area will allow for the target to be imaged in higher resolution, which will aid target recognition. Another key effect of this alternative is the decoupling of the vehicle requirements and the payload requirements. Under this method, the vehicle could be entirely validated without a functioning payload. The pros and cons of this alternative are summarized in Table 3.7.

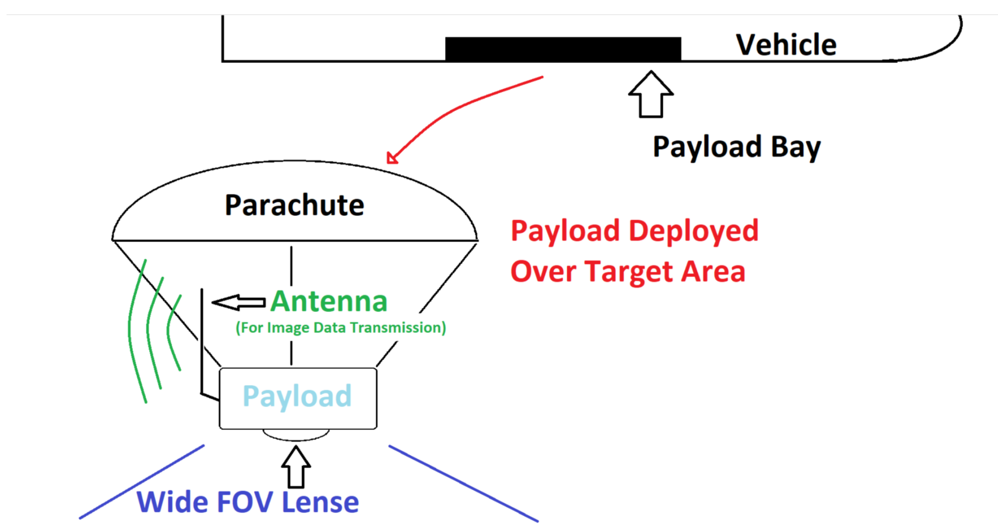

Figure 3.9. Diagram of Deployable Payload

Description	Pro	Con
Vehicle and Payload Functionality/System Decoupling	X	
Closer Images of Target	X	
Highly Dependant on Vehicle Trajectory		X
Vehicle/Payload must decide when to eject		X
Requires Redundant Power/Sensors/Comms for Payload and Vehicle		X

Table 3.7. Pros and Cons of the Deployable Payload

3.3. Landing Method

Once the vehicle and imaging systems have reached the correct altitude, captured images, and transmitted them back to the ground station, the vehicle will then need to land. This landing procedure must be controlled as required by **FR 6** and, more specifically, **DR 6.4**. Other factors that will be important when designing a landing method will be the cost, weight, and complexity. The cost is of importance due to the strict budget of this project. Providing a cheaper means of gaining imagery intelligence is also a large part of the problem statement which motivated this project to begin with. Having a landing method which adds little weight to the vehicle will allow the vehicle to reach higher altitudes faster with less thrust required from the engine. It could also allow for a heavier imaging system. The complexity of the landing method will be an important factor as well. Designing for a more complex method will require more time to implement successfully as well as increasing the risk for failure. Due to the strict time limitations on this project as well as the expensive hardware being included on the vehicle, it will be important that this method can be implemented rather quickly and with a low chance of failure. Four possible landing methods were considered for the design of this project;

- Deployable Parachute
- Soft Belly Landing
- Landing Gear
- Crash Landing

3.3.1. Deployable Parachute

A deployable parachute is one of the simplest methods for landing a UAV. Plenty of off the shelf options are available, including the Harrier Parachute Bundle shown below and sold by Fruity Chutes. Bundles like this are extremely easy to implement, they only need to be properly mounted on the vehicle, and the servo ejection channel needs to be connected to the flight controller. While this type of landing method does ensure that minimal to no damage occurs to the vehicle, it offers little to no control. Additionally, these deployable parachutes can be quite expensive and add weight to the vehicle.

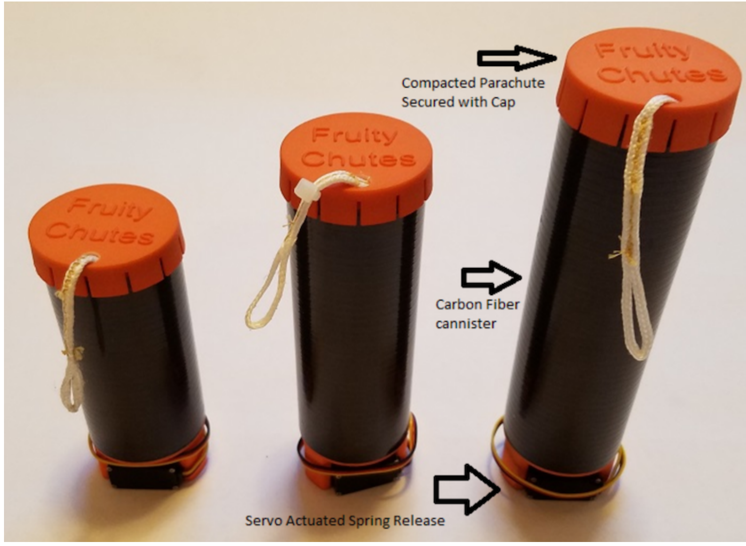

Figure 3.10. Diagram of deploy-able parachute

Description	Pro	Con
Protects vehicle/payload from damage	X	
Simple implementation	X	
Little to no control of landing		X
Can be expensive		X
Additional weight added to launch vehicle		X

Table 3.8. Pros and cons of deployable parachute

3.3.2. Soft Belly Landing

Many on board flight controllers include landing sequences. One option for landing the vehicle would be to utilize this function of the flight controller to softly touch down on its belly. Below is a diagram of the Pixhawk 4 flight controller which has available landing sequences for fixed wing aircraft. Although this would add some complexity to the project, it would add no additional weight and would provide significant control during landing. In addition, a flight controller will already be necessary for the success of this mission so taking advantage of it for landing would add little to no to additional costs to the project. One concern with this method would be the risk of damaging the on board electronics. If the terrain is particularly rocky, for example, the vehicle may tumble once contacting the ground and damage the hardware. It would therefore be important to add additional protection to the electronics, such as a small skid, if this method was chosen.

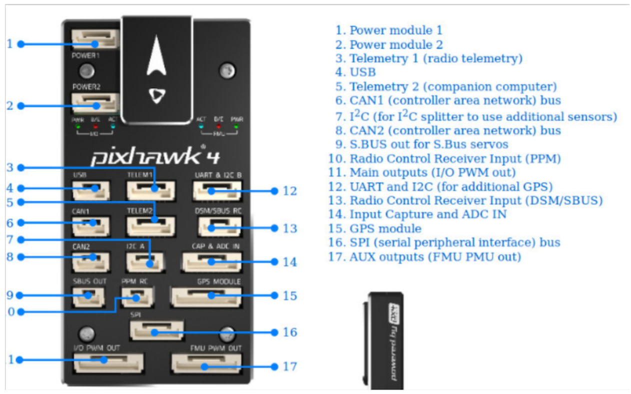

Figure 3.11. Diagram of Pixhawk 4

Description	Pro	Con
No additional weight added to launch vehicle	X	
Highly controlled landing	X	
No additional cost	X	
Risk of damage to electronics		X

Table 3.9. Pros and cons of belly landing

3.3.3. Landing Gear

Instead of a soft belly landing, the vehicle could also utilize a set of landing gears. Adding a landing gear to the vehicle would significantly help in protecting the electronics and adding control to the vehicle as it touches down. It would be capable of landing in a wider variety of terrain with less risk of failure. Unfortunately, the landing gear would add more weight and complexity to the vehicle. In addition, it would cost more money to implement this solution. Unless the gears were retractable, it would also affect the aerodynamic capabilities of the vehicle adding a significant amount of drag. Making the gears retractable, however, would complicate the landing method tremendously and add even more weight.

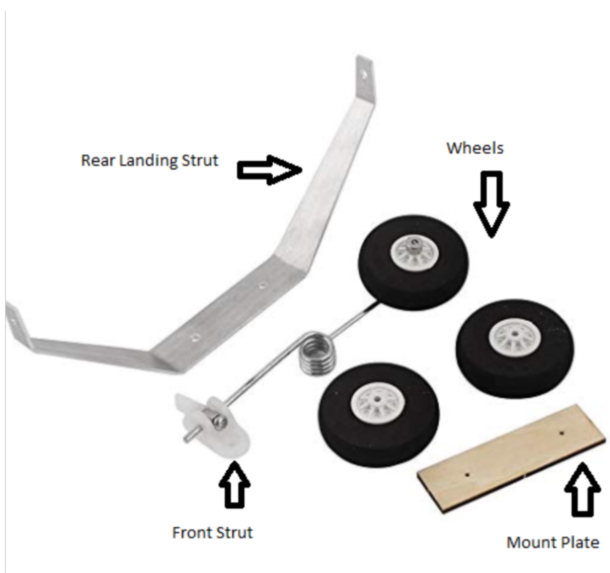

Figure 3.12. Diagram of landing gear parts

Description	Pro	Con
Ability to land in rugged terrain	X	
Highly controlled landing	X	
Added complexity		X
Additional cost		X
Additional weight added to launch vehicle		X

Table 3.10. Pros and cons of landing gear

3.3.4. Crash Landing

The simplest possible method of landing the vehicle would be an uncontrolled crash landing. This method has the benefit of being incredibly easy to implement; there would be no design needed for this option. Therefore the complexity and additional cost of this option is very favorable. In addition, this method would require no additional weight being added to the vehicle. A major concern, however, is in violating **DR 6.4**. It would be extremely dangerous to test a vehicle which loses all control upon landing. Additionally, the FAA requires that UAVs maintain control throughout the entire duration of their flight. Landing in this manner would also certainly destroy all on-board electronics no matter what type of terrain it is being landed in.

Description	Pro	Con
No additional weight added to vehicle	X	
No added complexity	X	
No additional cost	X	
Certain destruction of electronics		X
No control of landing		X

Table 3.11. Pros and cons of crash landing

3.4. Deployment Method

The deployment method must be portable by one person of average strength and size and deployable in rugged and uneven terrain, up to a a ten percent grade. This requirement is outlined in more detail in **FR 2**, **DR 2.1**, **DR 2.2**, and **DR 2.3**. The deployment system, in addition to being lightweight, must be small enough in size to be carried while carrying other gear - such as a backpack. After considering all of these requirements, the deployment method has been narrowed the following possibilities.

- Hand Thrown
- Single Fixed Rod
- Single Variable Rod
- Variable Rails with Hydraulic Launch Initiation

3.4.1. Hand Thrown

This design concept utilizes the user of the RAPTR system to launch the vehicle. This method would be designed for someone of average height and build in the United States to use. There are no design elements of this design concept as the entire method relies on the person throwing the vehicle. The user would initialize all internal elements of the vehicle, pick up the vehicle, and throw the vehicle in the general direction the user would like to investigate. At that point, the vehicle has achieved some momentum from the user throwing it and an internal accelerometer would initiate a process to commence the powered propulsive phase of the mission.

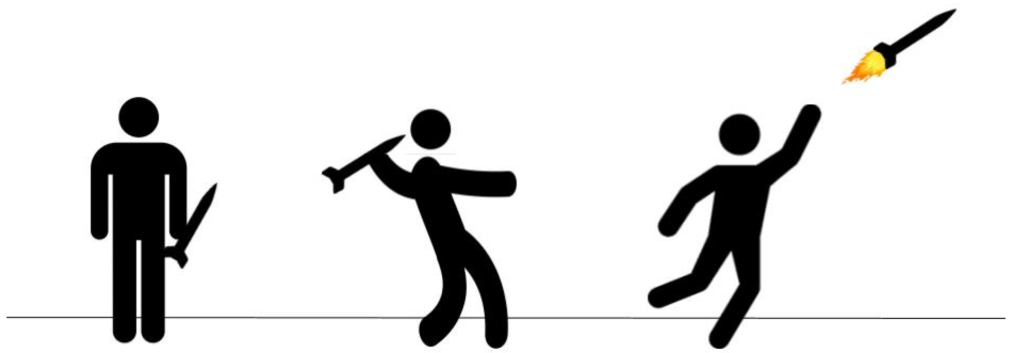

Figure 3.13. Hand Thrown Deployment Method

Description	Pro	Con
No equipment required besides a person's arm and throwing capability - weight and additional cost are zero	X	
Ability to deploy the vehicle on any terrain without concern for grade or ground composition	X	
Initial direction is dictated by the thrower, which is less exact then GPS coordinates		X
Inability to calculate and recreate a throw		X
Reliability of the person throwing the vehicle exponentially increases possibility of human error		X
The possibility of a faulty main engine start could result in more work for the thrower to retrieve the vehicle if the main engine starts late and could cause serious injury to the thrower if the main engine starts prematurely		X

Table 3.12. Pros and Cons of Hand Thrown Deployability.

3.4.2. Single Fixed Rod

This design concept would utilize a fixed rod and platform attached to stable legs as the base for the deployment method. No additional impulse would be provided to the vehicle outside of it's own propulsive element. This deployment system would utilize both a launch pad and the internal propulsive system of the vehicle. The vehicle would be attached to the fixed rod upright, as seen in Figure 3.14. All internal elements of the vehicle and payload would then be initialized by the user. At this point the user would ignite the propulsive element, either through a connection to the brain of the vehicle, or manually at the base of the vehicle. An example of what this deployment concept might look like is shown in Figure 3.14.

Figure 3.14. Single Fixed Rod Deployment Method[11]

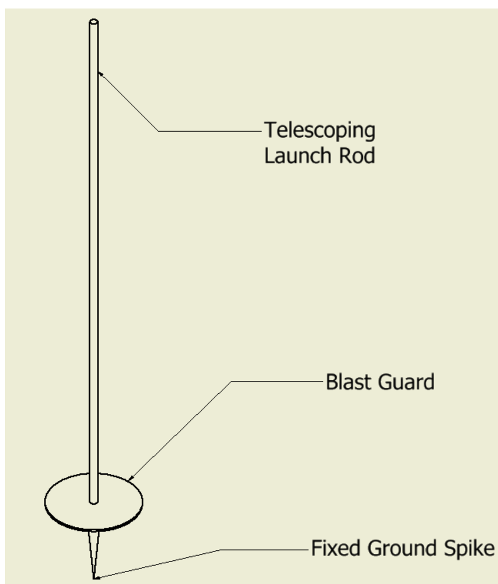

Figure 3.15. Drawing of Fixed Rod

Description	Pro	Con
Launch pad is stable and unlikely to be disrupted during launch	X	
Pad is structurally sound and reusable and therefore launches could be recreated to a high degree of accuracy if necessary	X	
Relatively inexpensive	X	
Launch pad is metal and therefore heavy		X
Incapable of adjusting to variable terrain		X

Table 3.13. Pros and Cons of Single Fixed Rod Deployability.

3.4.3. Single Variable Rod

This design concept would utilize a stable yet variable rod and platform attached to stable legs as the base for the deployment method. No additional impulse would be provided to the vehicle outside of it's own propulsive element. This deployment system would utilize both a launch pad and the internal propulsive system of the vehicle. The vehicle would be attached to the rod at whatever angle is desired by the user. An example photograph of one such angled installment can be seen in Fig. 3.17. All internal elements of the vehicle and payload would then be initialized by the user. At this point the user would ignite the propulsive element, either through a connection to the brain of the vehicle, or manually at the base of the vehicle. An example of what this deployment concept might look like is shown in Fig. 3.16.

Figure 3.16. Single Variable Rod Deployment Method[1]

Figure 3.17. Single Variable Rod Angled Deployment Method[9]

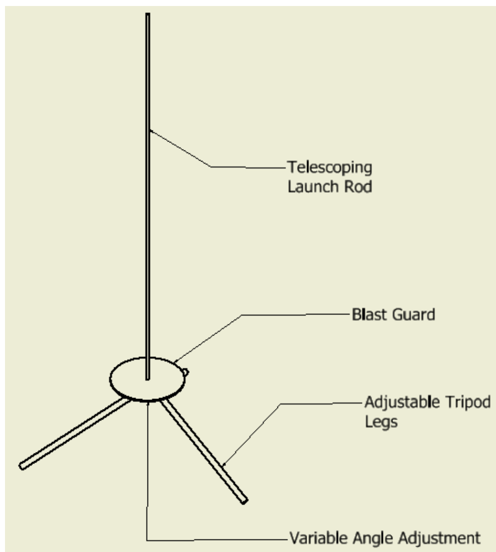

Figure 3.18. Drawing of Variable Launch Rod

Description	Pro	Con
Launch pad is stable and unlikely to be disrupted during launch	X	
Pad is structurally sound and reusable and therefore launches could be recreated to a high degree of accuracy if necessary	X	
Relatively inexpensive	X	
All mechanical elements are durable and do not depend on any electrical or hydraulic inputs, therefore reliability is high	X	
Mechanical elements are simple and probability of user error is low	X	
Capable of adjusting to variable terrain and incredibly sturdy for any rugged environments	X	
Variable launch angle allows for greater variability in possible range and altitude reached	X	
Launch pad is metal and therefore heavy		X

Table 3.14. Pros and Cons of Single Variable Rod Deployability.

3.4.4. Variable Rails with Hydraulic Launch Initiation

This design concept would utilize a variable rail design and platform attached to stable legs as the base for the deployment method. This design concept has the capability to introduce a secondary propulsive device, most likely hydraulic pistons, to provide extra impulse to the vehicle. This deployment system would utilize both a launch pad and the internal propulsive system of the vehicle. The vehicle would be attached to the rod at whatever angle is desired by the user. All internal elements of the vehicle and payload would then be initialized by the user. At this point, the user would initiate the hydraulic mechanism and then, after the vehicle has left the launch pad, ignite the propulsive element, using a built-in function dependent on an accelerometer readings within the nose of the vehicle. An example of what this deployment concept might look on a smaller scale like is shown in Figure 3.19.

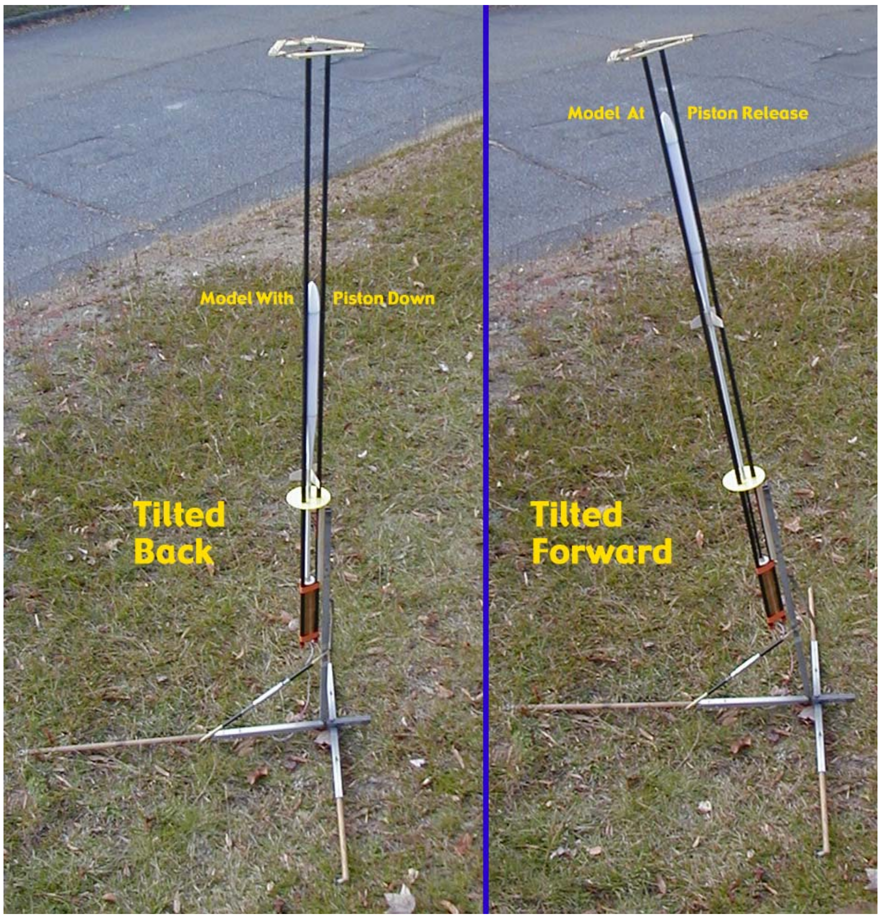

Figure 3.19. Variable Rail with Piston Deployment Method [14]

Description	Pro	Con
Stable launch pad base	X	
Multiple launch rails for vehicle to sit on increases stability during launch and the first phases of flight	X	
Increased cost with addition of hydraulic element		X
Inability to launch on extreme terrain		X
Complex launch system increases weight, cost, and likelihood of user error or device malfunction and decreases reliability		X
Rail system is not collapsible and will not fit into size constraint		X

Table 3.15. Pros and Cons of Hydraulic and Multiple Rail Deployability.

3.5. Sensor Suite

3.5.1. Attitude Determination Subsystem

If the vehicle is to maintain stable flight, then it is essential the vehicle has an attitude determination system capable knowing the vehicle's precise attitude for use by the autopilot. The attitude determination system must be able to detect any rotation about the vehicles X, Y, and Z axis (roll, pitch, and yaw)[7]. Without this, the autopilot would be unable to accurately roll, pitch, or yaw at a given rate. The attitude determination must be able to decipher its orientation relative to the Earth. If the autopilot did not have this attribute it would still be able to roll, pitch, and yaw, but these rotations must be relative to some fixed coordinate or the vehicle will inevitability crash into the ground. Given the vehicle's attitude determination can now rotate and avoid a crash landing, the final variable necessary for stable flight is a heading. This allows the vehicle to determine the immediate direction in which it is flying. Table 3.16 lists the four sensor suites capable of accomplishing all three attitude determination criteria.

Number	Attitude Subsystem
1	3-Axis Gyroscope, 3-Axis Accelerometer, and Magnetometer
2	3-Axis Gyroscope, 3-Axis Accelerometer, and GPS
3	3-Axis Gyroscope, 3-Axis Accelerometer, and Infrared
4	3-GPS

Table 3.16. Four possible sensor suites able to determine attitude.

3-AXIS GYROSCOPE, 3-AXIS ACCELEROMETER, AND MAGNETOMETER

The first possible attitude determination sensor suite incorporates one 3-axis gyroscope, one 3-axis accelerometer, and one magnetometer. The gyroscope provides data on the vehicles rotational speed about its own axises. This information may be interpreted by a PID controller and used to stabilize the vehicle during steady slight and maneuvers. The accelerometers are used to determine which direction is up, which direction is down, and what the current attitude is. The accelerometer does this by using the acceleration of gravity as a reference, but, because of this, the accelerometer may have trouble differentiating between the vehicle's acceleration and the Earth's acceleration. Finally, a magnetometer that controls the heading of the vehicle through magnetic interference may skew the magnetometer's readings. Figure 3.20 gives a graphical representation of the 3-axis gyroscope, 3-axis accelerometer, and magnetometer sensor subsystem and Table 3.17 lists various pros and cons of the subsystem.

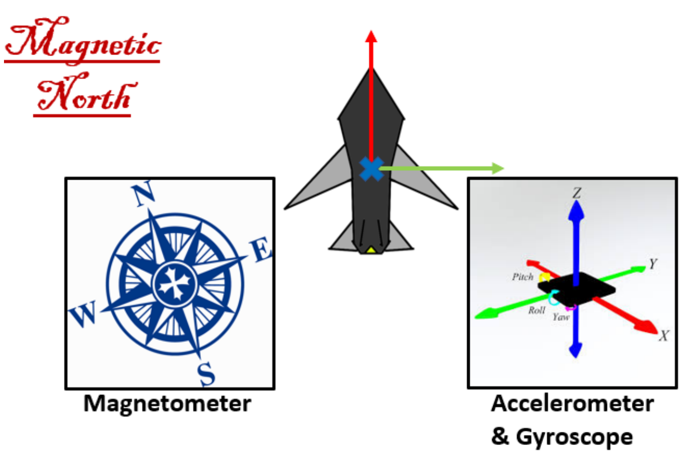

Figure 3.20. Diagram of 3-axis gyroscope, 3-axis accelerometer, and magnetometer sensor suite.

Description	Pro	Con
Provides rotational speed about roll, pitch, and yaw axis	X	
Can determine where is up, where is down, and current attitude	X	
Subject to magnetic field interference		X

Table 3.17. Pros and Cons of a 3-axis gyroscope, 3-axis accelerometer, and magnetometer attitude sensor suite.

3-Axis Gyroscope, 3-Axis Accelerometer, and GPS

The second possible attitude determination sensor suite utilizes a 3-axis gyroscope, 3-axis accelerometer, and GPS. The 3-axis gyroscope and 3-axis accelerometer function in the same method as the case above. Instead of using a magnetometer as a heading indicator, this method uses GPS. Though GPS only tracks position, GPS uses each past incremental position estimate to approximate the vehicles heading. Due to GPS's slow update rate, this method works best for stable, slow flight. Figure 3.21 depicts the 3-axis gyroscope, 3-axis accelerometer, and GPS sensor subsystem and Table 3.18 lists pros and cons of this sensor suite.

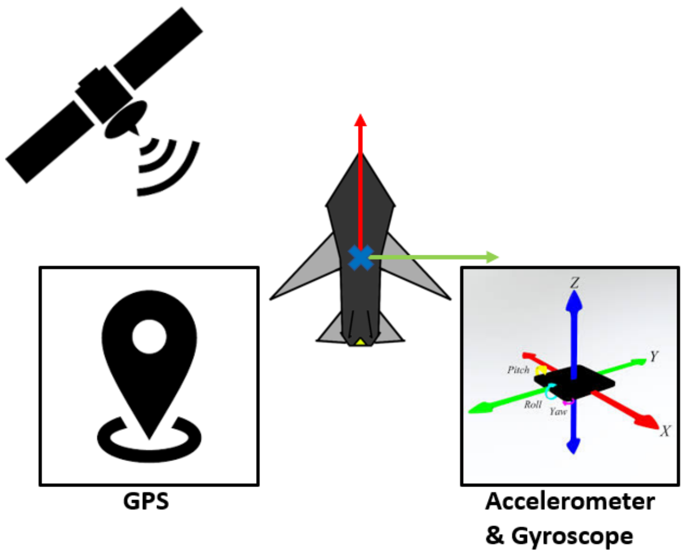

Figure 3.21. Diagram of 3-axis gyroscope, 3-axis accelerometer, and GPS sensor suite.

Description	Pro	Con
Provides rotational speed about roll, pitch, and yaw axis	X	
Can determine where is up, where is down, and current attitude	X	
GPS necessary for positional determination	X	
GPS has slow update rate		X
GPS subjected to short term heading errors		X

Table 3.18. Pros and Cons of the 3-axis gyroscope, 3-axis accelerometer, and GPS attitude sensor suite.

3-Axis Gyroscope, 3-Axis Accelerometer, and Infrared

The third possible attitude determination sensor suite implements a 3-axis gyroscope, 3-axis accelerometer, and an infrared horizon sensor. Again the 3-axis gyroscope and 3-axis accelerometer function in the same method as the previous two cases above. The infrared sensor functions by sensing a temperature difference between the Earth's surface and the sky[13]. Recently this method has become quite accurate and relatively inexpensive; however, any mountains, buildings, fires, haze, etc. will cause the infrared to produce faulty results. Figure 3.22 graphically presents the 3-axis gyroscope, 3-axis accelerometer, and infrared sensor subsystem and Table 3.19 lists pros and cons of the sensor suite.

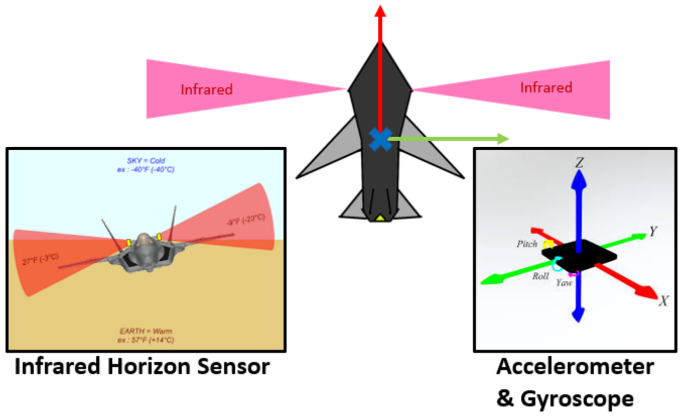

Figure 3.22. Diagram of 3-axis gyroscope, 3-axis accelerometer, and infrared sensor suite.

Description	Pro	Con
Provides rotational speed about roll, pitch, and yaw axis	X	
Can determine where is up, where is down, and current attitude	X	
Needs clear view of horizon		X
Environmental interference from haze, mountains, buildings, etc.		X

Table 3.19. Pros and Cons of the 3-axis gyroscope, 3-axis accelerometer, and infared horizon attitude sensor suite.

3-GPS

The fourth possible attitude determination sensor suite consists of three GPS units located at strategic locations on the vehicle. Thinking of the vehicle as a plane represented by three points, the orientation of a plane may be found if the position of all three points are known. GPS coordinates located at three different locations on the vehicle would, hypothetically, allow for the vehicle's orientation to be determined. This works with larger vehicles but due to the size of the vehicle used in this project the positional error in GPS signal exceeds the actual size of the vehicle. Figure 3.23 displays the 3-GPS sensor subsystem and Table 3.20 lists the pros and cons of the sensor suites.

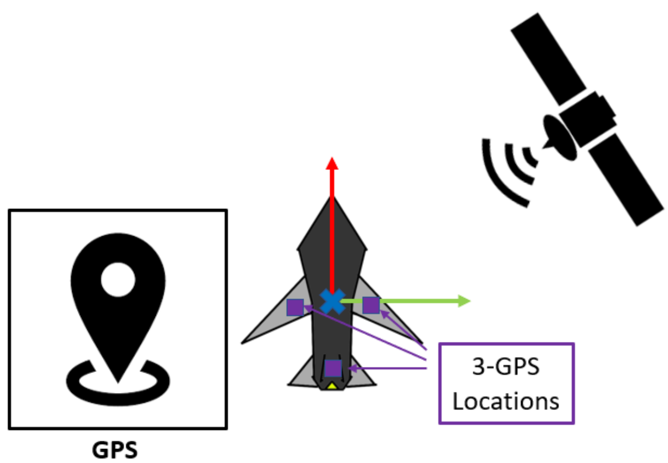

Figure 3.23. Diagram of 3-GPS sensor suite.

Description	Pro	Con
GPS necessary for positional determination	X	
Lack of accuracy for minute attitude adjustments		X
GPS has slow update rate		X
GPS subjected to short term heading errors		X

Table 3.20. Pros and Cons of the 3-GPS attitude sensor suite.

3.5.2. Position Determination

The attitude system alone is not enough to track the full trajectory of the vehicle. The vehicle's acceleration and rotation may be integrated; however, errors will creep into the mathematics over time. Since the purpose of this project is to precisely calculate the location of a target, this method is unacceptable. Instead GPS will be utilized to determine the position of the vehicle. This will significantly bound the positional error of the vehicle. GPS yields a particularly accurate lateral position; however, GPS's accuracy in the vertical direction is much more poor. Again the true position of the vehicle is very important to the end product so a trade study on vertical altitude sensors is necessary. Table 3.21 lists the three components this trade study is performed on.

Number	Method
1	Barometer
2	Sonar Proximity Sensor
3	Laser Proximity Sensor

Table 3.21.

Altimeter

The first method of determining the vertical altitude is an altimeter. An altimeter is the most common method used in drones. This is due to an altimeter's high level of accuracy relative to its cost (far cheaper than most alternatives). The accuracy of an altimeter is subject to the environment around it. An altimeter compares the sea level pressure to the pressure during flight to provide an altitude of the vehicle. Pressure fluctuations from inclement weather may cause these readings to be skewed. Table 3.22 lists the pros and cons of a barometer.

Description	Pro	Con
Only needs exposure to ambient pressure	X	
Cheap and easy to implement from COTS components	X	
Local sea level pressure must be known to determine AGL altitude		X
Prone to drift due to errors from reference pressure		X
Pressure varies with environmental changes such as wind		X

Table 3.22. Pros and Cons of the barometer sensor suite.

Sonar Proximity Sensor

The second method of calculating the altitude involves a sonar range finder located beneath the vehicle and pointing at the ground. The range finder emits a high frequency sound toward the ground which then bounces back and is received by the vehicle. The sonar proximity sensor measures the time taken to receive the signal and, since the speed of sound can be determined from temperature, is able to calculate the distance to the ground. Table 3.23 lists the pros and cons of the sonar proximity sensor suite.

Description	Pro	Con
Extremely accurate altitude reading	X	
Not affected by drift	X	
Range limited to several meters		X
Must be pointed toward the ground at all times		X
More complex than other COTS alternatives		X

Table 3.23. Pros and Cons of the sonar proximity sensor suite.

LASER PROXIMITY SENSOR

The third method of computing the altitude is by using a laser proximity sensor located beneath the vehicle and pointing at the ground. The laser proximity sensor projects a varying powered laser beam toward the ground which then bounces back and is received by the vehicle. The laser proximity sensor indirectly measures the time taken to receive the signal by observing the power frequency of the received beam and, since the speed of sound can be determined from temperature, is able to calculate the distance to the ground. Table 3.23 lists the pros and cons of the sonar proximity sensor suite.

Description	Pro	Con
Extremely accurate altitude reading	X	
Delivers speed of light altitude reading	X	
Must be pointed toward the surface at all times		X
More complex than other COTS alternatives		X

Table 3.24. Pros and Cons of the laser proximity sensor suite.

3.5.3. Autopilot Subsystem

One of the driving forces for the decision of what flight control board to choose for the RAPTR is what autopilot platforms it supports. For this project, only open source platforms are being considered mostly because closed source autopilots are thousands of dollars and an open source platform allows for more customization of the control system. The platforms being considered in this project (Table 3.25) are some of the more popular open source autopilot platforms because these will be the platforms that are compatible with the largest number of flight control boards.

Number	Autopilot Platform Options
1	Paparazzi
2	Ardupilot
3	PX4

Table 3.25. Four Potential Options for Autopilot Firmware

PAPARAZZI

The first autopilot platform being considered is Paparazzi UAV, the first real open source project for drone autopilot. This is the most technical of the platforms being considered, meaning that it will be more difficult to work with initially than the other platforms being considered but it will have the most features without having to change any source code.

Description	Pro	Con
Longest running open source autopilot being considered (2003)	X	
Can be written in C and Python	X	
Only runs on Linux and Mac OSX		X
Relatively difficult to obtain hardware		X

Table 3.26. Pros and Cons of the Paparazzi Autopilot Platform

ARDUPILOT

Ardupilot is one of the most popular open source autopilot platforms. This leads to it also having one of the best developer communities and forums to provide information and assistance. The Ardupilot platform being so popular also allows for it to be supported by most of the popular flight control boards so acquiring the hardware will be easy if the Ardupilot platform is used. This comes with the trade-off of the platform being created with hobbyists in mind so a much more advanced mission profile such as the RAPTR mission will require more editing of the source code.

Description	Pro	Con
Compatible with most easily available hardware	X	
Large developer community	X	
Any changes made to source code must be made public		X
Lacking in certain important mission control functions		X

Table 3.27. Pros and Cons of the Ardupilot Autopilot Platform

PX4

The PX4 autopilot platform is very similar to Ardupilot in many aspects such as out of the box features and supported hardware. One of the main distinguishing factors between the Ardupilot and PX4 platforms is the software licenses that they use. PX4 uses a BSD license while Ardupilot uses a GPL license. The license that PX4 uses allows for a user to make changes to the source code and keep those changes private if they so choose whereas any change that is made to the Ardupilot source code must be made public. This becomes important when the autopilot is being used for a private project that is being sold and the developer does not want to release the specifics of what they did.

Description	Pro	Con
Changes made to source code may be kept private	X	
Active community forum and slack channel	X	
Only runs on Linux and Mac OSX		X
Only major board supported is the PixHawk		X

Table 3.28. Pros and Cons of the PX4 Autopilot Platform

3.5.4. Imaging Subsystem

To satisfy the first functional requirement of being able to detect and identify targets of interest, RAPTR must be equipped with an imaging system that can provide data to the ground processing station. The detection, recognition, and identification (DRI) algorithms that will be employed by the image processing station require a certain image resolution to be able to perform these tasks, which limit the amount of options possible for the RAPTR imaging suite. Additionally, since the target of interest's location falls within an annulus of 2000-4000 feet, the imaging suite must be capable of finding the target within this region. The functional and derived requirements for imaging processing, as well as the overall problem statement and concept of operations, narrow down the potential design options to those listed in table 3.29.

Number	Imaging Sensor Options
1	Single Optical Camera
2	Multiple Optical Cameras
3	Optical Camera and Thermal Camera Combination
4	LIDAR Scanner

Table 3.29. Four Potential Options for Target Imaging

SINGLE OPTICAL CAMERA The first option considered is a single standard digital camera integrated within the vehicle. Table 3.30 lists the pros and cons of taking this approach, while Fig. 3.24 shows how the imaging suite will work with only a single camera. The most prominent benefit of the single camera is that it will be the simplest to integrate into the vehicle, and that there will be less data needing to be transmitted to the ground in real time. This approach lacks, however, in its ability to image a wide area on the ground for a given gimbal angle, which may require a predetermined sweeping motion of either the camera mount or the vehicle itself. Furthermore, the camera requires good visibility to be able to image the target, which may not always be available when in use.

Description	Pro	Con
Simple integration, data transmission, and image processing	X	
Cheapest option	X	
Limited Field of View		X
Requires good visibility conditions		X

Table 3.30. Pros and Cons of using a single optical camera for target imaging

As seen in Fig. 3.24, the single camera will be able to image an area of approximately 540x400 ft with a resolution of approximately 4208x3120 pixels. These values were determined based on the average resolution and field of view of commonly used drone cameras, as well as by the recommendation of the electrical engineering team for how much data can be transferred in real time to the ground station. The camera will image the ground over its field of view, and then send the image data back to the ground station for further processing.

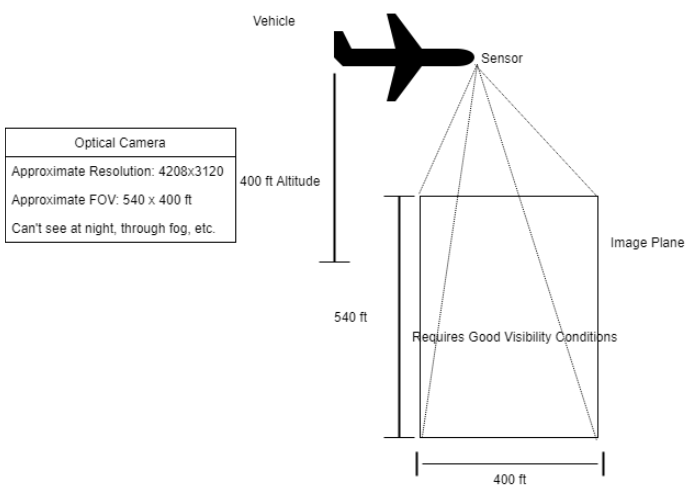

Figure 3.24. Diagram of a single camera imaging system

MULTIPLE OPTICAL CAMERAS Instead of limiting the imaging suite to a single digital camera, this approach considers utilizing multiple cameras at once. Table 3.31 lists the pros and cons to this approach, and Fig. 3.25 provides a diagram for how two cameras would be used in operation. this approach most notably will have a wider field of view, which will increase the ease of detecting the target of interest given its annulus of uncertainty. The primary detriment to this approach lies in the added complexity of its integration into the vehicle, as well as in the increase in data sent to the ground station.

Description	Pro	Con
Wider Field of View & higher resolution	X	
Removes need for controlled camera pointing	X	
More difficult integration, data transmission, & image processing		X
Still Requires good visibility conditions		X

Table 3.31. Pros and Cons of using multiple optical cameras for target imaging

The operation of a multiple camera imaging suite is very similar to that of the single camera, and only differs in the increased FOV width due to different camera gimbaling. If the cameras have no FOV overlap, then the FOV will be effectively doubled from that of the single camera.

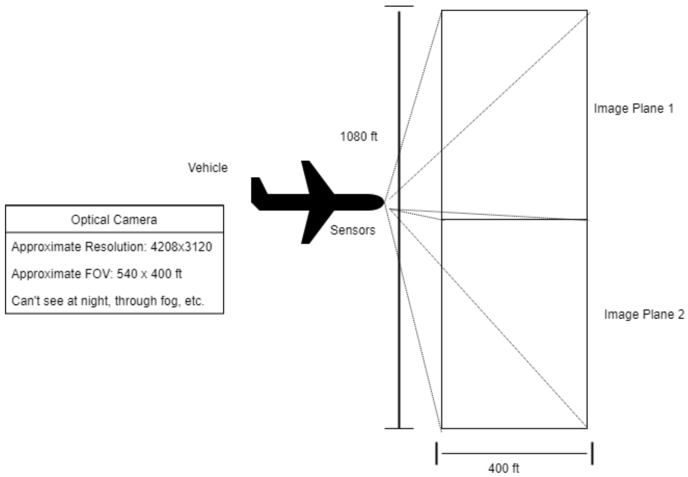

Figure 3.25. Diagram of a two camera imaging system

OPTICAL AND THERMAL CAMERA COMBINATION The next approach considers adding a thermal sensor to go along with the aforementioned digital cameras. Table 3.32 lists the pros and cons to this approach, and figure 3.26 shows a diagram of how this setup would function. A thermal sensor will be integrated along with the digital camera, where the two fields of view will overlap. The pros to this approach almost singularly lie in the thermal sensor's ability to image through low visibility, while the cons lie in the added complexity of integration as well as the cost for a thermal sensor.

Description	Pro	Con
Can image targets through poor visibility conditions	X	
Can design sensor positioning to optimize probability of target detection	X	
Very complex integration, data transmission, and image processing		X
Thermal sensors are expensive and have comparably poor resolution		X

Table 3.32. Pros and Cons of using an optical camera and thermal sensor combination

In Fig. 3.26, the camera and digital sensor have overlapping fields of view, since the ground processing can be done in a way that cross references the data from both the camera and the thermal sensor. The camera and thermal sensor will have to be integrated in such a way which accomplishes this overlap.

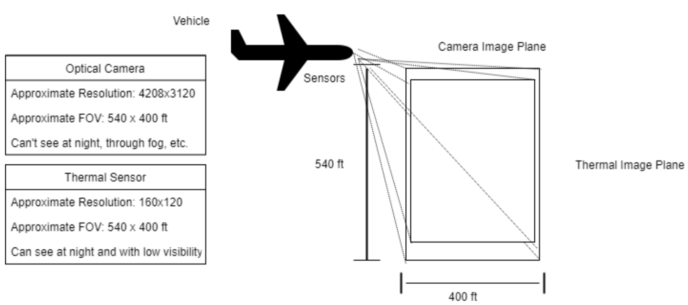

Figure 3.26. Diagram of camera and thermal sensor combo

LIDAR The final design option for an imaging suite is using a LIDAR 3D scanner which scans the ground as the vehicle passes overhead. The pros and cons of this approach are listed in Table 3.33, while the diagram for operation is given as Fig. 3.27. The LIDAR sensor is unique in that it measures distances instead of taking light or thermal data, which has benefits in the ability to build a 3D model of any objects that it is capable of scanning. This is the most prominent benefit to the approach, however there are a few very notable cons. Mostly, a LIDAR scanner would be very expensive for the range that it would be operating in, and it would be very heavy in comparison to the vehicle.

Description	Pro	Con
Can generate 3D point cloud for Optimal target recognition	X	
Simple & accurate target location, can image through trees and low visibility	X	
Extremely expensive		X
Difficult integration due to size & scanning requirements		X
More difficult target identification without camera		X

Table 3.33. Pros and Cons of using a LIDAR scanner for imaging the target

As the LIDAR system operates, it continuously scans an area while sending back point cloud data to the ground station for processing. This width depends on the capabilities of the scanner device, however it would ideally be similar to the horizontal field of view of the two camera system shown in figure 3.25. This scanning will continue for the duration of the flight of the vehicle, and the LIDAR will be capable of imaging through poor visibility as well as through trees and other potential objects.

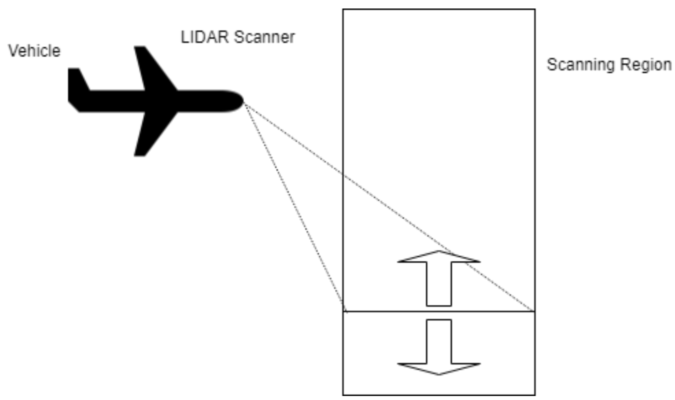

Figure 3.27. Diagram of a LIDAR imaging system

4. Trade Study Process and Results

4.1. Vehicle

4.1.1. Trade Metrics and Trade Study

Metric	Weight	Description
Ability to Meet Requirements	25%	The vehicle must be able to meet all preset functional and derived requirements in order to achieve mission success.
Manufacturability	20%	The vehicle must be able to be manufactured in approximately three months using the resources available through the University of Colorado.
Performance	20%	The vehicle will have to achieve a high airspeed to get to the target area quickly. Additionally, it must be controllable, stable, and able to deliver the payload in multiple different conditions.
Reliability	15%	The vehicle must not get broken during storage, transportation, or deployment. The propulsion system must also function properly when needed.
Level of Expertise Required	10%	The vehicle and its operating procedure must be able to be quickly understood by people with ranging levels of life experience and formal education.
Cost	10%	The cost of the vehicle must be kept to a minimum since the total budget for the aerospace portion of the project is $ 5,000.

Table 4.1. Vehicle Metric Description

Metric	1	2	3	4	5
Ability to Meet Requirements	Able to meet only 1 - 2 functional requirements and very few of their derived requirements	Able to meet three of the functional requirements and some of their derived requirements	Able to meet four functional requirements and most of their derived requirements	Able to meet five functional requirements and almost all derived requirements	Able to meet all functional and all derived requirements
Manufacturability	80 percent or more of the parts needed would be custom ordered	60 - 79 percent of the parts needed would be custom ordered	40 - 59 percent of the parts needed would be custom ordered	20 - 39 percent of the parts needed would be custom ordered	0 - 19 percent of the parts needed would be custom ordered
Performance	Not able to meet minimum horizontal speed requirement or rate of climb requirement	Able to meet rate of climb requirement, but not horizontal speed requirement	Able to meet horizontal speed requirement while coming within 10 ft/s of rate of climb requirement	Able to meet both horizontal speed and rate of climb requirements on a clear, low-wind day	Able to meet both horizontal speed and rate of climb requirements in any condition.
Reliability	Rarely ever (< 25 percent of the time) works correctly, almost no durability	Works correctly 26 - 50 percent of the time in a controlled environment, not very durable	Works correctly 51 - 75 percent of the time in a controlled environment, semi-durable	Works correctly 76 - 100 percent of the time in controlled environment, durable	Works correctly 76 - 100 percent of the time in almost any open-air environment, very durable
Level of Expertise Required	Can only be operated by developers or college graduate level researchers	Could only be operated by trained specialist	Could only be operated by high school educated adults	Could be easily operated by most teenagers	Could possibly be operated by a small child
Cost	$2500+	$2499 - $2000	$1999 - $1500	$1499 - $1000	Less than $999

Table 4.2. Vehicle Metric Point Assignment

	Rocket Powered Glider	Electric Aircraft	Traditional Rocket	Quad-Copter
Meets Requirements (25%)	5	5	3	3
Manufacturability (20%)	4	4	5	4
Performance (20%)	5	4	2	2
Reliability (15%)	5	3	4	4
Level of Expertise (10%)	3	4	4	4
Cost (10%)	5	4	5	3
Final Score	**4.6**	**4.1**	**3.65**	**3.25**

Table 4.3. Vehicle Trade Table

4.1.2. Vehicle Trade Discussion

The metrics and and the rubric used for the vehicle design trade study are shown above in Tables 4.1 and 4.2 respectively. The final results of the trade study are summarized in Table 4.3.

The rocket glider scored very well in all of it's metrics except the level of expertise needed. This system likely needs someone with at least high school education to successfully be operated. Not only because of the danger associated with rockets, but also because the user will be needed to correctly set up the launch and possibly enter initial flight parameters (heading, wind, etc.) into the ground station. Other than that the combination of rocket and glider seems to combine the best traits of the rocket and RC plane into one. The rocket gets rid of the need for fragile propellers and extra batteries, and the glider control surfaces get rid of the lack of control one would have with a traditional rocket. Also, the cost of solid rocket motors is relatively low so multiple test flights may be a possibility later on. All in all, the rocket powered glider takes the best traits from the other vehicle options and combines them to suit the mission objectives almost perfectly.

Like the rocket powered glider, an electric aircraft will be able to fulfill all functional and derived requirements of the project. The electric aircraft also scores high in the manufacturability category. This is because of the large number of off the shelf products that are available specifically designed for electric aircraft. Moving on to Performance, the electric aircraft scores well here. There are examples of electric aircraft that achieve the required speed for this project, but the motors and batteries required to support them are heavy. This extra weight takes away from the payload capacity causing this vehicle to not get full points here. The electric aircraft struggles when it comes to reliability. This is for two reasons. The first is that this vehicle depends on fragile propellers which could be easily broken during storage or handling of the vehicle. The second is the number of electrical connections needed and the need for a fully charged battery. Both of these elements add potential failure points to the vehicle system. Electric aircraft are also easy to operate and can be built for a relatively low cost. For these reasons, this vehicle scores well in the level of expertise and cost categories. Overall, this vehicle design could perform the mission, but it does have draw backs, specifically with reliability and performance.

The traditional rocket design falls short. Since the rocket is designed to go straight up and then straight down at a high rate of speed, it is not able to meet some of the project requirements. The rocket gets full marks for manufactura-bility, however. This is because there are many rockets designed to carry a payload that can be bought off the shelf. The rocket scores poorly in the performance category. This is because it is designed to go straight up, but for this project a large lateral distance is required as well. Also, most rockets are designed to be spin stabilized. This would make it next to impossible for the payload to image the target area. Another benefit of the rocket is its reliability. Since solid rocket motors have no moving parts they are extremely reliable. Rockets are also relatively easy to operate, but some care must be taken with the engines since they can be dangerous. Finally, these rockets are inexpensive since there are not many parts that make them up. The traditional rocket design has many benefits; however, its shortcomings in the performance and meets requirements section make it a poor choice for the intended mission of this project.

The quadcopter is one of the better performing vehicles that can be purchased off the shelf, specifically with regards to aerial imagery. However, these quadcopters are limited by the limiting factor of all rotor driven aerial vehicles in that they usually have a slow horizontal speed. The high end quadcopters researched, such as the DJI Phantom 4, have a top lateral speed of about 65.61 ft/s which is well under the 100 ft/s requirement.[6] Top racing drone setups can achieve speeds an upwards of 240 ft/s, but with speed the cost and amount of custom parts needed goes way up.[7] Also, not only do the rotors and intricate parts on quadcopters make them more difficult to manufacture, they mean more complex controls and less durability. In conclusion, the types of quadcopters that came close to the horizontal speed requirements already cost an upwards of $1500, and to modify them to fit a payload could cost thousands of dollars more. The quadcopter is still a great UAV for imaging small areas and getting around obstacles, but sadly it can only travel so far so fast. That, along with other factors like poor durability, is why it ended up doing the worst out of any vehicle option on the trade study.

4.2. Payload Mounting

4.2.1. Trade Metrics and Trade Study

Metric	Weight	Description
Mechanical Complexity	25%	The payload mounting system's ultimate choice may introduce varying degrees of mechanical difficulty. As the mechanical system may be required to complete the payload's mission of successfully capturing images of the target, the mechanical system carries substantial weight.
Software Complexity	25%	Similar to the mechanical system, the needs of the payload mounting system will also increase the complexity of on-board processing actions, such as search and pointing functionality independent of the vehicle body.
Cost	10%	The price of components for each mounting alternative will be a critical piece of the mission design, as the entire aerospace project segment must be kept below the $5,000 budget
Weight	20%	The weight of the payload mounting assembly, in conjunction with the weight of the payload, will have major impacts on the dynamics and pointing ability of the vehicle itself
Power	20%	All other payload systems will be useless without any power to drive their operations. Therefore, the power system will have to be adjusted uniquely for each mounting alternative.

Table 4.4. Payload Mounting Metric Description

Metric	**1**	**2**	**3**	**4**	**5**
Mechanical Complexity	5+ months	4 months	3 months	2 months	1 month
Software Complexity	5+ months	4 months	3 months	2 months	1 month/NA
Cost	$1000+	$750	$500	$250	$100
Weight	4+ lbs	3 lbs	2 lbs	1 lb	Negligible mass
Power	20% total draw	15% total draw	10% total draw	5% total draw	Negligible/No draw

Table 4.5. Payload Mounting Metric Point Assignment

	Internal Aperture	External Dome	Deployable Payload
Mechanical (25%)	5	2	3
Software (25%)	3	1	4
Cost (10%)	5	3	4
Weight (20%)	5	2	4
Power (20%)	5	2	3
Final Score	4.5	1.85	3.55

Table 4.6. Payload Mounting Trade Table

4.2.2. Payload Mounting Trade Discussion

The trade study of the alternatives for payload mounting may be viewed in Table 4.6, with descriptions of the metrics and their associated scored found in Tables 4.4 and 4.5, respectively.

The first payload mounting alternative to be considered was an internal aperture set within the nosecone of the vehicle, with a transparent material allowing the payload sight of the ground for imaging. The internal aperture is mechanically simple, involving a fixed field-of-view (FoV) relative to the vehicle and no moving parts within the vehicle. However, the internal aperture necessitates coordination with the vehicle to correct the payload's field-of-view, should error be introduced as the system. As such, the software would be more complex with this alternative, requiring communication between the vehicle and payload to allow control surface adjustments as needed. The vehicle may also need to drastically adjust its flight path to make the FoV of the payload include the target, further increasing the software complexity. The cost of an internal aperture is trivial, requiring only a small, transparent section of material on the underside of the nosecone for the payload to "see" through and any small materials needed to secure the payload within the vehicle. A material as simple as acrylic plastic is available in thin variants of 8 square feet for only $15 from vendors [12]. Similarly, the internal aperture does not require much excess weight. The materials involved in creating the window and internal mounts are minimal. This includes transparent materials that are relatively light weight and any screws, bolts, or otherwise composed of various metal alloys. Power is an important consideration in any system, particularly for a vehicle with a power intensive payload and trasmitter. As such, the internal aperture mounting will require no power to function. Any additional power resulting from this alternative would be in the form of control surface actuation and communication between the vehicle and the payload. As a whole, this mounting option is economical in all aspects, albeit with the potential for heavy software and vehicle adjustments to ensure payload success.

The second payload mounting alternative was an external dome featuring azimuth and elevation axis rotations. This solution was created to maximize the pointing capability of the payload, independent of the vehicle. Unfortunately, this introduces extreme degrees of difficulty and risk in both the mechanical and software aspects of the mounting system. Mechanically, a two-axis rotating dome carries an immense amount of risk. If one axis of rotation should fail, or the vehicle fly too far before the gears can adjust to the targets location relative to the vehicle, then the vehicle will have failed to deliver the payload to its objective. Ensuring that the mechanical system works reliably would involved much assembly and testing. Likewise, the software aspect of the mounting system would have to include a searching functionality to locate the target in the case of a non-nominal deployment and vehicle trajectory. This would be greatly complex, and possibly beyond the scope of the year's work in ASEN 4018. Compounded with the interplay of the software and mechanical system, both may be declared to be nonviable within the scope of the project. This alternative would also cost much more than the other two options, as the materials and components required to create two-axis rotation as well as an external, mounted dome would likely require enough materials for several iterations. The increased machinery and materials would also drive up the weight of the vehicle at the location of the payload mount, affecting the dynamics of the vehicle to a greater degree than the other alternatives. The required power to actuate the payload along two axes, particularly if a "target search" function in necessary, has the potential to be immensely draining to the power system. This is undesirable, as the payload will also need a great deal of power to successfully transmit the data and communicate with the vehicle. Overall, this alternative is sub-optimal, adding complexity and unsustainable risk to the project, while accounting for potentially large issues such as vehicle flight path deviations.

The third payload mounting alternative was a mid-body, deployable payload by way of bay doors built into the vehicle. The bay doors and deployment mechanism create mechanical failure points. While not as risky as the dome option, the testing of the door operation in conjunction with the deployment mechanism of the payload would require many iterations and a long time period to ensure proper and consistent performance. The actuators to open the door would also require custom or ordered mechanical components that must be well understood to ensure proper performance. The software involved with the bay door/deployment coordination would also require intensive work. Additionally, this alternative requires the vehicle to correct its flight path following deployment to be near where the target is thought to be. This ensures the highest possible chance of payload success, at the cost of software complexity. The cost of this mounting alternative lies between the other two. While one or two actuators would be necessary for the bay door and deployment mechanism, each would also have to be less complicated than the dome case. Additionally, the material for the bay door would already exist as a part of the vehicle, reducing the demand for purchasing raw materials. This joint use of material would also help reduce the weight of the mounting system relative to the vehicle, and would shift the center of mass more towards the middle of the vehicle body. However, the mechanisms would still weigh more than the aperture alternative. Finally, the power draw of this mounting mechanism would be slightly improved over the dome, while still being more demanding than the aperture. The bay doors would have to be powered enough to open at least once, and likely close in order to not adversely affect vehicle aerodynamics for long. As such, this power cost must be included as a significant draw in power system design. This alternative features preferable options over the dome, but also potentially creates problems for the payload's imaging capability after it separates from the vehicle.

4.3. Landing Methods

4.3.1. Trade Metrics and Trade Study

Metric	Weight	Description
Cost	30%	The cost of any landing system implemented in the project is critical, as it consumes resources that could be more effectively spent elsewhere in the design and testing process. As the landing is of lesser importance than other areas of the mission, it is important that the systems implemented are a minimal resource drain.
Weight	20%	Similar to the reasoning behind the cost metric, the weight of the landing system must be kept as low as possible to minimize the additional development that is required to launch heavier vehicles.
Control/Re-usability	30%	The purpose of the landing system is to, ideally, allow for the safe recovery and ultimate reuse of the vehicle. A vehicle that lands with severe damage holds little advantage over a vehicle that simply disappears once the images have been transmitted since the recovery of a crippled vehicle provides nothing of value.
Complexity	20%	Because the landing of the vehicle is not the primary purpose of the mission, having a simple and easy to implement landing system is important because it frees up resources to be used in other mission critical areas. Less complex systems with lower failure rates are desired.

Table 4.7. Landing Method Metric Description

Metric	**1**	**2**	**3**	**4**	**5**
Cost	$700+	$500-699	$300-499	$100-299	$100 or less
Weight	4+ lbs	3-4 lbs	2-3 lbs	1-2 lbs	1 lb or less
Control/Re-usability	Vehicle destroyed, no control over final location	Probable damage, minimal control over location	Possible damage, moderate location control	Unlikely damage, good location control	No damage, precise location control
Complexity	More than 2 months	1-2 months	2-4 weeks	1-2 weeks	Less than 1 week

Table 4.8. Landing Method Metric Point Assignment

	Deployable Parachute	Belly Landing	Landing Gear	Crash Landing
Cost (30%)	3	4	2	5
Weight (20%)	4	5	2	5
Control/Re-usability (30%)	3	4	5	1
Complexity (20%)	5	3	2	5
Final Score	**3.7**	**4.0**	**2.9**	**3.8**

Table 4.9. Trade Table for Landing Methods

4.3.2. Landing Method Trade Discussion

The trade study of the options for Landing Methods may be viewed in Table 4.9, with descriptions of the metrics themselves found in Table 4.7.

The simplest option for the landing method, and the baseline to which all other options were compared, was the crash landing. The reason this makes a good baseline is because it has the lowest complexity of any possible option, since a crash landing doesn't require any additional control or components to implement. Because of this, the crash landing also scores high marks in both Cost and Weight. Since there are no added components, the cost and weight effects of a crash landing are precisely zero. Where the crash landing falls short, however, is in the Control and Re-usability category. A crash landing is, by definition, an uncontrolled landing. The operator would have no ability to determine where it would land, how it would land, or whether or not it would be re-usable after the fact.

Beyond the baseline of a crash landing, the first method to ensure the safe recovery of the vehicle that was considered is the use of a deployable parachute. Due to their widespread use in model rocketry, the cost of a deployable parachute isn't excessively expensive but it still represents a somewhat significant cost. A 36 inch chute with a 10 pound capacity costs in the neighborhood of $100, while a 60 inch chute with a 20 pound carrying capacity would cost $200. If the vehicle and payload are heavy enough, however, an 84 inch parachute with the capacity for 40 pounds would cost $300. The weight of the parachute is one of its strengths, however, as even the large 84 inch parachute comes to only approximately 18 ounces in added weight. For control and re-usability, the parachute represents a large improvement over the crash landing due to the fact that it doesn't destroy the plane. What it lacks, however, is control over where the vehicle lands (due to winds) in addition to the fact that the vehicle or the parachute itself could become stuck or still be damaged during its descent. The complexity of the parachute is anything but complex, however, since off the shelf parachute kits are readily available. This means a minimum of development time would need to be devoted to this landing method if chosen.

Another option under consideration was to emulate modern aircraft, including gliders, by attaching a landing gear to the vehicle. This has the advantage of providing the most control and re-usability to the vehicle due to the nature of the landing gear. A gliding descent with wheels for landing would provide the most precise control over landing location and provide the least risk for damage due to the fact that no portion of the vehicle itself, besides the wheels, would come into contact with the ground. Unfortunately, the rest of the attributes were not as optimal on the landing gear option. The cost of a landing gear is the most prohibitive of all the options, in large part due to the complexity required. Since few landing gear kits capable of sustaining the vehicle's weight are available on the open market, a fair amount of the parts would need to be custom fabricated - driving up the cost and the time to complete it. In addition, the complexity of controls required to actually successfully land the vehicle would be no small task, with much of difficulty coming from attempting to keep the craft stable and upright upon touchdown. The final area where the landing gear loses points is its weight, as it is by far the heaviest of all the available options.

The final option presented is that of making a belly landing with the plane. This was proposed as an attempt to shore up the weaknesses offered by both the parachute and landing gear options by combining the best of each. The cost of belly landings are low, since it would simply require a tough skidplate to be added to the belly and abrasion resistant materials placed on any other surface that could come into contact with the ground. Because lightweight materials such as Nylon and other plastics may be used for this purpose the overall weight of the system is another positive, surpassing even the parachute's weight rating. In terms of control and re-usability, belly landing loses some points for having the potential of vehicle damage, simply due to uneven terrain or rocks. However, the control of this method is nearly as high as that of the landing gear landing. The biggest downfall of the belly landing, however, is the complexity. This primarily comes from the requirement that the vehicle would need to glide towards the ground in a controlled fashion at a shallow angle, increasing the difficulty in tuning the controls. It doesn't require the same complexity as the landing gear option though, since once it touches down and begins to slide there is no need to maintain control all the way up to the stop.

4.4. Deployment Method

Metric	Weight	Description
Stability and Accuracy	35%	Project success is dependent on the vehicle reaching a lateral distance from the user of 2000 feet and an altitude of 400 feet above the user. For these success criteria to be met the deployment method needs to provide the launch vehicle the capability to reach this distance. This capability can be achieve through the stability of the launch pad and the accuracy of the angle at which the launch vehicle is launched. The stability of the deployment method is also dependent on the terrain the user is launching the vehicle from and stability is being defined to meet the requirement for the vehicle to be deployable from terrain with a 10% grade.
Weight and Mobility	25%	An element of project success is the mobility of the entire RAPTR system, including the deployment method of the vehicle. The deployment method could easily become the largest and heaviest element of RAPTR and therefore must be chosen carefully to minimize weight and volume to allow a user of average size and strength to carry it.
Durability	20%	The deployment method must be able to support multiple uses of RAPTR and therefore needs to be durable. This is an important element of the deployment method choice because it will determine how feasible each design option is for a long project life.
User Compatibility	10%	For the project so succeed the user needs to interface with both the ground station and the vehicle. The deployment method needs to be chosen with a user of average intelligence in mind to ensure that it will be functional in any situation.
Cost	10%	Cost is a determining factor in any engineering project. As the success of the vehicle is dependent on being properly launched the cost metric has a lower weight than stability and accuracy, but the financial importance still needs to be taken into account.

Table 4.10. Deployment Method Metric Description

Metric	1	2	3	4	5
Stability and Accuracy	Unable to launch the vehicle accurately on command and unable to launch from any sort of variable terrain.	Able to launch the vehicle on command to a low degree of accuracy and unable to launch from terrain with a grade over 1%.	Able to launch the vehicle on command to a low degree of accuracy and unable to launch from terrain with a grade over 5%.	Able to launch the vehicle on command to a high degree of accuracy and unable to launch from terrain with a grade over 5%.	Able to launch the vehicle on command to a very high degree of accuracy and able to launch from terrain with a grade of 10%.
Weight and Mobility	Weighs more then 25 pounds and has a high likelihood of breaking during transport	Weighs more than 20 pounds and has a high likelihood of breaking during transport	Weighs 15-20 pounds and has a low likelihood of breaking during transport	Weighs 10-14.9 pounds and has a low likelihood of breaking during transport	Weighs less than 10 pounds and has a very low likelihood of breaking during transport
Durability	Unable to provide a successful launch more than once between transportation.	Unable to survive ground transportation over five miles and launch reliably.	Able to survive ground transportation over five miles and launch reliably with some adjustments.	Able to survive ground transportation over 10 miles and launch reliably with minimal adjustments.	Able to survive ground transportation over 20 miles and launch reliably with minimal adjustments.
User Compatibility	User is unable to use the deployment method without specific training lasting longer than 2 hours.	User feels uncomfortable using the deployment method without specific training lasting longer than 2 hours.	User feels uncomfortable using the deployment method without specific training lasting longer than 1 hour.	User is comfortable with the deployment method with some specific training.	User is comfortable with the deployment method with no specific training.
Cost	$1000+	$800 - $999	$600 - $799	$400 - $599	Less than $400

Table 4.11. Deployment Method Metric Point Assignment

	Hand Thrown	Single Fixed Rod	Single Variable Rod	Variable Rails with Hydraulic Launch Initiation
Stability and Accuracy (35%)	1	3	5	4
Weight and Mobility (25%)	5	4	3	1
Durability (20%)	5	4	4	2
User Compatibility (10%)	5	4	4	1
Cost (10%)	5	5	4	3
Final Score	**3.60**	**3.75**	**4.10**	**2.45**

Table 4.12. Trade Table for Deployment Alternatives

4.4.1. Deployment Method Trade Discussion

The criterion used for this trade study are outlined in Table 4.10, with the designation for each level of success explained in Table 4.11. The final trade study of the deployment method options is given in Table 4.12. The deployment method chosen was a single variable rod.

The options listed are given from the most simplistic to the most complicated. The simplest, most light weight and cost efficient method to was throw the vehicle and have the propulsive element of the vehicle ignite after it has left the user's hand. While this method fulfills criterion for weight and cost, as no additional weight or cost is required for this deployment method, the accuracy of the throw left much to be desired. The user would throw the vehicle towards the general direction they believe the target to be and there would be no way to control the exact angle, force, and therefore initial trajectory of the vehicle. Because the metric for stability and accuracy is rated so highly for the project to meet its requirements, at 35%, this method was discarded.

The second method analyzed was the single fixed rod, which closely resembles the single variable rod method. The single fixed rod would provide more accuracy than the hand thrown method but provides less range of motion and therefore less accuracy than a single variable rod. While a variable rod has more components that need to be robust to survive transportation and is therefore heavier than a fixed rod, the increased accuracy of this method makes it superior to a single fixed rod.

The most complex method analyzed was a deployment method consisting of variable rails with hydraulic launch initiation. While this deployment method would supply increased thrust to vehicle, the increased weight, cost, and user training required for successful deployment made this option impractical.

The single variable rod scored a 5 in stability and accuracy because it allows a range of angles and initial projectile trajectories that neither the hand thrown or single fixed option offer. It would, theoretically, be able to successfully launch the vehicle on command to a very high degree of accuracy every time. The single variable rod would also have adjustable legs that make it suitable to launch from almost any terrain, including rugged terrain and terrain with a 10% grade. This method scored a 3 for weight and mobility, the lowest it scored in any metric, because it would most likely weigh between 15 and 20 pounds, based on existing models of this method, but because it is heavy and robust would most likely not break during any transport. The single variable rod deployment method scored a 4 in the durability matrix because there are several components that could break during transportation but due to the strength of the components (again in examples of this method) the likelihood of them breaking is very low and adjustments upon launch site arrival would be minimal.This method scored a 4 for both user compatibility and cost as well. The user would require minimal training to operate this deployment method and the method would, based upon research of existing models, cost somewhere between $400 and $500.

4.5. Sensor Suite

4.5.1. Attitude Determination

Metric	Weight	Description
Implementation Robustness	25%	The sensors shall be able to function in unison with the rest of the vehicle. This includes any sensor interference with the vehicle structure and electronics
Accuracy	35%	The attitude determination sensor suite shall be capable of accurately measuring the orientation of the vehicle. This includes the precision of any attitude information necessary for controlling the vehicle.
User Complexity	25%	The attitude determination sensor suite shall be mechanically and electrically simple enough to allow for user adjustments.
Cost	15%	The cost of the attitude determination suite shall be minimized but bounded to the quality of the sensors.

Table 4.13. Attitude Determination Metric Description

Metric	1	2	3	4	5
Implementation Robustness	All interference types	Structural Interference	Electrical interference	Environmental interference	Negligible interference
Error Subjectivity	< 10 degrees	< 7 degrees	< 5 degrees	< 3 degrees	< 1 degrees
User Complexity	Federal restrictions	Federal limitation	Closed source	Professional use only	College level
Cost	> $100	< $100	< $50	< $30	< $10

Table 4.14. Attitude Determination Metric Point Assignment

	Accelerometer, Gyroscope, and Magnetometer	Accelerometer, Gyroscope, and GPS	Accelerometer, Gyroscope, and Infrared	3-GPS
Implementation Robustness	3	4	4	3
Error Subjectivity	5	3	5	1
User Complexity	5	2	3	2
Cost	4	2	3	1
Final Score	**4.35**	**2.85**	**3.95**	**1.75**

Table 4.15. Attitude Trade Table

Attitude Determination Trade Discussion

Table 4.13 lays out the metrics against which each attitude determination system is weighted. Each component of the attitude determination sensor suite must be able to sustain the turbulence of vehicle launch. In particular, the attitude determination subsystem must be able to function internally in the vehicle. Being inside the vehicle presents challenges as far as interference with the vehicle structure, other electronics, and the overall atmosphere at 400ft but is necessary to protect the electronics during flight. Accuracy is a substantial factor in attitude determination. If the attitude of the vehicle is not known then it will be nearly impossible to determine in which direction on board cameras are pointing. This will make the reverse engineering of a target's location extremely difficult. Due the time constraints of the project, sensor integration is also an essential trait and the attitude determination package should be made of reasonable complexity for a senior project. A significant amount of development and manufacturing costs will be necessary for other components of vehicle so cost also contributes to the sensor packages rating.

The first three attitude determination design options all incorporate a 3-axis accelerometer and a 3-axis gyroscope. This allows precise control over the vehicles movement in the X-axis and Y-axis but not the Z-axis (the heading of the vehicle). A magnetometer provides accurate heading readings but caution must be taken in regards to stray magnetic fields as other electronics around the magnetometer can skew its readings. Due to its wide use a magnetometer provides accurate heading readings for a relatively simplistic design at a low cost.

A GPS can also obtain a heading reading. Though it is less affected by surrounding electronics commercial GPS has an error of $\pm 6ft$ and so is a poor choice for precise heading adjustments. GPS also takes significantly longer to update, this is not optimal when time is a driving constraint. GPS will add some superfluous complexity and cost to the attitude determination system.

An infrared proximity sensor is a promising alternative as it provides a median cost between the magnetometer and GPS. The major drawbacks of an infrared range finder occur in its implementation and added complexity. In order to provide proper readings the infrared sensor would have to be externally mounted, a contradiction to a robust design. Additionally, the infrared measurements are skewed by haze, mountains, and buildings. Since the vehicle is to be deployed in a variety of environments, infrared would not be the optimal choice.

The final option is three separate GPS units located on the vehicle. The primary deficit with this option is that the error of each GPS is larger than the vehicle itself. This setup would provide erroneous attitude data that is primarily useless and so is not a viable option for this small application.

Table 4.14 presents a grading breakdown and Table 4.15 lists the scores for each attitude senor suite. At the bottom of Table 4.15 the weighted score of each attitude determination subsystem is listed. Despite electrical interference problems the 3-axis accelerometer, 3-axis gyroscope, and magnetometer sensor suite is the clear winner as it provides accurate data at a cheap cost and with user simplicity.

4.5.2. Altitude Determination

Metric	Weight	Description
Accuracy	30%	The vertical determination sensors shall be able to accurately provide altitude data of the vehicle.
Range	30%	The vertical determination subsystem must provide accurate readings at an altitude of 400ft.
Usability	25%	The components must be simple enough to be integrated electrically into the rest of the navigation system.
Cost	15%	The cost of the vertical determination suite shall be minimized but bounded to the quality of the sensors.

Table 4.16. Positional Determination Metric Description

Metric	1	2	3	4	5
Accuracy	>3 feet	<3 feet	<2 feet	<1 feet	<0.5 feet
Range (AGL)	<50 feet	<100 feet	<200 feet	<400 feet	>400 feet
Usability	Federally restricted	Federal limitation	Mission limiting	Developmental stage	College level
Cost	> $100	< $100	< $50	< $30	< $10

Table 4.17. Attitude Determination Metric Point Assignment

	Barometer	Sonar Proximity Sensor	Laser Proximity Sensor
Accuracy	3	5	5
Range	5	1	5
Usability	5	3	3
Cost	4	4	1
Final Score	**4.25**	**3**	**3.9**

Table 4.18. Attitude Trade Table

ALTITUDE DETERMINATION TRADE DISCUSSION

Not only is it critical to know the vehicle's precision attitude but also its position. Both the attitude and position of the vehicle must be known for RAPTR to be capable of returning the coordinates of a target to a user. GPS will be used to determine the vehicle's position in the vehicle's X and Y plane very accurately; however, GPS lacks precision in the vehicle's Z-axis (altitude above ground). To determine the sensor suite most fit for deciphering the vehicle's altitude Table 4.16 lays out key traits of the sensor suite. A trait to note, that has not been aforementioned, is range. The altitude determination sensor must be able to provide accurate altitude measurements to the user while at 400ft AGL.

Table 4.16 graphically lays out the metric criteria for the altitude determination sensor suite. The range requirement almost immediately disqualifies the sonar proximity sensor with a maximum range of around 30ft. The laser proximity provides a more accurate altitude reading at the same range as a barometer. The laser proximity sensor is cast aside due to a project constraint on the portability of RAPTR. Laser range finders, though accurate, are far more bulky and heavy than a barometer. Increasing the size of the sensors means increasing the size and capabilities of the vehicle which will cause a skyrocket in price. The barometer provides an altitude reading under 2ft which will be sufficient for RAPTR. Table 4.18 depicts the winner of the altitude determination suite as a barometer.

4.5.3. Autopilot Subsystem

Metric	Weight	Description
Hardware Support	10%	The hardware that is supported by the autopilot platform will affect the possibilities for what kind of peripherals and sensors can be used in the mission.
Mission Capabilities	25%	The autopilot must be very customizable as the RAPTR vehicle will be flying a very unique mission. The autopilot must be able to deal with unique scenarios
Extras	25%	Choosing an autopilot platform is difficult to do with standardized metrics so this metric will allow for any unique features to be accounted for in the trade study.
Development Resources	30%	The autopilot controls for this project must be developed rather quickly so having a plethora of available resources to help development is a must.
Development Learning Curve	10%	Similar to the development resources, it is important that the autopilot platform chosen is easy to learn so that development may start as soon as possible.

Table 4.19. Autopilot Metric Description

Metric	1	2	3	4	5
Hardware Support	Supports very few boards that are difficult to obtain	Supports very few boards that are easy to obtain	Supports a medium amount of boards that are somewhat difficult to obtain	Supports medium amount of difficult to obtain boards with some support of more popular boards	Supports most or all of the most popular boards
Mission Capabilities	Platform has minimal mission design capabilities	Platform has some mission design capabilities but is missing many advanced features	Platform supports some advanced mission design features	Platform has many advanced mission design capabilities	Platform has most advanced mission design capabilities that would be needed for this project
Extras	Extra features are not relevant to this project	Extra features are slightly relevant to this project	Extra features are somewhat relevant to this project	Extra features are relevant to this project	Extra features are very relevant to this project
Development Resources	Only resource is online documentation	Resources include documentation and some way to contact the platform's developers	Resources include documentation and some online community for the platform	Resources include documentation, an online community, and some way to contact the developers	Resources include documentation, one or more online communities, and several ways to easily contact developers
Ease of Use	Platform is extremely difficult to learn	Platform is somewhat difficult to learn	Platform can be learned in a timely fashion	Platform can be learned quickly	Platform can be learned very quickly

Table 4.20. Autopilot Platform Metric Point Assignment

	Ardupilot	PX4	Paparazzi
Hardware Support	5	2	4
Mission Capability	4	3	5
Extras	2	3	4
Development Resources	5	4	1
Development Learning Curve	4	5	2
Final Score	**3.9**	**3.65**	**3.15**

Table 4.21. Autopilot Trade Table

Autopilot Trade Discussion

The trade study of options for autopilot platform may be seen in Table 4.21, and a description of the metrics on which the options were compared may be found in Table 4.19 with a description of each grade in Table 4.20.

The first metric considered is also one of the easiest to determine, that being the hardware supported by each autopilot platform. This metric is easy to determine because all autopilot platforms have a list of all supported hardware that is not hard to find and is much less subjective than the other metrics. Hardware support will be a limiting factor when it comes time to start buying flight control boards but most boards have similar capabilities so the most important differentiating factor is how difficult it will be to obtain the boards, which is why hardware support has the lowest weight of any metric. The Ardupilot platform easily has the most widespread support of any platform being considered, with the Ardupilot being one of the most popular autopilot platforms for hobbyists. Because of this the Ardupilot has support for most of the more popular flight control boards. The PX4, on the other hand, was created almost specifically for the Pixhawk micro-controller board. PX4 does have support for other boards but many of them are specifically for racing or for quadcopters so as far as this project is concerned, the Pixhawk is the only supported board. Thankfully, the Pixhawk is a very capable and easily available so this is not a large hindrance. The Paparazzi platform is somewhere in the middle with most of the supported hardware being more obscure and difficult to obtain boards but recently has begun supporting the Pixhawk board.

The next metric considered is mission capability. Mission capability is considered to be the possibilities of mission design that are available out of the box for the platform. Since this project is on a small time scale, it is preferable to spend as little time as possible building custom mission profiles so that all effort can be spent on the control system itself. The Ardupilot platform being very popular is very helpful because it has had many people iterate on the open source project, leading to a plethora of modules to help design a mission profile. The PX4 is very similar to Ardupilot but is missing certain capabilities that make it slightly less qualified than the Ardupilot. The Paparazzi is the most technical autopilot platform of the alternatives being considered and it was also created with fully automatic flight in mind. Because of this it has the most robust mission design capabilities of all the alternatives.

The extras metric allows for the asymmetric design of these autopilot platforms to be considered in the trades study. The most important extra to be considered for the Ardupilot platform is its ability to natively control a camera for stabilization and shutter control. The only problem is that this may not be relevant since the camera used for this project may not be compatible with the Ardupilot firmware but this extra should still be accounted for in the trade study. The extra being considered for the PX4 is the software license it uses. One of the major differences between the Ardupilot and PX4 platforms is the software licenses that each use. The license that Ardupilot uses requires that any changes made to the software be made public, while the software license of the PX4 allows for one to make changes to the source code and keep the changes private if they so choose. This is somewhat relevant as this project is being contracted by a private company so being able to own the IP for the autopilot code is important. The extra feature being considered for the Paparazzi platform is the fact that it is a platform primarily focused on fully automatic flight, as opposed to the other alternatives which are at least equally focused on manual flight. This allows for greater mission capabilities which have already been accounted for in this trade study but more importantly this means that, while the development resources are not that great, the developers of the Paparazzi platform will be very knowledgeable on fully automatic flights. This will allow for better help even if there is not as great of access to the development resources.

Development resources is a measure of how many resources there are to help troubleshoot problems and learn how to develop an autopilot system on a given platform. Ardupilot has fantastic resources available online with a user forum and several ways to contact the primary developers of the platform. Similarly, PX4 also has some fantastic resources with a user forum and a slack channel for contacting developers. Paparazzi, on the other hand, does not have great resources with the largest problem being the lack of a user forum. The only way to contact the developers is through a chat system on the Paparazzi wiki or github which is not ideal.

The final metric to be considered for the trade study on autopilot platforms is development learning curve. Ardupilot being very popular helps greatly with the learning curve but there is still plenty of advanced capabilities that may take some time to get acquainted with. The PX4 is very similar to the Ardupilot but with some simplifications that will make it easier to pick up. Paparazzi is the most technical of all the alternatives considered so it has the most difficult to learn development.

4.5.4. *Imaging Subsystem*

Metric	Weight	Description
Meeting Resolution Requirements	15%	The imaging system must meet the minimum resolution requirements for object detection, recognition, and identification from 400 ft altitude.
Size of Field of View	20%	With a larger width of field of view, there is a higher likelihood the target will be detected for a constant gimbal angle.
Ability to Image in Poor Visibility	25%	This measures the capability of the imaging suite to image in poor visibility and around objects.
Mechanical Complexity & Power Draw	15%	This measures the total complexity of integrating the imaging suite to the vehicle, as well as allocating power, data, and communication streams
Cost, weight, and data collected	25%	This measures the financial price, size and weight, and data sent for the imaging suite to function.

Table 4.22. Imaging Suite Metric Description

Metric	1	2	3	4	5
Resolution Requirements	Object won't be able to be detected	Object may be able to be detected with high contrast	Object can be easily detected even with non ideal conditions	Object can be recognized as a certain shape	Object can be identified as a certain kind of object, vehicle, etc.
Field of View	Fixed FOV and <200 ft width	Fixed FOV and <400 ft width	Fixed FOV and <600 ft width	Fixed FOV and <1000 ft width	Adjustable FOV
Poor Visibility Imaging	Object can't be detected in low lighting	Object can't be detected through smoke, fog, or other visual impediments	Object can't be detected at night	Object can be detected in all lightings and environmental conditions	Object can be detected through trees and other obstacles
Complexity & Power draw	Requires significant wiring and integration configurations	Requires complex mounting or has a large power draw	May require a slightly more complex integration or has a slightly larger power draw	Optimal in being either very mechanically simple or has a very low power draw	Is very simple to integrate and has a low power draw
Cost, Weight, and Data	Has a large cost, is very heavy, and requires a massive data stream to the ground station	Has significant drawbacks in two of cost, weight, and data stream	Has a drawback in either cost, weight, or data stream	No significant drawbacks, and excels in at least one metric	No significant drawbacks, and excels in at least two metrics

Table 4.23. Imaging Suite Metric Point Assignment

	Single Camera	Multiple Cameras	Camera and Thermal Sensor Together	LIDAR Scanner
Resolution	5	5	1	3
Field of View	3	4	3	5
Visibility	2	2	4	5
Complexity/Power	5	3	4	1
Cost/Weight/Data	5	3	4	1
Final Score	**3.85**	**3.25**	**3.35**	**3.1**

Table 4.24. Imaging Trade Table

IMAGING TRADE DISCUSSION When considering different imaging suite options, five different criteria were selected for weighing the merits of each option and the feasibility for implementation into the mission of RAPTR. These were: meeting the resolution requirements found in the derived requirements section,the width of the image plane field of view and its capability for adjustment, the visibility conditions required for imaging, the mechanical complexity and power draw needs, and the cost, weight, and amount of data being sent to the ground station. These were selected as the critical metrics of each design since they each relate either to the requirements of the mission, the total capability of the imaging suite, or the feasibility of integration.

The metrics were assigned a score based on either certain specific performance parameters, or based on a relative scale when compared to the options. The resolution, field of view, and visibility metrics fall into the former category, while the complexity/power and cost/weight/data metrics were scaled with the best option receiving a five and the worst option receiving a one. The weights assigned to each option are based on the importance to meeting the functional requirements of the mission. The resolution and complexity/power metrics had the lowest weight since both metrics could be easily improved with better hardware or with more time spent on accommodating the sensor. The poor visibility imaging and cost/weight/data metrics consequently have the highest weight, since RAPTR may frequently be used in these visibility conditions and cost/weight/data of the sensor can be prohibitive to the overall function of RAPTR as a whole. The field of view metric falls into a similar boat as the resolution and complexity/power metrics in that it can be more easily mitigated, however it carries a slightly higher weight since it can make the mission a failure if not properly accounted for.

The single camera baseline design scored the highest in the trade study, and it excelled particularly in the resolution, complexity/power, and cost/weight/data metrics. Since the camera is expected to have 4K resolution, it will be able to meet the highest level identification requirements without issue. Additionally, since the camera is the only image sensor, it will be the easiest to integrate with the vehicle as it won't have to battle with vision or power issues from another sensor. The Single camera will be the most cost effective by itself, will trivially have the lowest weight out of the options, and has the least amount of data to transmit to the ground station without any overlap from other sensors. The only two issues with the single camera approach are the minimal field of view offered and the necessity of good visibility conditions to image, where it ties for the worst option in both cases. To meet the resolution requirements, the single camera has a limited field of view, which may necessitate either camera gimbaling or a scanning motion from the vehicle to allow for the camera to spot the target. Additionally, since the camera is dependent on the lighting and environmental visibility conditions, it won't be able to meet the mission requirements if operated at night or if these condition are poor.

The second option considered was the multiple camera approach, which came in third place in the trade matrix. The only advantage to using multiple cameras instead of a single one is the expanded field of view, which increases the likelihood that a target would be detected over a wider search path. The resolution and visibility constraints will be equal to the single camera, however employing multiple cameras would result in impactful drawbacks in the complexity/power and cost/weight/data metrics. Utilizing multiple cameras would require more difficult mounting to make sure that there is no image plane overlap, and that each camera has a clear line of sight with no other cameras in the way. On top of this, the power, weight, cost, and data sent would all increase by a factor of how many cameras are added.

The third option of using a thermal sensor along with a digital camera finished in second place in the trade matrix, where it excels in visibility and struggles in image resolution. Common thermal sensors used in industry and within the project budget have a much lower resolution than digital cameras, wherein these resolutions are too low to be able to detect a target from 400 feet altitude. The field of view would be the same as the single camera, and the complexity/power and cost/weight/data metrics would all be better than using multiple cameras but not as ideal as using a single camera. The uniqueness of the thermal sensor lies in its ability to image through poor lighting and environmental conditions, since it is only dependent on the heat signatures of the objects in its field of view. This benefit did not prove significant enough in the end, however, as the drawbacks from the other areas proved too costly.

The final option considered was a LIDAR scanner, which finished last in the trade matrix due to a few very costly drawbacks. The LIDAR will offer only enough resolution to be able to detect and potentially recognize the object, which doesn't satisfy the highest level of success of target identification that the camera options do. The LIDAR system additionally fails in its extreme complexity and power draw requirements, as well as in cost, weight, and data size. The LIDAR system would be many times heavier than any other payload option, and it would be extremely expensive to find a LIDAR scanner that can operate at the desired mission range. The primary benefit to employing such a system would be in its ability to easily scan a wide area in search of the target, as well as in its ability to find targets through foliage or through other objects that a camera or thermal sensor wouldn't be able to image through.

5. Selection of Baseline Design

The results of the trade studies conducted in the previous section are listed in table 5.1. The options listed there scored the highest among the alternatives and satisfied the trade's requirements; for these reasons they will constitute the baseline design of RAPTR.

RAPTR will be a rocket powered powered glider which will launch from a guide rod onto a glide path that will pass over the target area. The vehicle guidance will be controlled by an Ardupilot autopilot system. Attitude and Altitude information will be provided by a sensor suite composed of an accelerometer, gyroscope, magnetometer, GPS, and barometer. RAPTR will use a single camera to capture images of the target corridor. The camera will be internally fixed and point through an aperture. During testing, after the target zone has been passed and the mission completed, RAPTR will perform a belly landing to terminate the flight.

Trade	Selected Design Option	Description
Vehicle	Rocket Powered Glider	All of the options considered brought their own pros and cons to the table, but ultimately the rocket glider seemed to have the least cons and give the best of both worlds in terms of propulsion and simplicity.
Payload Mounting	Internal Aperture	Using the fixed internal mount with an aperture was selected as the best design option. This option is the least complex and will reduce software and hardware development times.
Landing Methods	Belly Landing	The Ardupilot autopilot being implemented on the vehicle and control surfaces will be utilized to facilitate a soft belly landing at the end of the vehicle's mission. This will provide significant control of the landing without adding much more complexity, weight, or cost.
Deployment	Single Variable Rod	A variable launch rod will be used to deploy the vehicle. This option will be able to deliver the optimal launch angle and be able to collapse and occupy only a small volume while providing launch stability on variable terrain.
Attitude Determination	Accelerometer, Gyroscope, and Magnetometer	A gyroscope will precisely control the roll, pitch, and yaw of the vehicle. An accelerometer will provide orientation data for the vehicle. A magnetometer will provide heading data to the vehicle
Altitude Determination	Barometer	A barometer will assist the GPS in providing precise altitude data to the vehicle
Autopilot	Ardupilot	The Ardupilot was found to be the best option for the autopilot platform of this project. This was largely decided by the capabilities of the platform itself as well as the plethora of resources to aid in the process of learning the autopilot software.
Imaging Sensors	Single Camera	The single camera will be used as the baseline for target imaging due primarily to the extensive benefits in resolution, lack of complexity, and low cost, weight, and data collected. This selection greatly simplifies the target detection, recognition, and identification process due to the single data source, and it enables more options for integration with the payload when compared to the alternatives.

Table 5.1. Selection of Baseline Design

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