University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

ANACONDA

ANtenna with **A**utonomous, **CON**tinuous, **D**ata tr**A**nsfer
Conceptual Design Document

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1.0 Information

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2.0 Project Description

The Research and Engineering Center for Unmanned Vehicles (RECUV) group at the University of Colorado-Boulder flies many different missions using Unmanned Aerial Vehicles (UAVs). Constant communication between the UAV and the ground station is required to receive data back from the aircraft to monitor its health and status as well as to relay high level commands from the ground station to the UAV. Up until now, the RECUV group has required an antenna to be pointed manually at the UAV while looking at a meter for signal strength. This is a draining effort for the team, especially if the mission duration is more than a few hours.

The ANACONDA project will design and construct an autonomous tracking and communication support system for an antenna or antenna array that is able to operate independently of other, pre-existing systems, and maintain constant communication between the ground station and the UAV up to a 30 km slant range. The antenna or antenna array shall herein be referred to as the "antenna system," while ANACONDA or ANACONDA project shall refer to the deliverables of the project as a whole. This antenna system needs to be transportable by fitting within a $1ft^3$ volume excluding support hardware, be able to be set-up by a single person in 10 minutes, and be mountable on the ground as well as on top of an unmodified vehicle. In either case, the antenna system must be raised to a minimum of 5 meters above ground level. The antenna system will need to be able to receive and transmit data at a minimum of 10 kbits/s from the UAV and, if communication is lost, needs to be able to reacquire the link within an allotted time frame of 20 seconds. This entails that the antenna system must have 360° continuous azimuthal coverage as well as -30° to 90° elevation coverage.

A successful project will eliminate the need for manual tracking and could allow the RECUV group to complete longer mission durations with a smaller crew. An autonomous system will also remove the need for human line of sight in order to communicate with the UAV and provide the potential for less error and a stronger radio signal. The ANACONDA project will be verified as successful by conducting tests to verify that its range, coverage, tracking, and signal characteristics perform as outlined above.

The specific objectives of this project have been summarized into three success levels, described below. The ANACONDA project will fulfill all of these levels for the highest success.

Level 1:
ANACONDA will be a completely autonomous UAV tracking system capable of maintaining communication between the ground station and the UAV. The antenna system and ground station will communicate through a USB connection, while the antenna system and the UAV will communicate wirelessly through radio at 2.4GHz. The antenna system will be able to be mounted from the ground, and will extend to an altitude of five meters. The system will run on 9-13VDC.

Level 2:
In addition to complying with Level 1 criteria, ANACONDA will relocate and reestablish connection with the UAV if communication is lost. The system will be mountable on both an unmodified vehicle and from the ground to an altitude of five meters. The system should have a volume of less than one cubic foot excluding the mounting supports.

Level 3:
In addition to complying with Level 2 criteria, ANACONDA will communicate with the UAV that travels up to 45 m/s ground speed within a specified sphere of influence. This sphere of influence consists of a 30km slant radius for 360° azimuth angle as well as a -30º to 90º range for the elevation angle. The communication between the antenna system and the ground station will be wireless. The communication between the antenna system and the UAV will be able to operate at both 2.4GHz and 900MHz with a transfer rate of at least 10 kbit/s. If communication is lost then the antenna system will relocate and reestablish connection with the UAV within a 20 second timeframe. The system will be easily transportable and can be assembled in less than 10 minutes by a single person. The ANACONDA system will be rugged enough to withstand winds up to 30 m/s, as well as environmental impacts such as dust and precipitation.

The deliverables for the project will include working hardware and software that achieve the requirements. A series of tests will be used to determine that the hardware and software designs have met the customer's requirements. There will be a tracking model developed for initial software testing to ensure that ANACONDA will perform as expected in a simulated environment. Software and data tests will be run to ensure that the electronics and software developed are running as expected. There will be an initial static test where the UAV is set at a known location to verify that ANACONDA can acquire the signal from the UAV. Once the static test is complete, a dynamic test will be performed to show that ANACONDA can resolve the location of a moving ground target. Finally, a full mission test of all functional requirements will be done using either a manned or an unmanned aircraft. Additional testing will be done to verify the ruggedness and weather resistance of ANACONDA by simulating adverse weather conditions such as rain, wind, etc. The UAVs that will be used for testing shall be borrowed from RECUV.

The Functional Block Diagram (FBD) and Concept of Operations (CONOPS) are shown in Figures 1 and 2 below to illustrate the mission layout and scope of the ANACONDA project.

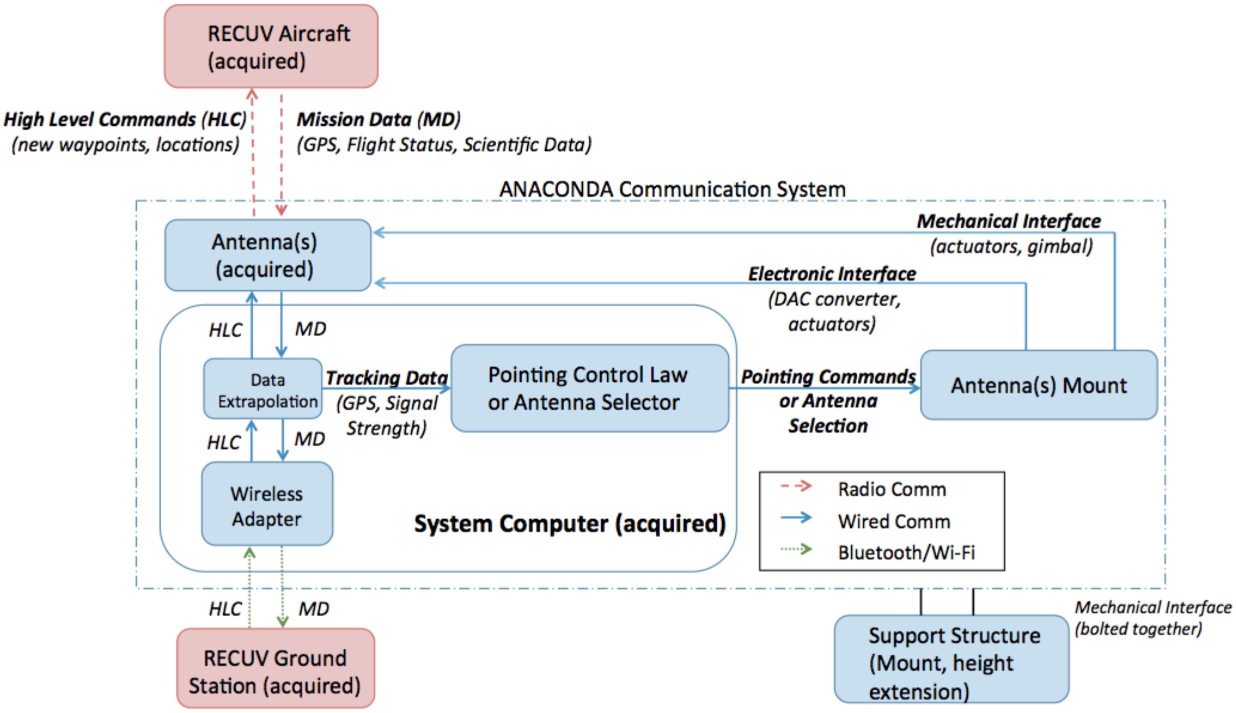

Figure 1: Functional Block Diagram for ANACONDA

As seen from the diagram above, ANACONDA will act as the communication liaison between the RECUV UAV and ground station. The RECUV UAV will broadcast Mission Data (MD), which will be received by the ANACONDA antenna system. The received signal will then be interpreted and data will be extrapolated from the signal. This mission data will be sent from the system computer to the RECUV ground station via a wireless adapter between ANACONDA and the ground station. The communications system must track the UAV in order to maintain a signal. The system computer will utilize the provided MD and interpret this data to derive tracking data, which will then undergo interpretation by a Pointing Control Law / Antenna Selector system. This Pointing Control Law / Antenna Selector will issue pointing commands to an Antenna Mount which will provide antenna redirect or switch the antenna currently being used electronically, mechanically or through a combination of the two. Continuous communication between the UAV and the ground station shall be achieved by repeating this process.

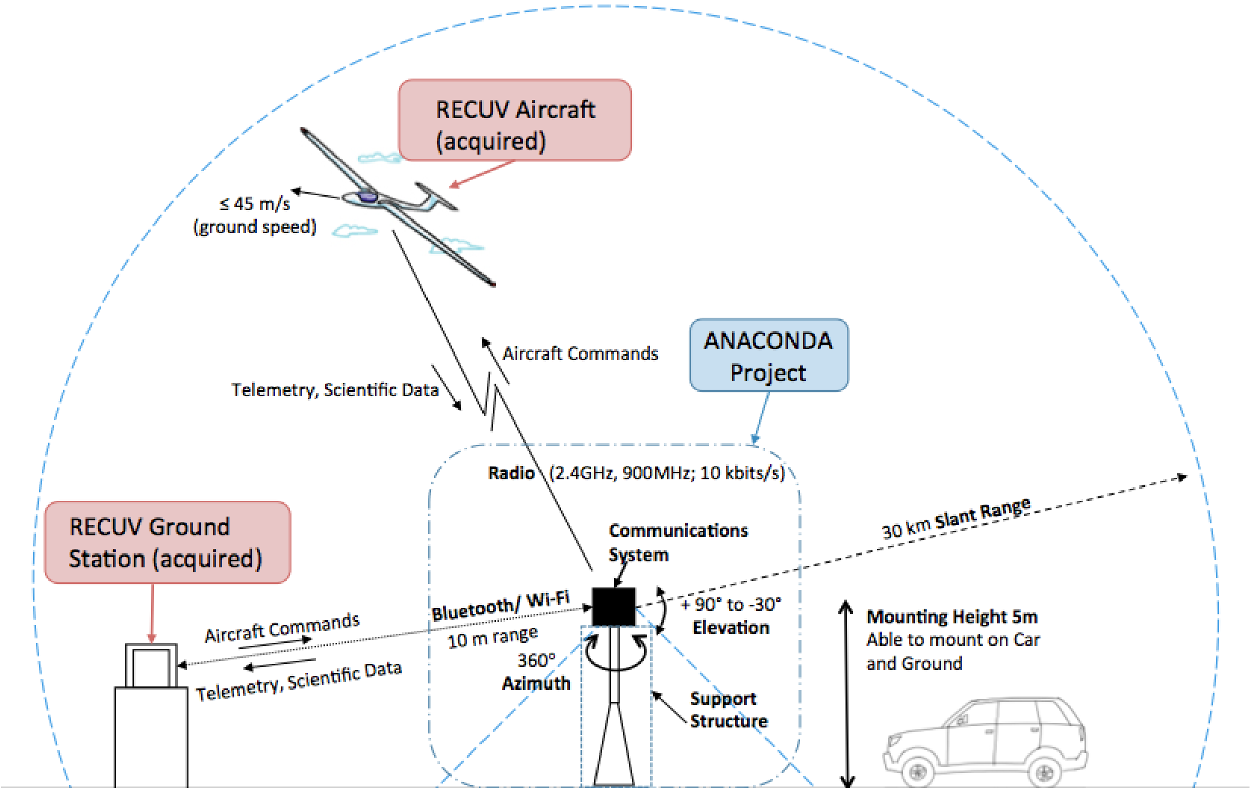

Figure 2: Concept of Operations for ANACONDA

The Concept of Operations diagram for the ANACONDA project can be found above in Figure 2. As discussed previously, the ANACONDA system will act as a communication liaison between the RECUV UAV and ground station, providing continuous data transfer between the two. As can be seen from the figure, the ANACONDA will communicate on either 2.4GHz or 900MHz frequencies, with a data transfer rate of 10 kbit/s. By supporting 360° azimuthal coverage and -30° to +90° elevation coverage within the 30km slant range, ANACONDA will provide communication coverage over the vast majority of the UAV's flight domain. The communication link achieved between the UAV and the ground station will be capable of sending mission data, such as telemetry and scientific data, down to the ground station and be capable of sending aircraft commands to the UAV from the ground station. As shown, ANACONDA will be ground and car mountable.

In order to ensure mission success, elements of this design project that are considered critical must be defined. The critical project elements (CPEs) for ANACONDA are stated below.

Technical:

The ANACONDA team must:

CPE.1.1 **Have an accurate model to predict the expected gain pattern of the system if an antenna array is chosen for the design.** An accurate model of the expected gain pattern of the system must be known in order to ensure a full 360° continuous azimuthal coverage. A facility will be needed to test the gain pattern of the antenna array. A nearby Boulder company, First RF, is a likely candidate but the team will need to seek permission from the company before testing can occur.

CPE.1.2 **Develop tracking and reacquisition algorithms.** While it is not mission critical if the signal is temporarily lost, it is critical that the link is regained within 20 seconds in order to prevent lost-signal flight termination. This will require time to develop and test an algorithm to reacquire the UAV position as well as time to develop and test an algorithm to track and maintain communication with the UAV.

CPE.1.3 **Be able to mount the antenna system to achieve 5 m elevation.** In order to maintain communication with the UAV with a greater slant range and less signal interference, ANACONDA must be mounted 5m above the ground. This type of mount is not readily available, and will need to be designed to be easily transportable in a car, and stable enough to withstand winds up to 30 m/s.

CPE.1.4 **Have a mechanical pointing system with a resolution sufficient for communication with the UAV if a high gain directional antenna is chosen for the design.** The pointing system will be comprised of off-the-shelf components but the overall assembly and interface between the electrical system, gimbal, and actuators will need be designed for this unique application. This will require a significant amount of time and resources for testing.

Logistical:

The ANACONDA team must:

CPE.2.1 **Acquire all legal permissions in order to test the antenna tracking system using either an unmanned or manned aircraft.** These rules are strict with regards to civilian air space, UAV restrictions, and radio communication. Without a method of testing it is impossible to fully validate the ANACONDA system.

CPE.2.2 **Acquire field equipment and software from RECUV in order to design for integration with existing hardware.** RECUV ground station software, UAV(s), transponders/radios, and vehicle charged power supply will need to be borrowed for the team to fully validate the ANACONDA system. This will require planning and collaboration with the RECUV team in order to fully test the ANACONDA system.

Financial:

ANACONDA has no critical financial elements at this time.

3.0 Design Requirements

Functional requirements (FNC.X) as well as design requirements (DES.X.X) for ANACONDA are specified below to improve project clarity.

FNC.1 The communication link between RECUV ground station and the UAV shall be provided by ANACONDA.

DES.1.1 The communication between ANACONDA and the UAV shall be independent from the communication between ANACONDA and the ground station.

DES.1.1.1 The communication system operation shall be autonomous (i.e. not dependent on the UAV ground control station for its functionality).

DES.1.2 ANACONDA shall communicate continuously with the RECUV ground station.

DES.1.2.1 Either WiFi (preferred) or USB shall be used for communication at a range of at least 10 m.

DES.1.3 ANACONDA and the UAV shall remain in communication.

DES.1.3.1 Communication link shall be acquired with a UAV flying up to 45 m/s (ground speed).

DES.1.3.2 Communication link shall be reacquired in less than 20 seconds after a communication link loss.

DES.1.3.3 Communication link shall be acquired with a UAV flying at a slant range of up to 30 km.

DES.1.3.4 Communication at either 900 MHz or 2.4 GHz shall be supported.

DES.1.3.5 ANACONDA shall comply with FCC EIRP limitations for ISM frequency bands. Testing will comply with all FAA, FCC, and local laws.

DES.1.3.6 The data rate shall be at least 10 kbits/sec.

DES.1.3.7 ANACONDA shall provide coverage to the volume enveloped by the 30km slant range, with a -30° to +90° elevation angle, and a 360° azimuth angle.

FNC.2 ANACONDA shall perform in various adverse conditions.

DES.2.1 The ANACONDA system shall survive adverse environmental conditions.

DES.2.1.1 Wind shall not disrupt the performance of ANACONDA.

DES.2.1.1.1 ANACONDA shall function in wind speeds of up to 15m/s, and remain intact in wind speeds of up to 30 m/s.

DES.2.1.2 Dust and Precipitation shall not disrupt the performance of ANACONDA.

DES.2.1.2.1 ANACONDA shall have an Ingress Protection level of IP53, so that the overall system will be protected against dust limited ingress (no harmful deposit), as well as direct sprays of water up to 60 degrees from the vertical. [1]

DES.2.2 The ANACONDA system shall survive human induced errors.

DES.2.2.1 If dropped from 3 feet onto an unpaved surface, ANACONDA shall be able to function properly without needing maintenance.

FNC.3 ANACONDA shall be portable.

DES.3.1 The Communication System shall fit in a volume of one cubic foot.

DES.3.2 The Support Structure for ANACONDA shall be transportable by an unmodified commuter vehicle.

DES.3.3 ANACONDA shall be able to be collapsed or separated into discrete bundles each weighing no more than 40 lbs.

DES.3.4 ANACONDA shall be able to be set up within 10 minutes by a single person without the aid of tools.

DES.3.5 The Communication System shall contain or utilize easy-to-switch radio bands, with antennas that can be switched at the mission site, if applicable.

4.0 Key Design Options Considered

In order to start viewing different design options for ANACONDA, the various design requirements must be considered. If the design team continued to view ANACONDA as a black box such as in the CONOPS for this project, what would it need to do? There are a limited number of designs for the Support System and most choices involve deciding between commercially-off-the-shelf (COTS) products, therefore the Support System of ANACONDA will not be considered in this trade study. Aside from the physical constraints, such as mass and size, the system would also need to be generally rugged and able to be weatherproofed. It must also be able to communicate with both the RECUV UAV and the RECUV ground station. Most of the components required for this project, such as the parts for the communication system, are available COTS, but will need to be reconfigured to fit the unique design criteria for this project. The software complexity as well as the ease of attaining the necessary slant range of 30 km will be driving factors in the design options considered. The initial flow down diagram for a trade study is shown in Figure 3. This flow down diagram shows the various broad options for antenna communication systems that were considered for this design project. A top-level conceptual analysis shows the three main antenna communication categories: stationary, semi-stationary, and non-stationary- each with varying degrees of freedom in their movement. From there, the team chose four primary conceptual designs to study within the three top-level categories.

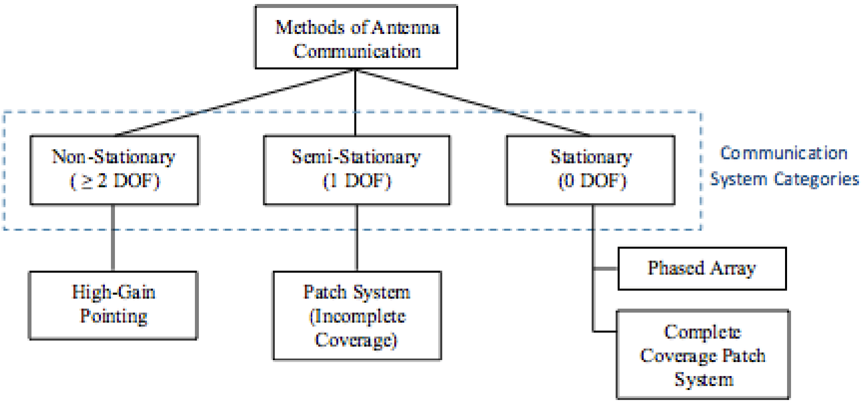

Figure 3: Methods of Antenna Communication Flow Down- Conceptual Designs

The antenna choice and configuration of the ANACONDA project will also depend on a link budget analysis in order to calculate the gain values necessary to achieve the highest success requirements. The initial link budget analysis is shown below in Table 2.

Figure 4 shows a diagram of RF communication between two antennas. This diagram can be used to perform a link budget in order to determine the necessary gain for the communications system of ANACONDA. A link budget is calculated by summing the power, gains, and losses from both the transmitter and the receiver as shown in Eq. (1).

$$P_r(dB) = P_t(dB) + G_t(dB) - Losses(dB) + G_r(dB) \tag{1}$$

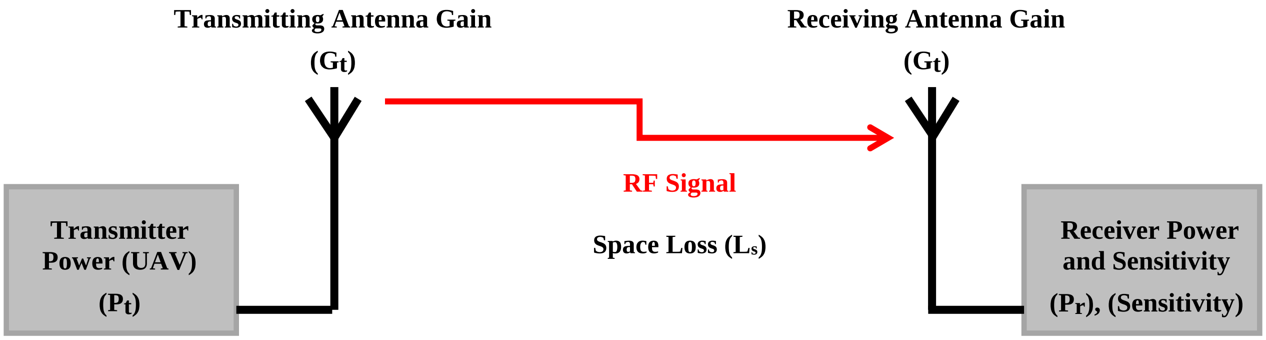

Figure 4: RF Communication Diagram.

Additionally, for all of the antennas considered (excluding the helical antenna) there is a polarity issue. If the UAV were to bank 45°, there would be a -3 dB power loss. This loss is significant at the 30 km slant range and would require a larger receiving antenna gain to account for it. The transmitting radio power and sensitivity are known for RECUV's UAVs and can be seen for each radio frequency considered in Table 1. The gain used for the UAV antenna is a 2dBi whip antenna. Here the unit dBi is the decibel gain ratio of the actual antenna to an isentropic radiating antenna. The unit of dBm, seen in Table 1 below, is the power ratio in reference to 1mW.

Table 1: RECUV Antenna Radios.

Frequency	2.4 GHz	900 MHz
Radio	XBee-Pro 2.4 [2]	XBee-Pro 900HP [3]
Power (dBm)	18	24
Sensitivity (dBm)	-100	-110

Using the UAV as the transmitter and the ANACONDA Communications System as the receiver, the link budget was calculated and can be seen in Table 2 below. The receiving radio for the Communications System is kept at the same value as that of the UAV for this link budget analysis.

Table 2: Link Budget Analysis.

Term	Value (dB)	
	2.4 GHz	**900 MHz**
Transmitter Power, P_t	18	24
Transmitter Gain, G_t	2	2
Space Loss, L_s	-130	-130
Polarity Loss, L_p	-3	-3
Receiver Gain, G_r	G_r	G_r
TOTAL	**G_r - 113**	**G_r - 107**

The receiving antenna (ANACONDA Communications System) was calculated to have a design margin of 2dB above the noise floor at -95 dB. The results from the link budget show that a 20dBi gain antenna is needed for the 2.4GHz signal and a 14dBi gain antenna for the 900MHz signal. However, this does not include other possible losses and interferences due to the cables, the atmosphere, or multipath.

Keeping this link budget in mind, the four main categories of antenna design options that were considered are elaborated upon below.

High-Gain Pointing Antenna

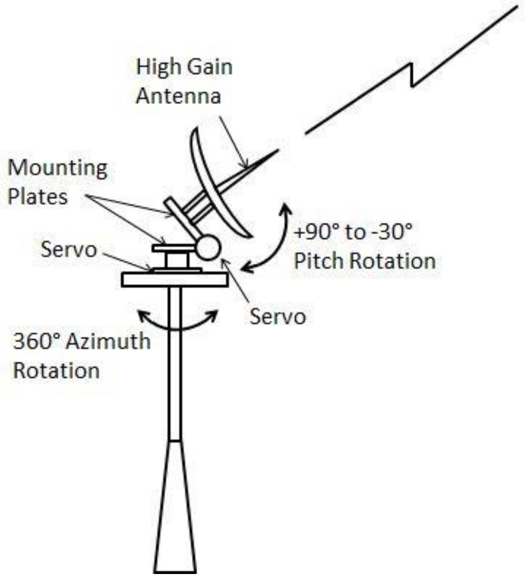

Figure 5: High-Gain Pointing Antenna Conceptual Design.

The pointing antenna design involves one high-gain antenna that is physically pointed at the UAV so that the UAV remains inside the gain pattern for the antenna. The Communications System would track the UAV primarily by intercepting the GPS coordinates emitted by the UAV prior to relaying the data to the ground station. In the event that the communication is lost, a searching algorithm would be initiated and would use signal strength to reacquire the link.

To achieve the elevation and azimuthal coverage requirements with a single antenna, the mechanical assembly that would need to provide two degrees of freedom for movement. The antenna is required to be able to rotate 360° continuously for azimuthal coverage, and is required to be able to pitch between -30 and 90° (where 90° is straight up relative to the earth). The azimuthal coverage would be handled using a gear motor that can rotate in either direction, and must be able to continuously rotate indefinitely. This rotation will provide a design challenge as the system must provide a method to prevent extraneous power or communication wires from tangling around the base of the system. The pitch axis would also use a gear system to rotate a mounting plate that attaches to the antenna. Both motors would be internally controlled by the communications system, and would require the development of control laws to take GPS coordinates as inputs to control the motors in order to point the antenna to the desired location.

Tracking the UAV is a critical part of this design option. The UAV transmits its location in GPS coordinates as part of its data package. The communications system would unpack the data, read the GPS coordinates and then repack the data so that it could be relayed to the ground station. This requires software to parse the UAV data packages, and will only work while communication with the UAV is maintained. If communication with the UAV is lost, the antenna will enter a search pattern to regain communications. The search pattern may be a programmed routine, like a spiral search or signal strength dithering, but could be intelligently directed by utilizing methods such as velocity and position prediction from the GPS data that was acquired from the UAV while communication was still intact.

While this system uses multiple motors to point the antenna, the antenna itself and its mounting structure are the largest parts of the design. This means that the physical system could be designed to fit into the 1 cubic foot volume requirement, since many of the components are small with the exception of the antenna itself. L-Comm, 2.4 GHz reflector grid antennas range in outer volume from 0.3079 cubic feet to 8.332 cubic feet for a 15-dBi antenna and a 27-dBi antenna respectively [4,5]. This system also requires two sets of moving parts, with the motors to move the antenna. These moving parts may not survive an impact as well as a system that does not contain similar moving parts and they are more likely to fail due to usage fatigue. The motors may also need to be geared to attain a good slew rate for tracking a fast-moving aircraft. The fastest aircraft speed that the pointing system would have to track is 45 m/s ground speed. The most difficult tracking case for the pointing system would be if the aircraft were flying at maximum speed straight over the pointing unit at a close range. This case would require the largest slew rate for the controls, and would require the most coupling between the two planes of control. Additionally, the two degrees of freedom provide added complexity to weatherproofing the system relative to a stationary system as the gears and moving parts must meet the requirements.

The overall cost of such a system would be driven by the antenna and the cost of the gimbal. The L-Comm 2.4 GHz reflector grid antennas range in price from $39.95 to $199.95 for a 15 dBi antenna and a 27 dBi antenna respectively [4,5]. COTS 2 axis gimbals come in a range of prices depending on the size, speed, resolution, and power required by the systems. Comparable systems seen in the RECUV shop utilize gimbals such as the ServoCity PT785-S pan and tilt system, which costs $349.99 [6]. It is important to note that it is also possible for such a system to be custom designed by the team to specifically fit our own application for the cost of the motors and materials.

The last concern for this system is the room for error apparent in the combination of data and controls used to track the UAV and point the antenna. While GPS is a preferred method for locating the UAV, it contains error in its measurements, particularly in the altitude dimension. This would be most noticeable at closer slant distances because the angles for the slant location of the UAV would be larger, and the error would be magnified. The motors or servos would also need to be calibrated accurately so they have an accurate reference to feed into the control law for their position. The control law also needs to be designed so that the result of applying the law yields the expected result with little offset (which would likely require a component of integral control). If the combination of GPS error and calibration errors for the mechanical pointing systems is sufficiently great, the UAV may remain outside the gain pattern of the antenna, and will suffer communication loss more frequently than expected.

Table 3: Pros and Cons for High-Gain Pointing Antenna Design Option.

Pros	Cons
Potentially only needs one antenna	Moving parts may be damaged after fall (less rugged system)
Smaller system, easier to meet volume constraint	May be hard to track if aircraft is moving quickly and overhead
Gives visual cue as to location of the aircraft	Controls and tracking both have potential for error

Phased Antenna Array

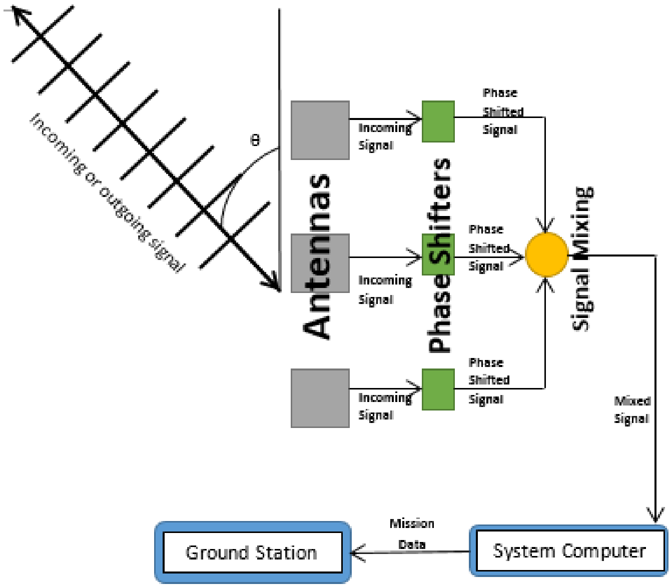

Figure 6: Phased Array Antenna Design Concept.

The phased antenna array communication system relies on the principle of using multiple antennas acting together to form a single summing antenna array system. This system acts much like a directional, high gain antenna, but without the need for mechanical pointing. Since a waveform takes time to propagate through space, any non-perpendicular waveform incident on the antenna array will strike the closer antennas before striking those further away, as shown in Figure 6. While only the signal received situation is shown, the process could be reversed to send out commands to the UAV.

By offsetting each antenna's received signal by a certain phase angle, the antenna can electrically combine the received signals to create an overall stronger signal. The required phase shift angle can be found using Equation 2, where ψ represents the phase shift between adjacent antennas, θ represents the angle of incidence of the signal on the antennas, and λ represents the wavelength of the signal.

$$\psi = \frac{2\pi d*\sin(\theta)}{\lambda} \tag{2}$$

Since the strength of the received signal is dependent upon the number of antennas involved in the system, and the needed antenna gain can be found using the aforementioned link budget (10 dB for 900 MHz, and 18 dB for 2.4 GHz), the number of antennas needed to fulfill the 30km slant range of DES.1.3.3 can be found using Equation 3:

$$\Delta Sensitivity_{array}(dB) = 10 * log_{10}(N) \tag{3}$$

By solving for the number of antennas needed (N), based on the needed additional gain of the antenna array from that of a single antenna $(\Delta Sensitivity_{array})$, and using a 5 dB gain whip antenna as a sample, it is found that for 900 MHz, at least 8 antennas are needed, while 2.4 GHz requires at least 32 antennas. For example, while using a 5 dBi gain single antenna for the 2.4 GHz signal, the array of these antennas must make up the 15 dBi sensitivity difference. Thus, 15 dBi can be used as the difference in sensitivity, and the number of antennas is found. Since these antennas are omnidirectional- and simply shifting the phase of a line of antennas changes the gain pattern to point along that plane- a two dimensional array of antennas could provide three dimensional omnidirectional coverage, fulfilling the coverage requirement; DES.1.3.7 [7]. The power allowed for transmission is regulated by the EIRP band limitations. At a required antenna array gain of 15 dBi for 2.4 GHz, the maximum power the array transmitter can have is 21 dBm. This is calculated from understanding that a 20 dBi antenna gain is required for 2.4 GHz. The phased array requires transmission power of 18 dBm, which is within legal limits [8].

By changing the spacing of the antennas, a beam width can be chosen, thus allowing for higher or lower resolution at longer ranges. Naturally, a trade off exists, as higher accuracy pointing creates a higher degree of complexity in reacquiring lock, and thus better software will be required[7]. Omnidirectional, high gain antennas range from 5dBi for around $22[9], to 8dBi for around $140[10] .Real-time phase shifters can be acquired for approximately $36 each [11], and frequency mixers can be acquired for roughly $7 [12].Since this method involves mixing multiple signals, only one radio would be necessary, but it would require the implementation of a computer controller over the phase shifters. Therefore, for every antenna needed, approximately $60 in cost would be added to the antenna system. So long as the cost of each antenna and its respective phase shifter is kept relatively low, this approach to antenna communication could prove to be economically feasible, but has the potential to increase the total cost.

In addition, this antenna system may prove to be the most complex in terms of software, as it not only requires precise tracking methods and algorithms, but also requires additional understanding of how electrical phase shifters can be controlled and manipulated by a computer using the needed phase shifting precision. Overall, the software is more complex relative to other antenna systems as it adds an additional level of phase shifting and signal mixing. The design group has minimal experience in both of these areas.

Table 4: Pros and Cons for Phased Array Antenna Design Concept.

Pros	Cons
Increased durability and reliability from no moving parts	Many antennas and phase shifters needed, creating a potentially high cost compared to other designs.
Designable focus of beam to ignore background noise and better provide quality tracking	Advanced concepts with minimal current understanding
Easy to switch between transmit and receive	Difficult to program or calibrate
Can compact into one cubic foot easily	Requires two different arrays for 900 MHz and 2.4 GHz.

Fixed Antenna Array

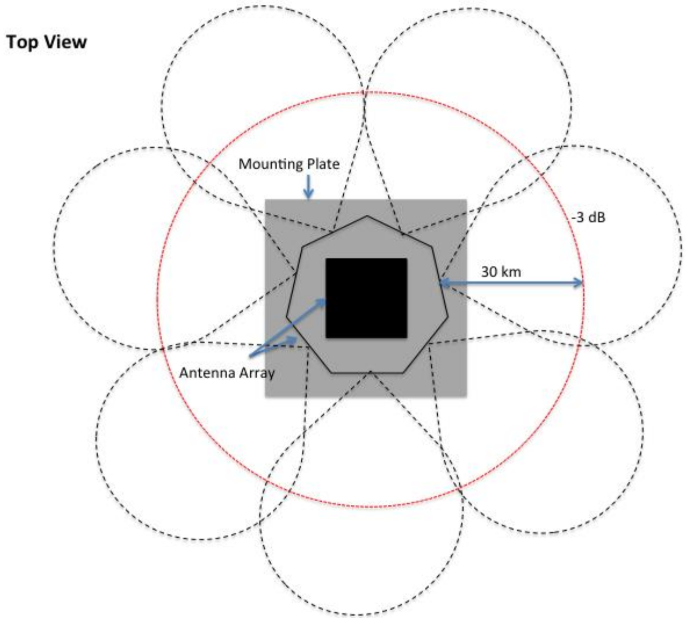

Figure 7: Fixed Antenna Array Design Concept.

For this design solution, multiple antennas would be set up such that the array will span a full 360° azimuthally with an elevation angle ranging from -30° to 90° without any system movement and without combining the antenna signals, like in a phased array. There are several types of antennas that could be used for this method.

One antenna that could be used is the patch antenna. A patch antenna could not be found above 12.5 dBi at 900 MHz [13]. If this design were chosen, the patch antenna would have to be designed. Likewise for 2.4 GHz, the highest gain found was 19 dBi [14]. For this design solution, the range will be difficult to achieve with a patch antenna. For the 12.5 dBi patch antenna at 900 MHz, the half power beam width is 42° (vertical and horizontal) [13]. A minimum of 9 antennas would be needed to get 360° azimuthal coverage. An additional antenna would then be needed to get the full elevation range. At 2.4 GHz, the 19 dBi patch antenna has a 18° half power beam width (vertical and horizontal), which would require a larger minimum amount of antennas than the 900 MHz case [14]. After designing a patch antenna with a higher gain, the beam width would decrease, and the minimum number of antennas would increase. The weight for each antenna ranges from 2 to 4 lbs., which equates to a total weight of 20 to 40 lbs., assuming the minimum of 10 antennas is sufficient to meet both coverage requirements [13, 14]. The surface area of both the 900 MHz and 2.4 GHz is 15.4 in^2 [13, 14]. The maximum input power would be around 30 W per antenna [13, 14].

The software needed for this design solution would include simple signal strength checks to determine which antenna within the array will communicate with the UAV. GPS could be used with signal strength for predictive tracking. Software for this, however, will need to be optimized to quickly parse the data packet coming from the UAV for the GPS data. The most difficult mechanical aspect of this method would be to electrically connect all the antennas, and to attempt to arrange or fold the array in such a way that it does not exceed the volume restraint. Once the array is mounted, a plastic dome could simply be placed over the array to weatherproof it.

Table 5: Pros and Cons for Fixed Antenna Array Design Concept.

Pros	Cons
No moving parts	Would require a large number of antennas
No concern with regards to angular resolution of the motor	Software algorithms would need to be optimized to minimize computation time if predictive tracking is used. Data packets will need to be parsed quickly to obtain GPS data before they are sent to the ground station
Track at any speed	Volume restraint violated due to the large number of antennas needed
Easy to weatherproof as there are no moving parts	Antenna will need to be designed to reach 30 km range
Tracking software will need only compare signal strength between all the antennas	

Semi-Stationary Antenna Array

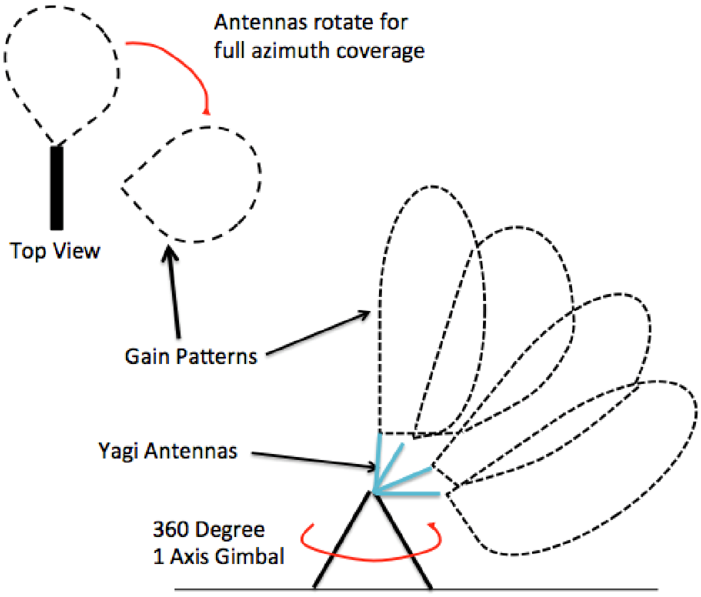

Figure 8: Semi-Stationary Antenna Array Design Concept.

A semi-stationary array contains concepts from both the completely stationary array as well as from the pointing method with a single high gain antenna. A semi stationary array would use, at minimum, 4 yagi antennas for 900 MHz oriented at different vertical angles. As stated earlier in the link budget, each 900 MHz antenna would need to have a maximum gain of 14 dB in order to meet the range requirements. This gives each antenna a horizontal and vertical coverage of about 30 degrees 3dB beam width for typical antennas of this gain[15]. This allows for total coverage of the required elevation angles with four antennas. The two antennas would be mounted on a single-axis rotating gimbal, which allows for coverage of the entire azimuthal area. Commercially available antennas of this size are usually around 43 inches long. For 2.4 GHz, 20 dB antennas would need to be used in order to meet the range requirements. Commercially available 18 dBi yagi antennas typically have 20° horizontal and vertical 3dB beam width[16], requiring 6 antennas to cover the entire elevation angle range. If 20 dB antennas were used, even more antennas would be required. One advantage to the semi stationary array is that the 360° continuous azimuthal coverage is achieved with only one actuator, making it simpler than the purely pointing design. This design will also require fewer antennas than a completely fixed array in order to provide the same coverage. However, having multiple antennas requires a radio for each antenna, increasing the electrical complexity of the project compared to a single high gain antenna. Additional antennas and radios require a method to choose which antenna to use for receiving and sending data. At 900 MHz the antenna array would require fewer antennas than at 2.4 GHz. This is because the wavelength at 2.4 GHz is smaller leading to a smaller beam width, thus more antennas are needed to cover the coverage space.

Using more antennas increases the overall size and weight of the array. This design will have higher costs associated with purchasing more radios, antennas, and a gimbal/actuator, making it more expensive than a pointing system or phased array system. This design will not be more expensive than a fixed array system since the extra gimbal will not cost more than the additional radios and antennas that need to be purchased for the fixed array. The software for this design will include a tracking algorithm using GPS or Radio Signal Strength (RSS) that tells the gimbal which direction to point, as well as an algorithm that chooses the strongest antenna signal to be relayed back to the ground station. This software will be more complex than a completely fixed array, as it includes a tracking algorithm, but will not be as complex as a phased array as it requires no signal mixing. Weatherproofing of this design will be more difficult than a stationary system since it must move, and the joint must be water/ dust proof, as well as impact resistant.

Table 6: Pros and Cons for Semi-Stationary Antenna Array Design Concept.

Pros	Cons
Simple mechanical and tracking software	Somewhat mechanically complex (minimum 1 axis of rotation)
Requires fewer antennas than a completely fixed array	Many antennas are required with 2.4 GHz
Design challenge of continuous azimuthal coverage is easily met as system does not have to rotate 360°	Need at least one radio for every antenna, results in increased electrical complexity
	Takes up more space with more antennas relative to a single high gain antenna

5.0 Trade Study Process and Results

While individuals may have a specific design in mind, and thus show bias towards a particular concept, it is essential for project success that the “best” design solution is chosen for further analysis. This “best” design solution can be quantitatively found using a trade study. This "best" design solution was chosen by attaching weights to critical design parameters, rating each design on a scale of 1-5, and summing the score of each design. In general for this trade study, a score of 1 is considered least desirable, while a score of 5 is considered ideal. The weighting of each parameter was based on the group’s perceived difficulty of optimizing that parameter, as well as how critical it is to mission success. These weights were applied relative to each other in the trade study.

While pros and cons of each design option were provided, the trade study provides a quantifiable means to suggest the “best” solution. Trade studies also eliminate designs that do not prove to be the best solution. Thus, a trade study was conducted based on the parameters that are most pertinent to this project. Below in Table 7 is a detailed description of each parameter and why it is important to the overall design.

It must be noted that range is very important to consider in the design of the ANACONDA project. The functional requirement of a 30 km slant range will be challenging to achieve. As each design option must meet this range requirement, it is not a parameter of the trade study. However it is important to note that each of the parameters below have a direct impact on achieving a 30 km slant range and will be factored into this analysis.

Table 7: Trade Study Parameters, Weights, and Reasoning.

Parameter	Description	Weight	Scale (1-5)
Mass	While there is no functional requirement specifying a maximum weight of the ANACONDA system, it is an important parameter to consider, as it directly affects the set-up time, portability, and safety of the system. The maximum level of success requires that the ANACONDA system must be able to be set up by a single person less than 10 minutes and must be easily transportable. The lighter the system is the easier it will be to transport and carry. In terms of safety, a lighter weight system provides the benefit of having less destructive potential in the event of a support system failure.	0.15	1: indicates a high mass (≥ 40 lb) 5: indicates a low mass

Size	The size parameter has two important metrics; the storable volume and the surface area of the deployed system. A requirement of the system is that it must be able to be transported in a one cubic foot volume. Even with this requirement, a smaller system will give RECUV many advantages. The other metric is the surface area of the deployed system. This is important because the antenna system will be mounted 5 m above the ground and must be able to remain standing in 30 m/s winds. Initial calculations have shown that the drag force on the system will vary up to an order of magnitude for various parabolic antennas. Thus, attention must be paid to the drag force created by the geometries and surface areas of the Communications System.	0.2	1: indicates a large size and surface area 5: indicates a small size and surface area
Weather-Proofing Ease	The ANACONDA system must be weatherproof in terms of resistance to dust and precipitation. The metric being measured here is the relative ease of weatherproofing the design rather than the amount of weatherproofing. For example a stationary system will be easier to weatherproof, as no motion of the system is required.	0.1	1: indicates the system is difficult to weatherproof 5: indicates the system is easy to weatherproof
Software Complexity	Regardless of design choice, software will be required onboard the system in order to process incoming information and relay it to either the ground station or the UAV. However, some designs will require advanced pointing or tracking systems that will add significant complexity to the algorithms. As software is the component with which the ANACONDA team collectively has the least experience, software complexity is an important metric to the design.	0.25	1: indicates coding will require complex algorithms 5: indicates a minimal amount of coding is required
Mechanical Complexity	Several metrics that contribute to this parameter. Complex mechanical systems include several small moving parts. Many moving parts will be less rugged in terms of drop resistance. Another concern with this is the added risk of failure due to friction, sealing, and wire routing. Another metric is the manufacturability of the system. Complicated gimbaled designs will require more time and design effort to develop an accurate pointing system relative to a stationary design.	0.2	1: indicates that the system requires many moving parts or custom manufacturing 5: indicates mechanical design will be minimal
Obtainability/ Cost	While many of the components of this project are available off the shelf, the overall cost and obtainability of parts will affect the final design option. Lower cost will be important to ensure that the project stays under budget, but it is not a design driving parameter.	0.1	1: indicates the system is expensive or requires components that are not available 5: indicates the system is inexpensive and parts are accessible

The trade study for ANACONDA antenna design concepts is shown below.

Table 8: Trade Study for ANACONDA Design Concepts.

Parameter	Weights	Pointing	Phase	Semi-Stationary	Fixed
Mass	**0.15**	**3**	**4**	**2**	**1**
Size	**0.2**	**3**	**2**	**2**	**1**
Weather-Proof	**0.1**	**3**	**4**	**4**	**5**
Software Complexity	**0.25**	**4**	**1**	**3**	**4**
Mechanical Complexity	**0.2**	**2**	**4**	**3**	**5**
Cost	**0.1**	**3**	**2**	**3**	**1**
Total	**1.0**	**3.05**	**2.65**	**2.75**	**2.95**

6.0 Selection of Baseline

The pointing method was chosen based on its score in the trade study and other qualitative advantages. The mass of the pointing method was a midpoint between phased, which would be the lightest since only whip antennas are needed, and fixed, which would require multiple antennas. The pointing method would only require one antenna thus limiting the antenna weight, but would require more mechanical hardware.

The size of the pointing method scored better than the rest, because it would contain only one antenna while all other options require multiple antennas. The mounting would only need to hold the gimbal system and not multiple antennas like it would for the rest of the choices. Furthermore, the wet surface area of a grid antenna used for a pointing system is smaller than the other designs, thus limiting the drag force induced by the wind requirement.

The ANACONDA must withstand dust and rain to the standard described in design requirement 2.1.2.1, and the ease of weatherproofing each design was factored into how each option was scored. The pointing method has more moving parts, giving it a lower score than the fixed or the phase antennas, which don't move. The phase antenna also has no moving parts, but requires more electronics, and was ranked almost as low as the pointing antenna. Even with this drawback, the pointing method was not given a minimum score, which indicates that it is possible to meet the requirements, but it will require more design.

The software complexity of the pointing method is equal to the fixed array because they both only have one main process to perform. The pointing method does have to move the antenna in two degrees of freedom but the only process required is to point the antenna. The fixed array process must choose the best antenna in the array for data transfer. The semi-stationary would require the software to track the UAV azimuthally as well as choose which antenna to use for data transfer. The phase method would require the most complicated software because, in addition to the algorithm to point the beam, and similar to the pointing method, the phase method also requires the algorithm to synchronize each of the antennas through phase shifting making this the most complex of all the options traded.

The mechanical complexity of the pointing method is the most difficult out of all of the design options because it has the most moving parts. This will make it the most difficult to ensure that it is rugged enough to meet the requirements explained in DES.2.2.1. The phase method would have the least moving parts and would thus be more simplistic in the mechanical aspect.

The cost of the pointing method would be one of the lowest because there is only one antenna required contrary to other methods which might require more antennas. Buying or machining the gimbals will be manageable and can be accomplished without much financial difficulty in comparison to the phased method which would require two completely separate systems to achieve both the 2.4 GHz frequency band as well as the 900 MHz. The semi-stationary would be slightly more difficult to accomplish than the pointing method because the cost of having multiple antennas would limit the design range of that method.

Moving forward after the trade study, it is clear that the pointing method is the baseline design choice of this project. With a score of 3.05 out of 5 the pointing method is the most favorable out of all the options that were studied. The next closest was the fixed method with only 3.28% difference between them, 0.10 out of 5, this could have been a viable option however this method received three ones indicating undesirable traits. The pointing method has the best score overall due to the fact that is has high scores in the most heavily weighted areas, and did not receive any ones in any of the categories. When it comes down to the most critical parts of the project, the pointing method succeeds over its competitors.

Now that the pointing method has been selected as the baseline design the ANACONDA team will move forward to implement this idea. Although the overall system has been selected, many options remain as to which antenna will be best for this system as well as types of gimbals. This design will keep both the 900 MHz and 2.4 GHz frequency bands in mind such that to switch bands used by the system will require a simple antenna change without modifying the rest of the system. Research will be conducted on commercially available gimbal systems to determine if it will be more beneficial for the team to purchase this component or if a custom gimbal needs to be designed. Additionally a support system will be designed in order to mount the antenna system on both a car and ground in compliance with DES.3.2 and DES.2.1.1.1.

7.0 Resources

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