Systems Engineering Approach:

Mission Requirement Analysis:

It was determined that the Unmanned Aerial System (UAS) must be able to fly a 4-mile waypoint path, carry and release an autonomous rover, and search for objects. This must all be done within 30 minutes and while avoiding stationary obstacles.

The design decision that needed to be made was to choose either a fixed wing or rotary wing platform. Fixed wing platforms can quickly fly the waypoint path and maintain good endurance while carrying heavy objects, such as the autonomous rover. These attributes allow them to maximize available search time and relax rover weight limits. However, rotary wing platforms' ability to hover and instantaneously change direction make the release process of the rover significantly less risky and the search program much simpler to create. After evaluating these factors, it was decided that we would build a lightweight quadcopter with T-Motor MN4010 motors paired with 16" propellers to capture the benefits of rotary wing platforms while still providing sufficient heavy lift capability and flight efficiency. Using the motors, Electronic Speed Controllers (ESCs), and propellers that we already owned also relieved strain on our limited budget.

Design Rationale:

Five requirements were identified for the UAS to meet: autonomous flight; obstacle avoidance; object detection, classification, and localization; and air drop. To meet these requirements, we had 2 computer science student hours per week, 6 aerospace/mechanical engineering student hours per week, and a $800 budget. We chose to include the Ardupilot autopilot system in our design to meet the autonomous flight and object avoidance requirements. This open source autopilot system is capable of piloting UASs through a series of waypoints, and it is also Mavlink compatible so the Artificially Intelligent Control System, EagleEye, can command the UAS through the layer of abstraction provided by the autopilot, allowing for simpler implementation. These features aren't present in simpler autopilot systems including Cleanflight, Multiwii, etc. The only other system we investigated that had similar features was the Vector system, but its difficulty of integration with EagleEye made choosing Ardupilot an easy decision.

We chose to create EagleEye because it makes autonomous search possible. EagleEye is composed of two parts: a rotation invariant character detection computer vision algorithm and a navigation program that chooses an unexplored target and guides the UAS toward it. Additional features in the pipeline include obstacle avoidance and altitude control. We explored currently available commercial and open source solutions to achieve these tasks, but none of them contained the feature set that we were looking for, so we built EagleEye on the OpenCV library ourselves.

The decision was also made to run EagleEye on the Ground Control Station (GCS) instead of onboard the UAS because EagleEye is too resource intensive to run on a Raspberry Pi in real time. We have much more computing resources on the ground, and the transmission of the video through a 5.8GHz analog First Person View (FPV) system to a ground Analog to Digital Converter (ADC) to get the video feed to the computer introduces less than a second of latency. The transmission of Mavlink commands back to the autopilot through the 900MHz telemetry link is near instantaneous. EagleEye sends only position change commands, never velocity commands, so short dropouts and latency have minimal impact on its safety and performance. Running it airside would either require significantly down sampling images, which reduces object detection accuracy to undesirable levels, or waiting over 10 seconds for each frame to be processed and acted on, significantly slower than the less than one second processing time on the ground, even when combined with the transmission overheads.

System Design:

Aircraft:

As mentioned in the mission requirements analysis, we chose to design a quadcopter with four T-Motor MN4010 brushless motors with sixteen-inch diameter propellers to create an efficient, heavy lift, hover-capable UAS. As can be seen in Table 1, the 13.51 grams of thrust per watt was better than the best efficiency we could get compared to any other power system combination we found that was within our budget. A carbon fiber airframe with 12-inch-long cylindrical booms was chosen to minimize weight and maximize endurance. Diagrams of the UAS are included in Figure 1 and 2.

Autopilot:

An APM 2.5.4 running Ardupilot 3.3 is used by the UAS. It abstracts away the Pulse Width Modulation (PWM) motor control, sensor reading and processing, and Proportional Integral Derivative (PID) control to allow EagleEye simple position control of the UAS. This forms part of the foundation for the system that underlies every mission task. The autopilot also provides waypoint and failsafe functionality (automatic return to home). A picture of the associated GCS, Mission Planner, is attached in Figure 3. Mission Planner provides monitoring functions of all sensors including RC input, gyroscope, accelerometer, compass, Global Positioning System (GPS), barometer, current draw, battery voltage, and telemetry signal strength. It also provides the interface for uploading waypoints, initiating Return to Home (RTH) failsafe in emergencies, changing flight modes, and adjusting autopilot settings.

Obstacle Avoidance:

EagleEye's obstacle avoidance module is being designed to use A* search to find the optimal path around obstacles for the UAS to take to get to its goal location. The states are modelled as latitude, longitude, and altitude above ground level (AGL) arrays each one meter away from the surrounding 6. The actions are modelled as moving in one of the four cardinal directions by one meter, or up or down one meter. Any action that would send the UAS into an obstacle is considered invalid. The heuristic used is the straight-line distance from the UAS to the goal location. The goal is considered reached when the UAS is within one meter of the goal. Once the optimal path is found, it is converted into a series of waypoints and sent to the autopilot.

Imaging System:

The imaging system consists of a Xiaomi Yi camera outputting analog video through the USB port to a 5.8 GHz analog video transmitter. A 5.8 GHz analog video receiver receives the video on the ground and feeds it via RCA to an EasyCap USB ADC. EagleEye then receives the video input and acts on it. This imaging system was tested at an altitude of 80 feet with sample objects and had perfect success identifying and classifying them in real time. The camera also records to a SD card for easy post-processing of video should the unlikely circumstance where an object isn't classified successfully.

Object Detection, Classification, Localization:

EagleEye is built on a rotationally invariant convolutional neural network model that was trained on letters of various fonts randomly rotated and overlaid on various images of fields downloaded using the google image downloader tool. This model detects and classifies the letters and bounds them in a box. The box is then cropped out of the image and canny edge detection is run on the result. Next, an array of geometric shape detection algorithms is run on the image and the one with the highest confidence is chosen as the background shape. The shape is then cropped out of the original image and a color histogram is generated with the result. The color that appears with the highest frequency is chosen as the background color, and the color that appears with the second highest frequency is chosen as the letter color. Finally, the location of the object is assigned based upon the offset from the center of the image, the pitch and bank of the quadcopter, and the quadcopter's location and altitude by simple trigonometry.

Communications:

2.4 GHz Radio: This radio sends manual controls to the UAS. It controls the autopilot mode through the receiver and allows for manual override of control in emergencies.

5.8 GHz FPV: This video system sends video from the UAS to the GCS through an analog transmitter and receiver.

915 MHz Telemetry: This sends UAS sensor information to the GCS and waypoints from the GCS to the UAS. It is a bidirectional link.

A diagram can be found in Figure 4.

Air Drop:

The payload is a rover carrying a water bottle. It is dropped by a winch system that allows the UAS to hover at 30 feet and slowly lover the rover to the ground. This system guarantees that the rover with touch the ground right-side up and prevents bouncing. The optimal drop time is when the UAS is directly above the drop zone and has stopped moving.

Cyber Security:

Security is a concern for UASs because they present a physical danger as large flying objects. Therefore, we chose a Futaba frequency hopping radio system that requires receiver binding to prevent hijacking of control. Additionally, we changed the telemetry module Net ID to a random ID to prevent hijacking of the autopilot. Finally, we have implemented failsafe measures to terminate flight if the UAS should ever leave the flight area. They turn off all motors to prevent further flight.

Safety, Risks, and Mitigations:

Developmental:

The developmental process involved the generation of dust, Volatile Organic Compounds (VOCs), sharp objects, and high voltages. These risks were mitigated by using Personal Protective Equipment (PPE) including safety glasses, goggles, masks, respirators, gloves, and closed-toed shoes whenever necessary. For example, when cutting carbon fiber and generating carbon fiber dust, respirators and goggles were used to mitigate risk to the eyes and lungs. Gluing and soldering were done in well ventilated areas. Battery leads were always soldered one at a time and covered with heat shrink tubing or electrical tape whenever exposed. They are also charged and stored in fireproof containers.

Mission:

The operation of UASs come with inherent risks. We have put in place procedures to mitigate them as much as possible. In addition to the cyber security measures described above, we have also put in place measures to prevent accidents. Quality build procedures including using thread locker on all screws, heat shrink wrapping all solder joints, and redundant component attachment methods minimize operational hazards. Pre-flight checklists ensure that all components are in proper working order before takeoff preventing emergencies before they even begin. Post-flight checklists prevent surprises and allow ample time to address any problems discovered. During operation, we will always have a spotter keeping the UAS within visual line of sight to ensure manual override by the safety pilot happens safely and smoothly. We have also developed thorough checklists covering a variety of situations encountered and imagined and detailing exact steps to take to optimally resolve the problem. These are designed to enhance time-sensitive decision making during operation.

We have also assigned a single switch on the transmitter to completely override EagleEye and Ardupilot to activate AltHold mode that isn't dependent on the GPS or compass. Another switch activates Stabilize mode that removes dependence on the barometer in addition to the GPS and compass. Finally, automatic failsafe systems are implemented on both the Ardupilot and EagleEye system. EagleEye continuously monitors its own outputs and automatically alerts and shuts down gracefully if they are not within limits of normal operation. Ardupilot is set up to automatically fly the UAS back to the takeoff location and land in cases where it exits the flight area or its battery is run down to a reserve capacity of 20%. This is intended to prevent crashes. In the case that the UAS still does not return to the flight area in 3 seconds after failsafe activation, all motor power is cut to zero and the runaway copter will crash land. These safety procedures and systems minimize risk to people, property, and the mission.

Table 1

Item No.	Volts (V)	Prop	Throttle	Amps (A)	Watts (W)	Thrust (G)	RPM	Efficiency (G/W)	Operating temperature(℃)
MN4010 KV370	14.8	T-MOTOR 14*4.8CF	50%	2.1	31.08	360	3100	11.58	44
			65%	3.1	45.88	510	3600	11.12	
			75%	4.1	60.68	640	3960	10.55	
			85%	5.4	79.92	810	4400	10.14	
			100%	6.5	96.20	920	4700	9.56	
		T-MOTOR 15*5CF	50%	2.3	34.04	430	2800	12.63	44
			65%	3.8	56.24	640	3400	11.38	
			75%	5.1	75.48	820	3800	10.86	
			85%	6.9	102.12	1020	4250	9.99	
			100%	8.2	121.36	1160	4450	9.56	
		T-MOTOR 16*5.4CF	50%	2.5	37.00	500	2650	13.51	45
			65%	4.3	63.64	770	3300	12.10	
			75%	6.1	90.28	970	3650	10.74	
			85%	8	118.40	1200	4000	10.14	
			100%	9.6	142.08	1380	4300	9.71	
	22.2	T-MOTOR 12*4CF	50%	3	66.60	600	5000	9.01	40
			65%	4	88.80	730	5600	8.22	
			75%	5	111.00	860	6200	7.75	
			85%	6.6	146.52	1090	6800	7.44	
			100%	7.7	170.94	1200	7300	7.02	
		T-MOTOR 13*4.4CF	50%	3.1	68.82	650	4800	9.44	47
			65%	4.3	95.46	810	5300	8.49	
			75%	5.5	122.10	970	6000	7.94	
			85%	7.1	157.62	1160	6700	7.36	
			100%	8.5	188.70	1340	7100	7.10	
		T-MOTOR 14*4.8CF	50%	3.5	77.70	780	4400	10.04	51
			65%	5.7	126.54	1060	5100	8.38	
			75%	7.6	168.72	1310	5700	7.76	
			85%	9.8	217.56	1590	6300	7.31	
			100%	11.7	259.74	1830	6600	7.05	
		T-MOTOR 15*5CF	50%	4.2	93.24	940	3900	10.08	52
			65%	7	155.40	1300	4800	8.37	
			75%	9.3	206.46	1620	5350	7.85	
			85%	12.2	270.84	1950	5700	7.20	
			100%	14.6	324.12	2240	6100	6.91	

Notes:The test condition of temperature is motor surface temperature in 100% throttle while the motor run 10 min.

Figure 1

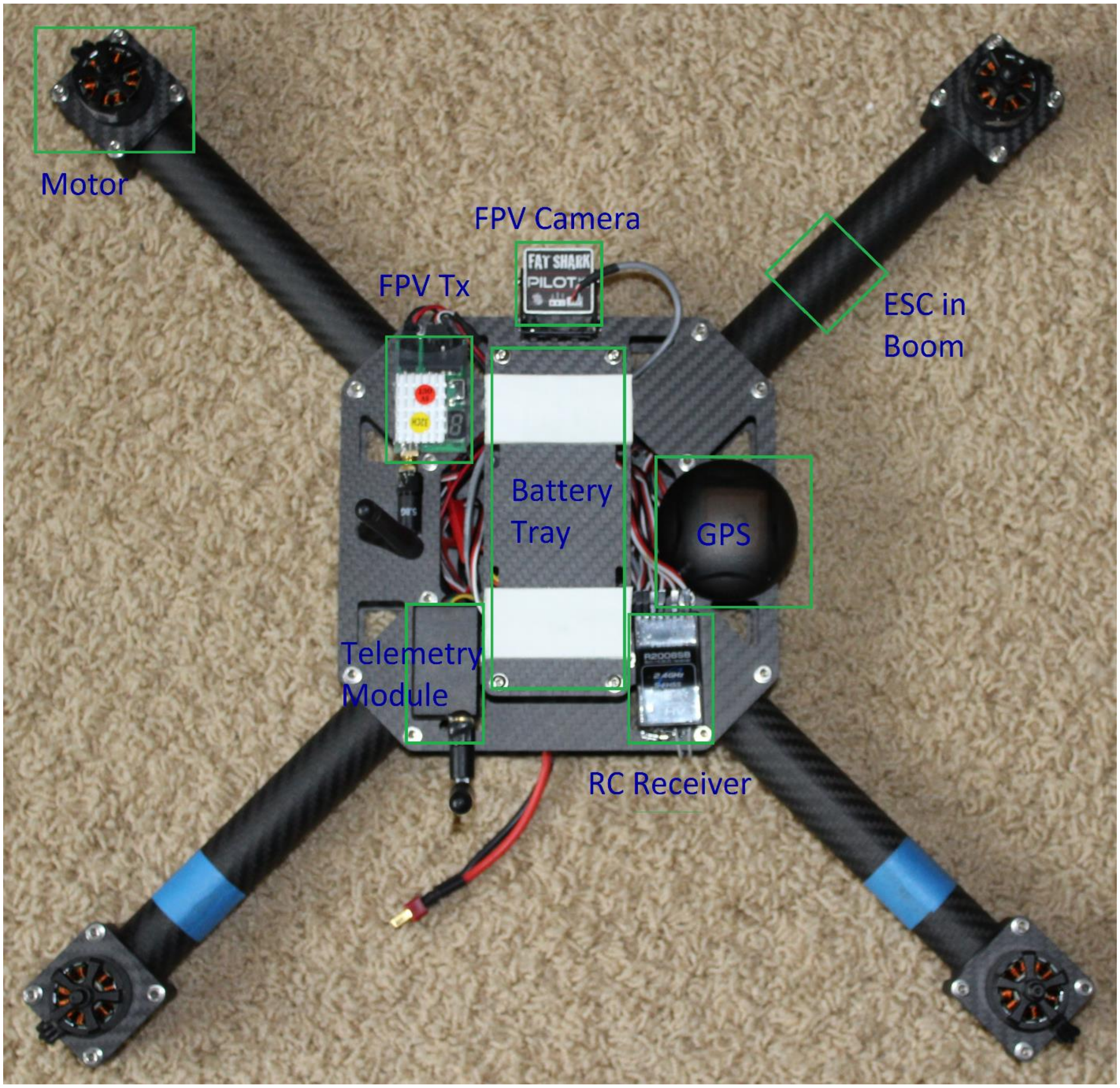

Motor
FPV Camera
FPV Tx
ESC in
Boom
Battery
Tray
GPS
Telemetry
Module
RC Receiver

Figure 2

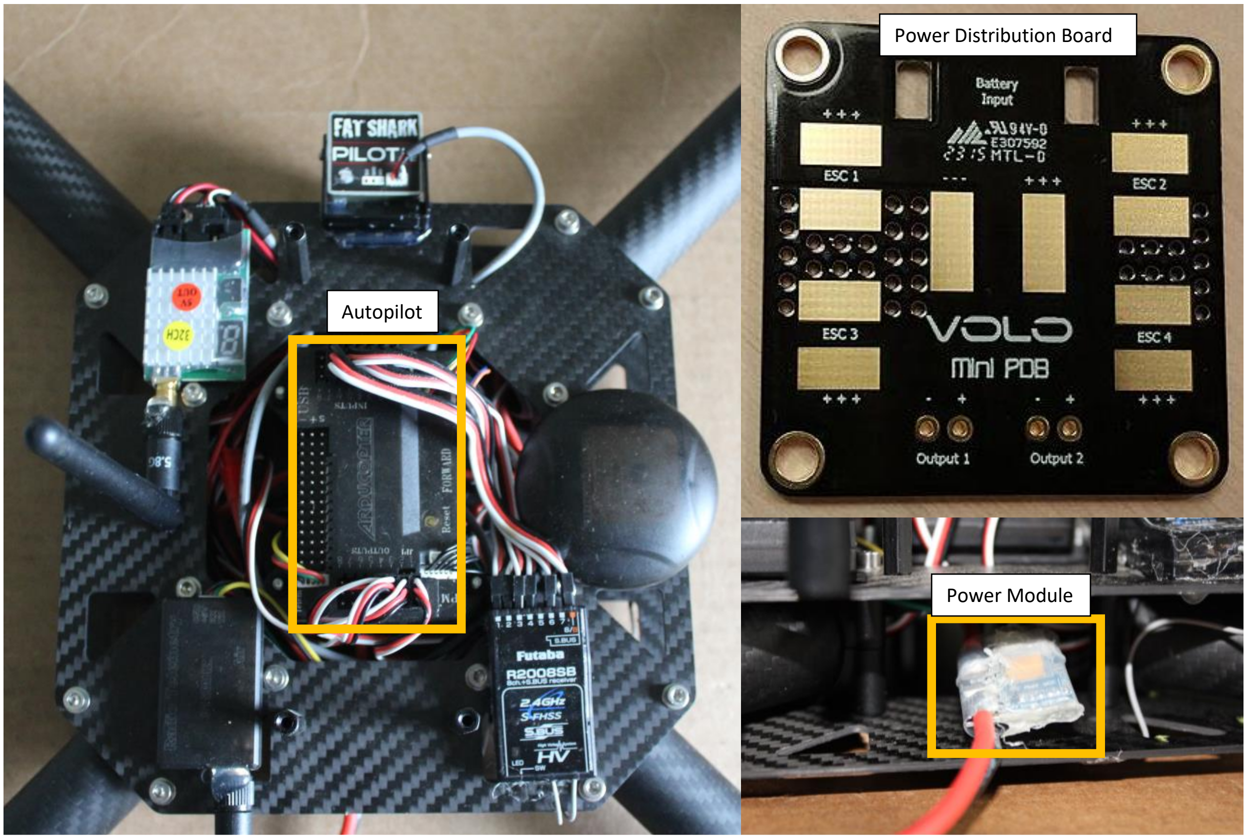
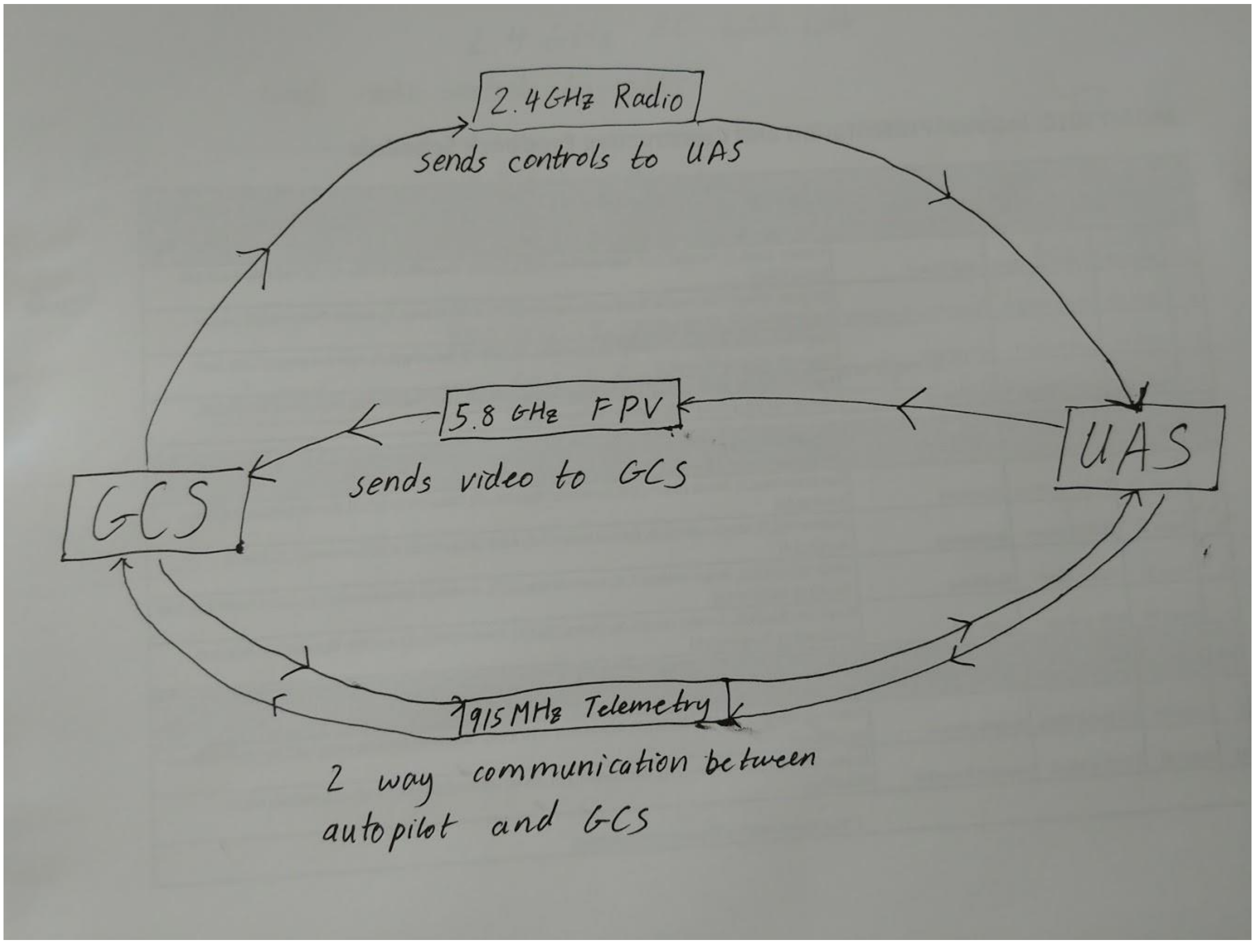

FAT SHARK
PILOT
Autopilot
Futaba
R2008SB
2.4GHz
S-FHSS
S.BUS
HV
Power Distribution Board
Battery
Input
ESC 1
ESC 2
ESC 3
ESC 4
VOLO
Mini PDB
Output 1
Output 2
Power Module

Figure 3


Mission Planner 1.3.39 build 1.1.6038.12291
FLIGHT DATA
FLIGHT PLAN
INITIAL SETUP
CONFIG/TUNING
SIMULATION
TERMINAL
HELP
DONATE
COM4
57600
Stats...
DISCONNECT
Bat 11.12v 20.0 A 53%
EKF
Vibe
GPS: 3D Fix
Loiter
Quick
Actions
PreFlight
Gauges
Status
Servo
Telemetry Logs
DataFlash Logs
Altitude (m)
1.14
GroundSpeed (m/s)
0.13
Latitude (dd)
40.17
Longitude (dd)
-85.32
Gps HDOP
1.14
Bat Voltage (V)
11.12
hdop: 1.1
Sats: 12
Current Heading
Direct to current WP
Target Heading
GPS Track (Black)
GEO
40.171514 -85.319960 1.14m
Tuning
Auto Pan
Zoom
17.0
Search Windows
1:48 PM
8/20/2016

Figure 4



2.4GHz Radio
sends controls to UAS
5.8 GHz FPV
sends video to GCS
GCS
UAS
915 MHz Telemetry
2 way communication between autopilot and GCS