Lahore University of Management Sciences Unmanned Air Systems

2018 AUVSI Student UAS Competition

Journal Paper

Figure 1: Our VTOL UAV designed for AUVSI SUAS Competition

Abstract

LUMS-UAV is one of the first teams from Pakistan working on state of art UAVs since last five of years and has won National Engineering and Robotic Contest (NERC) in last three years, consecutively. The team members from various backgrounds (Electrical Engineering, Computer Science and Aeromodelling) have been working on applications of UAVs in agriculture and water management. We have extended our expertise from multirotor and fixed wing aircraft to Vertical Take Off and Landing (VTOL) hybrid UAVs. We purchased "Skywalker EVE 2000", modified it to VTOL configuration and integrated autopilot system with redundant avionics. The redundant communication system, a very powerful vision system and an advance object detection capability and testing of system throughout the year ensure each module of whole system is sound. By following the safety standards, we ensure safety of the people and properties around.

1 Systems Engineering Approach

The Skywalker EVE 2000", EPO foam based aircraft commercially available which has been modified to VTOL as shown in figure 1 and tested to perform an autonomous flight reliably and safely. The VTOL system is capable of autonomous flight, surveillance, autonomous target detection, and air delivery.

1.1 Mission Requirement Analysis

LUMS-UAV is designed to accomplish the mission tasks 0f AUVSI-SUAS 2018 in provided time duration with maximum precision, following all the rules and minimizing the risk. The team analyzed all the tasks and divided them into different categories and assigned to expert of that area. The mission tasks were prioritized according to team's skills and its dependence upon success of whole mission. The details of mission and their importance is discussed below.

Timeline: The team has to follow the timeline given for each task including setup in 20 minutes, mission time 45 minutes and 10 minutes to close up all the equipment. It is 10% worth of total competition.

Autonomous flight: UAS system with capabilities of autonomous flight are economic in operation hence would perform better. It is 30% worth of mission further divided into autonomous flight (40%) where takeover by safety pilot has 10% penalty of 40%, waypoint capture (10%) and waypoint accuracy (50%). All waypoints are equally weighted and ratio of points received per waypoint is calculated using formula: $max\,(100tf\ -\ distance)/100ft$. There is penalty if aircraft goes out of bounds (10%), TFOA (25%) and crash (30%) of autonomous flight points.

Obstacle avoidance: The aircraft should have capabilities of obstacle avoidance for 20% of total points which are further equally divided into avoidance of stationary and moving obstacle.

Object Detection, Classification, Localization (20%): The UAS shall detect, classify and localize standard and emerging objects, where autonomy of vision system takes 20%, five characteristics of object (20%) and geo-localization (30%). However, submission of actionable objects prior to flight completion takes remaining 20% of the points.

Air Delivery: We will not be attempting airborne delivery task.

The team that shows good operation professionalism, communication between members, reaction to system failures, attention to safety would be given 10% of total mission points for operational excellence.

1.2 Design Rationale

By analyzing the mission requirements for SUAS 2018 tasks, and given the constraints of our team, we have come up with the following design rationale for our UAV system.

This is the first time we are participating in this competition therefore our team doesn't have much experience with the competition tasks and we should design every system from scratch. The overall system should be kept as simple as possible to avoid multiple points of failure and design complexities. Our team's experience is limited to electric aircrafts so we decided to use a EPO foam based airframe for the competition.

We modified the airframe to a VTOL Hybrid aircraft for fully autonomous mission including takeoffs and landings. The VTOL configuration also enables the aircraft to hover at speeds below its stall speed using assistance from vertical thrust system which can help in target detection and localization.

We used state of the art autopilot system Pixhawk 2.1 and a very powerful embedded computer Nvidia Jetson TX2 for onboard processing.

2 System Design

Following is an overview diagram of our System design given in figure 2. Our complete system is divided into two parts: UAV and ground control station (GCS).

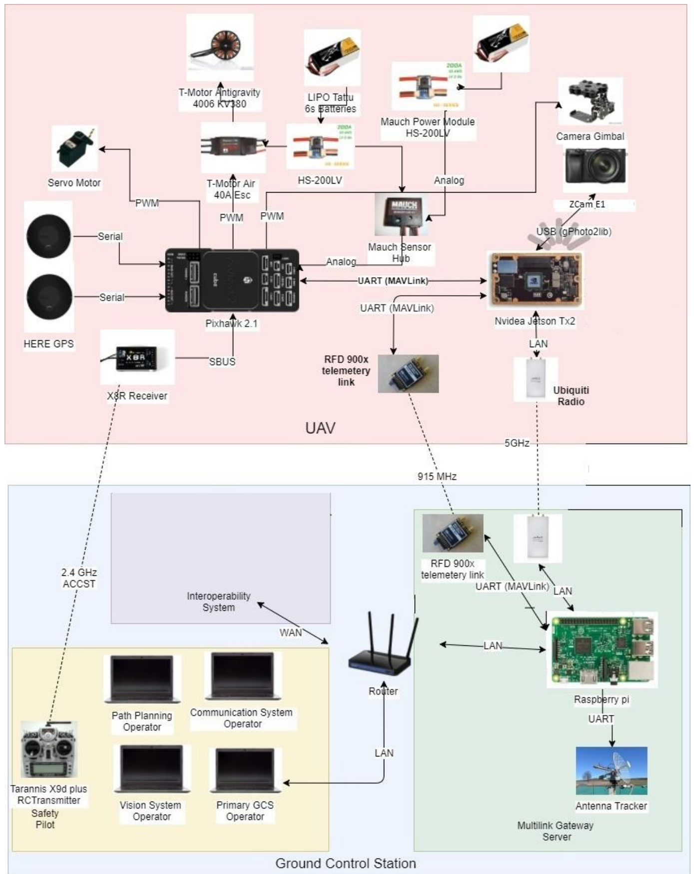

Figure 2: Hardware flow diagram of our UAV system

The hardware is controlled using software packages, the flow diagram of our software is given Figure 2.

2.1 Aircraft

Our UAV airframe is based on "Skywalker EVE 2000", EPO foam based aircraft as given in figure 1. It has a wingspan of 2240mm. It is powered by two electric motors in a twin tractor configuration. It has been modified for Vertical Takeoff and Landing (VTOL) hybrid system. We have used eight motors in an octa-quad configuration for the vertical lift system. This choice of thrust system allows a safe landing in case one of the motors/ESCs fail in both horizontal as well as vertical flight modes. Our aircraft has a maximum take-off weight (MTOW) of less than 10kgs.

The stall speed of our UAV in fixed wing mode has been calculated to be less than 20 knots. But our UAV is able to operate at speeds below its stall speed with lift assistance from vertical lift motors even when in fixed wing mode. It can also hover at zero airspeed in quad plane mode. The speed of the UAV will be maintained via airspeed sensor as well as speed from GPS.

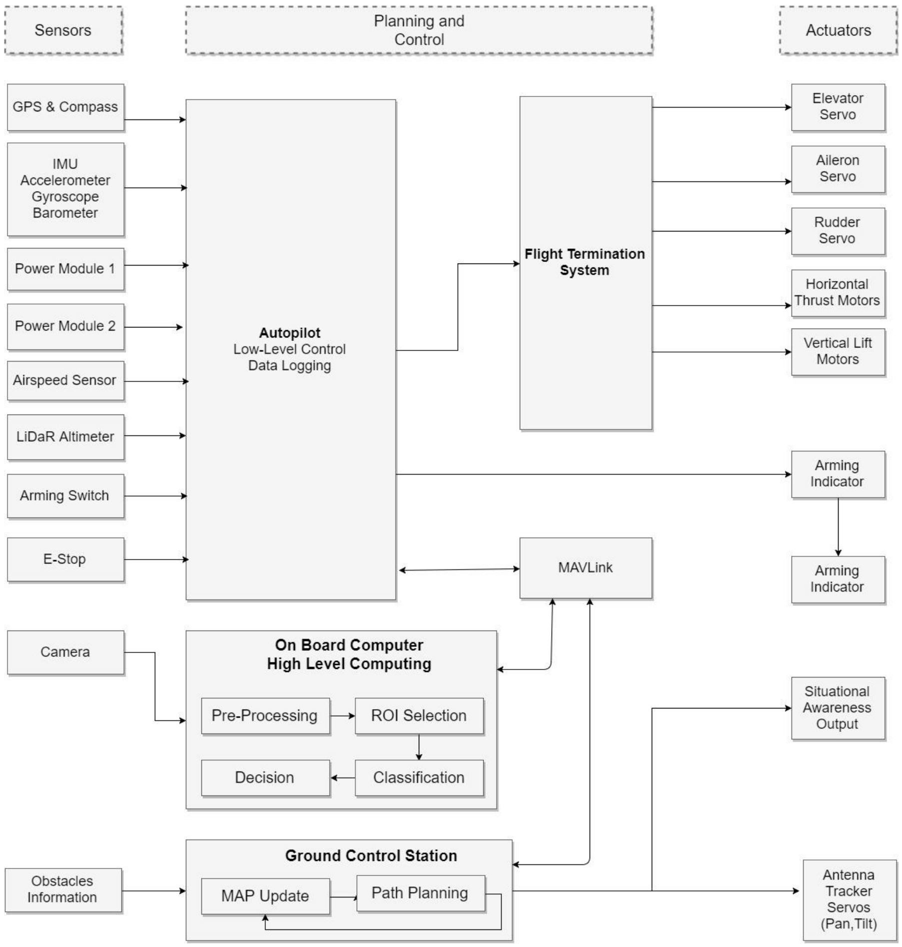

Figure 3: Software flow diagram of our complete system

2.2 Autopilot

Our UAV is using Pixhawk 2.1 autopilot system running Arduplane firmware from Ardupilot. The hardware and software of our autopilot are open source which enables ease of integration with other systems as well as modifications required to meet the requirements of the UAV Challenge. The Pixhawk 2.1 autopilot features triple redundant Inertial Measurement Units (IMUs) which are maintained at an optimum temperature with a built-in thermostat for maximum accuracy. We have attached dual GPS systems with the autopilot to reduce the chance of failure. The autopilot is powered by two independent power systems to ensure safe operation of the aircraft.

2.3 On-Board Computer:

On-board companion computer system is used for running obstacle avoidance and image processing software. We are using Nvidia Jetson TX2 Embedded Computer running a Linux based operating system. Robot Operating System (ROS) is being used for running real-time obstacle avoidance algorithms. OpenCV and Tensorflow are being used for running image processing algorithms required for Target detection and Localization.

2.4 Ground Control Station:

Ground Control Station will consist of a gateway server which will aggregate the telemetry data from multiple links and forward it to multiple laptops through a networking router. This will ensure smooth operation in case one of the laptops fails. The gateway server will also be used to communicate with the interoperability server.

2.5 Flight Termination System:

For flight termination system we will be using Advanced Failsafe System of the Ardupilot firmware. This system has been designed to meet the requirements of the UAV Challenge. This failsafe system is implemented on a separate PX4IO coprocessor part of the Pixhawk autopilot system. This failsafe processor has exclusive control to all the motors and flight control surfaces outputs. The autopilot is powered by two independent power systems (primary flight battery and avionics backup battery) to meet the separate power system requirements of the termination system.

The failsafe coprocessor continuously monitors all the failsafe conditions as well as heartbeat from main processor and initiates flight termination in case of a failure or GeoFence breach

2.6 Obstacle Avoidance:

Our system is capable to plan a new path during run time using rapidly exploring random tree (RRT) path planning algorithm. This algorithm is well known in robotics path planning especially in self-driving cars due to its fast processing and accurate obstacle avoidance by incorporating the constraints such as turn radius, vehicle speed, obstacle speed and direction etc. The system generates a virtual map where it introduces obstacles and uses RRT to get path to the destination, here we have waypoints as destination points. During flight, as the stationary obstacle position becomes available, the system puts a virtual object in map graph and generates a new path at a safe distance from obstacle. If the provided obstacle has some velocity, our system simulates its trajectory and computes the collision point with UAV's trajectory. Thus, considering the collusion point, the system invokes RRT to compute a new path. A simulation result of RRT used by our system is shown in figure 4.

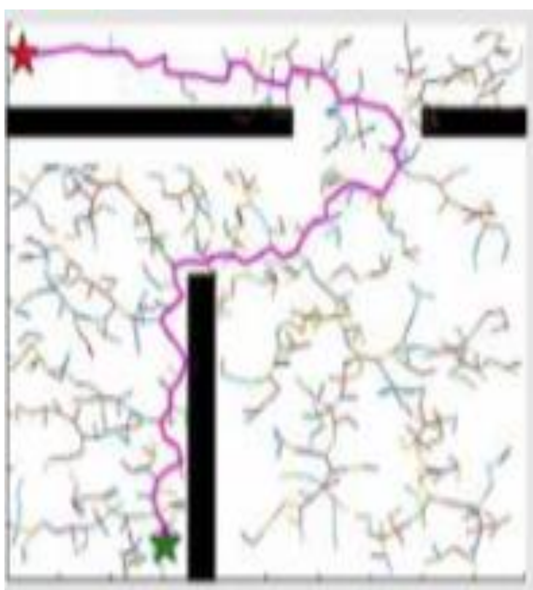

Figure 4: Simulation of RRT algorithm for obstacle avoidance and path planning.

2.7 Imaging System

2.7.1 Camera

The Camera we need should be able to get high resolution images at high altitudes so that the Image processing tasks could be done accurately. Keeping this objective in mind, the camera that LUMS UAV chose is ZCAM E1 with a 14-42mm Panasonic Lumix Lens. The resolution of the camera is 16 MP thus providing high definition images even at high altitudes.

ZCAM E1 has a built-in HTTP API, UART serial interface, and independent 802.11n Wi-Fi network. As the camera is continuously taking images that need to be sent to the GCS so the interface of the onboard computer with the camera is quite important and ZCAM E1 makes it very easy to send images because of its built-in API and serial interface.

At an altitude of 50 m, the ZCAM E1, with its micro four-thirds sensor size, gives a ground resolution of almost 2 cm which is less than the thickness of the alphanumeric character as specified in the rules. So, it will be quite easy for the detection algorithm to detect the alphanumeric characters.

2.7.2 Object detection, classification and localization

The vision system detects target objects, classifies to category and finally localizes it in global positioning system. Deep learning based methods such as MobileNet, YOLO, region proposal R-CNN etc. provide complete solution to the project of object detection and localization with almost 90% accuracy, but these methods require very large training dataset and are computationally expensive at test time as well. We, therefore, decided a hybrid approach that employs classical geometry based computer vision algorithms and the most recent deep learning methods. Our whole vision system consists of multiple modules as shown in figure 5.

Preprocessing: The very first step is filtration of noise due to lightning conditions, vibration and motion. The system applies motion filter to remove effect of motion and then gaussian filter to remove noise.

ROI selection: The success of target detection is based upon detection of region of interest. There are number of method available in literature employing blob-features, template matching and region proposals using deep learning. Our system applied canny edges detector with several thresholds and groups those which lie in certain radius to get a blob. The blobs are threshold on size and the remaining are considered initial ROIs.

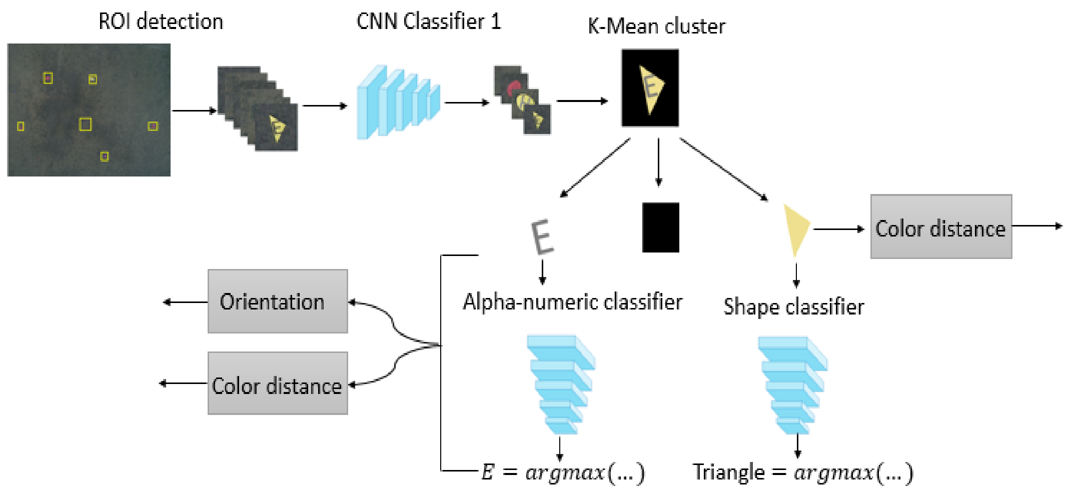

Figure 5: Autonomous Vision System: Classifier-1 removes which do not have any object of interest in it. Alphanumeric and shape classifier are two separate deep CNN classifiers. Orientation is calculated using geometry and color is identified based on numerical distance with intensities of colors in database.

Object identification/classification: The ROIs are given to deep learning based classifier that classifies whether selected ROI has any object of interest or not, thus discards false positives with 98% accuracy. This leave few ROIs for K-Mean clustering to segment foreground and background. We have trained a very deep state of art residual architecture based CNN classifier (ResNet-18) that classified objects (alphanumeric and shape) with 90% accuracy on our test set.

Color identification: We select the mean color value a cluster resulted by K-mean and convert it from RGB to color space (HSV) and compute distance with HSV of known colors.
Orientation: The system computes transformation between character in ROI and reference image of that object in database. The system takes aircraft's orientation from its localization system and computes the orientation of the object in global positioning system.

False Positive Elimination: Each module of the system reports False positives occasionally due to noise and different objects in the field. To maximize score, the system attempts to eliminate false positives to avoid extra-object penalties; the system does not report any region of interest that fails shape and alphanumeric segmentation or has low classification probability in either of the two classification stages.

2.7.3 Vision System Evaluation:

The vision system was designed in a modular fashion where complete pipeline is divided into five sequential modules. This allows us to improve any module independent of other modules. A through study was done on theoretical as well as practical evaluation of different algorithms considering the computation verse accuracy of the model. Initially, all modules of the system were naively designed and tested and the complexity of each module was increased. Following table gives the comparative study on different CNN well known CNN classifiers. The ResNet-4 contains only four layers of ResNet-4 and classifier-1 classifier if the selected ROI has any object of interest or not, therefore, this module reduces computation job for following modules.

	Vgg16	**ResNet -4**	**ResNet 18**
Classifier -1 (ROI)	85%	97.5%	98.2
Alphanumeric classifier	87.3%	82%	90%
Shape Classifier	75%	80%	90%

Table 1: Accuracy of CNN classifier networks.

When we combine all five modules of autonomous vision system, we have to play with accuracy and computation both. We, therefore, studied this trade-off and report the frame rate of complete pipeline on test time in following table. For processing computer used was Core-i7, 16GB RAM, GTX-1060 (6GB) GPU.

ROI	**Classifier-1**		**Clustering K-mean**	**Alphanumeric classifier**		**Shape classifier**		**Accuracy**		**Frame rate**
Canny	C1	C2		C1	C2	C1	C2	Alphanumeric	Shape	
●	●			●		●		50%	45%	110
●		●	●	●		●		54%	52%	78
●	●				●		●	80%	60%	72
●	●		●		●		●	85%	73%	45
●		●	●		●	●		85.5%	73%	12

Table 2: Accuracy of complete pipeline on alphanumeric and shape identification. M1 is ResNet-4 classifier model and M2 is ResNet-18 classifier model

	RGB Space	HSV Space
Shape color accuracy	45%	62%
Alphanumeric color accuracy	40%	56%

Table 3: Color identification accuracy

We plan to improve classifier modules by using deeper network which will sure increase classification accuracy at cost of computation. We will train ResNet-101 and Google-Net, two major state of the art classifier network, for our problem which will take almost two days.

2.8 Communications

There are three independent radio links to the UAV. For manual flight takeover the RC link used is FrSky Taranis radio control system. It is an ACCST system running at 2.4GHz.

For telemetry and control link RFD900x radio modems was used running at 915MHz.

For Image Transmission System we are using Ubiquiti Radios running at 5.8 GHz. Ubiquiti Rocket 5AC is used on the UAV and Ubiquiti LiteBeam 5AC is used at the Ground Control Station.

2.9 Cyber Security

RFD 900x Telemetry Radios use hardware accelerated AES Encryption and Ubiquiti Radios use WPA2/AES Encryption to prevent unauthorized access. All the communication between GCS Laptops is done via ethernet and wireless access is disabled to reduce the risk of unauthorized access. All the web servers and configuration pages are protected with passwords to prevent any unauthorized access. All the RF links use Frequency Hopping Spread Spectrum (FHSS) to minimize the risk of RF interference and jamming.

3 Safety, Risks, & Mitigation

3.1 Risk assessment

Based on our test results we did a thorough assessment of risk; the detail is provided in the following table.

Risk Assessment	**Risk Mitigation**
Flight Safety	• Initial test flights are carried out at local aeromodelling club MAAL in line with their operational and safety procedures. • Long range testing will be carried out at a dedicated testing facility of a local UAV manufacturer Satuma to ensure safety during tests.
Batteries	• Batteries are stored safely when not in use, and will be handled carefully. • LiPo Safe Bags are used during charging to reduce fire hazard.
Assembly	• Airframe assembly is carried out by experienced aero modelers. • Stress testing is performed to ensure integrity of airframe.

Flight Operations	Flight operations follow MAAL procedures and preflight checklists are made to ensure safe and smooth operation.
Electrical Power	• Two separate power systems are used, one for avionics and second for motors and servos which will also act as backup power system for avionics systems. • Industry standard procedures will be followed to ensure electrical safety of all the equipment used at GCS.
Connections, wirings and soldering	• All the connections, wiring and soldering are carried out by experienced personnel having several years of experience in UAV building. • All the wiring is checked with multimeter and boom stopper is used for testing the power system for the first time.
Autopilot	Failure of autopilot will result in immediate flight termination.
Geo-fencing System Failure	The geo-fencing system will be monitored by advanced failsafe system through heartbeat and flight will be terminated if the system fails.
Air Traffic	During test flights air traffic will be monitored using ADS-B receiver as well as flight radar 24 to ensure safe operation.
Software Failure	Software will be tested using rigorous simulations covering all scenarios and verified on the hardware using Hardware in Loop (HIL) simulations.
Weather	Weather forecast is checked before scheduling flights and flight will be cancelled if weather conditions become unfavorable or dangerous.
Vision System Failure	Deep learning based object detection will be used, it might fail if there is shadow. To counter this challenge, our system ensure all detection multiple times.
Ground Control Station	To reduce the risk of GCS failure, multiple computers will be used in a network and all computers will be capable of full mission control.
Aircraft Flyaway	Geo-fencing system will be used to reduce the risk of flyaway.

Low Battery	Battery voltage is checked before flight and remaining capacity is monitored during flight to ensure that the aircraft has enough reserve capacity for a safe return to launch.
Accidental Arming of Propellers	Safety Switch is always disarmed and it is only armed just before the mission to ensure that there are no accidental injuries during pre-flight checks and aircraft walkout.

Table 4: Risk evaluation table

3.2 Risks Associated with Autonomous Takeoff and Landing:

Risk Assessment	**Risk Mitigation**
Unfavorable Weather	• Weather conditions and forecast will be checked before flight to ensure that there is no chance of rain/storm during the mission. • Aircraft will not be operated in wind conditions that can cause instability and damage.
Rough Landing	• Landing gear installed will have certain level of flexibility to absorb the shock from a rough landing. • The aircraft's attitude will be checked from GCS HUD to ensure that aircraft's tilt angles are within limits for a smooth takeoff.
Harm to People	Aircraft will be disarmed after landing to ensure no one is harmed by moving propellers.

Table 5: Risk associated with autonomous flight

3.3 Risk Management

The safety should always be at high priority than development and testing. In order to make sure the safety of the team and people around, we consider all possible failure cases and risks that might happen. Level-1 redundancy of complete avionics system including IMU, GPS, Power supply, Communication links and VTOL makes our UAV robust to system failure. We have listed all possible risks and have discussed the ways to cater them.

3.3.1 Communication Failure Management

Loss of RC Link: RC link is only required during manual take-over if required. This is only possible in the visible range and failure of RC link over such short distances is highly unlikely. If RC link is lost for more than 1 second in manual takeover mode, flight termination will be initiated.

Loss of Data link: The Advanced Failsafe System monitors the integrity of data link through MAVLink heartbeat messages. If all the datalinks are lost for more than 10 seconds then the UAV will loiter at its position for 2 minutes, if communication is not regained the UAV will return to base. Failure of GPS during the communications loss mode will result in immediate flight termination.

GPS Failure: UAV is equipped with dual GPS Receivers to reduce the risk of GPS failure. If GPS signal is lost for more than 30 seconds the Autopilot will initiate GPS failure procedure and circle or hover at the current position (depending upon the flight mode) for 30 seconds while waiting to regain GPS signal. If there is no GPS signal after that time, landing will be initiated.

3.3.2 Autopilot Failure:

Advanced failsafe system of Ardupilot monitors the communication between main flight processor and IO processor and initiates flight termination if the communication is interrupted between the two processors due to a lockup or some other problem.

3.3.3 Failure of ground control station:

We have multiple laptops at the GCS to minimize the risk of GCS failure, each of them capable of fully independent mission control. If GCS fails the Autopilot will stop receiving MAVLink heartbeat packets. If no heartbeat packets are received for more than 10 seconds it will go to the communication failure mode.

3.3.4 Loss of Engine Power:

Our UAV system has a certain level of redundancy in terms of motor failure. In case one of the horizontal motors fails other motor can provide some amount of thrust for a smooth operation. Vertical lift system can land the aircraft safely in case both horizontal thrust motors fail. Vertical lift motors are also arranged in octa-quad configuration, enabling it to land safely in case of a single motor failure.

3.3.5 Lipo Battery management

Li-Po batteries will be used for our power systems as well as avionics. Li-Po batteries will be housed properly to minimize damage in case of a crash and will be covered with padding to reduce the risk of physical damage. The batteries will be stored in LiPo Safe bag during charging and transportation to reduce the risk of fire hazard.

LiPo battery operation etiquette will be followed to ensure safe operation. Overcharging will be protected using a suitable LiPo charger and over discharge will be prevented by monitoring the battery voltage as well as remaining capacity through the power modules. Batteries will be physically inspected regularly and batteries with any signs of damage will not be used. We will have a fire extinguisher at the GCS to minimize damages in case of lipo battery fire.

3.3.6 Bugs in Software

All the vision, robotics and network system software developed by our team are thoroughly tested in simulators before being implemented in the actual aircraft. This thorough testing involves virtually creating all the possible real-world scenarios so that all our software is bug free when implemented in the real aircraft.

4 Conclusion

We have developed a safe and reliable UAV system for the AUVSI SUAS 2018. This is the first time that we are participating in this challenge therefore our team should put in extra hours of work to develop everything from scratch. We are on schedule with our current development and hope to participate in the AUVSI SUAS 2018 with a fully integrated system.

The next step for our team is to integrate the machine vision and obstacle avoidance systems with the UAV and performing full scale mock missions.