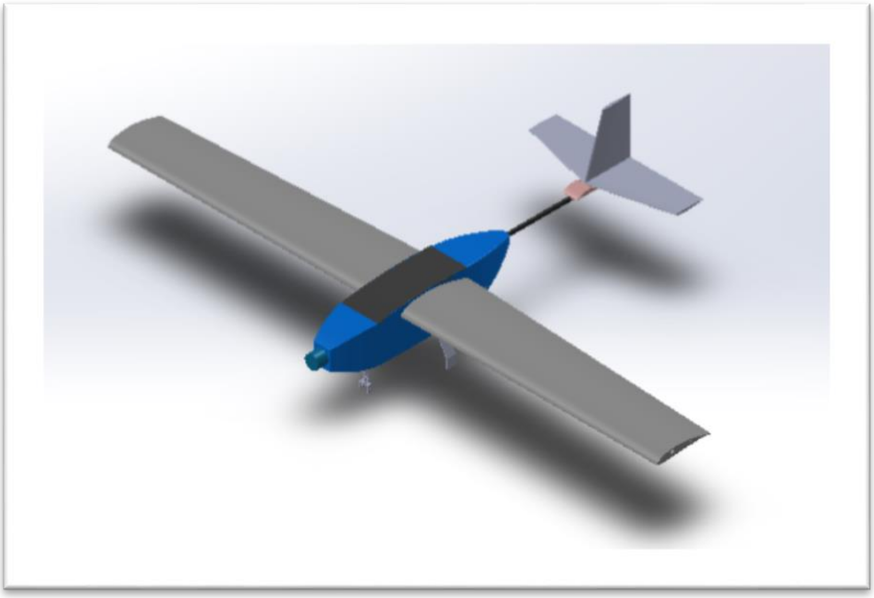
Team ARROW

Institute of Technology, Nirma University

Mechanical Engineering Department

Technical Design Paper for AUVSI Student UAS – 2018



Team Arrow UAV

Abstract

This paper briefly portrays the approach undertaken by Team ARROW to satisfy the requirements pertaining to AUVSI Student UAS 2018. The entire process was carried out by the team in three major phases, namely breakdown of the mission objectives, design of the UAS systems in order to achieve the mission tasks, and finally, system tests and test results analysis. The critical aspects like safety and cyber-safety were given utmost priority during each phase in order to provide the safest solution to both people as well as the hardware components. The Unmanned Aerial System designed by the team basically comprises of a battery-powered fixed-wing aircraft designed to provide reliable autonomous flight, satisfy all the proposed imagery requirements and ground communication which is capable enough to provide high redundancy. An improved payload allows for live transmission of geotagged pictures to a ground-based server, while custom ground software allows for real-time analysis of incoming pictures by multiple clients and precise target localization and identification. Another addition to the UAV is the integration of a water bottle drop system, based on a tried and tested releasing point algorithm.

CONTENTS

Chapter 1: System Engineering Approach

1.1 Mission Requirements Analysis

The first step taken by the team to excel at the competition was to analyse all the mission requirements along with the feasibility of each of them. Further, all the tasks were prioritized depending upon the allocated budget, available resources, time-frame, workflow analysis and specializations of the team members. The autonomous flight was identified as the primary task by the design team. The tasks like search area, ODCL, actionable intelligence, emergent target, airdrop, interoperability were classified as the secondary tasks. Afterwards, the team decided to proceed with obstacle avoidance, moving obstacle avoidance, off-axis, etc. in various developmental stages over the course of the event preparation.

The basic workflow approach of the team is described as follows:

- Instilling the capability of autonomous flight.
- Ability to fly accurately to each waypoint while remaining inside the flight boundaries.
- Ability to avoid stationary and moving obstacles, whose locations are received from the interoperability system.
- To take images/video of approximately 0.1 square miles in under 40 minutes to identify target characteristics and location.
- Deliver a standard 8oz water bottle to a drop location accurately.
- The team will be having personal protective equipment (PPE) which includes, at minimum, proper tools, gloves, eye protection, and hearing protection when appropriate.
- Safety risk mitigation has also been implemented, which includes team training, checklists, and radios for communication.
- To develop a reliable ground control station capable of displaying a map showing flight boundaries, UAS position, other competition elements, UAS speed, and altitude for the competition judges. It shall also send mission commands to the UAS, and receive imagery from the UAS. The team will ensure that it is portable and possible to set up in less than 20 minutes.

1.2 Design Rationale

The team began with planning and execution of various tasks in June 2017 with a budget of 400,000 INR. The team consists of five senior members, three from Mechanical Engineering discipline and two from Electrical Engineering discipline. The rest of the team comprises of 8 junior members form different academic backgrounds keeping in mind, the need to satisfy all the mission requirements. The team has experience in CAD modelling, aerodynamic analysis, electronic circuit design, and computer vision as well as computer networks. With this wide range of skills, the team is confident enough to achieve all tasks at the competition.
The team only considered fixed-wing aircraft because of the team’s previous experience and expertise with fixed wings.

The key points considered during the overall system design process are highlighted as follows:

- To reduce the weight of the aircraft without decreasing its strength.
- To fabricate the aerodynamically stable aircraft capable of giving rigorous flights.
- To use a reliable and effective control system and parameters for carrying out autonomous flight.
- To perform image processing correctly and effectively.
- To prepare a system that can do airdrops in a practical and accurate way.

The carbon fibre composite material was preferred for the reinforcing the structure of fuselage and wings in order to provide lightness without reducing the strength. A high-performance on-board computer was selected for fast image processing and transferring. Pixhawk autopilot has been selected for autonomously take off, flight and landing. M5 bullet has been selected to provide desired link performance. The airdrop mechanism was designed to be lightweight and with little friction. A suitable camera with high resolution and auto focus has been preferred. As highlighted earlier, during the complete design process, safety was the most important criteria. All improvements have been made keeping in mind that the team also ensures the reliability of the solution.

1.3 Programmatic Risks and Mitigation Methods

Considering the multidisciplinary nature and wide scope of work that has to be covered in order to satisfy the mission requirements, the team can encounter with various risks and unexpected negative situations during the course of the entire year. In order to plan properly, the risks that may be encountered in management, production and test process were listed based on the old experiences of the team members. Further, the team created mitigation plans to prevent being affected by them. The same is highlighted in the following table.

Risk	Cause	Likelihood	Impact	Mitigation Plan
Delay in fabrication and testing	Non-availability of components, air conditions, workspace issues	Medium	High	Purchase of back-up components, Paid workspace for carrying out work related to composites reinforcement.
Damage of airframe structure	Crash during flight test, Improper storage	Medium	High	Carbon fiber reinforcement, Labs at Institute employed for storage
Financial inadequacy of the team	Lack of sponsorship	High	High	Sponsorship agreements made for travel tickets, visa process, etc.; Funding approvals from the institute.
Lack of collaboration and communication between team members	Conventional project management methodology	Low	Medium	Agile Scrum project management methodology was adopted.
Selection of wrong electronic equipments	Incorrect component selection	Low	High	Comprehensive Literature Review encouraged before purchase
Lack of expertise desired from team members	Error in team building	High	High	Continuous monitoring and rigorous training of the juniors by the senior members of the team.
Safety and Legal Issues	Lack of literature and market survey by the team	Medium	High	Consulting a safety officer who is aware of laws pertaining to Unmanned Aerial Vehicles.

Chapter 2: System Design

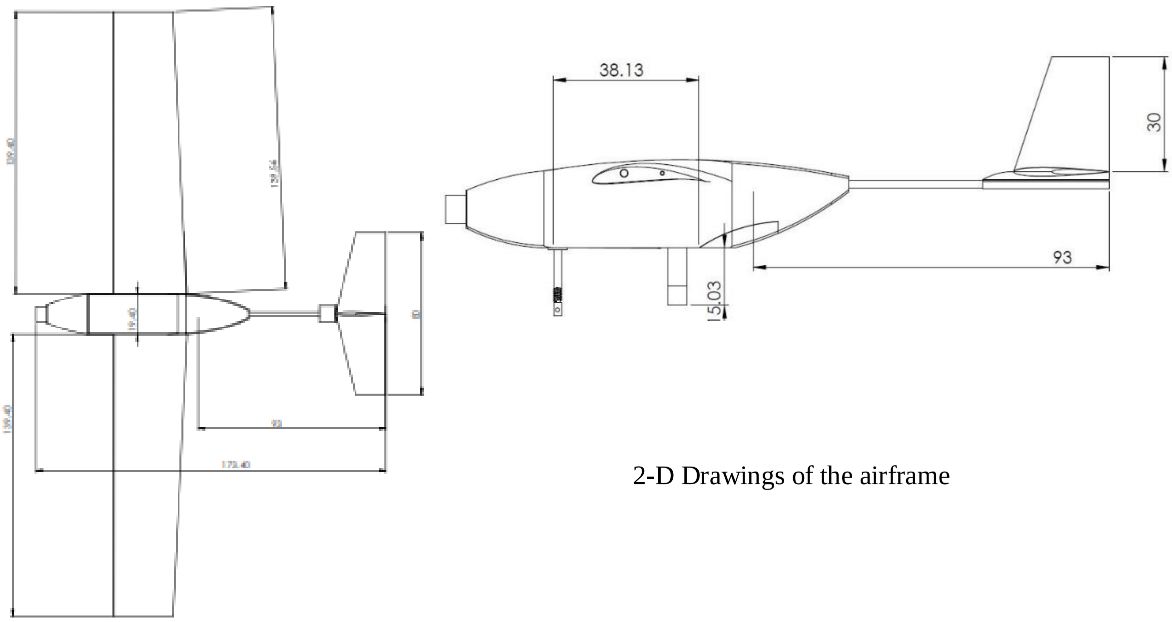
2.1 Aircraft

2.1.1 Fabrication

The major components of aircrafts includes carbon fibre reinforced wings in two parts, glass fibre fuselage, an empennage, carbon fibre tail boom, tricycle landing gear and an electric-powered motor. The team has fabricated a standard fixed wing aircraft with fuselage made of glass fibre composite. The wing structure is made of balsa wood, skin covered with one layer of Rohacell foam and two layers carbon fibre composite. This made wing strong enough to resist any sort of impact during crash. To resist wing under bending during flying the team has used two carbon fibre tubes of 20 mm outer diameter and 18 inner diameter, and 10mm outer diameter and 8 inner diameter.

The UAS is designed for a cruise speed of 20 m/s which helps it cover a wide range of area. It possesses a wing area of 9834cm^2 and aspect ratio of 9.030 which gives us maximum stability at slower speeds too. The taper ratio has been kept as 0.8 to improve the stall characteristics. In order to satisfy high cruise speed and maximum lift coefficient and drag bucket for wide range of lift coefficient, MH114 has been chosen as the wing airfoil. The wing configuration is a high wing configuration to make plane more stable according to requirements to be completed in the competition as tight manoeuvring is not required as per the mission requirements. An in-house genetic algorithm has been used to solve for a wing and tail geometry that offers optimal longitudinal and lateral stability.

The airframe has been designed around fuselage with detachable wings for easy transportation and modification. The total weight of aircraft is 12.5 kgs. including all payloads. The airframe dimensions are shown in corresponding figure.



2-D Drawings of the airframe

2.1.2 Wings

The total wingspan is 2998 mm. The tip chord is 295mm and root chord is 365mm, this gives us the taper ratio of 0.8 and aspect ratio of 9.030. The airfoil selected is MH114 which is a high speed and lift coefficient airfoil based on testing of different airfoil on XFLR5 software. The C_{Lmax}= 0.98 and max C_L/C_D is 3.4. This is the max C_L/C_D ratio obtained using CFD analysis of wing.

Carbon Fibre sheeting on the wing

General Characteristics	Specificaton
Total Length	1730mm
Total wing Span	2998mm
Empty Weight	6.8kgs
MTOW	12.5 kgs
Cruise Speed	20m/s
Maximum Speed	25m/s
Stall Speed	18m/s

Vertical Stabilizer Parameter	Specificaton
Airfoil	NACA 0009
Span	600 mm
Aspect Ratio	3
Taper Ratio	0.6
Root Chord	250 mm
Tip Chord	150 mm
Area	600 cm^2
MAC	204 mm

Horizontal Stabilizer Parameter	Specificaton
Airfoil	NACA 0009
Span	800 mm
Aspect Ratio	4
Taper Ratio	0.6
Root Chord	250 mm
Tip Chord	150 mm
Area	1600 cm^2
MAC	204 mm

Wing Parameter	Specification
Airfoil	MH114
Span	2998 mm
Aspect Ratio	9.030
Taper Ratio	0.8
Root Chord	365mm
Tip Chord	295mm
Area	9834cm^2
MAC	331.24mm

Propulsion equipment	Component Selected
Motor	E-Flite Power 90 Brushless Outrunner Motor 325kV
Electronic Speed Controller	Castle Creations Talon 90 Amp ESC
Propeller Size	APC Electric E 18*6 (2 blades)
Battery	LiPo 25/35c 6S 16000 mAh
Power Module	APM 2.8 Power Module

2.1.3 Aerodynamics

The dimensions of the wing were finalized using the software XFLR5 made by MIT researchers. It was used to analyse the 2D and 3D aerodynamic performance using vortex lattice method (VLM). Moreover, the book "Aircraft Design: A Conceptual Approach" written by Daniel P Raymer was used as an important reference for the design of the complete aircraft.

The first step of the design was to determine the stall speed. With a maximum of 30° roll angle in turn, it was determined that the stall speed is 18m/s. It was also estimated that the lift was equal to the weight at the cruse speed. With this assumption, it is possible to isolate the wing surface in the equation.

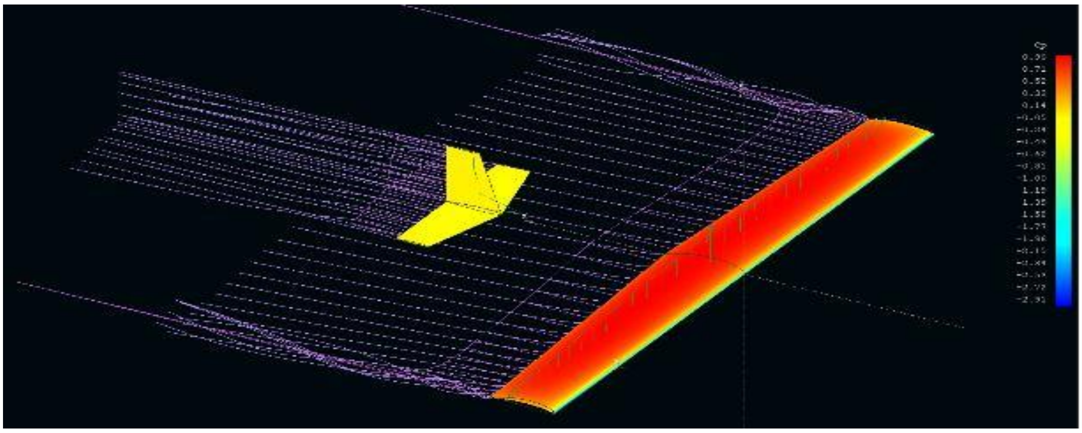
$$s = \frac{2W}{\rho_\infty V_{Stall}^2 \; Cl_{max}}$$

The first lift coefficient (C_l) was determined with a realist 2D analysis on XFLR5. Then with the stall speed (V_{stall}), knowing that the plane will weigh a maximum of 12.5 kg (m) and the air density (ρ) at the flight altitude, a first iteration of the minimum wing surface can be achieved. The next step was to determine the aspect ratio needed.

$$\text{AR} = \frac{b^2}{S}$$

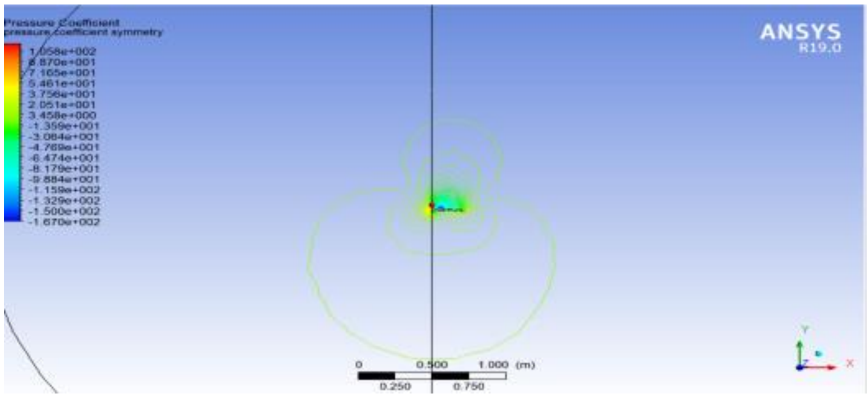
Here, AR stands for aspect ratio, b is the wingspan and S the wing surface. Moreover, it was assumed that the thickness of the wing is 9% of the chord (c). For reasons pertaining to ease in fabrication and structural assembly, the minimum thickness is 30 mm, which limits the cord to a minimum of 360 mm. The iterations were made with different configurations to reduce the power required at cruise speed. The optimal aspect ratio found was 9.030

with a taper of 0.8. Finally, with some iterations with 3D simulations on XFLR5 to reduce the *CL/CD* ratio, a proper airfoil was chosen. After all calculations were done and verified, the first wings were made.

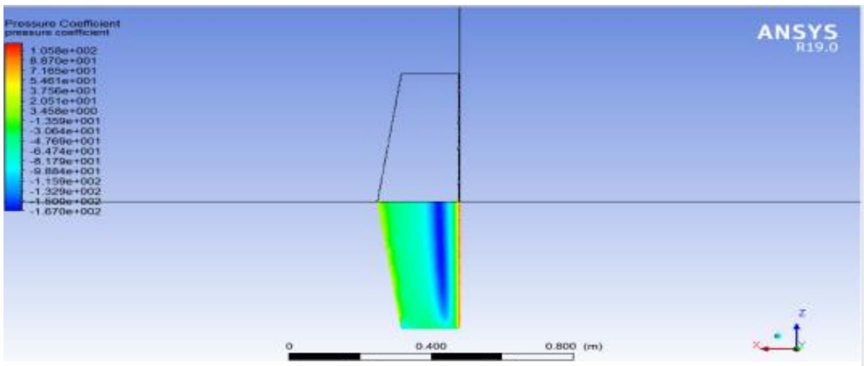


XFLR Analysis

For the control surface, flaps were not found necessary on wings because of the high camber ratio of the airfoil, advanced aerodynamic C_L/C_D ratio and low stall speed characteristics. The ailerons were designed as length about 60% of half wingspan, and width about 25% of root chord. This sizing provided greater manuverability.



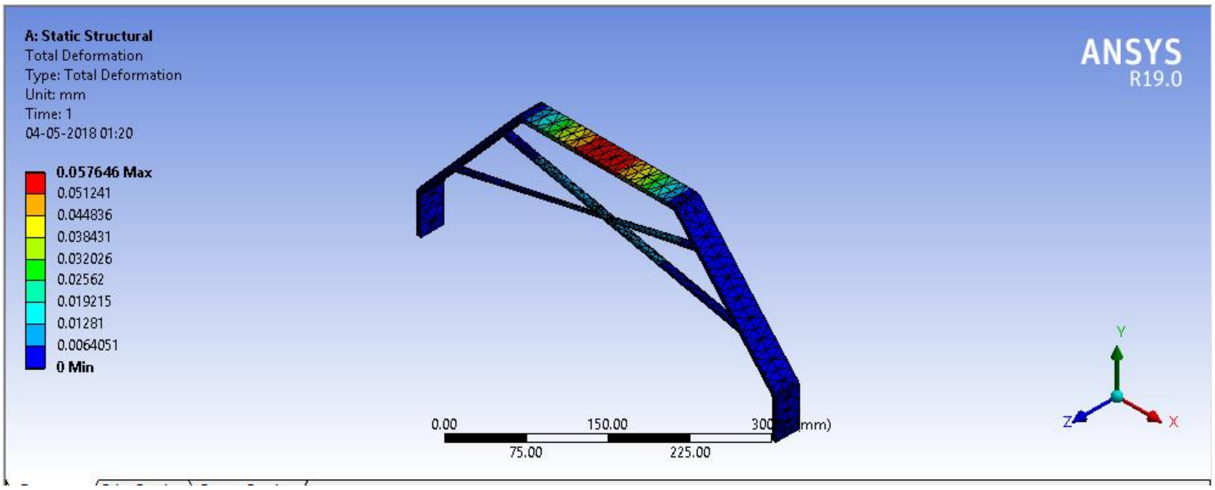
Pressure Coefficient of Airfoil



Top View Pressure Gradient on the Wing

2.1.4 Landing Gears

The design, analysis and fabrication of the landing gear was done to provide the desired balance and durability. Tri-cycle landing gear consisting of main and nose parts was chosen due to the advantage of take-off and landing run and stability during taxi. The wheelbase of main landing gear was determined to provide the necessary force absorption during landing and stability during rotation. The height of the landing gear was calculated so that the tail and the propeller do not hit the ground. The landing gear is made by 6061 grade aluminium alloy. Moreover, from the CFD results it can be seen that on the max possible load, a deformation of 0.05 mm is obtained, which is within the desirable limits. The two extra supporting rods are kept to provide adequate support to the landing gear.



2.2 Autopilot:

To make the plane fly autonomously and develop a fully integrated robust system, an autopilot is needed. The team has decided to use the 3DRobotics Pixhawk, which is the best commercial option available. It has integrated IMU, barometric sensors and plenty of interfaces. It is able to fulfil the mission requirements of autonomous take off, navigating to the waypoints and land. Moreover its capabilities include changing the flight plan while the aircraft is airborne. This completes the primary requirement of obstacle avoidance.

It is responsible for the control of motor for propulsion, servos for all control surfaces and for the airdrop mechanism. The plug and play capability for RC receiver made it possible for inflight manual takeover. It has the ability to communicate via two telemetry ports. It was utilized by the team by connecting an SBC onboard to TELEM2 port. It will be providing GPS coordinates for controlling the orientation of camera gimbal.

Pixhawk with its Interfaces

The firmware running in the autopilot is ArduPlane 3.8 version. It was so chosen because of its vast acceptance around the world and being favourite for open source community. Its features include precise navigation towards waypoint, automatic take-off and landing. The most important feature is the one that binds the aircraft in the specified geofence and automatically triggers the failsafe action set by the user.

Ground Control Station:

A ground control station, which is keeping track of UAS every instance should have a better viewable GUI that shows the location, orientation of aircraft in space, path that UAS has gone through and parameters like speed, heading towards next waypoint etc.

Mission Planner was the best choice available as per the mission requirements, as it can accomplish following:

1) Loading of firmware into the Pixhawk and tune the vehicle for optimum performance.
2) To plan, save and load missions wirelessly to autopilot.
3) Monitor vehicle status while in operation.
4) Download log for analysing the past flights.

It has a number of parameters that can be set by user to acquire an airframe specific flight. The software also comprises of a separate window that gives access to all tuning parameters. Finally, it is open source that enables us to customize it as per our task specific requirements.

2.3 Imaging System

To accomplish the task of photography from the higher altitude, the camera should have the capability of taking pictures of small targets in a large field of view. The team selected the Sony A5000 camera for its higher resolution, which allow maximum light to reach for each pixel and grab a noise free image. Moreover, the camera offers control over its optical zoom and angle of aperture, exposure and shutter speed.

2-axis Camera Gimbal

Sony A5000

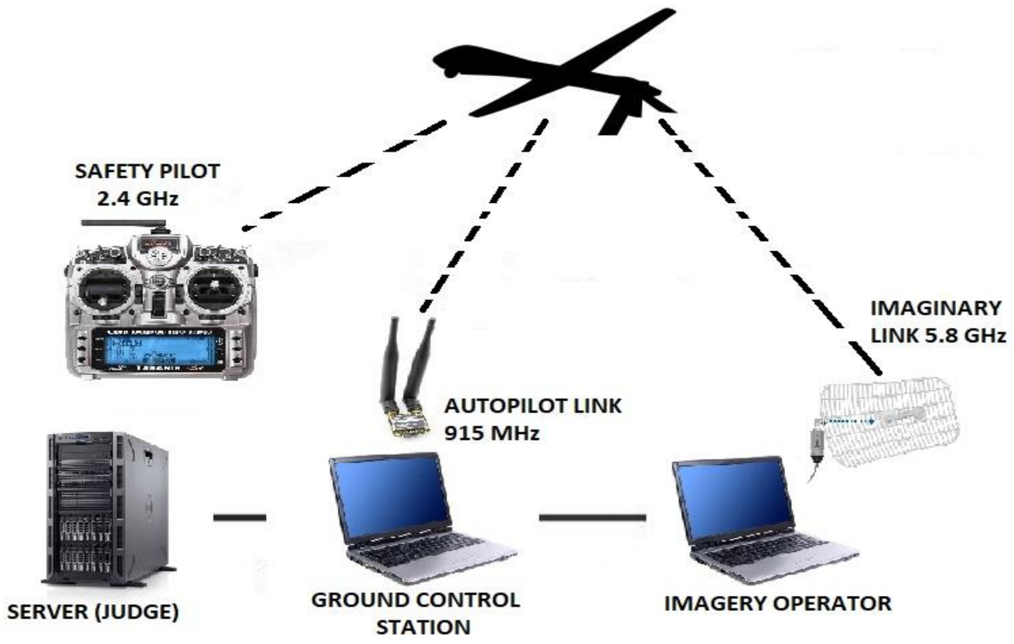
At an altitude of 250 ft., the Sony A5000 has pixel density of 0.485 in^2/pixel. Having this much pixel density, the farthest target is still more than 1000 pixels large. The camera perfectly balances the trade-off between weight and quality.

Camera Selection:

Camera	*Sony A6000*	*Sony A5000*	*Canon Eos Rebel SL1*
Shutter Speed	30 - 1/4000	40 - 1/4000	30 - 1/4000
Resolution	24,3 MP 6000 x 4000	20.1 MP (4224x3156)	18 MP
Auto Focus	YES	YES	YES
Weight	285 g	268 g	370 g
Dimensions	120 x 67 x 45 mm	110 x 63 x 36 mm	117 x 91 x 69 mm
Price	$450	$430	$499

2.4 Communications

The UAS is having three wireless links to ground operators.



Communication Links

Pilot Communication:

The radio controller used is FrSky Taranis to enable manual takeover of UAS if autonomy fails during flight. The onboard receiver is FrSky D4R-ii which utilizes the 2.4 GHz band and sends data to pixhawk with a PPM output which provides reliable communication backup.

Autopilot Communication:

The mavlink connection between UAS and GCS is carried out at 902-928 MHz band. RFD900+ proved out to be the best choice due to its transmitting power of 1000 mW for long distance telemetry data transfer. It can transfer data at rate b/w 4 to 250kbps.
The main goals of this communication are:

- Providing a real time telemetry to GCS
- Allowing to modify mid-flight plan
- Sending a heartbeat to UAS so that in case of communication lost, it can enter the failsafe mode

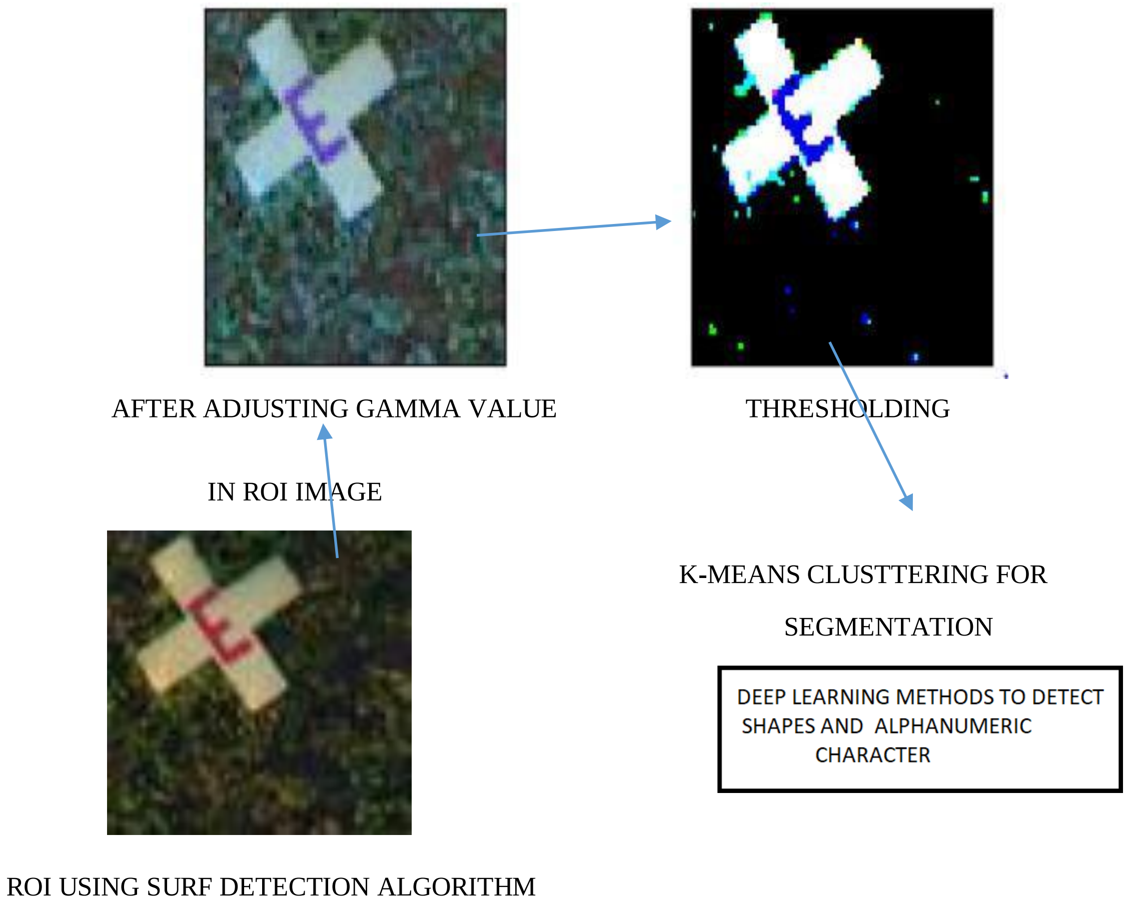
Imaging system communication:

The third link is for transferring data from onboard computer to the ground operator's computer. It is a 5.8 GHz frequency link providing faster image transmission. The imagery link is established by omnidirectional Ubiquity Bullet-M5 onboard and directional Ubiquity AG-HP-5G27 ground antenna model. Air antenna power is

28dBm/600mW and that of ground antenna is 25dBm/316 mW. It is more than sufficient to meet the communication requirements.

2.5 Object Detection, Classification, Localisation (ODCL)

The Autonomous Detection, Localization, and Classification (ADLC) system uses OpenCV surf detection algorithms, K-means clustering and deep learning using TensorFlow framework to detect and identify target sightings in images recovered from the aircraft through the GCS.



Algorithms used for autonomous detection

First the region of interest was evaluated using Open CV surf detection algorithm from the cropped image which was retrieved from aircraft through the GCS. After finding region of interest of an image, thresholding was performed in order to extract the target letter and shape from the background. The K-Means clustering algorithm has been implemented to segment a target into a shape and an alphanumeric character. K-Means was chosen because it effectively segments groups of colours given the number of groups (e.g. given that there are three colours: background, shape and alphanumeric character. Now after segmentation the deep learning methods using TensorFlow framework and CNN networks using MOBILENET model were used to detect shapes and alphabets.

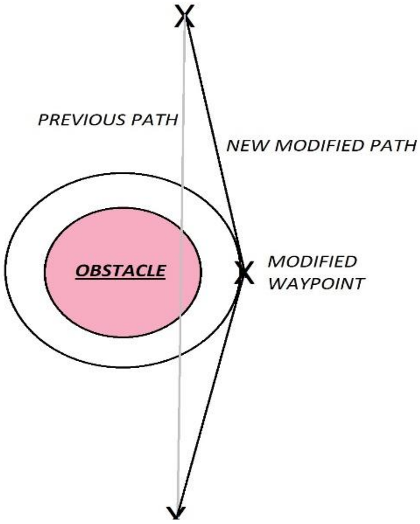
The shape classification strategy utilizes Fourier analysis on the shape contours to recover inexact shape descriptors. These are named shapes by a neural network prepared on produced information. The sectioned alphanumeric is passed into the Tesseract Optical Character Acknowledgment engine for classification. The introduction of the picture is additionally revealed by the classification engine as the edge at which the most elevated certainty character was perceived. Once the portioned areas for alphanumeric and shape are resolved, the normal colour of every area is named a specific colour in view of its separation to known colour esteems.

2.6 Obstacle Avoidance

The team has decided to attempt stationary obstacle avoidance only. The task was divided into following two parts:

1) Detection:
The method is quite straight forward. The path between two waypoints is a straight line that should not go through the area covered by obstacle. It is checked by a simple algorithm which takes discrete points on the line between waypoints at a specified distance and radius, GPS coordinates of centre and height of the obstacle as the input parameters.

2) Avoidance:
Initially, the height parameter is checked, i.e., whether it is possible to avoid obstacle by simply manipulating height of the UAS. For that, target climb-rate is key factor that should not exceed the limit. If that does not do, the path of UAS is modified. In order to do so, every obstacle size is increased by 2 meters and a waypoint is automatically estimated and created on the tangent of new obstacle considering the orientation / direction of UAS as a key parameter.

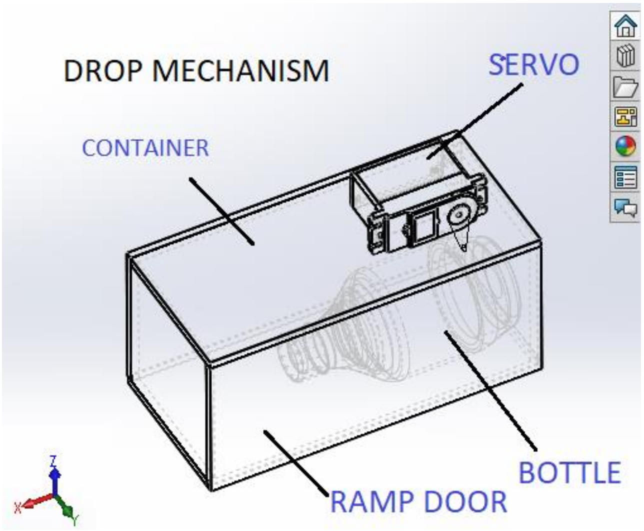


Stationary Obstacle Avoidance

2.7 Air Delivery

In order to complete the air delivery task, the minimum height from which bottle would break was found out by practical means. Further, when UAS would attempt the task, it would be directed for that minimum height. This was so as to avoid air drag as much as possible, which would have generated a considerable extent of uncertainty in actual drop point of bottle.

Release Mechanism:
The release mechanism consists of the bottle in a bottle container. It is a basic ramp door mechanism, similar to that used in Antonov Cargo planes. The ramp motion is controlled by using a servo motor, which in turn is connected to the Pixhawk. The whole mechanism can be initiated just by the push of a button from the GCS or the safety pilot control unit.



Payload Drop Mechanism

Algorithm:

The sequence of waypoint was preset before attempting the airdrop. That is to make sure bottle lands to its best target.

The calculation of optimum time to drop was calculated by ballistic missile equations and the following formulas were derived:

$$t = \frac{1}{p}\ln(-1 + 2e^{\left(\frac{p}{v_t}\right)y} + 2\sqrt{(e^{\left(\frac{2p}{v_t}\right)y} - e^{\left(\frac{p}{v_t}\right)y}})$$

$$x = \frac{V_t{}^2}{g}\ln(\frac{V_t{}^2 + ugt}{V_t{}^2})$$

where, u = ground speed
y = altitude
x = actual drop point distance at any time
g, p and v_t are constants

It was quite hard to mathematically derive the drag coefficient of water bottle. Henceforth, it was estimated by practically attempting airdrop from UAS and then adjusting it to most accurate figure possible.

2.8 Interoperability

The interoperability framework has three fundamental undertakings: getting assignment data, understanding it and sending UAV status to the server ceaselessly. The software created by the team utilizes TCP/IP for correspondence with the server utilizing post and get methods.

2.9 Cyber Security

Cyber security is the technique of protecting computers, networks, programs and data from unauthorized access or attacks that are aimed for exploitation. There is always risk of hijacking the communication links wherever wireless communication is established. In order to avoid this risk, the team has adopted the following methods:

Sr.No.	Link	Risk	Alleviation	Fall back Plan
1	Autopilot link	Jamming	900 MHz is regulated, so only malicious sources can jam.	Use of Wi-Fi link and Flight View for primary telemetry communications until link is regained.
2	Safety Pilot Link	Jamming	RC receivers are placed on either wing to decrease ambient noise and provide redundancy	Plane will return to land after 30 seconds.
3	Wi-Fi Link	Hacking	WPA2 security and encryption.	To be deecided

Chapter 3: Conclusion

The team started preparing for AUVSI Student UAS 2018 competition from June 2017, with an aim to conduct a complete conceptual design, perform thorough engineering analysis and complete the fabrication of an Unmanned Aerial System that would meet all the requirements and constraints laid out by the jury. A sufficient amount of literature survey was carried out for the initial couple of weeks. Based on the team's experience during previous events namely, SAE Aerodesign Challenge 2016 and 2017, it was decided that the fixed wing would be preferred. The carbon fibre reinforcement over the entire airframe was a major step taken up by the team members. The Electronics and Communications team was capable enough to understand the overall system as well as mission requirements and act accordingly, starting with selection of the appropriate components.

Several problems like proper material selection, appropriate dimensioning of the airframe, proper finish of the fabricated structures, cost and time incurred as compared to other materials and manufacturing techniques, etc. were focused upon and addressed by the team. The design team suggested that initial prototype developed was not up to the mark as per the mission requirements and could not be considered to be brought at AUVSI SUAS 2018. The research team, then analysed the errors, worked upon the subject matter continuously for a couple of days, and a new prototype was fabricated which resolved the issue.

Overall, it was a very good and happy learning experience for all the team members, along with the support of our faculty advisor, fellow batch mates, and family members. The team finally conveys its sincere thanks to the organizers to conduct an event of the sort, thus encouraging the young enthusiasts and hobbyists to showcase their talent in this particular domain. Meanwhile, the students learnt some important and interesting lessons in aerodynamic design, time management, cost analysis and budgeting, team management, selection of efficient and appropriate manufacturing technique, etc. Displaying unmatched creativity, dedication and smart work, Team ARROW has finally designed and fabricated an Unmanned Aerial System that will certainly comply with the requirements in the final event.

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