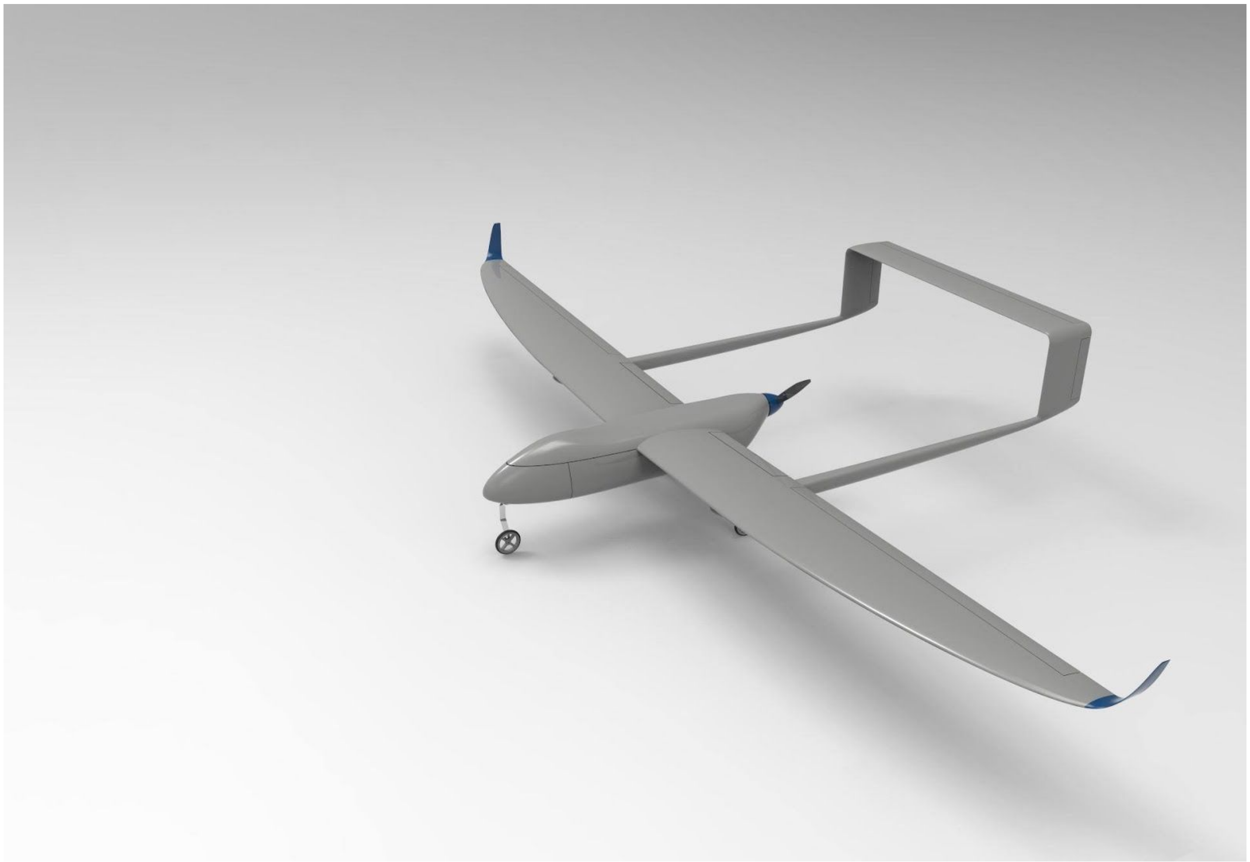
AUVSI SUAS Competition 2017
AERODESIGN

Poznan University of Technology



Abstract

This paper describes design and development process of aircraft system for AUVSI SUAS Competition. Basing on our knowledge gained during SAE Aero Design competitions we decided to take on challenges of different kind of missions. Plane design was strongly focused on aerodynamic performance and airframe robustness for autonomous flight and object detection. To accommodate many different requirements set forth by competition tasks the team consisted of a wide range of specialists: mechanical engineers, IT specialist and electrotechnic engineers. This joint effort resulted in an aircraft which is able to complete most parts of the mission.

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1. Systems Engineering Approach

1.1. Mission Requirement Analysis

According to the Competition Rules teams have to complete several tasks to score points. Missions were categorized in two groups:

- will attempt
- will accomplish

Our team also decided to group this tasks depending on the priority. In this competition we focused on autonomous flight and object detection.

Priority	Task	Status
Primary	Autonomous Flight	Will accomplish
Primary	Obstacle Avoidance	Will accomplish
Primary	Object Detection, Classification, Localization	Will accomplish
Secondary	Search Area	Will accomplish
Secondary	Automatic detection	Will accomplish
Secondary	Off-Axis	Will attempt
Primary	Air Delivery	Will attempt
Primary	Interoperability	Will accomplish

1.2. Design Rationale

Since the tasks set forth by the competition rules are diverse and complex it is obvious that a robust platform is needed to accomplish those.

When setting parameters for our system we wanted to have a learning opportunity with all our systems.

Airframe - we wanted to design and build a modern high performance composite UAV platform

Telemetry system - we wanted to gain experience with modern medium range (30km) communication systems.

Image capturing - we wanted to utilize a high resolution commercially available camera

Image processing - we set a goal of using an onboard image processing system based on neural networks

1.3. Expected Task Performance

Based on our experience in previous years we are certain that the airframe will perform its tasks with no major issues providing adequate performance. We are utilising as much proven of the shelf components as we can to mitigate the risks involved. This was the main rationale in choosing the Pixhawk family autopilot and power systems. A multistage parallel testing regime was also implemented to further lower risks and speed up the process. Neural net image processing algorithms were extensively tested and were performing adequately. Main performance issues are expected to be integration issues. since the airframe is newly designed high performance one, and so are electronic systems as well as the camera system and the integration schedule is very short we are expecting to encounter issues and assigned appropriate run-in time.

1.4. Programmatic Risks and Mitigation Methods

Risk Factor	Description of risk	Impact	Likelihood	Mitigation Method
Delays	Delays in design, building or programming problems can influence time spended on flights	Low	High	While designing team made schedule for tasks completion
Integration issues	Full system consist of systems which are independently developed and have to work with each other	Medium	High	We selected an auditor who is responsible for communication between students and for keeping the plan
Loss of system scripts and programs	In result of disk memory damage progress made with programs and scripts can be lost	Low	High	All codes and designs were backed up regularly, and stored on a cloud storage servers and remote repositories.
Loss of airframe	Crash during test flights or damaged plane	Medium	Medium	For competition several parts of of airframe are doubled

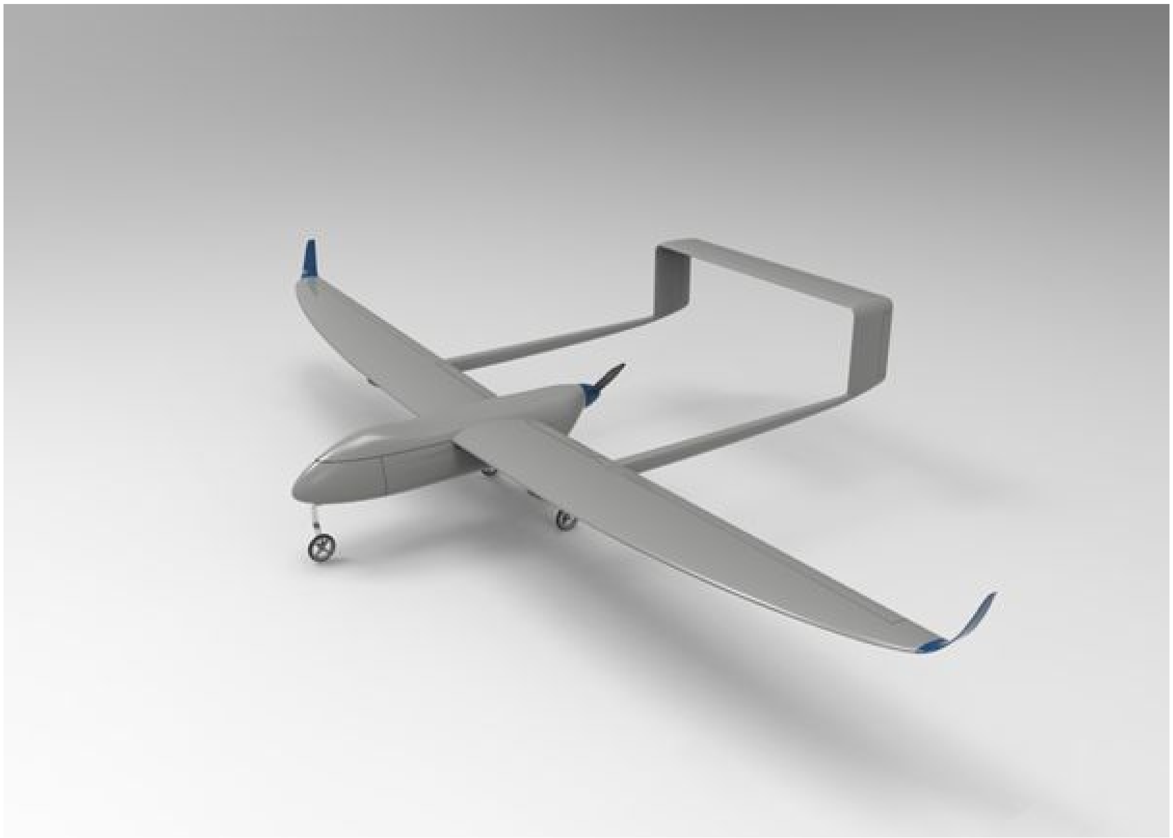
2. UAS design

2.1. Airframe

Academic Flight Club of Poznań University of Technology presents a detailed design of an UAV for the AUVSI SUAS. After very thorough examination of our past performances and manpower available this year our team decided that to minimize risk we would base our design on our design used previously in SAE Aero Design. Though low empty weight and good handling qualities are still our main goals, there two more ease of system integration and reliability. A lot of attention was paid to increasing efficiency of propulsion of our aircraft. Several motors and prop combinations along with different control methods were considered – even a variable pitch one

Parameter	**Value**
MTOW	21 kg
Empty Weight	14 kg
Wingspan	4 m
Length	2.3 m
Wing Area	0.9 m^2
Propulsion type	Brushless
Propulsion power (maximum)	3700 W
Battery type	Lithium Polymer
Battery capacity	30000 mAh
Max Payload	7 kg
Takeoff method	Runway, catapult
Environmental protection	Sealed against rain

Parameter	Value
Endurance	90minutes
Cruise Speed	22m/s
Stall Speed (open flaps)	13m/s
Max Level Speed	32m/s
Take off run	60m
CL max(open flaps)	1.7
Cl max (w/o flaps)	1.3
Ceiling	2000m

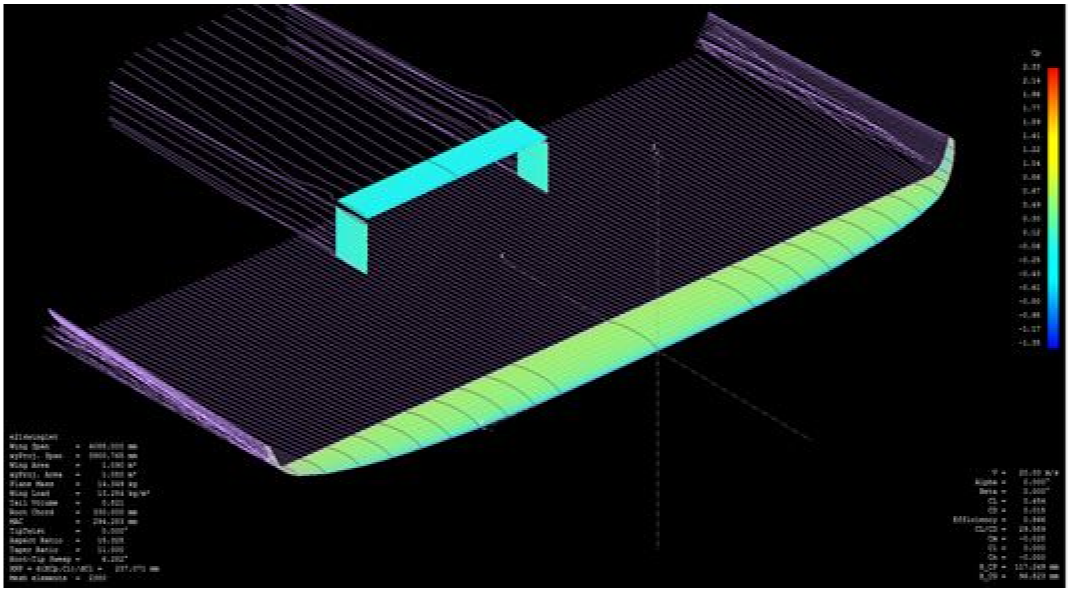


The first step in designing our UAV was to perform a feasibility study by identifying existing UAVs with similar geometry, size, and mission requirements. Using available data from existing UAVs, a parametric study was performed to determine initial wingspan, power requirements, and UAVs maximum speed.

2.1.1. Aerodynamic Design Process

The process used to develop the Aerodynamic model of our UAV consisted of three steps:

- Step 1: Make design choices such as the airfoils for the main wing and tail, the configuration of the plane such as propeller location - pusher or puller, maximum span, location of wings relative to each other and chord length.
- Step 2: Perform analysis on the geometry of the aerodynamic surfaces of the aircraft. Once the geometry of the aircraft is refined, it is possible to estimate lift-to-drag ratios,stability static margin, and performance capabilities.
- Step 3: Use the XFLR5 computational fluid dynamics software package to model final aerodynamic characteristics of the proposed UAV.



2.1.2. Structural design process

Material considerations:

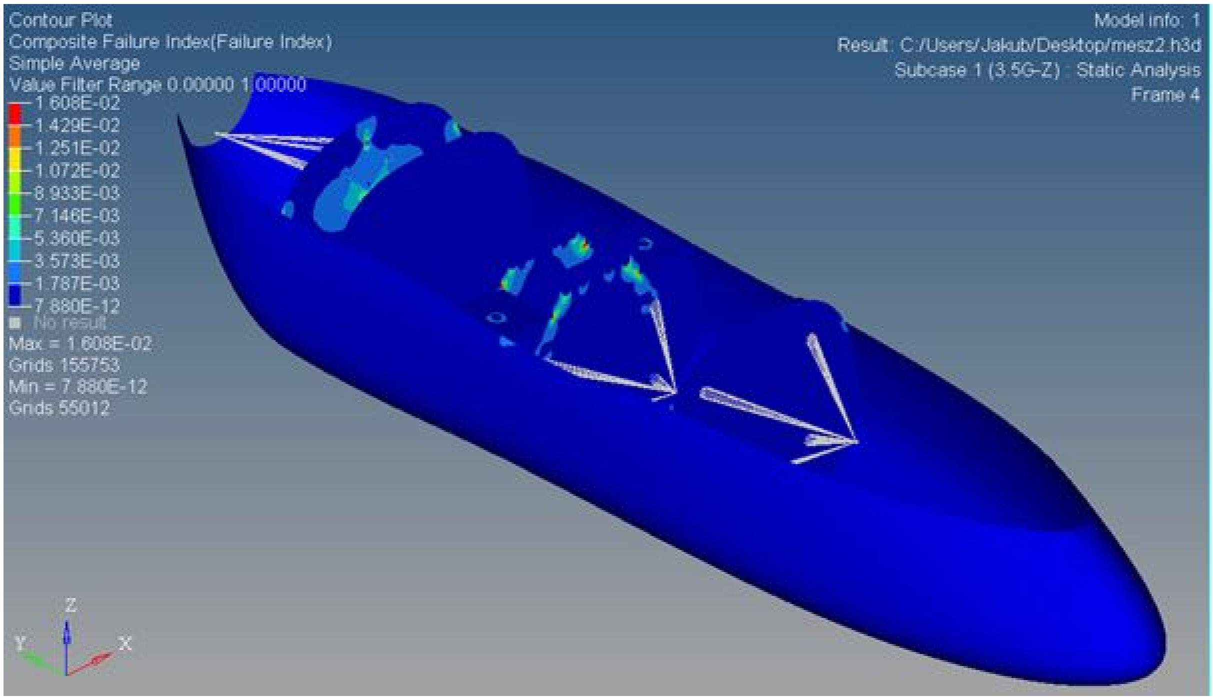
During the preliminary design process we evaluate structural considerations. The main scope was to build and extremely lightweight airframe, which shall:

- withstand external and internal loads,
- carry propulsion, electronic and termination systems,
- survive parachute hard landing due to system fail
- can be easily manufactured in low series scheme

All this requirements can be fulfilled by using FRP materials. We chose carbon fiber in woven form and rowing tapes as main material. The structural adhesive is epoxy glue with high shear strength (>20MPa) that can be applied at room temperature.

Structural analysis

A FEA model was developed to determine the permissible stresses within the aircraft skin and internal structures. For simplicity, only structural elements of the aircraft are modeled. All panels were modeled using 2-D orthotropic materials and laminate properties to determine membrane forces, bending moments, and transverse shear loads. The fuselage and wing skins are composed of sandwich panels made from composite materials. The material properties of the face materials were then defined within the FEM using core material properties specified by the manufacturer. Geometry for the finite element model was imported from Siemens NX, and the imported surfaces were meshed with the laminate properties to simulate the sandwich panels.



Example of stress analysis (TSAI failure index)

2.1.3. Electrical Diagram

The team decided to use two separate batteries to power the aircraft. First of them is intended to supply power to the motor and servos whereas second to most of the electronic equipment. This solution reduces interferences caused by ESC and improves reliability of the whole system. For safety reasons, system contains also one redundant battery pack that will be used in case of over-discharge of main battery. Switch between these battery packs occurs automatically when voltage of main battery drops below certain level. This solution ensures that autopilot and all communication system will work even in case of main power source failure. General electrical schematic was shown in Figure 2.1.

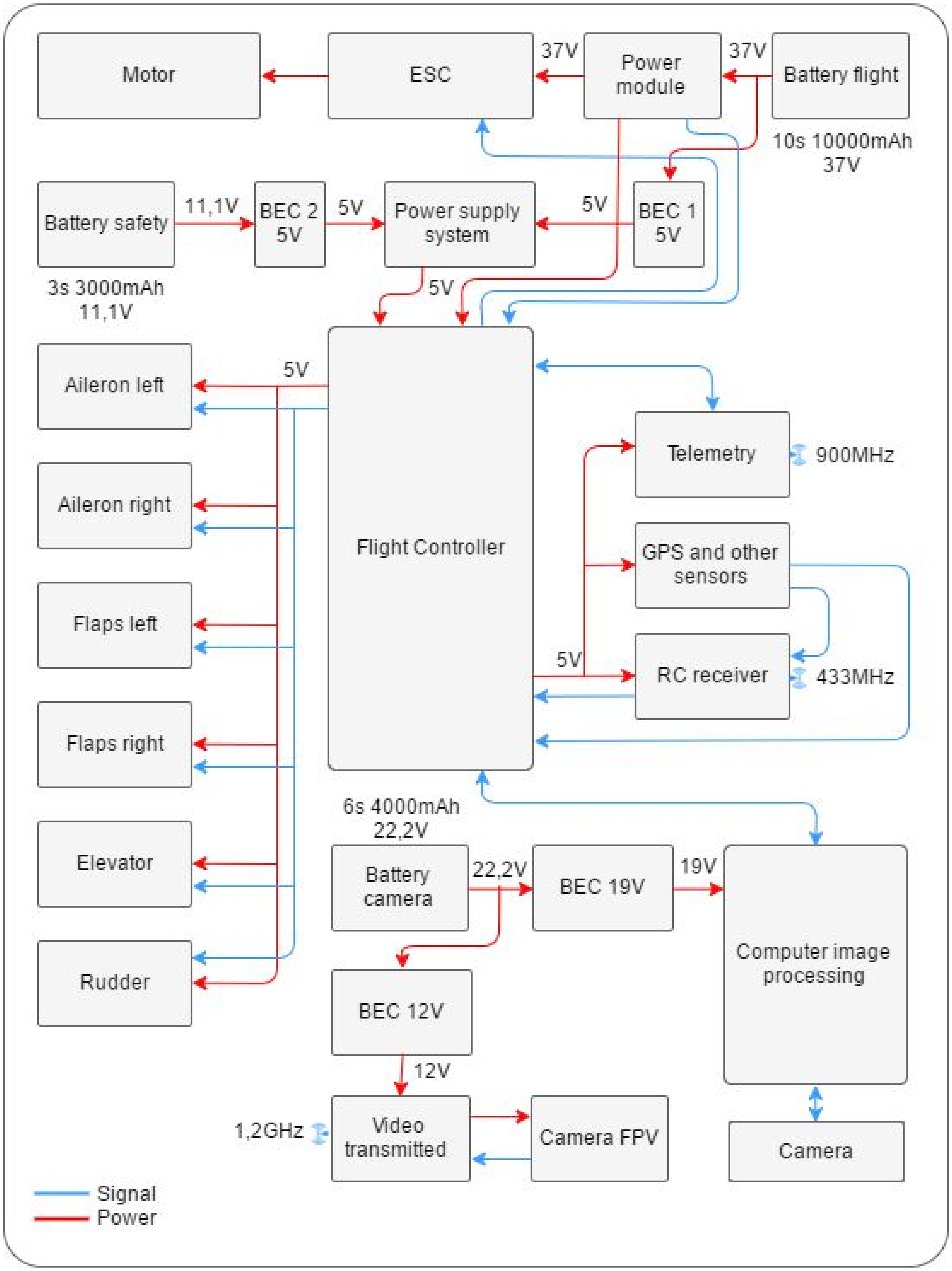


Figure 2.1 Electrical Diagram

Both Autopilot and On Board Computer (OBC) must be powered with specific and stable voltage source. For this purpose we used separate Power Modules that are basically buck-boost converters. FPV camera and video transmitter does not require specific voltage value, but arealso powered using 12V BEC module.

2.1.4. Onboard Computer

Selection of onboard computer was crucial due to computationally demanding algorithms running onboard UAV such as ADLC. As automatic recognition with use of CNN can be greatly accelerated with use of GPU it was decided to use one of Jetson platforms. Two possibilities were considered - Jetson TK1 and Jetson TX1. Their parameters are presented below:

	Jetson TK1	Jetson TX1
CPU	NVIDIA 4-Plus-1™ Quad-Core ARM® Cortex™-A15 CPU	Quad-core ARM® Cortex®-A57 MPCore Processor
GPU	NVIDIA Kepler GPU with 192 CUDA Cores	NVIDIA Maxwell™ GPU with 256 NVIDIA® CUDA® Cores
RAM	2 GB x16 Memory with 64-bit Width	4 GB LPDDR4 Memory
Data Storage	16 GB 4.51 eMMC Memory	16 GB eMMC 5.1 Flash Storage
Interfaces:	DP/LVDS, Touch SPI 1x4 + 1x1 CSI-2, GPIOs, UART, HSIC, I2C	UART, SPI, I2C, I2S, GPIOs
Cost	199$	499$

Jetson OBCs are easily integrated with Caffe library and it's GPUs are compatible with CUDA and CUDNN libraries. Jetson TX1 was chosen because of its better performance, especially with deep learning tasks - according to benchmarks provided by www.phoronix.com Caffe AlexNet on Jetson TX1 is 2 times faster than TK1. It can provide extremely efficient environment for ADLC task.

2.1.5. Gimbal and Camera

Two camera models were considered after preliminary selection process: Nikon D3200 and Sony A6000. Comparison of their parameters is presented in the table below:

	Sony Alpha A6000	Nikon D3200
Resolution:	24,3 MP	24,7 MP
Sensor size:	23.5 x 15.6mm	23.2 x 15.4mm
Dimensions:	120 x 66.9 x 45.1 mm	125 x 96 x 76,5 mm
Weight:	344 g	505 g
Battery life:	420 shots	540 shots
Max fps:	11	4
gphoto compatible:	Yes	Yes
Price:	625$	450$

It was decided to choose Sony A6000 owing to it’s popularity both in student projects and in commercial applications.

One of the most important factors in classification of images from the camera is ground resolution. It was computed using formula::

$$groundRes = \frac{altitude \cdot sensorwidth}{lens \cdot resolution}$$

another important factor is area coverage:

$$span = groundRes \cdot pixels$$

These parameters were taken into consideration when image resolution and camera lens were selected. Maximal ground resolutions (size of 1 pixel on the ground) and areas covered with lenses considered are gathered in table below:

Resolution	Sony SEL20F20F28	Sony SELP1650
6000 x 4000	1.0 x 1.0 cm	1.3 x 1.3 cm
4240 x 2832	1.5 x 1.5 cm	1.8 x 1.8 cm
3008 x 2000	2.1 x 2.1 cm	2.6 x 2.6 cm
Area covered:	61.9 x 41.1 m	77.3 x 51.3 m

Choosing image resolution, lens and it’s focal length is tradeoff between area covered by one photo and size of pixel. Taking into account size of objects for recognition (1 foot with 1 inch thick lettering) and speed of UAV (around 22 m/s) Sony SELP1650 was chosen shooting images at full resolution (6000 x 4000).

To perform the off-axis task we will utilise our main camera that will be tilted using a gimbal. To calculate this angle we are using *resGround* formula multiplied by *resolution*. This gives us the width of the photographed area. We assume that the flight distance to boundary should be 30 meters(100 feet). The search area will be 76.2 meters(250 feet) wide. To make sure we photograph the object we add a 30 meters margin to the photo range. The flight will be executed at 80 meters AGL. All this results in camera tilt of about 24 degrees.

2.1.6. Gimbal construction

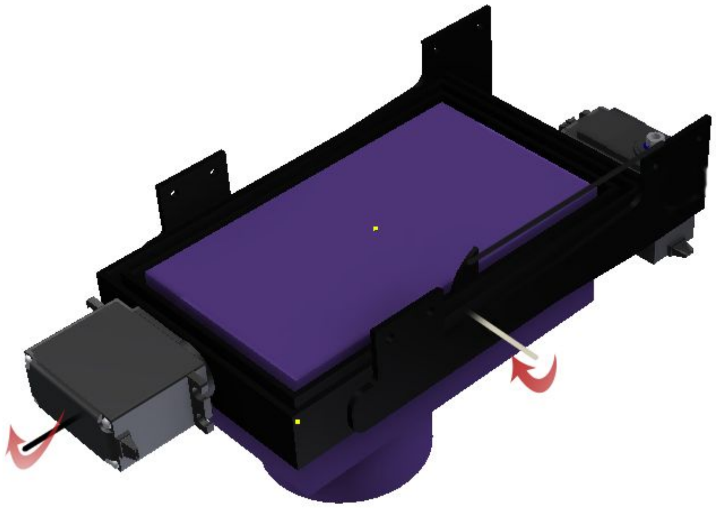


Figure 2.2 Gimbal construction conception

Gimbal has stabilizer-gyro 2 axis. Axis is controlled by two servos. Servos are controlled by storm32 module. Controller has inputs to manually control gimbal. It is Important when gimbal must be set in the correct position.

2.2. Autopilot System

2.2.1. Air System

In order to perform autonomous flight the team decided to use 3DR Pixhawk Flight Controller. The Pixhawk module is an open-source autopilot system which is capable of navigating to previously planned waypoints. Main reason for choosing Pixhawk was its exceptional performance and software susceptible to customization. It is equipped with all necessary sensors to calculate the accurate data for navigation, including inertial measurement unit, magnetometer, barometer and externally connected GPS module. To provide additional information about battery status, voltage and current sensors are used. All important telemetry information is sent to the ground station in real time using RFD900x modules. External sensors and modules, that were connected to Pixhawk, are shown in Figure 2.1.

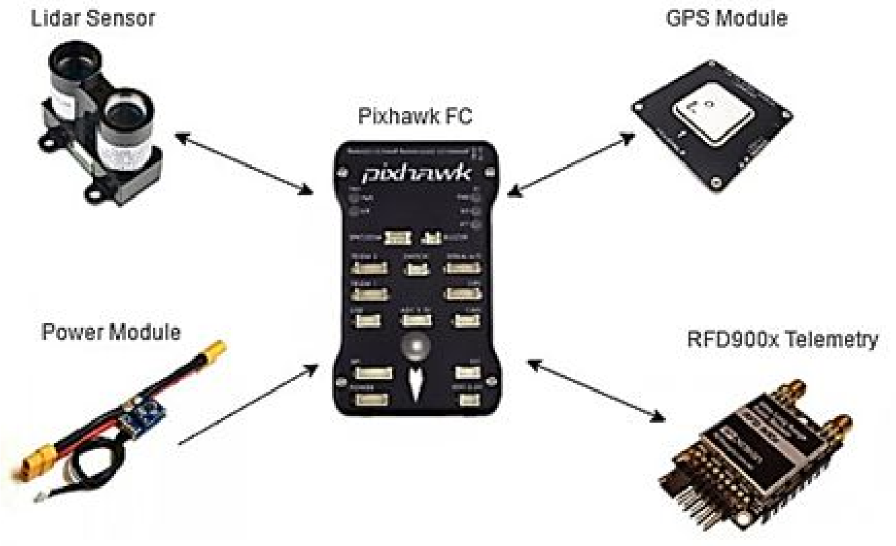


Figure 2.2 Pixhawk Sensors and Telemetry

This system is powered via Power Module which also provides information about current being drawn and battery voltage. Alternatively power can be supplied by 5V BEC attached to servo connector on Pixhawk board. This solution is most reliable as it contains redundant power source that will be automatically used in case of Power Module failure. Most critical element in autopilot system that has to work properly in order to perform mission successfully is GPS module. We decided to use Drotek M8N module with built-in compass. It supports GPS and GLONASS systems for enhanced accuracy. Moreover, it has power line filters and EMI shielding that reduces influence of external interferences.

2.2.2. Ground System

On Ground Station we are using MAVProxy and MissionPlanner to plan mission and control flight route.

2.3. Autonomous Vision System

The main task of that system is automatic detection, localization and classification. It was decided, that all image processing is going to be performed autonomously, onboard UAV. It simplifies the communication and greatly reduces amount of data that must be transferred.

From all possible solutions for image processing, the state-of-art deep learning approach was chosen. That approach provides robustness for noise and changes in illumination and enables to process images in real time.

First part of algorithm is detection of possible targets. It is realized by MSER detector. Algorithm is computationally demanding and it’s processing time strongly depends on image size, so it is processed in lower resolution. Samples which sizes are too small are rejected. Information about localization of potential targets is then used to cut the sample to detect from full image resolution.

Images retrieved from full resolution image are then fed into CNN trained on hundreds of thousands of sample images. It performs multilabel classification – from one image information about background color, font color, shape and character orientation is going to be retrieved. If it occurs, that CNN cannot be trained with such amount of labels character orientation is going to be computed in a different way described below.

Character is retrieved from image using k-means clustering algorithm and resulting binary image is fed into another, simpler CNN which recognize this as letter from given set. If orientation information is gained by previous CNN, sample is rotated with a proper angle, otherwise CNN is fed with several copies and it is classified to the group which returned highest score. Models of CNNs are prepared in Caffe framework.

Another possibility that is being verified is using one CNN for detection and classification of targets - image semantic segmentation. In this solution one CNN is used to localize and classify targets. This approach requires more complicated network, much longer learning process and more computational power onboard.

Learning process demands a lot of computation and it is going to be performed in Poznan Supercomputing and Networking Center. Owing to possibility of using the clusters at PCSS we can test different architectures of CNN and choose the one that gives the best accuracy on test data.

2.4. Data Links

The Aircraft uses three kinds of transmissions with different frequencies to every communication module.
Modules include:
- manual aircraft control,
- autopilot commands and telemetry,
- camera preview (FPV – First Person View).

Frequencies work in the same time and don’t disrupt each other.

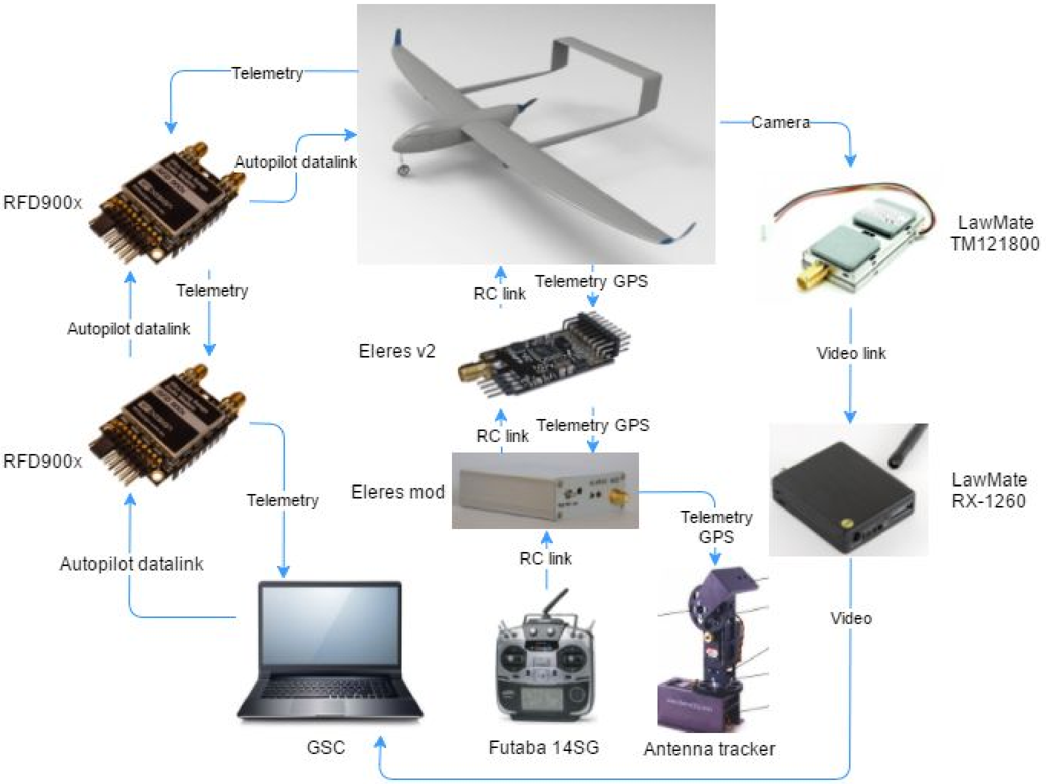


Figure 2.3 Data link system

Telemetry:
It ensures constant, bidirectional communication with autopilot. Telemetry can monitor the autopilot status and issue modifications to the flight plan in the real time. RFD900x modules (1W power, 900MHz frequency) are used for communication. Omnidirectional antenna is used to obtain stable connection. The module communicates with autopilot using UART connector. The Ground Station module was connected to the computer by USB and antenna was located on the Mast.

RFD900x Overview	
Frequency Range:	902 - 928 MHz
Output Power:	1W
Air data rate:	500kbit/s
Line-of-sight range:	40km

Safety pilot:
It allows manual aircraft control when autopilot is broken. The pilot always can take over control over the UAV. The communication uses 433MHz frequency utilizing LRS modules. The Transmitter EleresMOD is connected to the transmitter (Futaba 14SG) using PPM signal over trainer port. The transmitter has power regulation in steps: 100, 200, 500mW. The omnidirectional antenna and 500mW power allows for 40km communication range.

Eleres V2 Overview	
Frequency Range:	413-453Mhz
Output Power:	100mW
PWM channel:	12 channel and 5 binary
PPM channel:	8 channel and 1 RSI or 9 channel

eLeReS MOD Overview	
Frequency Range:	413-453 Mhz Frequency Hopping (FHSS)
Output Power:	100 mW, 200 mW, 500 mW
Channel:	12 proportional channels and 5 binary

First Person view:
The module with the camera in the aircraft transmits video in the real time to ground station. LawMate modules were used (1,2 GHz frequency, 1W power) for FPV. Omnidirectional antenna was used in the transmitter. Ground module uses antenna tracker with a directional antenna.

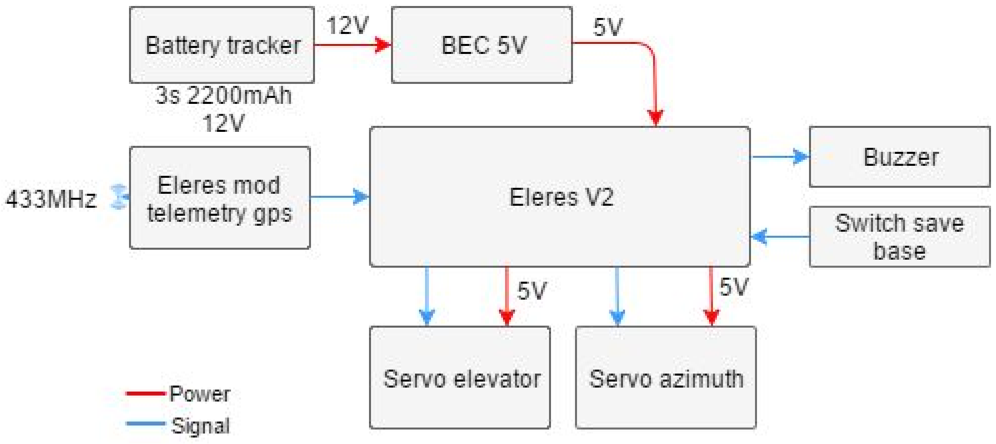


Figure 2.4 Antenna tracker system

Tracking is working with based on relative GPS positions of aircraft and ground station. Eleres modules allow for sending telemetry data. GPS coordinates are being sent from the aircraft to the transmitter. The transmitter sends data to the tracker. Tracker uses second Eleres V2 receiver with modified software. To the receiver two servos are connected: elevator servo and azimuth servo. The receiver controls servos according to position of aircraft. The tracker when is turning on, records base station position, additionally, position can be recorded manually

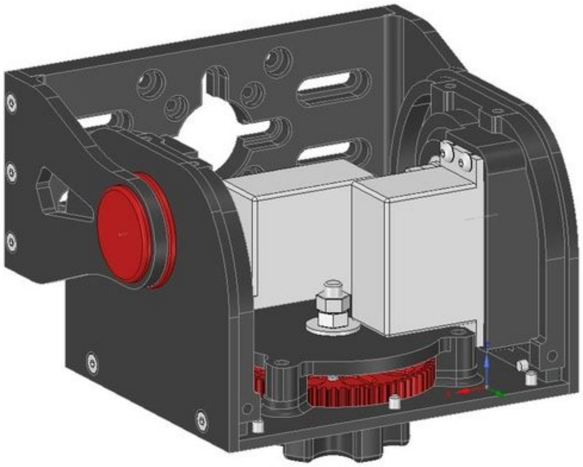


Figure 2.5 Antenna tracker system

Antenna tracker was fully printed on a 3D printer and was installed on a mast. To drive we use Hitec standard servos Everything is powered from a LiPo 3s 2200mAh battery.

3. Test and Evaluation

3.1. Autopilot Tests

3.1.1. Waypoint Navigation

Flight controller performance was successfully tested during subsequent tests. Initially, whole autopilot system was installed on separate test airframe to ensure that everything is working correctly. In order to obtain best flying characteristics, we used built-in autotune mode to determine optimal parameters of PID controller that is responsible for airplane control. Accuracy of waypoint navigation highly relies on weather conditions, especially wind speed and planned mission path. During test flights in windless conditions we managed to reach waypoint accuracy up to several feet. Another important factor that has to be taken into consideration is GPS signal strength. The stronger it is, the more precisely position of airplane can be estimated.

3.1.2. Automatic Takeoff and Landing

For automatic takeoff and landing, we used algorithm implemented in Pixhawk software. Most important parameter that has to be estimated precisely during landing maneuvers is airplane altitude. Pixhawk determines altitude based on GPS and barometer data, but none of mentioned sensors take into consideration terrain roughness. In order to minimize risk of unsuccessful landing we are going to install Lidar Sensor that measures distance relative to ground level with an accuracy of several centimeters. This will ensure that landing maneuver will be started in adequate moment regardless of terrain characteristics.

Photo taken during autonomous flight

4. Safety Considerations

4.1. Return to Land

The UAV has implemented safety features in case of sudden communications loss. Return to Land (RTL) function is automatically activated if signal is lost for more than 30 seconds. RTL procedure can also be initiated by safety pilot or ground station by using single switch. This is very important feature for security reasons as it will ensure that airplane will not transgress airport boundaries. This maneuver can only be performed on the assumption that GPS signal is good enough. Otherwise, autopilot will not be able to determine its coordinates and home destination. In that case autopilot will terminate flight by turning off the motor.

4.2. Cyber Security

One of the most important aspect of radio communication is its security. Each link should be protected against unauthorized access like spoofing and spying. For this purpose, autopilot telemetry system uses AES Encryption that prevents access to transmitted data to third parties. In case of signal jamming occurrence, autopilot will switch into RTL mode and safely return to launch position. Another sensitive to cyber attacks device is GPS. In case of GPS signal jamming, UAV can not determine neither its current localization nor path to launch spot. This type of cyber attack is hard to prevent but it can be detected by analyzing sudden change of number of satellites or by utilizing Extended Kalman Filter (EKF) data and GPS signal variance.

5. Conclusion

This paper summarizes the work done by Aerodesign Team in preparation for the AUVSI SUAS 2017 competition. With new members in our team, we were able to connect different fields of engineering and build complex system for this mission. We used neutral networks with image recognition for finding and identifying objects. Autonomous flight solutions allowed us to make the task automatic without human intervention. We improved our skills and managed to build a robust system for this competition.