ÇANKAYA UNIVERSITY

CENG 408- ME 408-EE 408

UNMANNED AERIAL VEHICLE

(UAV)

PROJECT REPORT

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1. INTRODUCTION

About Us

The project aims to design and program an unmanned aerial vehicle to perform some tasks automatically. It will decide and perform actions itself. We will approach this task from 3 different angles; Mechanical, Electrical, and Software. This project covers all the necessary approaches to build a drone completely. Our team consists of three different departments; computer engineering, mechanical engineering and, electrical and electronics engineering. We are all third-grade or fourth-grade students.

Motivation

We all wanted to enter competitions about an unmanned aerial vehicle and decided to design a complete UAV as our project. Instead of a single department, our group contains three different departments it will be our first real multi-department project experience. We are all highly motivated because we each love designing and creating and most importantly robotics.

Problem Statement

Our drone will be task-driven. We divided each task and they will be handled individually. The first task is the autonomous take-off and then learning and creating a digital map of the task track, our drone first flies through an empty track and learns and records the target and tools locations separately. For example, if the task is put out of the fire, the target will be the location of the fire and the tool will be the location of water. Secondly, after learning locations drones will start doing missions and their requirements. For example, in the previous example, this task will be first going to the location of water and take some water to the fire location and beginning to extinguish process. Lastly, after the mission is completed the task is to return to the start location and autonomously land.

2. REQUIREMENTS SPESIFICATION

2.1 SOFTWARE REQUIREMENTS SPECIFICATION

2.1.1 Image Processing And Flight Control Software

A single-board computer with a minimum of 2 GHz or faster processor speed and a minimum of 4 Gb of ram is needed for the necessary transaction speed so that drone can decide and process the data at the same time.

A flight control card will be used for all the information gathering needed for the main program to decide what is the next move that drones do and do not. So flight control card has to have the necessary sensors. Lastly a camera is needed for video input and one other camera is needed for visual presentation of flight.

2.1.2 Operating Systems

In raspberry pie, we will use Linux based operating system. And for autopilot software, we will use ArduPilot or ROS(Robot Operating System) these are works best with raspberry-pie and Emlid-Navio flight card.

2.1.3 Realtime Telemetry Flight Parameters

We will need real-time information software on our computers or smartphones so that we will keep track of our drone's real-time information like UAV range, height, speed, GNSS strength, remaining battery power, and warnings. We will use Ardu-Pilot for that.

2.1.4 Mission Planer(Ardu-pilot)

This software requires Windows 10 or newer versions. Integrated mouse , keyboard and at least 2 Gb of ram for minimal usage.

2.2 ELECTRICAL & ELECTRONIC REQUIREMENTS SPECIFICATION

2.2.1 Thrust System Requirements

Motor

Brushless DC motor selection will be adjusted by considering the weight of the total body and other equipment and the amount of total energy storage. The so-called KV rating of the motor is representing the ratio of the motor's unloaded rpm to the peak voltage. KV will be chosen by the drone's weight.
980KV motor will turn around 10,000 rpm so that four of them will be carrying the drone.

Speed Controller

To regulate the amount of current which the motor is consumed, an **electronic speed controller (ESC)** is used. ESC provides a motor to control correctly its speed and spin direction.
The normal current provided by the ESC will be 40A.

Power Distribution Board

Since Quadcopter has 4 motors and 4 ESCs attached to them, a power distribution process is needed. ESC is run by a single battery pack and a single battery pack has only one DC output, i.e. one positive wire and one negative wire. Thus, it needs to be extended into 4 connection wires in order to distribute all the needed energy to the ESCs and then motors.

2.2.2 Energy Storage Requirements

Battery

The main energy source of a UAV is a **LiPo** battery. In almost every aerial application, LiPo batteries are used instead of other lithium variations. LiPo batteries have lesser weight and a high discharge ratio which gives the vehicle a higher capacity for energy usage.

Voltage of Batteries

Almost every industrial LiPo battery has a standard voltage value which is 3.7 V. They are generally represented by *S.*

3.7 V is represented by 1S.

Therefore, $2 \times (3.7V) = 7.4V = 2S$ and so on.

Batteries, also have *'mAh'* value means *'milliAmp hour'*. This value is used to measure the energy capacity of a battery.

Energy drawn by the motors will decide the amount of S.

A 3S battery will be enough to provide energy for all the drone parts.

Flight Controller

The brain of the drone will be chosen by some criteria which are incoming parameters from sensors, handling voltage, telecommunication parts, and other drone equipment.

In addition, control system parameters will be designed on the basis of the automated drive.

The software will be loaded into a flight control card.

Telecommunication

Telecommunication requirements will be chosen considering the range between receiver and transmitter. Although there is no need to interrupt the drone with a remote controller due to autopilot, still there will be a GPS antenna, receiver, and telemetry.

Environmental Hardware

a. **Connectors**
   Most of the electrical parts of a UAV are several parts that need to be connected to the proper location. ESC, Power Distribution Board, etc. all need to be connected via a connector.

b. **Battery Charger**

c. **Multimeter**

2.3. MECHANICAL REQUIREMENTS SPECIFICATION

2.3.1 3D Model Requirements

2.3.1.1 CAD Usage

All components of the quadcopter will be modeled in the CAD program. Autodesk Fusion 360 will be mainly used program, but other programs also can be used. Components will be assemble together included electronic parts. Their fastening method will be properly designed.

2.3.1.2 Dimensions and Tolerances

The modeled parts need proper dimensions and tolerances in mechanical matter. There is no way to have exact dimension in reality. So, it should be considered that after manufacturing, do the parts fit each other or not. In 3D model session this situation should be mind and proper design should be created.

2.3.2 Frame Strength Requirements

2.3.2.1 FEA Usage

Finite Element Analysis will be used to calculate stress and strain levels on the designed parts. Since this method is a numeric and iterative solution method, mesh sensitivity analysis should be done to make sure that the data from FEA is accurate enough. Boundary conditions, mesh type and size should be selected properly, and simulation should be made in a reasonable way. FEA will be done on ANSYS.

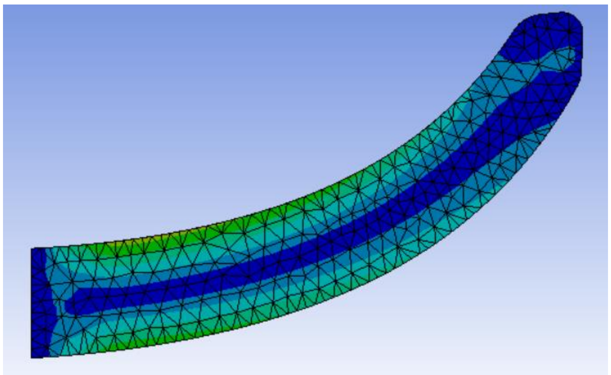


Figure 1) Stress Distribution Example

2.3.2.2 Material Selection Strength Basis

All the components have different purposes in the design so their material should be selected according to these purposes. The main parameters when selecting material are strength, mass, stiffness, vibration absorption capacity, RC wave permeability.

2.3.3 Mass Budget Requirements

2.3.3.1 Total Mass Calculation

After selecting materials of the parts, their density should be multiplied by their volumes so we can list their masses. Mechanical parts' masses will be calculated in the design session and electronic parts masses will be taken from the catalogue data. By this way, total mass will be calculated with a reasonable margin. Maximum mass according to competition is 4kg but also the drone should be light as possible to decrease the cost of the thrust system. Also, the competition's score sheet considers mass as a parameter that lighter drones can get higher scores.

2.3.3.2 Topology Optimization

Since this project is an aerial vehicle, mass should be considered properly. In a mechanical manner, generally, more mass means more strength. However, with a careful calculation, we can design a lighter but equally tough drone. By doing topology optimization, a wiser geometrical shape which distributes stress more equally can be developed. To accomplish that ANSYS will be used.

Figure 2) After Topology Optimization Example

2.3.4 Thrust System Requirements

2.3.4.1 Motor and Propeller Selection

Motor and propeller selection should be done according to mass of the total system. Motor's thrust weight ratio should be between 2 and 3 so the drone can fly properly. Motors should be attached to a convenient propeller. Greater propeller usually means greater thrust, but the efficiency of the motor can decrease after a point of this size increase.

2.3.4.2 Vibration Elimination

Cyclic motion of motors creates vibration. This vibration should be decreased to a certain level. So, the electronics, especially sensors, can work properly. Also, vibration have fatigue effect in mechanical manner. This fatigue can cause unexpected fracture. To eliminate vibration necessary damper elements will be used in critical points and propeller balancing operation will be done. To balance propellers, a necessary mechanism will be manufactured by using 3D printer.

Figure 3) Propeller Balancer

2.3.5 Manufacturing Requirements

2.3.5.1 Manufacturable Design

There are some designs which are impossible to manufacture. There is no logic on designing a part which can not be manufactured. So, manufacturability should be considered at the beginning. Also, some designs cost so much while manufacturing although there can be a way that the design is simpler but can meet the needs and it can be manufactured cheaper.

2.3.5.2 Additive Manufacturing

Most of the mechanical parts will be manufactured in 3D printer with proper filament. Creality Ender 3 V2 is used as printer and Cura as software. Designs should be transformed to g code to be used in 3D printer. Process parameters should be selected properly while 3D printing. This is an experimental and iterative procedure. That means many prototype parts should be printed until finding proper parameters.

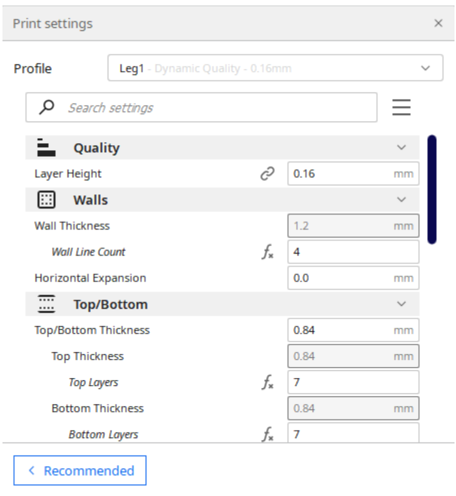


Figure 4) 3D Printing Parameters Example

2.3.6 P.I.D. Control Requirements

2.3.6.1 Selection of Parameters

P.I.D. Control Algorithm has three fundamental parameters which are Kp, Ki and Kd. These parameters have different effects on control of the drone. They should be iteratively changed and checked if the system works properly or not.

2.3.6.2 Manufacturing Test Setup

Parameters will be checked in mechanical test setups. It is not wise to create a complete drone and test it while it is flying. So, some experimental setups which simulate the drone’s flight will be manufactured.

2.3.7 Test and Verification Requirements

2.3.7.1 Measurements and Fit Check

After manufacturing 3D models, it should be tested that if the parts are in desired dimensions or not. Parts’ connections will be tested if they fit each other or not.

2.3.7.2 Strength Test

FEA or hand calculations are just foresight in stress, strain, and safety factor specification. So, experimental results are badly needed. Experimental setups should be created to simulate the real operating process and parts should be tested if they fracture under proper conditions or not.

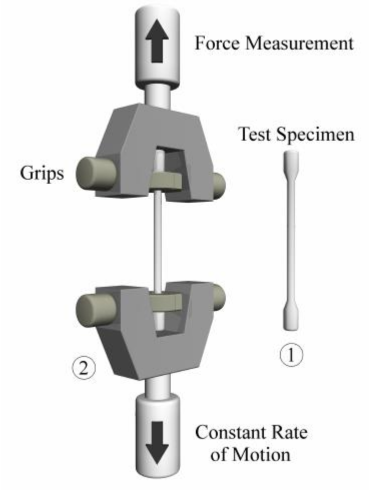


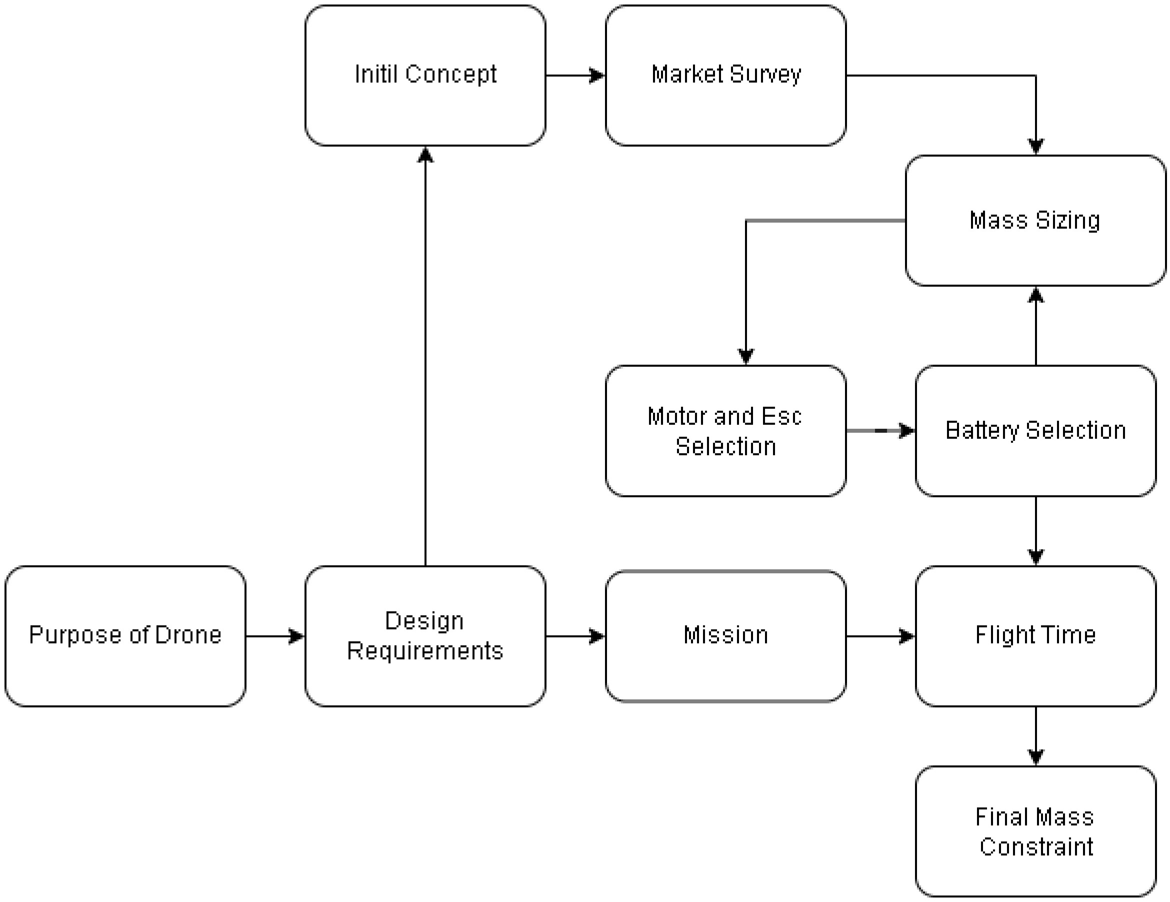
Figure 5) Strength Test (Tensile) Example

2.3.7.3 Inspection

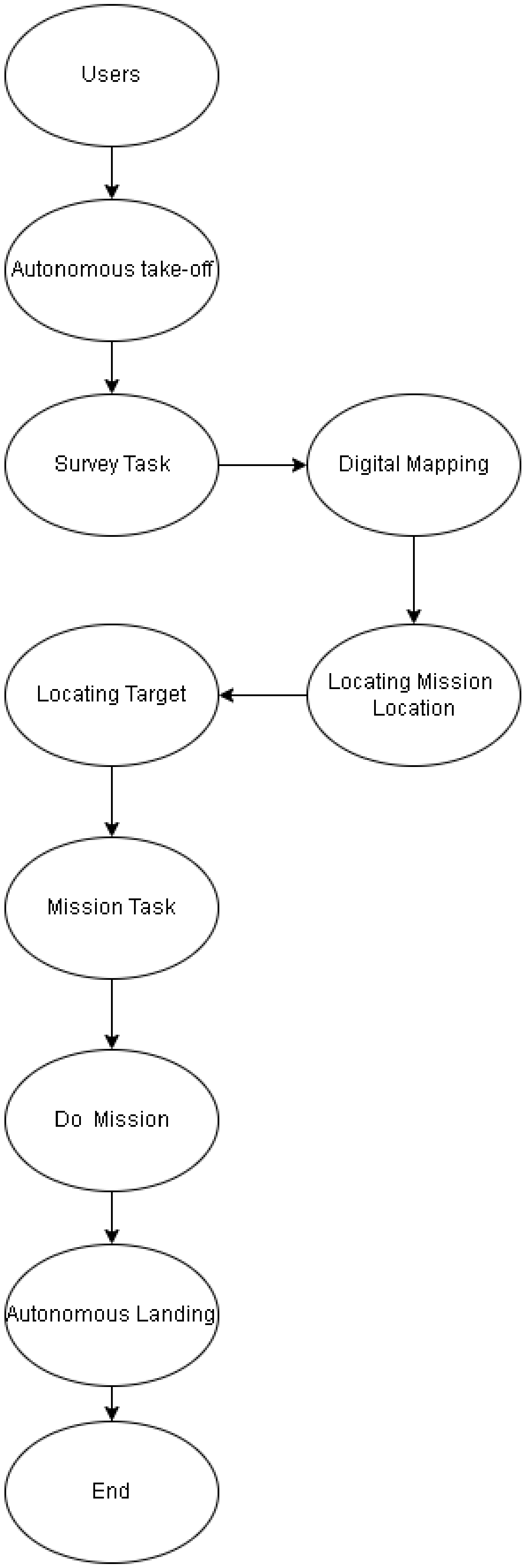
After manufacturing, there can be some defects on the parts. These defects can degrade surface quality, strength, or they can cause crack propagation. By inspection, it will be tried to see if there are any defects or not.

3. DESIGN DOCUMENT

Firstly we desing our desing life cycle and it is as below



Our mission design as below chart.

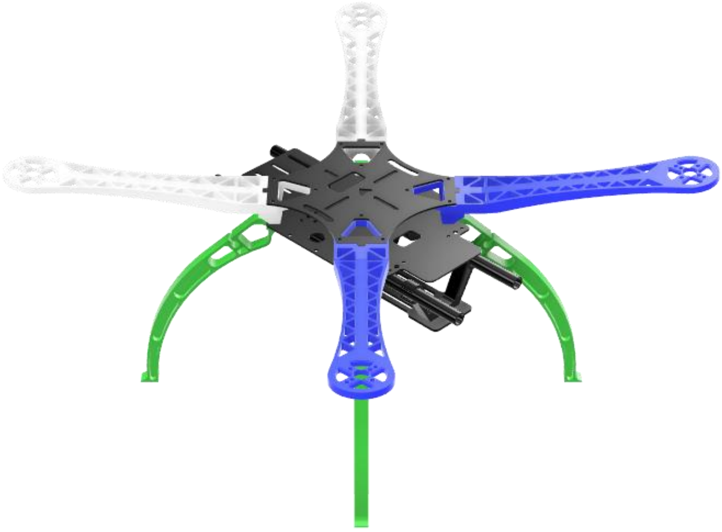

Users
Autonomous take-off
Survey Task
Digital Mapping
Locating Mission Location
Locating Target
Mission Task
Do Mission
Autonomous Landing
End

3.1 MECHANICAL DESIGN DOCUMENT

3.1.1 Conceptual Design

3.1.1.1 Reference Design

There are many types of drone frames. According to competition requirements, a quadcopter having less then 4kg mass will be designed. Based on this requirement as a reference design S-500 frame is selected. Its size is 50cm which means that distance from the edge of one arm to the edge of across arm is 50cm.

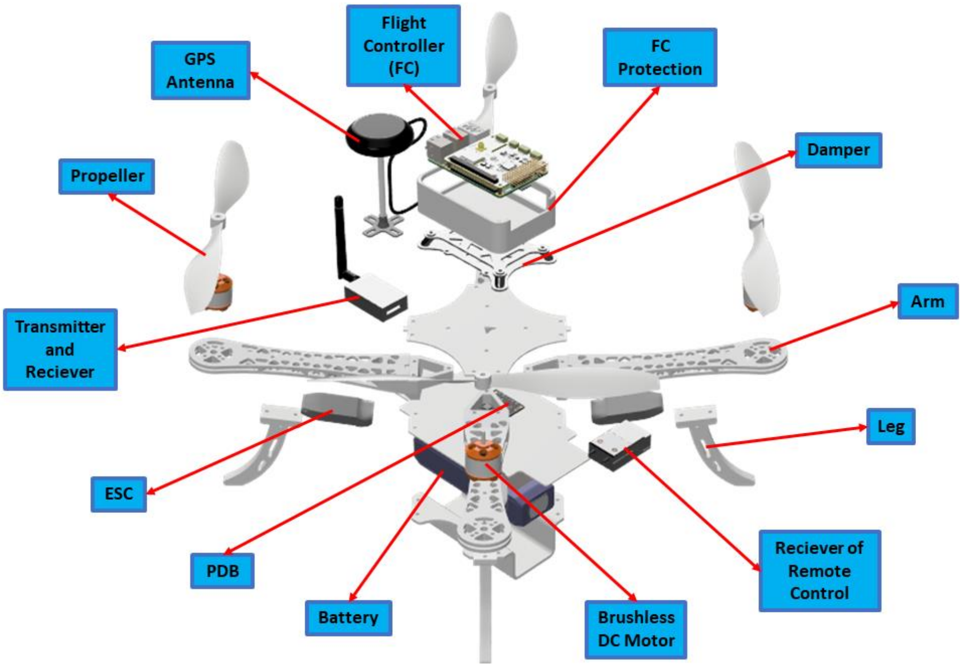


Reference Design

In this frame generally carbon fiber chassis, arms and legs are used. So, the stress level can be relatively higher than a plastic frame. Cross sectional area of arms should be increased if we want to design a plastic frame. Moreover, legs have a concave structure, but a convex structure will be safer for landing. The chassis have mass reduction spaces, different fastening holes or rails, etc. This type of properties should be specific to the design according to its electronical layout.

3.1.1.2 New Design

New Design

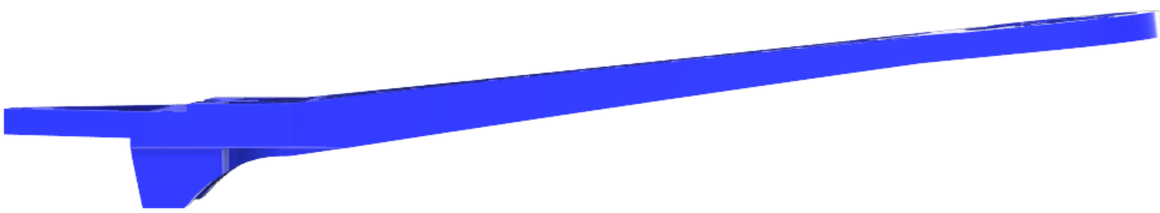


Exploded View

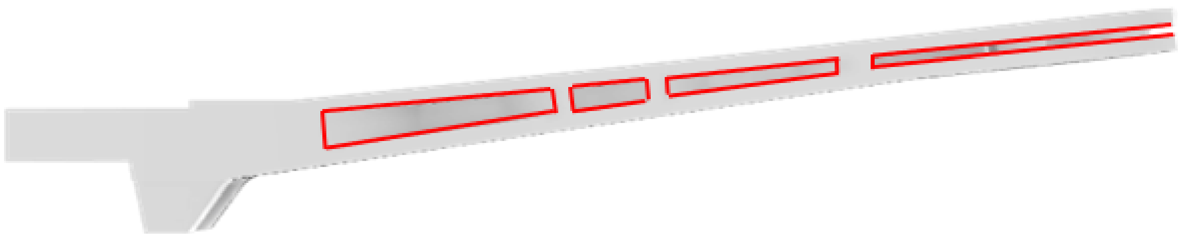
3.1.1.3 Overview

Many changes are done on reference design and at the end a distinctive design is appeared. In this design, arms are improved until stress level decrease to a certain level. Convex legs are designed from beginning. Chassis and the protective parts of the electronics are created according to the electronics which are chosen. Electronics mounting methods are considered.

a. Arm Design

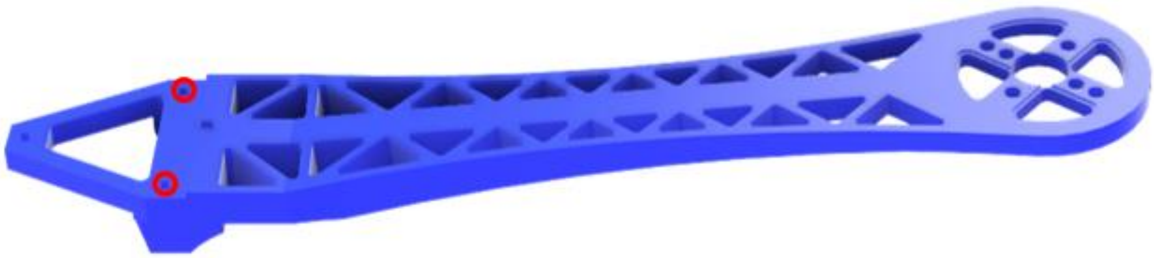


Reference Arm



New Arm

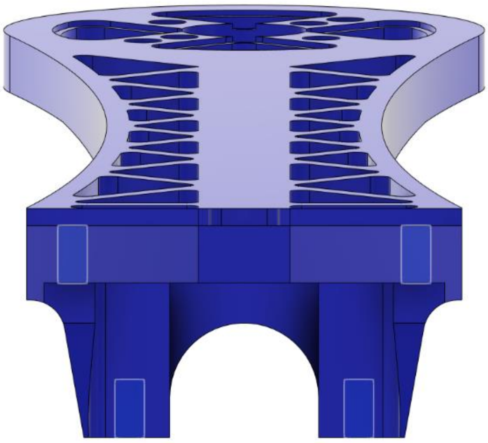
The cross-sectional area of the arm is increased to increase second moment of area. While doing this, to avoid highly increase in mass red areas in the figure are evacuated. As a result, in certain conditions, mass didn't increase as much as stress level is decreased.



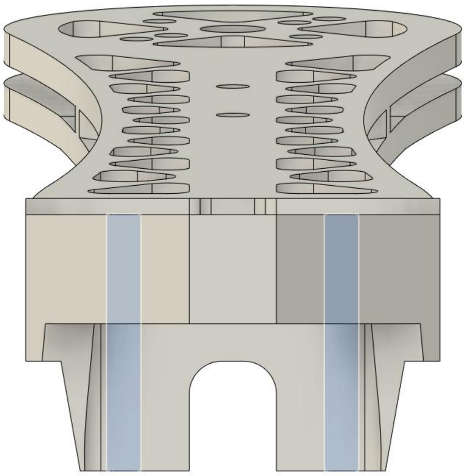
Reference Arm

New Arm

In S500 Arm the holes that are used for connection to chassis by using screws were not thru holes and it is a condition that weaken the integrity of the frame. Hence, these holes are designed again as thru holes.
Inside cavities has fillets on their edges. In S500 fillet radiuses were not enough to dissipate the stress concentration at those points. Thus, fillet radiuses are increased in new design.
S500 design have Leg connections right under the chassis. To get more wide distances between connection points where the legs touch to the ground, leg connections are carried to the arms, and we get advantage of arms improved strength on this situation.
At the motor base of arm where the motor is fastened, inside hole's wall thickness is increased because while printing the arms, printing done on space, so it couldn't be completed. However, new design could deal with this problem. Also, strength is increased at that section.

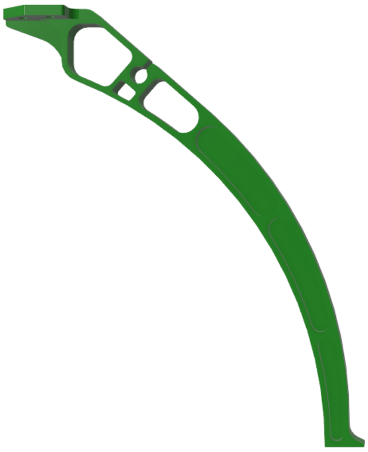


Blind Hole

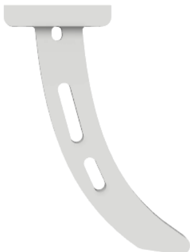


Thru Hole

b. Leg Design



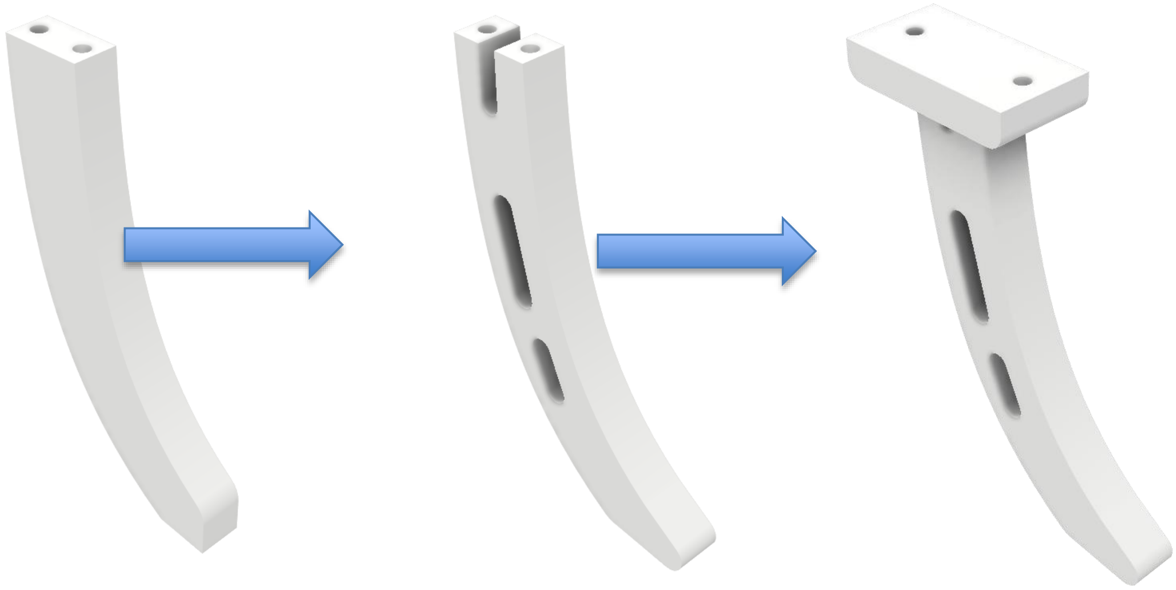
Reference Leg



New Leg

Mass of the reference leg is nearly equal to the new leg. However, the size and orientation of the leg has been changed. Small size provided more strong structure and convex structure instead of concave structure provided more stable landing capability because of the distance between one leg to the other.

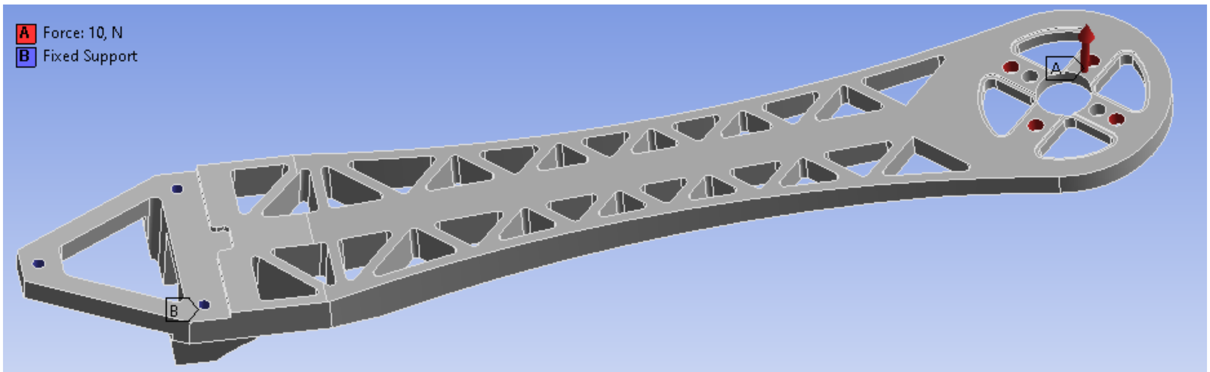
Design Stages

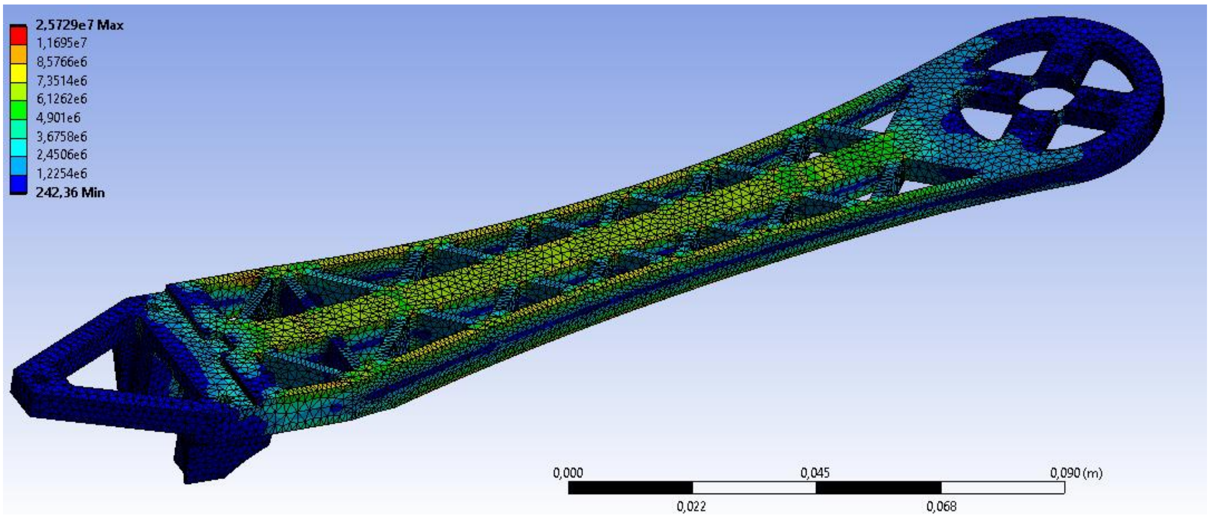


According to FEA results and topology optimization leg is designed stage by stage as shown.

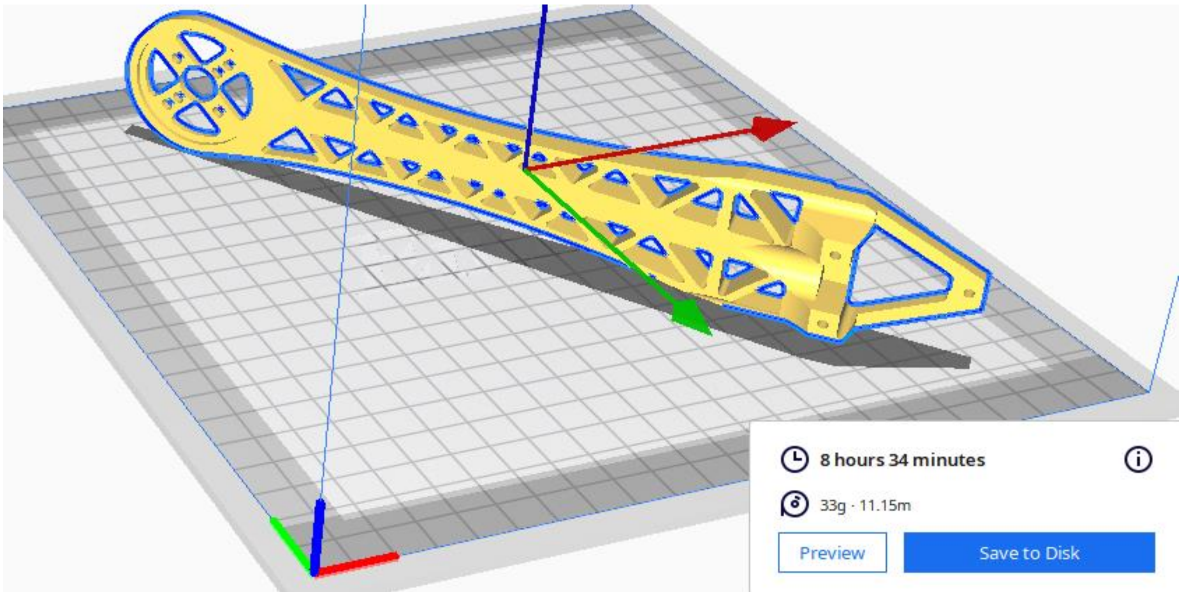
3.1.2 Strength Calculations

3.1.1.1 Arm

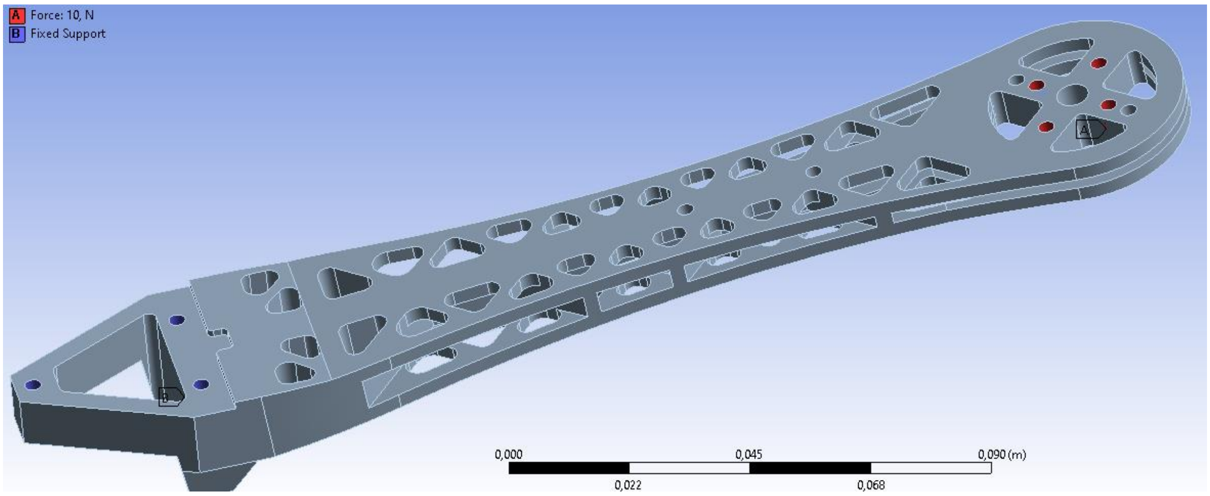


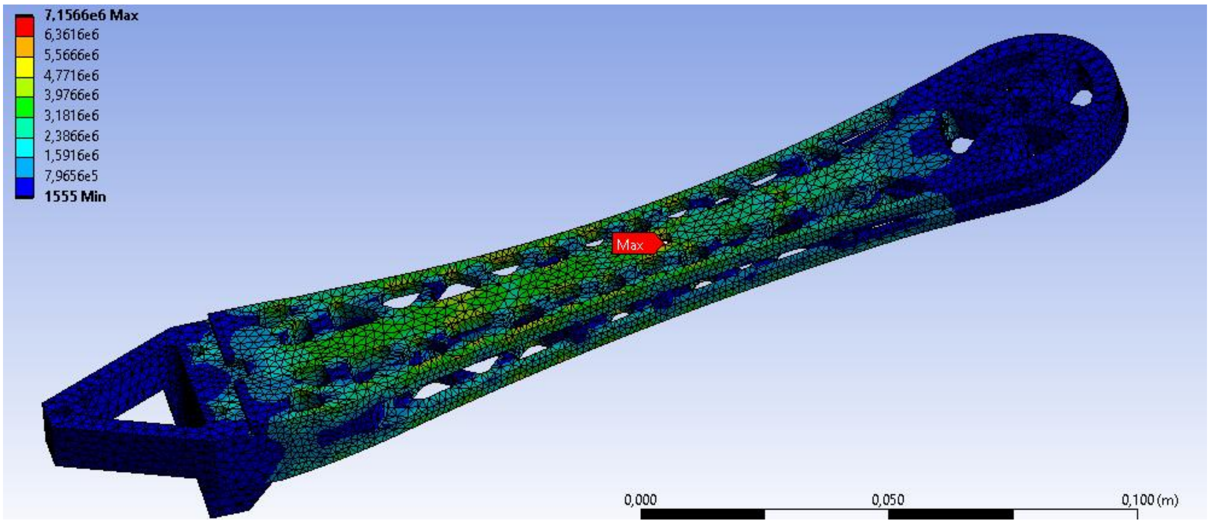


Under the certain boundary conditions the maximum equivalent von mises stress of reference arm is equal to 25.7MPa. The yield strength of the PLA filament around 50MPa in the market. According to these data factor of safety F.S.= 1.9.

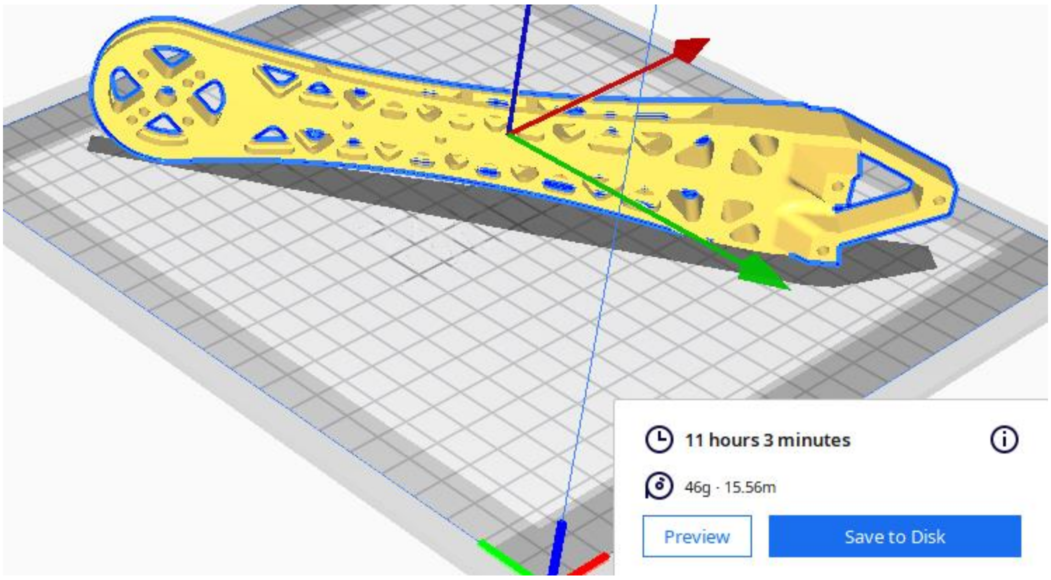


Mass of reference arm under certain printing conditions without supports is 33g.





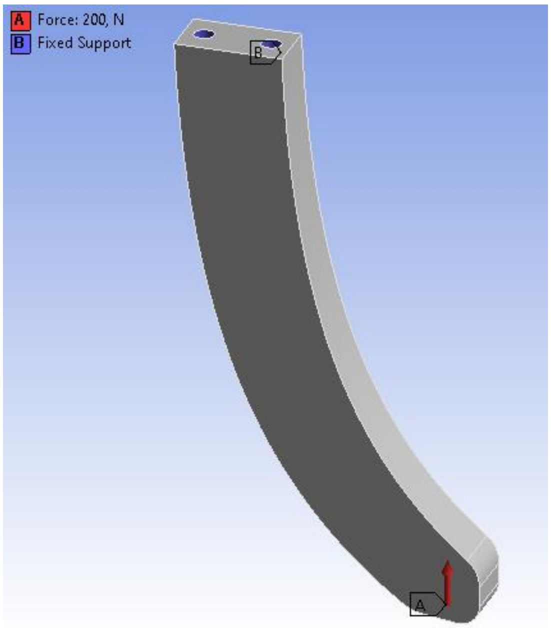
Under the certain boundary conditions the maximum equivalent von mises stress of new arm is equal to 7.1MPa. The yield strength of the PLA filament around 50MPa in the market. According to these data factor of safety F.S.= 7.

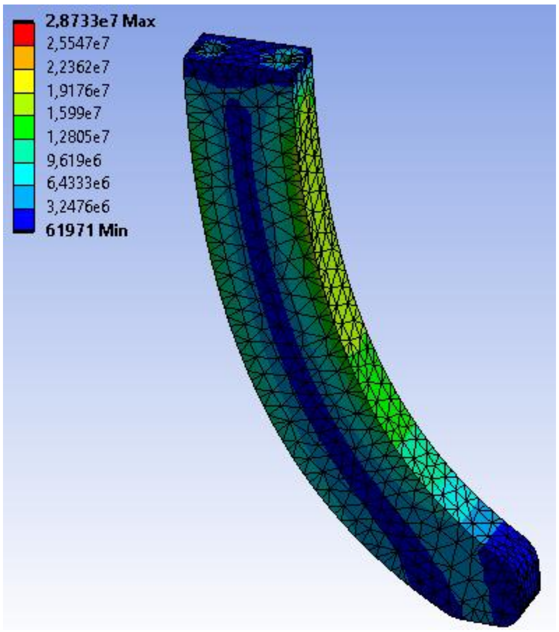


Mass of reference arm under certain printing conditions without supports is 46g.

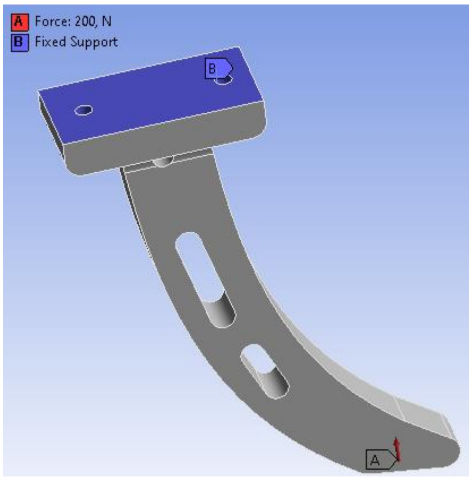
As a result, we can see that F.S. of the arm is increase from 1.9 to 7 which means 268% improvement. At this time the mass is increased from 33g to just 46g which means an only 39% increase.

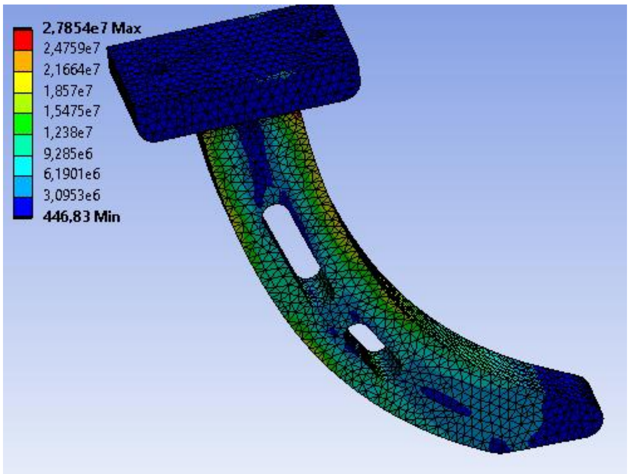
3.1.1.2 Leg



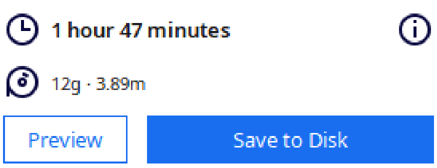


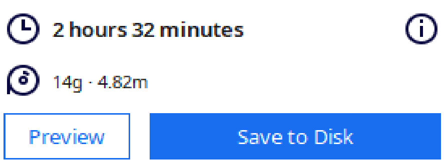
While designing a leg, first a coarse design is created. Under certain boundary conditions this designs’ equivalent stress level is 29MPa. Thus, the factor of safety F.S. = 1.7.





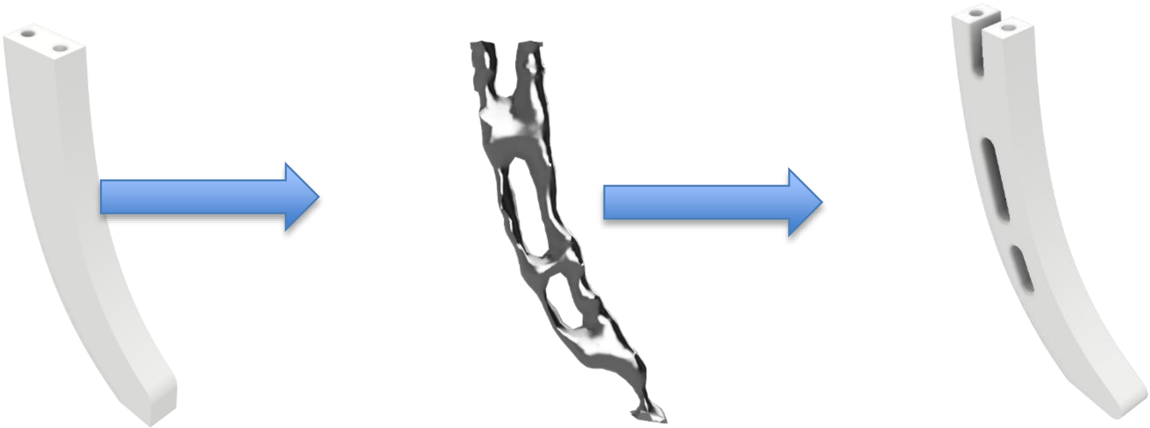
At final design we have mass reduction spaces but also, we have more strong and wide connection area. According to data shown the stress under certain conditions is 28MPa and the factor of safety F.S. = 1.8.





So, we can see that factor of safety is nearly equal and the mass is slightly changed. However, we gained a wide and strong connection area.

3.1.2 Topology Optimization



Topology analysis has done on the coarse leg design and the mass of the leg is decreased by trimming the unnecessary mass from the 3D model. By this way we gained the ability of improving connection edge of the leg to the arm by adding extra mass on the structure.

3.1.3 Mass Estimation

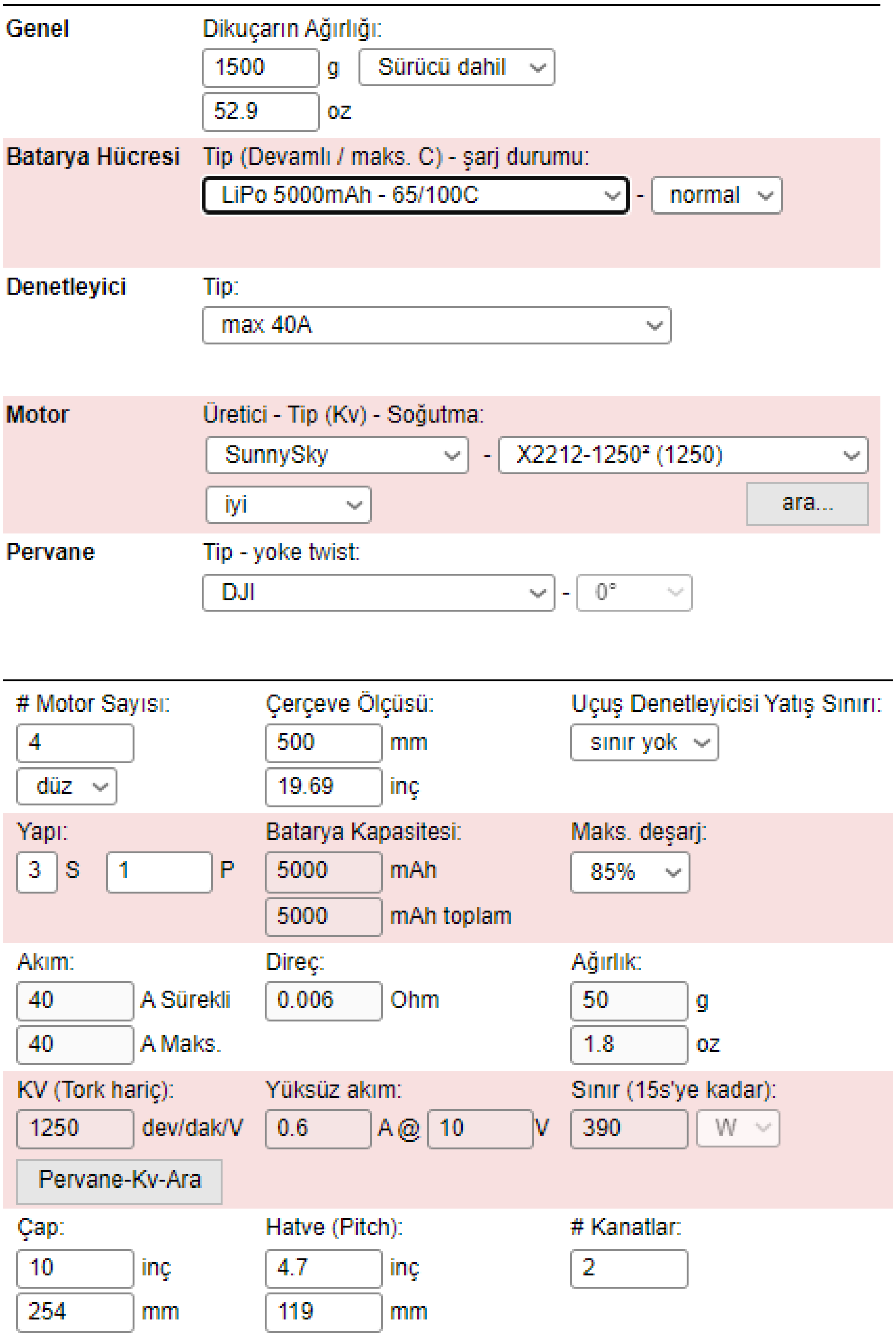
Component	Number of Pieces	Unit Mass (g)	Total Mass of the Component (g)
Arm	4	46	184
Leg	4	14	56
Bottom Chassis	1	53	53
Upper Chassis	1	34	34
Battery Protection	1	69	69
FC Protection	1	33	33
Brushless DC Motor	4	56	224
Battery	1	379	379
ESC	4	28	112
FC	1	80	80
GPS Antenna	1	30	30
PDB	1	11	11
Propeller	4	18	72
			Total Mass of Drone (g)
			1337

We are calculating the total mass of known components as 1337g. With a margin of 163g because of the uncertainties and unknown masses of some components. We are estimating the total mass of the drone around 1.5kg.

3.1.4 Thrust System Design

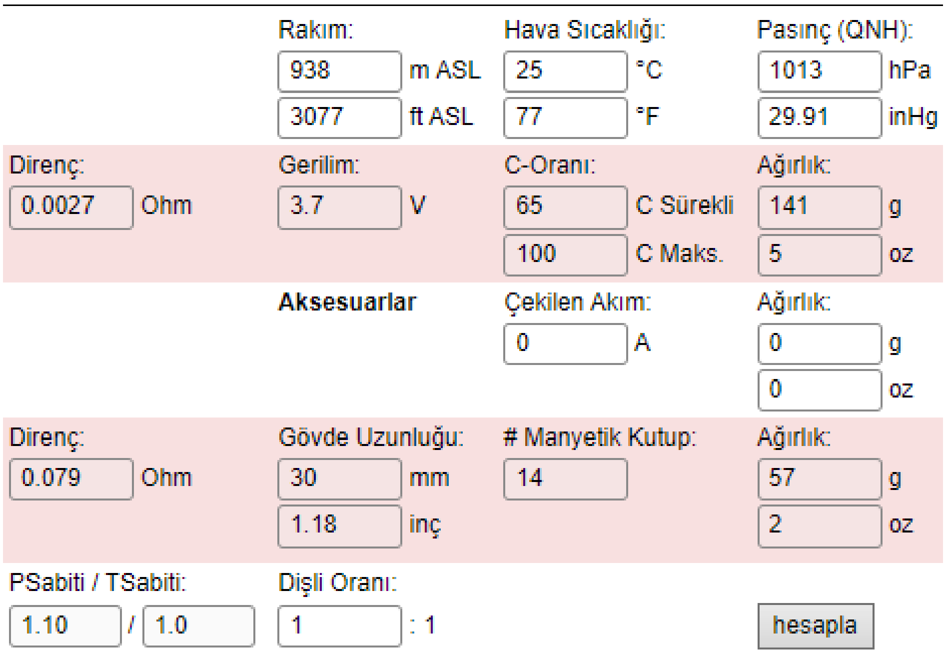
According to mass estimated and components selected, thrust calculations are done in the web site: https://www.ecalc.ch/xcoptercalc.php.

Inputs:

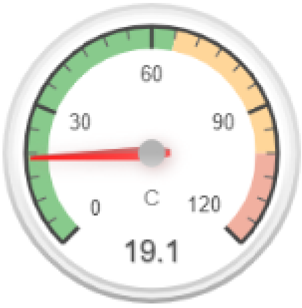


Genel	Dikuçarın Ağırlığı: 1500 g Sürücü dahil; 52.9 oz
Batarya Hücresi	Tip (Devamlı / maks. C) - şarj durumu: LiPo 5000mAh - 65/100C - normal
Denetleyici	Tip: max 40A
Motor	Üretici - Tip (Kv) - Soğutma: SunnySky - X2212-1250² (1250); iyi; ara...
Pervane	Tip - yoke twist: DJI - 0°

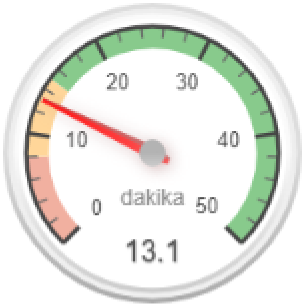
# Motor Sayısı: 4; düz	Çerçeve Ölçüsü: 500 mm; 19.69 inç	Uçuş Denetleyicisi Yatış Sınırı: sınır yok
Yapı: 3 S 1 P	Batarya Kapasitesi: 5000 mAh; 5000 mAh toplam	Maks. deşarj: 85%
Akım: 40 A Sürekli; 40 A Maks.	Direç: 0.006 Ohm	Ağırlık: 50 g; 1.8 oz
KV (Tork hariç): 1250 dev/dak/V; Pervane-Kv-Ara	Yüksüz akım: 0.6 A @ 10 V	Sınır (15s'ye kadar): 390 W
Çap: 10 inç; 254 mm	Hatve (Pitch): 4.7 inç; 119 mm	# Kanatlar: 2



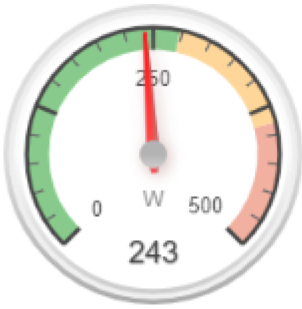
Outputs:



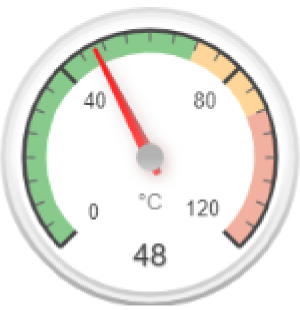
Battery Discharge



Flight Time (min)

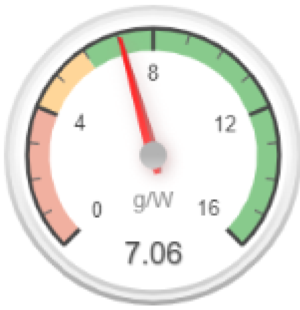


Electrical Power (W)



Estimated Temperature

Thrust Weight Ratio



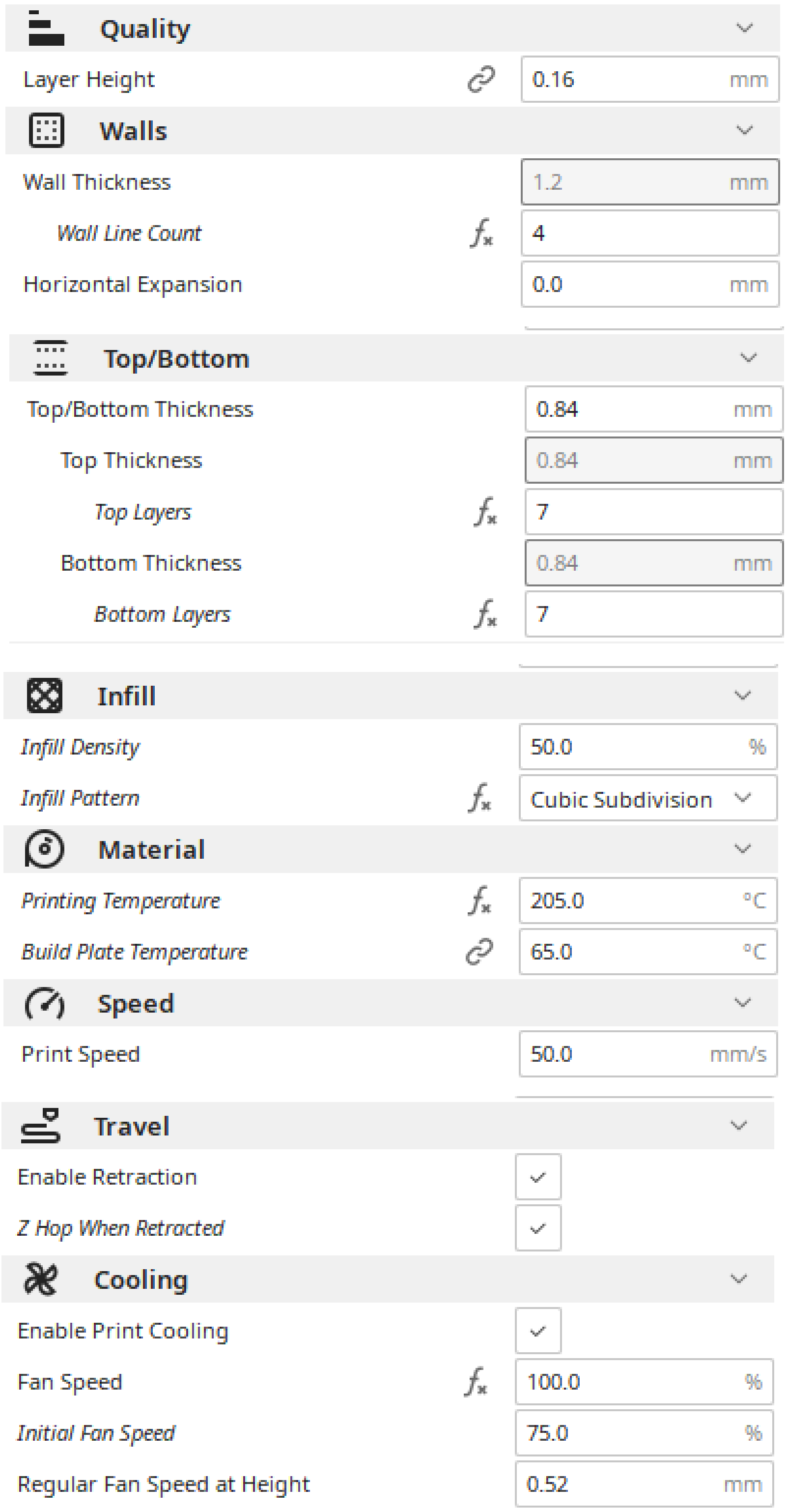
Thrust Power Ratio (g/W)

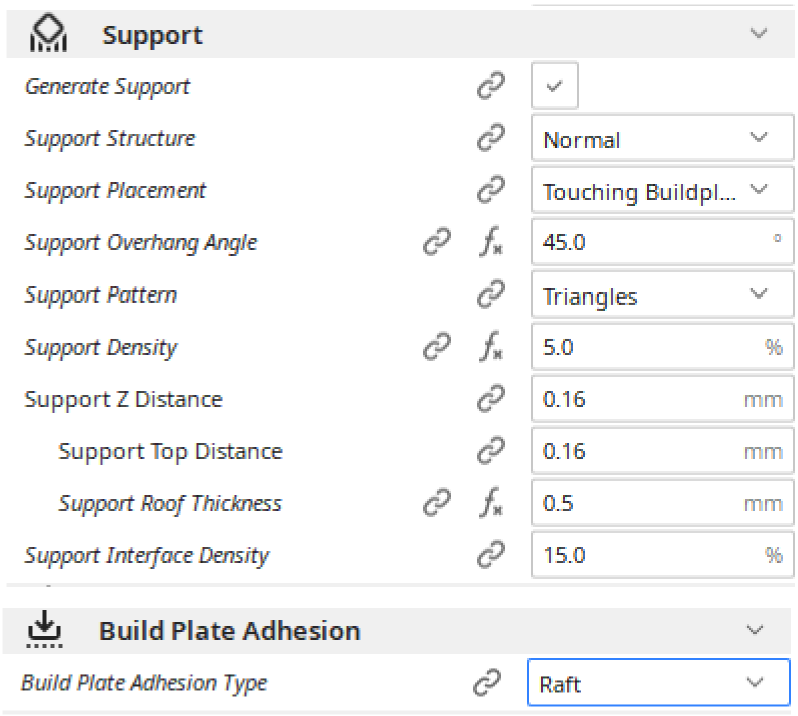
We can see that all the parameters which are important for a drone design are in the green areas except flight time but also flight time is close enough to the green area and 13.1 minute is enough to complete a mission in the competition of TEKNOFEST.

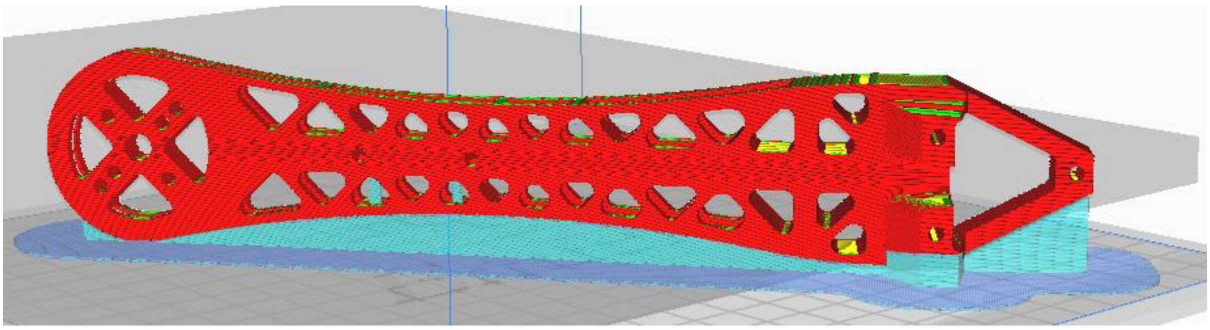
3.1.5 Prototype Production

a. Arm Production

As a result of many attempts on 3D Printing Arm and Leg components of the drone, optimum 3D Printing settings are found as shown.

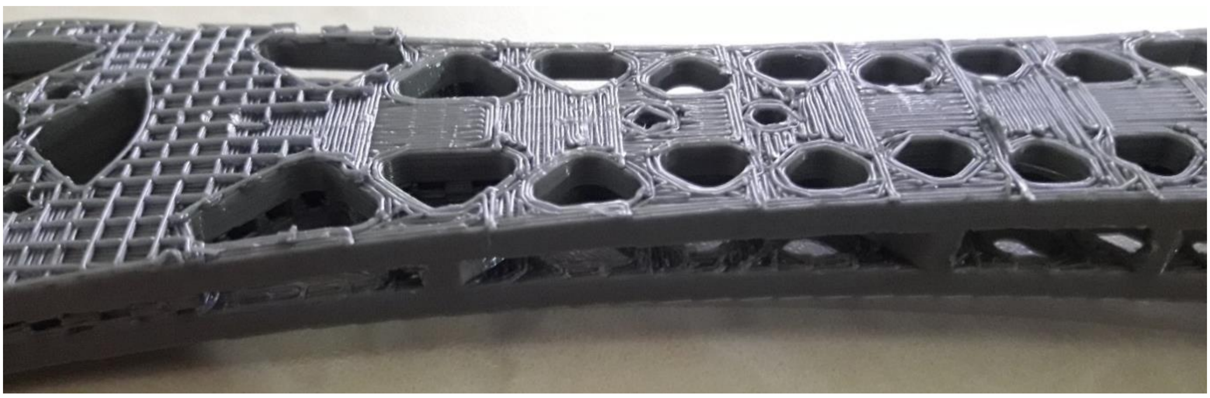






The arm is printed in this orientation because other orientations caused difficult support cleaning and low surface quality. In this orientation there are places where the printer is printing to the space but the distances between walls of the structure are not too much in this orientation. So the printer is capable to print the model nearly perfect.

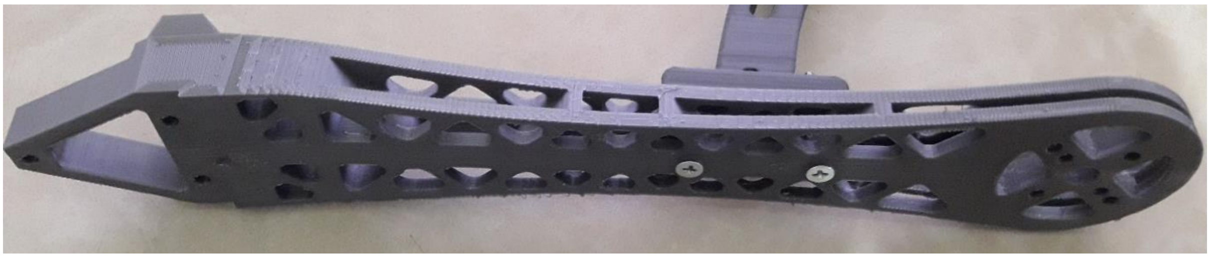
Fail Printings Because of the Wrong Orientation and Setting:



Support cleaning was a big problem because the arm is printed as top surface at the bottom. Also, cleaning support from inside cavities was so difficult. As a result, surface quality is degraded.

In this error, inside holes' wall was so thin, so printer couldn't accomplish the mission.

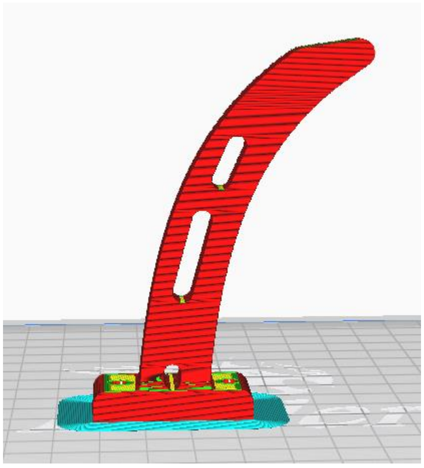
Successful Printing:



The surface quality is satisfaction. Only the one side of the arm has support residue, but it can be cleaned easily by using emery. Also, there is no support residue inside the cavities.

b. Leg Production:

Printed Leg



Printing Orientation

Leg production was simpler than the arm production because of simpler geometry and not needing supports. Printer settings are same with arm, only difference was support setting was closed. Surface quality is satisfaction.

c. Propeller Balancer Production:

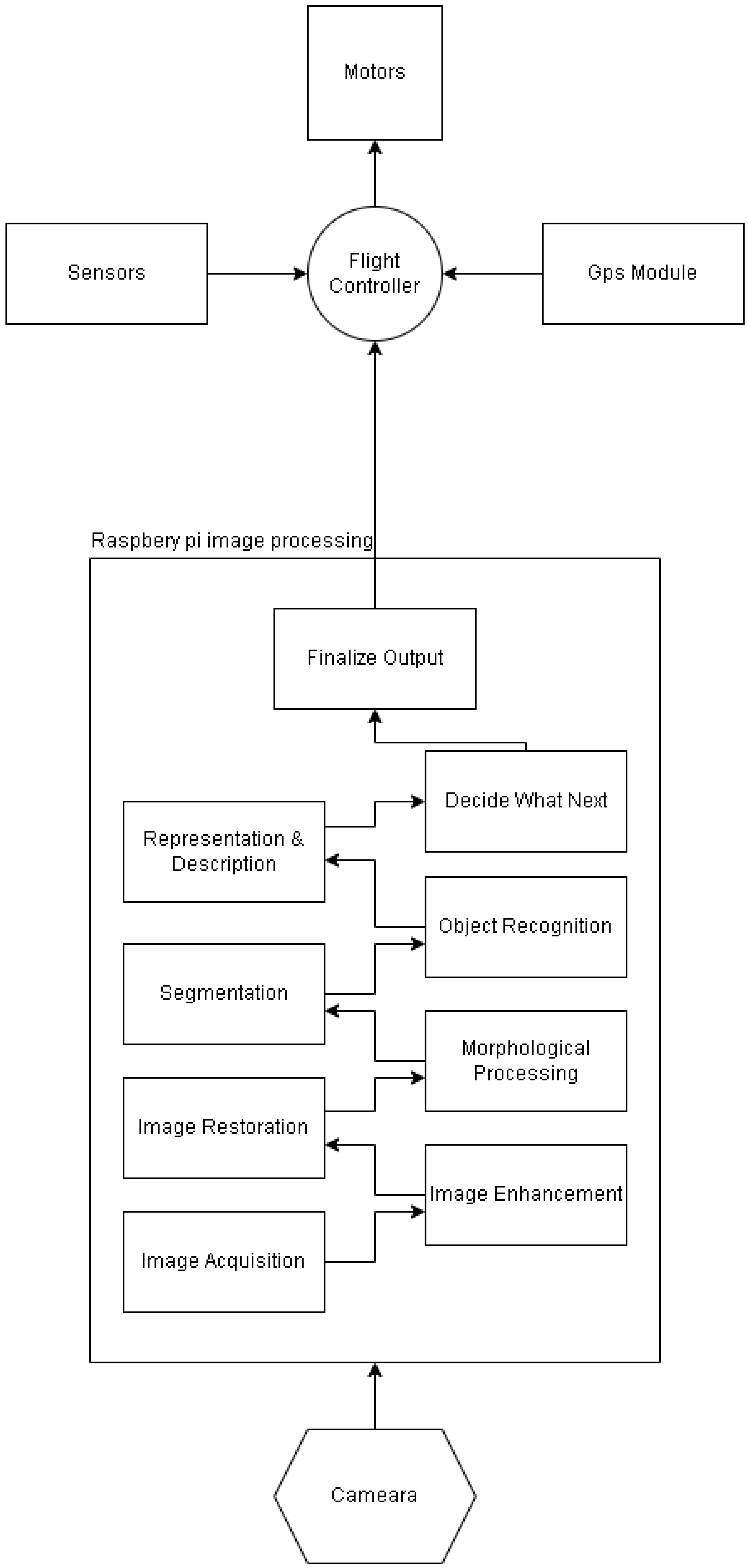
Since the propeller balancers in the market are expensive and the mechanism can be modeled and printed easily. We did our own propeller balancer.

Reference Propeller Balancer

Our Propeller Balancer

3.2 SOFTWARE DESIGN DOCUMENT

Firstly Pi-Camera gathers images while the drone flies, and they are transported to raspberry pie to process. Image processing software searches for mission elements such as targets and tools. If it founds it stores their locations. And after the mapping process drone will go to their locations and perform tasks expectedly. Raspberry pi is the brain of a drone and makes decisions according to the image process and gives orders to the flight computer. The flight controller takes variables from sensors and adjusts motors accordingly.


Motors
Sensors
Flight Controller
Gps Module
Raspbery pi image processing
Finalize Output
Decide What Next
Representation & Description
Object Recognition
Segmentation
Morphological Processing
Image Restoration
Image Enhancement
Image Acquisition
Cameara

3.3 Electrical & Electronics Design Document

1. Connecting, Soldering and Installing Electronic Components

Required components are prepared for connection, soldering and installing to the mother board.

   a. Connecting Motors To The Arm
   b. Soldering Motors to the ESC
   c. Soldering ESCs to the PDB
   d. Connecting ESC's Signal Cable to the Flight Control
   e. Installing Battery
   f. Connecting Power Module with Battery & Connecting Signal Cable to the Flight Control Card
   g. Connecting GPS Module, Telemetry and Receiver to the Flight Control Card

2. Electrical Specification of All Components
   a. 3-Phase motor is coupled mechanically to the propellers.
   b. ESCs have output of 5V/3A and power the 3-Phase motors.
   c. PDB is connected to the Power Module's 5.3 pinouts and Power module's signal cable is connected to the Flight Control Card.
   d. Battery have output of 11.1V and connected to the Power Module.
   e. All ESCs are connected to the Flight Control Card's 5V pinouts.
   f. 2.4 GHz / 12 Channel Receiver is connected to the Flight Control Card.
   g. All additional external components are connected to the 5V pinouts.

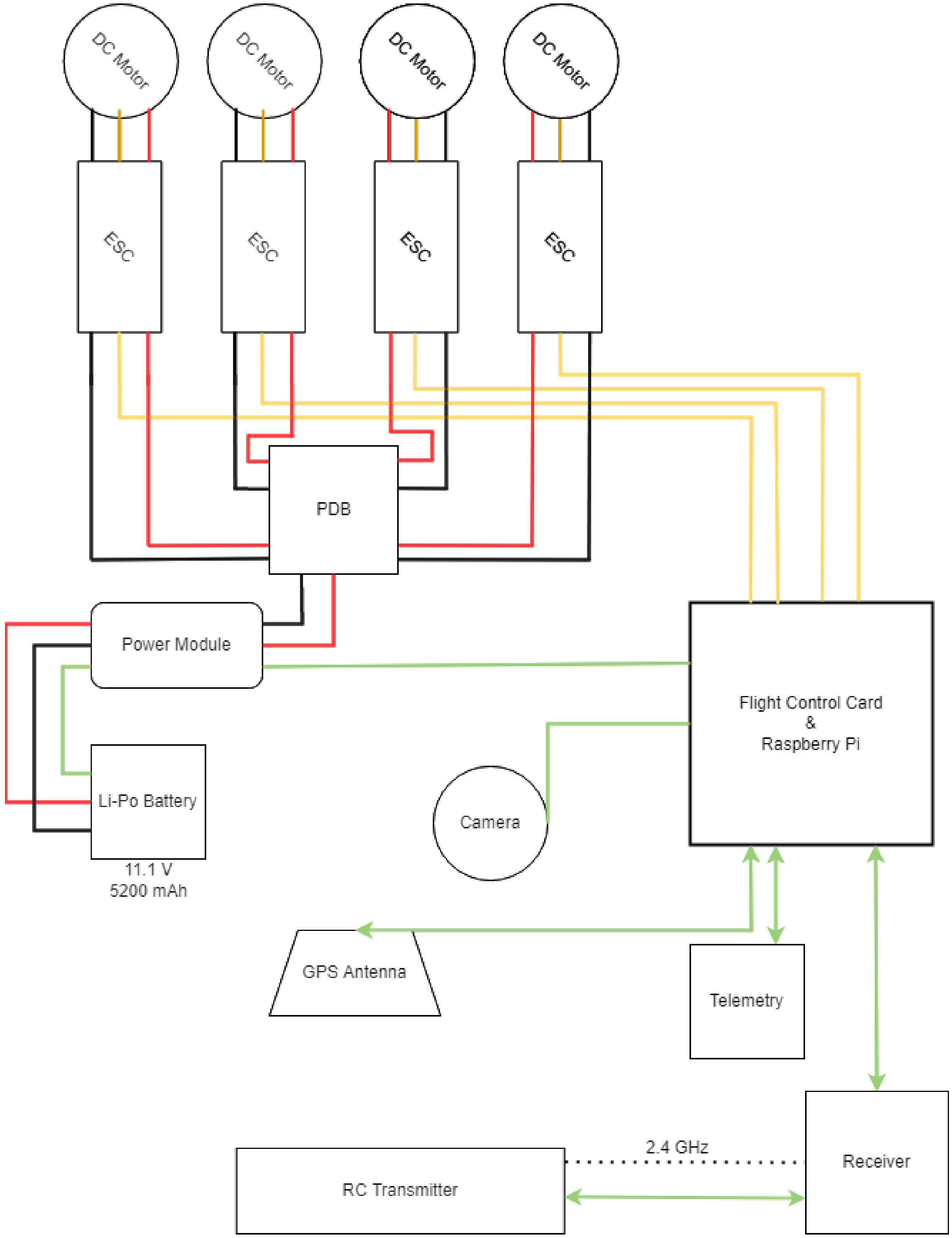


Figure 1 UAV Electronics Block Diagram

4. CONCLUSION & DISCUSSION

Firstly we decided what type of unmanned aerial vehicle we are going to produce. After the research process, we decided to create a quadcopter (X4 configuration multi rotor). Then we head towards researching the working principles of a quadcopter. We select and research all the necessary electronic and mechanical parts with all the necessary calculations about price, mass budget, power consumption, thrust weight ratio, and flight time in our minds. We design the 3D model of our drone with all the parts intact. Moreover, the frame of the drone is completely designed by our team. Most of the necessary stress simulations of our mechanical parts are done. Some prototype parts of our drone frame are printed by a 3D printer, and they fulfill all the requirements and surface quality expectations. Necessary courses about image processing and autopilot software have been bought and we start to watch them. In the Software Engineering department at Robotics Community, there was an old Unmanned Aerial Vehicle project designed and produced. We took the old parts and we are going to use some of them to produce our prototype while we are learning. We mostly discuss the parts that we are going to need, and we conclude this with the help of a technician of our school and our teachers. After all discussion, we decided on our equipment list as we listed below.

İsim	Model	Adet	Adet Fiyat (TL)	Link	Fiyat (TL)
Fırçasız Elektrik Motoru	SUNNYSKY A2212-980KV CCW	3	167,53	shorturl.at/dnCDM	502,59
Fırçasız Elektrik Motoru	SUNNYSKY A2212-980KV CW	3	167,53	shorturl.at/lotS0	502,59
Drone Frame + İniş Takımı	F450	1	158,92	shorturl.at/jtATU	158,92
Batarya Kılıfı	Lipo Pil Koruma	1	42,9	shorturl.at/corJS	42,9
Batarya Şarj Cihazı	Imax B6 Şarj Cihazı + Şarj Adaptörü	1	384,9	shorturl.at/gFLZ4	384,9
Li-Po Batarya	11.1V 5200mAH 3S 40C Leopard	2	637,91	shorturl.at/vLR29	1275,82
ESC	40A ESC Skywalker	6	216,86	shorturl.at/hmqEH	1301,16
Raspberry Pi 4	Raspberry Pi 4	1	1599	shorturl.at/girHO	1599
Uçuş Kontrol Kartı	Emlid Navio 2	1	3021,71	shorturl.at/dgtKR	3021,71
GPS Anteni	-	1	0	**Included in the Flight Controller**	0
Güç Modülü	-	1	0	**Included in the Flight Controller**	0
Receiver		1	758	frsky-l9r-alici	
Drone Güç Dağıtım Panosu	F18057/8	1	172,04	shorturl.at/fxBHV	172,04
Pervane	Dji 1045 (CCW + CW)	4	32,34	shorturl.at/bqNS7	129,36
Kumanda	Radiolink AT9S Kumanda 2.4ghz 9 Kanal	1	1456,36	shorturl.at/bsCF9	1456,36
Kumanda Alıcısı	R9DS	1	0	**Included in the Transmitter**	0
PCB Anten	Xbee 3 pro	2	590	shorturl.at/eoFPT	1180
Yarım Dalga Anten	2.4 GHz 4.5 Inch Yarım Dalga RP-SMA Xbee Anten	2	104,38	shorturl.at/mAKSY	208,76
Xbee Adapter	XBee Explorer USB	2	62,05	shorturl.at/kBWZ9	124,1
Xbee Adapter		1	25,23	shorturl.at/blyzM	25,23
Kamera	Raspberry Pi 3 ve 4 Uyumlu Kamera Modülü	1	164,02	shorturl.at/sEGJM	164,02
Filament	esun 1.75mm Siyah PLA+	1	156,62	shorturl.at/pyO49	156,62
Filament	esun 1.75mm Beyaz PLA+	1	190,04	shorturl.at/elHJK	190,04
LEhim Seti	Robotistan	1	169,76	shorturl.at/lyKRS	169,76
Kesme Matı	Çin	1	9,9	shorturl.at/cfjlJ	9,9
Multimetre		1	85,43	shorturl.at/foBKT	85,43
Batarya Voltaj Test Cihazı	Ready To Sky 3.7-30V 1-8S Batarya Voltaj Test Cihazı ve Alçak Gerilim Buzzer Alarmı	1	26,25	shorturl.at/ghtD9	26,25
Şok Emici Damper		4	14,3	shorturl.at/jzBDG	57,2
Çift Taraflı Bant	3M 03614 Akrilik Ultra Güçlü Çift Taraflı Bant (1,27Cm X 4,6 M)	2	40,25	shorturl.at/tvAGM	80,5
Banana Konnektör	Banana Gold Konnektör 3.5 mm (Erkek - Dişi)	24	6,15	shorturl.at/ntDN5	147,6
Xt60 Konnektör		5	7,13	shorturl.at/gA025	35,65
					13.208,41

5. TEST INTRODUCTION

5.1 Overview

All of the hardware and its connections, mechanical parts and electrical components will be tested.

5.2 Scope

This document includes all the necessary tests and calibrations for the drone hardware.

5.3 Terminology

Acronym	Definition
Autopilot	The microprocessor controls all of the motors via ESC's
FC	Flight Control Card
PC	Personal Computer
Mission Planner	Mission Planner software from ardupilot

6. COMPONENTS TO BE TESTED

6.1 Flight Control Card (Autopilot)

This is our microprocessor responsible for taking inputs from sensors and remote control and produce outputs for ESC to control motors .

6.2 Power Distribution Board Module (PDB)

The power module is responsible for taking power from the battery and distributing it to the whole system

6.3 Battery (BAT)

The battery is responsible for supplying all the power necessary for the system.

6.4 ESC (ESC)

ESC is responsible for taking inputs from the autopilot control card and giving motors to the corresponding electrical output for that digital input.

6.5 Motors (MTR)

Motors are responsible for producing enough moments to produce wanted action such as take-off or turning right or landing etc.

6.6 Telemetry (TLM)

The telemetry module is responsible for communication between ground control and the drone. All the information about the drone can be seen from ground control.

6.7 GPS (GPS)

The GPS module is responsible for generating GPS outputs for the flight control card.

6.8 Receiver (RCVR)

The receiver is responsible for taking inputs from the remote control and inputting that information to the flight control card to change pre-defined autonomous actions.

6.9 Communication (COMM)

Drone’s related parts of communication i.e., telemetry, receiver, radio control

6.10 Current and Voltage (CRNT)

Drone’s electronic parts are tested in aspects regarding to their voltage outputs, current ratings, short circuit test,

6.11 Fatigue Behavior (FTG)

For a single time load the mechanism can be strong. However, if the load is applied on a cycle or repeatedly, it can be dangerous

6.12 Main Frames Surface Quality (MFSQ)

Although this property is easily inspected, it has great importance. Any crack or deformation on the surface after manufacturing can be dangerous. A crack can propagate and fail the mechanism.

6.13 Mass (MFM)

Importance of mass in our case is that a drone needs to be light as much as possible. Hence, their designs are made under a mass budget condition.

6.14 Main Frame Shock Absorption (MFSA)

This is the capacity of energy absorption when an impact force takes place. Dampers are generally used to have this feature. According to the material type or geometry of the damper shock absorption can be different. For our situation this property is important in case of a fall or vibration.

6.15 Main Frame Strength (MFS)

This property is the most general parameter for the mechanism to protect integrity. It is the resistance to a break or deformation situation

7. FEATURES NOT TO BE TESTED

Further autopilot tests with the image processing will not be tested due to lack of equipment.

8. ITEM PASS/FAIL CRITERIA

Describe the general rule to use to decide when a test case passes and when it fails.

8.1 Condition of the Hardware

Overall condition is comprising of physical condition of the part.

Pass: Parts are in a good condition.
Fail: Parts are damaged, injured, burned, broken, falsely soldered.

8.2 State of the Hardware

State of a part is operating state.

Pass: There are no restrictions to work properly.
Fail: There are restrictions to work properly.

8.3 Voltage Output

Voltage values in which the electronic part is specified in their data sheet.

Pass: Measured voltage is ± **0.5V** than specified voltage in the data sheet.
Fail: Measured voltage is greater than ± **0.5V** than specified voltage in the data sheet.

8.4 Current Ratings

Current values between the connections among each part.

Pass: There is current flowing through, and it is not considered as harmful for other parts.
Fail: There is current flowing through, but it is considered as not to be harmful for other parts or there is no current whatsoever.

8.5 Short Circuit Test

Short circuit test between positive and negative terminals of each part after the soldering and assembling process over.

Pass: There is no short circuit between positive and negative terminals of electronic parts.
Fail: There is short circuit between positive and negative terminals of electronic parts.

8.6 Communication

Communication systems of drone and their data transmit over protocol.

Pass: Any communication system works properly. Data are both receiving and transmitting over the protocol.
Fail: All or any communication system does not work properly. Data are neither receiving nor transmitting or there are any missing info.

8.7 Drop Test

Durability test of the main frame simulated by free fall.

Pass: No visible damage or cracks on main frame or any hardware.
Fail: Any damage on main frame or on any hardware.

8.8 Mass Measurement

Total weight of the drone.

Pass: Mass is measured under the budget.
Fail: Mass is measured on the budget.

8.9 Static Load Test

Pass: No break on any parts.
Fail: Any break on a part.

8.10 Fatigue Test

Pass: No visible damage or cracks on main frame or any hardware.
Fail: Any damage on main frame or on any hardware.

8.11 Printing Quality Inspection

Pass: Any critical crack or deformation are not inspected.
Fail: Any critical crack or deformation are inspected.

8.12 Calibration Tests

Calibration tests of hardware.

Pass: Hardware responds correctly to given fake inputs.
Fail: Hardware responds wrongly to given fake inputs.

8.13 Acceleration Precision Test

Motor behavior for different throttle input

Pass: Motor responds correctly to given inputs.
Fail: Motor responds wrongly to given fake inputs.

8.14 Image Processing Software

Software responsible for recognizing objects.

Pass: Software recognize specified circle from video input.
Fail: Software doesn't recognize specified circle from video input.

9. TEST DESIGN SPECIFICATIONS

9.1 Condition of the Hardware (COH)

9.1.1 Motors

Each motor is inspected in its physical form and are rotated in both ways (clockwise and counterclockwise).

9.1.2 ESC

Each ESC is inspected in its physical form, connectors are checked.

9.1.3 PDB (Power Distribution Board)

PDB is inspected in its physical form. Mounted micro components are checked.

9.1.4 FC (Flight Control)

Control card is inspected in its physical form. Connection pins are checked.

9.1.5 Receiver

Receiver is inspected in its physical form. Antenna is checked for any deformation.

9.1.6 GPS

GPS is inspected in its physical form.

9.1.7 Telemetry

Telemetry is inspected in its physical form. Jumper connectors are checked.

9.1.8 Battery

Battery is inspected in its physical form. Connectors are checked.

9.1.9 Radio Control

Radio control is inspected in its physical form. Power supply is set for 11V to activate.

9.1.10 Test Cases

Here list all the related test cases for this feature

TC ID	Requirements	Priority	Scenario Description
COH.01	3.2	H	Check motors
COH.02	3.3	H	Check ESC
COH..03	3.3	H	Check PDB
COH.04	3.3	H	Check Flight Control
COH.05	3.3	H	Check Receiver
COH.06	3.3	H	Check GPS
COH.07	3.3	H	Check Telemetry
COH..08	3.3	H	Check Battery
COH.08	3.3	H	Check Radio Control

9.2 State of the Parts and Voltage Current Measurements (SPVCM)

9.2.1 Subfeatures to be tested

9.2.1.1 Motor

Each motor is supplied with 5-12-22V. Inspected the synchronization buzzer noise as expected.

9.2.1.2 ESC

Each ESC is supplied with 5-12-22V. Inspected any unexpected current

9.2.1.3 PDB

PDB is supplied with 5-12-22V. Inspected the red LED which means PDB is working properly. PDB is short circuited to see if the fuse is working properly.

9.2.1.4 Flight Control

Control card is connected to the PC. Inspected the LEDs are blinking, and software recognized the device. Device is moved to see if accelerometer and gyro is working properly.

9.2.1.5 Receiver

Receiver is connected to the FC. Inspected to see if PC reads the data received by the radio link.

9.2.1.6 GPS

GPS is connected to the FC. Inspected to see if PC reads the data and exact location of the drone.

9.2.1.7 Telemetry

Telemetry is connected to the FC. Inspected to see if PC reads the data

9.2.1.8 Battery

Battery is connected to the PDB. Inspected to see if it feeds the board and the electronic parts.

9.2.1.9 Radio Control

Radio control is supplied with 11V. Inspected to see if it is working properly.

9.2.2 Test Cases

Here list all the related test cases for this feature

TC ID	Requirements	Priority	Scenario Description
SPVCM.01	3.2	H	Each motor is supplied with 5-12-22V
SPVCM.02	3.3	H	Each ESC is supplied with 5-12-22V
SPVCM.03	3.2	H	PDB is supplied with 5-12-22V
SPVCM.04	3.3	H	Telemetry is connected to the FC
SPVCM.05	3.2	H	Receiver is connected to the FC
SPVCM.06	3.3	H	GPS is connected to the FC
SPVCM.07	3.2	H	Battery is connected to the PDB
SPVCM.08	3.2	H	Radio control is supplied with 11V
SPVCM.09	3.3	H	Control card is connected to the PC

9.3 Flight Control Calibration (FCC)

9.3.1 Subfeatures to be tested

9.3.1.1 Acceleration Calibration (FCC.AC)

Tests flight control card understand the acceleration position.

9.3.1.2 Inputs / Outputs (FCC.IO)

Test input and output stream of FC.

9.3.1.3 Compass (FCC.C)

Test if compass module works correctly.

9.3.2 Test Cases

Here list all the related test cases for this feature

TC ID	Requirements	Priority	Scenario Description
FCC.AC.01	3.2	H	Flight control card tilted to left
FCC.AC.02	3.2	H	Flight control card tilted to right
FCC.AC.03	3.2	H	Flight control card tilted upwards
FCC.AC.04	3.2	H	Flight control card tilted to downwards
FCC.IO.01	3.2	H	Given different inputs from radio control to FC
FCC.IO.02	3.2	H	Examining outputs of radio control inputs given to FC
FCC.C.01	3.2	H	Flight control faced north
FCC.C.02	3.2	H	Flight control faced south
FCC.C.03	3.2	H	Flight control faced east
FCC.C.04	3.2	H	Flight control faced west

9.4 Main Frame Tests (MFT)

9.4.1 Subfeatures to be tested

9.4.1.1 Drop Test (MFT.DT)

Tests main frame strength.

9.4.1.2 Mass Measurement (MFT.MM)

Tests mass of the main frame.

9.4.1.3 Fatigue Test (MFT.FT)

Apply drop test multiple times.

9.4.1.4 Static Load Test (MFT.SLT)

Place weights on the frame.

9.4.2 Test Cases

Here list all the related test cases for this feature

TC ID	Requirements	Priority	Scenario Description
MFT.DT.01	3.2	H	Drop main frame from 0 to 2 meters.
MFT.MM.01	3.2	H	Take weight of drone
MFT.FT.01	3.2	H	Apply drop test multiple times.
MFT.SLT.01	3.2	H	Place weights on main frame 0 to 14.5 kg

9.5 Image Processing (IP)

9.5.1 Subfeatures to be tested

9.5.1.1 Speed(IP.S)

UAV speed test for image processing

9.5.1.2 Ground Clearance(IP.GC)

Required high UAV fly to radius ratio.

9.5.1.3 Light (IP.L)

Optimum light test.

9.5.1.4 Camera Constancy (IP.CC)

Required camera constancy time in flight for image processing.

9.5.2 Test Cases

Here list all the related test cases for this feature

TC ID	Requirements	Priority	Scenario Description
IP.S.xx	*Give corresponding requirement no*	*High or Medium or Low*	*A brief description*
IP.S.01	3.1	H	UAV s tested max and min speed for image processing is possible
IP.GC.01	3.1	H	UAV s tested optimum ratio high x circles radius
IP.L.01	3.1	M	Optimum enviroment light
IP.CC.01	3.1	H	Required camera constancy time in flight for image processing.

10. Detailed Test Cases

10.1 IP.S.01

TC_ID	IP.S.01
Purpose	UAV s tested max and min speed for image processing is possible.
Requirements	3.1
Priority	High.
Estimated Time Needed	15 Minutes
Dependency	In zero speed image processing should work correctly
Setup	Place a circle between initial point and final point then changing speed, record video and record time.
Procedure	[A01] Place the camera initial point.
	[A02] Let the camera and flows with rope until final point.
	[V01] Observe image processing live camera
	[V02] Observe image processing via camera record
	[V03] Changing the ropes slope try it faster or slower
Cleanup	

10.2 IP.GC.01

TC_ID	IP.GC.01
Purpose	UAV s tested optimum ratio high x circles radius
Requirements	3.1
Priority	High.
Estimated Time Needed	10 Minutes
Dependency	In image processing should circle should work circle radius x 10 meter high
Setup	Place a circle and a camera 10 meter high, then change circle radius and record video.
Procedure	[A01] Place the camera 10 meter high.
	[A02] Place the circle in ground
	[V01] Observe image processing live camera
	[V02] Observe image processing via camera record
	[V03] Changing the circle radius try image processing

10.3 IP.L.01

TC_ID	IP.L.01
Purpose	Optimum enviroment light
Requirements	3.1
Priority	Medium.
Estimated Time Needed	10 Hours.
Dependency	Image processing should work correctly in daylight.
Setup	Place a circle and a camera 10 meter high, then record video in different day lights.
Procedure	[A01] Place the camera 10 meter high.
	[A02] Place the circle in ground
	[V01] Observe image processing live camera
	[V02] Observe image processing via camera record

	[V03] 12 am to 10 pm check every hour can camera recognize the circle

10.4 IP.CC.01

TC_ID	IP.L.01
Purpose	Required camera constancy time in flight for image processing
Requirements	3.1
Priority	High.
Estimated Time Needed	20 minutes.
Dependency	Image processing should work correctly while stable moving camera.
Setup	Place a circle between initial point and final point then changing oscillation, record video.
Procedure	[A01] Place the camera 10 meter high.
	[A02] Let the camera and flows with rope until final point.
	[V01] Observe image processing live camera
	[V02] Observe image processing via camera record
	[V03] Changing the fixation camera try image process
Cleanup	

10.5 MFT.DT.01

TC_ID	MFT.DT.01
Purpose	Check strenght of main frame
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Completed main frame in equipment
Setup	Main frame should handle the free fall without taken any damage
Procedure	[A01] Drop main frame from 1 to 2 meters
	[V01] Observe the main frame and look for any damage
Cleanup	Clean the drop site

10.6 MFT.MM.01

TC_ID	MFT.MM.01
Purpose	Check mass of main frame
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Completed main frame in equipment
Setup	Mass of the frame should be displayed on the screen in scale
Procedure	[A01] Balance the frame on the scale
	[V01] Check display and compare with budget.
Cleanup	Turn scale off

10.7 MFT.FT.01

TC_ID	MFT.FT.01
Purpose	Fatigue test of the main frame
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Completed main frame in equipment
Setup	Main frame should handle the free fall without taken any damage multiple times
Procedure	[A01] Drop main frame from 1 to 2 meters 10 times
	[V01] Observe the main frame and look for any damage after the 10th fall
Cleanup	Clean the drop site

10.8 MFT.SLT.01

TC_ID	MFT.DT.01
Purpose	Check static load of main frame
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Completed main frame in equipment
Setup	Main frame should handle extra weight without breaking
Procedure	[A01] Gradually place the weights on the frame from 1 to 14.5 kg
	[V01] Observe the main frame and look for any damage
Cleanup	Clean the test area

10.9 FCC.AC.01

TC_ID	FCC.AC.01
Purpose	Calibrate FC
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC connected to Mission Planner on PC
Setup	In smulation drone should tilt left
Procedure	[A01] Tilt FC to left manually
	[V01] Observe the simulation on Mission Planner
Cleanup	Close Mission Planner

10.10 FCC.AC.02

TC_ID	FCC.AC.02
Purpose	Calibrate FC
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC connected to Mission Planner on PC
Setup	In smulation drone should tilt right
Procedure	[A01] Tilt FC to right manually
	[V01] Observe the simulation on Mission Planner
Cleanup	Close Mission Planner

10.11 FCC.AC.03

TC_ID	FCC.AC.03
Purpose	Calibrate FC
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC connected to Mission Planner on PC
Setup	In smulation drone should tilt upwards
Procedure	[A01] Tilt FC upwards manually
	[V01] Observe the simulation on Mission Planner
Cleanup	Close Mission Planner

10.12 FCC.AC.04

TC_ID	FCC.AC.04
Purpose	Calibrate FC
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC connected to Mission Planner on PC
Setup	In smulation drone should tilt downwards
Procedure	[A01] Tilt FC downwards manually
	[V01] Observe the simulation on Mission Planner
Cleanup	Close Mission Planner

10.13 FCC.IO.01

TC_ID	FCC.IO.01
Purpose	Calibrate radio controller input
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with receiver connected to Mission Planner on PC
Setup	Working radio control needed
Procedure	[A01] Open simulation in Mission Planner
	[A02] Press all of the buttons individually on remote radio controller
	[V01] Observe in simulation same button is pressed
Cleanup	Logout

10.14 FCC.IO.02

TC_ID	FCC.IO.02
Purpose	Calibrate radio controller output
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with receiver connected to Mission Planner on PC
Setup	Working radio control needed
Procedure	[A01] Open simulation in Mission Planner
	[A02] Press all of the buttons individually on remote radio controller
	[V01] Observe in simulation outputs of the FC
Cleanup	Logout

10.15 FCC.C.01

TC_ID	FCC.C.01
Purpose	Calibrate Compass
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with compass is connected to Mission Planner on PC
Setup	In smulation drone should face north
Procedure	[A01] Place FC on level faced north
	[V01] Observe the compass values in simulation on Mission Planner
Cleanup	Close Mission Planner

10.16 FCC.C.02

TC_ID	FCC.C.02
Purpose	Calibrate Compass
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with compass is connected to Mission Planner on PC
Setup	In smulation drone should face south
Procedure	[A01] Place FC on level faced south
	[V01] Observe the compass values in simulation on Mission Planner
Cleanup	Close Mission Planner

10.17 FCC.C.03

TC_ID	FCC.C.03
Purpose	Calibrate Compass
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with compass is connected to Mission Planner on PC
Setup	In smulation drone should face east
Procedure	[A01] Place FC on level faced east
	[V01] Observe the compass values in simulation on Mission Planner
Cleanup	Close Mission Planner

10.18 FCC.C.04

TC_ID	FCC.C.02
Purpose	Calibrate Compass
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	FC with compass is connected to Mission Planner on PC
Setup	In smulation drone should face west
Procedure	[A01] Place FC on level faced west
	[V01] Observe the compass values in simulation on Mission Planner
Cleanup	Close Mission Planner

10.19 SPVCM.09

TC_ID	SPVCM.09
Purpose	Connect FC to PC
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	A working FC in equipment , a PC with Mission Planner installed
Setup	FC connected to PC wia usb (COM3-5 Port)
Procedure	[A01] Check on PC if FC driver installed automatically
	[A02] Install driver manually if A01 failed
	[A03] Check in device manager within ports if FC is shown
	[A04] Click on the “Login” button.
	[V01] Observe that the login is successful and the admin page appears
	-
Cleanup	Logout

10.20 SPVCM.08

TC_ID	SPVCM.08
Purpose	Radio Control integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Radio Control should be in equipment.
Setup	All the necessary electrical circuits completed
Procedure	[A01] Radio Control is supplied with 11V
	[A02] All buttons default position
	[V01] Observe the screen of radio control for any errors
Cleanup	Turn radio control off

10.21 SPVCM.07

TC_ID	SPVCM.07
Purpose	Battery integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Battery should be in equipment and fully charged
Setup	All the necessary electrical circuits completed
Procedure	[A01] Voltage tester is connected to the battery
	[V01] Observe the readings and values on the battery reader
Cleanup	Turn circuit off, unplug Voltage tester.

10.22 SPVCM.06

TC_ID	SPVCM.06
Purpose	GPS integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	GPS should be in equipment.
Setup	GPS is connected to the FC. FC connected to PC
Procedure	[A01] In PC observe the current GPS values
	[V01] Compare observed GPS values with real location.
Cleanup	Turn circuit and PC off

10.23 SPVCM.05

TC_ID	SPVCM.05
Purpose	Receiver integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Receiver should be in equipment.
Setup	All the necessary electrical circuits completed and receiver connected to FC , FC connected to PC
Procedure	[A01] Give instructions via remote radio controller
	[V01] Observe the readings on PC comes from receiver
Cleanup	Turn circuit off

10.24 SPVCM.04

TC_ID	SPVCM.04
Purpose	Telemetry integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Telemetry should be in equipment.
Setup	All the necessary electrical circuits completed and telemetry connected to FC
Procedure	[A01] Check on PC if telemetry sends any data
	[V01] Confirm data integrity
Cleanup	Turn circuit and PC off

10.25 SPVCM.03

TC_ID	SPVCM.03
Purpose	PDB integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	PDB should be in equipment.
Setup	All the necessary electrical circuits completed
Procedure	[A01] PDB is supplied with 5V
	[A02] PDB is supplied with 12V
	[A03] PDB is supplied with 22V
	[V01] Observe the red led on the PDB and look for short circuit.
Cleanup	Turn circuit off

10.26 SPVCM.02

TC_ID	SPVCM.02
Purpose	ESC integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	ESC should be in equipment.
Setup	All the necessary electrical circuits completed
Procedure	[A01] Each ESC is supplied with 5V
	[A02] Each ESC is supplied with 12V
	[A03] Each ESC is supplied with 22V
	[V01] Observe ESC and look for unexpected current values.
Cleanup	Turn circuit off

10.27 SPVCM.01

TC_ID	SPVCM.01
Purpose	Motors integrity
Requirements	3.1
Priority	High.
Estimated Time Needed	5 Minutes
Dependency	Motors should be in equipment.
Setup	All the necessary electrical circuits completed
Procedure	[A01] Each motor is supplied with 5V
	[A02] Each motor is supplied with 12V
	[A03] Each motor is supplied with 22V
	[V01] Observe Motors
Cleanup	Turn circuit off

11. Test Results

11.1.1 Electrical Test Results

All of the components working fine with each given voltage.

11.1.2 Calibration Test Results

After calibration current GPS and Compass module is not working correctly. They need to replaced with newer models.

11.1.3 Mechanical Test Results

After all the stress tests main frame is intact and no visable damage.

11.1.4 Image Processing Test

IP.S.01 UAV can fly between 0 to 7.2 km/h speed for optimum image processing results.
IP.GC.01 UAV can fly about, circle radius x 3 to circle radius x 10 meter.
IP.L.01 Flying aera must be light up if it is dark. Optimum day light is about 4 pm, reflections must be minimized.
IP.CC.01 Camera should constant at least 1 second without no oscillation to recognizing the circle.

12. REFERENCES

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