TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

DRONE MODEL FOR SCHOOLCHILDREN

DROONI MUDEL KOOLILASTELE

MASTER THESIS

Student: Kamran Omarov

Student code: 195653 MAHM

Supervisor: Anton Rassõlkin

Tallinn 2021

(*On the reverse side of title page*)

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Department of Electrical Power Engineering and Mechatronics

THESIS TASK

Student: Kamran Omarov, 195653MAHM(name, student code)

Study programme, MAHM02/18 - Mechatronics (code and title)

main speciality: Mechatronics MSc

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Thesis topic:

(in English) DRONE MODEL FOR SCHOOLCHILDREN

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Thesis main objectives:

1. Improve currently used mini-drone frame design
2. Apply generative design technology to new model
3. Implement easy fastening techniques

Thesis tasks and time schedule:

No	Assignment	Expected date
1.	Review of literature and existing products	December
2.	Choosing electrical components and controller	January
3.	Design of main components	February
4.	Development of the prototype	March - April
5.	Experimental results	May
6.	Thesis defense	June

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Student: Kamran Omarov .... "......."...............................20....a

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PREFACE

This topic had been proposed by Professor Anton Rassõlkin and I accepted the challenge of studying it as my master's thesis. I have an excitement to the mechatronics, robotics, dynamics, mechanical design and exploring new techniques in order to propose new methods and solutions more user friendly and efficient. The work on this thesis has been done in Estonia, Tallinn. Some thesis work has been done in the laboratory of university and different software has been used which free student versions are available for Tallinn University of Technology students.

The thesis is about to develop new special frame model of quadcopter which is used in a workshop by schoolchildren starting from high school (10+ years old users). The new model will inspire and motivate them to investigate technology and enhance their problem-solving skills. The new developed model should be reusable, robust, and easy to assemble and to reassemble by bare hands.

I would like to thank my supervisor, Anton Rassõlkin who throughout my studies at the Tallinn University of Technology, helped me find answers to all my questions and cope with the emerging difficulties. Under his guidance, I successfully completed the task and gained a lot of new knowledge.

I am deeply grateful to Prof. Mart Tamre for all the thesis-related suggestions and help with research paper during the “Master Seminar” course and after.

Keywords: Quadcopter, Block drone, drone frame, generative design, snap-fit fastening method.

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List of abbreviations and symbols

UAV – Unmanned Aerial Vehicle

RPV – Remotely Piloted Vehicle

UAS – Unmanned Aircraft System

STEAM – Science, Technology, Engineering, Art, and Mathematics

DIY – Do it yourself

FEA – Finite Element Analysis

ASTM – American Society for Testing and Materials

CAD – Computer-aided Design

ESC – Electronic Speed Controller

ABS – Acrylonitrile butadiene styrene

mm – Millimeter

DC – Direct current

V – Volt

mA – Milliampere

RPM – Revolutions per minute

CW – Clockwise

CCW – Counterclockwise

LED – Light-emitting diode

GHz – Gigahertz

Li-Po – Lithium polymer battery

mAh – Milliampere hour

m/s – Metre per second

MPa – Megapascal

PETG – Polyethylene Terephthalate Glycol

FDM – Fused Deposition Modeling

FFF – Fused Filament Fabrication

1. INTRODUCTION

Nowadays, Unmanned Aerial Vehicles, also Remotely Piloted Vehicle, or Unmanned Aircraft System, or simply Drones are playing a crutial role in the real-world. For the past few years, unmanned aerial vehicles are being more widely used for commercial and academic purposes. This huge interest and widespread usage of drones, motivated educational systems to implement drones in their studies starting from school age. Therefore, different curriculums such as STEAM (science, technology, engineering, art, and mathematics) implement re-constructable drones in their programs in order to give a chance for pupils to discover areas like robotics, electronics, programming, dynamics and physics [1]. Drones vary in types, sizes and capabilities which increase their prospects to be used in education from basic to advanced level.

Currently, in Tallinn University of Technology Block type DIY (do it yourself) drones of different companies are used in activities for shoolchildren. However, these drones are less durable and fragile which are not efficient for long time use and create difficulties both for pupils and instructors. More in detail, Block type drones are falling in pieces after each minor contact with objects, like hitting walls and during landing.

Thus, the aim of the work will be to design and develop reusable and robust drone models by applying the generative design technology and shape optimization [2], which will be produced and used in Tallinn University of Technology. Additionally, the designed model should be easy to assemble and reassemble, as it will be used by schoolchildren.

Along with that, safety requirements and regulations will be considered to develop new model which will excite schoolchildren and attract them to learn and experiment technology and gain experience and new skills during a course.

As a result of this thesis project, a real product (drone) will be designed and produced practically, afterwards can be used for educational purposes. The main parts will be produced in the university laboratory by 3D printer. Other main components, such as rotors, batteries, controller will be chosen accordingly and ordered from respective providers.

Thesis structure

This thesis is divided into several parts, mainly focused on the modelling and design system, design methodology, development, and the experimental results.

In Chapter 2, existing products, designs, and solutions will be analysed more in detail, some major solution methods will be estimated.

In Chapter 3, chosen solution methods will be discussed, main components will be chosen (batteries, controller, rotors, cabling etc.).

In Chapter 4, generative design technology and shape orientation methods will be implemented to design phase, initial prototype will be simulated and analysed in different software.

In Chapter 5, the final designed product will be printed and assembled fully. Necessary tests will be conducted, changes will be done if needed.

In Chapter 6, all information during the experiment will be carried out and summarized.

2. LITERATURE REVIEW

2.1. Overview

The purpose of this chapter is to give an overview and summary of the topic. This chapter is going to define problems and methodology which currently is used and analyze challenges and literature related to the topic. Additionally, it includes theories and approaches which are going to be used in order to solve the problems. Moreover, different topics will be discussed, starting from the early history of Unmanned Aerial Vehicles, mainly quadcopters.

2.2. Existing methods and solutions

Currently, there are a wide range of drones for educational purposes with different shapes, sizes, and number of rotors. The multi-rotor drones, especially quadrotors (4-rotor) are highly maneuverable and thus they are mostly suitable for indoor or small area applications, such as classrooms and laboratories [3], [4]. Mainly, these drones could be classified in two categories: Block drones and Compact drones.

Block type drones provide more opportunities for pupils to discover and implement their own creativity. However, these type of drones are fragile and frail. As the main connection and joining methods are not strong enough, the drone components and Block bricks fall to pieces after an unexpected hit of the wall or the ground, for example during landing [5].

There are plenty of Block type drones available in stores with different design and complexity. However, all of them have the same issue - weak connection technique, figure 2.1 [6].

Figure 2.1 Block drone [6]

On the other hand, compact drone models provide high quality and strong drones, which can withstand hitting walls and inaccurate landing, figure 2.2 [7]. However, these kinds of drones are designed in a compact way, where pupils and users are not able to assemble and reassemble, check, and experiment main mechanical and electrical components. The main aim of these drones is to give a chance to the user to code and control the drone itself [8].

Figure 2.2 CoDrone compact drone [7]

Additionally, there are other aircrafts which can be classified as a combination of Block and compact type drones. One of them is an Airblock flying robot from Makeblock with a hexagonal shape, figure 2.3 [9]. The main purpose of this drone is to provide a chance for users to learn programming of the aircraft. This drone has 1 core part which consist of control board and battery, also other 6 power modules where motors and propellers are located. These modules connects magnetically between themselves. However, there is no chance for users to disassemble cover, frame and observe all components separately and reassemble again as in compact types. Also, magnetic connections are not robust as well. After every collision modules highly will fall apart as in Block drones.

Figure 2.3 Airblock aircraft [9]

2.3. Types and shapes of UAVs

Traditionally, Unmanned Aerial Vehicles were firstly used in military operations. However, after several years and continuous developments in drone technology, it gave a chance to use these machines in other fields where employing humans is not possible, dangerous, or insufficient. Today, drones are broadly used in agriculture, photography, shipping and delivery, disaster management, search and rescue, wildlife monitoring, educational, and many other applications [10].

The main drone categories are fixed-wing and multirotor systems. The majority of existing drones can be defined within these two types.

Fixed-wing is a term mainly used in the aviation industry to define aircraft that use fixed, static wings in combination with forward airspeed to generate lift. Examples of this type of aircraft are traditional airplanes, even a simple paper airplane can be defined as a fixed-wing system.

Multirotor systems are a subset of rotorcraft. The term rotorcraft is used in aviation to define aircraft that use rotary wings to generate lift. A popular example of a rotorcraft is the traditional helicopter. Rotorcraft can have one or multiple rotors. Drones using rotary systems are almost always equipped with multiple small rotors, which are necessary for their stability, hence the name multirotor systems. Commonly, these drones use at least four rotors to keep them flying [11].

There are plenty of different shapes of frames of quadcopters which are widely used now. The most popular and proven models are: „X“ shape, „Deadcat“ shape, „H“ shape, and „Plus“ shape, figure 2.4 [12].

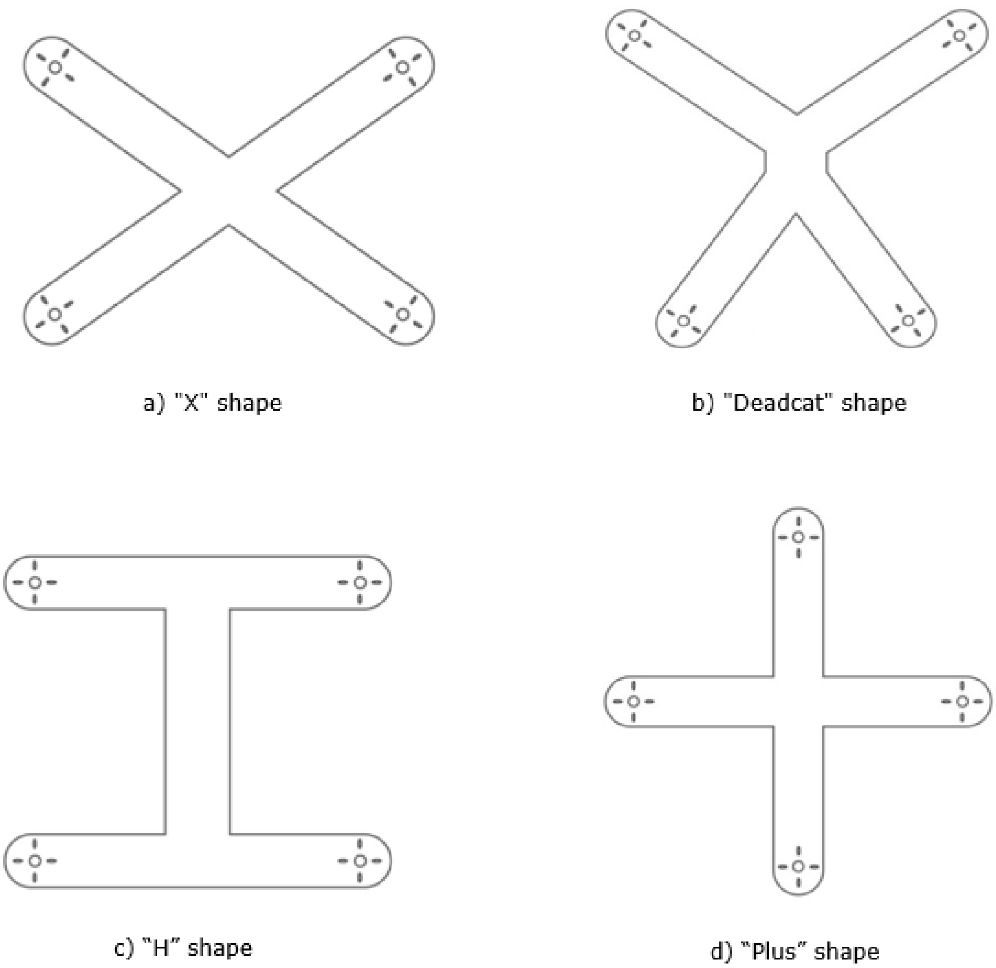

Figure 2.4 Shapes of quadrotors [12]

2.4. Analysis and manufacturing

For many years, the UAV industry relied mostly on widely popular and traditional machining methods, which in most cases creates toxic waste. In recent years, additive manufacturing provided considerable reduction in manufacturing cost, time, and waste, countless advantages over traditional manufacturing and production of the complex design and products [13], [14], [15].

In [16] research, authors emphasized on the design, analysis, and 3D printing of a quadrotor „X" shaped frame. The model was built in SolidWorks CAD software, then performed 3 types of finite analysis on the designed model: static structural, modal analysis, impact analysis. The final optimized model was printed on PRUSA I3 Mk3 3D printer by using carbon fiberglass material as the filament.

In article [17], researchers carry out initial design and analysis of quadcopter body frame with folded size 560mm (square model) based on fluid dynamic theories and FEA(Finite Element Analysis). The initial goal of this work was to fulfill qualities such as creating a good rigid body as light as possible and capable to carry weight, and also the placement of electronic components, sensors, and rotors.

In [18], the author investigated and fabricated a small UAV airframe by desktop 3D printer. Then, bending and tensile tests based on American Society for Testing and Materials (ASTM) were conducted on the 3D printed components of drone, and results seem promising. Additionally, at the end the author made a flight test, which indicated that the design was stable and controllable in sustained flight.

In [19] research, authors designed a 3D printable quadcopter via design software SolidWorks. The designed model was printed on the Stratasys Fortus 400mc 3D printing system. They used polylactic acid as a raw material for 3D printing, which is relatively cheap and has good durability despite its light weight. The further programming work was done in MATLAB.

2.5. Fastening methology

One of the main points of this thesis is to focus design and research procedure in mechanical fixings and joining technique. As it was mentioned before, the designed model should be easy to assemble and reassemble. In order to achieve this criteria, the first aim is to develop such a model, which can be assembled and reassembled without any tool [20]. In order to get a sufficient result, simple mechanical joining techniques, like snap-fits will be applied to development of the product[21], [22].

Snap-fit is a form-locking fastening which is used to attach parts without tools, or with bare hands [23], [24]. Snap-fit can be used for flexible materials such as plastic. For instance, in figure 2.5, shown 4 different design types of snap-fits, which differ with assemble and reassemble techniques [25].

In articles [26] and [27], authors described and practised general techniques and methods of snap-fits for 3D printing and by additive manufacturing. Additionally, there is useful information about design features and materials which can be implemented in order to reduce strain and stress on the snap-fit connections.

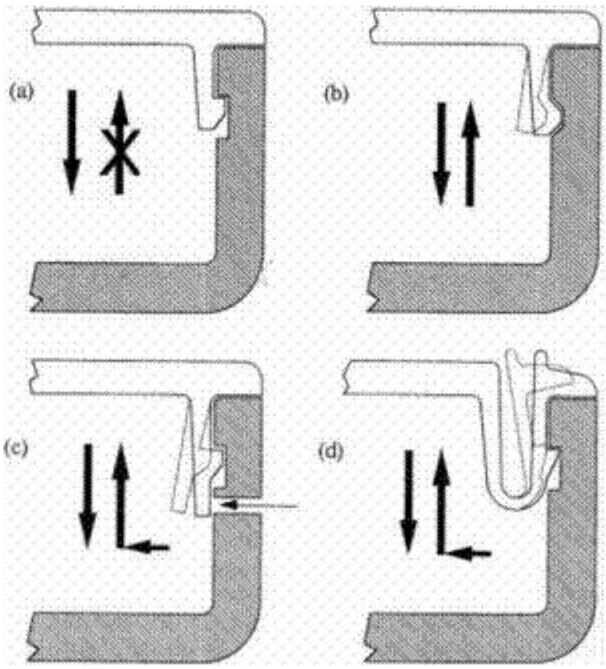

Figure 2.5 Types of snap-fits [25]

2.6. Generative design

Generative design is a CAD software function which helps to explore and generate the optimal versions of a traditional designed model by using algorithms. The generative design explores thousands of possible combinations of models by using parameters which designer or engineer outlined during setup, such as weight, strength, applied certain forces, materials, estimated cost, manufacturing methods etc [28], [29], [30].

The main benefits of generative design are:

- Increased efficiency.
- Customized product development.
- Reduce development time.
- Maintained or improved performance.
- Reduced weight.
- Increased creativity.

In figure 2.6 [31], is shown a sample of the metallic part of the generated model which would be hard and take a lot of time for engineers to design and develop without generative design.

Figure 2.6 Generative design [31]

In [32], the author implemented the generative design technique to quadcopter X-type frame in order to optimize the weight and increase durability. The results show that applying generative design decreased the weight of the drone by twice, which also lead to saving material and reducing manufactering time and process.

In article [33], the authors explored the design of drone frame by implementing Generative Design tools. During research they used gek Fusion 360 embedded generative design tools. Finally, the designed model was compared with a DJI F450 drone frame. As a result, the authors got 3 notable factors which shows that new model is healthier than the traditional model. The safety factor of the new model is almost 40 times higher, stress value is 11.4 times greater, and the maximum displacement under the load condition is approximately 400 times lower than the traditional one, which proves that the new model is much stronger and has greater resistance of yield and fracture.

2.7. Conclusion

Usage of drones in education provides an opportunity for pupils to discover technical devices, physics, aerodynamics, electronics and coding. Currently available products do not provide all necessary ability to learners to discover machines more deeply, each type has its own drawbacks, which put barriers in front of the user. In the previous chapter was discussed possible implementations of generative design and mechanical fastening methodology that can lead to new products which will be more flexible, user-friendly, and robust than existing drones. Additionally, in this paragraph pertinent literature and references were reviewed in order to familiarize readers with existing analysis and manufacturing methods. Various methods and techniques have been used in above research in order to obtain robust and lightweight design of drones and frames of drones, where many of them succeeded to reduce weight, material use, and production time. Also, implementation of the simple fastening methods can make the designed model more stable, reliable and adaptable.

2.8. Aims and Objectives

The main objective of this thesis project is to design and produce practically a real product (drone), which afterwards can be used for educational purposes. The main parts will be produced in the university laboratory by 3D printer.

The aims for this thesis project is:

- Conduct a relevant review and research in the field of drone design and assembly, generative design methodology, and mechanical assembly techniques.

- To design an appropriate model of drone which will be used for educational purposes and can be produced in TalTech laboratory.
- The designed model should meet criterias like robustness, ease and with no mechanical tools assemble and reassemble, and give an ability to users(pupils) to discover all main components of a drone.

3. ANALYSIS OF THE MODEL AND COMPONENTS

In this chapter major factors and main components of quadcopter such as motors, propellers, battery, charger, remote control, control board and shape of frame will be discussed. Additionally, the safety measurements and material choice for the designed model will be described.

3.1. System concept

As it is clear from the name, quadrotors contain 4 motors/rotors and 4 propellers where 2 of them are clockwise and 2 counterclockwise, figure 3.1. These motors are controlled by a control board which can have a great variety of futures, but the main purpose is to receive a signal from remote controller, joystick, or any kind of input and implement on motors accordingly. Electronic Speed Controller (ESC) controls the speed of motors, thus gives a chance to fly in different directions, rotate and maneuver.

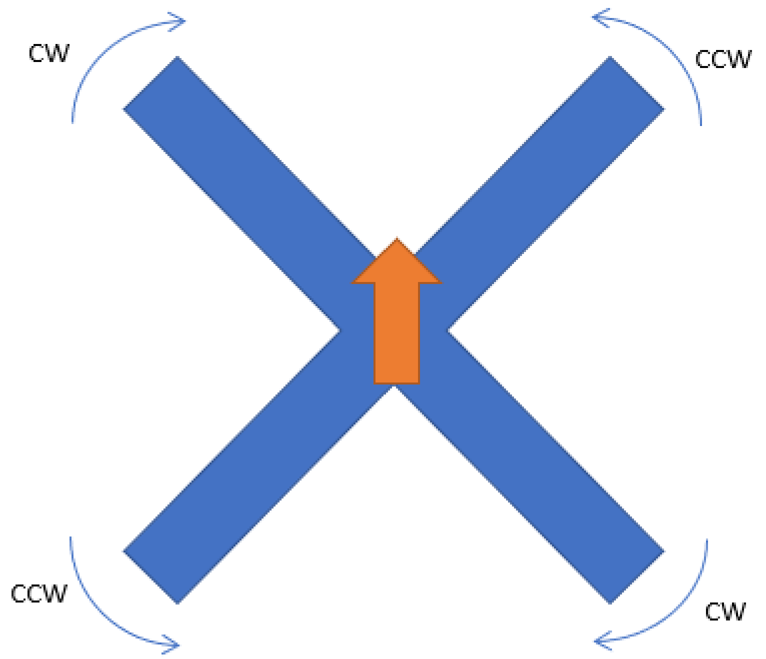

Figure 3.1 Propeller rotation directions

In figure 3.2 [34] shown the speed level of each motor during separate movements of drone. Movement of quadcopter, regardless of its shape and model, is categorized in 4 types according to relation motion between motors:

1. **Throttle** is a movement of the drone up or down regarding to the speed of the rotors. All motors are rotating at the same speed and as speed goes higher the drone is heading up, as speed goes lower then drone moves down.
2. **Pitch** is a movement of the drone forward or backward regarding to the speed of front of rear rotors.
    - If the speed of the front rotors is higher than rear rotors, then quadcopter will fly forward.
    - If the speed of the front rotors is lower than rear rotors, then quadcopter tends to fly backward.
3. **Roll** is a movement of the drone about the longitudinal axis based on the speed of the rotors on left and right side of the quadcopter.
    - If the speed of both right rotors is higher than left rotors, then quadcopter will move in left direction.
    - If the speed of both left rotors is higher than right rotors, then quadcopter will move in right direction.
4. **Yaw** is a rotation of the drone around its vertical axis.
    - If the speed of both clockwise propellers is higher than speed of counterclockwise rotors, then drone will rotate in clockwise direction.
    - If the speed of both counterclockwise propellers is higher than speed of clockwise rotors, then drone will rotate in counterclockwise direction.

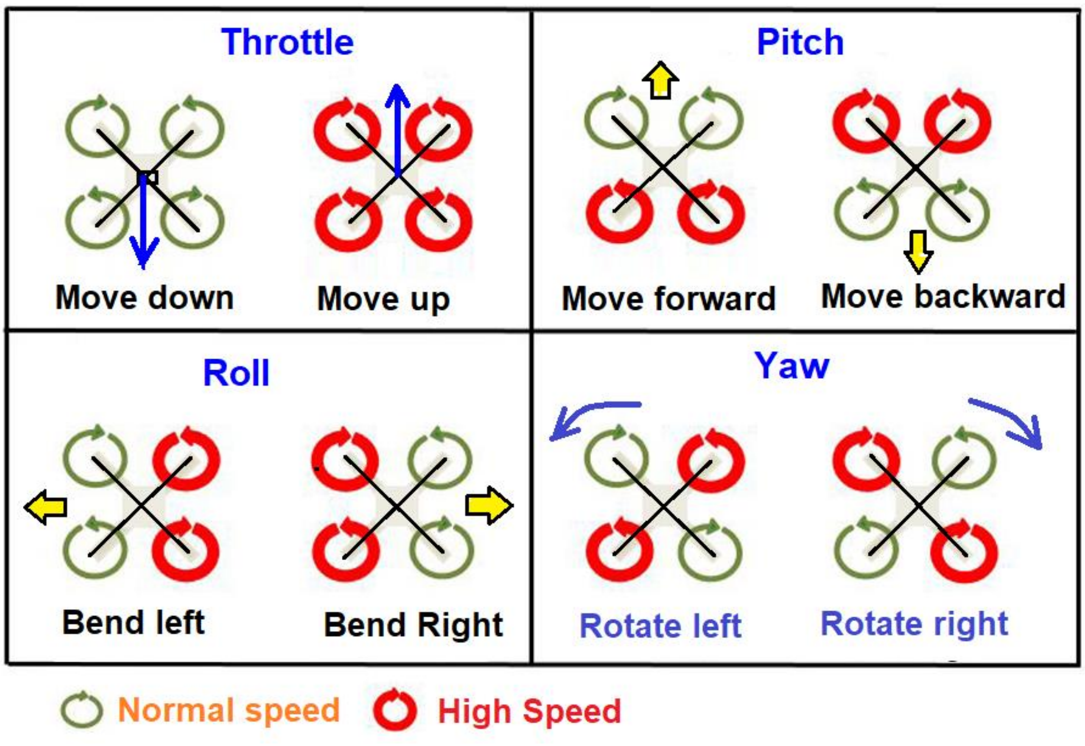

Figure 3.2 Dynamics of quadcopter [34]

As mentioned previously, there is a wide range in shapes of frames of quadcopter, where most popular shapes are "X" and "Plus" shapes due to simple design and most balanced performance, figure 2.4 [12].

3.2. Main components

Currently in curriculum of the course, Block type 6-axis gyroscope quadcopter is used, figure 3.4 [35]. However, as most Block drones, this drone is not strong enough and falls in pieces after every single collision or landing. Otherwise, components and performance of this quadcopter is satisfactory. Thus, the shape, orientation of the rotors, propellers, and electrical components will be taken from this UAV and new frame models will be designed and analyzed.

Figure 3.3 Block quadcopter [35]

The Block drone consists of 17 pieces of blocks from ABS plastic, 4 motors, 4 propellers, 1 control board, 1 battery, a charger, and 1 remote control (the solid model and part list can be seen in appendices section, Appendix 1). The frame shape of this drone is "X" shaped with distance between center of motors 100 mm and 104 mm, figure 3.5.

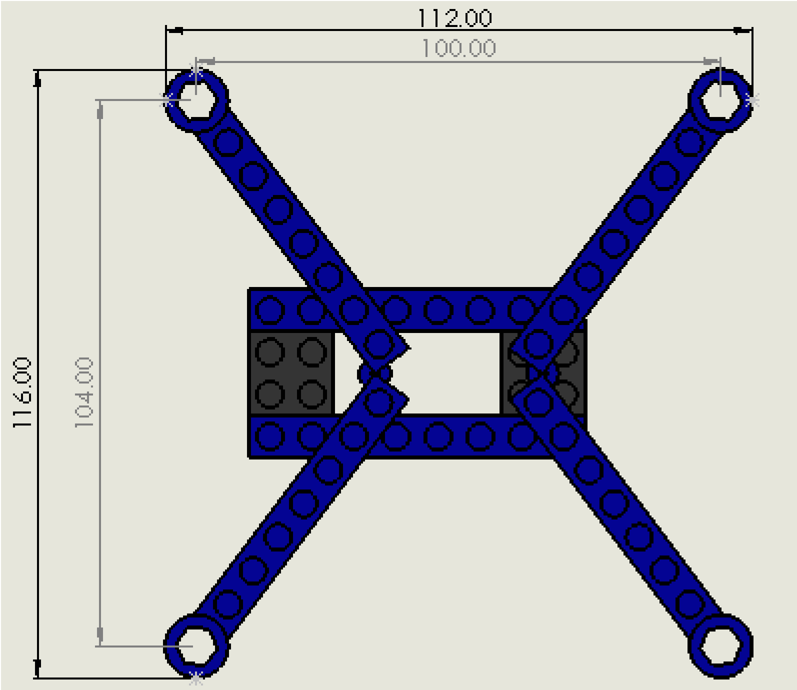

Figure 3.4 Locations of motors

3.2.1. Motors and propellers

In this drone DC coreless motors of model 720A (clockwise) and 720B (counterclockwise) are used, figure 3.4. The coreless motors are widely used in small UAV due to their high torque to weight ratio, high speed, and reduced operational noises.

Specification of motor:
With 80 mm cable and JST 1.25 mm male connector
Weight: 3.5 grams
Voltage: 3.7V
Current: 100 mA
Speed: 45000 RPM

According to the motor, 2 CW and 2 CCW 56 mm propellers are used, figure 3.4. These propellers are standard for coreless motors with 1 mm shaft diameter and generally can generate 20-25 grams of static thrust. The combination of these 4 motors and 4 propellers are capable to fly approximately 60 grams [36].

3.2.2. Control board and remote control

Control board can be considered as a brain of the quadcopter, which receives signals from user by help of remote controller and executes them accordingly. In this project LY – X101R-2.4G model control board is used, figure 3.5. This board has a built-in 6 axis gyroscope in order to ensure stable flight of drone. Additionally, there is a cable with JST connection for battery, antenna, and LED light. The 4 motors are connected to the control board with JST 1.25 mm connection as well. In addition, in each corner of board clued 5mm female connection stud which guarantee easy and strong assemble to the frame of quadcopter.
Aforesaid, signals transmit with help of 2.4 GHz, 4 channel transmitter which works with 3 1.5V AA batteries. The working range of remote controle is between 50 and 80 meters.

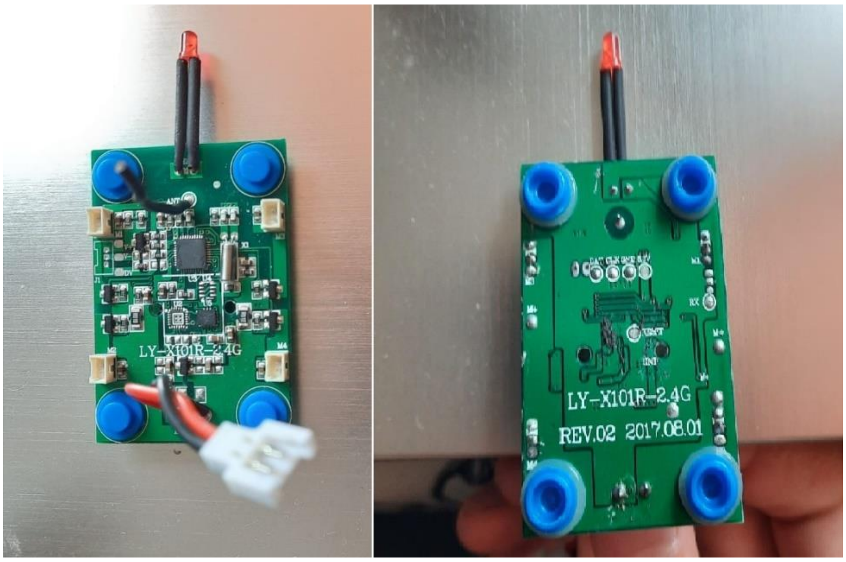

Figure 3.5 Control board

3.2.3. Battery and charger

As a power source of the drone, 752035 model Li-Po battery is used and weight of battery is 12 grams. The capacity of the battery is 400 mAh, and voltage is 3.7V. This battery provides approximately 8 minutes flight time and charges fully during 45 minutes with USB charger. When the battery is low, red LED light on control board starts to blink.

3.3. Safety regulations

Unfortunately, the hazardous statistics for drones are not available, as the end users are totally heterogeneous and not all users provide a hazardous report to the manufacturer. However, intuitively and based on practical challenges it is possible to say that the most dangerous part of the drone is its propeller which are rotating with high speed [37]. One of the best and practically proven way is to use propeller guards which prevent a direct contact of propellers and collided object, human in this case. Additionally, these propeller guards protect propellers from crashing after unwanted collisions.

As this drone will be used in workshop by schoolchildren starting from 10 years old, the safety requirements should be higher than regular. Another way of providing higher safety is material of the frame and propeller guards. The less dangerous and light materials are plastics.

Additionally, there are several safety instructions which are necessary to follow during course in a workshop:

- Fly drones in specifically designed fly zones.
- Do not fly drone over other participants of the room.
- Avoid flying close to walls, ceilings, and the floor.
- Do not pick up drone while propellers are spinning.
- Keep an eye on the drone while driving it.
- Safety glasses should be worn by all participants of the room.
- Fly only one drone at a time in one specifically designed fly zone.

4. DESIGN

The purpose of this section is to explain the design methodology of the quadcopter frame. Initial frame model will be optimized by generative design technology and analyzed further. Additionally, in this section propeller protections and snap-fit joint techniques will be discussed.

4.1. Quadcopter frame modelling

As stated above, the shape of frame will be “X” shape and distance between motors are 100 mm and 104 mm. In order to create an initial prototype of mechanical model which will be shaped further by help of generative design method, the total weight of other components and lifting limits should be considered. The total weight of all components of drone will be 33 grams and separate weight of all components is given in table 1.

Table 4.1 The weight of main components

Component	Quantity	Weight of individual component in grams
Motor	4	3.5
Propeller	4	0.25
Control board	1	6
Battery	1	12

The weight of Block frame is 21 grams, so desired maximum weight target of new frame will be taken approximately 21 grams as well. Additionally, it was mentioned that chosen 4 motors can lift a weight about 50-60 grams.

There are 2 main forces which influence stress on frame during flight are lift forces generated by motors and a gravity [38]. The lifting forces should exceed total weight of quadcopter for successful take off and hover, figure 4.1 [39].

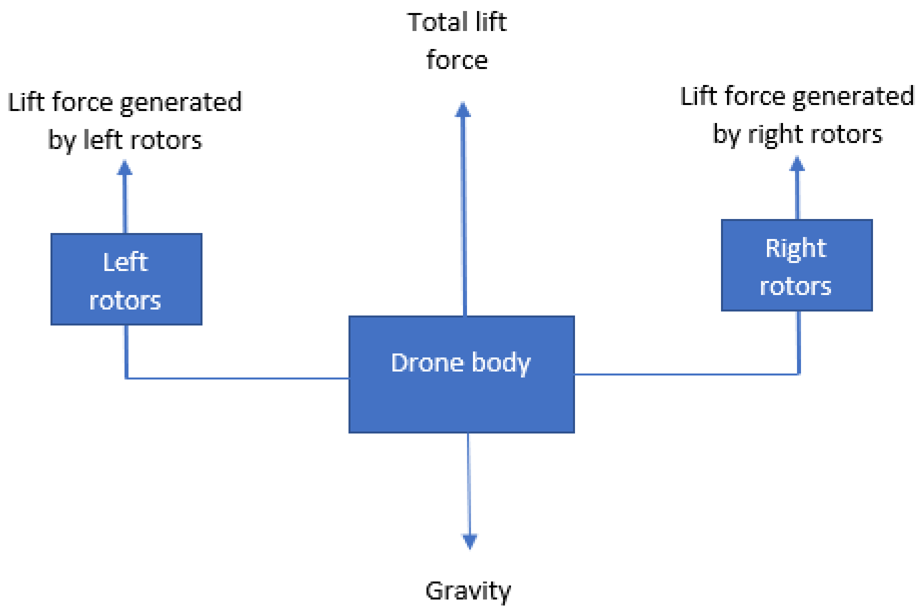

Figure 4.1 Free body diagram of total lift force.

4.2. Initial frame model

After considering all necessary parameters and motivated from current model, initial skeleton of frame was designed, figure 4.2 (detailed drawings in Appendix 2). Without initial model it is not possible to proceed with generative design.

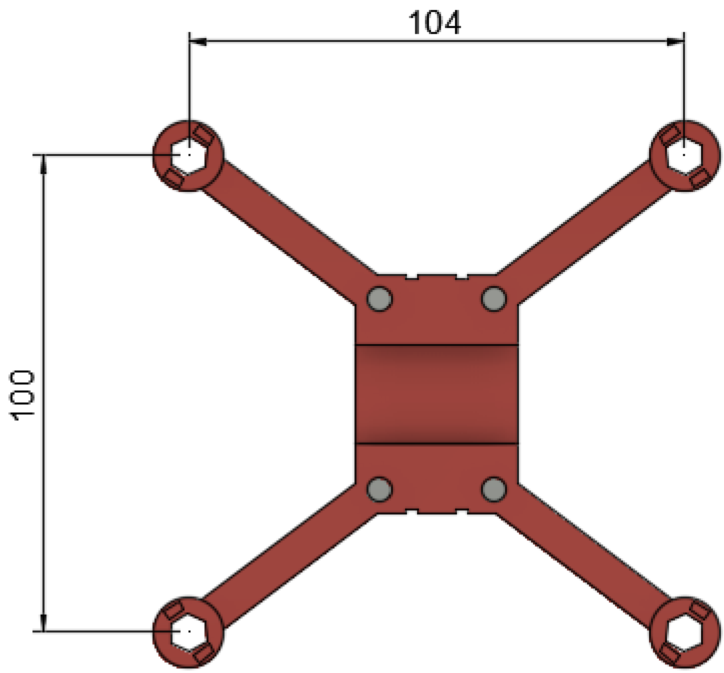

Figure 4.2 Initial frame model

As it seems from drawings, the motor locations are 100 mm and 104 mm as determined earlier. Additionally, there are 4 female connection studs with 4.8 mm diameter on control board for easy attaching to the frame, so 4 male connection studs were added to the frame with 0.1 mm tolerance in order to keep fixing method of control board.

4.3. Propeller protector

The first part which gets in contact with obstacles during a collision is propeller, so it can be considered as the weakest mechanical components of the quadcopters. As propellers rotates with high speed and mostly manufactured from plastic, they are not able to withstand unexpected collisions. Luckily, there is a way to protect propellers with propeller guards which simply creates physical barrier. Mainly these protectors can be classified in three types as single, double, and cage propeller guard: figure 4.3 [40].

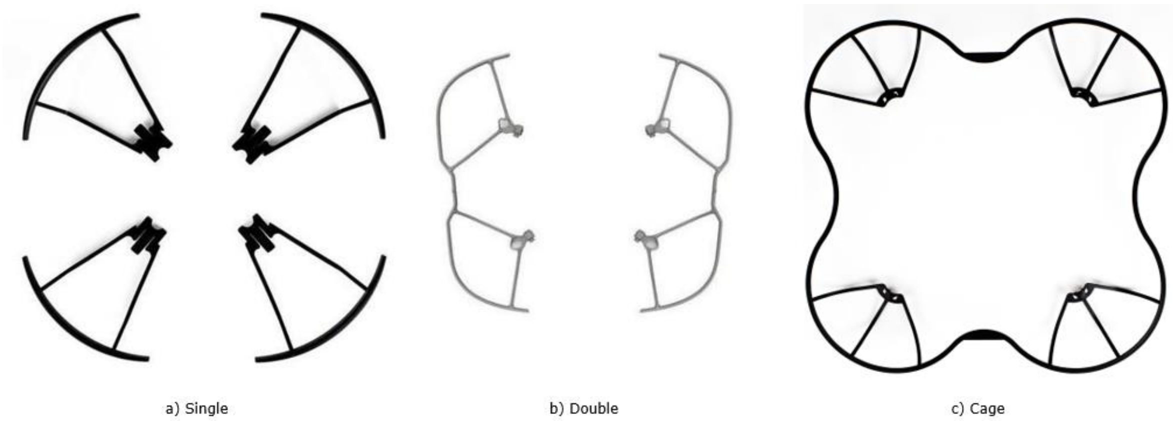

Figure 4.3 Types of propeller guards [40]

The single type propellers are chosen for new model as they straightforward to use and replace whenever needed. There are 3 main points which were taken into consideration while designing new propeller guard:

1. Size/measurements in order prevent intersection with propeller itself:

Propeller itself and size are mentioned in Chapter 3, and radius is 28 mm. In figure 4.4, free space between propeller and its guard can be observed.

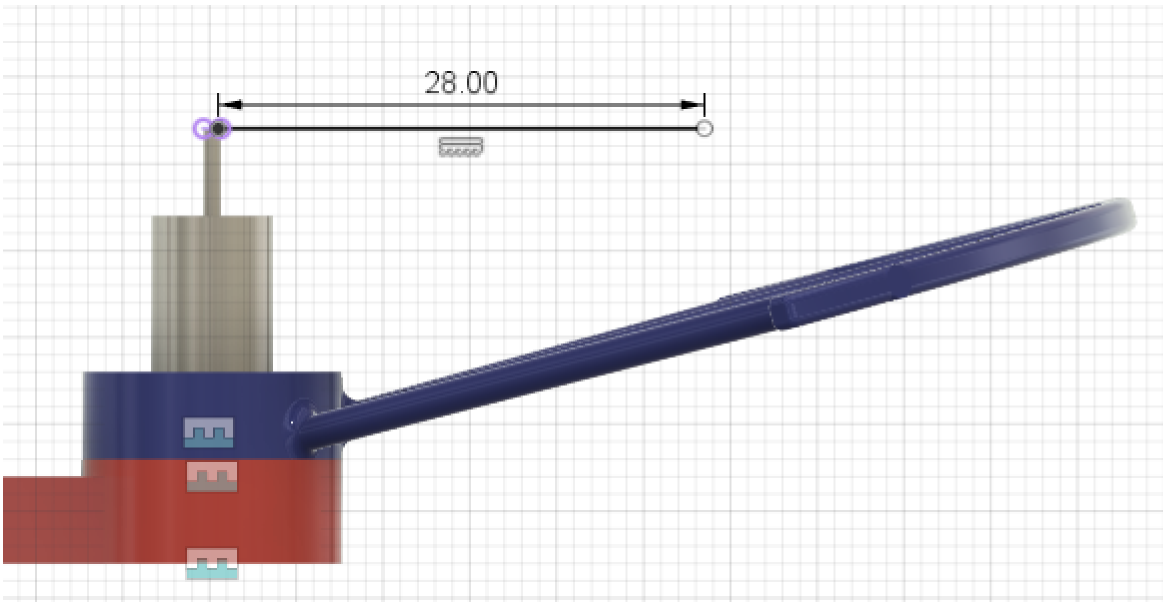

Figure 4.4 Free space between propeller and its guard

2. Assemble/fixing method:

In order to keep model and assemble procedure uncomplicated, tongue-and-groove joint methodology is implemented to the design. The tongue-and-groove joint is one of the popular and reliable type of the rigid integral attachment [41]. 2 rectangular slots with sizes 2 mm x 4 mm were cut by depth of 2 mm on the mating face of the propeller guard. Accordingly, 2 rectangular slots with the 0.2mm tolerance at width and length, and height 1.5mm sizes were added to the frame of quadcopter, detailed drawings can be found in Appendix 2 and 3.

3. Strength:

Initial model was designed based on 1st and 2nd points, and then analyzed in dynamic simulation. The simulation was settled as propeller guard is going to hit fixed wall from concrete material with speed 30 m/s(which is more than enough for drone with these components). Simulation result shows that overall propeller guard is able to withstand the collision with high speed, but there is higher stress in the connection of ribs and mount parts, figure 4.5.

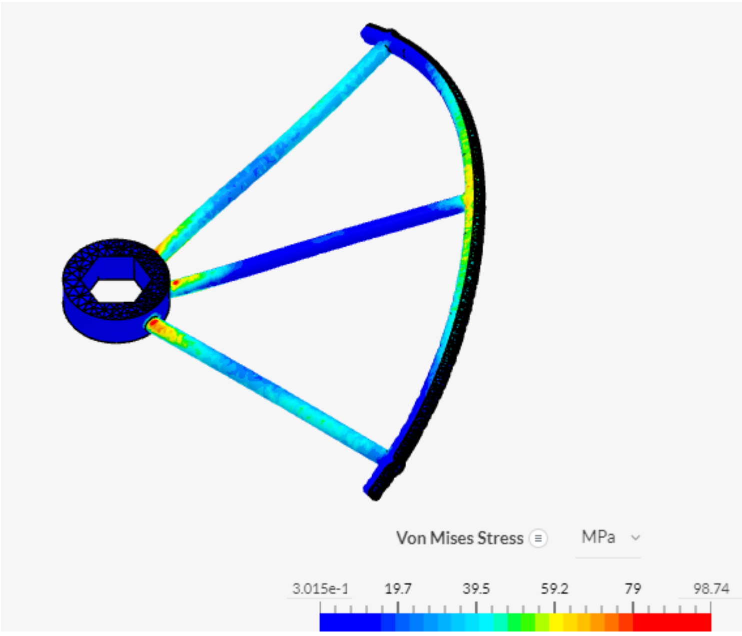

Figure 4.5 FEA of initial model

As a solution it has been decided to add fillets with 1.5 mm of radius around ribs and mounting part, which should increase strength of connection. The dynamic simulation is conducted with the same conditions. The simulation result shows that propeller guard is in safe range based on Von Mises criterion, figure 4.6. The final design of propeller guard can be seen in Appendix 3.

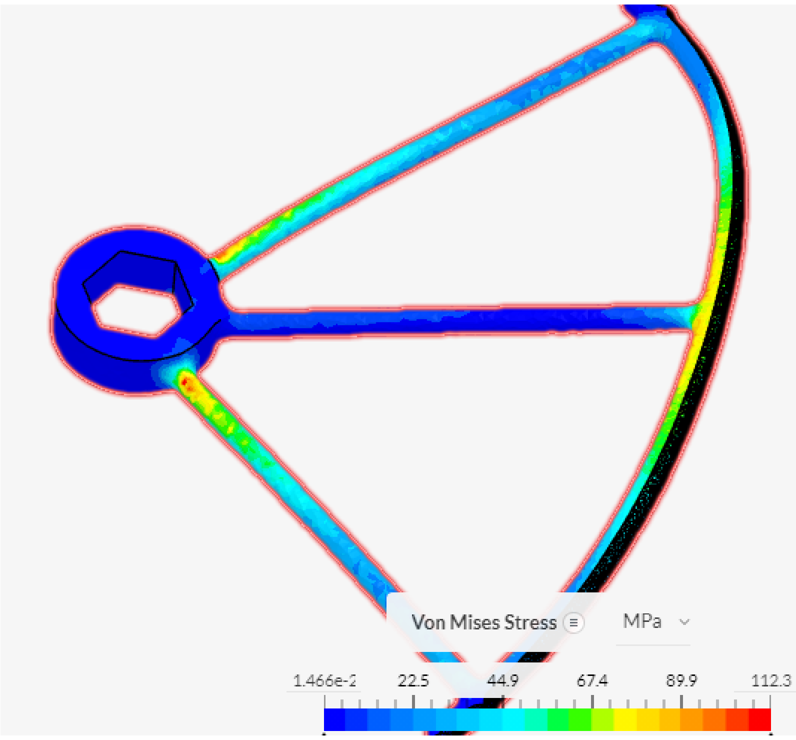

Figure 4. 6 FEA of final model

4.4. Cover with Snap-fit

Snap-fit fastening technology is one of the oldest, popular, and rapid locking futures which relies on elastic deflection of the material [41], [42]. In other words, one of mating components is slightly deflected during the joining and separating operation. Snap-fits can be separable and inseparable depending on the application and design.

There are several types of snap-fittings but most popular are cantilever snap-fit, U-shaped snap-fit, and annual snap joint, figure 4.7, [43], [44].

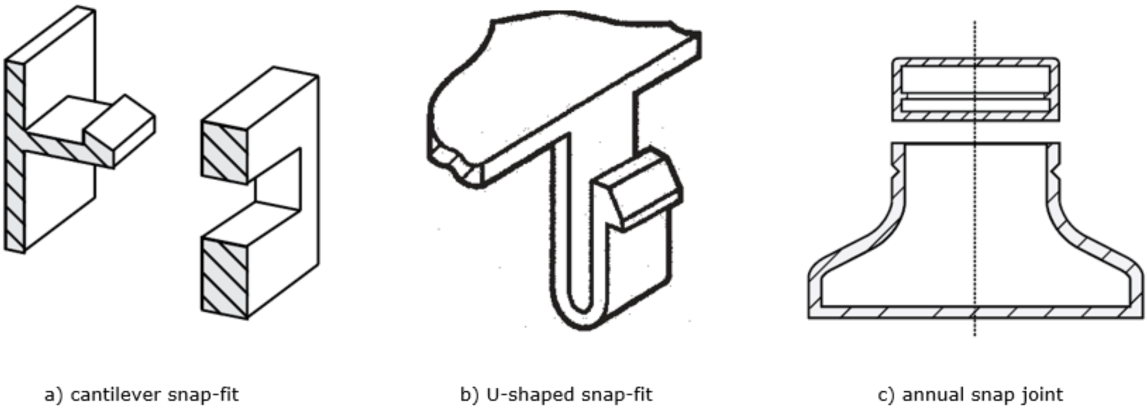

Figure 4.7 Types of snap-fits [43], [44]

In current model, cantilever snap-fit will be used for attaching top cover with frame. Top cover is going to protect control board and battery from external damages and helps to keep them on frame.

There are several types of cantilever snap-fits based on their shapes and cross sections. In this model will be designed and used straight snap-fit with rectangular cross section, figure 4.8, [45].

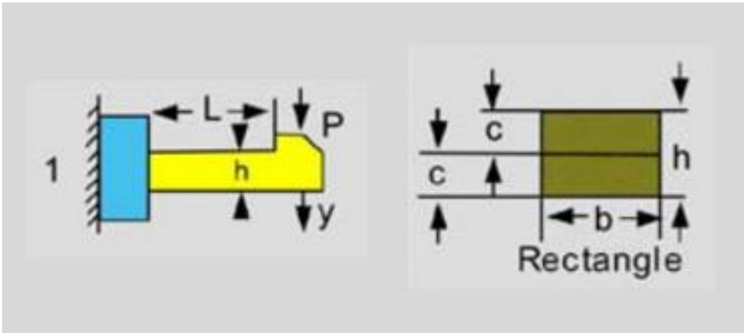

Figure 4.8 Straight snap-fit with rectangular cross section [45]

The suitable snap-fit for new model will be with 15 mm of length of arm, 2.5 mm thickness, and width 8 mm. The reflection distance was calculated according to the permissible deflection formula:

$$y = 0.67 \times \frac{\varepsilon \times l^2}{h} \qquad (4.1)$$

where ε - permissible strain,

l – length of arm, mm,

h – thickness at the root, mm.

Additionally, it is possible to calculate deflection force to understand how much force will need to reassemble snap-fit by formula:

$$F = \frac{E \times \varepsilon \times b \times h^2}{6 \times l} \qquad (4.2)$$

where E – secant modulus, MPa,

ε - permissible strain,

b – width, mm,

l – length of arm, mm,

h – thickness at the root, mm.

From different research and test it was carried out that permissible strain of PETG material is around 0.03 and secant modulus is around 40MPa. [46] [47], [48], [49].

According to above mentioned sizes and dimensions, snap-fit model was designed, figure 4.9 (detailed drawing can be checked in Appendix 4).

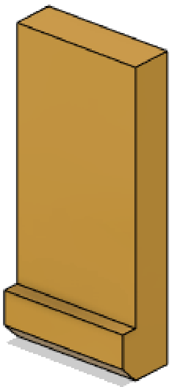

Figure 4.9 Snap-fit 3D model

Designed snap-fit model will be attached to the top cover and together it will be as a one part. The 3D model and technical drawing is in Appendix 5.

In order to check strength of snap-fit, static stress analysis have been conducted based on Von Mises Stress method. On outer face of snap-fit applied deflection force which had been calculated by formula 4.2. The simulation result shows that snap-fit is in safe range and will be stressed mainly in the connection part with top cover, figure 4.10.

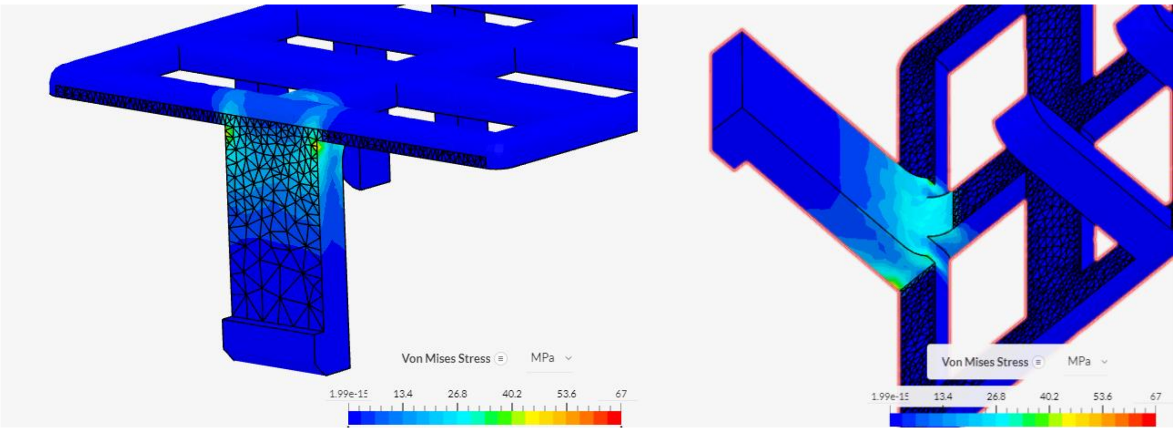

Figure 4.10 FEA of snap-fit

4.5. Generative design

Generative design is a tool in design world which become more popular in last years. The generative design working principle is based on mathematical formulations and algorithms to revise and reshape a model, based on different constrains and conditions. It is giving advanced and optimized models by evaluating the basic model and study setup like obstacles, preserved geometries, manufacturing process, material, and applied forces. Through an iterative process, generative design creates advanced and optimal models that would take a lot of time for engineer to calculate and develop [50], [51].

4.5.1. Conditions and set-up

The assembly model for a quadcopter had been designed and assembled based on specifications given in table 1 and chapters 4.1 and 4.2, figure 4.11 (detailed assembly drawing can be seen in Appendix 6).

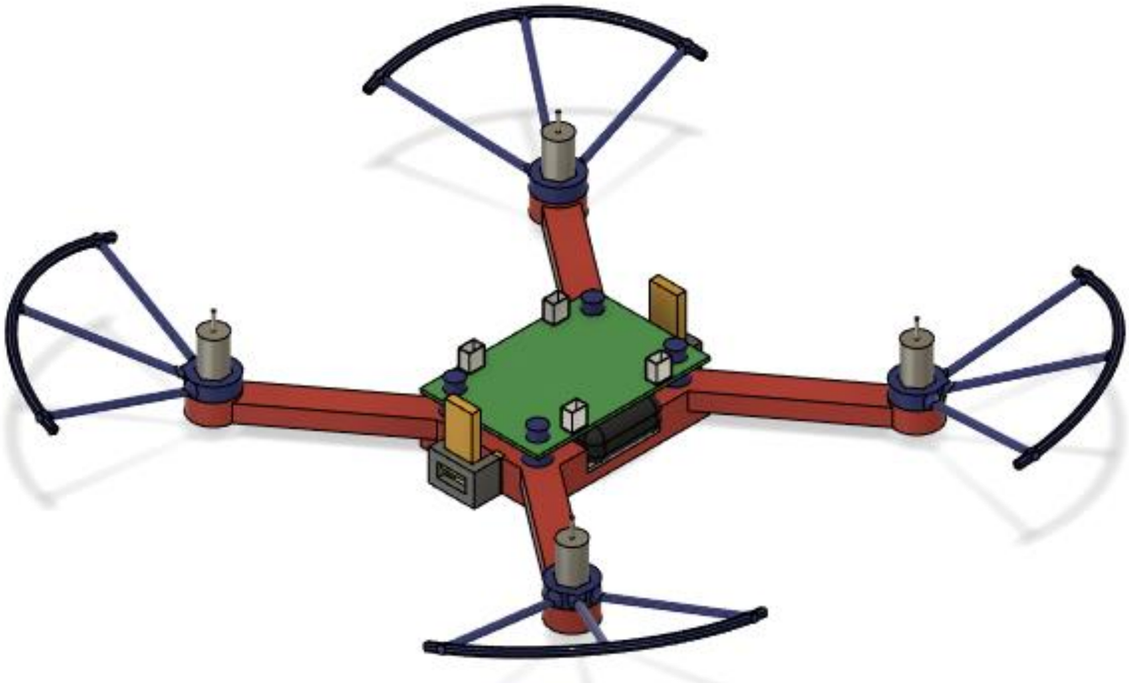

Figure 4.11 Initial asembly model

The initial weight of assembly is 85 grams and frame itself is 50 grams. As it was mentioned in Chapter 4.1, the motors can lift about 60 grams, so target for a new model is to decrease a weight of frame till assembly will fulfill motors lifting limits.

Second step is to determine preserve, obstacle, starting shape geometries in assembly.

The geometries which should be included in final generated model without any changes in shapes are considered as preserve geometries. In current assembly model motor mounts, male studs for control board connection, and snap-fit attaching parts are taken as preserved geometries, figure 4.12.

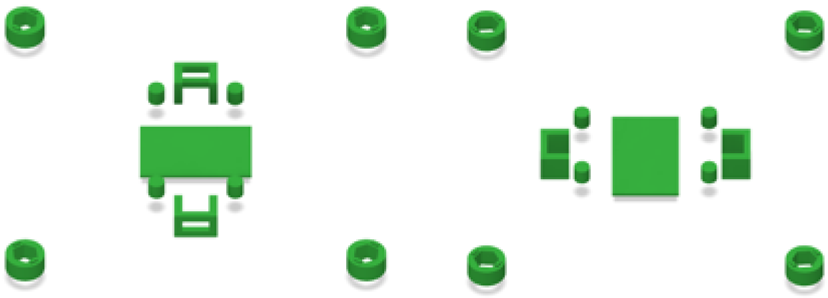

Figure 4.12 Preserve geometries

Obstacle geometries represent spaces which should be avoided during generating new model. In other words, no material can be created, added, or removed from that places. Propeller guards, motors, control board, battery, and snap-fits are considered as obstacle geometries in current model, figure 4.13.

Figure 4.13 Obstacle geometries

As an optional choice, it is possible to influence the generated models by choosing starting shape geometry. The starting shape geometry helps software to optimize and utilize new models based on given shape. Assigning starting shape is beneficial for reducing generation time, as it will prevent from creating useless variations of model.

The frame model without above mentioned parts was taken as an starting shape geometry, figure 4.14.

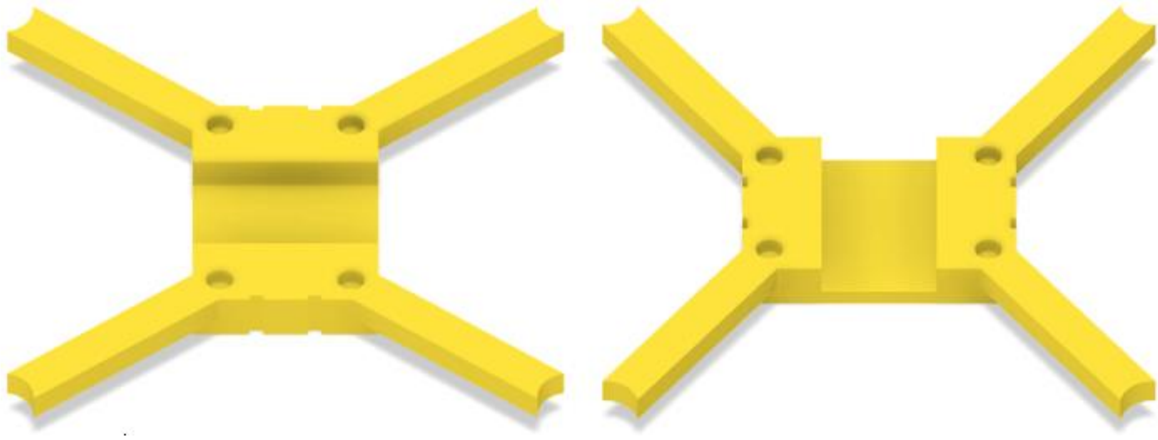

Figure 4.14 Starting shape geometry

Next step is assigning structural loads which applies on the quadcopter. The forces acting on a frame are determined based on different fly movements which are mentioned in Chapter 3.1, throttle, pitch, roll, and yaw. There are 4 types of forces acting on the frame are, figure 4.15 [34]:

1. The gravity force / weight,
2. Lift force,
3. Thrust force,
4. Drag force.

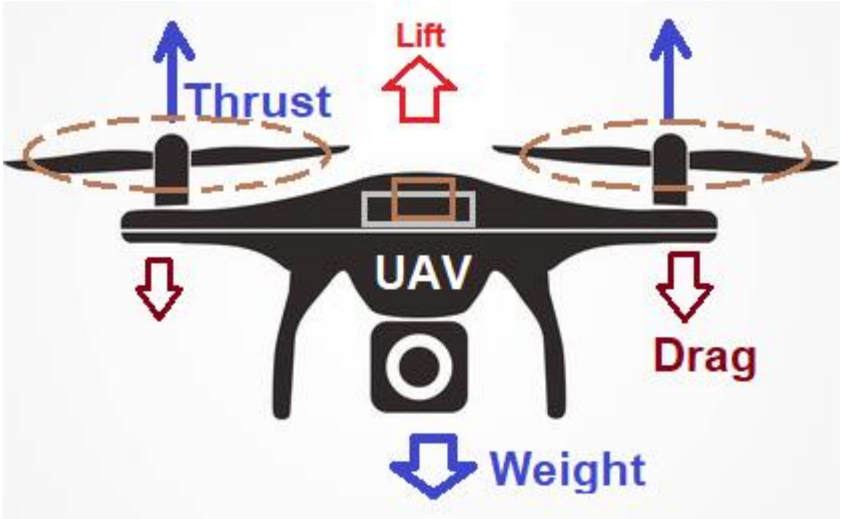

Figure 4.15 Structural loads [34]

As a final step, additive manufacturing process had been chosen with mass minimize objective. The PET plastic material had been assigned for model which is available in Autodesk Fusion 360 as a default material with 54.4 MPa Yield strength and 55.1 MPa Tensile strength.

4.5.2. Generated models

After various iterations, based on above mentioned inputs, the software generated 6 different models, figure 4.16. 2 outcomes of frame have been considered as most suitable models based on weight limitations, shapes, and stress analysis. These models are 4 and 5. The 3D model and drawings of outcome 4 and 5 can be seen in Appendices 7 and 8, respectively.

The outcome 1 and 3 are eliminated due to weakness on chassis, especially in arms. The outcome 2 has uneven and asymmetrical shape, especially in snap-fit mounting part, as a result it demonstrated critical behavior during simulation. The weight of 6^{th} model is 29 grams which is over limited weight for this case.

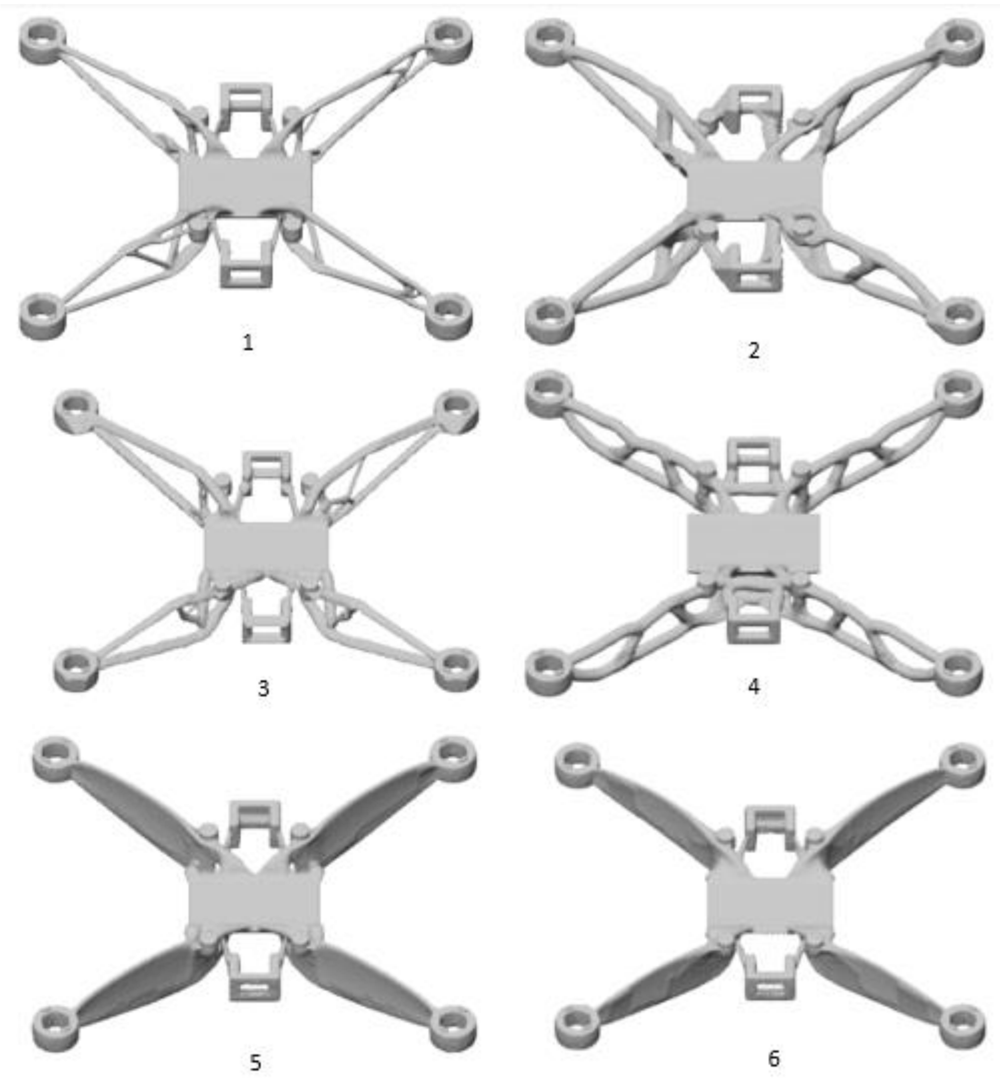

Figure 4.16 Outcome models of generative design

The outcomes 4 and 5, figure 4.17, are mostly suitable models and the weight of outcome models 4 and 5 are 20 and 17.5 grams, respectively. The 3D model and drawings of outcomes 4 and 5 can be checked in Appendix 7.

Figure 4.17 Outcome 4 and 5

4.5.3. Analysis of generative models

Stress analysis have been run on chosen generated models - 4 and 5. All forces mentioned in previous chapter are applied on the models and PET plastic material have been chosen. The result shows that both models are on safe range and able to withstand applied forces without any critical stressing. Simulation results can be checked in Appendix 9.

One of the main hazardous damages can be done during landing the quadcopter. The frame and mainly contact parts of frame with ground should be strong enough in order to absorb instant stress which occurs during landing or during free fall.

The free-falling simulation have been performed on the frame models. As this quadcopter will be used in school workshop, the maximum height of the room will be lower than 5 meters.

Initially, the free-falling simulation have been conducted to the outcome 4. The result shows that the stress affecting on chassis is critical and could lead to damage of frame, figure 4.18.

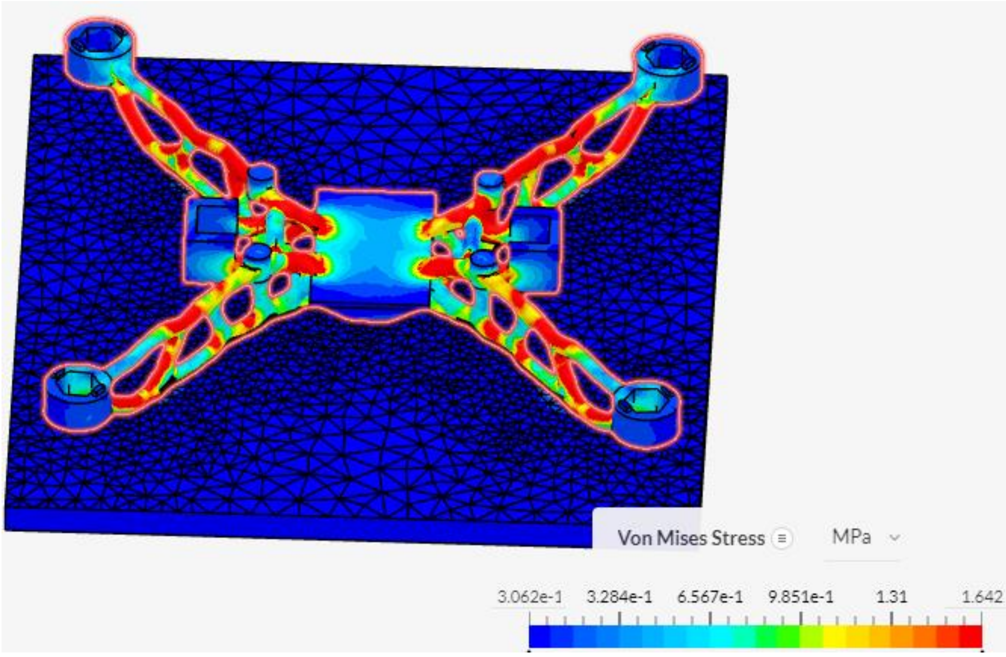

Figure 4.18 Free-falling simulation of Outcome 4

As a solution, it has been decided to add rectangular landing gear under the frame with length 7 mm, width 19 mm, and height 1.5 mm, figure 4.19. This additional layer plays crucial role as it absorbs some part of initial stress and transmit left over to the frame. In result, frame less stressed than in first simulations, figure 4.20.

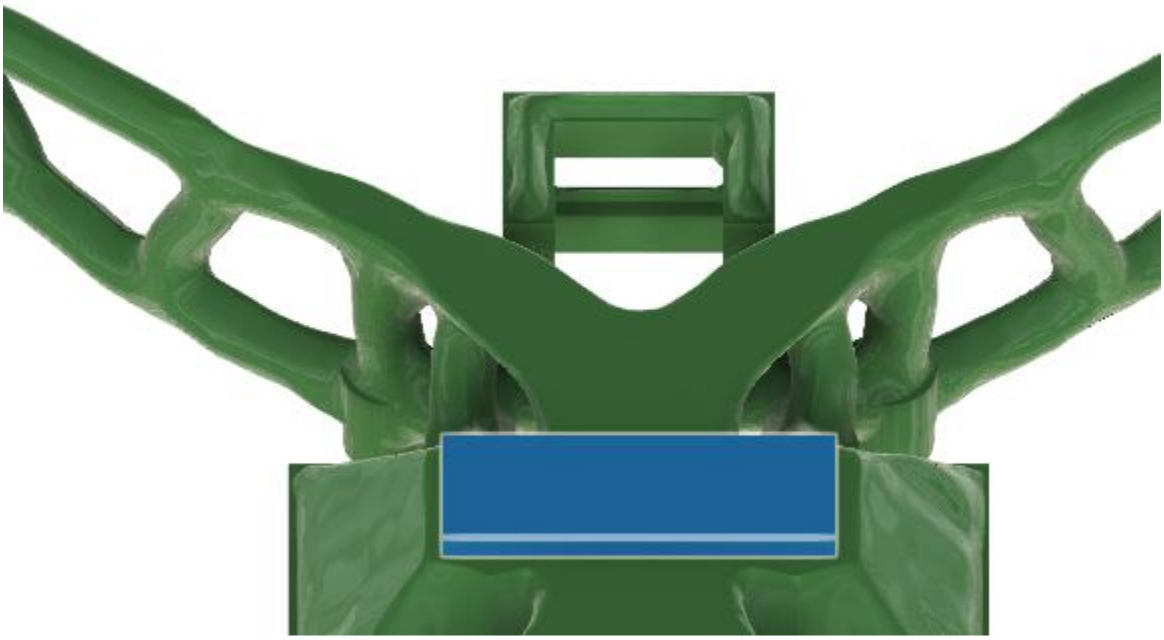

Figure 4. 19 Rectangular landing gear

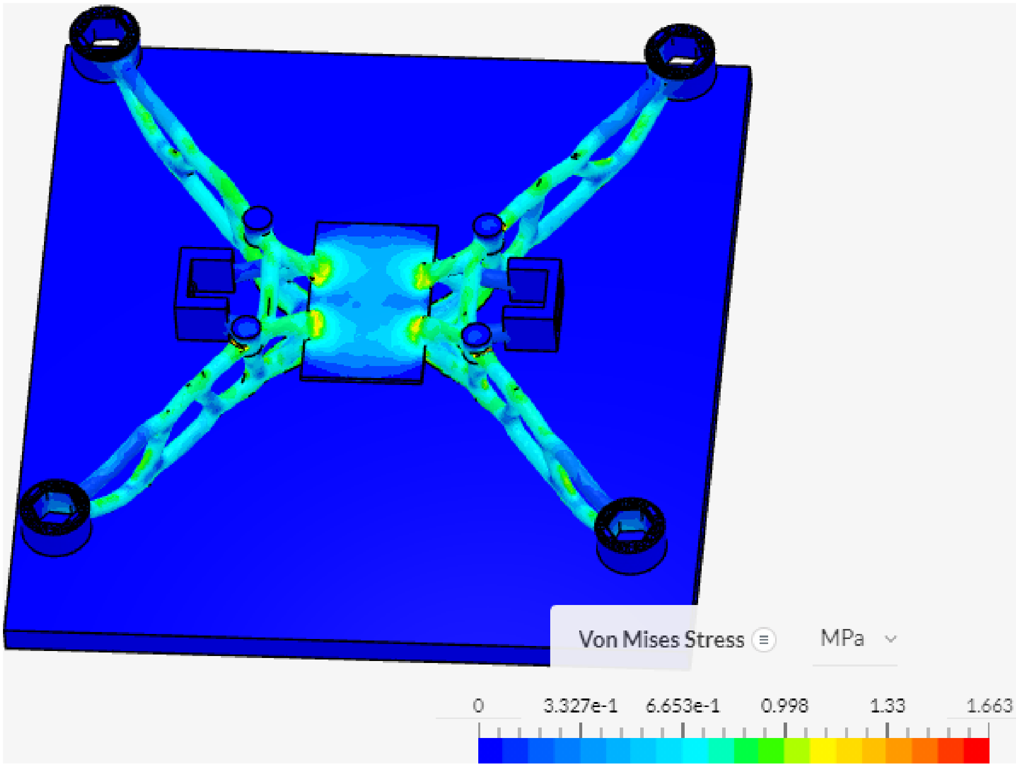

Figure 4.20 Free-falling simulation of Outcome 4 with landing gear

The same FEA had been conducted to the frame outcome 5. The simulation result is shown in figure 4.21. Simulation result of outcome 5 shows that frame of quadcopter is generally able to withstand stresses during free-fall. However, there is a higher stress range in battery housing.

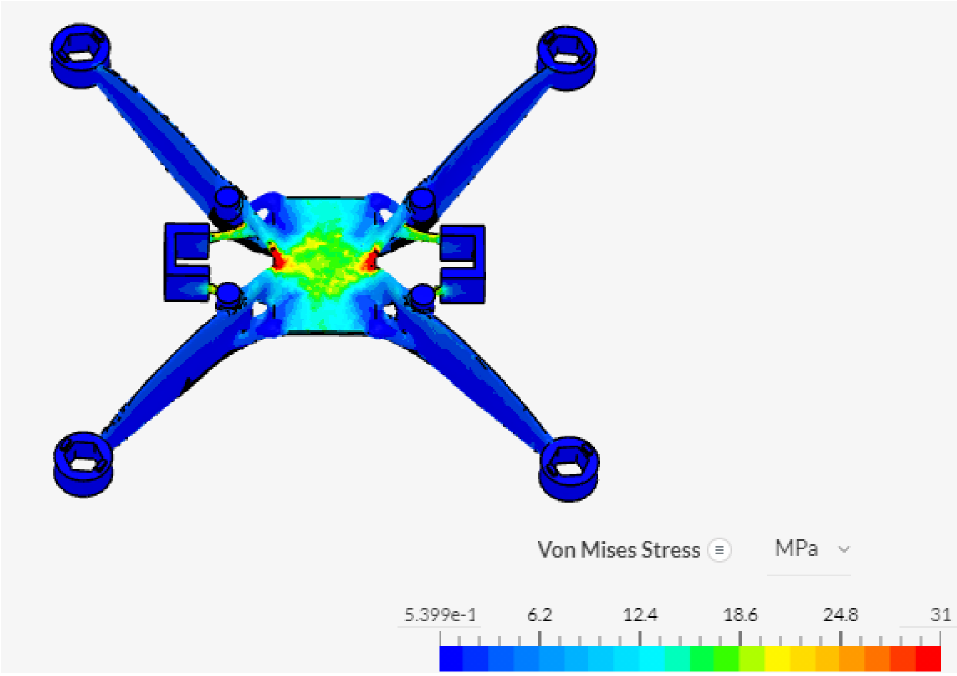

Figure 4. 21 Free-falling simulation of Outcome 5

5. ADDITIVE MANUFACTURING

In this chapter designed models will be printed by help of FDM printer and discussed in more details. The weaknesses of the initial models will be outlined, fixed and tested further.

5.1. 3D printed models

The additive manufacturing has been chosen for producing prototypes and analyze physical properties of designed models. The additive manufacturing is one of the most popular processes in production which helps to reduce time and cost of production, gives a chance to fabricate and analyze different designs and models in few hours [52], [53].

Fused deposition modeling, also known as fused filament fabrication, is the most widely used type of 3D printing. In this work FDM/FFF type printer has been used. Creality Ender 3 pro model printer with PETG material has been used, which is considered as a mid-level printer and has 0.1 mm precision.

As a slicing software, Ultimaker Cura 4.9.1 has been chosen, and all parts have been sliced with the same parameters which main of them mentioned bellow:

Layer height: 0.2 mm.
Infill density: 90%.
Infill pattern: Cubic.

Initially, both models, outcome 4 and outcome 5 has been printed, figure 5.1.

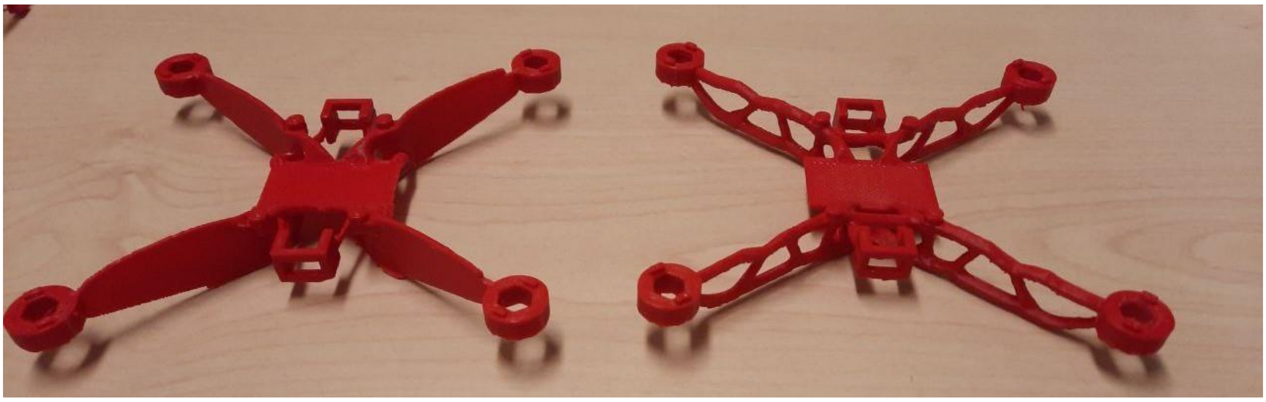

Figure 5.1 Outcome 4 and Outcome 5

The printed frames have been studied and analyzed physically. The outcome 4 is strong and meets needed criteria. It was noticed that Outcome 5 frame is weaker and can be bended more easily, figure 5.2. As these models will be used by schoolchildren, arms of outcome 5 seems critical and can be broken easily by users.

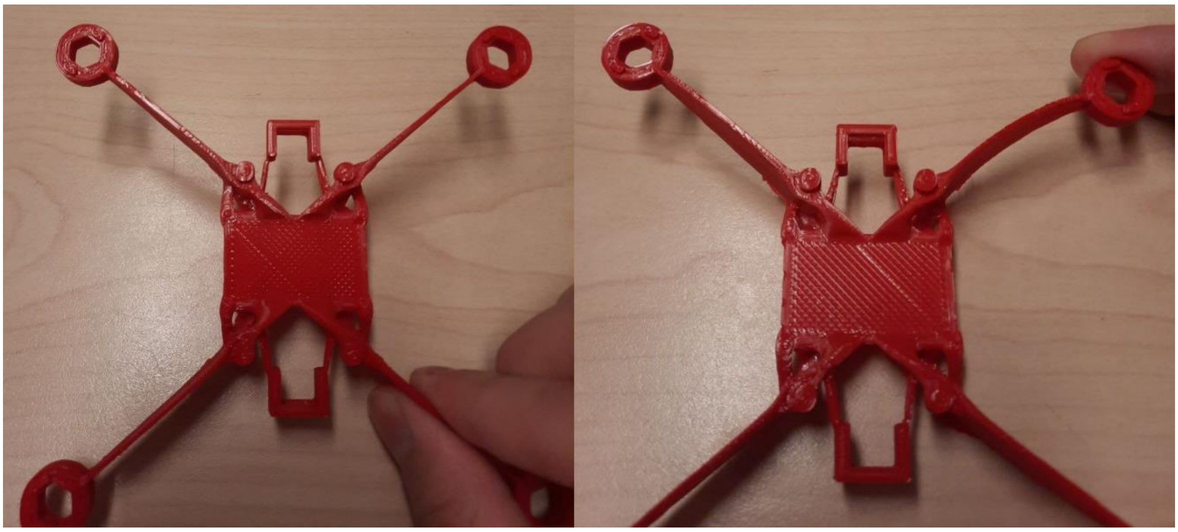

Figure 5.2 Normal and bended frame of Outcome 5

As a solution, the thickness of arms can be increased and tested again. However, increasing thickness will increase the total weight of frame and result can exceed current limitations. As a result, frame of outcome 5 has been eliminated as it is not applicable for existing conditions.

Next, top cover with snap-fit and propeller guards has been printed. The prototypes seem good and strong enough, figure 5.3.

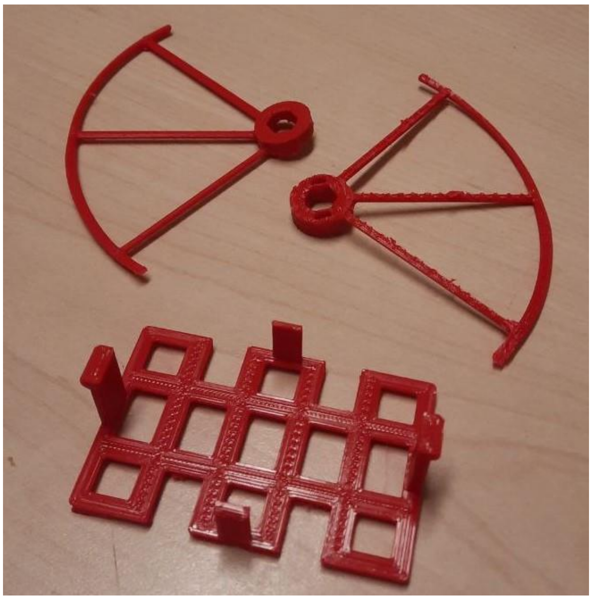

Figure 5.3 Printed top cover with snap-fit and propeller guards

Finally, figure 5.4, model has been assembled by frame of outcome 4, top cover with snap-fit and propeller guard, and other components which had been mentioned in Chapter 4.

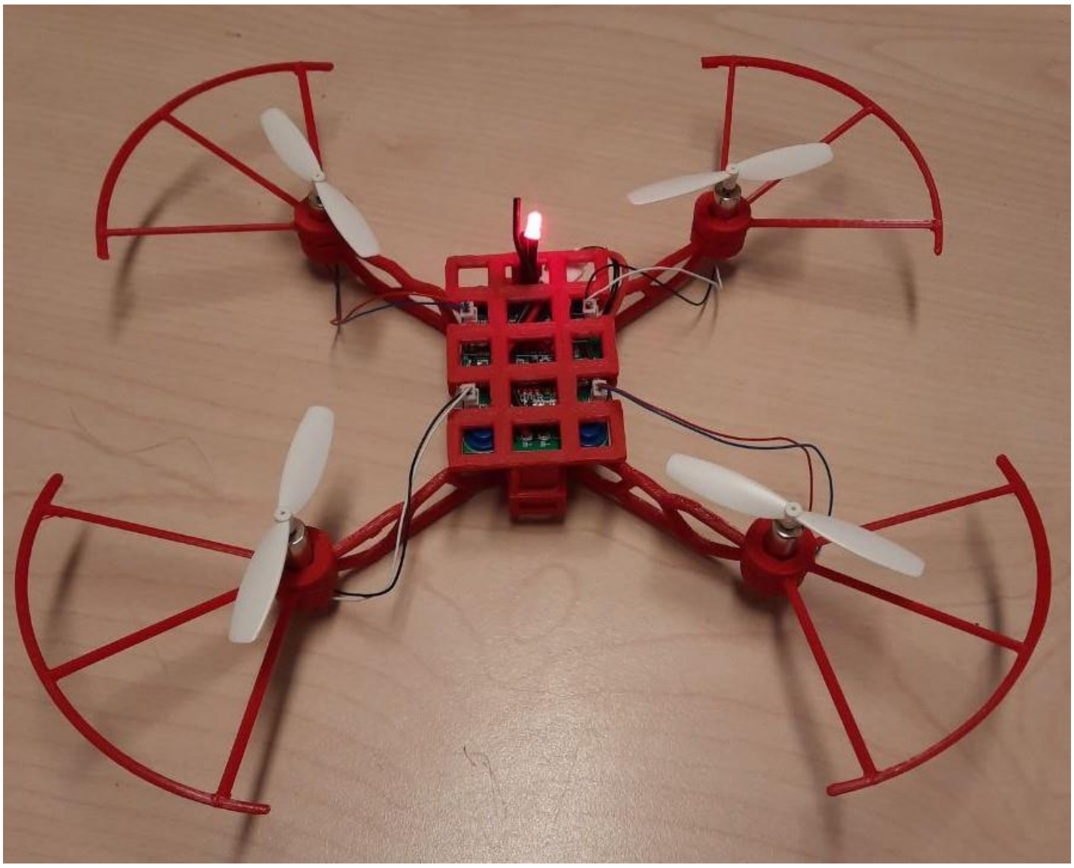

Figure 5.4 Assembled model

5.2. Experiments and improvements

The assembled drone has been flown for several hours and has been collided with different objects to test robustness of the model. Overall, flying parameters and performance did not change by new frame model. However, robustness of the model has been increased noticeably which was the target of this work.

Despite of being more robust and stronger than Block drone, it had been noticed that approximately in 4 collisions out of 10, propeller guards were detached which has been considered as a weak tongue-and-groove joint.

As a solution, it was decided to change sizes of tongue-and-groove joints and add additionally 2 more. Final model of propeller guard has 4 rectangular holes through all with dimensions 4 x 2 mm and respectively, additional rectangular slots have been added to the frame of outcome 4 with 0.2 mm tolerance, figure 5.5. Updated drawings and 3D models can be checked in Appendices 10 and 11.

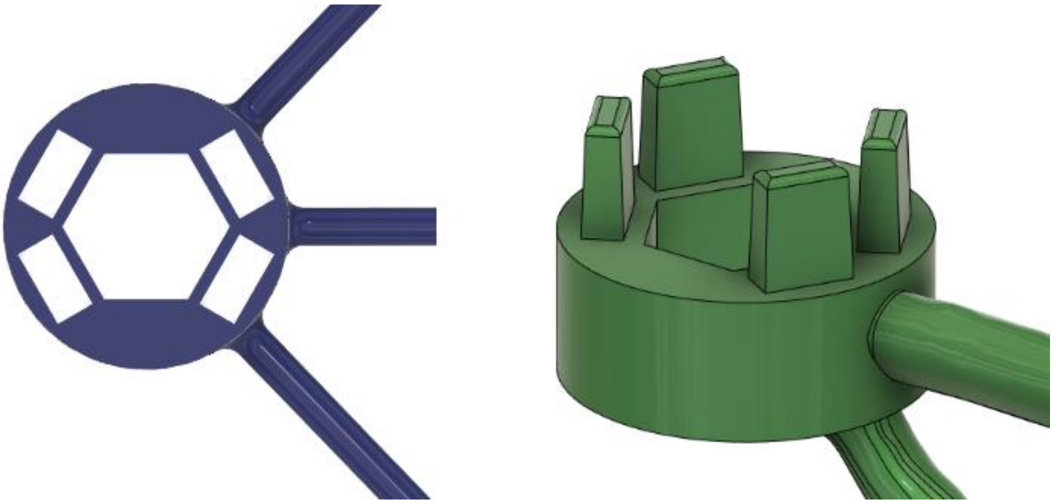

Figure 5.5 Tongue-and-groove joints of propeller guard with frame

Updated models of frame and propeller guards have been sliced and printed with the same parameters which had been mentioned in subchapter 5.1. Assembled model have been flown and tested, figure 5.6. After several collision and tests, it was noticeable that connection between propeller guards and frame is stronger and more reliable now.

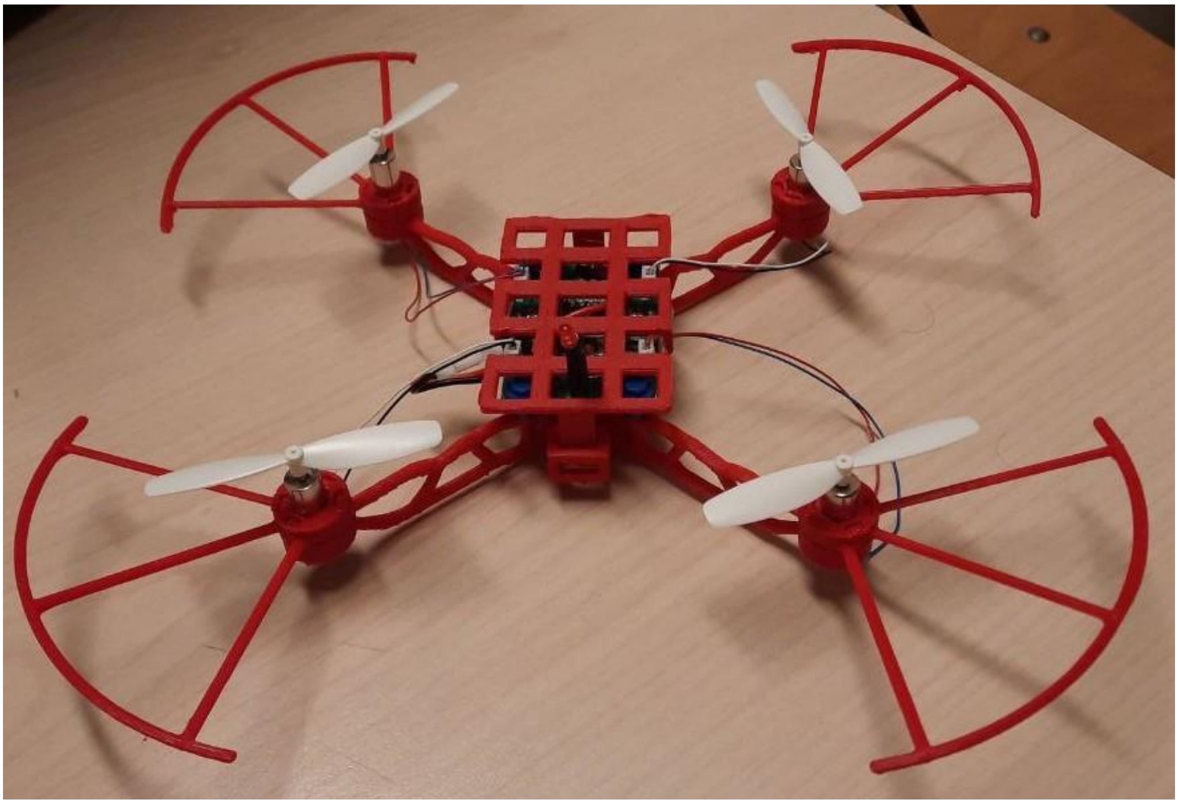

Figure 5.6 Final assembly of quadcopter

6. SUMMARY

This thesis work demonstrated in details development of the new special frame model of the mini quadcopter which will be used in workshop by schoolchildren. Initially, current market has been analyzed and critical points have been discussed. Further, the main components and safety regulations have been described which will be considered during design phase. Finally, design technology and rigid integral attachment techniques have been implemented to get optimized models.

In conclusion, the desired model has been designed successfully with implementation of the generative design and integral mechanical attachments, such as snap-fits. The result of the obtained models was as expected.

6.1. Future work

The core idea of the project is to create a such workshop where schoolchildren can get familiar with technology, enhance their technical knowledge, and improve problem-solving skills. Despite of the satisfactory result, the model still needs improvements to get to advanced level:

- Implementation of the new programmable control board which will provide a chance to schoolchildren to code and gain programming skills.
- Update electrical components like motors and battery to achieve better performance.
- Modify new frame where additional components like cameras can be attached.
- Analyse different manufacturing processes and materials in order to get better frame models.
- Use different generative design software and compare outcomes of new models.

7. KOKKUVÕTE

Antud lõputöö demonstreerib väikese drooni uue raami arendamist, mida hakatakse kasutama koolilastele mõeldud töötubades. Esialgu analüüsiti uut turgu ning arutati kriitiliste punktide üle. Seejärel, kirjeldati peamisi komponente ja ohutus regulatsioonidest tulenevaid nõudeid, mida jälgiti disaini loomisel. Lõpuks, võeti optimiseeritud mudelite jaoks kasutusele disaini tehnoloogia ja jäigalt integraalitud kinnitamise tehnikad.

Kokkuvõtteks, soovitud mudel disainiti edukalt kasutades genereerivat disaini ning integraalitud mehaanilise kinnitusi, millest üks on snap-fit.

7.1. Tulevikus tehtav töö

Projekti põhituumaks on luua sellised koolilaste töötoad, mis aitaksid lastel tutvuda tehnoloogiaga, arendada nende tehnilisi teadmisi ning võimendada probleemide lahendamise oskusi. Vaatamata rahuldavatele tulemuste vajab mudel uuendusi, et saavutada veelgi edukam toode:

- Uue programmeeritava trükkplaadi lisamine, mis aitaks koolilastel arendada programmeerimise oskust.
- Uuendada elektrilisi komponente nagu mootor ja aku, et saavutada parem jõudlus.
- Modifitseerida uut raami tekitades võimalusi lisa komponentide kinnitamiseks nagu seda on kaamera.
- Analüüsida erinevaid tootmise protsesse ja materjale, et saada veelgi parem raam.
- Kasutada erinevaid genereerivaid disaini tarkvarasid ning võrrelda nende poolt genereeritud tulemusi.

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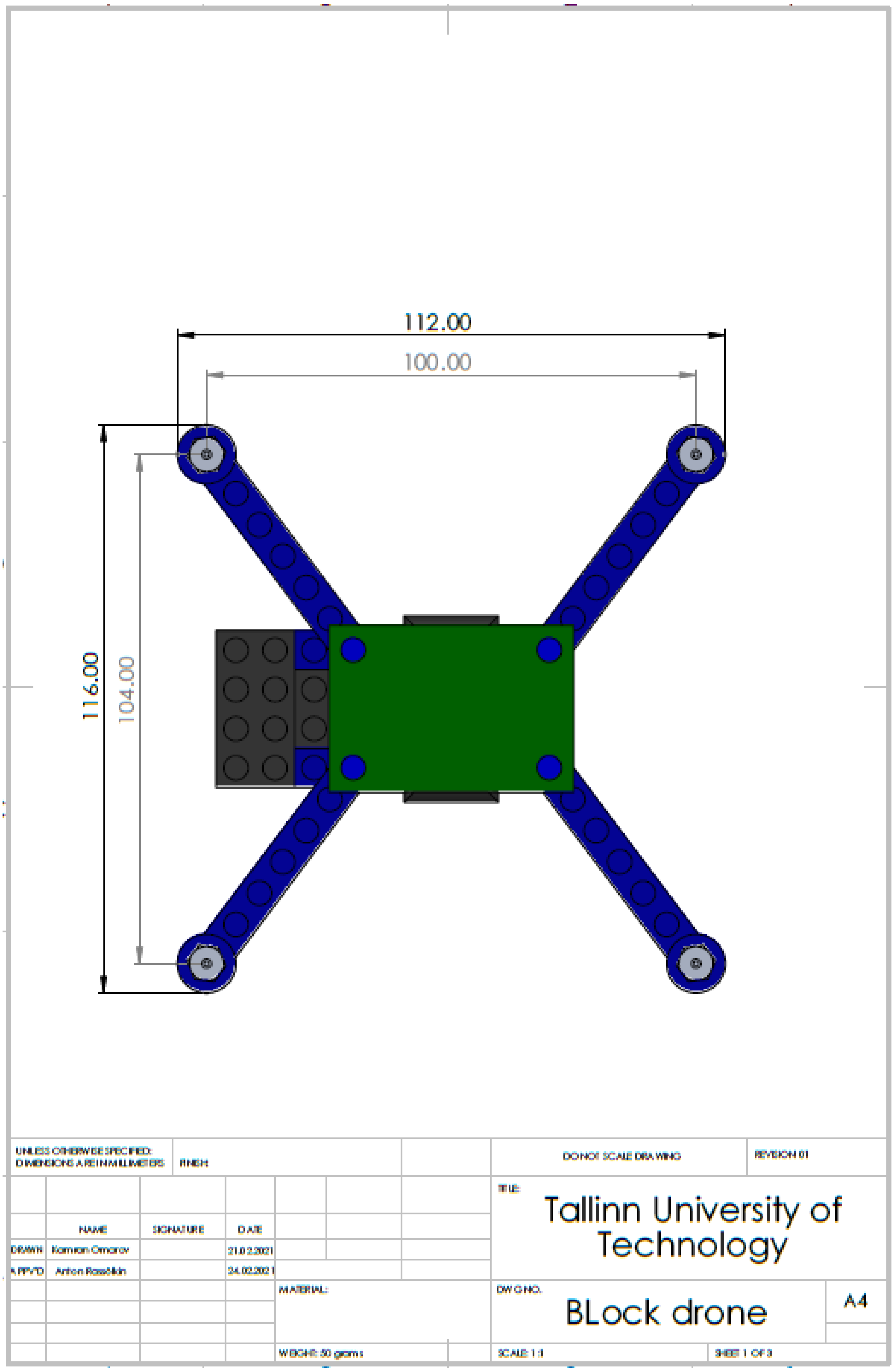
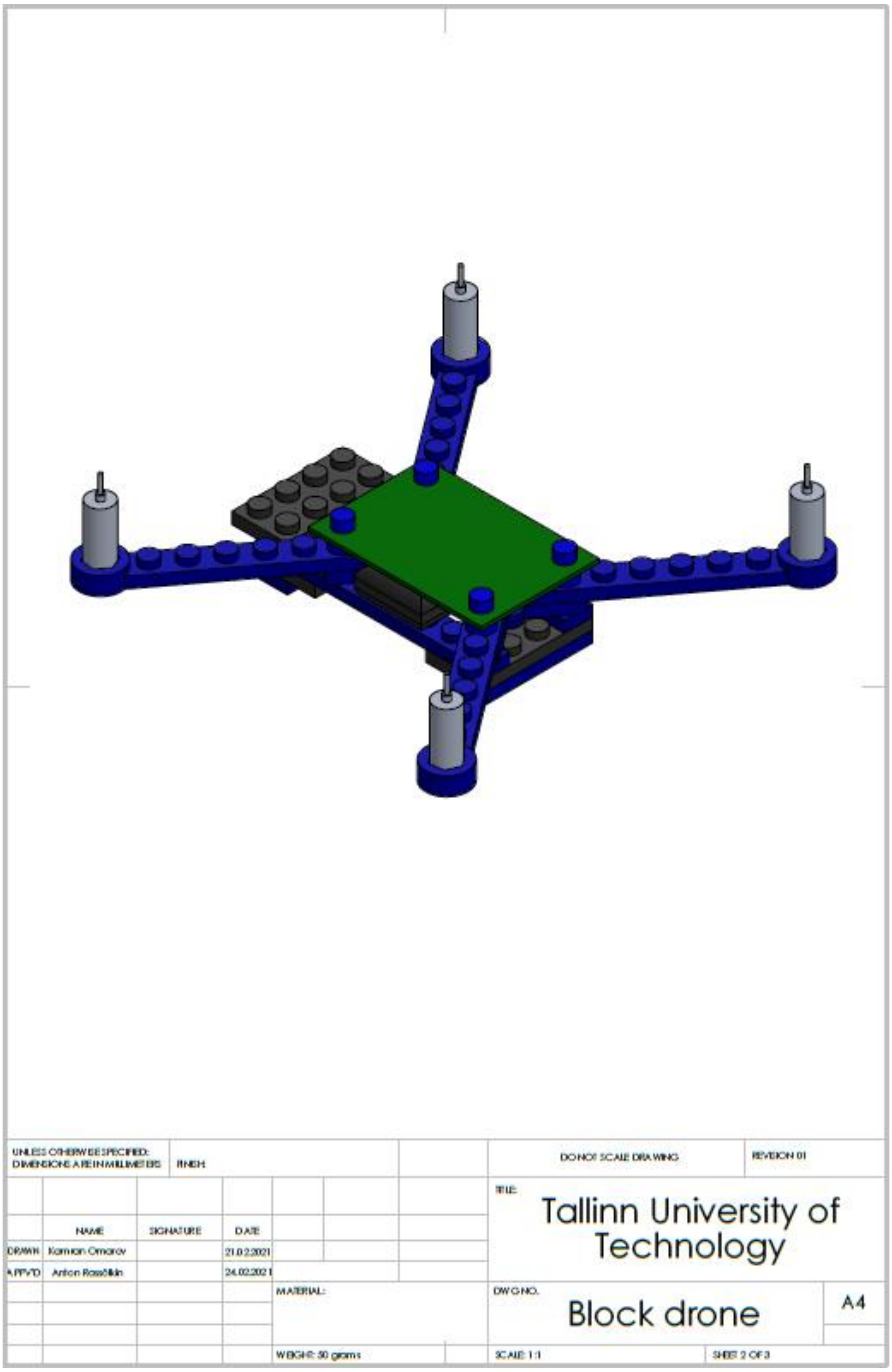
APPENDICES

Appendix 1. The solid model and part list of Block drone

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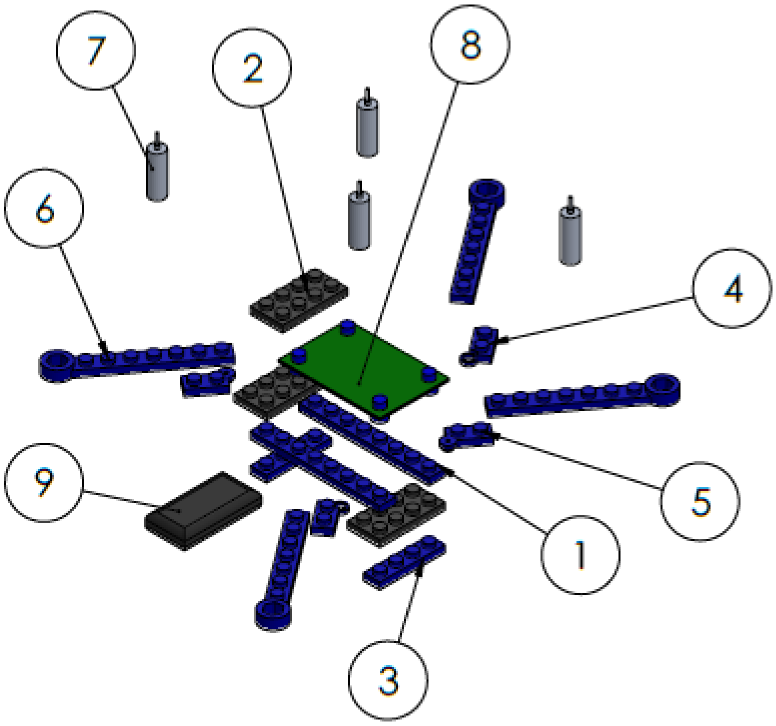
DIMENSIONS ARE IN MILLIMETERS
FINISH:
DO NOT SCALE DRAWING
REVISION 01
NAME
SIGNATURE
DATE
DRAWN
Kamran Omarov
21.02.2021
APPV'D
Anton Rassõlkin
24.02.2021
TITLE:
Tallinn University of Technology
MATERIAL:
DWG NO.
Block drone
A4
WEIGHT: 50 grams
SCALE 1:1
SHEET 2 OF 3

ITEM NO.	PART NUMBER	QTY.
1	Base long	2
2	Base wide	3
3	Base Short	2
4	Motor arm connector female	2
5	Motor arm connector male	2
6	Motor arm	4
7	Motor	4
8	Control board	1
9	Battery	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DO NOT SCALE DRAWING

REVISION 01

	NAME	SIGNATURE	DATE
DRAWN	Kamran Omarov		21.02.2021
APPV'D	Anton Rassõlkin		24.02.2021

TITLE: Tallinn University of Technology

MATERIAL:

DWG NO. Block drone

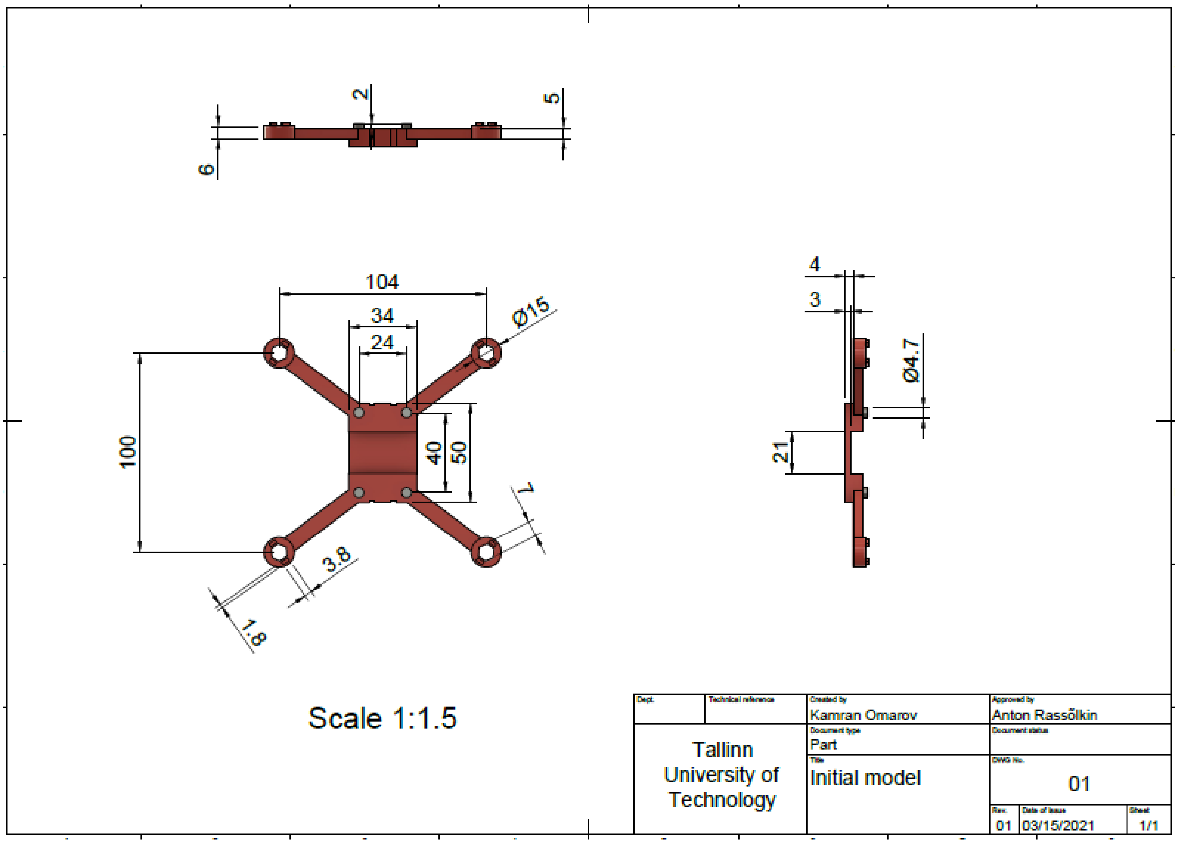
A4

WEIGHT: 50 grams

SCALE: 1:2

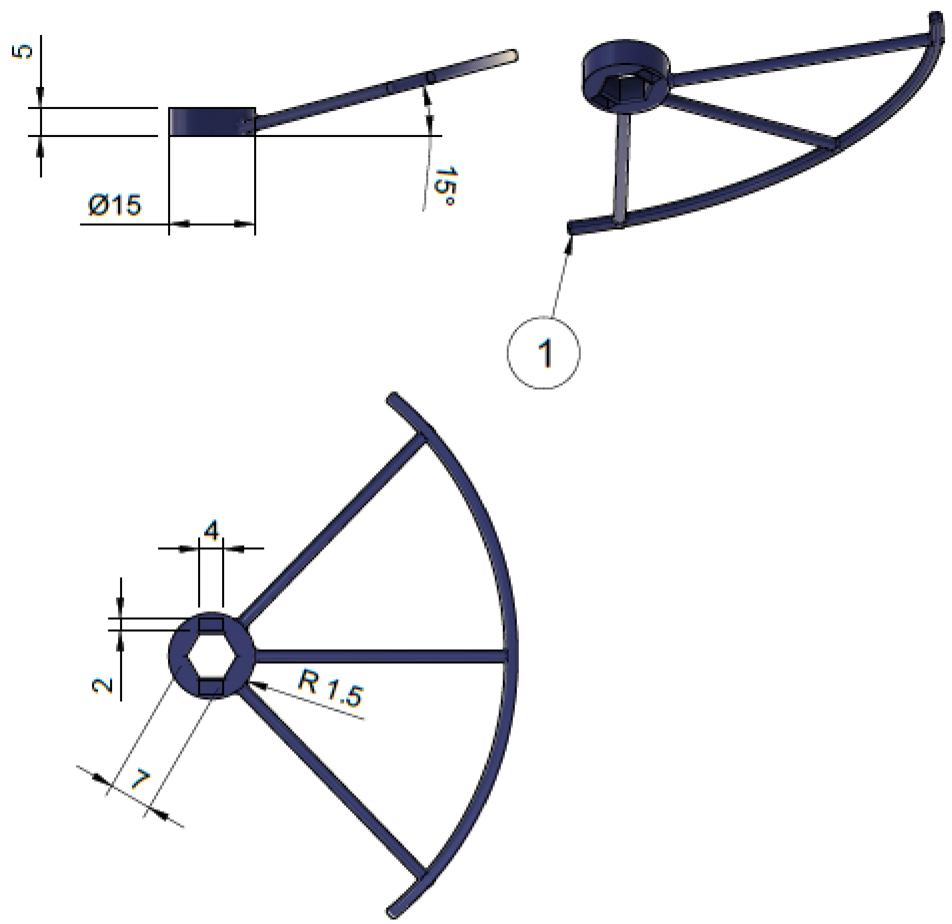
SHEET 3 OF 3

Appendix 2. Initial frame model



Appendix 3. Propeller guard 3D model

Parts List		
Part Number	Material	Mass
Propeller guard	PET Plastic	2.185 g

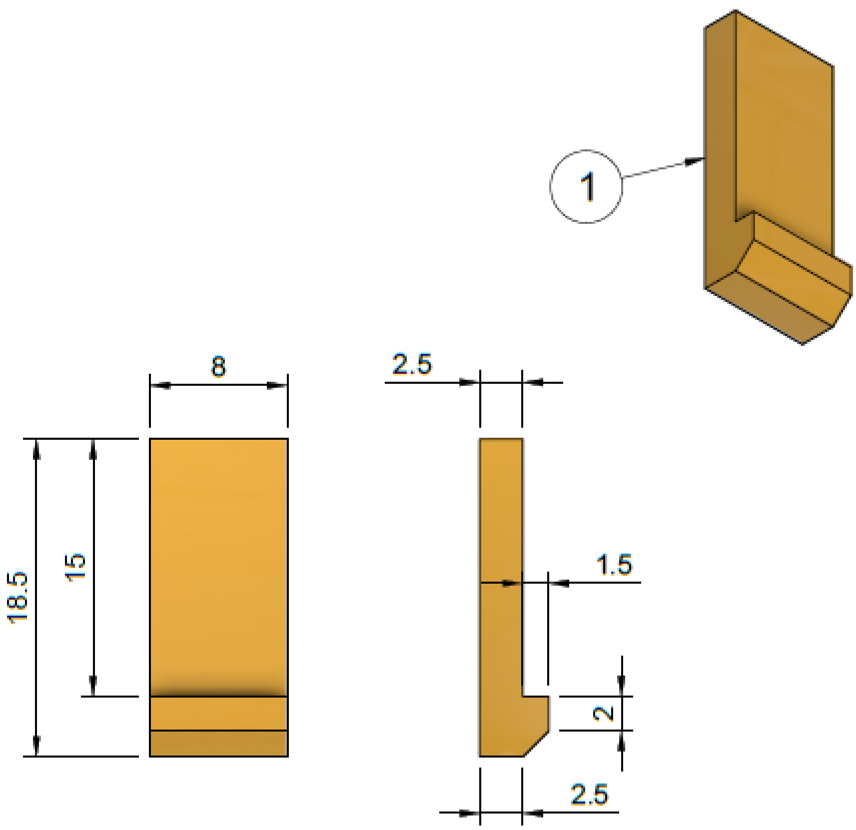


Dept.	Technical reference	Created by	Approved by
		Kamran Omarov	Anton Rassõlkin

Tallinn University of Technology	Document type: Part	Document status:
	Title: Propeller guard	DWG No.: 02
		Rev.: 01 · Date of issue: 04/09/2021 · Sheet: 1/1

Appendix 4. Snap-fit drawing

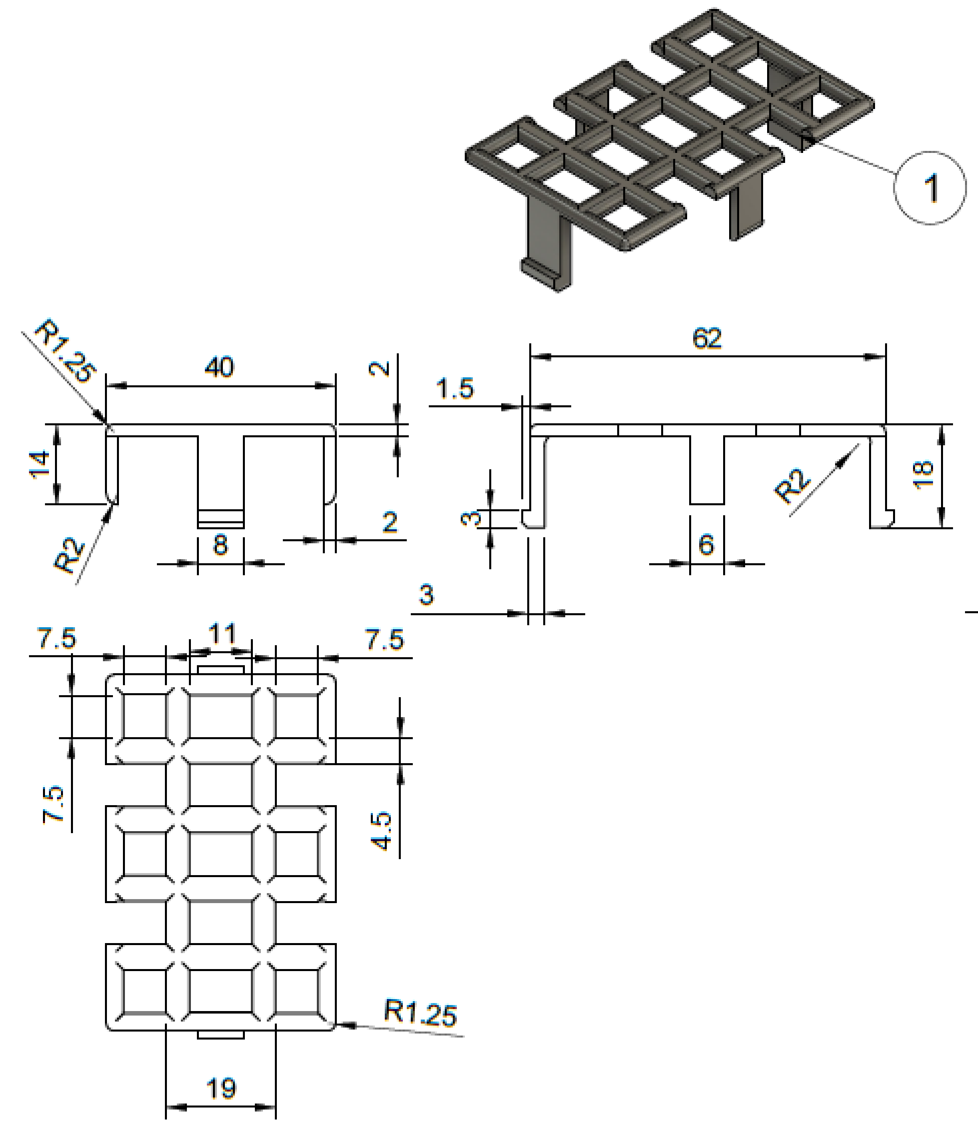
Parts List			
Item	Part Number	Material	Mass
1	Snap-fit	PET Plastic	0.621 g



Dept.	Technical reference	Created by	Approved by		
		Kamran Omarov	Anton Rassõlkin		
Tallinn University of Technology		Document type: Part	Document status:		
		Title: Snap-fit	DWG No.: 3		
			Rev.: 01	Date of issue: 4/14/2021	Sheet: 1/1

Appendix 5. Top cover with snap-fit

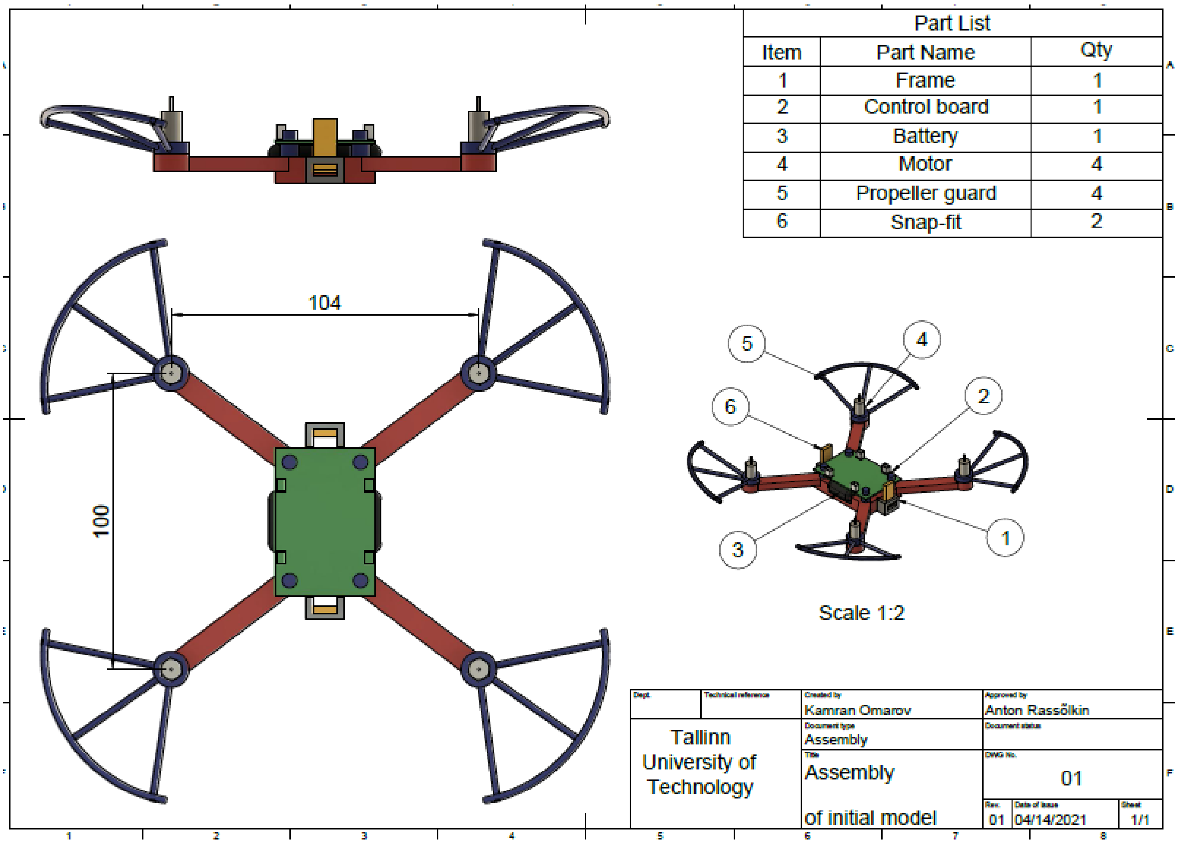
Parts List			
Item	Part Number	Material	Mass
1	Top cover with snap-fit	PET Plastic	5.538 g



Dept.	Technical reference	Created by	Approved by
		Kamran Omarov	Anton Rassõlkin

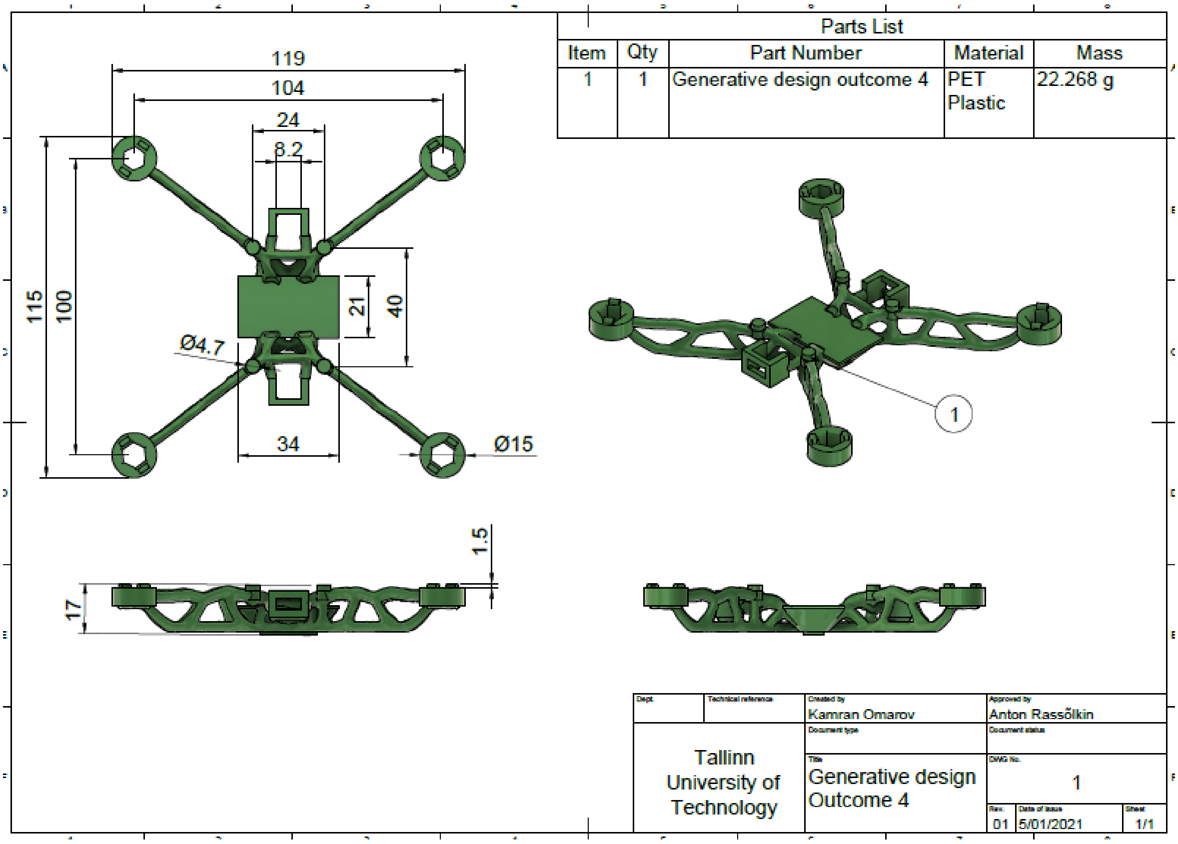
Tallinn University of Technology	Document type	Document status		
	Title: Top cover with snap-fit	DWG No.: 4		
		Rev.: 01	Date of issue: 04/15/2021	Sheet: 1/1

Appendix 6. Initial assembly drawing



Part List		
Item	Part Name	Qty
1	Frame	1
2	Control board	1
3	Battery	1
4	Motor	4
5	Propeller guard	4
6	Snap-fit	2

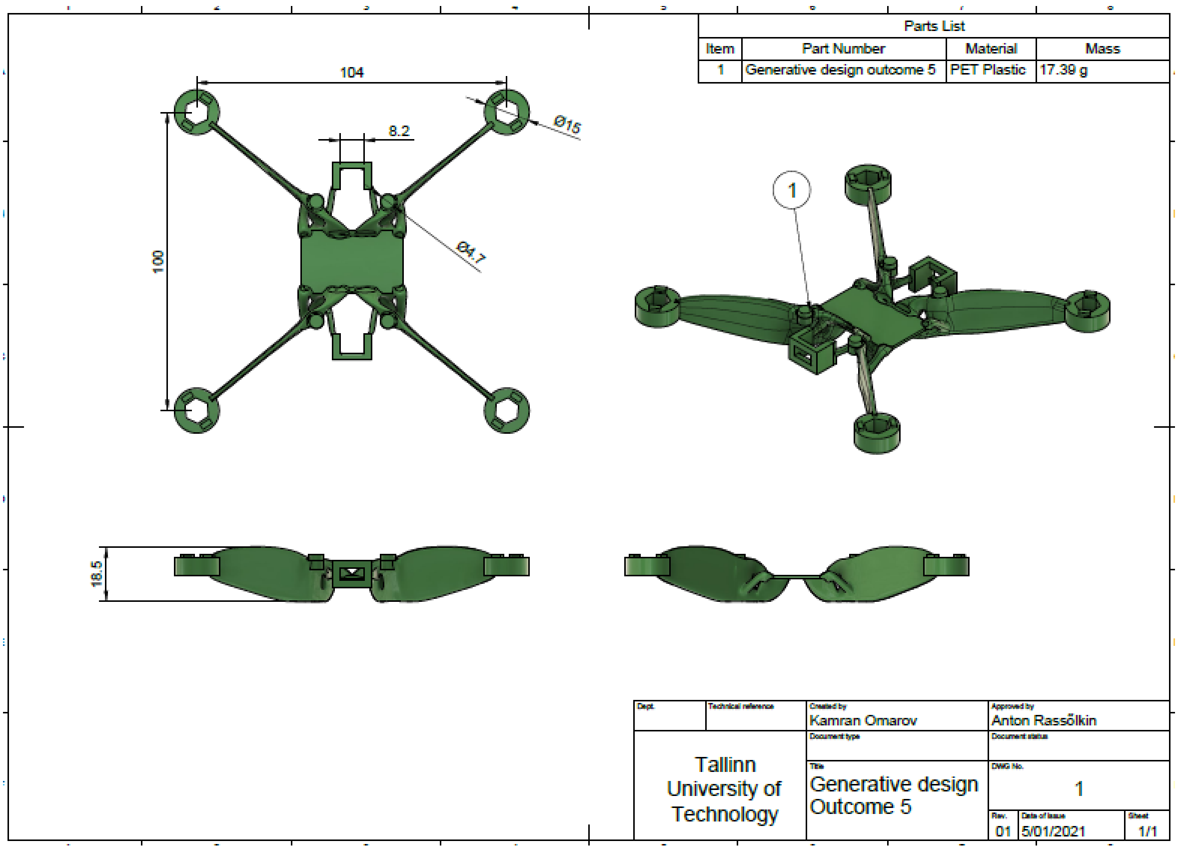
Appendix 7. 3D model and drawing of outcome 4



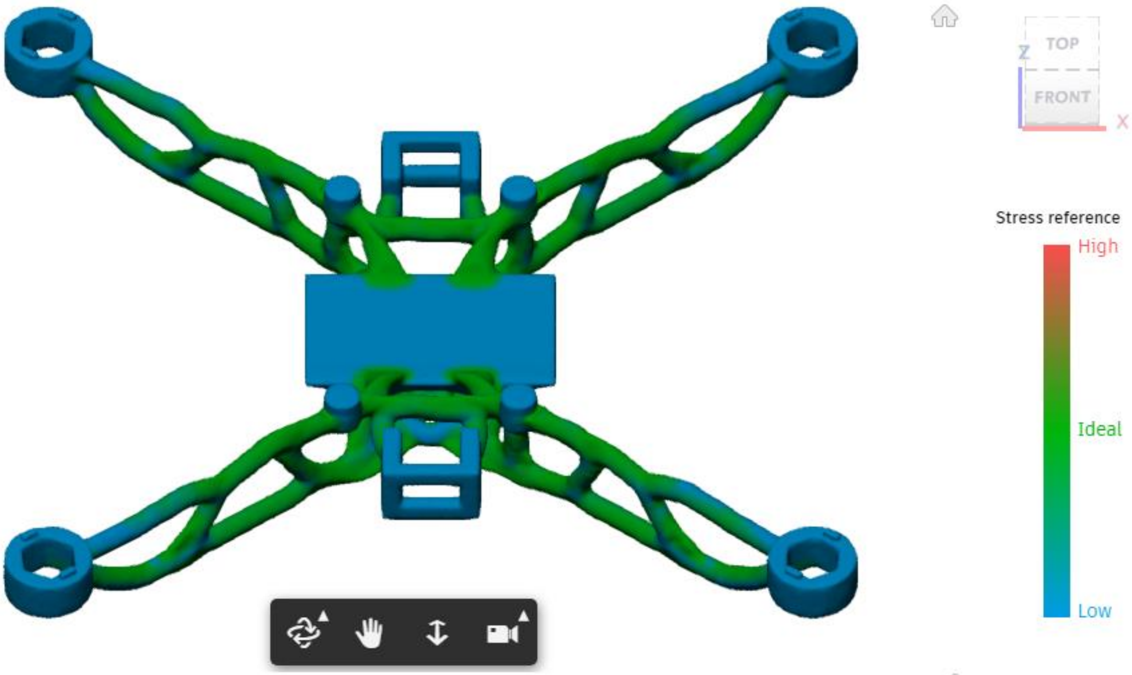
Parts List

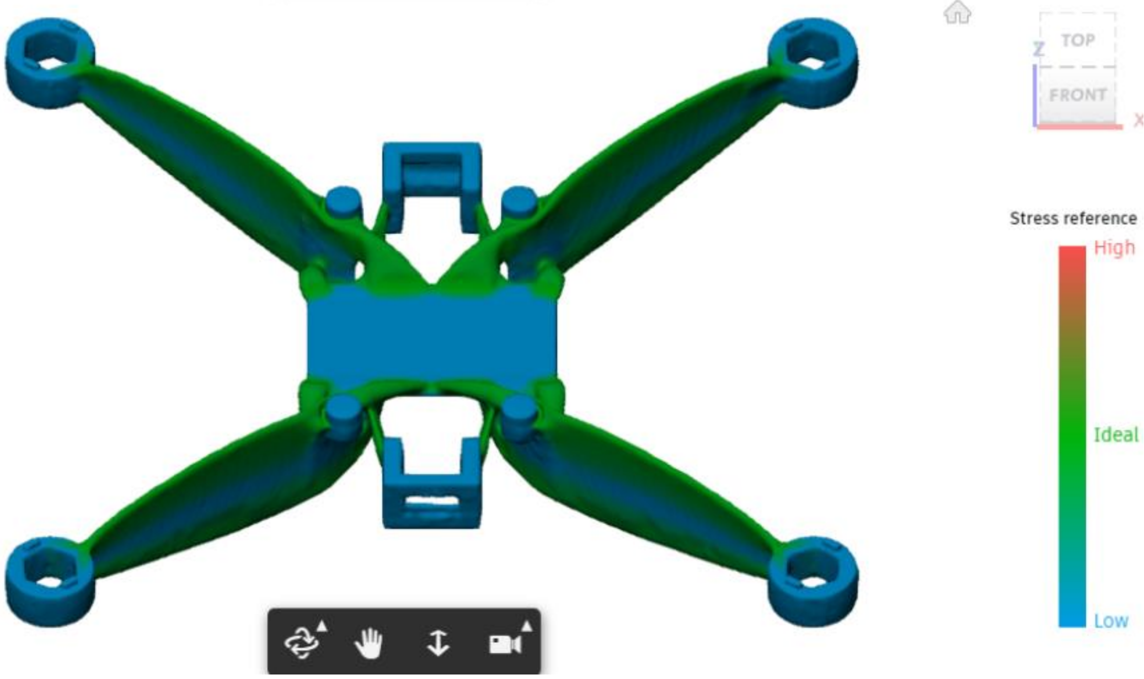
Item	Qty	Part Number	Material	Mass
1	1	Generative design outcome 4	PET Plastic	22.268 g

Appendix 8. 3D model and drawing of outcome 5



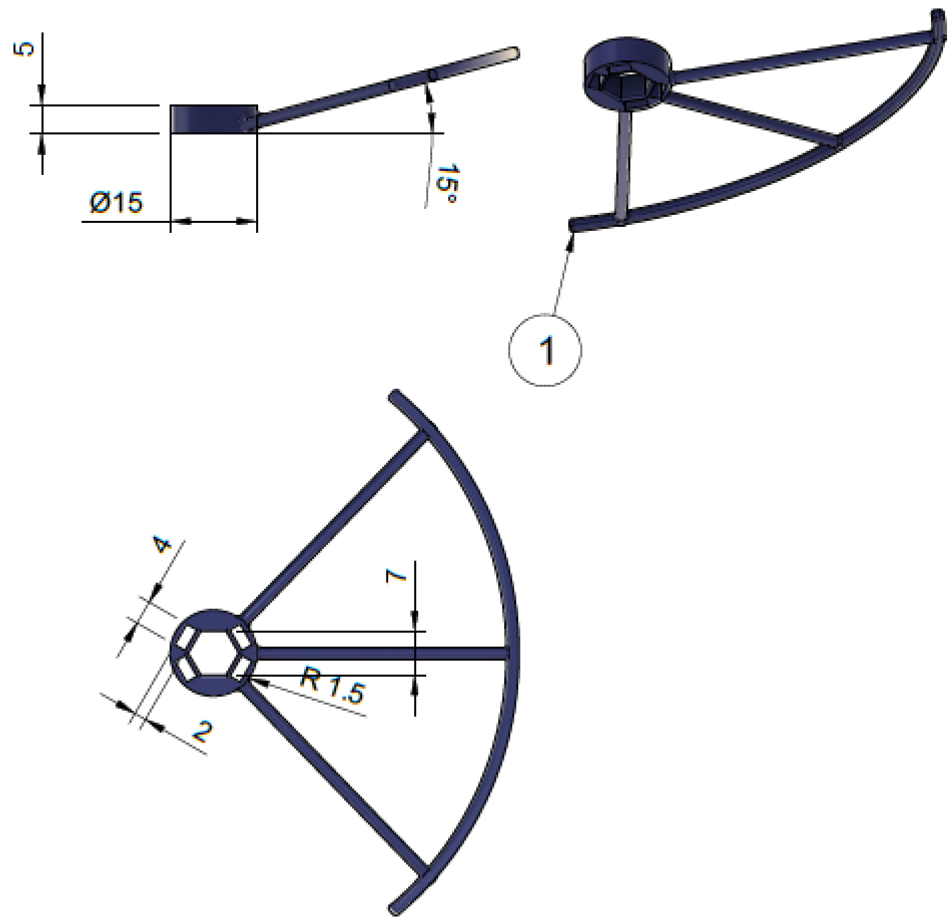
Appendix 9. FEA of chosen frames





Appendix 10. Propeller guard 3D model, Revision 2

Parts List		
Part Number	Material	Mass
Propeller guard	PET Plastic	1.97 g



Dept.	Technical reference	Created by Kamran Omarov	Approved by Anton Rassõlkin
Tallinn University of Technology		Document type Part	Document status
		Title Propeller guard	DWG No. 02
			Rev. 02 · Date of issue 05/10/2021 · Sheet 1/1

Appendix 11. 3D model and drawing of outcome 4, Revision 2