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

DEVELOPMENT OF DRONE PROTECTIVE CAGE

DROONI KAITSEVÕRE VÄLJATÖÖTAMINE

MASTER THESIS

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Tallinn 2022

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THESIS TASK

Student: Aleksei Poltoratski, 192575MAHM

Study programme, main speciality: MAHM02/18, Mechatronics

Supervisor: Lecturer, Kristjan Pütsep, 6203200

Thesis topic:

(in English) Development of Drone Protective Cage

(in Estonian) Drooni kaitsevõre väljatöötamine

Thesis main objectives:

1. Develop mechanical cage around the drone for protection
2. The proposed system suitable electronical components selection
3. Protective cage system control program creation

Thesis tasks and time schedule:

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1.	Literature review and introduction part	13.01.2021
2.	Design of the mechanical part	15.03.2021
3.	Controller overview and selection	20.03.2021
4.	Sensor system overview and selection	25.03.2021
5.	Electronic system programming	15.04.2021
6.	Proposed system testing, optimization	01.12.2021
7.	Updates in mechanical and electronical parts with additional components and their simulation	05.03.2022
8.	Preparing documentation for producing components used for frame assembly	15.04.2022
9.	Corrections and providing additional information of the developed protective system	06.05.2022
10.	Submission the thesis	18.05.2022

Language: English **Deadline for submission of thesis:** "18" May 2022.a

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CONTENTS

PREFACE

This thesis was proposed by the Department of Electrical Power Engineering and Mechatronics at Tallinn University of Technology. This system is an additional part of the safety system for the developed drone in Taltech.

The topic is actual as drone area is developing in the world. The situation with COVID-19 will have effect on this area. So the number of drones will grow. Due to this drone's protection from the effect of the collision and protection people from drones as well is very important nowadays.

I am very grateful for the opportunity to be involved in this area. It has a big potential for developing and will make a great contribution to the future of drones and their use.

Keywords: Drone, safety cage, system, obstacles detection, master thesis

List of abbreviations and symbols

- ABS - Acrylonitrile butadiene styrene
- BLE - Bluetooth Low Energy
- FMCW - Frequency modulated-continuous wave
- I/O - Input/output
- IP - Ingress Protection
- IR - Infrared
- PWM - Pulse width modulation
- KF - Kalman filter
- Li-ion - Lithium-ion
- ToF - Time-of-Flight
- TTL - Transistor-Transistor Logic
- UART - Universal asynchronous receiver/transmitter
- UAV - Unmanned aerial vehicle
- US - Ultrasonic
- WF - Weighted filter

1. INTRODUCTION

Nowadays the number of drones is significantly increased. Drones are being applied in wide area of applications like transportation, first aid, journalism, recreation, and military. Also, they are widely used for commercial and academic purposes.

The flight control of drones is not so easy task. It is needed to have more knowledge and practise to control. Very often happens that person tries to use drones inside of buildings where is less space and a big number of obstacles. As a problem, it is difficult to fly indoors. All this can lead to crash of drone. Of course, the developers of drones try to make control systems, motors, sensors, and software as reliably as possible, but the risk of crashing the drones remains.

In addition, unshielded spinning propellers can cause serious threat to injure and damage with people or obstacles. Only limited types of protection are available for drones. However, these types do not perform total protection. The main purpose of this master thesis is to design and develop a protective system for a drone to reduce the effects of collision with obstacles.

A robust collision prevention system is the next step towards more autonomy for the drone. Thus, the use of the drone expands and at the same time reduces the requirements for the skills of the pilot. Collision prevention is an ode to drone development, which is very interesting for research.

The field of using drones is significantly wide. This solution will be interesting not only for new users of drones but for professional users, companies that use them to reduce damage as well. Cages are a great option for users who are looking to take extra security so that their drone's propellers cannot hurt anyone. Unfortunately, a heavy cage leads to a shorter flight time. The extra weight of the extra cage will usually reduce the drone's battery life by about 50%. This is important point when additional cage are mounted on the drone.

Most drones that can be equipped with third-party cages require that the user turns off obstacle detection in order to fly with the cage. This is not good for using, especially if the user plans to use the cage to fly in a confined space. This safety system is designed to protect the drone when performing low speed manoeuvres in tight, confined, hazardous and hard-to-reach indoor spaces.

The main aim of this thesis is to develop the system which can reduce the effect of the collision with obstacle. For this purpose, the following steps will be taken:

1. Literature review of existing solutions.
2. Design of the mechanical part.
3. Sensor's selection.
4. Controller selection.
5. Electronic system programming.
6. Prototype testing, optimization.

Chapter 1 is an introduction chapter that describes the field of the research, the reason of solving this problem and the current situation in this area.

Chapter 2 gives an overview of the existing solutions of the safety systems of the drones, technologies which can be used to produce this system. It is given a brief explanation of working principle of obstacle detection sensors. The analyse existing solutions of cages is used to describe a potential solution of the proposed safety system.

Chapter 3 focus on the detailed explanation of the mechanical part of proposed drone cage. In this chapter is shown all steps of creation frame, box for electrical components and holders for lidar sensors. Also were done stress analyses of the frame in different conditions.

Chapter 4 is focused on the electronic system. Components are selected for program control, obstacle detection, frame rotation. Also important point of this system was communication between the developed system and user device. In addition, were made energy consumption by components.

Chapter 5 describes the way of obstacle detection by lidar sensors. Second point is the rotation of the cage by servomotor.

Chapter 6 describes the simulations which were done during this thesis. For this purpose were used simulation software.

Chapter 7 describes total cost for the new proposed system and proposes future developments for this system.

2. LITERATURE REVIEW AND BACKGROUND

2.1 Obstacle detection

Obstacle detection is a complex problem that has received a lot of attention. There are a number of obstacle detection technologies. Some of these techniques include ultrasonic, passive infrared, laser radar, impulse radar, frequency modulated-continuous wave (FMCW) radar, capacitive and vision-based video. The obstacle detection and collision avoidance systems can be created using combined types of sensors. For example, drones' producers use different sensors in their products [2]:

- Stereo vision sensor
- Ultrasonic sensor
- Time-of-Flight
- Infrared sensor
- Lidar sensor

Although there are different types of sensors available in the market, but they can all classified as **active** or **passive** sensors depending on the principle of their functionality. Active sensors have their own source which transmits light or emits a wave and read the reflected back-scatter. On the other hand, passive sensors only read the energy discharged by the object, from another source e.g. sunlight, reflected by the object [2].

Collision avoidance actions can be divided into four main approaches: **geometric**, which uses information about the location and velocity of the UAV and obstacles, usually by modelling trajectories, to perform a node transformation to avoid the collision, **force-field** in which the forces of attraction/repulsion are controlled to collision avoidance, **optimised** through which the already known obstacle parameters are used to optimise the route, and **sense and avoid** with the help of which collision avoidance decisions are made at the runtime based on obstacle detection (Figure 2.1) [2].

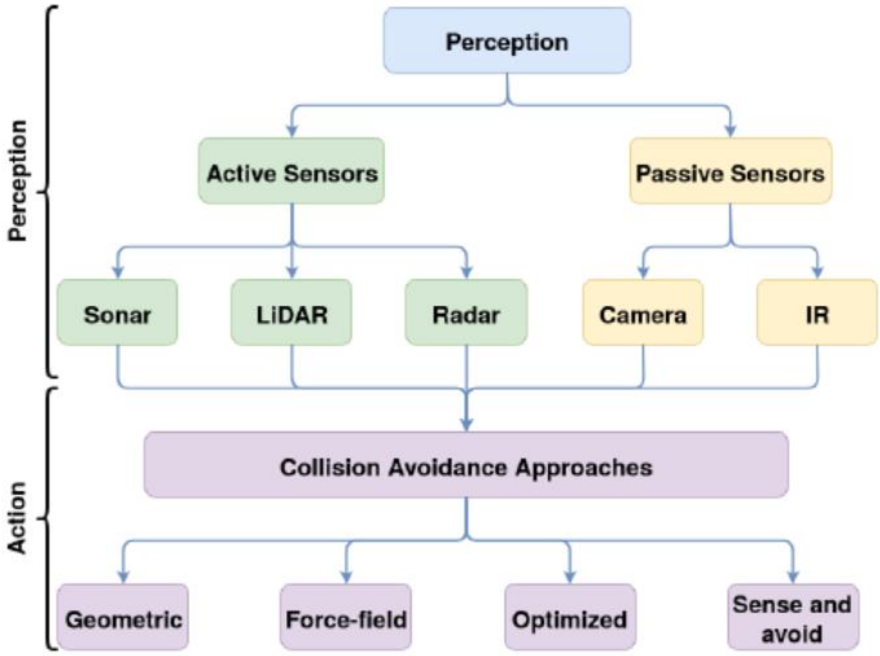


Figure 2.1 Collision Avoidance System Generalised Modules [2]

To detect obstacles, the drone must be able to sense its surroundings and environment (Figure 2.2). For this, it needs to be equipped with one or more sensors that act as a perception unit. Passive sensors can detect the energy discharged by the objects or the scenery during the observation. Most of the passive sensors that are used to identify different objects are optical or visual cameras, thermal or infrared (IR) cameras, and spectrometers [2].

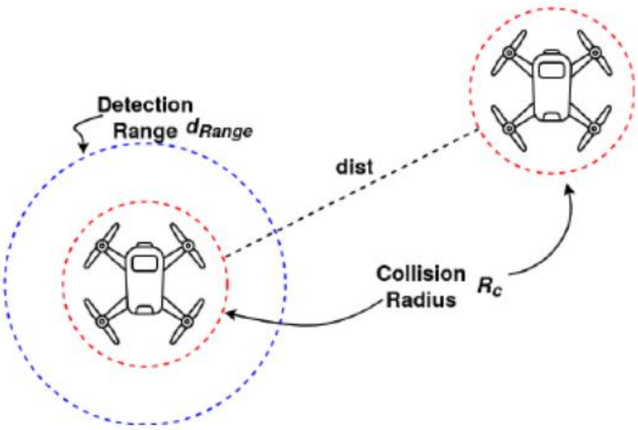


Figure 2.2 Detection Range (d_{Range}), Collision Radius (R_c) and distance between them [2]

Active sensors work by emitting radiation and reading the reflected radiation. An active sensor has its own transmitter (source) and receiver/detector. The transmitter emits a signal that can be in the form of e.g. a light wave, an electrical signal, or an acoustic signal. Then this signal is reflected from the object, and the receiver of the sensor reads the reflected signal. Examples of ranging sensors are: LiDARs, radars, sonar or ultrasonic sensors and active infrared sensors. These sensors are fast in response, require less processing power, can scan larger areas quickly, are less affected by the weather and lighting conditions, and can accurately return the obstacle parameters of interest, such as distance and angles (Table 2.1) [2].

Table 2.1 Sensor attribute comparison for Obstacle Detection: short (0-100 m), medium (100 - 1000 m), long (> 1000 m) [2]

Sensor	**Mode**	**Accuracy**	**Weather Condition**	**Range**	**Sensor Size**	**Power Required**
LiDAR	Active	High	Low Dependency	Medium	Small	Medium
Radar μ-wave	Active	High	Not Dependent	Long	Large	High
Ultrasonic	Active	Medium	Partial Dependency	Short	Small	Medium
Thermal or IR	Passive	Medium	High Dependency	Medium	Small	Low
Camera	Passive	Medium	High Dependency	Short	Small	Low

Another solution is to use color-based image sensors. A laser transmitter was used to project a high contrast tracking spot to calculate depth using conventional triangulation. The color discrimination point acts as a reference point for image tracking and depth calculations. Color filtering is used to distinguish the projection of a laser beam from an obstacle [3].

2.1.1 Stereo vision sensors for obstacle avoidance

The working principle of stereo vision works similarly to 3D sensing in human vision. Combining 2D images from two cameras at slightly different viewpoints can be calculated in stereoscopic vision. The same point observed by multiple cameras are identified in image pixels. Using the triangulation from each camera the 3D position of a point can be selected (Figure 2.3) [4]. One of the main tasks in stereo imaging is the problem of matching: for a given point in one image, how to find the same point in an image from another camera? Until a match is established, the difference, and therefore the depth, cannot be accurately determined. The solution to the problem of finding a match includes complex, computationally expensive algorithms for selecting elements and matching them. Selecting elements and matching them also requires sufficient intensity and color variability in the image for robust correlation. This requirement makes stereo vision less effective if objects do not exhibit such variability.

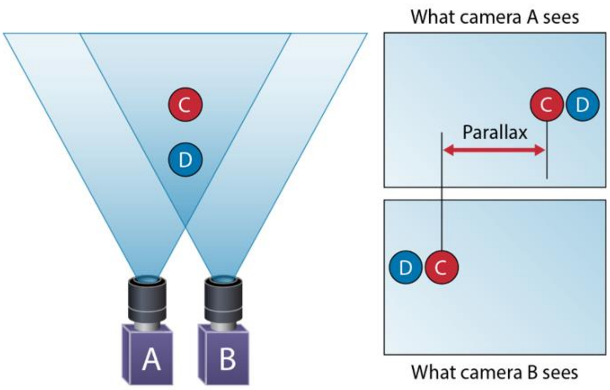


Figure 2.3 Stereo vision sensor setup. View of objects according to the camera position (A, B). D, C points [5]

2.1.2 Ultrasonic sensors for object detection

Ultrasound is one of the most widely used technologies due to its low cost compared to other technologies. Ultrasonic and infrared sensors find many applications for measuring distance at medium distances. Ultrasonic sensors can detect even small and hard to detect obstacles such as tree branches or cables at high frame rates, as well as transparent obstacles such as windows [6]. For example, ultrasonic sensor HC-SR04 can detect obstacles best in 30-degree angle (Figure 2.4).

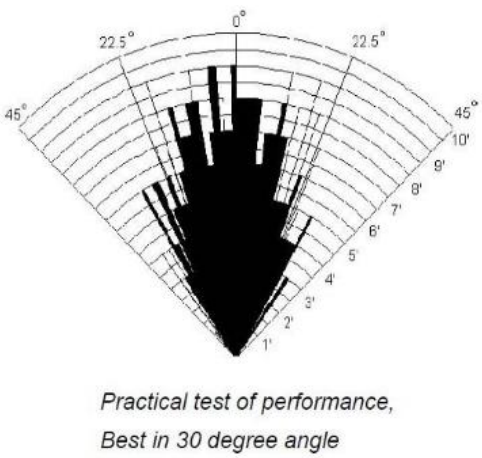


Figure 2.4 Ultrasonic sensor HC-SR04 detection performance. Best performance angle 30-degree [7]

An ultrasonic distance sensor determines the distance to an object by measuring the time it takes to display a sound wave from the object. The frequency of the sound wave is within the frequency of ultrasound, which provides a concentrated direction of the sound wave since sound with a high frequency is less scattered in the environment.

A typical ultrasonic distance sensor consists of two membranes, one of which generates sound and the other records the displayed echo. The sound generator creates a small ultrasonic pulse with a certain period and starts the timer. The second membrane registers the arrival of the displayed pulse and stops the timer. From the time of the timer by the speed of sound, it is possible to calculate the distance travelled by the sound wave. The distance of the object is approximately half the distance travelled by the sound wave.

2.1.3 Time-of-Flight (ToF) sensors for collision avoidance

A Time-of-Flight camera consists of a lens, an integrated light source, a sensor and an interface. This technology allows you to capture depth and intensity information simultaneously for each pixel in the image. This makes it quite fast with a high frame rate. The ToF sensors also record depth independently. This makes it easy to create obstacle avoidance algorithms. The advantage of ToF cameras is high accuracy [4]. The Time-of-Flight sensor, which works with reflected light, is also distance sensitive. However, for ToF, this disadvantage, if necessary, is eliminated by increasing the illumination energy.

The principle of working: the ToF camera uses a pulse or continuous wave light source to cover the whole scene including objects, and then observing the reflected light. All this is done for measuring the time of flight of the pulse from the emitter to the object and the time to back when pulse reflects from the observed object (Figure 2.5). Using the value of the speed of light, the distance between the camera and obstacle can be calculated. It is the fastest technology for getting 3D information [9].

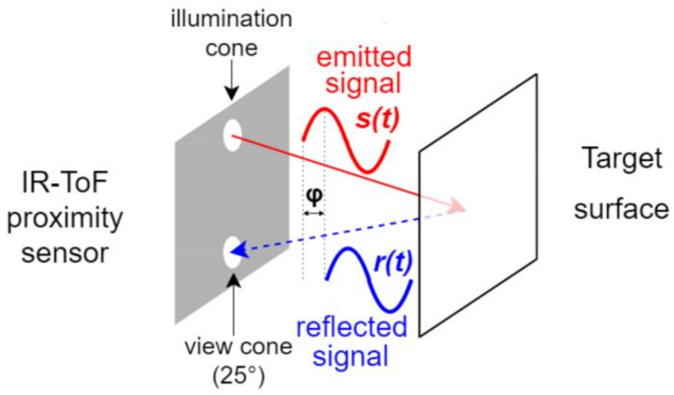


Figure 2.5 The Infrared Time-of-Flight proximity sensor (IR-ToF) provides the distance estimate from the target reflecting surface by measuring the phase shift φ between the emitted s(t) and the reflected r(t) signals [9]

2.1.4 Infrared sensor for obstacle detection

Another sensor which is used for obstacle detection is infrared (IR) sensor. The principle of working for detecting obstacles is based on the infrared reflection. This type of sensor consists of an infrared transmitter, an infrared receiver and a potentiometer. Considering the reflecting character of the obstacle, the object can be detected. In case there is an obstacle, the infrared ray faces with it and the ray will be reflected back to the infrared receiver. Then the infrared receiver detects this signal and confirms that obstacle is detected. If there is no obstacle, the emitted infrared ray will disappear at distance [4].

Infrared detectors work with a specific frequency. It is produced by the emitter, object from which signal was reflected and the receiver. All parameters are used to prevent confusing sensor by the light. The emitter and receiver selected with optimal sensitivity. [4].

The example of the infrared (IR) sensor is Sharp GP2Y0A02YK0F. The measuring distance range is 20 – 150 cm. The measuring is provided by a reflected ray of infrared light. Moreover using triangulation for the distance calculation, this sensor is less influenced by surface reflectivity, operating time and temperature [4].

2.1.5 Lidar for obstacle detection

For obstacle detection the lidar sensor can be used as well. One of the famous sensors in the list of sensors is the Velodyne Lidar. This type is used in the Google driverless cars. Into this sensor is combined multiple laser and detector. It can pulse at 20 kHz. This frequency allows for measurements of up to 1.3 million data points per second. Each of these measurements or results can then be converted into a 3D visualization, which is a point cloud.

It works similarly to radar and sonar but uses light waves from a laser instead of radio or sound waves. The lidar system calculates how long it takes for light to hit an object and reflect back to the scanner. Distance is calculated using the speed of light. [4]. The advantages of lidar are smaller size (can be installed anywhere), high angular resolution (about 180°), significant range (up to 250 m). At the same time, the laser radar is sensitive to changes in the road topography (rays can be reflected from the road surface and distort information). The efficiency of the lidar decreases in bad weather conditions (rain, snow, fog), as well as when the sensor becomes dirty.

2.2 Sensor's location

One of the ways for detecting obstacles is using combined types of sensors: low-cost ultrasonic and infrared sensors. IR sensors are much cheaper, but they are noisier than more expensive sensors, for example, laser scanners. The drawback of IR sensors is the impossibility to work in low light conditions like smoke or fog. Moreover, sensors cannot detect transparent obstacles. On the other hand, ultrasonic sensors do not have such disadvantages. However ultrasonic sensors cannot properly detect sound absorbing surfaces. At the same time, US sensors are not able to detect people on the not available distance from them [1].

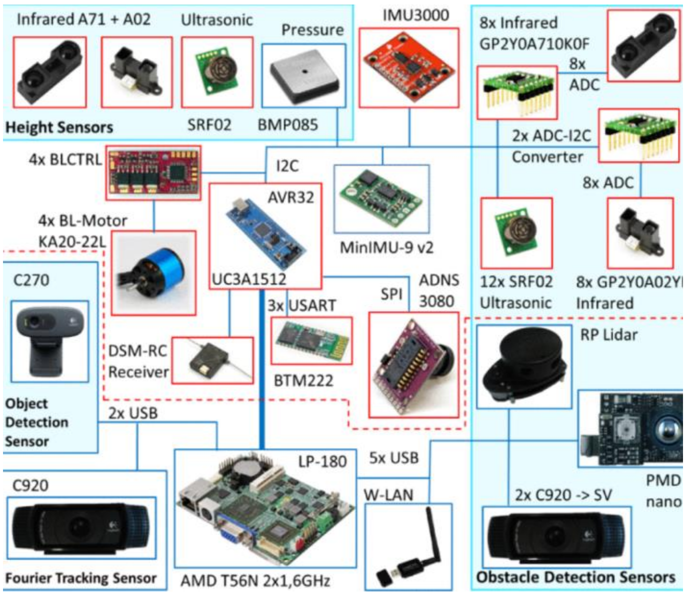


Figure 2.6 Hardware architecture of AQopterI8 [1]

In AQopterI8 project are used for obstacle detection 16 infrared sensors and 12 ultrasonic sensors (Figure 2.6). It covers 360° around the drone. In this research is used two types of sensors. The purpose is to increase the measuring range using these sensors (Figure 2.7). The weighted filter (WF) is used to obtain the best possible result of multiple sensors. The reliability of sensors can be represented as calculation of a weight for each sensor. The advantage of WF is easy design and realisation. In addition, it has a low counting load, in contrary to a Kalman filter (KF). WF is very adaptable to measurement jumps such as distance breaking of sudden obstacles, but a KF just minimizes the noise [1].

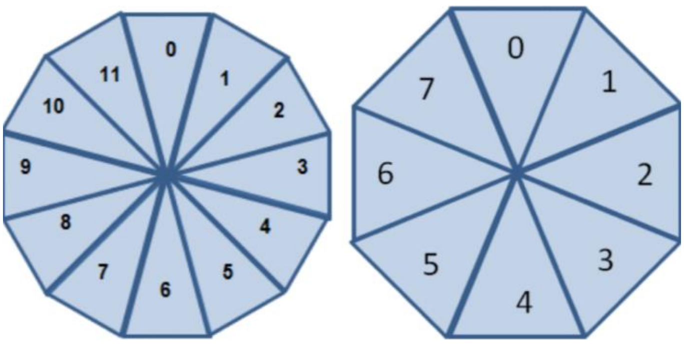


Figure 2.7 Left: the 12 ultrasonic sensors position around the drone. Right: 2×8 sensors position around the drone [1]

In a project was used a combination of ultrasonic (US) and infrared (IR) sensors. It was performed to obtain a reliable data on the detection range of obstacles [12].

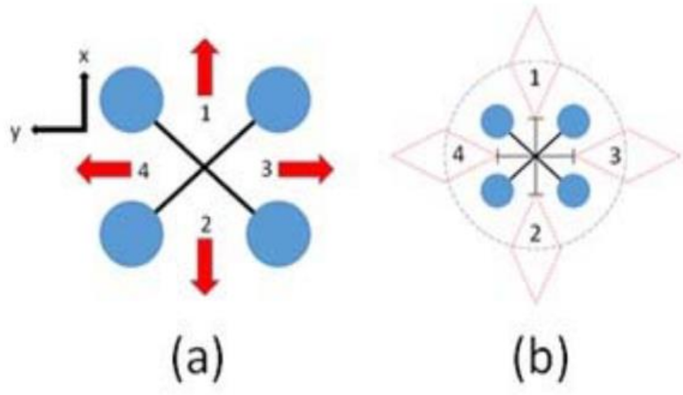


Figure 2.8 (a) Four primary flight directions; (b) Sensor location and obstacle detection directions [12]

As it was mentioned in the research papers earlier research of low-cost collision avoidance systems relied solely on one type of sensor, namely infrared and ultrasonic sensors, to detect obstacles. However, the range measurement of infrared sensor is influenced by light intensity of the environment and the reflectivity of surface of the measured objects, while the ultrasonic sensor is influenced by the type of material of the measured object. The level of interference in the environment, as well as cross interference when multiple sensors are used. A pair of infrared and ultrasonic sensors were installed between the arms of the quadcopter in four main directions (Figure 2.8) [12].

2.3 Mechanical cage solutions

The potential use of drones is widely spread, but the conditions of flying are still a challenge. To date, research on adapting drones to a cluttered environment has been carried out in two different directions: a) obstacle detection and avoidance and b) mechanical impact resilience. Traditional approaches have mainly focused on obstacle avoidance by using sensors [13].

Alternative method for protection is the mechanical resistance. The principle is not to avoid collisions, but to deal with them. This method can be additional to already existing protection. Usually drones unable to continue flight after a collision with the obstacle. A collision leads to loss of the flight control and it is a cause of a drone crash. Traditional drones do not have any impact resilience systems which can reduce the effect of collision. The missing of this system can cause not only the damage components of drone, but can lead to unstable flight, which is dangerous for people around the drone [13].

To improve flight safety and to expand the field of application where is a high probability of collision with obstacles. For solving these problems concepts were designed. However, these concepts are heavy and massive. All this leads to decreasing the flight time and the ability of flying in constrained and narrow places [13].

In research paper a new concept of passive safety system was presented. The proposed solution consists of a special parachute and an airbag attached to the UAV. The authors focus on the airbag development process. A decisive role in predicting the response of impacting object plays a gas leakage that is caused by fabric porosity or vents located on airbag surface (Figure 2.9) [14].

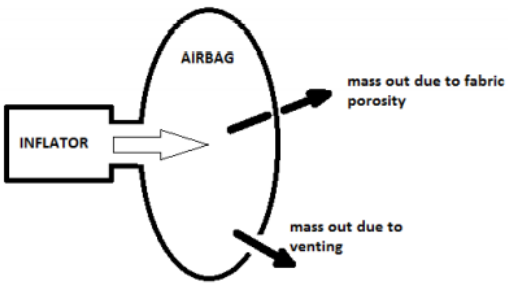


Figure 2.9 Schematic illustration of the gas leakage from the airbag through the fabric porosity and venting [14]

The purpose of applying the parachute is to protect UAVs in case of failure at high altitudes. The airbag is a suitable device when the use of a parachute is not possible, when the altitude of the object is lower than the threshold value. The use of an additional airbag in the UAV safety system significantly reduces the range of dangerous heights. It combines the advantages of a parachute and a special airbag design to protect an additional device moved by a flying object [14].

In another research was proposed a passive foldable airframe. The origami-inspired manufacturing paradigm is a way of mechanical protection which is designed. In case of an accidental collision in the middle of the flight, the deformable airframe is mechanically activated (Figure 2.10) [15].

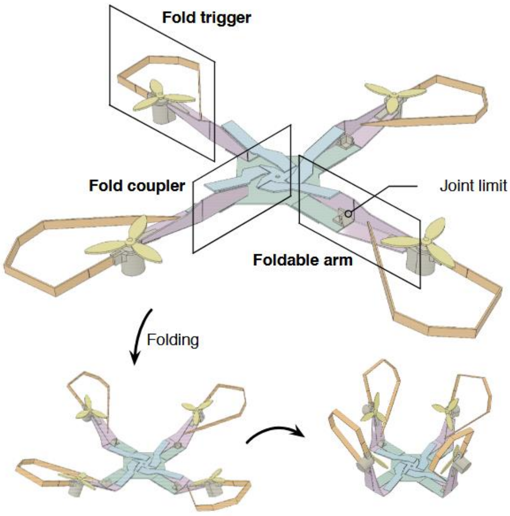


Figure 2.10 An illustration of the three major components (foldable arm, fold coupler, and fold trigger), joint limits, and the folding sequence [15]

Different studies have suggested different ways to manage collisions. At the moment, one way is to reduce the impact of the collision, to maintain stability during the flight and not lead to the destruction of the drone. For this can be used a protective frame that absorb impact collision. This impact rotates the fold trigger to push part of the arms. But this proposed mechanism does not protect the robot from top or bottom collisions [15].

The cage provides an all-round protective structure that physically separates the propellers from the environment. Traditional origami structures are composed of tiles joined by folds. In the cage, tiles are replaced by spacers connected by flexible joints to create a spatial structure that does not obstruct the airflow generated by the enclosed propellers (Figure 2.11). The cage has a modular design consisting of repeating multiple foldable segments. Each segment is the result of a tessellation of congruent isosceles triangles where the edges are spacers and the vertices are flexible joints. The spatial structure of the cell is obtained by connecting the free ends of several segments forming the upper and lower joint. The cage can be folded by pushing the first and the last segment apart. The upper and lower central joints become closer together, resulting in a folded polygonal cage shape [16].

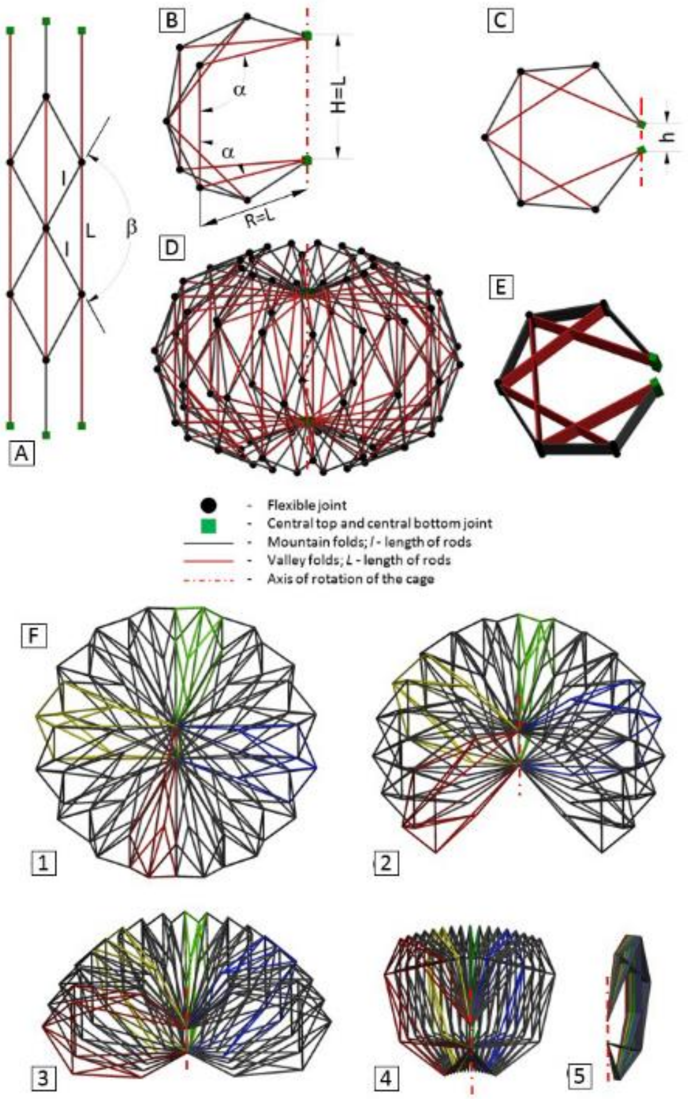


Figure 2.11 A) Top view of the flat pattern of one segment. B) Segment in deployed stage. C) Shape of the folded segment. D) Cage in the fully deployed state. E) Fully folded cage in an isometric view. F) Folding process [16]

The cage is made of carbon-fiber tubes connected by soft joints that are 3D printed using flexible material. The flexible joints provide smooth folding without affecting the cage rigidity when deployed, thanks to the strength of the carbon-fibers tubes. The rigidity of the cage is mandatory to prevent unwanted vibrations during flight, which can destabilize the drone. The central top and bottom joints of the cage are composed of a 3D printed flexible strip and multiple connections for the tubes. This part takes the shape of a hollowed cylinder when the cage is deployed and is flattened when the cage is folded. This design prevents collision of the tubes during folding and allows to achieve a flat configuration of the edges of the cage when folded [16].

2.4 Conclusion

There are many researches made to detect and avoid obstacles and to make mechanical impact resilience. Traditional approaches have mainly focused on obstacle avoidance by using sensors. Mechanical resistance is an alternative approach to impact protection.
A combination of sensors can be used to increase the measuring range. From the mechanical point of view it is not convenient to use airbag solution due to disposable use. Alternative way to use the origami-inspired manufacturing paradigm. It provides an all-round protective structure, consisting of repeating multiple foldable segments.

After the analysing of existing solutions in literature, the problems which will be solved in this thesis can be defined as following:

- Such safety system which can open safety cage around the drone when detects obstacles has not been developed yet.
- Automatic cage opening mechanism has not been done before.
- The analyses of existing solutions in research papers missing.
- As it is planned to develop a design for new solution, the problem is how to develop such system which is safety, cheap and that will work properly.
- The solution for sensors placing when safety cage is opened, and its proper performance is missing.

All these problems are expected to be solved in this thesis.

3. PROPOSED SOLUTION FOR FRAME CONSTRUCTION

3.1 Design of mechanical part

The solution of this cage can be implemented for different types of drones. Depending on the size of drone the safety cage can be changed and updated according to the drone size. For this thesis as the base was taken drone from Taltech researchers' group (Figure 3.1).

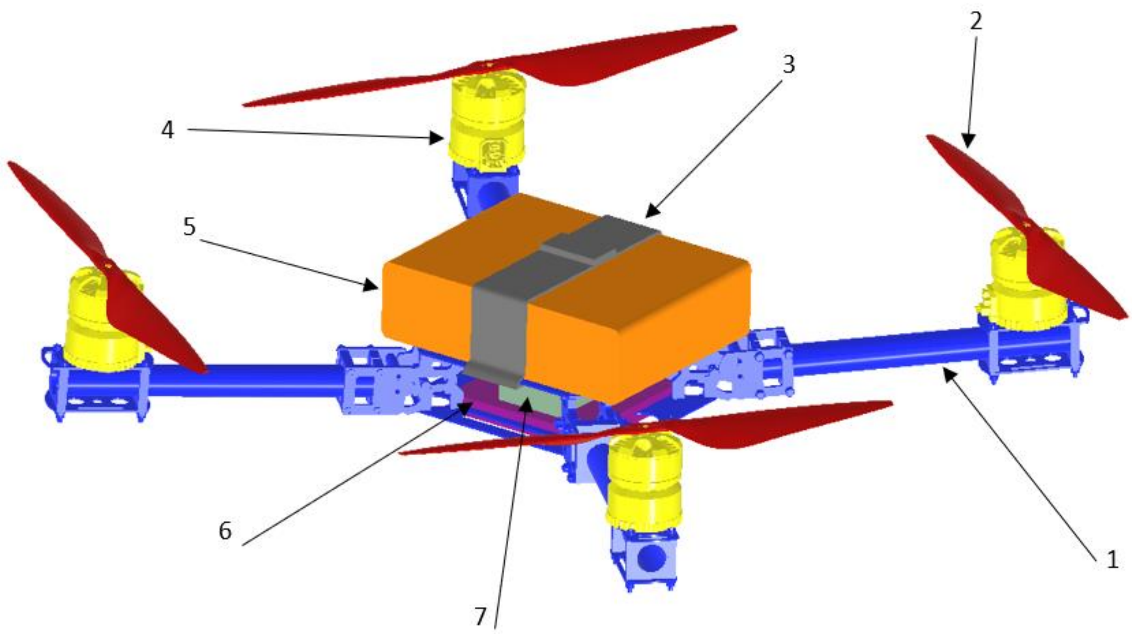


Figure 3.1 Main parts of 3D model of Taltech drone

1. Drone frame
2. Propeller (4 pcs)
3. Strap
4. Motor (4 pcs)
5. Battery
6. Mounting plate
7. Controller

Considering the size of drone the solution of the cage should be bigger than the final part of propellers. In this way a cage could not damage propellers during the rotation and will protect drone's parts from obstacles. The distance between the protruding parts of the drone without propellers length is 475 mm. The length of propellers is 325 mm. Taking into account the length of the propellers the area of protection cage should be minimal 890 mm. In this way, the drone will be fully protected and propellers will not have contacts with cage parts. The center of the drone will be a center of the proposed cage frame (Figure 3.2).

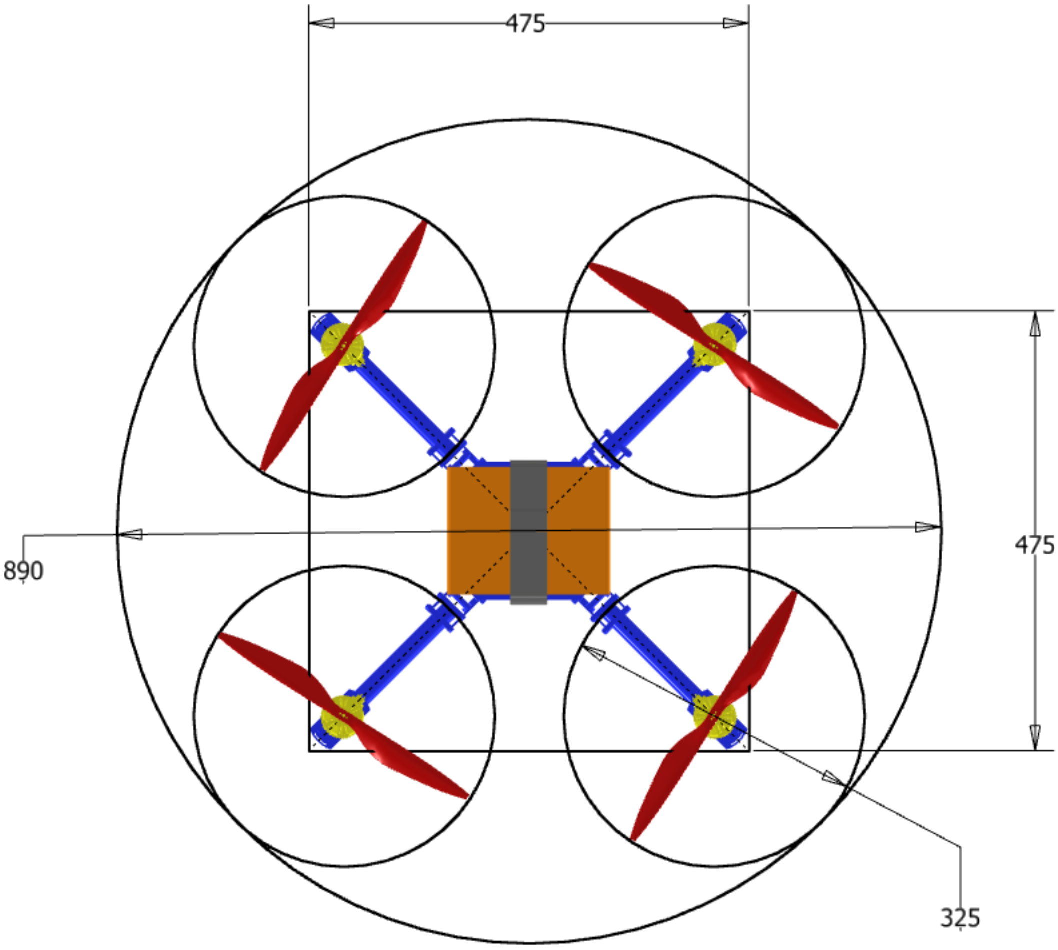


Figure 3.2 Top view of Taltech drone with dimensions in mm

The height of this drone is 112 mm (Figure 3.3). This value is without legs for landing. For this safety cage will be used the height of drone and the height for placing electrical, controlling parts. So the cage will protect drone itself and electrical components. All added components are placed above the drone.

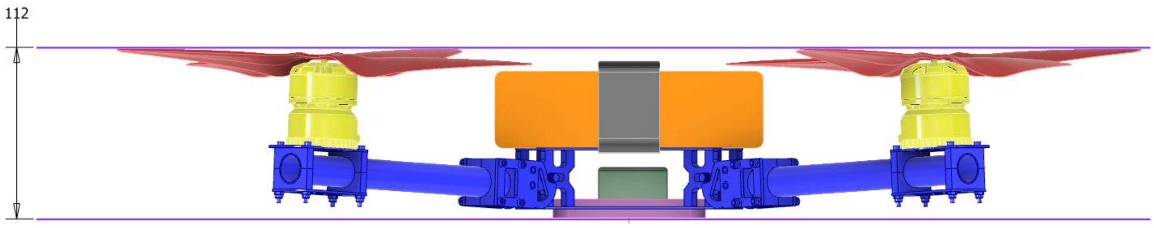


Figure 3.3 Front view of drone with dimension of height from the mounting plate to the ends of propellers in mm

The different solutions of this cage can be proposed, but the point is to made cage compact and not to raise extra space. As the drone can be used in narrow spaces (inside collapsed buildings or outside), so the size of the cage is very critical. Also the weight of the frame is very important and will be taken into account during frame development.

The safety cage is made of carbon-fibre tubes as the base of the cage. The optimal size of the tubes was taken to perform needed requirements for the cage such as weight, strength of the cage (650 MPa) [17]. For the connection of tubes are used 3D printed parts. Tubes from the carbon-fibre are used as they have light weight and at the same time, they are strong enough to protect drone from the effect from collision. In addition, some parts of the cage are done from carbon-fibre plates. All these materials can be ordered on the market and easily received by customers. The carbon-fibre tubes are glued together with connectors. This will not increase the weight of the cage, but it will be strong enough.

The solution of the cage is made of the 4 frames which have the identical number of parts and their form. The only difference is in the total height of each frame. This is due to fact that each centred part of frame lies on top of each other. In Figure 3.4 can be seen the assembled frames parts description and their position in the assembly according to each other.

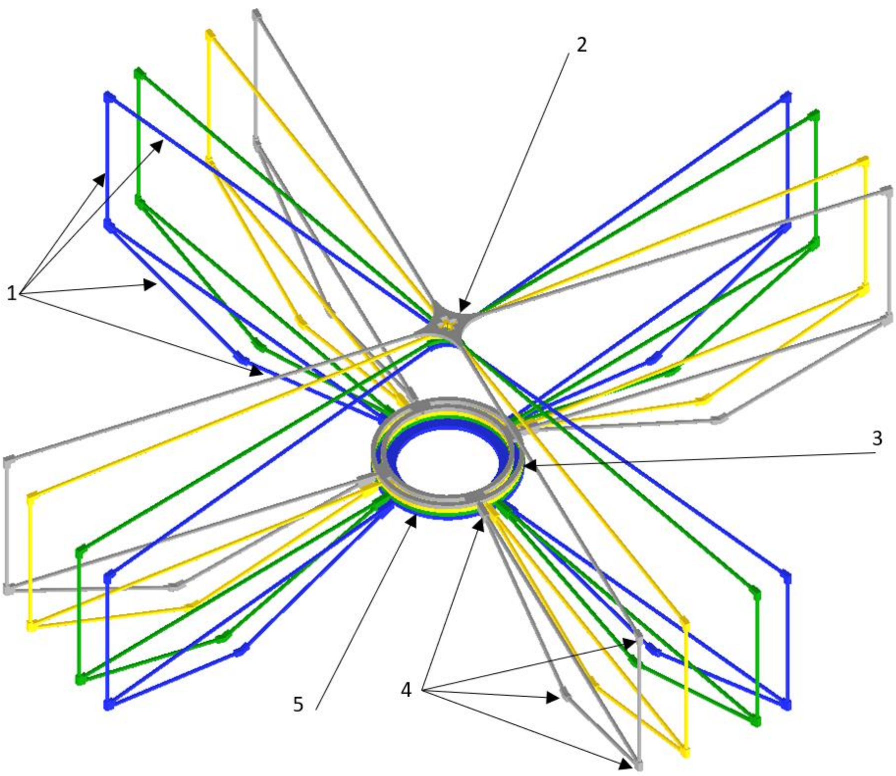


Figure 3.4 View of 4 frames with assembled parts. Each frame, components are highlighted with different colors

1. Carbon-fibre tubes
2. Centred part
3. Connection plate
4. Carbon-fibre tubes connectors
5. Connection bottom plate

One frame can be divided into 6 main elements. There are 4 of them which are identical assemblies. Other 2 parts are used for connection assemblies together. To assemble upper tubes is used centred component at the top of the cage (Figure 3.5). The weight of this part is 6 grams and made from carbon-fibre. The dimensions of this part can be seen in Appendix 1. In additional, at the bottom are used special connection plates to connect bottom tubes.

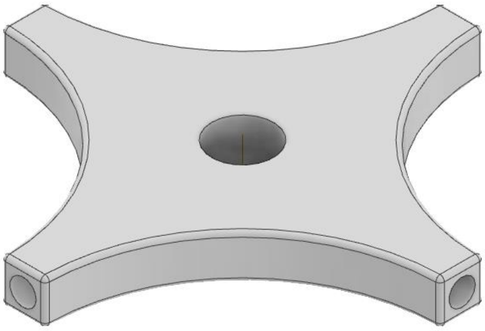


Figure 3.5 Centred components view

If we see the part of assembly of the frame more detailed it can be seen in Figure 3.6 that this part consists of 5 carbon-fibre tubes with different length. The inner diameter of these tubes is 3 mm and the outer diameter is 4 mm. The table of lengths for the tubes is added in Appendix 2.

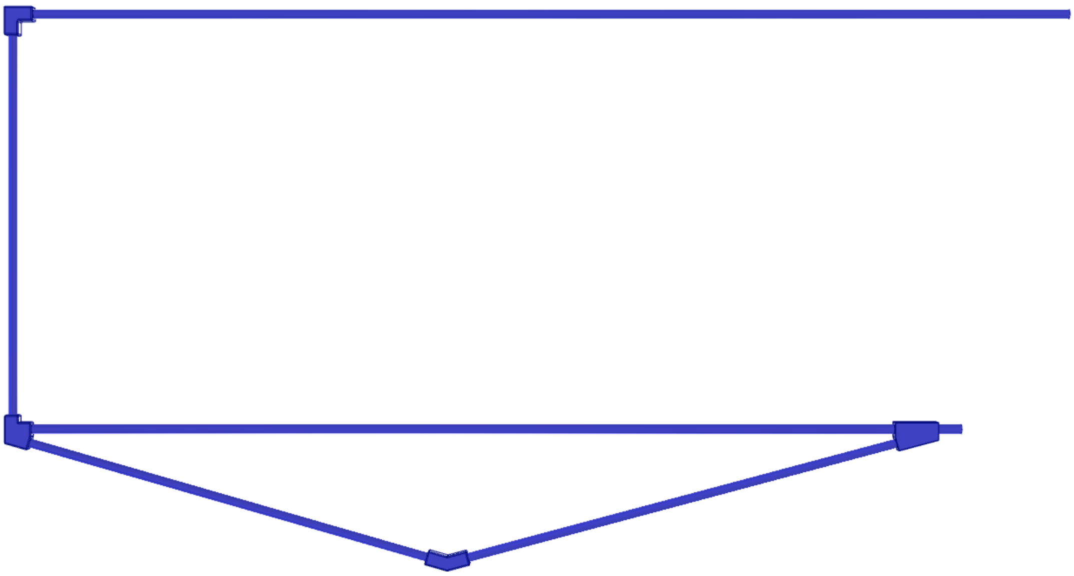


Figure 3.6 View of one part of the assemblies in one frame with different types of tubes and connectors

To connect carbon-fibre tubes together are use 3D printed connection corners in quantity 4 pcs for 1 assembly. These parts are different and was made for exact connection with tubes. The position of these corners can be seen in Figure 3.6 as well.

The first type of corner connects upper horizontal and vertical tubes (Figure 3.7). The weight of this component is 1 g. The detailed parameters of dimensions can be seen in the drawing in Appendix 3.

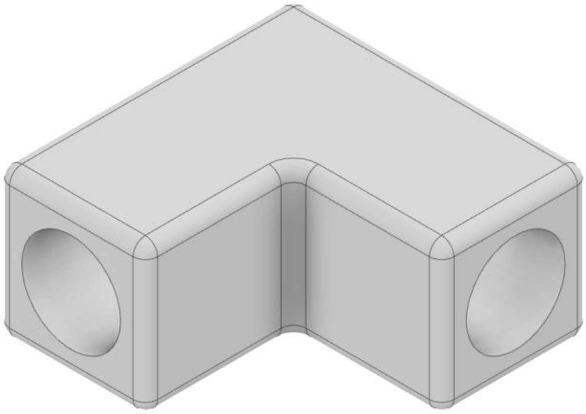


Figure 3.7 Corner for connection upper horizontal and vertical tubes (Type 1)

The second type of corner connects three tubes (Figure 3.8). The weight of this component is 1 g. The only difference with the first type is in the number of holes, as it was designed for connection of 3 tubes. The detailed dimensions can be seen in Appendix 4.

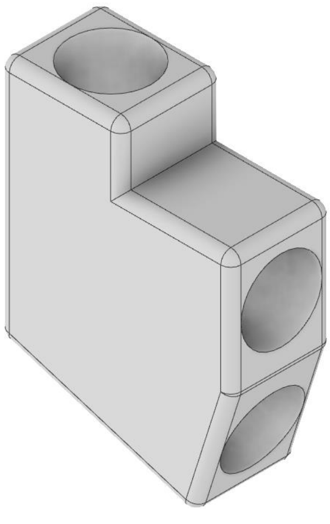


Figure 3.8 Corner for connection of three tubes (Type 2)

In addition, for connecting inclined tubes is used another type of corner (Figure 3.9). The weight of this component is 1 g. The difference of this part is in the angle of the part. As the heights of 4 frames are different so for this point was made parts with different angles of connection. The dimensions of this part can be seen in Appendix 5.

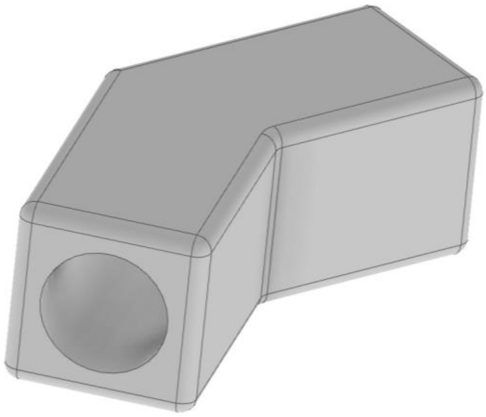


Figure 3.9 Corner for inclined tubes (Type 3)

The last type of connection parts has weight 1 g. It differs from previous parts as it has through hole for horizontal tube (Figure 3.10). The detailed dimensions of this component are shown in Appendix 6.

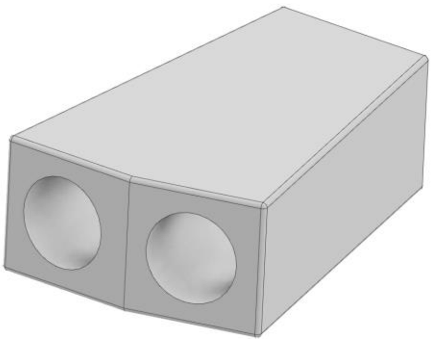


Figure 3.10 Corner for connection bottom and inclined tubes (Type 4)

The connection plate plays as a double role in the assembly of the cage (Figure 3.11). First of all, it connects tube of the frame. This gives the stable and strong connection for the assembly. The second purpose is the rotation ability of this part. The holes inside the plate are used as guiding path for the frame's movement. The outer diameter of the plate is 150 mm and inner is 120 mm. The weight of the part is 32 g.

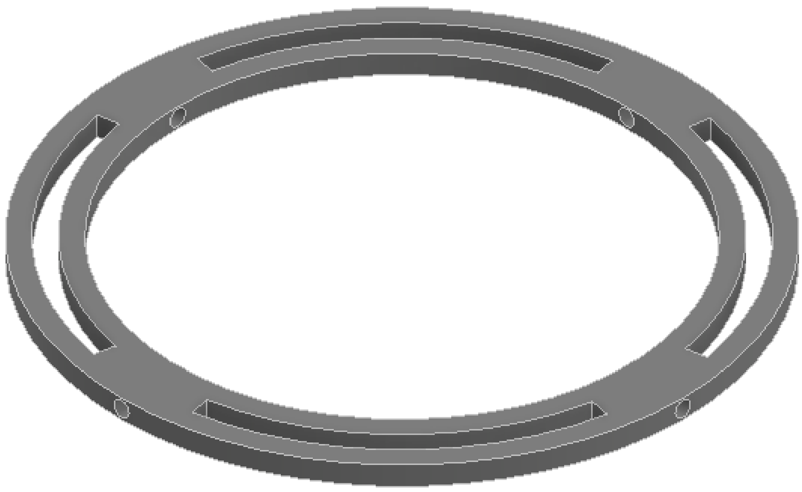


Figure 3.11 Connection plate view

Another plate is used to connect fixed frame (Figure 3.12). Instead of guiding groves there are done 4 holes. Through these holes are placed studs. This is needed that another type of connection plate will move according to the grove. Studs are connected with the frame of the drone. In this way the frame is fixed from top and bottom sides. Tubes of the frames are connected to the horizontal holes. The dimensions of the hole are the same as the dimensions of the tube. The outer diameter is the same as for the previous plate and it is 150 mm but the inner diameter is another and it is 100 mm. Also the weight of this part is more and it is 68 g.

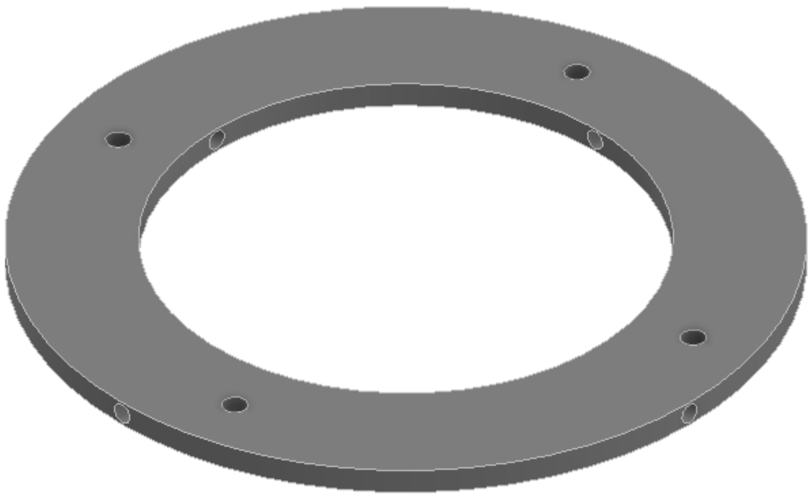


Figure 3.12 Connection bottom plate view

In the Table 3.1 is shown the quantity of components used for assembly of 4 frames. All carbon fibre tubes with different lengths as well as carbon-fibre connectors with different shapes were summed together in the table. So the total quantity of parts is 152 pieces.

Table 3.1 List of components used for assembly of 4 frames

Component	**Quantity (pcs)**
Carbon fibre tubes with different length	80
Centred part	4
Connection plate	3
Carbon fibre connectors with different shape	64
Connection bottom plate	1

According to the solution first bottom frame of the cage is fixed to the box with electrical components (Figure 3.13). For this purpose were user 4 holders.

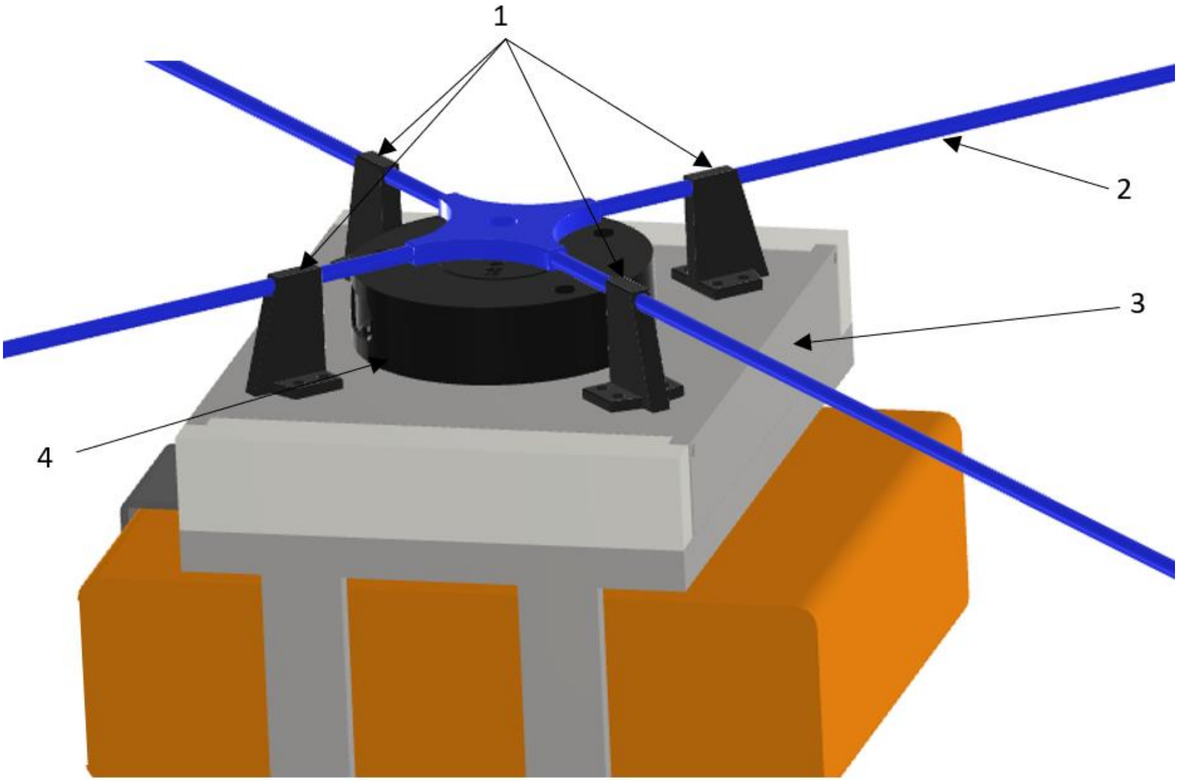


Figure 3.13 Position of fixed frame on the cage holder

1. Frame holders
2. Frame
3. Box with electrical components
4. RPLIDAR A1 [18]

The holders are also fixed to the cover by using screws. In the upper plate of box for electrical components are made places for this connection. The holes are made using thread inserts M4 in quantity of 16 pcs. All this will keep frame in the initial position without any movements.

The holders are 3D printed and have holes with the same diameter as the tubes to have the tight connection (Figure 3.14). The weight of 1 holder is 1 g. The height of a holder is designed in this way that there is minimal distance between the centred part of a frame and the lidar sensor placed on the electrical box.

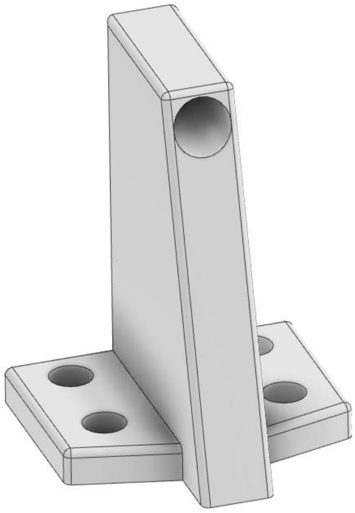


Figure 3.14 View of holder for fixing frame

Through all 4 frame’s center parts goes shaft. At the top of this assembly is placed holder. The center parts of the frames lie on top of each other (Figure 3.15).

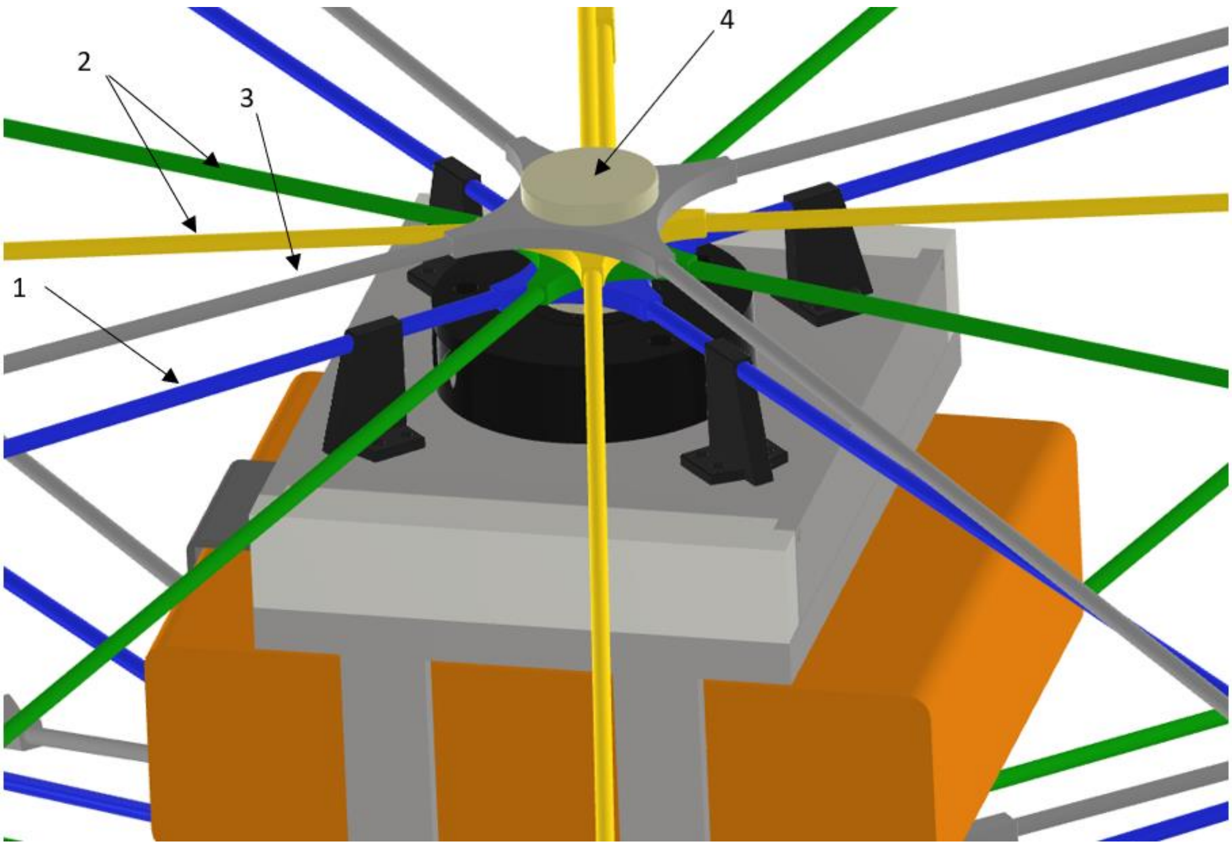


Figure 3.15 The view of the position and connection of rotating frames marked with different colors and have different aims

1. Fixed frame
2. Ordinary frames
3. Upper frame
4. Top holder

For this cage are used 3 types of frames. First is lead frame – upper one which is rotated by the servo motor. Second is ordinary frame – which is under the lead frame and move beyond the lead one. Third frame is fixed and does not rotate (Figure 3.16).

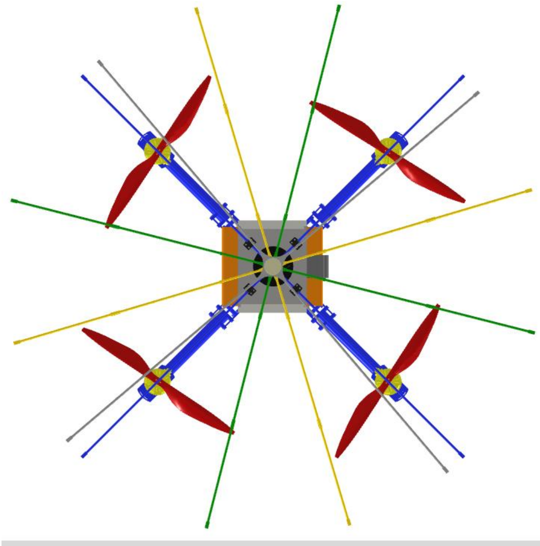


Figure 3.16 Position of frames in open stage. Gray – lead frame, orange, red – ordinary frames, blue – fixed frame

In the closed stage these frames protect propellers and drone itself as well (Figure 3.17). This is an additional protection in urgent cases where the safety is critical. When frames are in closed stage the cage will not disturb the camera during the flight and parts of cage will not be on the video from the camera. So in case video camera is attached to the drone it will be a big advantage over the stationary safety cages.

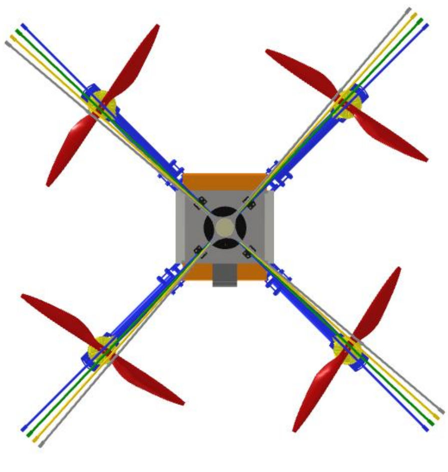


Figure 3.17 Cage in closed stage. All 4 frames are placed over the drone motors

Each frame is connected together through plates as well (Figure 3.18). These plates are needed for the opening cage and rotating frames. The movable by servo motor frame pulls using these plates other frames. Also these plates make additional protection for the drone from all sides and make frame construction stronger.

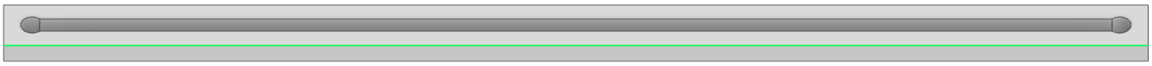


Figure 3.18 Plate for connection between frames

There are two layers of plates - upper and bottom. For these parts are used carbon fibre plates. The weight of 1 plate is 8 g. The shape of the plates was done in this way to decrease the weight as much as possible but at the same time plate should perform the needed aim.

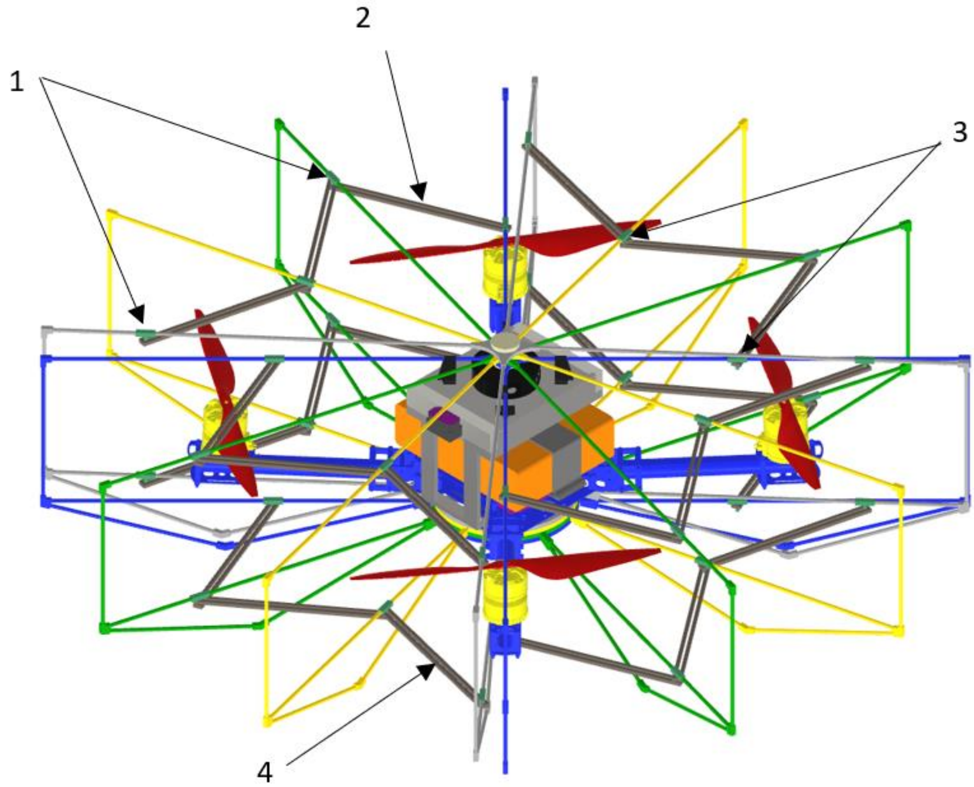


Figure 3.19 Position and connection of plates and connectors on the frame

1. Movable connector
2. Upper layer plate
3. Fixed connector
4. Bottom layer plate

All plates are joined with frames by movable and fixed connectors (Figure 3.19). First type of connector is sliding along the tube on the frame. Second connector is fixed on the tube and does not move. Although these are the same parts, but the aims are different as it was stated before. The dimensions of the connector can be seen in Appendix 7.

The types of connectors alternate on the frames. For the material of connectors was selected PC/ABS plastic. As the weight of the whole system is important part so 1 part of this connector has the weight of 1 g.

For the connection of the servomotor and the frame was created a special plate which was attached to the movable frame (Figure 3.20). Starting rotating movable frame first after that other frames will be moved.

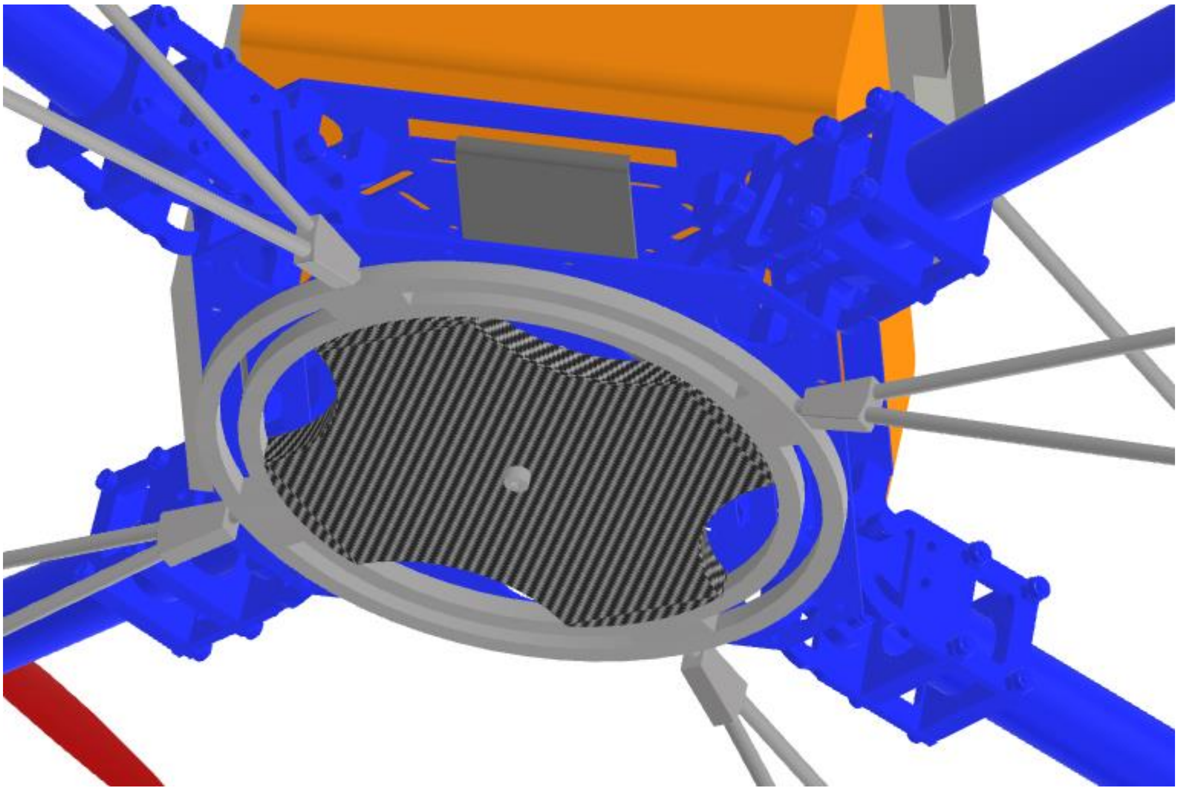


Figure 3.20 Special plate for connection servomotor and movable frame.

Summing up additional parts for the frame it can be said that there are used 12 pcs of plates, 32 pcs of connectors. All these parts can be easily produced and replaced if some kind of the rework is needed. For the assembly were used 16 different names of components. The total quantity of parts is 201 pcs. The list of components which are used for the frame assembly is presented in the Table A.1 in Appendix 8.

At the top of the drone is installed the box with electrical components inside (Figure 3.21). The dimensions of this part are 160 x 120 x 33 mm. The size of this part was made as small as possible to make the drone cage compact. Inside this box are placed controller Arduino Mega2560, battery and lidar. Holders from both sides keep this box over the drone battery.

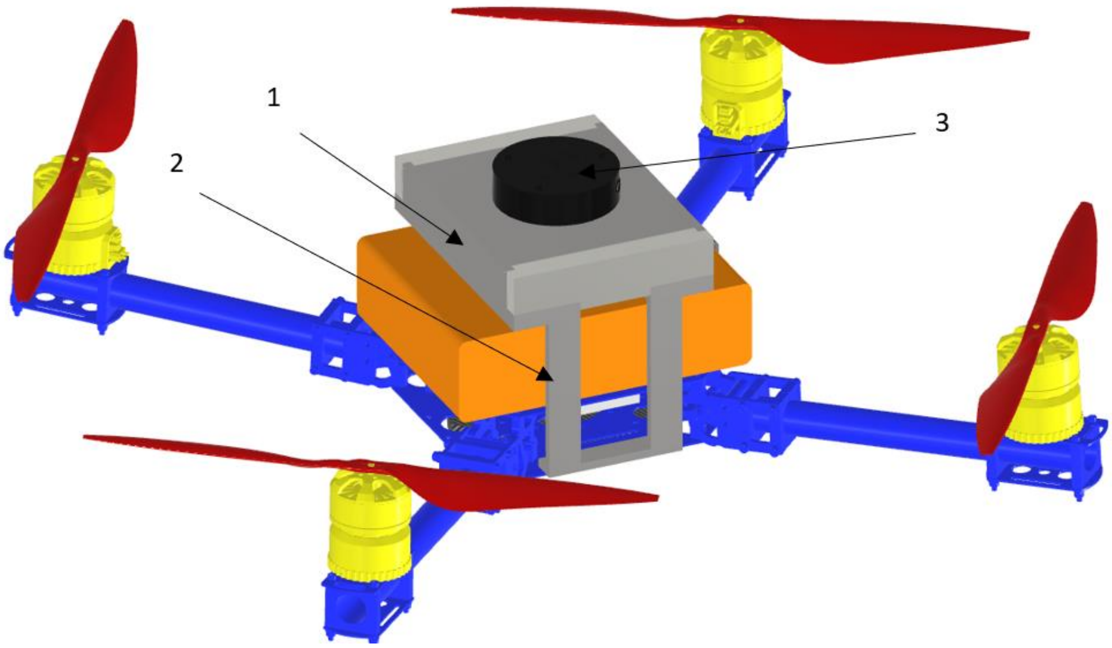


Figure 3.21 Box with electrical components attached to the drone

1. Box with electrical components
2. Box's holders
3. Lidar RPLIDAR A1

As it is supposed that this cage will be once placed and will not be removed anymore. So all electrical parts should be easily accessible for users. The replacement of the battery or maintenance of the controller can be easily done thanks to opening cover from both sides (Figure 3.22). As it can be seen from the picture frames are fixed in this way that during opening cover does not touch the frame tubes.

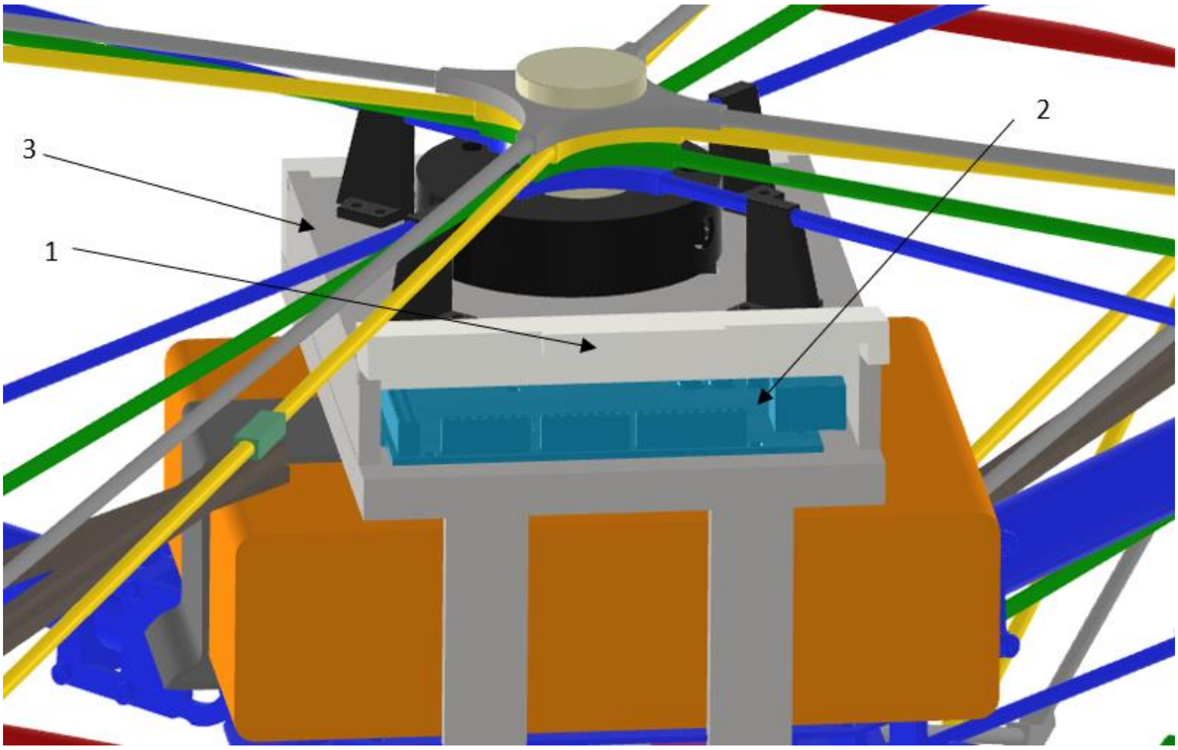


Figure 3.22 View of opened cover, Arduino Mega2560 position inside the box

1. Cover
2. Controller Arduino Mega2560
3. Box with electrical components

Inside the box on one side is placed Arduino Mega2560, on another side – battery, in the middle is placed lidar. Access for these components is provided for both sides. During the flight of the drone, the cover is fixed and cannot be opened. Also, to prevent dust and moisture from entering the inside of the box, a gasket is installed along the perimeter of the covers. The gasket is fixed in the grove with adhesive tape, which is able to use inside and outside as well.

Another important part is the sensors for obstacle detection placing around the drone which can be seen in Figure 3.23 and Figure 3.24. 1 sensor was used for 360-degrees obstacle detection around the drone. Additional 2 sensors were placed above and under the drone. In this way the surrounding area is fully under the control which perform good protection during the flight.

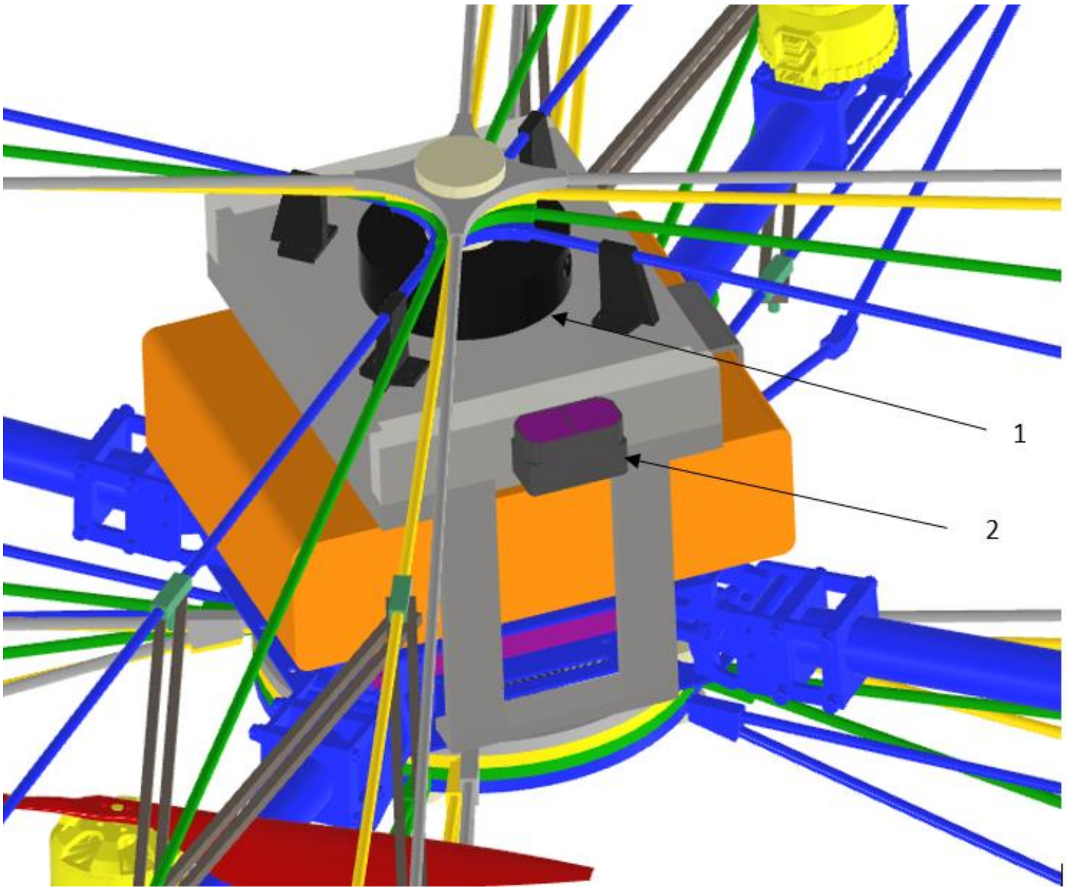


Figure 3.23 View of sensors position placed on the drone on the top side

1. RPLIDAR A1
2. TFmini Plus

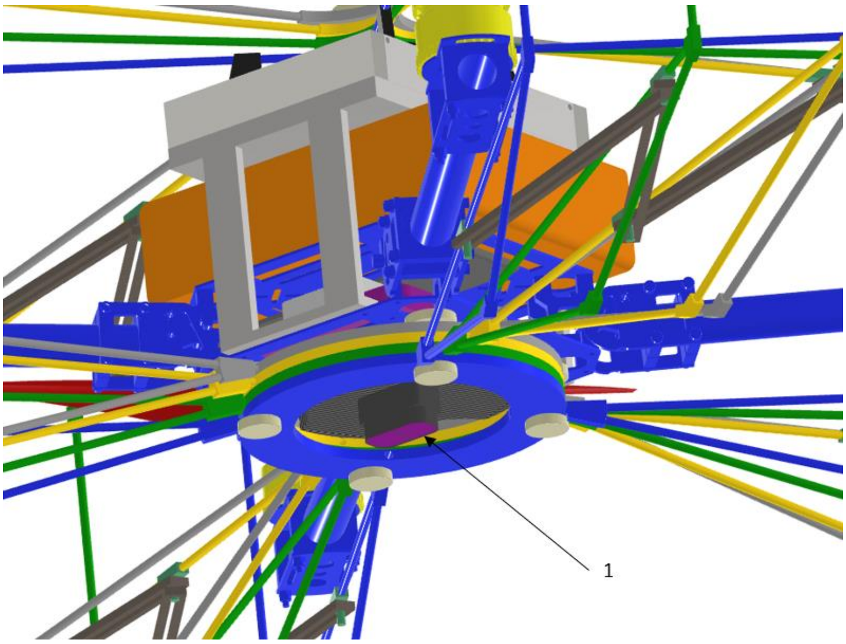


Figure 3.24 View of the sensor paced on the bottom side of the cage 1) TFmini Plus

For the top sensor TFmini Plus which is attached to the box with electrical components was designed a holder which will keep the correct position. The weight of this holder is 3 g. The holder is fixed to the box by the screws. The design of the component was done according to the shape of the lidar sensor (Figure 3.25).

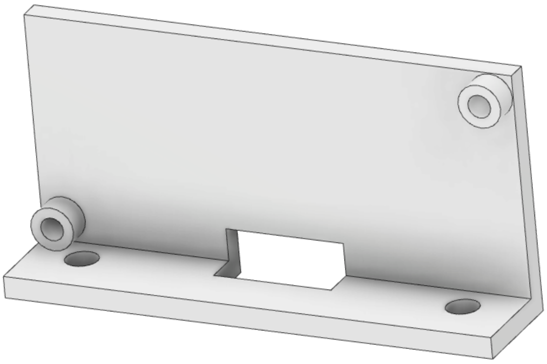


Figure 3.25 TFmini Pus sensor holder

Final view of the drone cage system will show the view during the flight in close stage when there are no obstacles (Figure 3.26). Cage elements protect drone from top, bottom, sides. The total weight of this cage without electronic components is 1,185 kg. Most of the weight are parts made for frame (tubes, plates, corners, connectors). The diameter of this cage is 943 mm and total height is 230 mm.

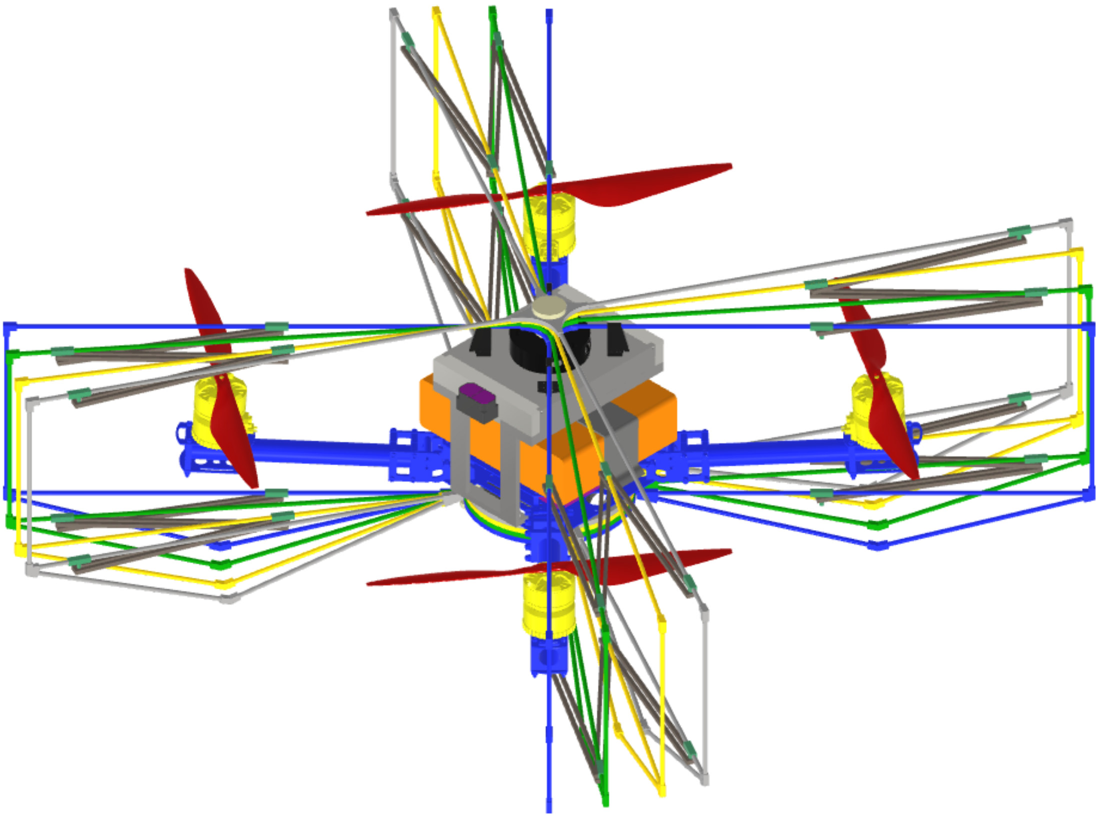


Figure 3.26 View of proposed solution with frame, sensors, box with electrical components installed on the drone

3.2 Analyses of frame

As the proposed cage system was developed it was needed to make tests to make sure that cage and supported part are able to withstand the load. For this purpose was used Autodesk Inventor Pro 2021 software built in simulation and testing environment. According to received information was possible to update provided cage frame. The values of the maximum and minimum displacement and Von Mises stress, as well as safety factors can be obtained.

The maximum von Mises stress criterion is based on the von Mises-Hencky theory, also known as the theory of energy of shape change. In terms of the principal stresses σ1, σ2, σ3, the von Mises stress is expressed as:

$$\sigma_{\mathrm{vonMises}} = \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]/2\}} \tag{3.1}$$

where $\sigma_{vonMises}$ - von Mises stress, MPa,
σ1, σ2, σ3 - principal stresses, MPa.

The theory states that the plastic material begins to damage in places where the von Mises stress becomes equal to the ultimate stress. In most cases, the yield point is used as the ultimate stress. However, the program allows to use the tensile limit or set own ultimate stress.

$$\sigma_{\mathrm{vonMises}} >= \sigma_{\mathrm{limit}} \tag{3.2}$$

where $\sigma_{vonMises}$ - von Mises stress, MPa,
σ_{limit} - tensile limit, MPa.

The yield point is a temperature-dependent property. The present target value for the yield strength must take into account the temperature of the component. The safety factor at a given location is calculated based on:

$$\text{Factor of Safety (FOS)} = \sigma_{\mathrm{limit}} / \sigma_{\mathrm{vonMises}} \tag{3.3}$$

where $\sigma_{vonMises}$ - von Mises stress, MPa,
σ_{limit} - tensile limit, MPa.

In the case of pure shear, $\sigma_{12} = \sigma_{21} \neq 0$, while other $\sigma_{12} = 0$, the von Mises criterion stress is expressed as:

$$\sigma_{12}\,\max = \sigma_{\mathrm{yield}} / \sqrt{3} = 0.5777\,\sigma_{\mathrm{yield}} \tag{3.4}$$

where σ_{12} - shear stress, MPa,
σ_{yield} - von Mises yield criterion, MPa.

This means that, at the onset of yielding, the maximum shear stress in pure shear is √3 times lower than the yield stress in the case of simple tension [19].

The developed solution can be divided into 2 separate parts. First part is a holder for the box with electrical components attached to the drone. The second part is the assembly of the frames.

The edges of holders are fixed in the simulation like it will be done on the real drone.

For testing the developed frame were done different simulations: **a)** without any additional loads applied at the frame, **b)** in opened, **c)** in closed stages, **d)** with load applied on the top holder, **e)** with load applied on the sides, **f)** frame as support of the drone. According to these results were made sure that the construction of the frame is able to withstand the loads and protect the drone.

In the simulation of the frame were fixed holes on the box holders and the holders of connection plates at the bottom of the frame. The results for the frame in the opened stage without any added load show that frame strength is enough. The maximum deformation is 0,149 mm (Figure A.1) and maximum stress value is 8,255 MPa (Figure A.2). The main concentration is in the corner of the connection of 3 tubes. The minimal deformation is in the center of the whole frame construction.

In the closed stage frame without additional load maximum Von Mises stress value is 2,387 MPa (Figure A.3). These results show that in the closed way frame has in 3,5 times less stress than in opened way. At the same time, these results are less than strength of the materials of components.

In addition, the maximal deformation is 0,035 mm (Figure A.4). It is in 4 times less displaced than when drone frame is opened. Also these results show that in both cases the displacement of cage parts cannot influence at the drone components, as the example drone's propellers.

Next simulations were done with the additional loads attached to the frames. For the analyses were taken into account parameters of the already developed drone cages which can be installed on the drone. According to the producer information, developed cage can withstand 6 kg of force from the top, and 12 kg from the front, rear and sides [20].

As the top holder is the highest part of the frame, so were decided to test first the top holder ability to withstand load on the frame. For this point, was selected the force of 18 kg applied on the top holder. According to the results the maximum value of stress is 22,76 MPa (Figure A.5) and displacement is 0,036 mm (Figure A.6). This shows that the construction of the central part of the frame can withstand applied force. Also safety factor shows that there is enough strength of the frame for additional load.

In addition, was done simulation of the frame with applied force on the sides. For this was used value of 18 kg for both sides. According to results it can be seen that maximum Von Mises Stress value location is 247,5 MPa in the connection of 3 tubes (Figure A.7). The maximum displacement value is 5,6 mm (Figure A.8). There is extra distance to the propellers 53 mm, so the displacement cannot influence on the parts of the drone.

Also it was analysed in case drone can use frames as the support without additional legs to stand on the surface before and after the flight. As the simulation results show frame can withstand 18 kg applied on the frame. The maximum displacement is 3,64 mm (Figure A.9) and Von Mises Stress value is 169,1 MPa (Figure A.10). So, summing up all analyses it can be stated that the frame can fulfil the expected parameters for the frame.

The results of the tests were collected and presented in a Table 3.2 for better understanding and vision. According to this information the maximum displacement is 5,6 mm and Von Mises Stress value is 247,5 MPa.

Table 3.2 Test cases results displacement and Von Mises Stress values of simulations

Test case	**Displacement, mm**	**Von Mises Stress, MPa**
a) and b)	0,149	8,255
a) and c)	0,035	2,387
d)	0,036	22,76
e)	5,6	247,5
f)	3,64	169,1

4. PROPOSED SOLUTION FOR ELECTRONICAL SYSTEM

4.1 Electronical components selection

The main part of this thesis is the detection of obstacles during the flight. So the second step of developing this system it to design and develop electronical part. For this point it is needed to choose controlling, detection, motion and power supply devices.

The controlling device was chosen from the Arduino area. It is a ready-made hardware and software platform, the main components of which are a small I/O controller board and a Processing/Wiring-based development environment. The hardware part consists of electronic boards with a microcontroller, accompanying elements (power stabilizer, quartz resonator, blocking capacitors), a port for communication with a personal computer, connectors for input-output signals.

Arduino Mega2560 a microcontroller board based on the ATmega2560. It has 54 input/output pins, 14 of them are PWM pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The Mega2560 board is compatible with most sensors. Support I^2C communication using the libraries. Also it provides 4 hardware UARTs for TTL (5 V) serial communication. Serial interface: pins 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX) Serial 3: 15 (RX) and 14 (TX) [21]. These pins are used to receive (RX) and transmit (TX) data over the serial interface. From the variety of Arduino series, Mega2560 is the best choice for this development (Table 4.1).

Table 4.1 Microcontroller ATmega2560 parameters

Parameters	**Values**
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Digital I/O Pins	54 (of which 14 provide PWM output)
Serial Pins	4
Analog Input Pins	16
Length	101,52 mm
Width	53,3 mm
Weight	37 g

The Arduino Mega2560 can be powered via a USB connection or from an external power supply. External power (not USB) can be supplied via an AC/DC converter or battery.

The battery is connected to the GND and Vin pins of the POWER connector. The platform can operate with external power supply from 6 V to 20 V. When the supply voltage is below 7 V, the 5 V pin can supply less than 5 V, and the platform may be unstable. When using voltages above 12 V, the voltage regulator may overheat and damage the board [21].

For the detection sensors selection need to understand the areas which are needed to be checked during the flight and keep them under the control. That areas are around the drone, top and bottom sides. In this way for detection is required minimal 3 sensors placed in different areas.

For the sensors selection were taken most popular sensors which are used for obstacle and distance detection. These sensors are Ultrasonic sensor, RP Lidar, Lidar. The criteria of the selection are:

1. distance of detection,
2. measuring angle,
3. sampling frequency,
4. cost of the sensor.

One of the most popular sensors is HC-SR04. It is widely spread for objects detection in robotics. The detection distance is from 2 cm to 400 cm with the ranging accuracy can reach to 3 mm. The HC-SR04 can be connected directly to an Arduino or other microcontroller and it operates on 5 V. The additional working parameters of HC-SR04 can be seen in the Table 4.2. It’s a low current device so it’s suitable for battery powered devices. The sensor is equipped with four leads (standard 2,54 mm).

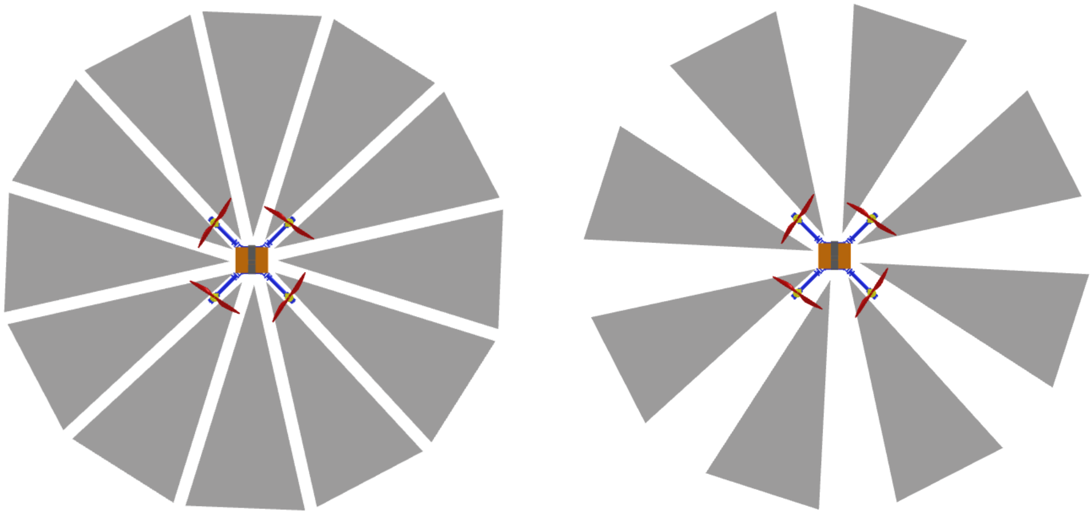
Table 4.2 Ultrasonic sensors HC-SR04 additional parameters

Parameters	**Values**
Working Voltage	DC 5 V
Working Current	15 mA
Working Frequency	40 Hz
Dimension	45*20*15 mm
Weight	8,5 g

The HC-SR04 has the following connections:

1. VCC – 5 V power supply pin.
2. Trig – Send the ultrasound wave from the transmitter.
3. Echo – This is an Output pin, produces a pulse when the reflected signal is received. The length of the pulse is proportional to the time it took for the transmitted signal to be detected.
4. GND – The Ground Connection.

The angle of detection of this sensor is 30°, so for the 360° control it is needed 12 sensors placed around the drone. In case of using a smaller number of ultrasonic sensors the area of detection will be not fully achieved. For example, if between the frame of the drone place 2 sensors, so total number will be 8 pcs. Taking into account, that 1 ultrasonic sensor angle detection is 30°, so total angle detected around the drone is 240°. So this is 33% less that it can be detected using 12 ultrasonic sensors (Figure 4.1).



a) b)

Figure 4.1 Areas of sensors detection around the drone: a) 12 sensors, b) 8 sensors. In case of using 8 sensors case, the detection area will be 33% less than using 12 sensors solution.

Considering that for 360° control there are used 12 ultrasonic sensors, will be needed 12 pins with PWM and 12 digital pins for this connection. So Arduino Mega2560 will be good solution as it has the biggest number of PWM ports in the range of Arduino controllers which are needed for ultrasonic sensors connection as there are used 12 ultrasonic sensors. By measuring the echo pulse width, the distance to target can easily be calculated. These sensors are much cheaper than LIDAR sensors, can detect objects reasonably close and these sensors are very easy to use.

The important part of the selection is the weight of the sensor. One ultrasonic sensor weight is 8,5 g. Considering, that for the good ability of the detection are needed 12 pcs, so the total weight of the 12 ultrasonic sensors will be 102 g. In addition, to control the area above and under the drone, additional sensors are needed. So there will be minimal 2 additional ultrasonic sensors. The total weight of all sensors will be 119 g. This value was taken into account during the sensor selection.

Another type of sensors is lidars. In the range of lidar sensors can be found different types with different costs. The cost of such sensors is bigger that ultrasonic sensors. Comparing these 2 types, the difference in the cost between the cheapest ultrasonic sensors and lidars is in 10 times and more. For example, the cost of 1 ultrasonic sensor is 4 €, the cost of the cheapest lidar sensor is 40 €. Despite this fact, the detection distance, accuracy of the distance measurements of the lidars are much better comparing with ultrasonic sensors.

One of the inexpensive lidar sensor comparing with other sensors is TFmini. This type of sensor has maximum detection distance 12 meters. TFmini also supports 100 Hz sampling resolution. According to the datasheet, this sensor within 6 meters, has accuracy within 4 cm, 6~12 meters, accuracy within 6 cm. Also it has scan angle of 2,3 degree. This sensor has strong anti-interference. Due to this fact it can work in outdoor light. Also important point is the overall weight, which is 4,7 g [22]. It is a good choice because of its small size, light weight and low power consumption. This sensor can be supplied by standard 5 V. The average power consumption is 0,6 W.

TFmini LiDAR adopts UART (TTL) communication interface. One of the advantages of this sensor is that it can be compatible with a variety of Arduino controllers. Since TF mini is a serial device and the ordinary Arduino, for example Arduino Uno, which has only one hardware serial port, user can face with an issue of using this device. So it is better to use a software serial port to connect it during uploading the code to the microcontroller and test with the sensor at the same time. It will be convenient for users to use multi-serial port devices such as Arduino Leonardo or Arduino Mega2560.

The TFmini has the following connections:

1. GND – The Ground Connection.
2. VCC – Power supply, the TF Mini requires 5 V DC.
3. TXD – Transmit Data. Accepts 3,3 V logic signal.
4. RXD – Receive Data. Accepts 3,3 V logic signal.

According to the specification TFmini uses 3,3 V for the logic pins on the device. So to connect Arduino 5 V output pin to the TFmini logic pin will be needed to decrease voltage. The best way to handle this situation is to use an inexpensive logic level converter which can convert both the input and output voltages on both sides.
The updated version of the TFmini is TFmini Plus. It has greatly improved performance — increasing the measurement frequency, reducing blind zone, improving accuracy and stability. Only the disadvantage is that the weight of a TFmini Plus is increased. The main differences between these two models of sensors compared in the Table 4.3.

Table 4.3 Comparison of TF mini and TFmini Plus

Parameters	TFmini	TFmini Plus
Distance Range	0,3 - 12 m	0,1 - 12 m
Measure Frequency	1000 times/s	1 - 1000 times/s (Adjustable)
Time of Each Measurement	0,01 ms	0,01 ms
Average current	≤140 mA	≤110 mA
Waterproof Level	NO	IP65
Scan Angle	2,3°	3,6°
Dimensions	42*15*16 mm	35*21*18,5 mm
Weight	4,7 g	12 g

By optimizing the light path and algorithm, TFmini Plus minimizes the impact of the environment on distance measurement performance.

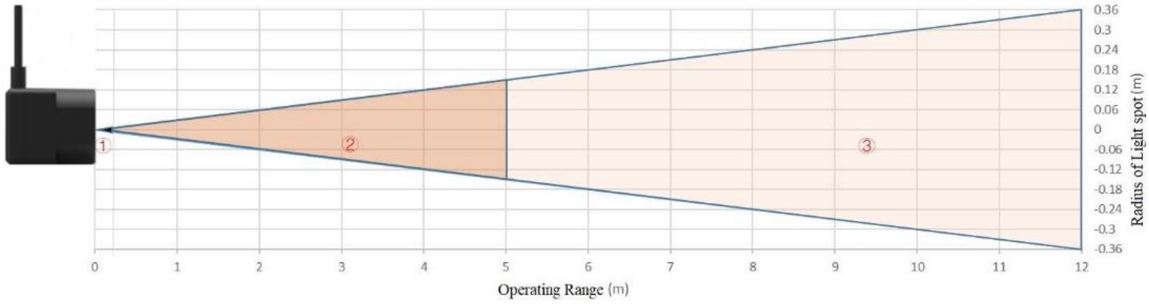


Figure 4.2 Schematic diagram of TFmini Plus distance measurement [23]

As it is shown in Figure 4.2:

1. The detection blind zone of TFmini Plus, 0-10 cm, within which the output data is unreliable.
2. The operating range of TFmini Plus detecting black target with 10% reflectivity, 0,1-5 m.
3. The operating range of TFmini Plus detecting white target with 90% reflectivity, 0,1-12 m [23].

It was mentioned in the Table 4.3, the updated sensor has IP65 protection that could effectively prevent water and dust. This will make the sensor more adaptable to outdoor light and environment with different temperatures and reflectance. This is an important point of the using sensors inside and outside the buildings.

Ingress Protection (IP) is a classification system for the degree of protection of electrical equipment against the penetration of solid objects and water in accordance with the international standard IEC 60529 [24]. The rating consists of the letters IP followed by two digits, the higher the number the better the protection. This standard shows different type of water, dust protection for devices.

PROTECTION AGAINST SOLID PARTICLES (first digit):

0 - no protection

1 - protection against the penetration of solid particles with a size of at least 50 mm

2 - protected from the penetration of solid particles with a size of at least 12,5 mm

3 - protection against the penetration of solid particles with a size of at least 2,5 mm (tools cables)

4 - protected from the penetration of solid particles with a size of at least 1 mm (thin tools, wire)

5 - protection against dust penetration in quantities that do not affect the performance of the product

6 - full protection against dust penetration

PROTECTION AGAINST LIQUID PENETRATION (second digit):

0 - no protection

1 - protection against vertically falling drops of water (condensate)

2 - protection against drops of water falling at an angle of not more than 15° from the vertical

3 - protection against raindrops falling at an angle of not more than 60° from the vertical

4 - protection against splashing water from all directions

5 - protection against water jets from all directions

6 - protection against the effects of water, identical to the waves

7 - protection against water penetration when immersed to a depth of 1 m

8 - protection against water penetration during prolonged immersion under pressure

Comparing with other IP types it can be seen that this protection can fulfil requirements of the environmental protection. So in case of outdoor using the protection applied on the TFmini Plus will protect equipment from different weather conditions. In addition, protection from the dust will allow to work devices for long time with good quality.

Next sensor which was under the selection is a lidar with 360-degree detection. In case of using lidar with 360-degree the area around the drone can be fully controlled. One of such devices is RPLIDAR A1 which was developed by SLAMTEC. The system can scan within 12 meter range. As it is shown in the Table 4.4 the distance resolution is less than 1% of the distance. In the range of the 360-degree detection devices this sensor is the cheapest one with the good performance. The weight of this device is 170 g.

Table 4.4 RPLIDAR A1 parameters

Parameters	Values
Distance Range	0,15 - 12 m
Angular Range	0 - 360 degree
Distance Resolution	< 1%
Angular Resolution	≤ 1°
Sample Frequency	≥ 8000 Hz
Scan Rate	2 – 10 Hz
Average current	100 mA
Weight	170 g

The produced 2D point cloud data can be used for mapping, localization and object/environment modelling. The RPLIDAR A1 is based on the principle of laser triangulation and uses high-speed image acquisition and processing equipment developed by SLAMTEC. The system measures distance data over 8000 times per second. Users can adjust the scan speed by alternating the PWM signal of the motor [25].

The RPLIDAR device has a 7-pin connector:

1. GND – The Ground connection for scanner
2. RXD – Receive Data. This is a 5 V TTL level pin
3. TXD – Transmit Data. This is a 5 V TTL level pin
4. VCC – 5 V power for the RPLIDAR A1 electronics
5. GND – The Ground connection for motor
6. MOTOCTL – Enable signal for Motor/PWM control signal. A 5 V PWM signal is applied to control the motor speed.
7. VMOTO – Power supply for RPLIDAR A1 Motor. The motor requires 5 V.

Important part is RPLIDAR A1 is safety to human and pets. The system uses a low power (< 5 mW) infrared laser as its light source and drives it using modulated pulse. The laser emits in a very short time frame, due to that it is safety to human and pets as well. It reaches Class I laser safety standard complies with 21 CFR 1040.10 and 1040.11 except for deviations pursuant to Laser Notice No. 50, dated June 24, 2007 [25].

After the selection of the sensors used for the electronical system it can be stated that for detection are used 3 lidar sensors: 2 pcs of TFmini Plus lidar and 1 pc of RPLidar A1. The area of the detection is 12 meters above and under the drone. Also around the drone is used lidar with 360-degree detection on the distance of 12 meters.

In addition, to connect sensors to the Arduino Mega2560 are needed 3 Tx and 3 Rx pins. Arduino Mega2560 has this quantity of pins so there is no additional equipment needed for these purposes. The connection description between Arduino Mega2560 and detection sensors can be seen in Table 4.5.

Table 4.5 Connection between Arduino Mega2560 and sensors used in proposed system

Arduino Mega2560	RP Lidar A1	Logic Converter				TFmini Plus 1	TFmini Plus 2
		5	3,3	5	3,3		
GND	GND	GND	GND	GND	GND	GND	GND
Pin 19 (RX1)	TX						
Pin 18 (TX1)	RX						
Pin 17 (RX2)		5A	3A			TX	
Pin 16 (TX2)		5B	3B			RX	
Pin 15 (RX3)				5A	3A		TX
Pin 14 (TX3)				5B	3B		RX
Pin 3	MOTOCTL						
5 V		VIN		VIN			
3,3 V			3V3		3V3		

Another point of this proposed solution is an opportunity to receive information from the protective cage system about the stage of the system, is it opened or closed. In this case, user can understand that some obstacles are detected and according to this information person can behave more accurate during the flight to avoid any issues.

For this purpose can be used different ways of working and equipment. All these systems have advantages and disadvantages at the same time. So the selection of the final solution was done according to the following point: distance of receiving signal, consumption of power, cost, easy of setup.

The selection was done between different solutions: Bluetooth, Wi-Fi. First way from the proposed solutions is Bluetooth, which is currently one of the most popular wireless technologies. The HM-10 is a readily available Bluetooth 4.0 module used for establishing wireless data communication. It also supports Bluetooth Low Energy (BLE) technology, which was specially designed to provide low energy consumption, which allows devices to work for a long time on a conventional battery.

The module includes a UART (Universal asynchronous receiver/transmitter), which makes it quite easy to connect it to various microcontrollers. HM-10 supports data rates up to 24 Mbps with low power consumption. At the same time, the HM-10 module provides a communication distance of up to 100 meters in open areas. The module is typically connected to 3,3 V standard power supply. The module is preferred where power consumption is issue. For the communication can be used mobile phone with installed application.

HM-10 module has the four pins:

1. GND – The Ground Connection.
2. VCC – Power supply, the TF Mini requires 5 V DC.
3. TXD – Transmit Data. Accepts 3,3 V logic signal.
4. RXD – Receive Data. Accepts 3,3 V logic signal.

Table 4.6 Bluetooth HM-10 module parameters

Parameters	Values
Working frequency	2,4 GHz
Supply voltage	3,3 V DC
Consumption current	50 mA
Communication distance	100 m
Size:	27 mm x 13 mm x 2,2 mm

Another solution is using Wi-Fi device to communicate between microcontroller and user device. ESP-01 is a Wi-Fi module based on the popular ESP8266EX chipset. On board the board is a 2 MB Flash memory chip, an ESP8266EX chip, a quartz resonator, two indicator LEDs, and a miniature antenna from a track on the top layer of the printed circuit board in the form of a snake. Flash memory is required to store software. Every time it is turned on the power, the software is automatically downloaded to the ESP8266EX chip. It is important to note that this module works with 3,3 V, so need to use logic level converter, as connecting the module to 5 V may damage it. The connection of the TX pin of the Wi-Fi module is done to the Arduino's RX and the RX pin of the module to the Arduino's TX. By default, the module is configured to work through "AT commands". The communication distance between devices is 400 m. Using additional antenna the distance will be increased. Due to this fact, it was selected to use Wi-Fi solution for receiving information.

Wi-Fi ESP-01 module has following connection:

1. VCC – Power supply 3,3 V
2. GND – The ground connection
3. RX, TX - UART pins
4. Output CH_PD - Chip enable
5. GPIO0, GPIO2 - digital pins

Table 4.7 Wi-Fi ESP-01 module parameters

Parameters	Values
WiFi 802.11b/g/n	802.11b/g/n
WiFi modes	client, hotspot
Supply voltage	1,8 -3,6 V
Communication interface	UART
Consumption current	220 mA

Table 4.7 continued

Communication distance	400 m
GPIO ports	4
Dimensions	13 × 21 mm

Last part of the component's selection is the frame rotating driver. It was selected servo motor. A servo is a mechanism with an electric motor controlled. It is able to rotate the mechanical drive at a given angle at a given speed or force. The most popular servos that maintain a given angle and servos that maintain a given rotational speed. Servos usually have a limited rotation angle of 180 degrees and they are called "180° servo". But there are servo drives with an unlimited angle of rotation of the axis. These are constant rotation servos or "360° servos".

Servo gears come in a variety of materials: plastic, carbon, metal. Plastic, most often nylon, gears are very lightweight, do not wear out, and are most common in servo drives. They cannot withstand heavy loads, but if the loads are supposed to be small, then nylon gears are the best choice. Carbon gears are more durable, practically do not wear out, several times stronger than nylon gears.

The main disadvantage is the high cost. The metal gears are the heaviest, but they can handle the maximum loads. They wear out quickly enough, so it is needed to change gears almost every season. Titanium gears are the favourite among metal gears, both in terms of performance and price. They are quite expensive. The speed if also important part. From the parameters of servo motor to rotate for 60° it takes 0.11 seconds. So for 85° (angle to which rotates frame) it will need 0.15 seconds. This time will be taken to open or close the cage around the drone. According to this information for rotational motor was chosen servomotor Savox SW-2290SG (Table 4.8).

Table 4.8 Servomotor SW-2290SG parameters

Parameters	**Values**
Rotation angle	130°
Operating Voltage	6 ~ 8,4 V
Torque	70 kg·cm (8,4 V)
Speed	0,11 s/60° (8,4 V)
Weight	81 g
Size	40,3 x 20,2 x 38,7 mm
Waterproof	IP67

The second part is servomotor and Arduino connection. Connecting one powerful servomotor can cause a large voltage drop and the controller will not have enough power. Also, the Arduino board has a low-power stabilizer that is not designed for high current consumption and excessive consumption can overheat it and damage the board.

To avoid this, when using powerful servos, it is needed to supply power to the servo separately. For this purpose was taken PWM pin from servomotor is connected to the Arduino digital pin 45.

Last part in the electronic section is power source. For this purpose is used battery 7,4 V, 5200 mAh Li-Po. The weight of the battery is 218 g.

For calculation of battery life was used formula below:

$$t = \frac{C_{BA}}{I_L \times K_I} \quad (4.1)$$

where t - battery life, h,
C_{BA} - battery capacity, mAh,
I_L - load current, mA,
K_I – coefficient of battery (1,428).

Taking into account that current for two parts of TFmini Plus and RPLIDAR A1 sensors, which is 320 mA, Arduino Mega2560 is also required 65 mA, for Wi-Fi ESP-01 it is needed 220 mA. Summing all needed currents was received value of 605 mA.

According to the formula (4.1) the battery life is 6,02 hours:

$$t = \frac{5200}{605 \times 1{,}428} = 6{,}02\ h$$

For the servomotor can be required up to 910 mA. So this value was taken as a maximum value and all calculations will be done using this value. In this case, a servomotor is connected with another battery. It was chosen 8,4 V, 4200 mAh NiMH battery. The weight of the battery is 365 g.

According to the formula (4.1) the battery life is 3,23 hours:

$$t = \frac{4200}{910 \times 1{,}428} = 3{,}23\ h$$

Comparing both results it can be noticed that the battery life using for servomotor supply is in 2 times less than the battery life for other devices. Taking into account that maximum value of the needed current for servomotor will be not constantly, so the battery life will be increased.

Summing up all mentioned components used for assembly of such system it can be said that total number of parts is 14. This system consists of the main parts: controller Arduino Mega2560, Lidar sensors for detection obstacles, servomotor and batteries for power source, Wi-Fi module. The total weight of this system is 865 g. The main part of the weight is batteries weight. The connection of all devices is presented in Appendix 14. All these components are available on the market and can be easily ordered online (Table 4.9).

Table 4.9 List of components for electronical part of the drone cage system

Component	**Quantity (pcs)**
Arduino Mega2560	1
Capacitor 0,1 μF	1
Capacitor 0,33 μF	1
Li-Po 7,4 V, 5200 mAh	1
NiMH 8,4 V, 4200 mAh	1
Servomotor SW2290SG-BE	1
RPLIDAR A1	1
TFmini Plus	2
Wi-Fi ESP-01	1
Logic level converters	1
Voltage regulator L7805	1
Wires	55

5. PROPOSED SOLUTION FOR SYSTEM CONTROL

5.1 Program control description

As the mechanical and electronical parts are selected and designed it is needed to move forward to the control part. This control can be divided into 2 sections. First is the obstacle detection with 3 lidar sensors, which are placed around the drone. Second point is the rotation of the cage by servomotor. For the program development and code writing was used Arduino Software (IDE). This software is free for users and allows easy to write codes and upload it to the board. In additional, any Arduino boards can be used with this software.

For the work of Arduino with the TFmini Plus and RPLIDAR A1, there are ready-made libraries – *TF Mini Library*, *RPLIDAR Library* and *SoftwareSerial Library*. For the Wi-Fi ESP-01 module is used special *ESP8266WiFi Library*. These libraries can be changed according to the user requirements: specified required values, pins.

For the second part, rotating the cage of drone is used the *Servo library* for working with the servo drive. Management is carried out by the following functions:

attach() - attaches an object to a specific pin. There are two possible syntaxes for this function: servo.attach(pin) and servo.attach(pin, min, max). In this case, pin is the number of the pin to which the servo is connected, min and max are the pulse lengths in microseconds, which are responsible for the rotation angles of 0° and 180°. By default, they are set equal to 544 μs and 2400 μs, respectively.

write() - instructs the servo to accept the value of the parameter. The syntax: servo.write(angle) where "angle" is the angle the servo should rotate.

read() - reads the current value of the angle in which the servo is located. The syntax: servo.read(), an integer value between 0 and 180 is returned.

attached() - checks if the object has been attached to a specific pin. The syntax: servo.attached(), boolean is returned if object was attached to pin or false otherwise.

detach() - performs the opposite action to attach(), detaches the object from the pin to which it was attached. The syntax: servo.detach().

Using previously mentioned libraries and functions was made the control of obstacle detection and rotation of the cage by the servomotor. For this purpose pins, global variables, servomotor position were initialized. While the program is running, TFmini Plus and RPLIDAR A1 sensors placed on the drone continuously scan the distances to the obstacles. If the distance to the object is in the range of 40 to 12000 the information about this will be send to user via Wi-Fi. At the same time, the position of the servomotor is checked. After that servomotor will rotate the frame on the needed angle. For this solution the angle is 85 degrees (Figure 5.1).

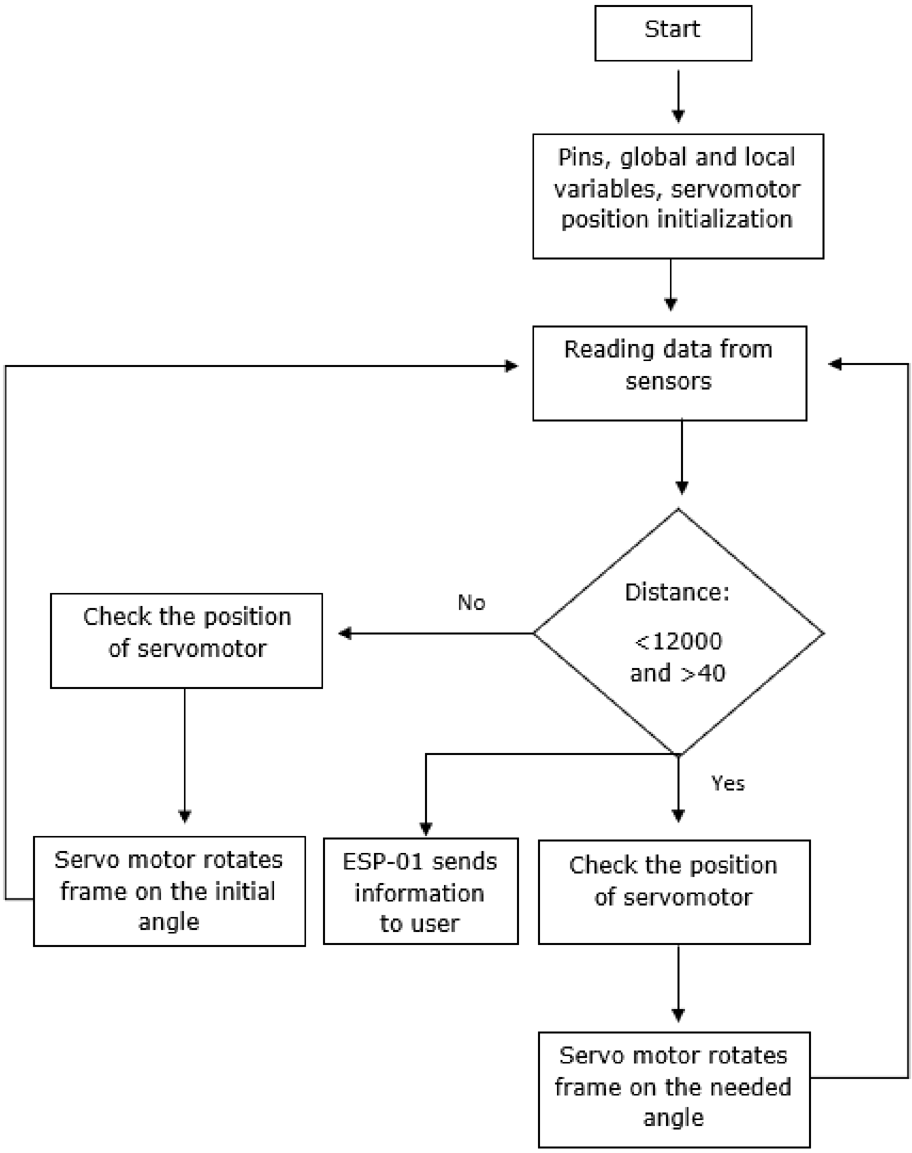


Figure 5.1 Simplified flowchart of the program control

After that the reading values from the sensors will be continued. If the value is more than was set in program the servo motor position will be checked and it will turn back the frame to the initial position. In this case the cage is open again. But if the distance to the object is still less than required value, servo motor will be checked and stay at the same position. The new measurements will be done continuously.

6. SIMULATIONS OF DRONE CAGE SYSTEM

6.1 Simulation of mechanical part

For the testing of the mechanical part was used software Autodesk Inventor Pro 2021. It proposes different opportunities to design mechanical parts, make assemblies and simulate developed solutions. Adding the relationships between rotating parts, moving components can be achieved real behaviour of working frame. Using joints in assembly helps to fully define the range of motion and preview the effect of assembly in the software.

The rotation of drone cage was done manually in simulation mode as it can be done with servo motor in real situation. The initial position before the obstacle detection is above the motors of the drone (Figure 6.1). So, in this way propellers of the drone are also protected. In addition, there is protection for people not to be injured by rotating propellers during the flight start, flight and landing.

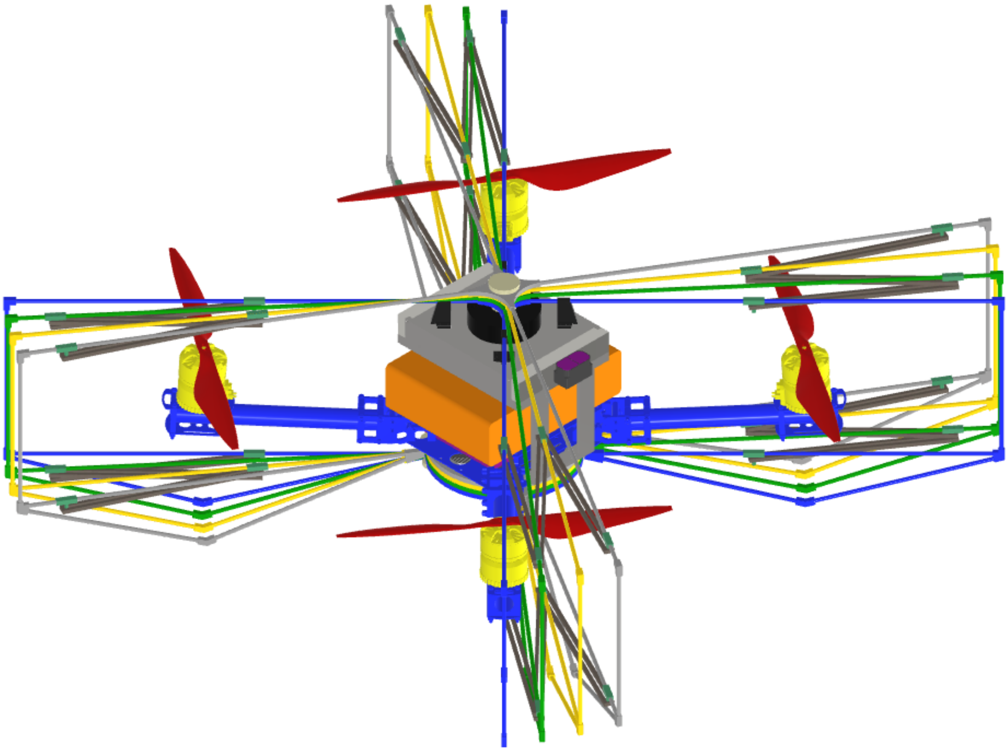


Figure 6.1 Initial position of drone cage before rotation in simulation mode

As for the first rotating frame was used the lead frame, so the rotation is counterclockwise. After the starting rotation when 1/3 of the path is passed the second and third frames started moving beyond the lead frame (Figure 6.2). The plates on the lead frame pull the second frame. At the same time the third frame is pulled by the second frame until the rotation is finished. The fixed frame stays at the initial position without any movements.

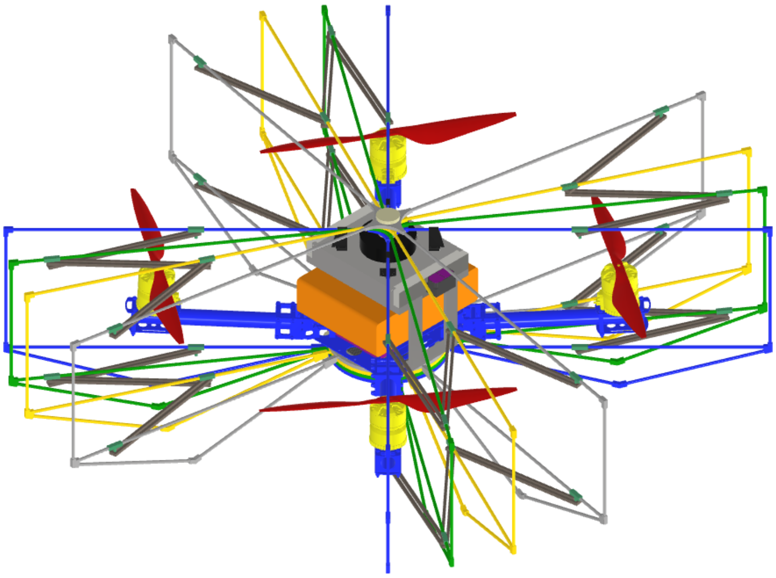


Figure 6.2 Intermediate position during the rotation in simulation mode

At the final position of the rotation frames are on the specified places and the cage is fully opened. The lead frame is located near the fixed frame. The frames between them got their position on the equal distance from each frame (Figure 6.3).

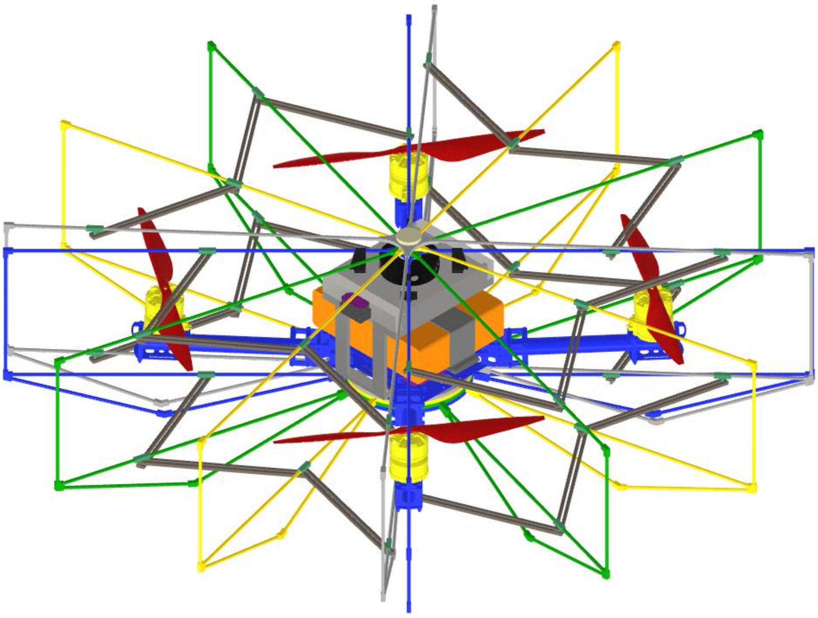


Figure 6.3 Final position of the opened drone cage

During the rotation back to the initial position the frames are closing in opposite direction. The lead frame pushes second and third frame until the initial position is achieved (Figure 6.4).

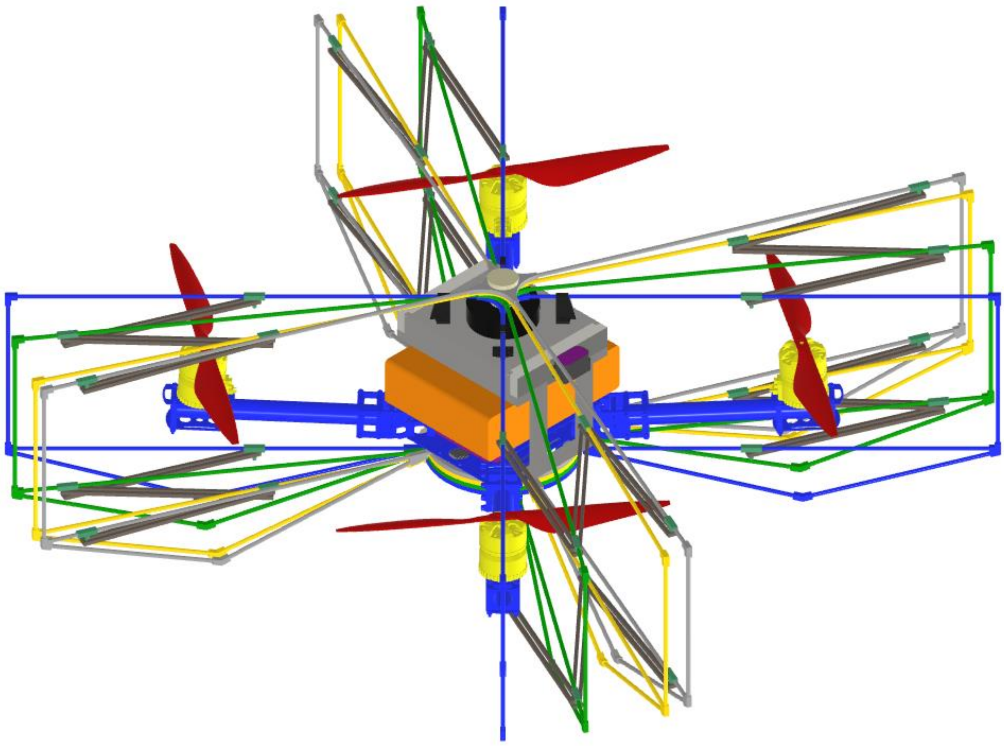


Figure 6.4 Rotation back to the initial position

7. TOTAL COST OF THE CAGE AND FUTURE DEVELOPMENTS

7.1 Cost of components

During the development of drone protective cage system were followed steps to achieve the system which is safety, cheap and that will work properly. For the mass production the cost of part will be cheaper than for the individual purposes. But during the developing were chosen components which have good quality of performance and at the same time these parts are not with high price. Total price of this system including all parts is 581,65 €. The price of each component is presented in Table 7.1.

The project costs were almost equally divided between mechanical and electronic components. The most expensive are servomotor, sensors, batteries and controller. For the good ability of detection obstacles during the flight were selected lidar sensors. They are more expensive comparing with ultrasonic sensors and the weight of such sensors is bigger, but the quality and performance of lidars are much higher.

For the mechanical material point of view carbon-fibre material price is too big. But in this case, was achieved low weight of the developed system with good ability to withstand the loads.

Table 7.1 Price of components used in the cage development

Component	**Price (€)**
Arduino Mega2560	35
Capacitor 0,1 μF	0,05
Capacitor 0,33 μF	0,1
Carbon-fibre plates	55
Carbon-fibre tubes	50
Li-Po 7,4 V, 5200 mAh	25
NiMH 8,4 V, 4200 mAh	30
Plastic for 3D printing	25
Servomotor SW2290SG-BE	140
RPLIDAR A1	95
TFmini Plus (2 pcs)	102
Wi-Fi ESP-01	3
Logic level converters (3 pcs)	9
Voltage regulator L7805	0,50
Wires	12

7.2 Future developments for drone protective cage

Future developments of this system can be important as a step to the new achievements. During the future updates of the mechanical part the several actions can be done. First of all, the weight of the cage with other parts can be decreased by using carbon-fibre materials. But it this way the total price will be increased.

The proposed solution for the frame supposes that frame will be assembled only one time on the drone. After that there will be no disassembles to remove the frame. There are several reasons when user of this cage needs to disassemble cage during the transportation time to make parts more compact or there is no need to use a cage during the flight. For this purpose the cage may be modified. For connection of center part and connection plates with tubes can be used thread inserts. These parts will be placed into tubes and plates. For assembly are used screws. Although the weight of whole frame increases but in provides ability to disassemble parts. In addition, in case of the rework, needed parts can be easily replaced by new.

Additional point is dust and water protection. As it can happen that during the flight's components can get caught in the rain. For the protection it is proposed to and the rubber gasket around the edges inside the box with components. Although two sensors have the water and dust protection but the main RP lidar A1 does not have such good parameters. So additional protection for this sensor can be added to protect it or this sensor can be replaced with another lidar with IP protection. The cost will be increased but the user will be sure that due to the water the device will be not damaged and no extra cost will be needed to replace broken part. In this way it is able to work in open air. Water and dirt cannot affect after that on the working ability.

Another point of further developments can be receiving data from the sensors. Now user will receive information about the protective cage position. But as the sensors have an ability to scan the surrounding area and all points can be provided to user. So using this information can be created the system with the map of the obstacles. This will be a good tool scan and provide information of the scanned area to better understand what is inside or outside the building.

The solution of opening protective cage attached to the drone can be implemented in different areas. One of them is delivery goods by drones. The products will be attached to the drone inside the cage for safety delivery. Before starting the flight, user will open the cage and put products. After that protective cage will be closed. When the drone achieves the needed place, customer will open the cage and receive ordered products.

SUMMARY

This thesis was proposed by the Department of Electrical Power Engineering and Mechatronics at Tallinn University of Technology. This system is an additional part of the safety system for the developed drone in Taltech.

As the field of using drones is significantly wide. This solution will be interesting not only for new users of drones but for professional users, companies that use drones and want to reduce the effect after the damage as well. Cages are a great option for people who are looking to take extra security so that their drone's propellers cannot hurt anyone.

Nowadays different cages are presented on the market. Some of them can protect only propellers from damage. Also there are presented cages that completely surrounds the drone. All these cages have advantages and disadvantages. But the cages which are on the market done for medium sized drone. In addition, attaching the not-opening cage on the drone the view from the camera which can be placed on the drone will have parts of cage on the screen. This is inconvenient to see for ordinary users and for professional as well. Users had to choose between using the drone without a cage, which is very dangerous, or accepting the limited capabilities of the camera when using a cage.

So was made the solution for drone in Taltech which is large sized drone. The research has been done to find different solutions. Also was made the research of obstacle detection. The list of sensors with descriptions was composed to detect the optimal sensors for this project. Different ways of drone protection from the mechanical point of view were also discussed.

For mechanical part were developed frames which will protect drone. All mechanical components were developed in software Autodesk Inventor Pro 2021. The mechanism of the opening and closing cage during the flight is an important part to achieve needed result. The controller, sensors for obstacle detection and batteries are placed in the developed box above the drone. This will protect from the dust and moisture. Also this is extra protection for these parts during the flight. To change the battery or make maintenance of the controller can be easily done thanks to opening box from both sides. In addition, were done stress analyses of the frame in different conditions. The results showed that the frame can withstand the applied force of 18 kg.

This system has 360 degrees all-round view. The base of controller was used Arduino with TFmini Plus and RPLIDAR A1 sensors and servomotor for rotation. Electrical schemes of sensors and servomotor connection with Arduino Mega2560 were created. According to this was made the control program in the software Arduino IDE using the special libraries created for the devices.

In addition, was prepared a total cost of manufacturing drone cage with the proposed solution. For the future developments were suggested the ways which parts can be updated to achieve best performance, additional protection. This topic has a big potential for developing and will make a great contribution to the future of drones and their use.

KOKKUVÕTTE

Selle lõputöö ettepanek oli tehtud Tallinna Tehnikaülikooli Elektroenergeetika ja mehhatroonika instituudist. See süsteem on Tallinna Tehnikaülikoolis välja töötatud drooni turvasüsteemi täiendav osa.

Kuna droonide kasutamise valdkond on märkimisväärselt lai. See lahendus on huvitav mitte ainult uute droonikasutajate, vaid ka professionaalsete kasutajate, ettevõtete jaoks, kes kasutavad droone ja soovivad vähendada mõju ka pärast kahjustusi. Kaitsevõre on suurepärane võimalus inimestele, kes soovivad võtta lisaturvalisust, et nende drooni propellerid ei saaks kellelegi kahjustada.

Tänapäeval on turul palju erinevaid võre. Mõned neist võivad kaitsta ainult propellereid kahjustuste eest. Samuti on olemas võred, mis ümbritsevad drooni täielikult. Kõigil nendel võretel on nii eelised kui ka puudused. Kuid turul olevad võrgud on tehtud keskmise suurusega droonide jaoks. Lisaks sellele, kinnitades droonile avanemata võre, ekraanivaade kaameralt mis on võimalik paigutada droonile võib sisaldada nähtavaid võre osi. See on nii tavakasutajate kui ka spetsialistide jaoks ebamugav näha. Kasutajatele oli vaja teha valikut kas kasutada drooni ilma võreta mis on väga ohtlik või võre kasutades nõustuma kaamera piiratud võimalustega

Siis oli tehtud lahendus Tallinna Tehnikaülikooli droonile, mis on suurte mõõtmetega droon. Uuringud oli tehtud erinevate lahenduste leidmiseks. Samuti tehti takistuste tuvastamine uuring. Selle projekti jaoks optimaalsete andurite tuvastamiseks koostati kirjeldustega andurite loend. Samuti arutati erinevaid droonikaitse viise mehaanilisest vaatenurgast.

Mehaaniliste osade jaoks töötati välja droone kaitsvad raamid. Kõik mehaanilised komponendid töötati välja tarkvaras Autodesk Inventor Pro 2021. Võre avamise ja sulgemise mehhanism on oluline osa vajaliku tulemuse saavutamiseks. Kontroller, andurid takistuste tuvastamiseks ja akud asetatakse drooni kohal väljatöötatud kasti sees. See kaitseb tolmu ja niiskuse eest. Samuti on see kast nende osade jaoks lisakaitse. Aku vahetamiseks või kontrolleri hooldamiseks saab tänu kasti mõlemalt küljele avamisele hõlpsasti hakkama. Lisaks tehti raami pingeanalüüsid erinevates tingimustes. Tulemused näitasid, et raam talub rakendatud 18 kg jõudu.

Selle süsteemi vaade on 360 kraadi. Arduino kontrolleri alust kasutati TFmini Plus and RPLIDAR A1 ja servomootoriga pöörlemiseks. Loodi andurite elektriskeemid ja servomootori ühendus Arduino Mega2560-ga. Selle järgi tehti juhtimisprogramm tarkvaras Arduino IDE kasutades seadmetele loodud spetsiaalseid teeke.

Lisaks koostati pakutud lahendusega drooni valmistamise kogumaksumus. Edasiarengute jaoks on pakutud viise, kuidas osi värskendada maksimaalse jõudluse ja lisakaitse tagamiseks. Sellel teemal on suur arengupotentsiaal ja see annab suure panuse droonide tulevikku ja nende kasutamisse.

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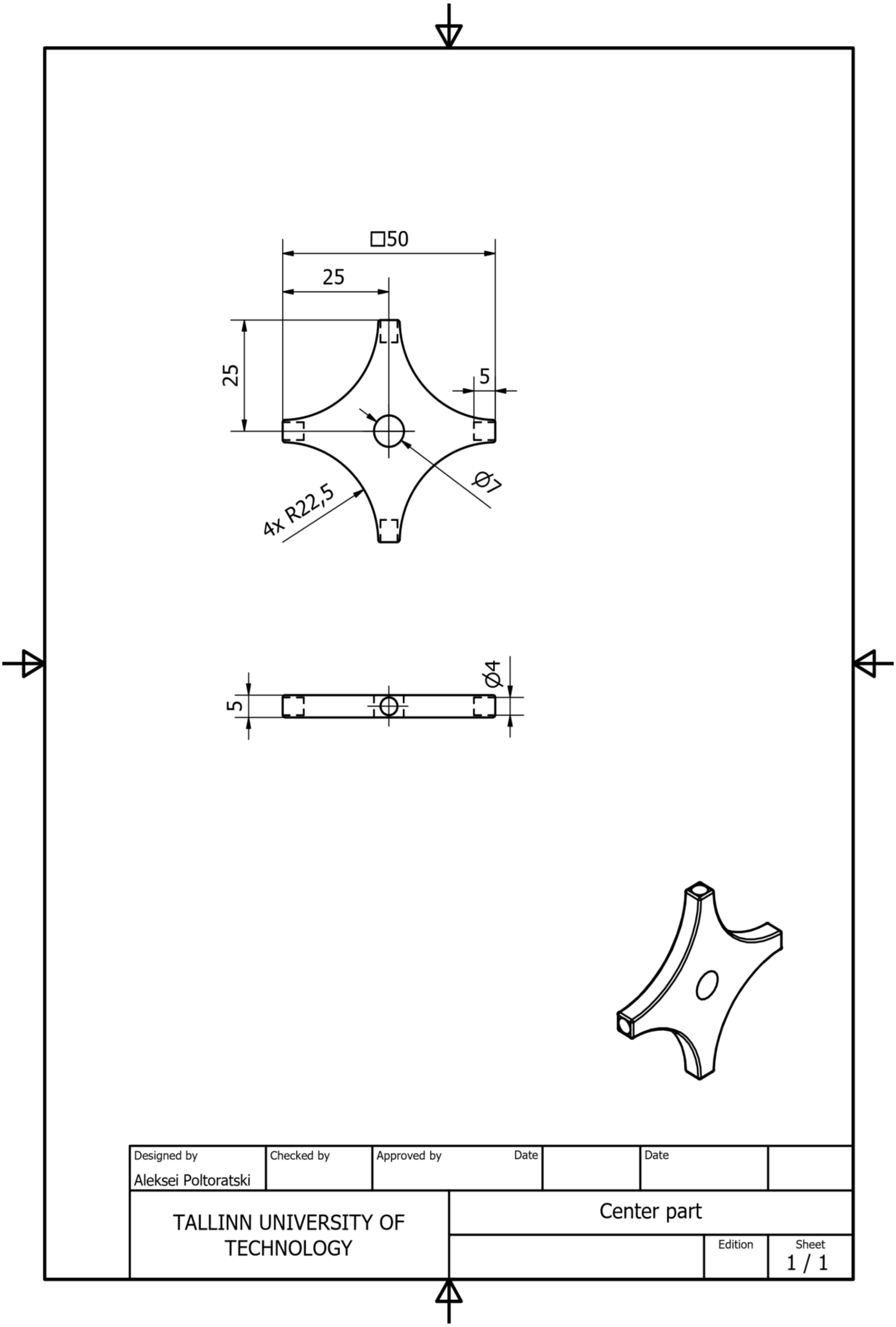
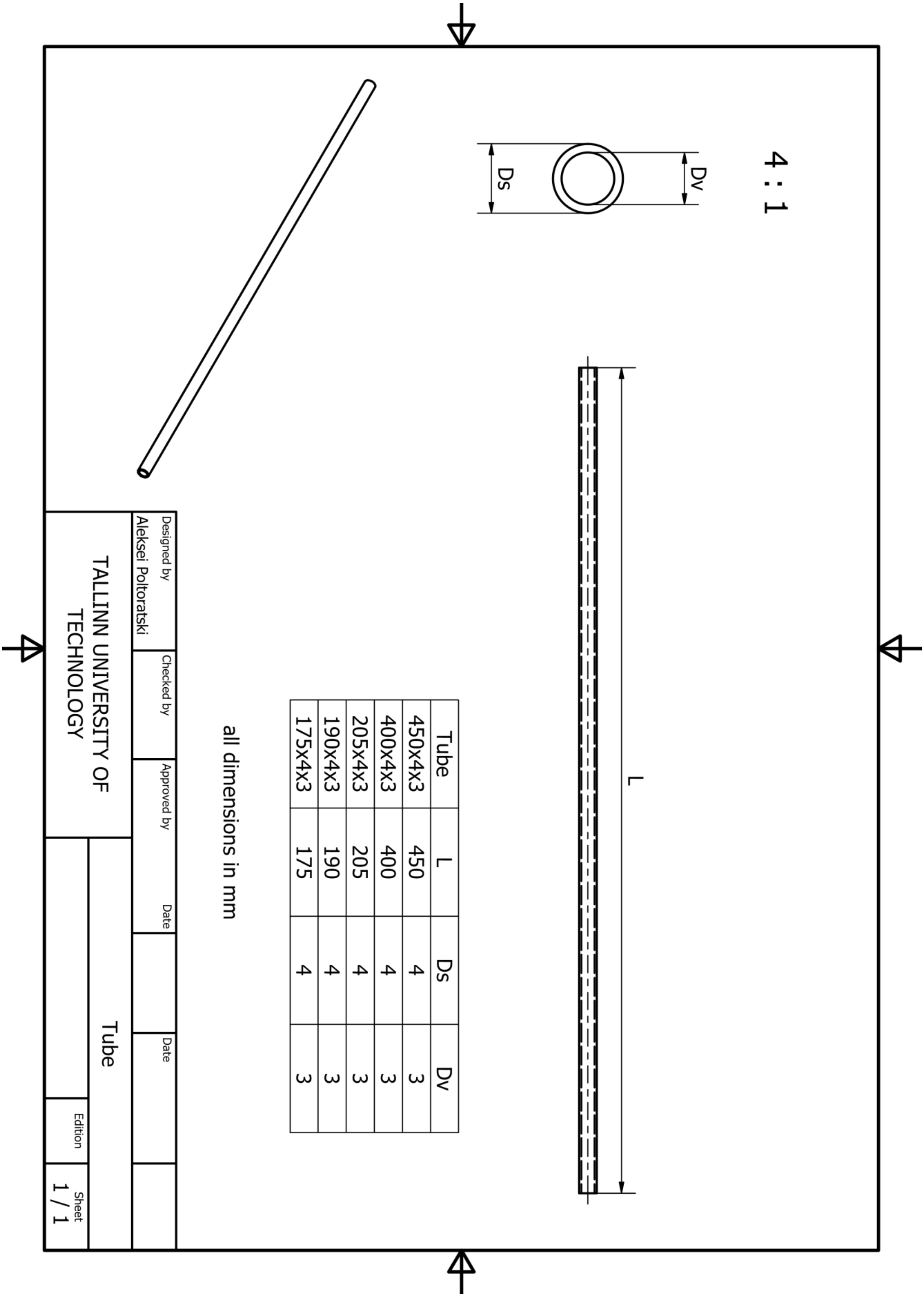
APPENDICES

Appendix 1 Drawing of center part

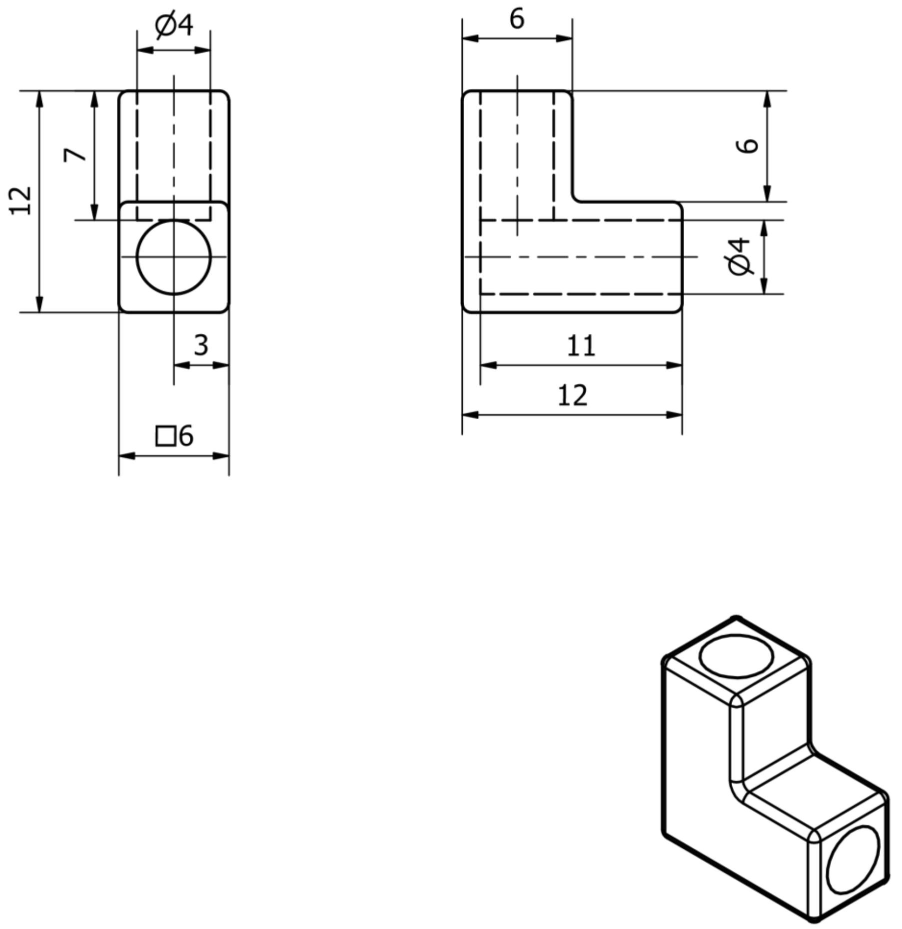


Appendix 2 Drawing of tube



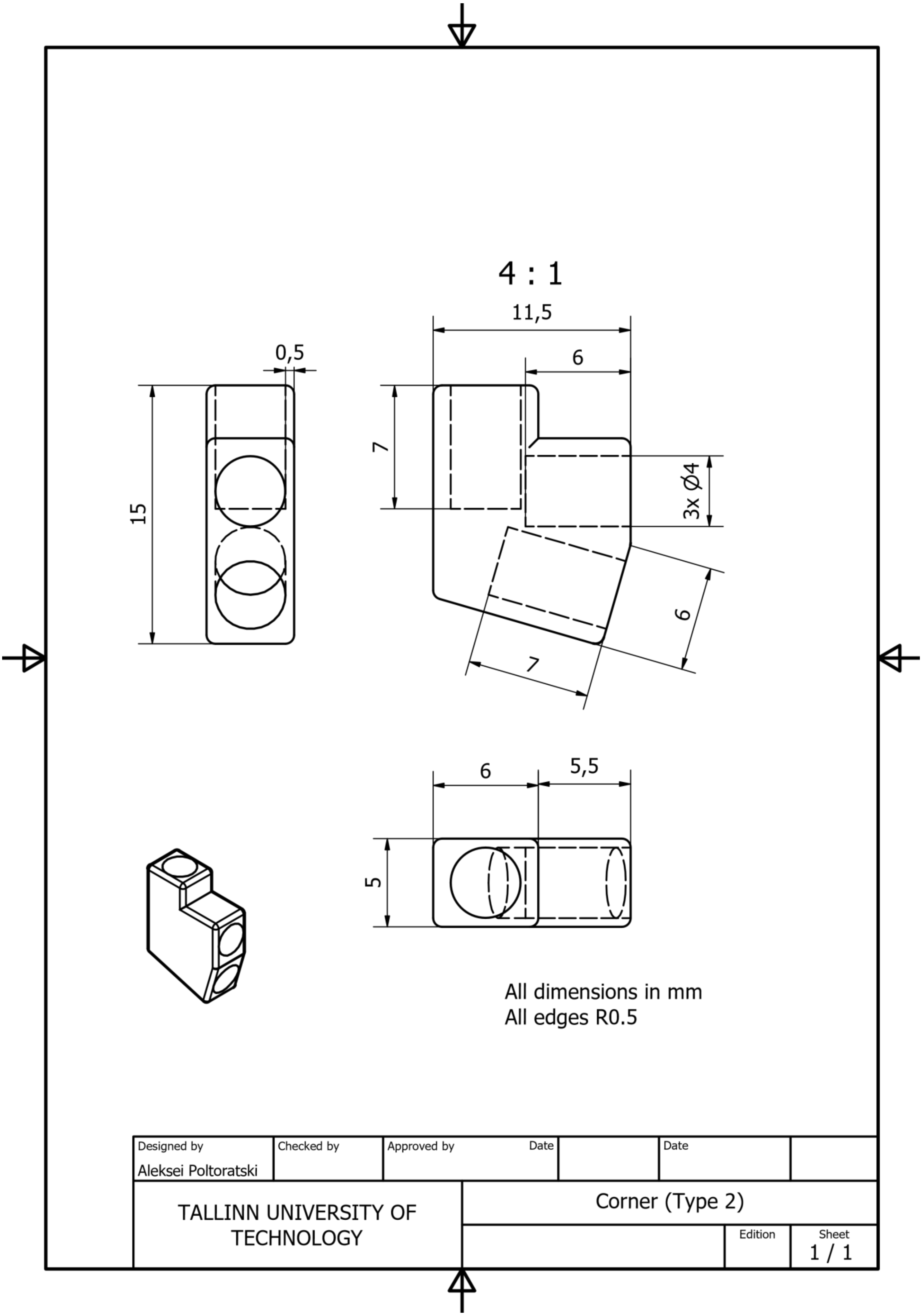
Tube	L	Ds	Dv
450x4x3	450	4	3
400x4x3	400	4	3
205x4x3	205	4	3
190x4x3	190	4	3
175x4x3	175	4	3

Appendix 3 Drawing of Corner (Type 1)

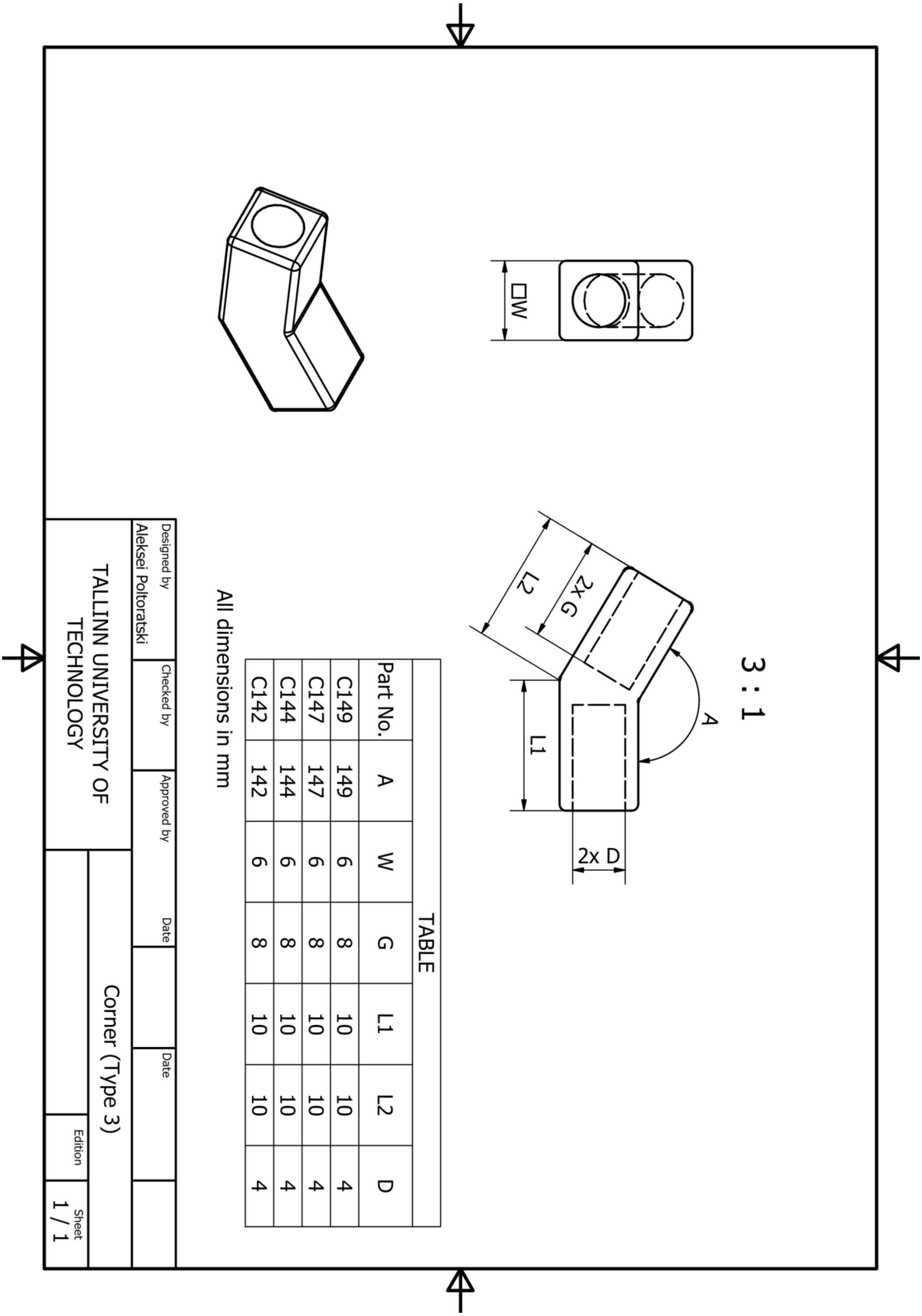


Designed by	Checked by	Approved by	Date		Date	
Aleksei Poltoratski						
TALLINN UNIVERSITY OF TECHNOLOGY		Corner (Type 1)				
		Corner90			Edition	Sheet 1 / 1

Appendix 4 Drawing of Corner (Type 2)



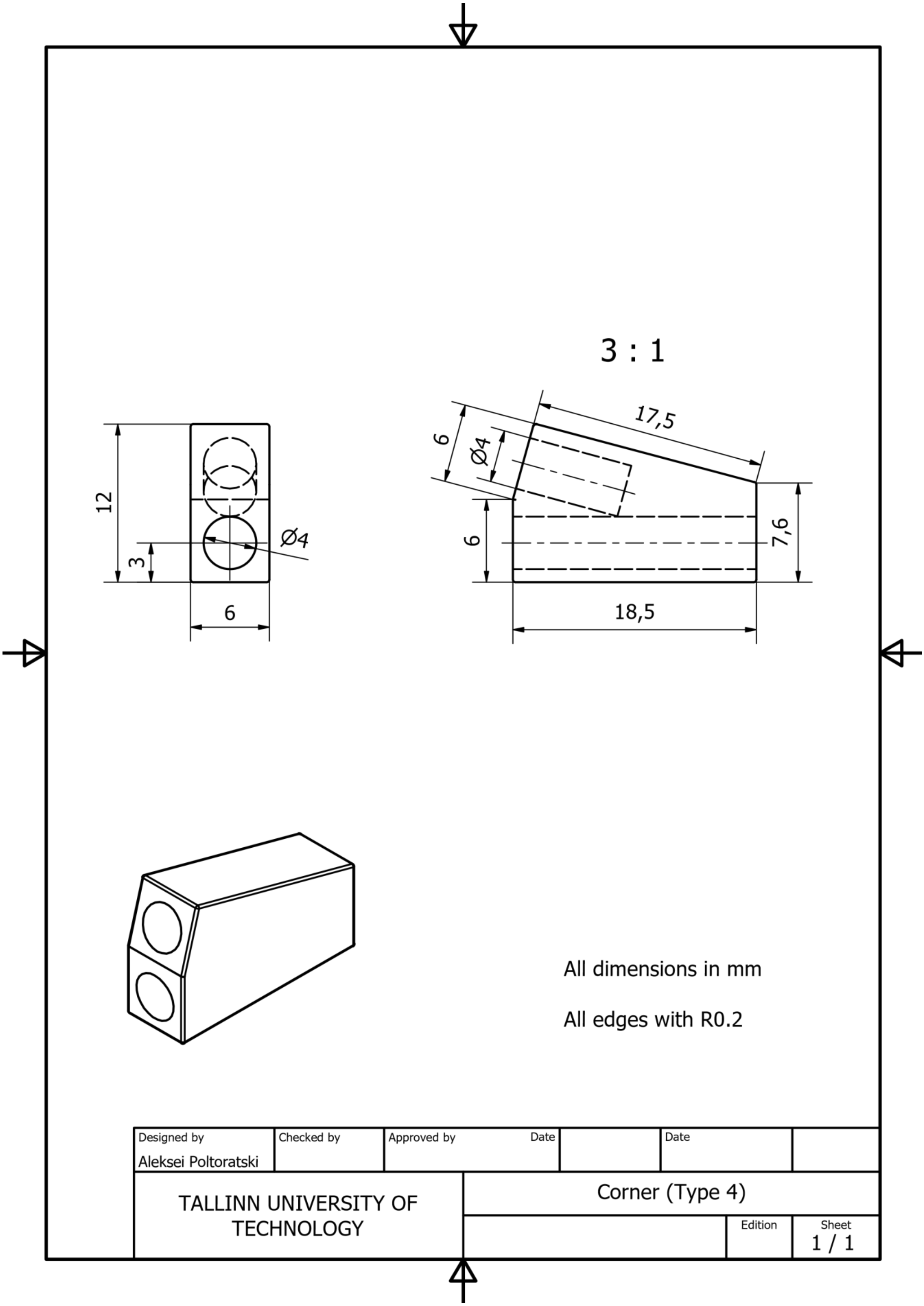
Appendix 5 Drawing of Corner (Type 3)



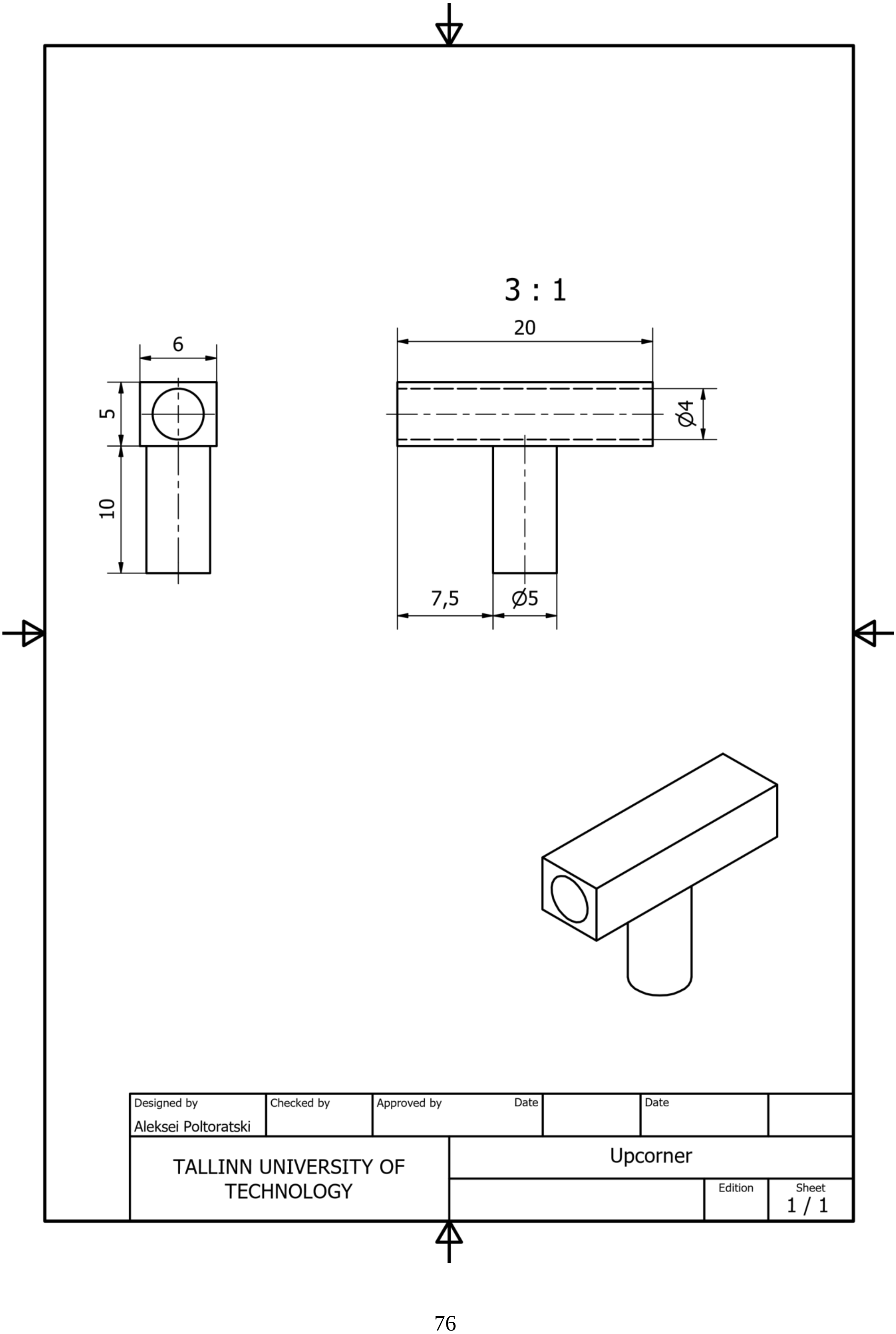
TABLE

Part No.	A	W	G	L1	L2	D
C149	149	6	8	10	10	4
C147	147	6	8	10	10	4
C144	144	6	8	10	10	4
C142	142	6	8	10	10	4

Appendix 6 Drawing of Corner (Type 4)



Appendix 7 Drawing of Upcorner



Appendix 8 List of components for frame assembly

Tabel A.0.1 List of components for frame assembly

Component	**Quantity (pcs)**
Carbon fibre connector (Type 1)	16
Carbon fibre connector (Type 2)	16
Carbon fibre connector (Type 3)	16
Carbon fibre connector (Type 4)	16
Carbon fibre tube 450x4x3	16
Carbon fibre tube 400x4x3	16
Carbon fibre tube 205x4x3	16
Carbon fibre tube 190x4x3	16
Carbon fibre tube 175x4x3	16
Connection bottom plate	1
Connection plate	3
Centred part	4
Frame holder	4
Plates for frames connection	12
Top holder	1
Upcorner	32

Appendix 9 Simulation results in opened stage without additional load

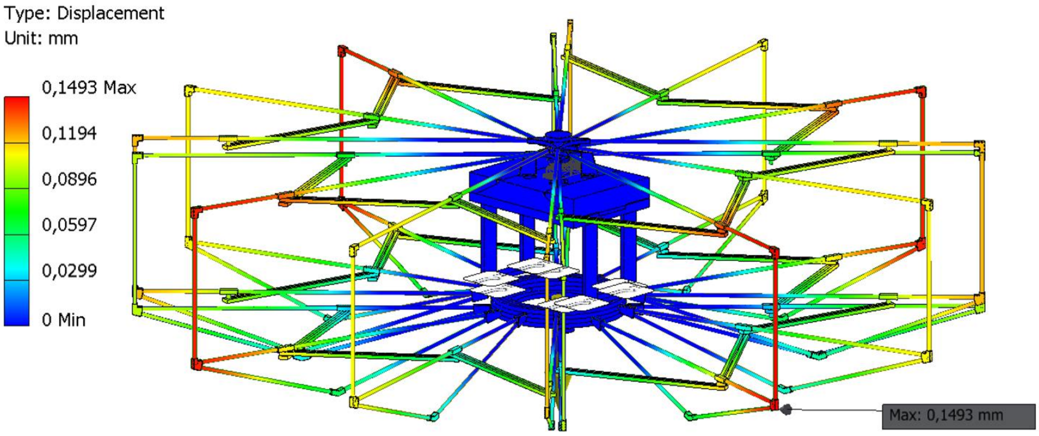


Figure A.1 Simulation results of displacement in opened stage without additional load

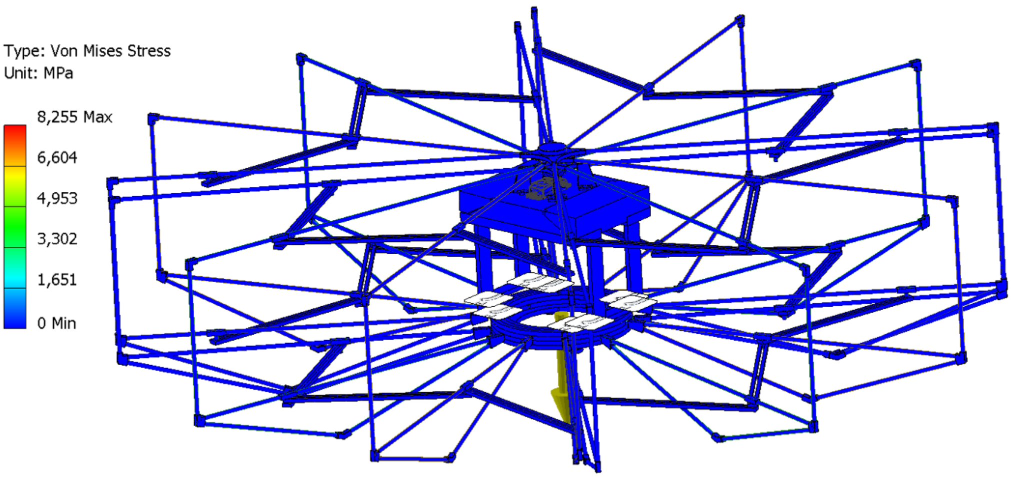


Figure A.2 Simulation results of Von Mises Stress in opened stage without additional load

Appendix 10 Simulation results in closed stage without additional load

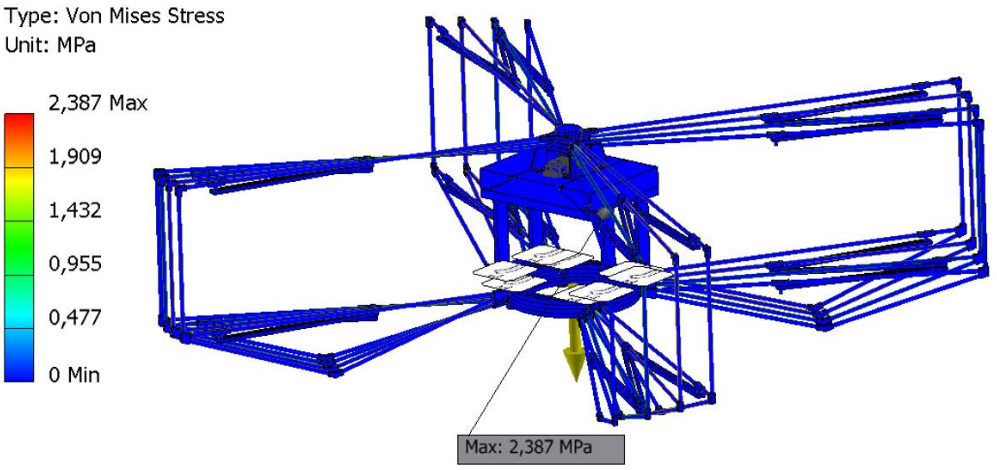


Figure A.3 Simulation results of Von Mises Stress in closed stage without additional load

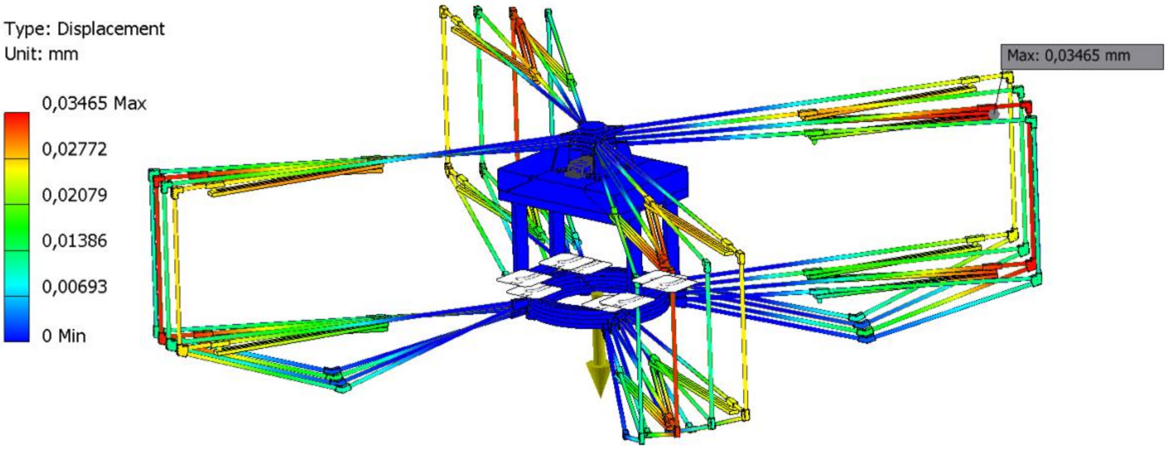


Figure A.4 Simulation results of displacement in closed stage without additional load

Appendix 11 Simulation results with load applied on top holder

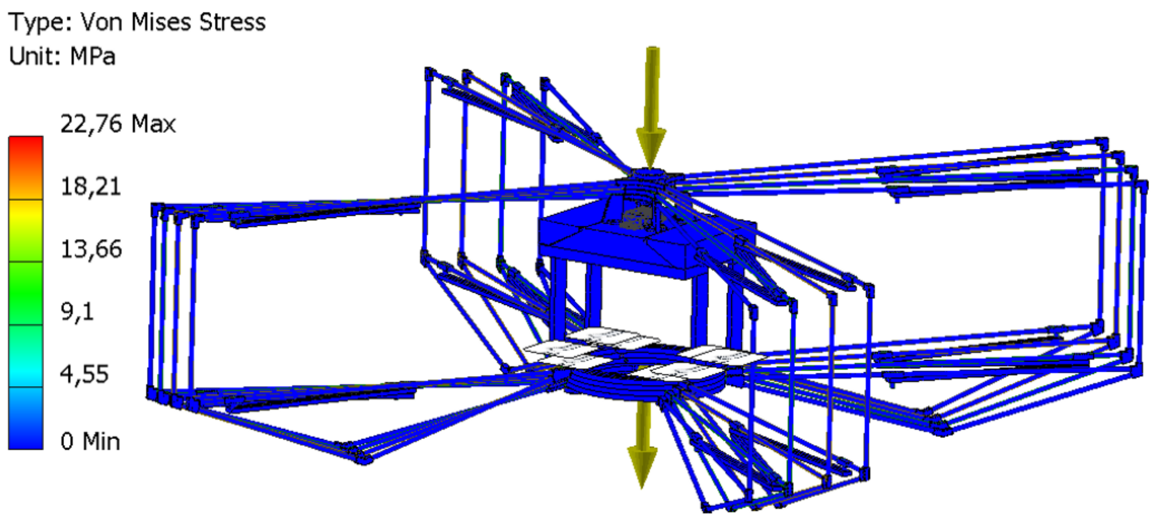


Figure A.5 Simulation results of Von Mises Stress with load applied on top holder

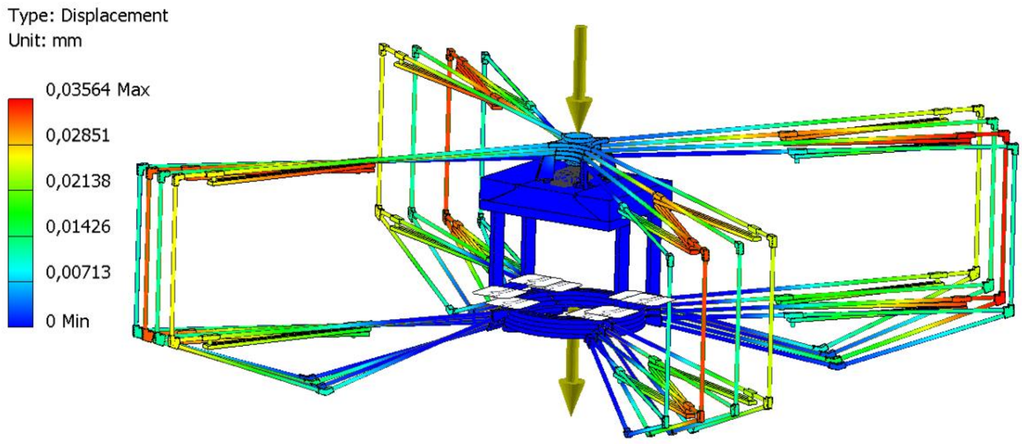


Figure A.6 Simulation results of displacement with load applied on top holder

Appendix 12 Simulation results with load applied on the sides

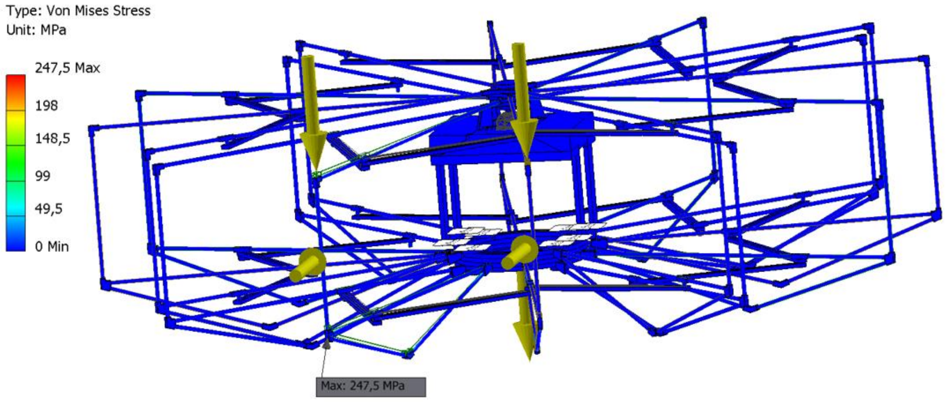


Figure A.7 Simulation results of Von Mises Stress with load applied on the sides

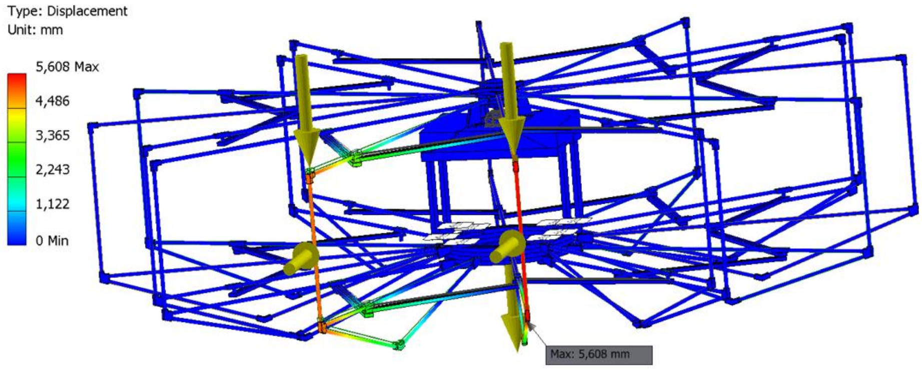


Figure A.8 Simulation results of displacement with load applied on the sides

Appendix 13 Simulation results of frame as support of drone

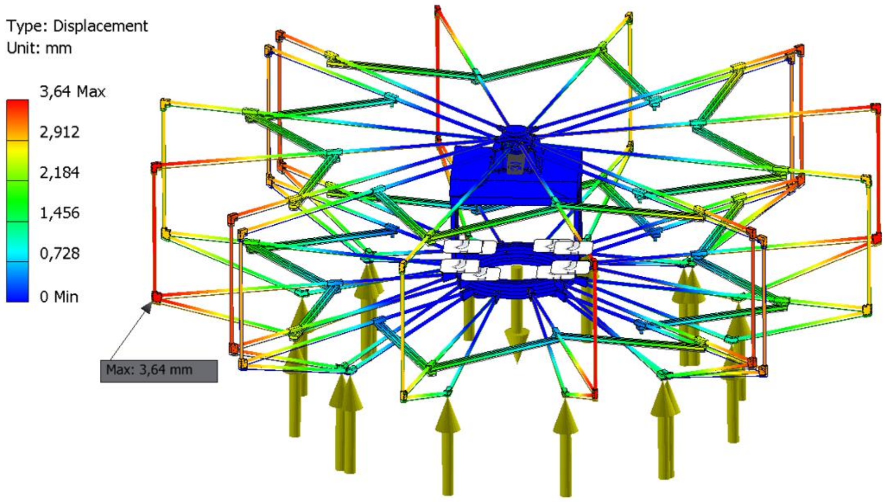


Figure A.9 Simulation results of frame displacement as support of drone

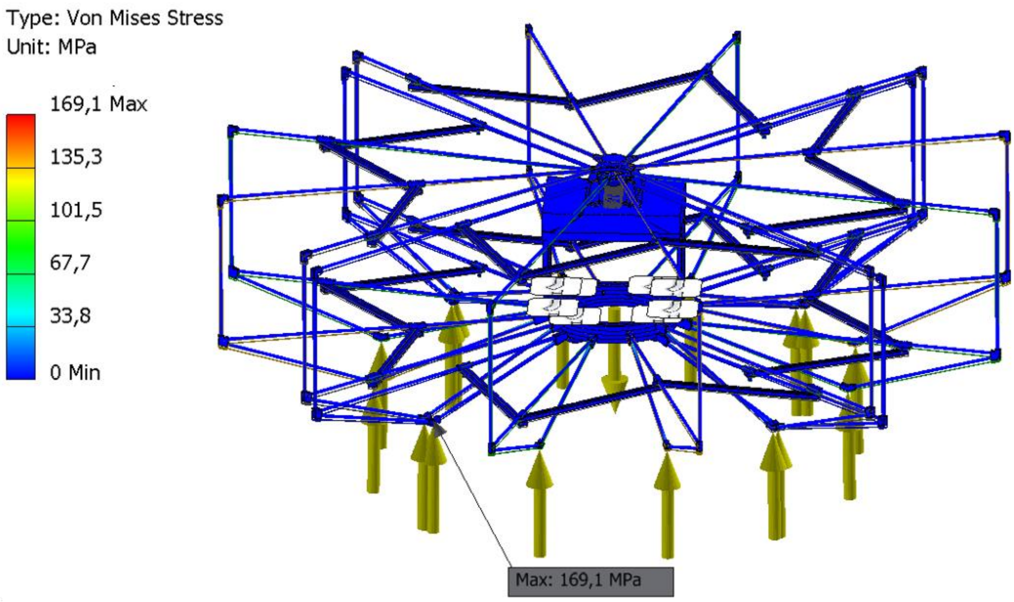


Figure A.10 Simulation results of Von Mises Stress frame as support for drone

Appendix 14 Electrical circuit of devices connection