TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Electrical Power Engineering and Mechatronics

DRONE PARCEL DELIVERY SYSTEM FOR TALTECH UNIVERSITY CAMPUS

DROONI PAKIVEO SÜSTEEM TALTECH KAMPUSES

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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Design an autonomous delivery system based on Wingcopter 178

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PREFACE

The following work would not exist without double degree program between Mechatronics Departments of two great universities – ITMO University and TalTech – that generously let me to study at both of them.
Mart Tamre initiated the thesis topic, and I appreciate him for entrusting this project to me. During the work process, Yurii Monakhov helped me to find better solutions for my ideas, and I am grateful for that.
And last thing but not least, I would like to mention the great help of Jalal Sadigli, who was cooperating in following work, providing fresh ideas and sharing his knowledge.

Definitely, this work gave me a great experience in understanding the drones combined with delivery systems. I have gained useful knowledge in modelling and controlling and even had an opportunity to use this knowledge in practice.

Key words: drone, delivery, SolidWorks.

List of abbreviations and symbols

AC – Alternating Current.

CAD – Computer-Aided Design.

CNC – Computer Numerical Control.

DC – Direct Current.

RC – Radio Control.

RPM – Rotations per Minute.

RPS – Rotations per Second.

UAV – Unmanned Aerial Vehicle.

VTOL – Vertical Take-Off and Landing.

INTRODUCTION

Last few decades clearly represent how humanity is becoming more and more dependent on digital world. Various types of robots are replacing different types of human labour over time. There could be little doubt that eventually mechanization of the whole world will reach the point, when robot activity will substitute almost every monotonous action.

Drones, originally made for military reasons, nowadays got smaller and lighter and they are now being used in healthcare and commercial delivery, cinematography, research and even investigation missions.
Accessibility of the drones and their speed are the main reasons why companies are getting interested in implementing drone delivery systems into their logistics. In compare with on-ground delivery, which is overloaded by any kinds of transport, on-air delivery is more tempting for the logistics of companies, because of its relative emptiness and level of freedom of movement.

Interested organization for this particular work is TalTech University. TalTech Mechatronics Department has Wingcopter 178 in laboratory, which is a VTOL type of drone. The task is to suggest a delivery system design, which allows sending and receiving a small cargo between the buildings of University.

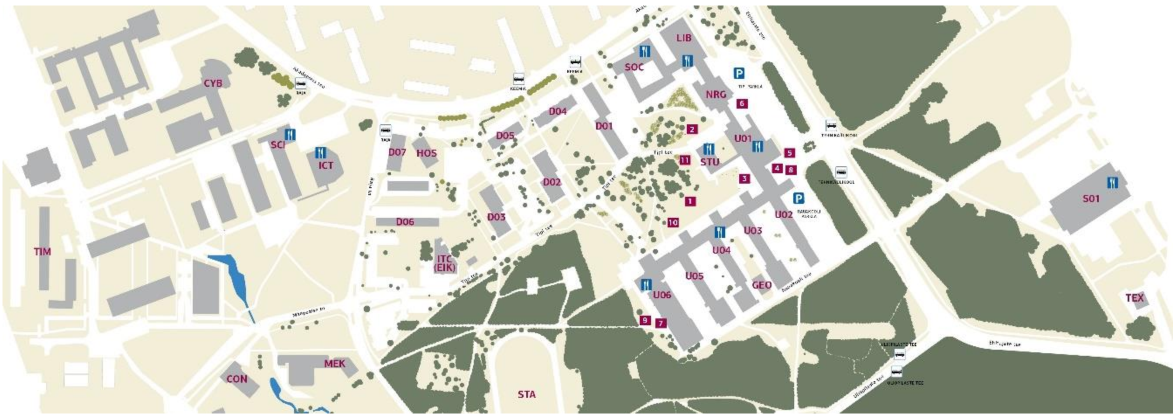


Figure 0.1: Map of TalTech buildings (named by red text) [1].

According to this scheme, two furthest buildings are “TIM” (Building of Woodworking) and “TEX” (Textile Technology Building). From Google Maps we can see that there are approximately 1,6 km between them.

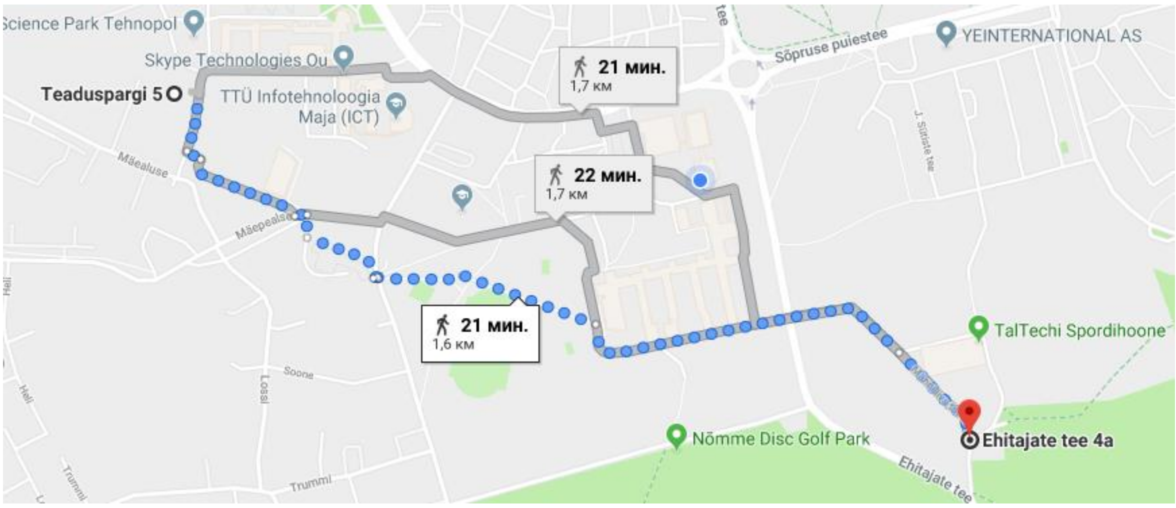


Figure 0.2: Distance between two furthest buildings of TalTech (screenshot is taken from Google Maps).

Therefore, for now we can mark main objectives:

1. Delivery system should be as autonomous as possible:
    a. User should not interact with the drone in any way possible (coming close to the drone, touching it and putting the cargo himself or taking it off);
    b. User should not control the whole delivery, since the drone is able to follow "missions" – so called pre-defined trajectory of the flight, including take-off and landing.
2. Drone is able to lift at least 2 kg according to the creators [2]**.** These 2 kg will include:
    a. The cargo;
    b. The box for cargo and grabbing system.
3. Field for further improvements such as increased distance between delivery points. For example, delivery between two towns or population centres. Besides, delivery system should consider the case of upgrading the drone to "Heavy Lift" version, when cargo mass will be increased to 5 kg.

Further in next chapters these objectives will be expanded and analysed in more detailed way.

1 EXISTING SOLUTIONS

Before starting to design the delivery system we need to analyse existing designs, which are implemented into companies' production flow or going to be in future.

1.1 Amazon Prime Air

Firstly announced in 2013 as a concept of drone-based delivery system by Amazon CEO Jeff Bezos. Currently project is still on concept stage. At the moment Amazon presented only their first deliveries by drone.

Figure 1.1: Amazon Prime Air drones designs [3].

Amazon has presented different designs of drones, but working principle is similar. Customer choses the product he wants to buy, then Amazon operator puts that product in the box and conveyor delivers the box to "scissor" type elevator, which lifts the box to the bottom of drone. Drone has simple grabbers, which will not let the box to fall off during the flight. Landing point should be marked by specific marker, so the camera under the drone will be able to detect it [3]. Project is designed for light and small goods, which are able to fit in the cargo box.

1.2 Flytrex Drone Delivery

Israeli drone logistics company Flytrex in cooperation with Iceland’s shopping website AHA created a drone-based delivery system.

Figure 1.2: Modified DJI Matrice 600 is the main vehicle of Flytrex for deliveries [4].

Project is oriented to deliver the food and small electronics. Drone is able to reach 10 km with maximum 3 kg load [5]. After customer has made his choice, operator puts the package with product into the box, which is attached to the drone’s legs. Then operator sets the trajectory for delivery.

Flytrex delivery drones started to operate in 2017. Though drone is not controlled the whole flight and it follows the pre-set trajectory, design is not fully autonomous, because on take-off and landing points there are operators of company to exclude customer interaction with the drone.

Company uses for the deliveries modified DJI Matrice 600: it has cargo box attached to the legs of the drone.

1.3 Wingcopter 178 Heavy Lift

Modified Wingcopter 178, which has additional cargo box for deliveries.

Figure 1.3: Wingcopter 178 Heavy Lift used in cooperation with DHL and GIZ for delivery missions in Tanzania [6]

Wingcopter 178 is a VTOL type of drone created in Germany in 2018. Originally it is a drone without any capability to deliver the cargo. But there is a modified version of the drone, which is called "Wingcopter 178 Heavy Lift": it has more powerful motors and a cargo box attached to the bottom of it and can be dropped manually or via remote control. This version (but coloured to DHL's logo as on Figure 1.3 above and called Parcelcopter 4.0) was used in delivery missions in Tanzania by DHL and GIZ for healthcare reasons: delivering medicine for regional hospitals and blood samples from there. The distance between two delivery points was 60 km and Parcelcopter 4.0 was flying it over in 40 minutes.

Wingcopter can be controlled manually with remote radio controller and automatically by pre-setting trajectory of the flight on tablet [7]. Though it is possible to drop the cargo box remotely, it is required for user to put the cargo into the box (or to take it out of the box) by himself. Regular version of drone is able to carry a payload with maximum mass of 2 kg and the "Heavy Lift" version – 6 kg. Mechatronics Department of TalTech has only the regular version of drone, therefore further work of thesis is based on it, but at some moments with consideration of upgrading it to "Heavy Lift" in future.

1.4 Other solutions and summary

Besides described solutions above there were other experiments and commercial systems with delivery drones.

American medical delivery company “Zipline International” oriented into deliveries by drones from 2014 and two years later they launched their delivery system in Rwanda. Their drones able to carry 1,5 kg payload and can fly over 120 km. Drones do not take off – they are launched by catapult, and in similar way they are caught by wire system (as an arresting gear on aircraft carriers). Flight trajectory is programmed by operators using satellite map. During the flight above the delivery point cargo drops with parachute and lands to the required place. In 2018 they started to use new generation drone, which is faster (128 km/h), able to reach 160 km and to carry 1,75 kg payload [8].

Other project is Wing, which was a company under “Google X”, now is independent department of Alphabet. Nowadays they offer drone delivery service in Finland and Australia. Delivery system is fully autonomous: customer orders a product, merchant packs the product into a special package, which will be connected by him to the tether from the drone, hovering at 7 m above; then tether pulls the package to the bottom of drone, and drone flies to the customer; reaching the delivery point, drone hovers at the same height, while tether will descend the package to the ground; as soon as the package is on the ground, tether goes back and drone flies away. Maximum mass of the package is 1,5 kg [9]. The problem is that the merchant is not able to attach the package to the drone as soon as he wants, but he needs to wait, until drone will come. Besides, customers must wait 2 m away until cardboard package will touch the ground, which might be not an option for customer.

And besides from these, there were experiments from other companies, here are some most popular ones of them:

- In 2014 mail services company La Poste tested delivery drone, controlled by operator during the whole flight. It was able to carry 4 kg payload and fly over 20 km [10].
- DHL has a “Parcelcopter” department, which is creating and testing different types of drones in hard-to-reach places such as open sea or mountainous regions. From 2013 until now they have created 4 generations of Parcelcopter [11]:
    - First prototype was tested to deliver medicine with mass about 1,2 kg Drone: manually controlled quadcopter; Maximum speed: 43 km/h; Maximum distance: 1 km.

    - Year later second model was tested. Drone was the same with same characteristics, but with following differences: autonomous control system and maximum flight distance 12 km.
    - In 2016 there DHL changed the drone to a tiltwing aircraft, which was able to carry 2 kg of payload to 8,3 km with 70 km/h speed and to reach 500 m altitude.
    - Fourth generation was made in 2018 in collaboration with Wingcopter, which was already described above.
- In 2017 Chinese company JD had 7 types of delivery drones, which were able to carry a payload with mass between 5 and 30 kg. But drones do not deliver the product directly to customer: at the delivery point operators take out the package to hand it over to customers by themselves [12].

Table 1.1: Summarised description of delivery systems presented in this chapter (some data is not provided by creators).

Name of company or drone	**Maximum payload mass**	**Maximum speed**	**Maximum distance**	**Delivery system autonomy**
Amazon Prime Air	2,25 kg	-	16 km	Fully autonomous, but has not been implemented yet.
Flytrex Drone Delivery	3 kg	-	10 km	Operators in storage and delivery points required.
Wingcopter 178 Heavy Lift	6 kg (2 kg)	130 km/h	65 km	Operators are required to put in (or take out) the goods.
Zipline International	1,75 kg	128 km/h	160 km	Operators launch the drone with a package.
Wing	1,5 kg	-	-	Fully autonomous.
JD	30 kg	-	-	Operators in storage and delivery points required.

As we see, currently optimal autonomous delivery drone system is offered only by Alphabet's Wing. So, based on described existing solutions and their problems we were able to mark main tasks, which are presented in Introduction chapter.

2 DESIGN PROCESS

2.1 Delivery scenario and division of the system

In order to design fully autonomous delivery system we need to divide the process of delivery into several steps to analyse each scenario and for:

1. User needs to send a certain cargo from building A of TalTech to building B. He goes up to the rooftop of building A with that cargo and puts it to the cargo box under the drone.
2. As it may be dangerous for ordinary user to interact with the drone there is a need to create one more "stage" between them. Function of this "stage" can be performed by specific robot, which delivers cargo box from a user to the drone. So, because of the additional robot, there may be required to keep the drone on certain platform, therefore robot will be able to hand over the cargo box to the drone.
3. There may be several options to hand over the cargo box to the drone.
    a. Robot itself hands over the cargo box to the drone by planting it on certain construction on the bottom of drone, placing it into it or fitting it.
    b. Robot just delivers the cargo box to the bottom of drone, and the grabbers under the drone take over the cargo by catching it.
    c. Combination of options "a" and "b": robot delivers the cargo box in certain position according to the position of drone and the drone grabs the cargo box after detecting it.
4. While the box is being transferred to the drone, user sets up a flight trajectory in a tablet (ground control centre) from building A to building B and leaves.
5. Drone starts the flight after the cargo box is attached.
6. When it reaches the building B, it lands on the platform, which is mentioned in step 2. That platform must adjust the position of the drone in certain way, because drone does not land at the same direction every time.
7. After the position of the drone has been adjusted, robot takes over the cargo box according the way chosen in step 3:
    a. Robot takes over the cargo box itself without any action from drone side.
    b. As the drone loosens its grabbers or any other mechanism on bottom of it, robot will catch the cargo box.

   c. By cooperation the drone helps the robot to catch the cargo box. This method assumes certain communication between robot and drone.
8. As the robot caught the cargo box, it moves towards the user, finishing the delivery process.

As we see, the whole delivery process consists of several main parts. Here is the short description of each of them:

- Platform.
  We need a platform as a place for drone to land. Main function of it is that it keeps the drone at certain height from floor, so the robot will be able to transfer the cargo box. Additional function is drone’s position adjusting mechanism, which will be installed on the platform. Additional function depends on the designing option.

- Robot-courier.
  Robot will be used to avoid human interaction with the drone. Main function is to transfer the cargo box from user to the drone and from the drone to user. Additionally it may be able to push the cargo box to fit into grabbers.

- Cargo box.
  This part of work must define, how cargo box will look like: external and internal shape. Besides, depending on grabbers construction, there must be defined the form of holes or any other chosen joint types.

- Grabbers.
  Here we need to ascertain the construction of grabbers: their form (are they static or controlled mechanisms), position (on the bottom of drone or on the cargo box itself) and what will be the material.

Therefore, further designing process will be divided into described parts, but with considering the fact that every part of designed delivery system works in combination.

2.2 Suggested solutions

During the designing process there were several solutions. These solutions are not final because they had their disadvantages. Some of suggested solutions are presented below with simplified schematic illustration of the design.

2.2.1 Conveyor with 3-axis platform

First solutions were mostly based on conveyors because of their relative simplicity in purchasing them and installing. To avoid human interaction with the drone, there could be a conveyor, which delivers the cargo box from the user to the drone and vice versa.

Drone is placed on the platform, which is able to move in 3 different axis and able to rotate the drone. Motion is provided by pneumatic motors or stepper motors as in CNC machine.

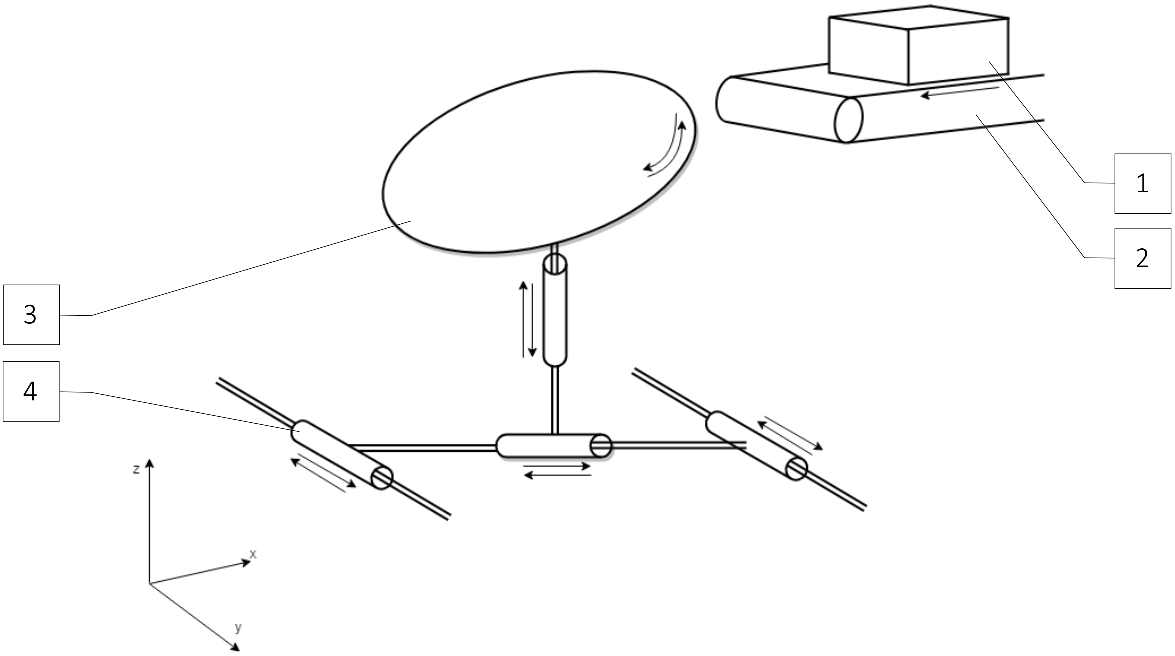


Figure 2.1: Scheme of suggested delivery system with a conveyor (on the right) and a 3-axis platform (in centre). 1 – Cargo box; 2 – Conveyor between a user and the drone; 3 – landing platform for drone; 4 – motors installed on shafts.

This design takes into account the drone landing differences, when the drone does not land the same position as it took off before. Rotation of the platform solves the wind problem, when it might change its direction completely: platform turns the drone opposite to the wind. And after that it will turn the drone towards the cargo box, coming on conveyor. Constructively this system is close to CNC machines, where end-effector is able to move in 3 different axis, but instead of the gripper there would be a landing platform.

2.2.2 Position adjusting conveyor

Complexity of the previous design prompted to come up with the simpler systems. This design consists of two conveyors: one of them performs the function of a courier between the drone and a user, other one – modified to be able to adjust the position of the drone.

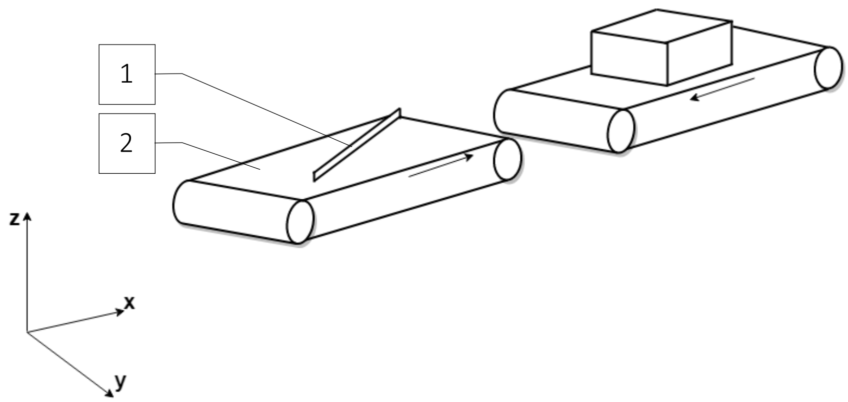


Figure 2.2: Scheme of delivery system with position adjusting conveyor. 1 – An obstacle installed on the conveyor in certain degree; 2 – conveyor as a landing platform.

It has an obstacle for the leg of the drone. By moving the conveyor forward, leg of the drone will get stuck on obstacle and because of the conveyor motion it will replace the drone to required direction.

But the main disadvantage of this design is that it is not intended for wind changes.

2.2.3 Moving platform

Moving platform is one of the versions of conveyors. As the conveyor belts will bend under the weight of the drone, especially when it is carrying the cargo box, it is unreasonable to use that type of conveyor. Slat and roller conveyors are much more expensive to design. In addition conveyor is perfect for continuous motion, but this case does not require it, since it is a landing platform. Therefore moving platform would be less expensive and more reasonable option.

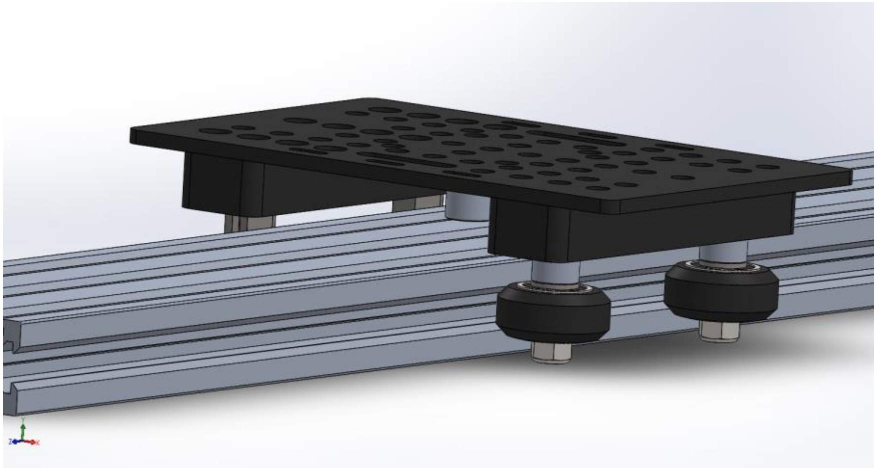


Figure 2.3: Model of V-slot belt driven actuator [13] as an example of landing platform instead of using a conveyor.

It consists of two platforms: upper one moves in two ways by horizontally installed wheels under it. They are rolling on the second platform with suitable cut-out, so the motion occurs as on the rails. Changed type of landing platform must be combined with construction of position adjusting conveyor, which is described above in 2.2.2.

2.2.4 Rotating platform

This design includes two platforms. One of the platforms is bigger and static, other one is smaller rotating platform, which is placed between the bigger one. It is used for the cargo box, which has a screw on it. Scenario of delivery: user puts the cargo box on the smaller platform; the drone lands with legs touching only bigger platform; the small platform starts the rotation, so the screw on the box plugs into the drone's screw holder inside of it.

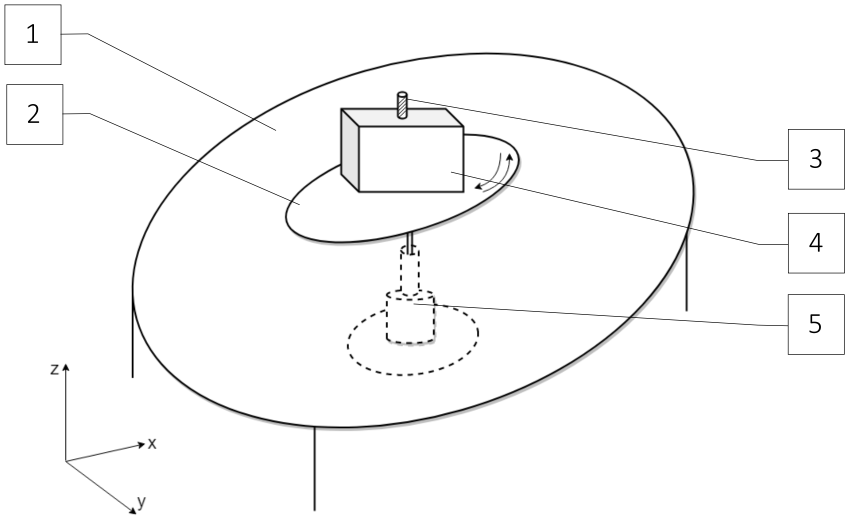


Figure 2.4: Scheme of delivery system with rotating platform. 1 – Big static landing platform; 2 – smaller rotating platform for cargo box; 3 – screw for attaching the cargo box to the drone; 4 – cargo box; 5 – base of smaller platform with motor, shaft etc. which will be under the landing platform.

The main weakness in this case is that the platform must detect the screw holder precisely, which is a problem, because otherwise screw will not get into the holder. If we decide not to detect the holder, then there is a problem with accuracy of landing of the drone.

2.2.5 Smart courier

This suggested design is as complex as the conveyor with 3-axis platform. Main idea is instead of installing a conveyor between a user and the drone, to create a smart robotic courier, which does all the work: takes a cargo from user, moves with it towards the drone, detecting it by himself (because the drone does not land on the same exact position every time), “climbs” up the drone’s grabbers and after the flight climbs down and moves to the end-user. The following figure of concept shows how the legs of this courier would look like (it is simplified, so the electronics are not presented in picture): at the end of them there are wheels, rotated by motors, two parts of the legs form a human-like knee, which allows the robot to lift itself up.

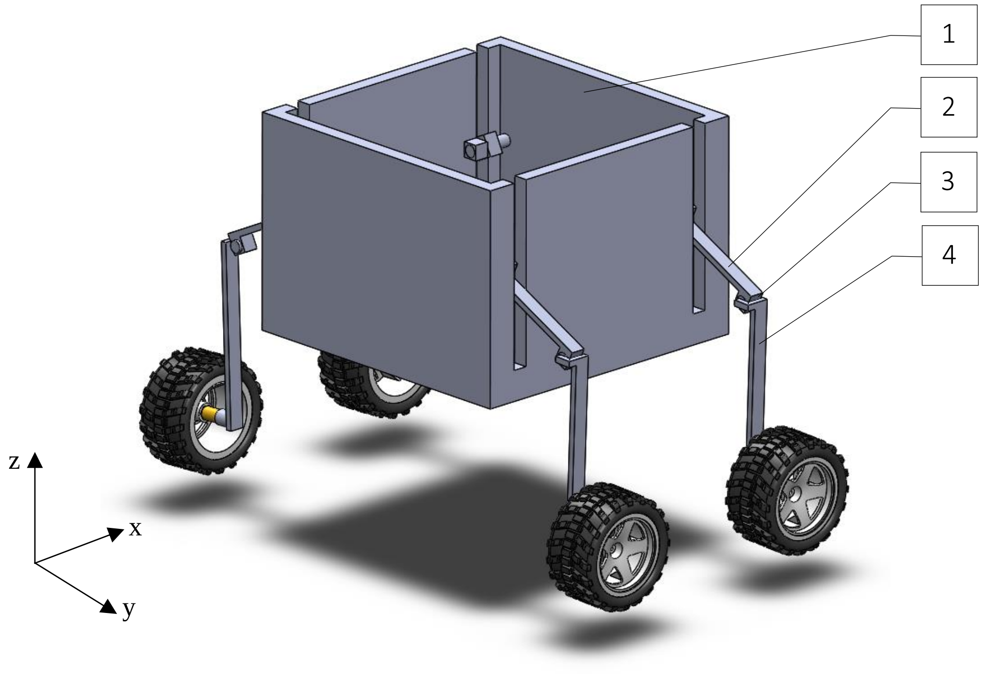


Figure 2.5: Concept of smart courier design. 1 – Box for a payload; 2 – upper part of the leg; 3 – knee; 4 – lower part of the leg with wheel.

The idea is very similar to the delivery robots from Starship Technologies, working in Tallinn [14]. Mainly the robot would be the same, but with implemented grabbing construction on top of it, so it can be attached to the drone.

As it is important for the courier to be mobile, there is no any possibility to use DC adapters. But because of the batteries weight of the payload drops significantly. Besides the batteries, there are even more components, such as wheels, motors and the case for all of it, which together do not leave any free weight for a cargo.

2.2.6 Conveyor-platform with pushing mechanism

Design of the conveyor-platform with pushing mechanism is close to the position adjusting conveyor, which is described in 2.1.2. It consists of the roller conveyor, but with the modified CNC linear guide installed on it. This construction will adjust the position of the drone, by moving it along X-axis on conveyor and pushing the legs of drone along Y-axis with linear guide. This design uses roller conveyor and because of that it was decided to change it. Described design is the closest to the final one, which will be presented in the next chapter section.

2.2.7 Cargo box grabbers

There is a need to create a grabbing mechanism to the drone, because the drone itself does not have it, since it is the regular model of the Wingcopter 178. Grabber's construction depends on the chosen type of system between a user and the drone.

There are different variations of robotic claws, used for drones. For example, here is aluminum robotic claw "Dagu".

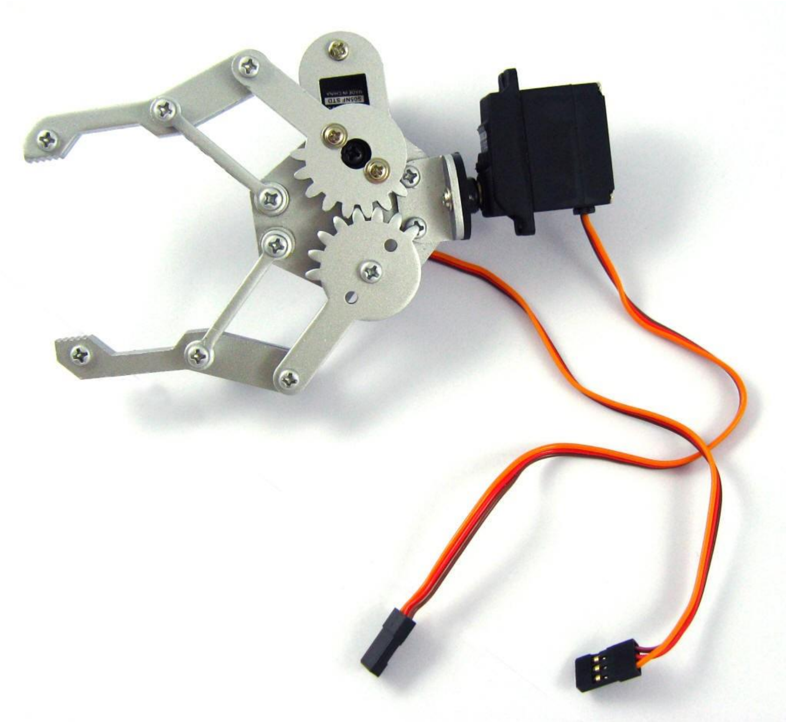


Figure 2.6: Robotic claw with servomotor [15].

They are controlled by a stepper motor, motion of claws and therefore gripping, grabbing or clamping function is carried out by the gears. This claw can be either installed on the cargo box or under the drone, but in any case there must be a "rings" to grab. Implementing this type of claws to perform the grabbing function will cause the swinging of the cargo box during the flight because of the speed changes.

Because of the swinging in claws it was needed to choose another type of grabber construction, which will not let the cargo box to conduct interfering movements. That has led to fork type grabbers on the drone, which will take on the cargo box on itself. First sketch of the design is shown below. The fork is installed closer to the nose of the drone and directed to the tail. At the end of the fork there is an anchorage, which is controlled by servomotor. When the cargo box is taken by fork, anchorage closes and holds the box.

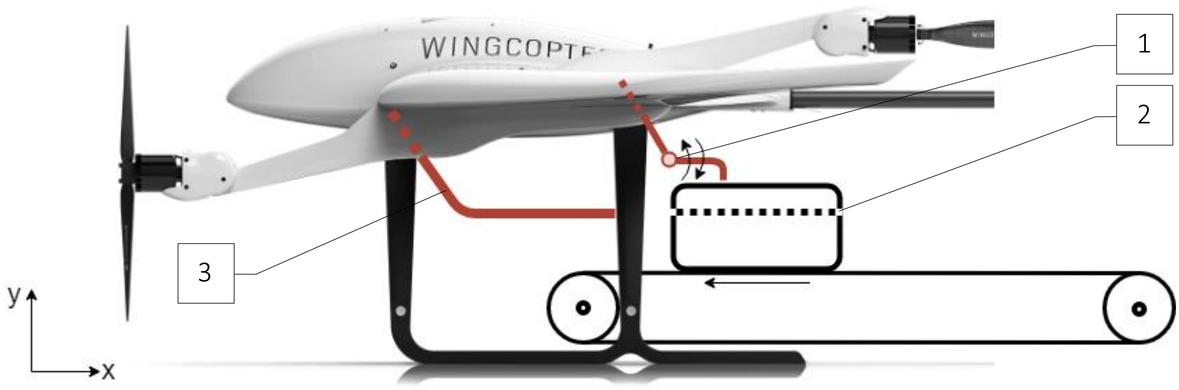


Figure 2.7: Sketch of fork type grabber on the Wingcopter's photo. Fork and anchorage are in red. 1 – Anchorage with servomotor; 2 – cargo box with a hole for the fork coming on a conveyor; 3 – the grabbing fork.

But there is a problem with reliability of the anchorage with servomotor. During the flight it will be under significant strain because of the horizontal force of cargo box. The servomotor in the middle of anchorage reduces the strength of it and therefore it was decided to choose fully mechanic way of holding the box by removing the servo.

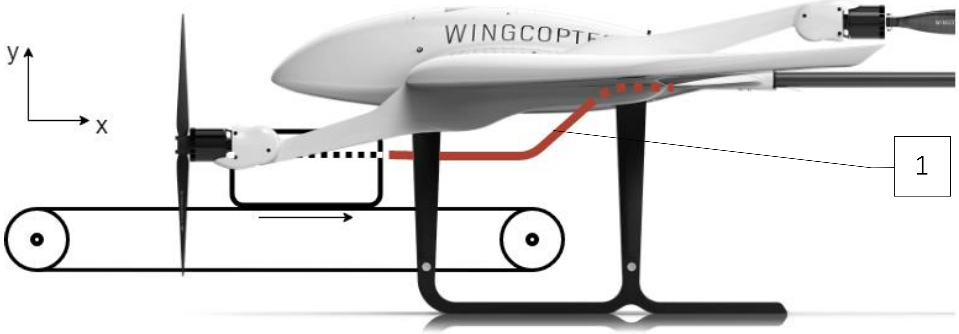


Figure 2.8: Modified sketch of fork type grabber (red). Now it is directed to the head of the drone. 1 – Grabbing fork is installed closer to the end of the fuselage.

So, instead of installing the fork at the beginning of the fuselage, it was replaced closer to the end of it as it is shown above.

Considering this design, we can start to work on interaction between the cargo box and the fork. Holes in the box for the fork must be made following the shape of the fork, so they will match with each other and keep the cargo box tight. Knowing these problems, there was created an indicative model of the cargo box with a fork type grabber.

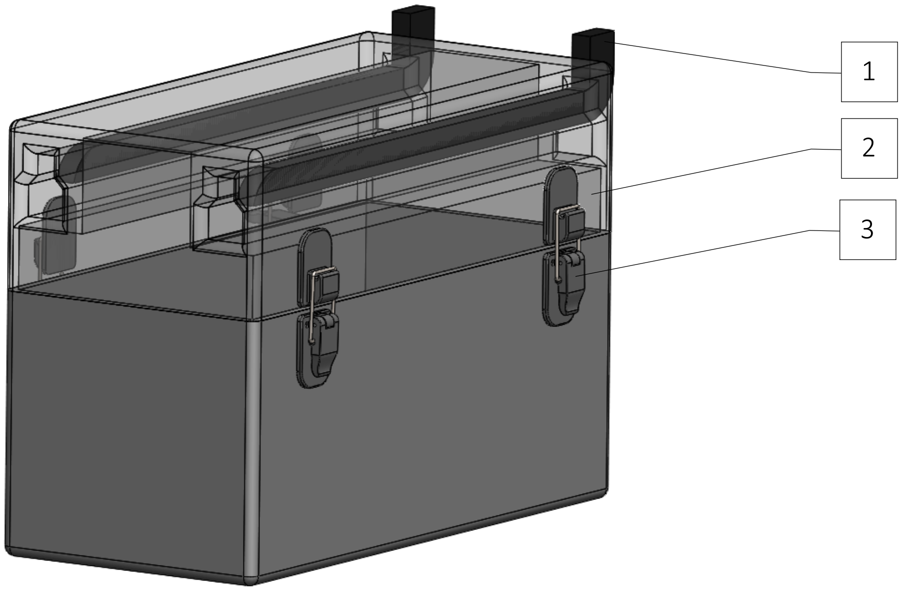


Figure 2.9: Cargo box with fork type grabber. 1 – Fork type grabber, the upper part of it is attached to the bottom of drone; 2 – top of the cargo box with two necessary holes for the fork; 3 – latches to keep the cargo box closed during the delivery process.

During the modelling of the fork it was decided to divide the hole on top of the box into two merged holes: bigger hole for the attaching process and smaller for carrying the cargo box. It was made to give the grabbing process a chance for errors.

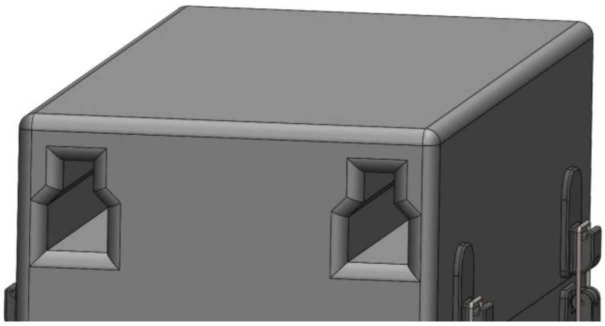


Figure 2.10: Concept for the hole on top of the cargo box.

As we have defined the mechanism of grabbing the cargo box, it can be proceeded to the detailed model of the fork and defining the place on bottom of the drone. This work will be done in next chapter.

2.3 Final solution

Final design derives from suggested solutions in previous chapter section. The following scheme shortly describes, what the idea is.

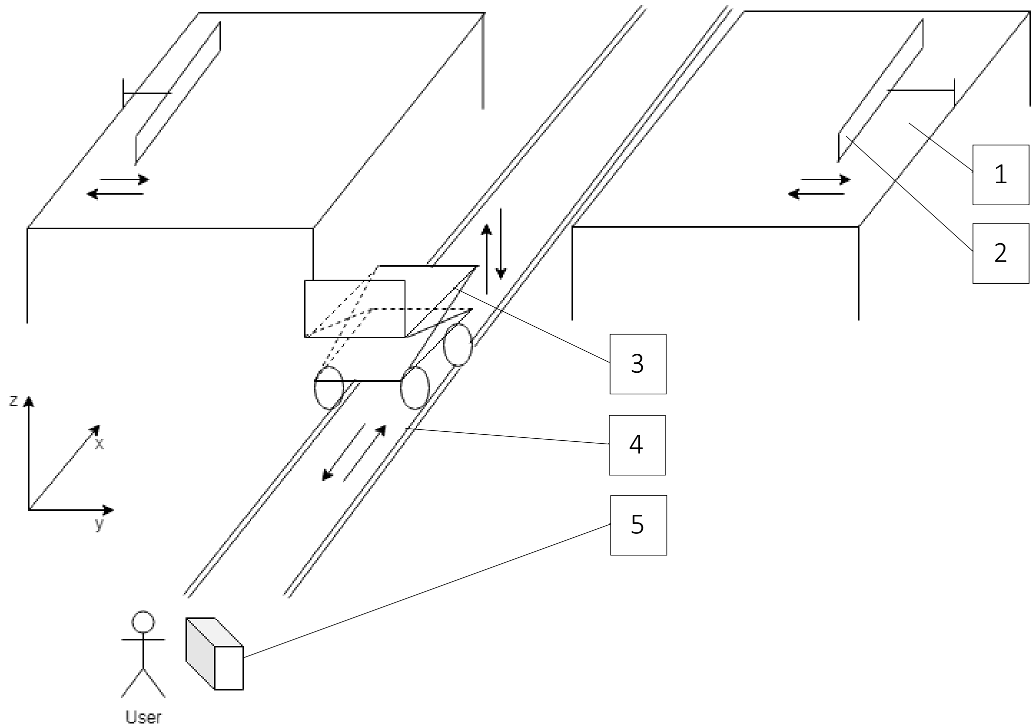


Figure 2.11: Simplified schematic representation of final suggested solution.

1 – Two static platforms;

2 – Pushing mechanisms, move along the Y-axis;

3 – Courier-elevator, moves along the X-axis and lifts the cargo along Z-axis;

4 – Rails for courier-elevator;

5 – User and his cargo;

Each delivery point will have presented landing system. There are two static platforms as a landing place for the drone – one for each leg of it. As the drone does not keep the position of taking off and therefore lands with the differences in position and angle of direction, there are pushing mechanisms installed on the platforms. These mechanisms will adjust the position and direction of the drone by pushing the legs of it. Once the drone position is adjusted, courier-elevator starts to move, carrying the cargo box. After reaching the certain point under the drone, it will lift the box and hooks it to the drone’s grabbers. Drone starts the flight; as it reaches the delivery point, drone will land on the platforms and the similar courier-elevator will unhook the cargo box.

It is obvious that all these parts must communicate with each other: for example, when pushing mechanism finished adjusting the position of drone, it must send a command to courier-elevator to start transferring the cargo box. For this purpose communication through Wi-Fi will be good enough: there are popular microcontrollers boards based on chips supporting Wi-Fi or these Wi-Fi chips can be connected with regular Arduino Uno, for example, but either way communication will be implemented.

Since the delivery system will be installed on the roof of campus and it will be used when necessary, it is not reasonable to use batteries as power supply. They require to be changed over time if they are not rechargeable, and if they are – then they need to be charged over time and most likely it will be done by reassembling them from the system. Therefore it is better to choose power supply from AC. This leads to using AC/DC convertor or DC adapter.

Described final delivery system in comparison with suggested solutions in previous chapter section has several benefits:

- Platforms construction allows the drone to land and take off in two directions along the X-axis.

  This is important because of the wind direction, when it is changed more than 90°. Creators require to put the drone's nose cone towards opposite direction of the wind and to stand facing the tail of the drone for safety reasons.

- Rails keep the courier-elevator on the same direction.

  Since the transferring of cargo box to the drone is the task of the courier-elevator, it is important for him to be precise in its movement. Putting the courier-elevator on the rails will exclude any angle direction changes of it: for example, differences of the wheels rotations, caused by DC motors control errors, effect on the accuracy of motion.

- Construction design allows to buy most of the parts of it.

  Because of the simplicity of construction most mechanisms can be bought and, if needed, modified according to the requirements. These parts are: platforms as a regular tables with certain height and cut-out; courier-elevator, which is modified scissor-lift; aluminium profiles as a rails; pushing mechanisms, made from CNC linear guide.

- Users do not need to control the whole delivery.

Since there is courier-elevator, transferring the cargo box to the drone, it is only required for user to put the cargo box on the courier-elevator and set the delivery destination on ground control platform. User at the delivery point needs only take the cargo from the cargo box, delivered to him on the courier-elevator.

When the delivery system plan has been defined, modelling works were started. The first rough model of the design is presented below. Mostly this model is close to the final model: it has all the main parts: two landing platforms with pushing mechanisms for legs of the drone, scissor lift as a courier-elevator on the rails and Wingcopter 178 itself with the cargo box. Further work will be based on more detailed analysis of these parts, so they can be modelled more precisely after.

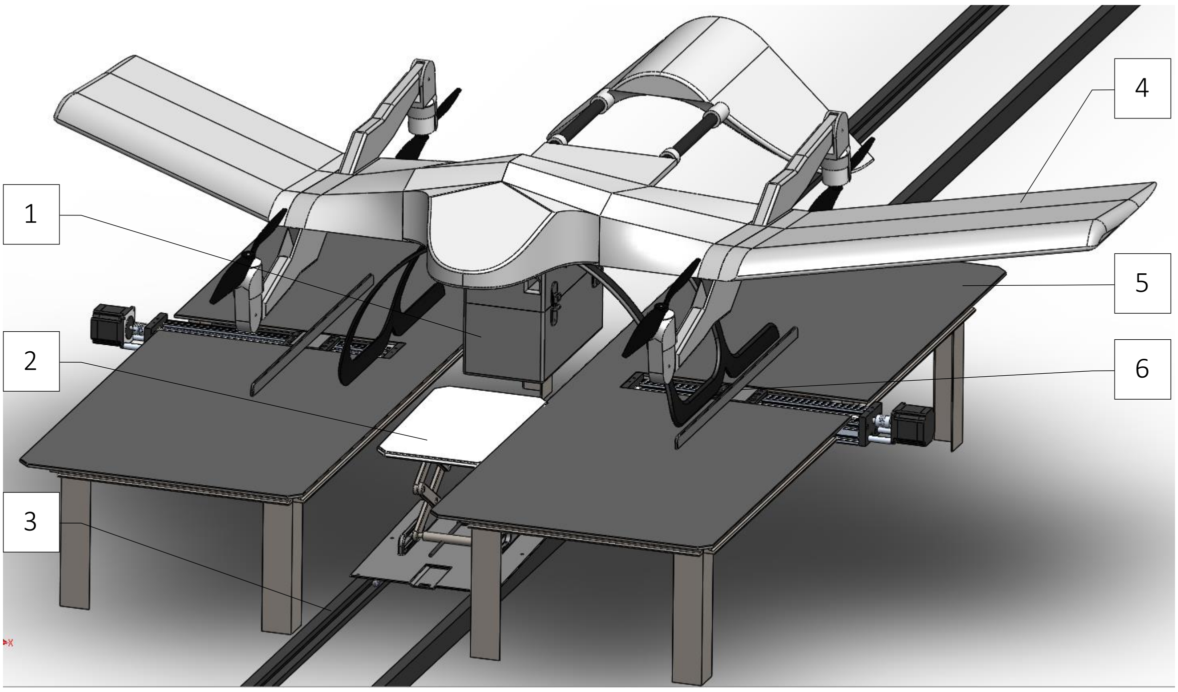


Figure 2.12: Rough model of the delivery design. 1 – Cargo box; 2 – courier-elevator; 3 – rails for courier-elevator; 4 – Wingcopter 178; 5 – landing platform; 6 – pushing mechanism.

3 PLATFORM, GRABBER AND CARGO BOX

The delivery system consists of two main parts, which require electronics: platform and courier. That is why following components are divided into two groups.

3.1 Platform

Platform mainly consists of two parts: table and pushing mechanism installed on it. Therefore this chapter section divided into two parts.

3.1.1 Table

Table can be bought from furniture market or it can be ordered with a custom design, but it must have following sizes and cut-out in the centre of it. Besides, top of it must be covered by HPL/CPL plastic (it is mostly used for covering tables and other furniture for aesthetic reasons), because drone's legs must slide on the surface of the table.

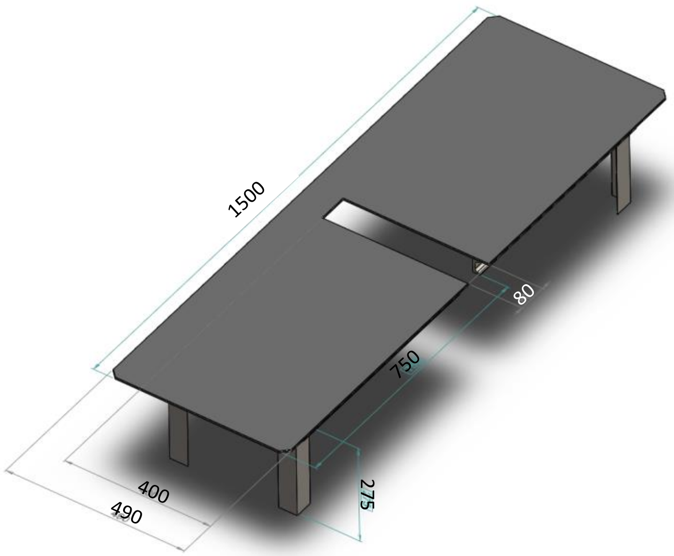


Figure 3.1: Landing platform sizes. All the dimensions are in millimetres.

This table requires a linear guide holder, which will be mounted on the bottom side of table under the cut-out. And besides it holds controller and driver for the motor, which will be chosen for pushing mechanism.

3.1.2 Pushing mechanism

In order to push the drone’s legs to adjust its position we need to build a linear guide mechanism. They are mostly popular in CNC machines and 3D printers. Electronics part of them consists of stepper motor, controller and stepper motor driver. Except that the linear guide mechanism needs to be modified to be able to move the drone by pushing on the legs of it.

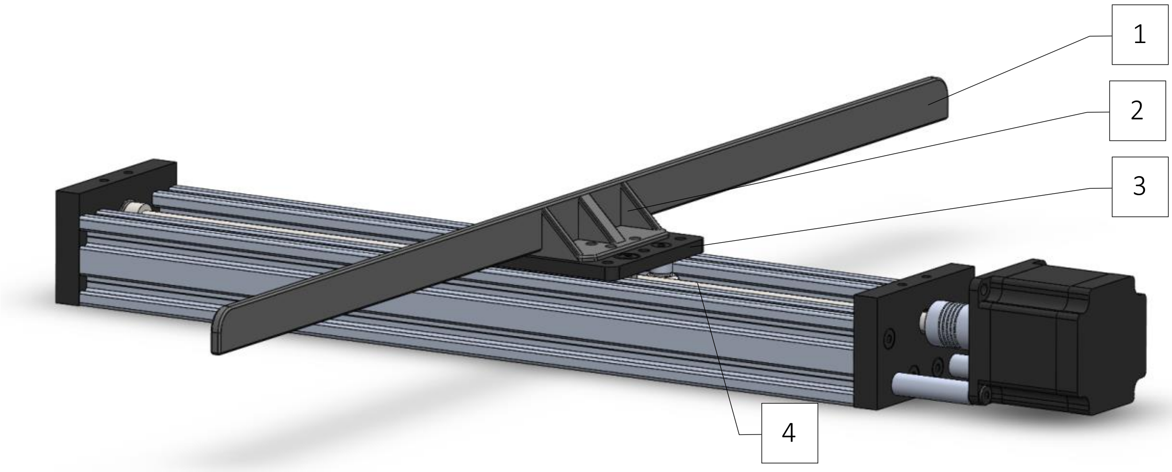


Figure 3.2: Modified linear rail guide (C-Beam linear actuator). 1 – Pusher with 2 – ribs; 3 – platform; 4 – shaft [13].

With a torque, generated by stepper motor, main shaft starts to rotate. The rotation of the shaft transforms to the rectilinear motion of the platform. As the pusher is mounted on the platform, it starts to move with it.

Sizes of pusher:

- Length: 600 mm;
- Width: 5 mm;
- Height: 20 mm.

Full distance of free movement of pusher is 380 mm.

Stepper motors are very common in projects where it is required to be precise in position control. Therefore, 3D printers and CNC machines are using them because of their relative accuracy of motion in comparison with ordinary DC motors.

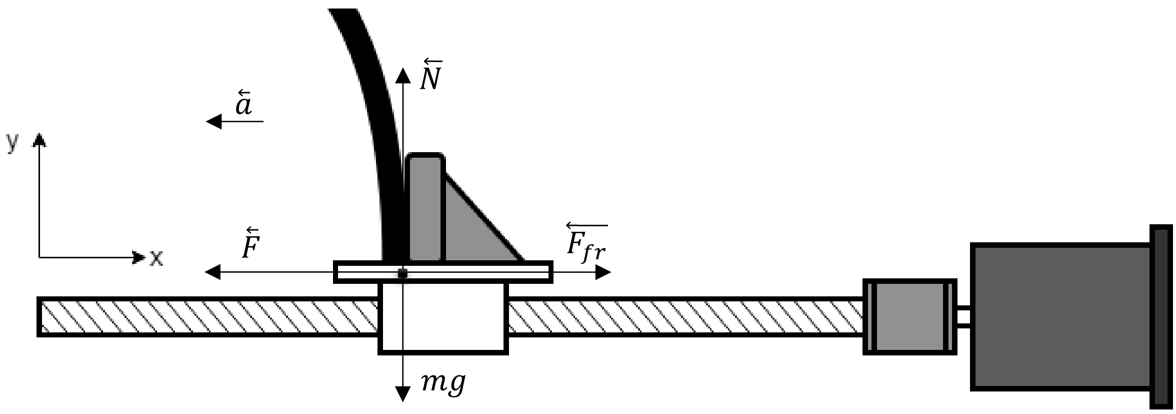


Figure 3.3: Schematic illustration of pushing mechanism during the work process.

To calculate the torque, required to move the drone first we need to find the force, needed for the motion.

According to the scheme above we are able to write the equation for motion:

$$m\overleftarrow{a} = m\overleftarrow{g} + \overleftarrow{F_{fr}} + \overleftarrow{N} + \overleftarrow{F} \quad (1)$$

On X-axis the equation will be: $ma = 0 - F_{fr} + 0 + F$ (2)

On Y-axis the equation will be: $0 = -mg + 0 + N + 0$ (3)

From 3-rd equation: $mg = N$

Since $F_{fr} = \mu N$, then $ma = -\mu mg + F$, which gives:

$$F = ma + \mu mg \quad (4)$$

This is the force required to move the drone of mass m with acceleration a.

Mass of the drone is 5 kg, maximum mass of the cargo with box for it is 2 kg. Therefore $m = 7$ kg.

Acceleration is equal to $a = 0.02\ m/s^2$.

μ – Friction coefficient of sliding surface ($\mu = 0{,}30$) [16]

Then

$$F = 7kg * \frac{0.02m}{s^2} + 0.3 * 7kg * \frac{9.8m}{s^2} = 0{,}14 + 20{,}58 = 20{,}72\ [N]$$

Load torque:

$$T_L = \left(\frac{FP_B}{2\pi\eta} + \frac{\mu_0 F_0 P_B}{2\pi}\right) * \frac{1}{i} \quad [17]\ [18]$$

Where

F – Force of moving direction (equation 4);

N – Normal force;

F_0 – Preload (it is approximately $F/3$);

μ_0 – Internal friction coefficient of preload nut (approximately $\mu \approx 0{,}2$);

η – Efficiency (0,85~0,95);

P_B – Ball screw lead;

i – Gear ratio (in this case it is not the gear ratio on motor's gearhead that is why there is no gear ratio).

With calculated force from equation 4 and substituting values of coefficients we are able to find load torque:

$$T_L = \left(\frac{20,72\ * 0{,}1}{2 * 3{,}14 * 0{,}90} + \frac{0{,}2 * 6{,}9 * 0{,}1}{2 * 3{,}14}\right) = 0{,}367 + 0{,}022 = 0{,}389\ [N * m]$$

Some resources show the torque for a motor in $[kg_f * cm]$, so $0.389\ [N * m]$ converts to $4\ [kg_f * cm]$;

To use this result for choosing the appropriate stepper motor we need to multiply it to safety factor K_S. It varies for different systems, commonly it is around 1,5 – 2 for this type of mechanisms without high requirements for the weight of construction [18].

Finally,

$$T_M = K_S * 0.389\ N * m = 2 * 0{,}389 = 0{,}8\ [N * m]$$

It converts to $8\ \left[kg_f * cm\right]$.

For this torque there is a Unipolar Nema 23 KM061F08 stepper motor with following characteristics [19].

Figure 3.4: Nema 23 KM06 type stepper motors [19].

Minimum holding torque: 0,904 $N * m$;

Mass: 0,73 kg;

Voltage: 14 V;

Current: 4 A;

Maximum shaft load:

- overhang – 70 N;
- thrust – 110 N.

Instead of creating the pushing mechanism from scratch there is an option to buy linear guide module for Nema 23 and modify it. According to the web-store it has the following characteristics [20]:

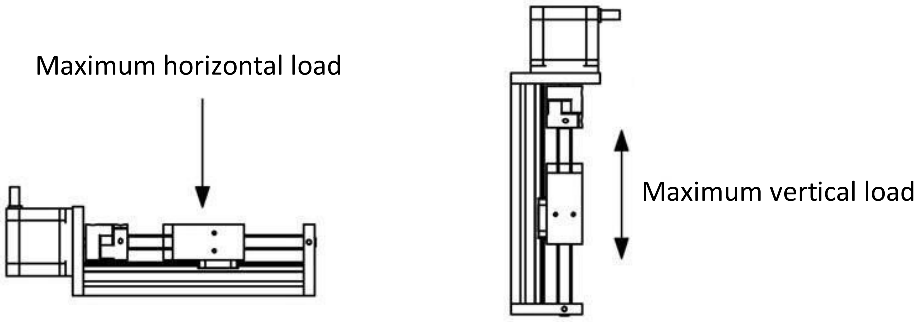


Figure 3.5: Scheme of loads direction. Since the module is performing pushing function, maximum vertical load is important for the project [21].

Diameter of guide shaft: 16 mm;

Accuracy: 0.03 mm;

Length: 400 mm;

Speed: 40 – 100 mm/s;

Maximum load mass:

- Horizontal: 50 kg;
- Vertical: 15 kg;

For this motor there was chosen a stepper motor driver TB6600 [22].

In order to detect the drone's position it was decided to use colour sensor, installed on the pushing mechanism. Coloured picture on the same height will be installed on the legs of the drone, so by the detected colour controller will get the information about the position of the drone. So for this purpose ISL29125 Colour sensor [23] was chosen. It is able to reject IR light sources, which is why it is able to operate at sunlight or in darkness. Therefore this colour sensor is suitable for the project.

3.2 Fork and cargo box

After researching different grabbing designs, presented in previous chapter, there was created a model for a grabber. Wingcopter has a rectangular hole on the bottom – that place will be a base for a fork to be mounted. It is important to make it light and at the same time it must be able to carry the load. There was created following model of the fork considering described points.

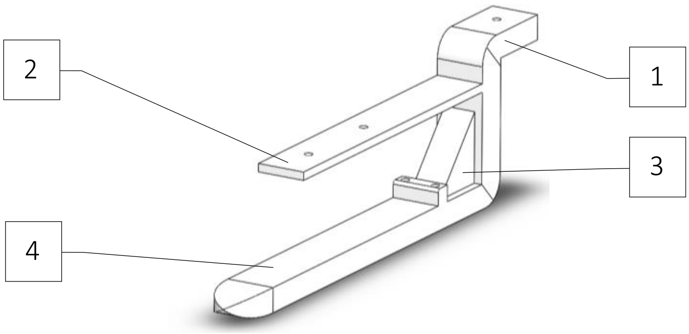


Figure 3.6: One of two branches of grabbing fork for the drone. 1 – Fixing part on the bottom of drone at back side; 2 – fixing part under the bottom of drone at front side; 3 – rib; 4 – place where the cargo box will be carried on.

Front tip of the fork is rounded for the purpose of aerodynamics. It will be fixed under the bottom of the drone along the carrying branch and on the bottom of the drone towards the back side of the drone to spread the load.

To create a cargo box it was important to make it smooth in order to be aerodynamic as possible during the flight. It consists of two parts: upper – with two holes for the fork grabber and lower – with two “legs” to pry the box during transferring process (top platform of the courier-elevator has two sockets for them, it will be shown in next chapter section). Besides, they will help user to put the box on exact place every time.

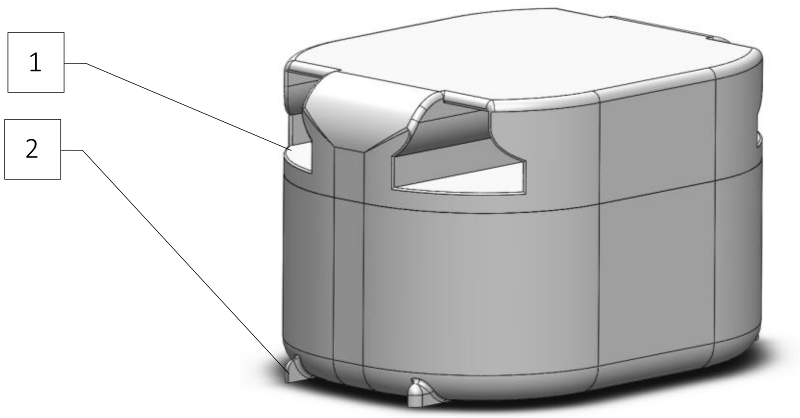


Figure 3.7: Model of the cargo box. 1 – Hole for grabber; 2 – “legs” of cargo box.

Sizes of the box: 240 x 180 x 150 mm. Upper part of the box has sockets for latches. Latches are on top of the lower part of the box (figure below). Instead of regular latches, shown in first model of cargo box, these latches are internal, so they will not interfere with the physics of the cargo box. To open the box it is enough to press on the places of lower part of the box, where the latches are. Latches have tilted cover, therefore to close the cargo box user needs to press on top of it.

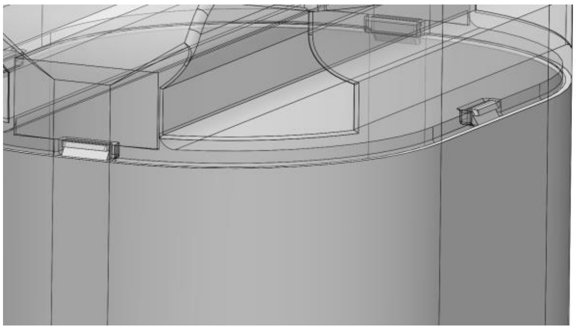


Figure 3.8: Latches for keeping the box closed.

As it was suggested in first model of the cargo box, it has two-sized hole for the forks. Lower part of the hole is for transferring process: when courier-elevator will be transferring the cargo box onto the forks of the drone, this part of the hole will allow courier-elevator to have a margin of space during its motion; as soon as forks will be fully inside of the cargo box, courier-elevator goes down, thus forks will move up – to the upper part of the hole because of the weight of the cargo box. Being in the upper part of the hole, forks will be fixed under the sizes of the smaller part of the hole.

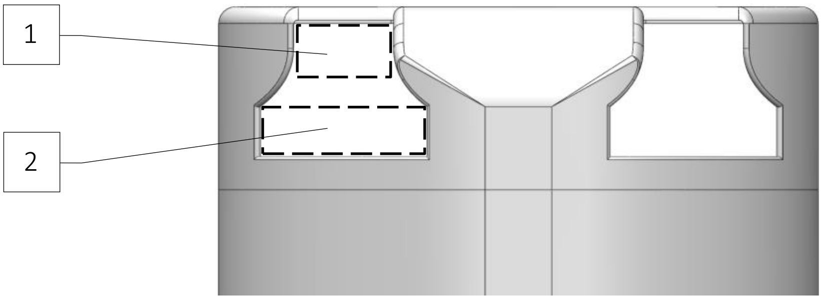


Figure 3.9: Profile of the holes for grabbers. 1 – Upper, smaller part of the hole for the forks; 2 – lower, bigger part of the hole.

By adding fork and especially a cargo box to the drone we are changing vertical position of its centre of gravity (figure below). It will lead to bigger load on front motors and therefore it must be regulated. Creators of the drone recommend to check the centre of gravity by lifting the drone from the top of it and moving the battery position according to the centre of gravity. The same technique will work for implemented delivery system. Batteries must be adjusted to the position, where they will not change the center too abruptly.

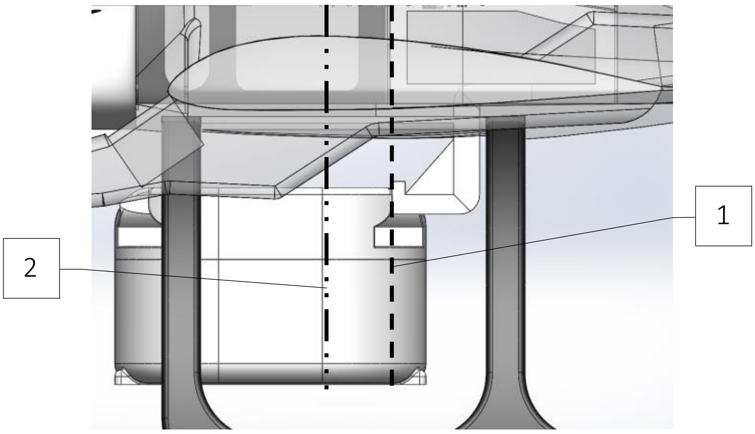


Figure 3.10: Fork and cargo box under the drone. 1 – Original centre of mass of the drone; 2 – new centre of mass of the drone with the same position of batteries.

Overall mass of cargo box and forks will be 1,5 kg. But regular Wingcopter 178 model is able to carry only 2 kg, which means that for payload there is only 0,5 kg left. So until the drone will not be updated with better motors (as in Wingcopter 178 Heavy Lift) delivery design will work only for light cargos.

4 COURIER-ELEVATOR

Task of the courier-elevator is connecting a user with the drone without any interaction between them. Which is why it must be able to move on certain path, carrying the cargo box, and lift it vertically to attach it to the drone's fork grabbers. Figure below illustrates final model of work, further it will be described, how it was designed. As it performs two different functions – lifting of a cargo box and moving along the rails – designing process will be divided into two main parts.

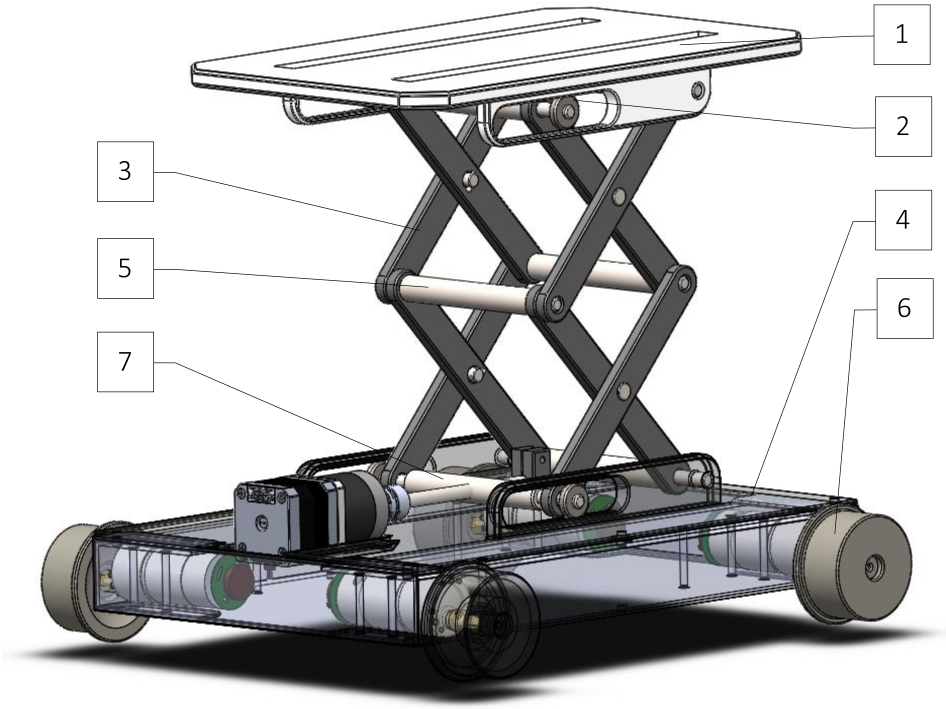


Figure 4.1: Final model of scissor lift created on chosen components. 1 – Top platform; 2 – supporting wheel; 3 – arm; 4 – base (chassis); 5 – support; 6 – main wheel; 7 – support with buttress thread.

4.1 Lifting

There is a scissor type mechanism commonly used to lift a load in different areas, and therefore has various sizes depending on type of the load it is lifting: for household items such as laptops to lift them to a height of 20 cm and for a lifting of a group of people to a height of 10 meters [24]. For this project it has two important factors: either it can be built in the laboratory or it can be bought from a web-store because of its popularity, and more importantly it is compact, so it fits between the platforms.

Figure 4.2: Scissor lift with screw jack [25]. 1 – Top platform; 2 – arm; 3 – support with buttress thread; 4 – base.

Scissor lifts consist of folding supports linked in crisscross with each other. Links of crisscross are called "arm". Lifting the top platform with a payload on it is provided by applying the force, generated by a pneumatic or electric motor (scissor lift on picture is mechanical and force for it intended to be generated manually), to one of moving supports through the screw in buttress thread profile.

When the mechanical scissor elevator is assembled, it needs to be modified, so it will be able to lift and lower the load by following controller commands. For this purpose there must be implemented a stepper motor with screw mechanism to one of the supports.

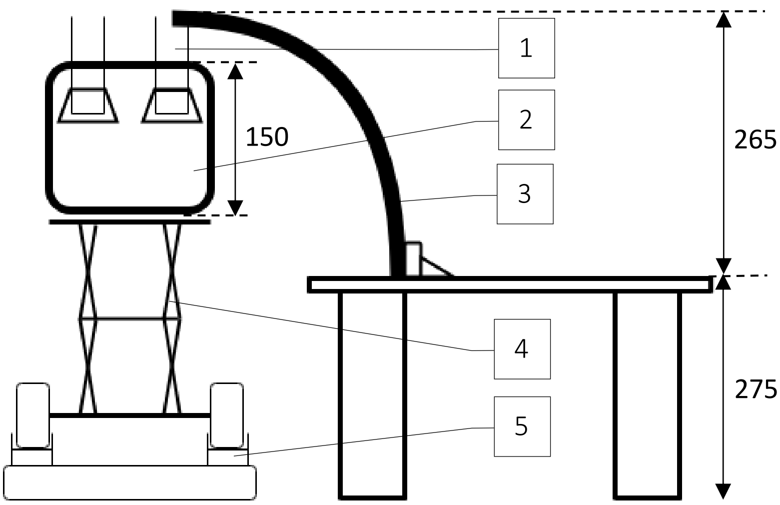


Figure 4.3: Sizes on scheme of delivery system. 1 – Drone's grabbers; 2 – Cargo box; 3 – Legs of drone; 4 – elevator trolley with scissor mechanism; 5 – rails for the trolley. Dimensions are given in millimeters.

Knowing the sizes of table, cargo box and drone legs height, there can be calculated the height for scissor to lift. It should consider the height of the rails, radius of the wheels of trolley and the height of the base of trolley, where it contains all the electronics. That is why chosen height of extended scissor (without trolley platform and wheels) equals to 300 mm.

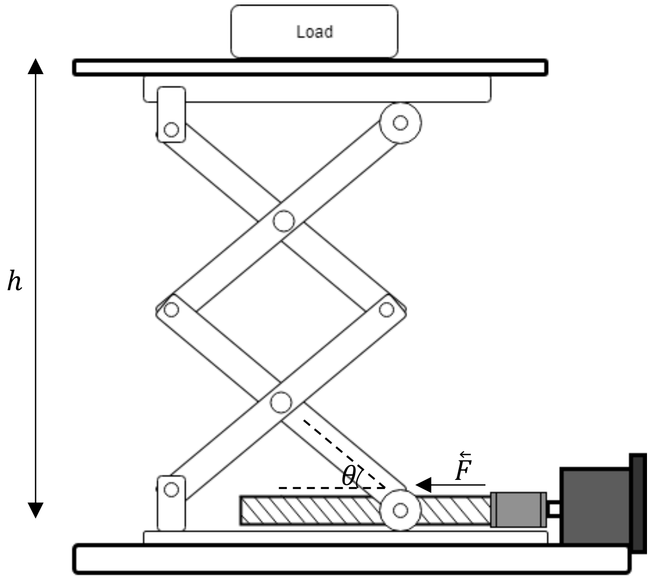


Figure 4.4: Scheme of scissor mechanism with screw jack and stepper motor.

The scheme above is an anticipated form of controlled scissor lift. The rotation of the shaft F is a force to move the support. If a load has weight of L. Since the scissor mechanism has its own weight too, it must be considered in further calculations. Stepper motors work is to lift the scissor lift to the height h. To examine the weight of the scissor lift during lifting process, imagine the scissor lift as a cube with dimensions a, b and h. Infinitesimal slice of this solid at a height y with thickness dy will have a mass:

$$m_{dy\ slice} = ab(dy)\rho \quad (4.1)$$

With potential energy:

$$W_{dy\ slice} = ab\rho y(dy) \quad (4.2)$$

Which leads to the potential energy of the whole cube (scissor lift) with height h:

$$W_{cube} = \int_{y=0}^{y=h} ab\rho y(dy) \quad (4.3)$$

Since the weight of cube is:

$$P_{lift} = P_{cube} = abh\rho \quad (4.4)$$

Then

$$W_{cube} = \int_{y=0}^{y=h} \frac{P_{lift}}{h} y(dy)$$
(4.5)

Solving the integral gives:

$$W_{cube} = \frac{P_{lift} h}{2} \quad (4.6)$$

We know that the height changes during lifting time, so the equation above will be transformed to:

$$W_{cube} = \frac{P_{lift}}{2}(h_2 - h_1) \quad (4.7)$$

It means that the work to keep the weight of scissor at the h_2 equals to the work to bring the half of scissor's weight to the h_2. Therefore, effective load, carried by motor, will be:

$$P_E = P_{Load} + \frac{P_{lift}}{2} \quad (4.8)$$

Knowing this we can calculate the force for the motor to move the support

$$F = \left(P_{Load} + \frac{P_{lift}}{2}\right)\frac{n}{\tan\theta} \quad (4.9)$$

Where n – number of crosses (in this case there are 2);

θ – angle created by an arm.

All the equations above for this part (equation 4.10 - 4.11) are taken from [26] [27].

Knowing that P_{Load} maximum can be 20 N (as maximum mass of load is 2 kg) and P_{lift} is 20 N too (as the mass of scissor mechanism without base is approximately 2 kg). Then required force of the actuator to reach the 60 degree (same as reaching the highest point) will be:

$$F = \left(20 + \frac{20}{2}\right)\frac{2}{\tan 60°} = 34{,}68\ [N]$$

Now we are able to use the equation 5, which was used for torque calculation for the stepper motor in pushing mechanism [17] [18]. Calculated force will be considered as an external force.

$$T_L = \left(\frac{FP_B}{2\pi\eta} + \frac{\mu_0 F_0 P_B}{2\pi}\right) = \left(\frac{34{,}68\ *0{,}1}{2*3{,}14*0{,}90} + \frac{0{,}2*11{,}56*0{,}1}{2*3{,}14}\right) = 0{,}613 + 0{,}037$$
$$= 0{,}65\ [N*m]$$

Where

F – Force of moving direction (equation 4.12);

N – Normal force;

F_0 – Preload (it is approximately $F/3$);

μ_0 – Internal friction coefficient of preload nut (approximately $\mu \approx 0{,}2$);

η – Efficiency (0,85~0,95);

P_B – Ball screw lead;

And again, to use this result for choosing the appropriate stepper motor we need to multiply it to safety coefficient $K_S = 2$.

Finally,

$$T_M = K_S * T_L = 2 * 0{,}65\ N * m = 1{,}3\ [N * m]$$

Converted to $\left[kg_f * cm\right]$ it will be $13{,}26\ \left[kg_f * cm\right]$.

For this amount of required torque to operate with lifting the cargo box by scissor mechanism it was decided instead of high torque expensive stepper motors to use Nema 17 with gearhead 5:1.

In order to control the stepper motor A4988 microstepping motor driver was chosen.

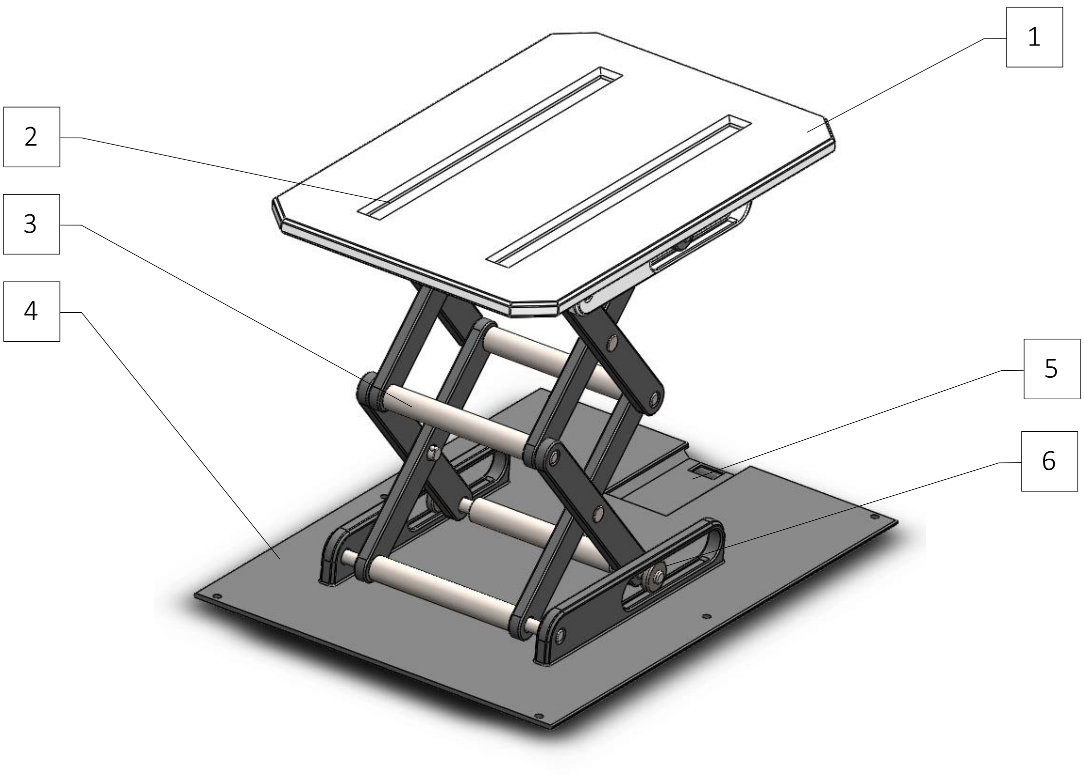


Figure 4.5: Created model of scissor mechanism. 1 – top platform for cargo box; 2 – sockets for the “legs” of the cargo box; 3 – support; 4 – base of scissor lift; 5 – socket for stepper motor; 6 – wheel for the support with buttress thread.

4.2 Moving

In order to move the scissor mechanism we need to attach to bottom of it a new base – case for containing all the electronics including DC motors. Case can be created from aluminum profiles or it can be bought from stores [28]. They sell it in a pack of robotics kit for learning and mainly they are used for RC cars or multifunctional robots on wheels, but they are suitable for this design too: the case has more than 4 main shaft-holes in order to be universal and changeable. The case must be constructed the way that it will be able to carry controller, motors and their drivers. Figure below shows how they look like.

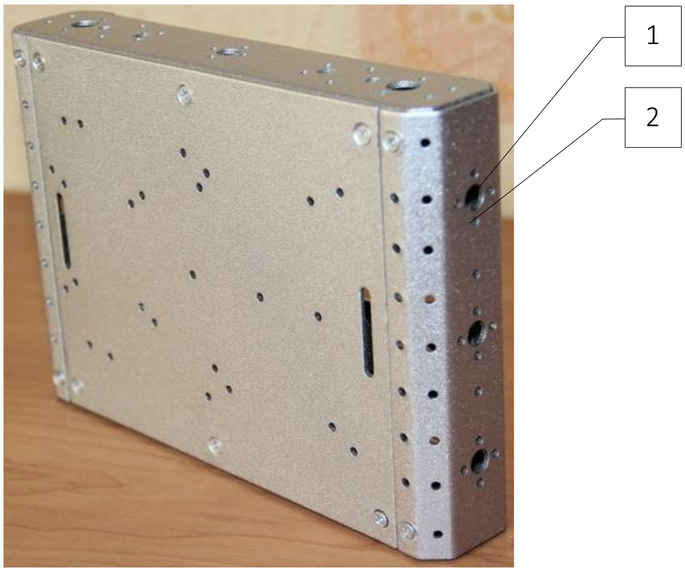


Figure 4.6: Universal chassis for the robots. 1 – Hole for a shaft of the DC motor, 2 – holes for fixing the motor [29].

In order to choose DC motors following calculations must be done [30].

Assuming that:

Full mass, required to be moved: $m = m_{box} + m_{lift} = 2 + 6 = 8\ kg$

Radius of the wheel $r_{wheel} = 0{,}03\ m$

Required speed of movement $v = 0{,}5\ m/s$

If

$$v = 2\pi r_{wheel}\omega_s = 0{,}5\ m/s$$

Where ω_s – rotations per second.

Then

$$\omega_s = \frac{v}{2\pi r_{wheel}} = \frac{0{,}5\ m/s}{2 * 3{,}14 * 0{,}03\ m} = 2{,}65\ RPS$$

ω_s converted to the minutes ω_m:

$$\omega_m = 2{,}65 * 60 \approx 160\ RPM$$

On account of safety and guarantee of the motion:

$$\omega_{m\,real} = 160 * 125\% = 200\ RPM$$

By knowing the final required speed of vehicle and the distance, on which it must reach the required speed, we are able to calculate the acceleration:

$$a = \frac{v^2}{2*d} = \frac{0{,}5^2}{2*0{,}5} = 0{,}25\ \frac{m}{s^2}$$

If we know the mass of whole vehicle m, acceleration a and the radius of wheels r_{wheel} we can calculate the minimum torque, required for the wheel rotation:

$$T = F * r_{wheel} = m * a * r_{wheel} = 8\ kg * 0{,}25 \frac{m}{s^2} * 0{,}03 = 0{,}06\ N * m$$

Then stall torque will be:

$$T_{stall} = 4 * 0{,}06\ Nm = 0{,}24\ [N * m]$$

Or in $kg_f * cm$ it will be 3 $[kg_f * cm]$.

For this torque suitable DC motor was chosen [31] (characteristics are in Appendix 4). The motor is commonly used in robots, RC cars. It comes with own encoder and a gearhead.

For further improvements it was decided to use four of chosen motors for each wheel. In order to control them we will need a driver. For this purpose according to the voltage of DC motor there was chosen motor driver board based on L298N H Bridge [32] (Appendix 4 and 6).

When all the calculations for electronics were done modelling works were started. First of all the scissor mechanism was created.

As a control board Izokee WeMos D1 Mini [33] based on ESP8266 CH340 chip (Appendix 5) was chosen since it is very close to the popular Arduino, it works on the same IDK, but besides it has a Wi-Fi, which was important for current project and it is cheap.

Certainly there is an option to use other an original Arduino Uno with ESP8266 chip to be able to have a Wi-Fi connection. ESP8266 is a microcontroller with Wi-Fi interface with following parameters:

Wi-Fi protocols 802.11 b/g/n with WEP, WPA, WPA2;

Has 14 I/O ports, SPI, I2C, UART;

Supports external memory up to 16 MB;

4 MB flash memory;

Required supply voltage: 2.2 – 3.6 V;

Current consumption: up to 300 mA;

But ESP8266, as it was shown above, requires voltage input not be more than 3,6 V and voltage on Arduino is 5 V, so the connection cannot be built directly, therefore there must be resistors (Appendix 5).

Minimum height, or distance between the top surfaces of upper platform and base is 100 mm. Maximum height is 300 mm. Supports and nuts are made of steel; arms, wheels and both platforms are made of ABS plastic. Overall mass is 2,25 kg.

Sockets for the cargo box are made to help at attaching the box to the fork under the drone. And their second function is that it is obvious for a user where and how exactly to put the cargo box on the courier-elevator.

Second part is to create an aluminium case for an electronics and wheels. The case (or chassis) consist of 3 parts mounted with each other. These parts can be made by order.

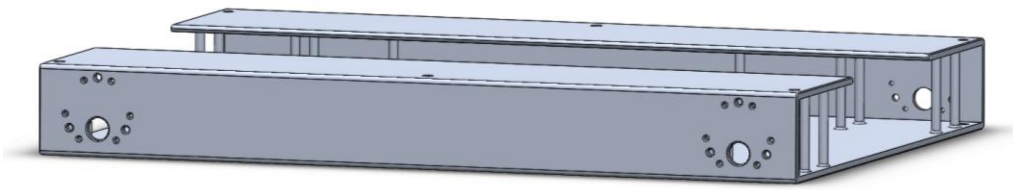


Figure 4.7: Middle part of the chassis.

As it was decided, there will be 4 DC motors. In this case there will occur errors in motion (some of the motors might provide higher torque than the others) and as a result wheels will roll differently effecting on the accuracy of vehicle's motion – either it will turn to sideways or move with wrong speed than required.

Therefore in order to keep the trolley lift on a straight line it was decided to use the rails. They can be created out of an aluminium extrusion profile, commonly used for robotic constructions.

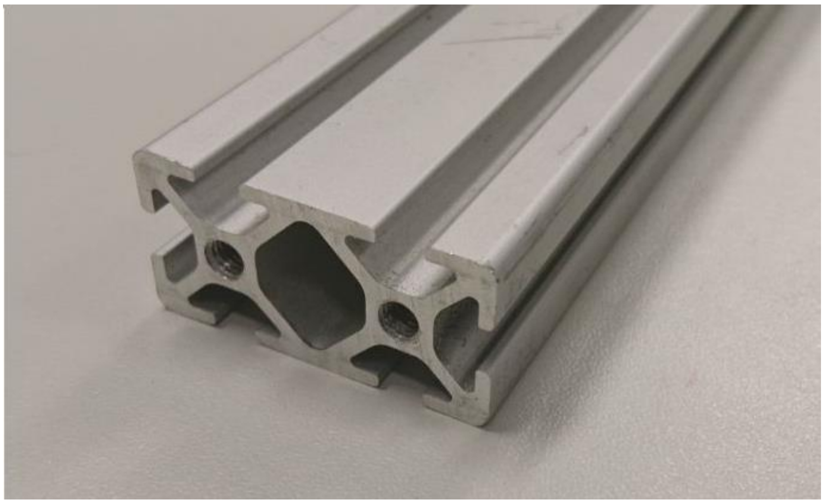


Figure 4.8: Aluminium extrusion profile.

There are different types of them, called V-Slot, T-Slot with various profiles. The profile we need is presented on picture above. It has 20 x 40 mm size. For the suggested delivery design it must be with minimum 5 m length. They are sold by 1 m length [34] or they can be made longer by order. Profile has trenches on each side and they will be used as a supporting guide for the wheels of trolley.

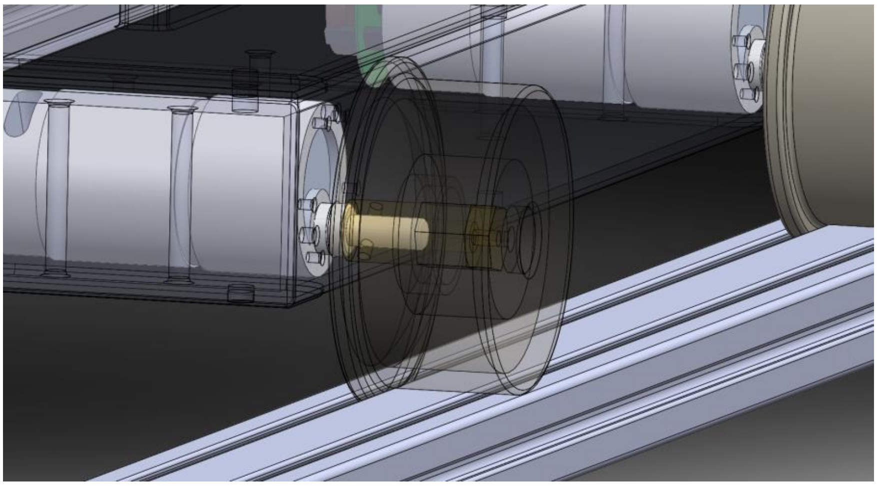


Figure 4.9: Wheel and profile matching.

Wheel can be printed on 3D printer, it consists of two parts with different diameters to create flange connection as in trains wheelset: main part has 60 mm diameter and 27 mm length, which carriers all vertical force, created by the mass of construction; and supporting part has 68 mm diameter and 3 mm length, which prevents sideway turns by thrusting on profile.

In order to transfer the torque on DC motor's shaft to the wheel it was needed to choose a coupler. There are couplers from copper with hexagonal head. It must be connected to a hexagonal slot in a wheel.

Figure 4.10: Wheel and coupler.

In order to detect the cargo box, when user puts it on the courier-elevator, there is a need to choose a sensor. For this kind of work HC-SR04 ultrasonic sensor is suitable (Appendix 5). Placed on the top platform of the scissor mechanism, it will detect the moment, when cargo box is on the courier-elevator.

When all the details are settled for the courier-elevator, it can be modelled fully by attaching scissor mechanism created before with chassis.

5 DRONE MODELLING

5.1 Scanify Fuel 3D

To be able to provide simulations it is important to create realistic model of the drone. Wingcopter 178 has a smooth body, fully consisting of curves. Therefore for the first time there were attempts to get the model of the drone in more automatic way – Mechatronics Department has a modelling instrument called Scanify Fuel 3D.

Figure 5.1: Scanify Fuel3D [35].

It is used for modelling small objects (20 mm x 30 mm). Even though creators recommend to use it on non-reflective and rough objects, there were attempts to model the drone with this instrument. Working principle of Scanify: user takes a photo on it of the object with tracking target, program detects tracking target on the photo and tries to create a model of the object.

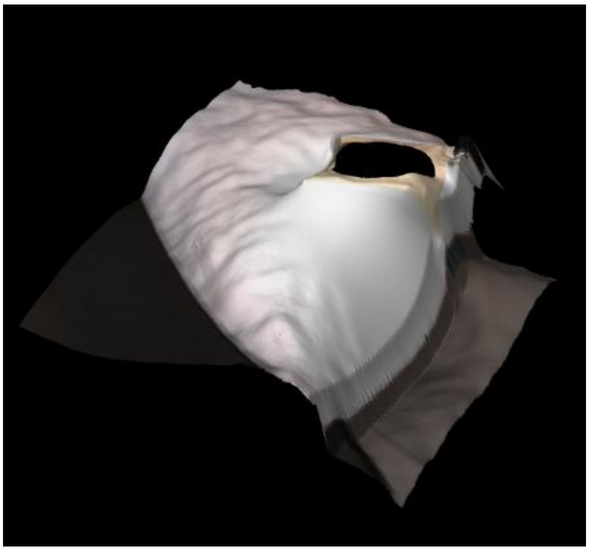


Figure 5.2: Result of one of the attempts to model a wing of Wingcopter on Scanify.

Obviously, result was not satisfying: models were distorted heavily. And besides, process of taking a photo was difficult, because Scanify does not allow to take a shot, if the light is not good enough, and considering smoothness and reflectiveness of the Wingcopter's parts, the modelling process with this instrument gets even more difficult. Therefore, it was decided not to use Scanify for modelling.

There was another option – one of other departments have professional modelling instruments, which allow to model even this type of objects (reflective, shiny, curvy), but the price for service was around €800, which is too expensive.

Third option was to model the drone manually from scratch in SolidWorks, by measuring all the parts. The final model of drone is presented below.

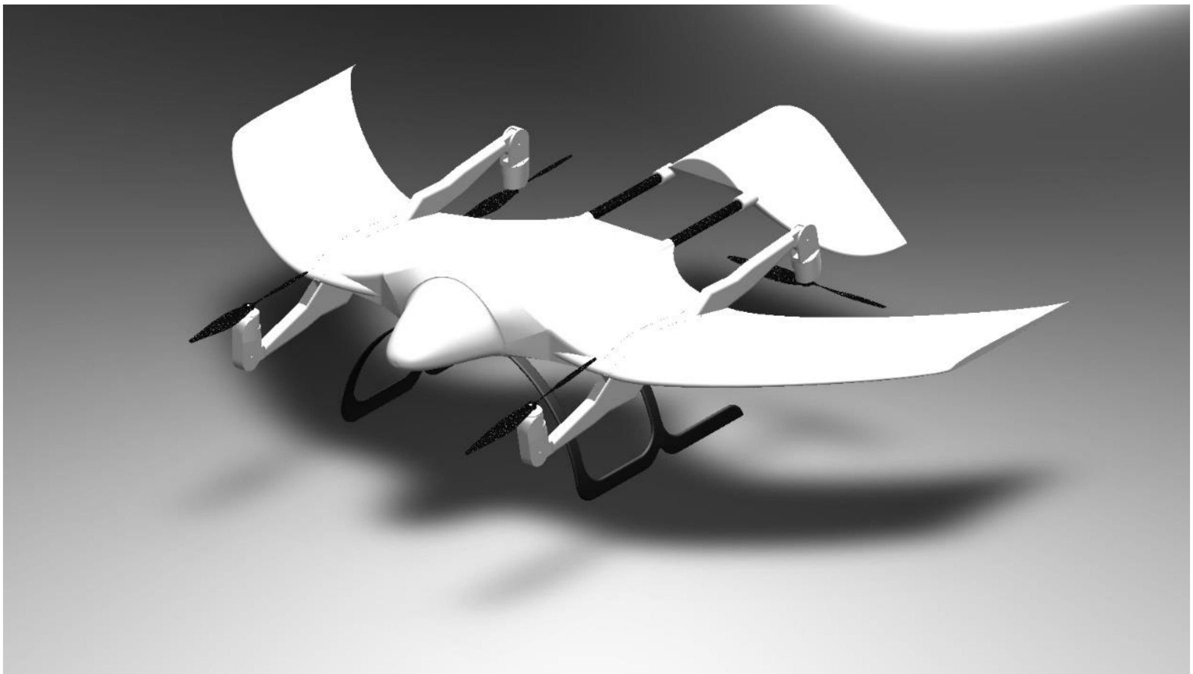


Figure 5.3: Final model of the drone in SolidWorks.

Reason for the huge difference between this model of drone and the model presented in Chapter 2: Design Process is that this model was created by "Lofted Boss/Base" function in combination with "Plane" instrument. This combination allows to reach the smoothness in curves at extruding process, which was not in previous model – it was created only by basic instruments "Extruded Boss/Base" and "Sketch".

For example, here is the process of creating a 3D model of the wing with "Lofted Boss/Base" and "Plane" instrument:

1. All the measurements were taken as accurate as possible with measuring tape.

2. Three sketches were created according to the approximate sizes in combination with 3D sketches.

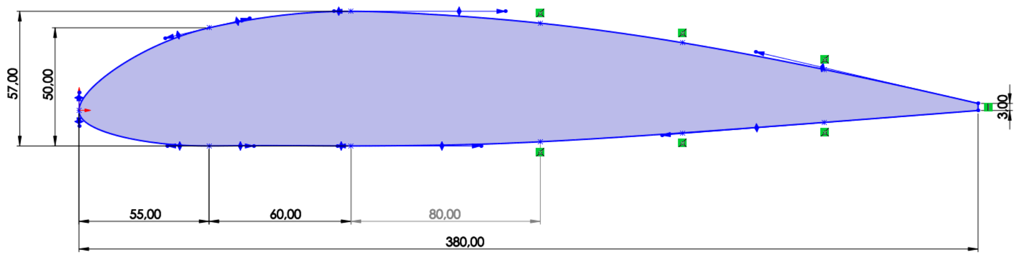


Figure 5.4: One of the sketches for the wing.

3. Based on these sketches 3D model was created with “Lofted Boss/Base” instrument.

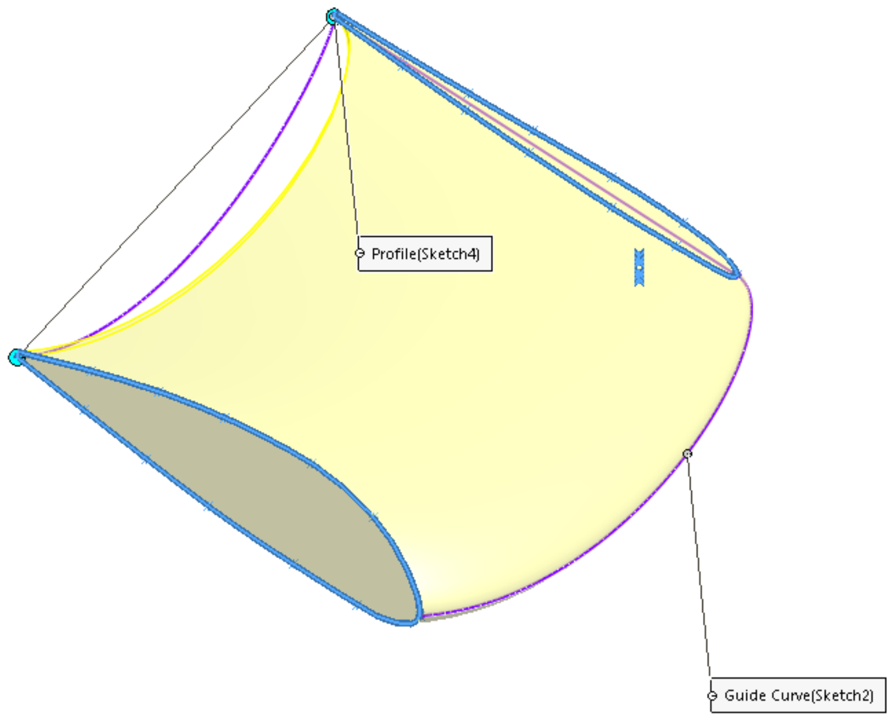


Figure 5.5: Loft operation. You can see how yellow line (automatically created by Loft operation) does not match with violet line (sketch line) at the back side of the wing.

Loft operation creates a model between two sketches through guide line. The problem is that the guide line can be only one. That is why front of the wing matches with a line drawn by measurements, but back side does not. This is one of the examples of simplifications were made.

The same way other curvy parts of the drone were made. The hardest part was “body” of the drone or fuselage. After creating approximate sketches three loft operations were done. First was intended to create half of the body without front side.

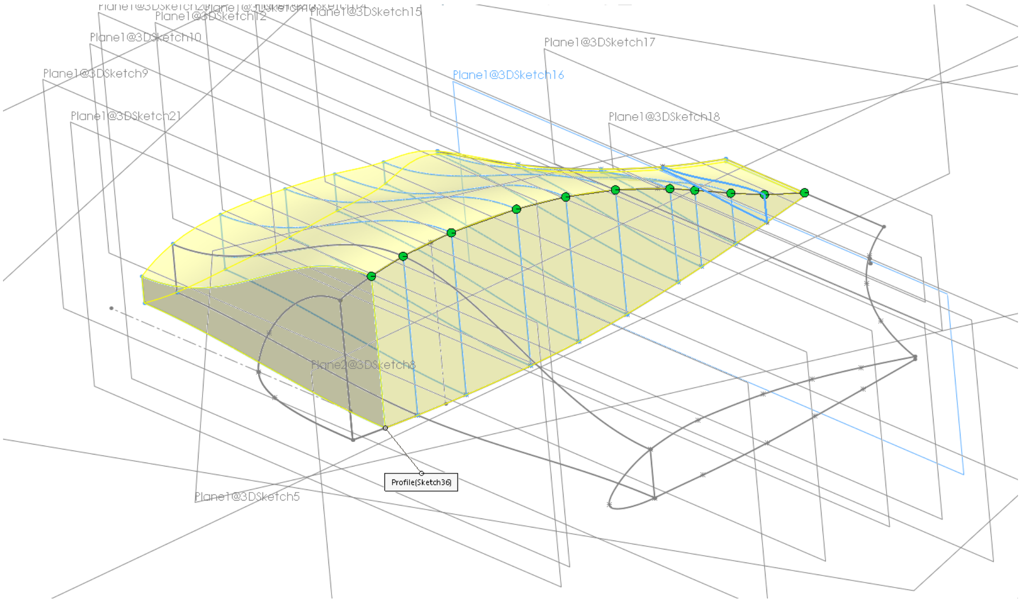


Figure 5.6: Loft operation for half of the body of the drone.

Second part was to create front side of the body and merge them together.

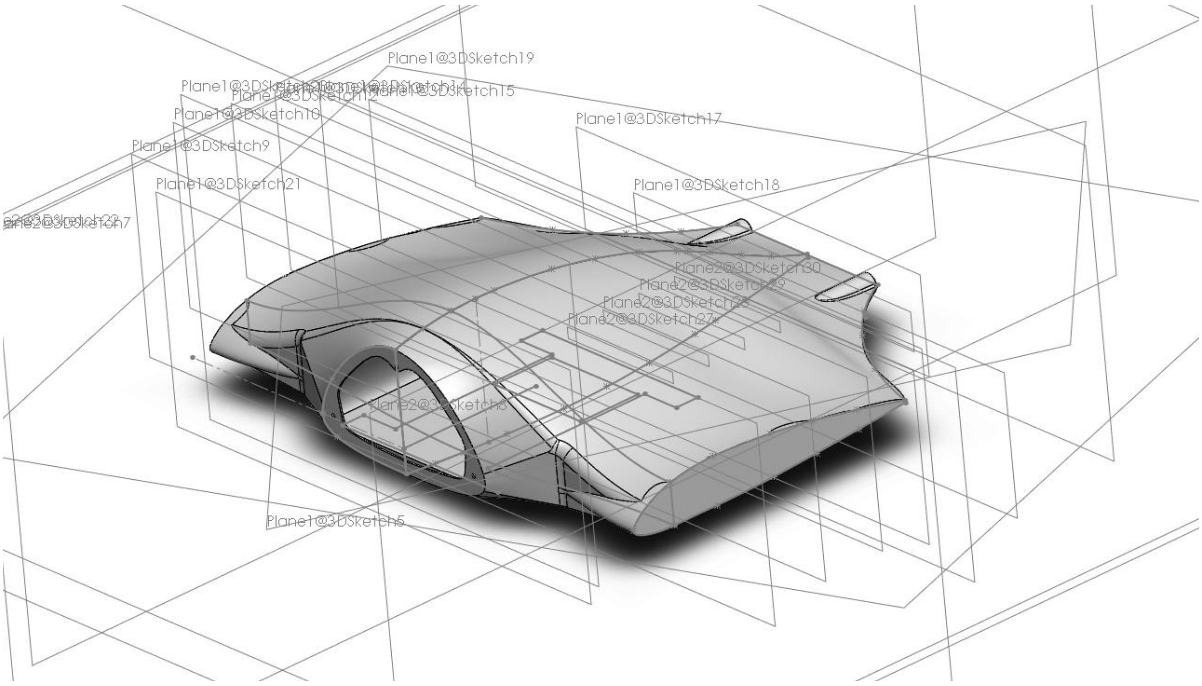


Figure 5.7: Full body of the drone.

But as we can see, it is problematic to merge different parts together if they are not a part of one single operation. Therefore there are lot of noticeable defects on created model concentrated on front side of the body. This type of difficulties appeared also in creating a tail of the drone. Other parts such as carbon-fiber tubes for the tail, legs of the drone and “shoulders” with motors did not create big problems during modelling.

Since there are every part of the delivery system is ready, the full assembly can be made. Here is the final design screenshot:

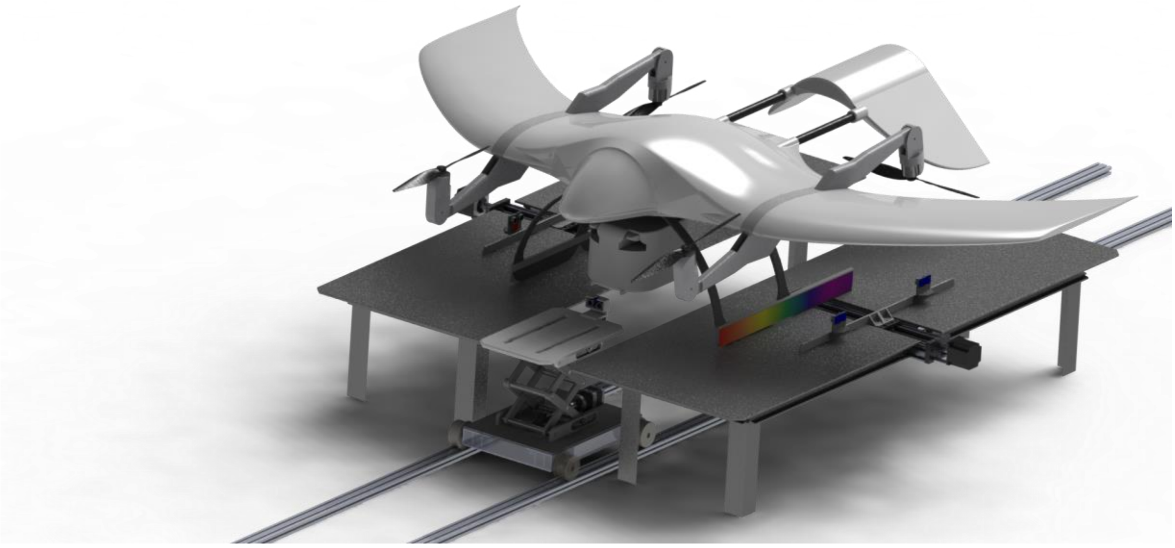


Figure 5.8: Full assembly of the drone delivery system.

6 SIMULATIONS

In order to test the models there were simulations done. Main program for simulations in this project – SolidWorks Simulations. This toolbox allows to test different types of loads on most of constructions.

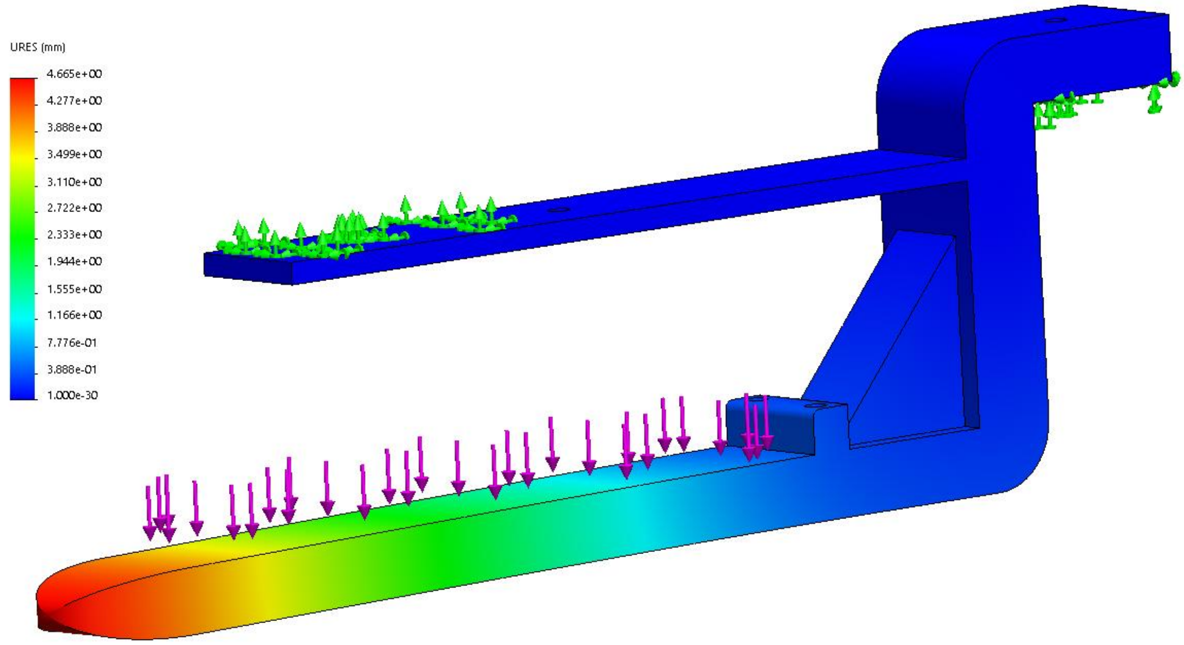
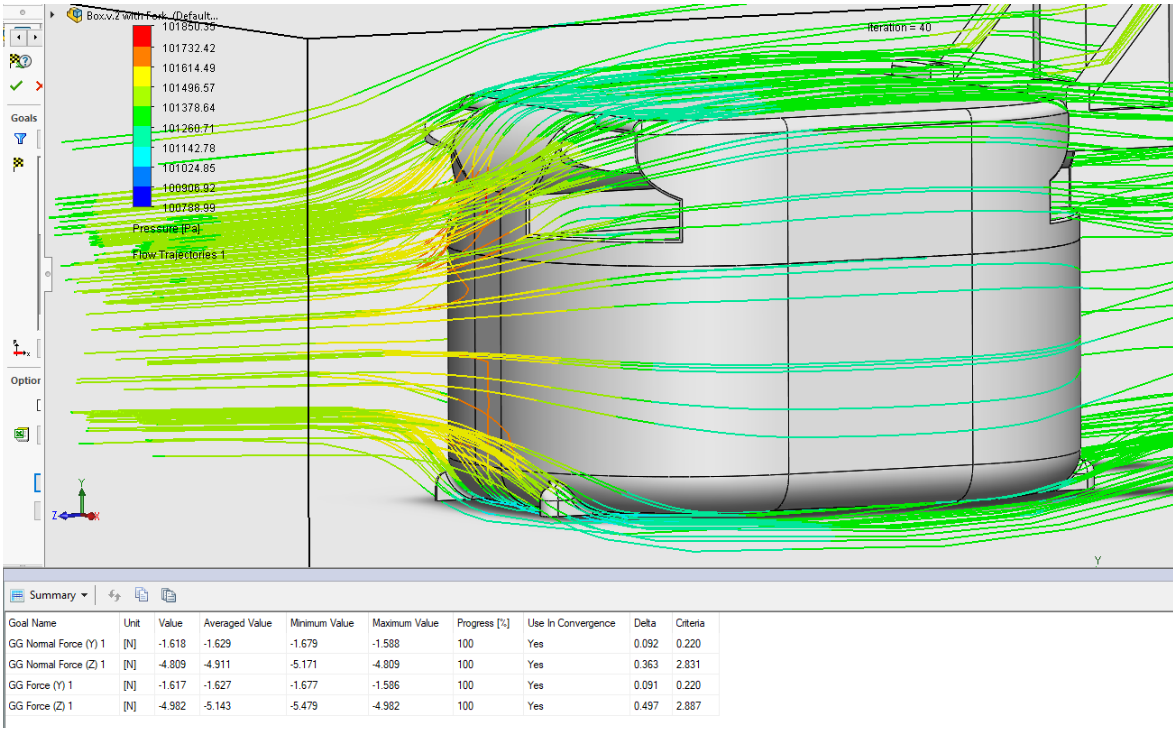


Figure 6.1: Vertical load simulation. Force equals to 40 N. Displacement is 4 mm.

First test shows the displacement under the weight of cargo box. Chosen force is 40 N – it is taken with a margin. Actual force of gravity would be around 10 N for one “finger” of the fork. Considering that the force is much bigger than required, displacement of 4 mm is a good result for the ABS plastic (besides, displacement point is fully concentrated at the end of the fork). So we can say that for the vertical force fork construction deals with the work.



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Normal Force (Y) 1	[N]	-1.618	-1.629	-1.679	-1.588	100	Yes	0.092	0.220
GG Normal Force (Z) 1	[N]	-4.809	-4.911	-5.171	-4.809	100	Yes	0.363	2.831
GG Force (Y) 1	[N]	-1.617	-1.627	-1.677	-1.586	100	Yes	0.091	0.220
GG Force (Z) 1	[N]	-4.982	-5.143	-5.479	-4.982	100	Yes	0.497	2.887

Figure 6.2: Air flow simulation results. Additional force on Z-axis is around 5 N.

In order to calculate the aerodynamic force, SolidWorks Flow Simulation toolbox was used. Speed was set to 90 km/h (25 m/s). For this horizontal speed of vehicle the force created by air will be 5 N. Now we will put this force to the place, where the most of the horizontal load of the cargo box will be.

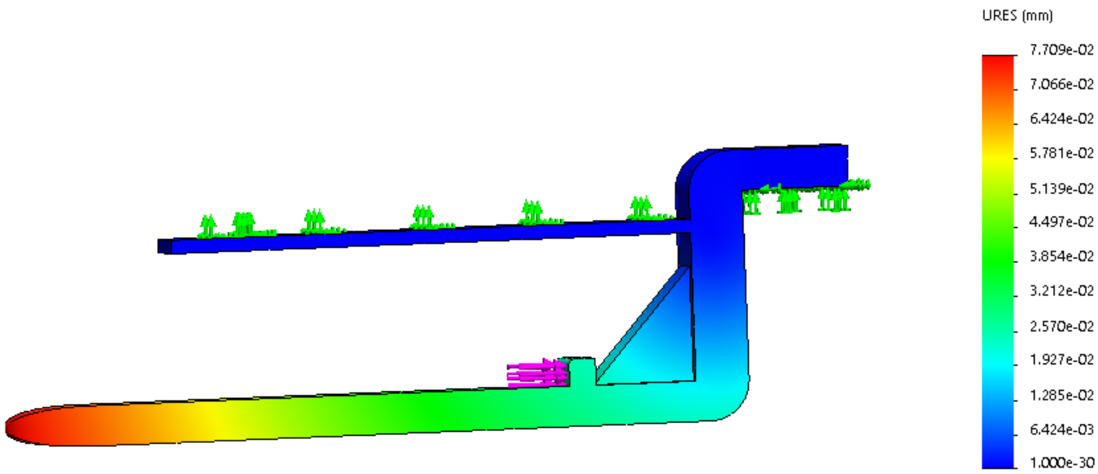


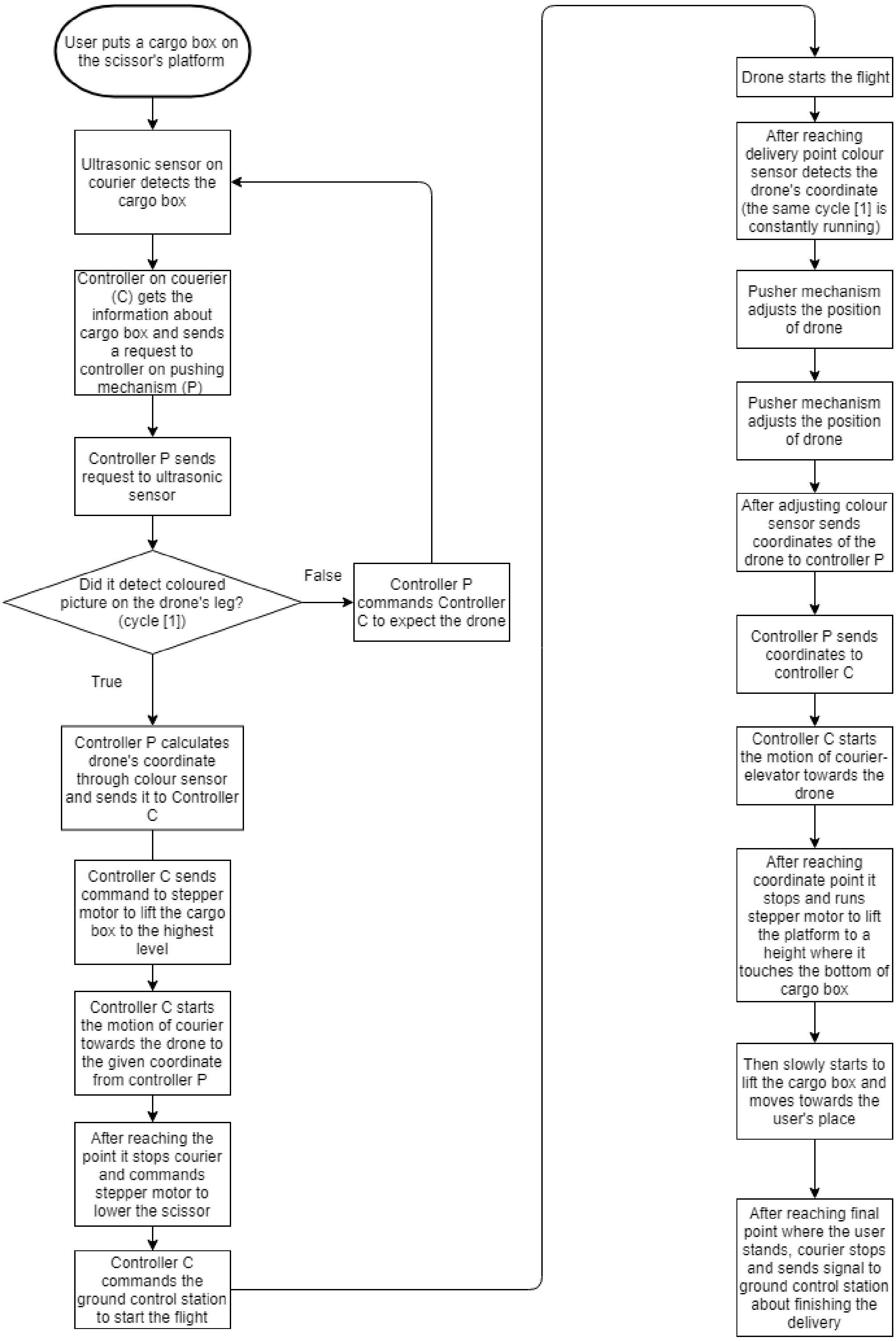
Figure 6.3: Displacement under horizontal force of 10 N is 0.08 mm.

As it was for previous simulation, applied force was taken more than a real: 10 N instead of 5 N. As a result construction does not have any problem with the horizontal load – displacement is 0.08 mm. Stress and Strain results are not problematic too.

7 ALGORITHM AND COST ESTIMATION

7.1 Algorithm of delivery process

Here is the schematic illustration of algorithm for one delivery process. Left part of the algorithm is point A, where a user puts cargo into a box. Right part is Point B – delivery point.



7.2 Cost estimation

This chapter section will show the estimated price of the project. It considers electronics and mechanical components price.

First table represents all the amount of electronics. As a result overall sum for electronics is €416.

Table 7.1: Electronics cost table.

Component	*Quantity*	*Cost, €*
Nema 23 KM061F08	2	35
Nema 17 Geared Stepper Motor	1	45
DC motors for wheels	4	20
TB6600 stepper driver	2	15
A4988 motor driver	1	6
L298N motor controller	1	7
Arduino Uno	3	19
HiLetgo ESP8266 Wi-Fi chip	3	11 (for all 3)
ISL29125 colour sensor	4	8
HC-SR04 rangefinder	5	3
DC Adapter	3	25

Next table is for mechanical components. Some of components, for example, nuts, couplers etc. are not presented here, because of their insignificance in overall price. Sum is €278.

Table 7.2: Mechanics cost table.

Component	*Quantity*	*Cost, €*
Linear rail module	2	70
Scissor lift	1	26
Aluminum profile	4 x 1.5 m	25

Table 7.3: Mechanics cost table.

Sum for electronics and mechanical components is €694. But it must be considered that the table, modification of mechanical components, 3D printing etc. are not included and it is implied that the handwork was free.

8 FURTHER WORK

First main problem is that the cargo box design takes ¾ of the full weight of a payload that Wingcopter 178 is able to carry. That is why either the drone must be updated or the grabbing system and cargo box must be made from other material than ABS. It might be more expensive, but material changing could help with the weight of the construction for carrying.

In a purpose of ecology and economy landing platforms might be covered with sun batteries. This way the whole system could supply itself with power independently.

Other option of development is to put power stations in both ends of courier-elevator’s path, so it will be able to recharge itself when hibernating. As a more wide improvement, instead of a power stations only to install there a package storage shelf with a conveyor. People are already used to them due to postal or delivery companies with their autonomous pickup points around the city. So with the smaller scale this system can be implemented to the suggested drone delivery system.

SUMMARY

This thesis project started with analysis of the current state of the delivery systems in the market provided by the drones. The main objective was to design a delivery system, based on a Wingcopter 178. Problem was divided into several main parts to solve it:

- Grabbing construction;
- Cargo box;
- Drone's position adjusting platform;
- Robot for excluding direct interaction between a user and the drone.

But to design the system it was not an option to consider each described part separately, because design of each part depends on chosen design of others. Therefore, at first there were suggested several solutions. Based on these suggested solutions there was designed final appearance of the delivery system.

When approximate design was chosen, there were started components selection. Calculations for the components were done, according to the results suitable motors were chosen.
After that final model of the delivery system was created. Static simulations of a load on the fork was done based on a simulation of air flow around cargo box. Speed for the horizontal air flow was set to 90 km/h. The results showed that the fork constructively is able to carry the load with at least 4 kg mass.

Cost estimation showed that all the components cost almost € 700. But it must to be considered that this amount of money only for electronics and mechanical components. With rest of the work price might raise up to € 1000.

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APPENDICES

Appendix 1

Drone’s bottom. This hole will be used as a base for a grabbing fork.

Appendix 2

Figure 0.1: TB6600 Stepper motor driver [22].

Table 0.1: Main specifications of TB6600 [22].

Supply voltage	9 – 42 V
Current	4 A
Logic signal current	8 – 10 mA

Table 0.2: ISL29125 Colour sensor [23]..

Table 0.3: ISL29125 colour sensor specifications [23].

Operating current	56 µA
Sensitivity ranges	0: 5.7 m lux to 375 lux 1: 0.152 lux to 10 000 lux
Power supply	2.25 – 3.63 V
Colour range	RGB spectral response
IR rejection	Yes

Appendix 3

Figure 0.2: Nema 17 with a gearhead for screw jack in scissor lift [36].

Table 0.4: Specifications of Nema 17 with 5.18:1 gearhead [36].

Step Angle	0.35 deg.
Polarity	Bipolar
Holding torque	2 N*m
Rated current	1.68 A
Phase resistance	1.65 ohms
Inductance	2.8 mH
Gearbox:	Planetary with a 5.18:1 gear ratio:
Efficiency	90%
Maximum permissible torque	2 Nm
Moment Permissible torque	4 Nm
Shaft maximum axial load	50 N
Shaft maximum radial load	100 N
Shaft diameter	8 mm
Number of leads	4
Mass	520 g

Table 0.5: Specifications of A4988 motor driver for NEMA 17 [37].

For stepper motors with polarity type	Bipolar
For step modes type	Full-, half-, quarter-, eighth-, sixteenth-step
Output current up to	±2 A
Load supply voltage up to	35 V
Output current up to	±2 A

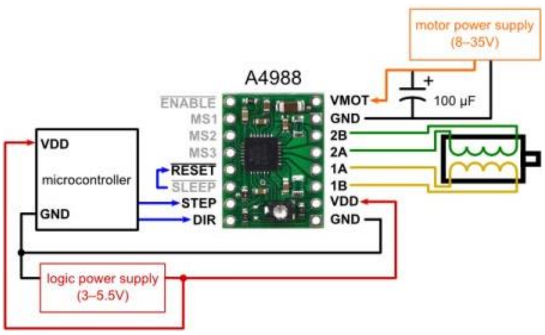


Figure 0.3: A4988 connection instruction [38].

Appendix 4

Figure 0.4: DC motor for the wheels of courier-elevator [31].

Table 0.6: Specifications of DC motor for movement of courier-elevator [31].

Nominal voltage	12 V
Reduction ratio of gearhead	56:1
Rotation speed of output shaft	200 RPM
Torque	5 kg_f cm
Shaft radius	6 mm
Mass	200 g

L298N H Bridge [32]:

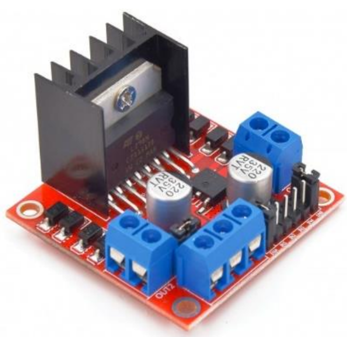


Figure 0.5: L298N chipset based motor driver board.

Motor supply: 7 to 24 V_{DC};

Control logic: Standard TTL logic level;

Output power: up to 2 A;

Enable and Direction control pins;

Power-On LED indicator;

4 Direction LED indicators.

Appendix 5

Figure 0.6: WeMos D1 Mini [39].

Main chip: ESP8266 CH340

Supports Wi-Fi;

1 Micro USB connection;

1 analogue input (max 3.3 V)

11 digital input/output pins.

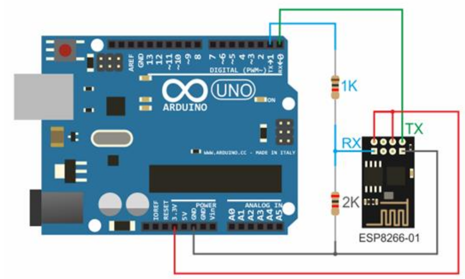


Figure 0.7: Example of connection of Arduino Uno and ESP8266 with resistors [40].

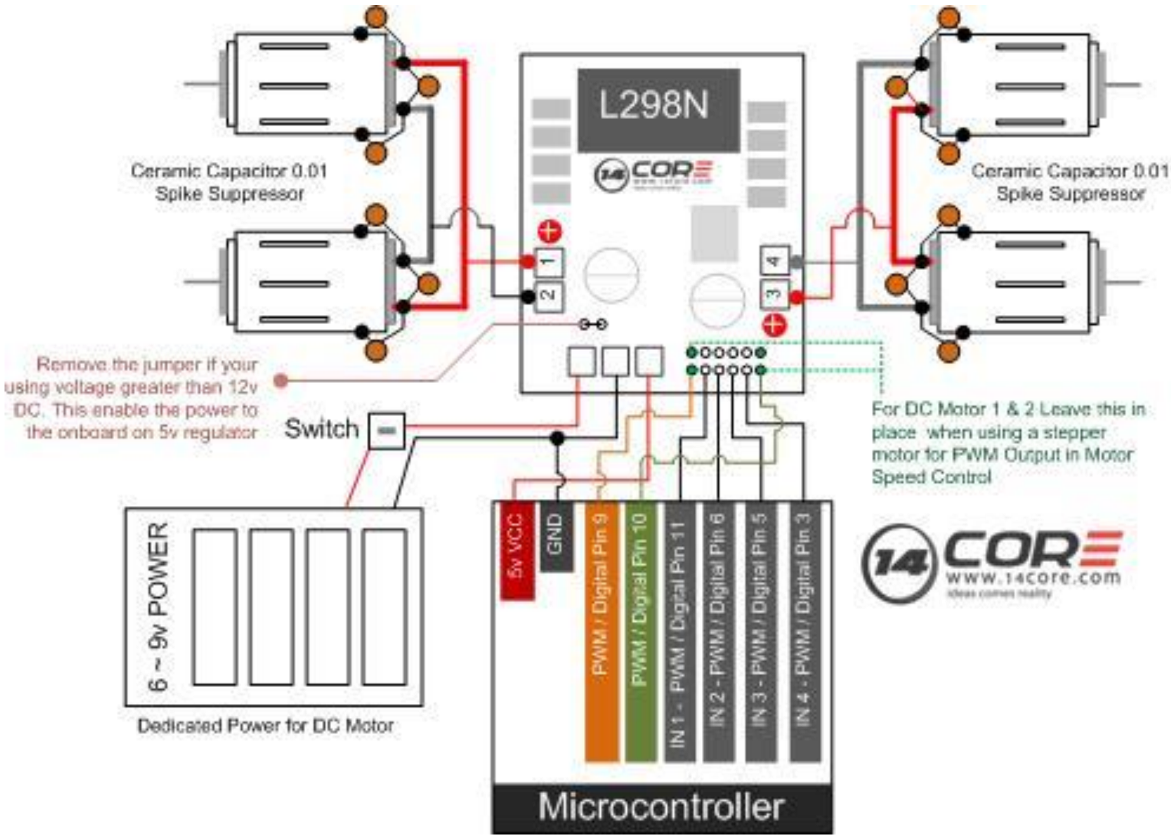
Figure 0.8: HC-SR04 ultrasonic sensor [41].

Table 0.7: HC-SR04 sensor specifications [41].

Supply voltage	5 V
Current	2 – 15 mA
Distance detection range	2 – 400 cm
Effective detection angle range	15°
Working frequency	40 Hz

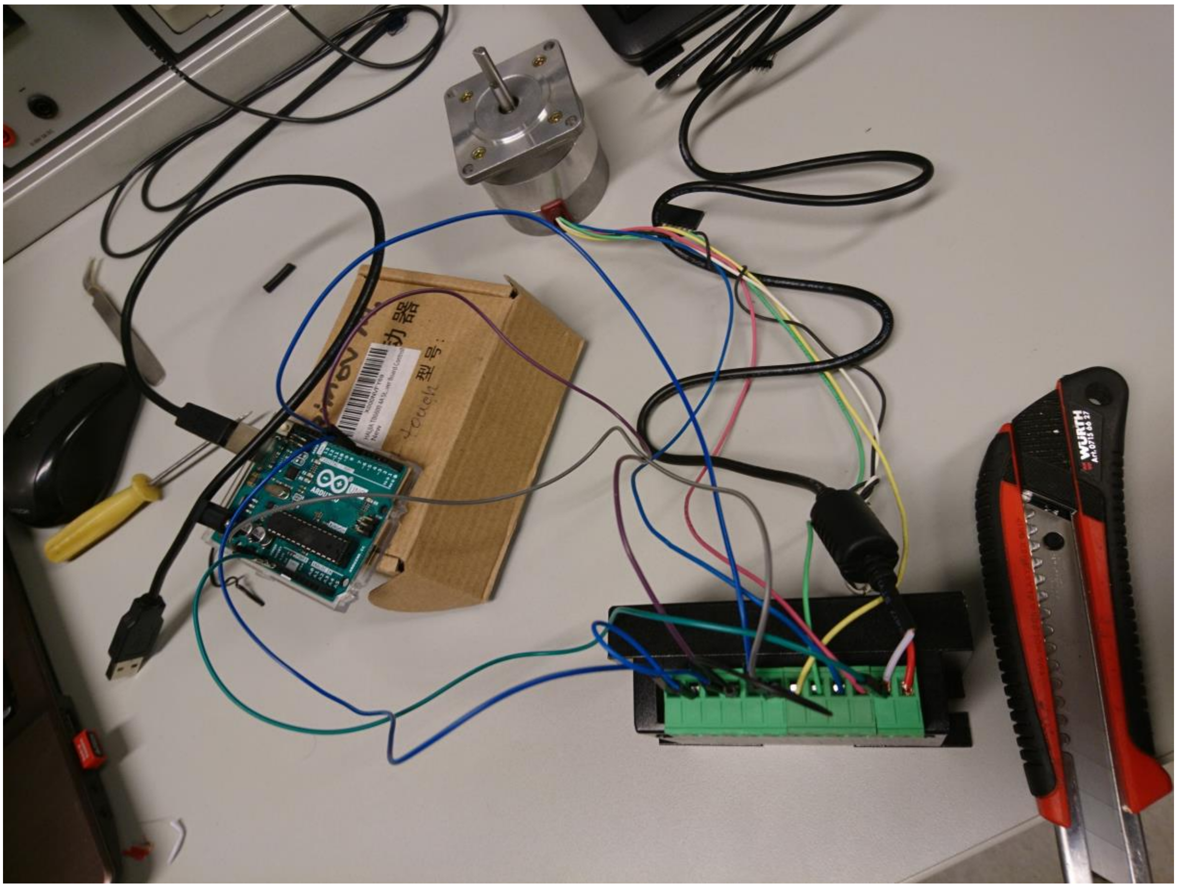
Appendix 6

The way to connect to a single L298N 4 DC motors [32].



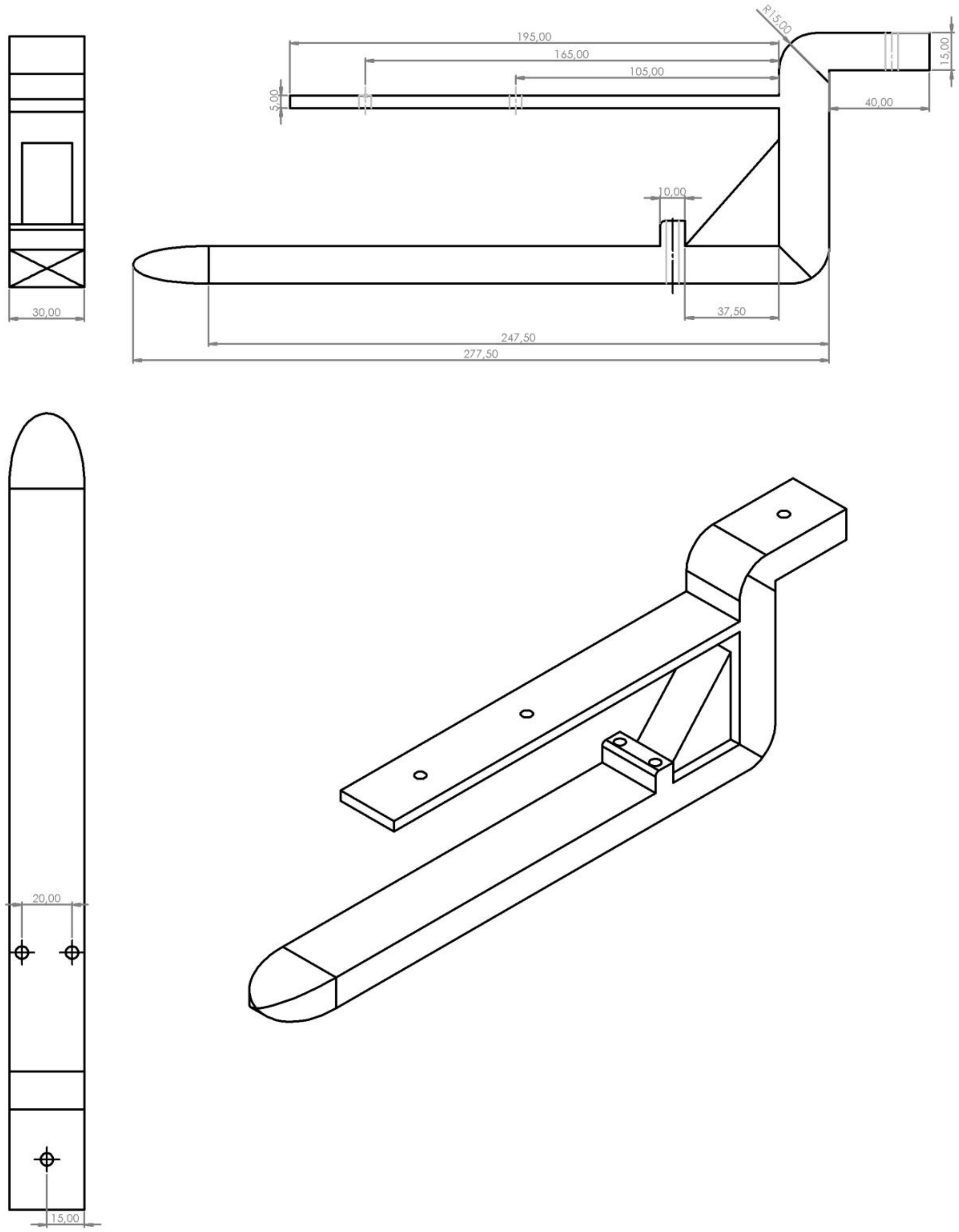
Appendix 7

There were test runs for the Vexta A2695-9212 stepper motor, which was in the laboratory to see how the stepper driver TB6600 works with it.



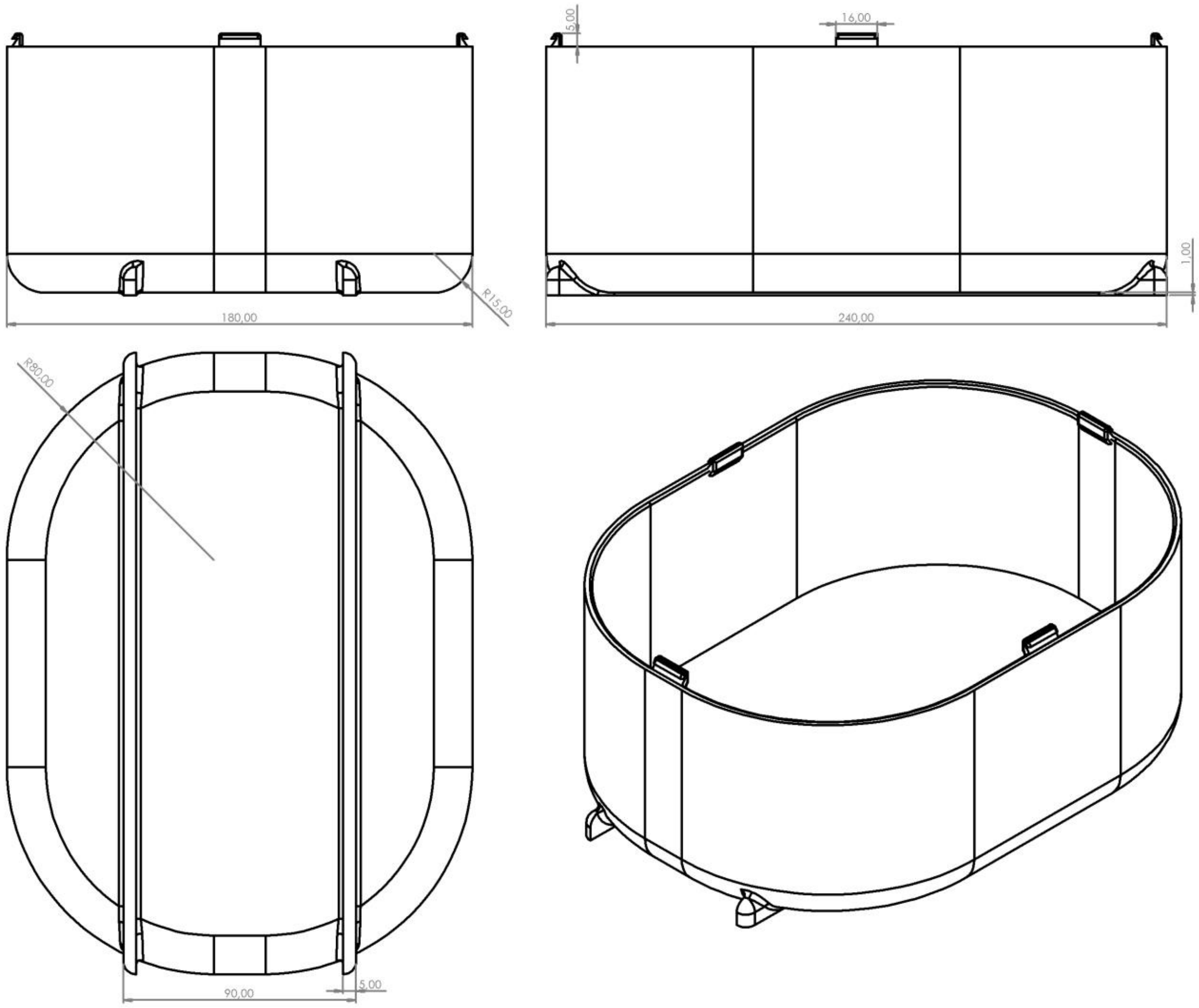
Appendix 8

Drawing of the fork. It was directly transformed in SolidWorks.



Appendix 9

Drawing for the lower part of cargo box. It was directly transformed in SolidWorks.



Appendix 10

Drawing for the upper part of cargo box. It was directly transformed in SolidWorks.