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Norwegian University of Science and Technology

Drone Design and Construction for Indoor Inspection Scenarios

Per Kristian Pöcher

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Supervisor: Tor Arne Johansen, ITK

Norwegian University of Science and Technology
Department of Engineering Cybernetics

Project Formulation

The goal of this project is to model and build a drone prototype for Scout Drone Inspection with key design elements of UAVs (drones) that are to be used in an indoor inspection scenario. The items that should be considered are:

- Overall design suggestions and key design elements that focus on weight, size, flight time, camera position with field of view and battery position.
- Modeling and building a $2 - 2,5$ kg class drone.
- Cooperation with Inventas to create a cover for the prototype.

Throughout the semester tasks where added to the project and had to be implemented into the final rapport. The tasks that were added are:

- Build a smaller version of the prototype with focus of having a known payload of 500g.
- Find a solutions on how and where Radars for a collision avoidance system can be mounted.
- Compare results and give a specific suggestion for how weight, size and flight time relate to another.

Preface

The following master thesis is my final contribution to achieve the title Master of Science from the Norwegian University of Science and Technology at the Department of Cybernetics.

This thesis will take its base in some of the key elements found from my previous work. A more detailed description of this can be found in the introduction.

First of all I want to sincerely thank my supervisor, Professor Tor Arne Johansen and co-supervisor Kristian Klausen for guidance and always answering on a short notice. I also want to thank them for giving me all the resources necessary for completing this thesis, and pushing me to be more constructive.

I would also like to thank Glenn Angell who has helped me produce parts at the workshop when ever it was needed.

By choosing this project and working with drones, motivation has been higher, and I hope the final product can set a standard in the field of indoor drone inspection.

Abstract

The need for using drones for indoor inspection scenarios is sought after. The benefits of reducing both time and risk are to big to not pursue a solution. This project has proven that a functional drone prototype for indoor inspection scenarios can been build. It has features that lets the camera perform inspections of walls and ceilings. It also has motorarms with the possibilities to mount connections for different collision avoidance radars to them. All things considered, the final prototype has the features necessary for indoor inspections that modern drones on the marked today lack.

During the process two prototypes were built. They are both the same design, but one is scaled down making it 25% smaller and 35% lighter. Because both designs focus on having desired features for an indoor inspection scenario, modifications were made such as flipping the front motors to create space for components on top of the drone. It was also split into two levels, letting us place the battery closer to the center of gravity for a longer endurance. The first prototype focused on being a $2 - 2,5$kg class drone. It uses T-Motor's MN3510 KV700 motors together with 12" propellers which makes the size 455 mm wide. The smaller design focused on taking the same design but making it as small as possible for a given payload. This led to using T-Motor's MN2212 KV920 motors together with 9,5" propellers, reducing the width to 350 mm.

Both drones consulted flight test with different loads to see how weight affected flight time. A mathematical function was found that showed this connection for both motor/propeller combination, and it was seen that the mini drone performed better regarding flight time if the external load was located between $0 - 1000$g. Because the mini drone also is smaller in size it is a more desirable design. However,

if extra sensors are needed in a later state the body of the mini drone might be to small. This concluded with a design where the original drone body was used together with the motor/propeller combination from the mini drone. By comparing size and predicting the flight time with our function, it showed that this solution would give the best balanced solution regarding size, weight and flight time.

Sammendrag

Behovet for bruk av droner for innendørs inspeksjonsscenarier er ettertraktet. Fordelene med å redusere både tid og risiko er for store til å ikke forfølge en løsning. Dette prosjektet har vist at en funksjonell drone prototype for innendørs inspeksjonsscenarier kan lages. Den har funksjoner som gjør at kameraet er plasert slik at det kan utføre inspeksjoner av både vegger og tak. Den har også motor holdere med muligheter for å montere tilkoblinger for ulike anti-kollisjons radarer. Alt tatt i betraktning så har den endelige prototypen de funksjonene som er nødvendige for innendørs inspeksjoner, noe som moderne droner på merket i dag mangler.

Under prosessen ble to prototyper bygget. De har begge samme design, men den ene er skalert ned og gjør den dermed 25% mindre og 35% lettere. Fordi begge designene fokuserer på å ha ønskede funksjoner for et innendørs inspeksjonsscenario ble det gjort modifikasjoner som å flippe front motorene for å lage plass til komponenter oppå dronen. Den ble også splittet for å lage to nivåer, slik at vi kan plassere batteriet nærmere tyngdepunktet for å få en lengre utholdenhet. Den første prototypen fokuserer på å være en $2 - 2,5$ kg drone. Den bruker T-Motors MN3510 KV700 motorer sammen med 12 tommers propeller som gjør at størrelsen er 455 mm bred. Den mindre dronen fokuserte på å ta samme design, men gjøre det så lite som mulig for en gitt nyttelast. Dette førte til at T-Motors MN2212 KV920 motorer ble brukt sammen med 9,5 tommers propeller, noe som reduserte bredden til 350 mm.

Begge dronene gjenomførte flyetester med forskjellige nyttelaster for å se hvordan vekten påvirket flyetiden. En matematisk funksjon ble funnet som viste denne forbindelsen for begge motor/propeller kombinasjonene, og det ble sett at

mini dronen hadde lenger flytid hvis den eksterne nyttelasten lå mellom $0 - 1000g$. Fordi mini dronen også er mindre i størrelse er det et mer ønskelig design. Derimot, hvis ekstra sensorer er nødvendig i et senere tidspunkt kan mini dronens kropp være for liten. Det ble dermed konkludert med et design der den originale drone kroppen blir brukt sammen med motor/propeller kombinasjonen fra mini dronen. Ved å sammenligne størrelse og forutsi flytid med vår funksjon viste det seg at denne løsningen ville gi den mest balansert løsning med tanke på størrelse, vekt og flytid.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

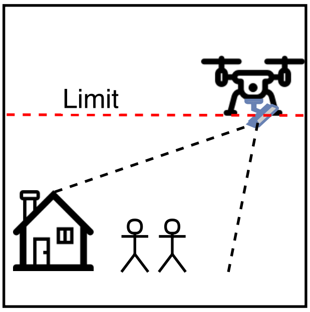
Industrial tanks are found all over the world and are the containers which are used to store liquid or gases for longer or shorter period of time. They can be found in various sizes and most of them are bigger then two storage houses. From time to time an inspection has to be consulted to check the integrity of the structure and see if it holds its requirements. This labor can be both time consuming and hard work. One of the key inspection methods is to do a visual inspection of the surface and welding joints to look for corrosion and deformations. Most of these inspection sites are to high up, and assisting aid such as scaffolds have to be set up to reach them. This takes time and involves risk when working at heights. The benefits of having a drone for these inspection scenarios are therefore many, and it would be very desirable to construct one.

1.1 Available Products

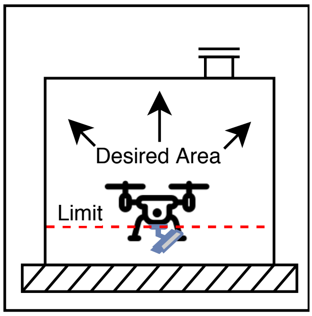
Drones have been around for years, and the development of them has expanded rapidly. They come in all different sizes and shapes, and are used for everything from toys to professional aerial photography. This leads to think that some of these drones can be used for indoor inspection scenarios.

The drones that can be considered for indoor inspection scenarios need to have a camera on board, and nearly all of them are build for one purpose only. That is to get the best "birds eye" perspective of events happening on the ground. To achieve this the camera is mounted under the drone body for best field of view. However, indoor inspection requires inspection of walls and ceilings. Hence, the camera system needs to be able to see up. A redesign is therefor absolutely necessary.

Figure 1.1a illustrates a traditional camera drone that is available on the marked today. It shows the limit of view with a illustrated stippled red line. Whereas Figure 1.1b illustrates the same drone with the view limit, but it also shows the desired area to inspect with the camera inside a tank. This shows clearly that traditional camera drones can not be used for indoor inspection scenarios.



(a) Birds Eye Perspective



(b) Inside Tank

Figure 1.1: Field of View Illustration

1.2 Previous work

In the previous work [5] two designs where modeled. The main focus was to have a design where the camera system was mounted on top of the drone, which was achieved. It focused also on what material to use and which motor/propeller combination to use on a 2 – 2, 5 kg class drone. The conclusion was to use prefabricated carbon fiber together with 3D printed parts to obtain a stiff and light weight structure. T-Motor's MN3510 KV700 [4] together with T-Motor's 12" carbon fiber propeller were found to be the optimal solution for a motor/propeller combination.

This work will use the conclusions found for what material to use as well as the best motor/propeller combination for a $2 - 2,5$kg class drone, and focus on redesigning the previous model to a "ready to build" state, meaning that all dimensions and all necessary features are included. Obtaining more space and finding good solutions for component placement are also key features in the redesign. The solutions will use size, weight and flight time as arguments for consideration. Further, a prototype will be build, and together with Inventas a cover will be made for a overall finished product.

1.3 Software

The software used for 3D modeling is SolidWorks 2016-2017 Student edition. All models are designed by the author using this software.

Chapter 2

Theory

When designing a drone there are important parameters to consider since they play a big roll in how the design evolves. It is also important to know how these parameters interact with another and how they can be changed without "destroying" the design.

2.1 Motor and Propeller

Before starting with designing a drone it is important to know what purpose and which main components you want to implement onto the drone. This is probably the most important part since a weight estimation has to be made for the end result before choosing the correct motors and propellers. The motor/propeller combination set the standard for the final size. Bigger propeller result in a bigger overall design.

A rule of thumb is that it is desirable to have the drone hover at 50% of maximum throttle value. This lets the drone be agile if necessary and it is also where the motors are most efficient. It is asked to build a $2-2,5$ kg class drone, and from previous work it was fount that T-Motor's MN3510 KV 700 with 12" carbon fiber propellers was the best solution for this. Table 2.1 is the part of the datasheet that shows these motors with the corresponding propellers.

Throttle	Current (A)	Power (W)	Thrust (g)	RPM	Efficiency ($\frac{g}{W}$)
50%	3.8	56.24	580	5000	10.31
65%	7.4	109,52	880	6300	8.04
75%	10.3	152.44	1100	7300	7.22
85%	14	207.20	1360	7700	6.56
100%	16.8	248.64	1600	8300	6.44

Table 2.1: MN3510 KV700 Datasheet with 12" Propeller

It can be seen that one motor can generate 580g of thrust at 50% throttle. This means that four motors generate 2320g of thrust. It can also be seen that the efficiency is 10.31 $\frac{g}{W}$. The efficiency is the amount of trust generated divided by the power consumed. If 50% of maximum throttle is compared to 100% throttle (maximum) it is clearly seen that the thrust generated is about three times as much whereas the power consumed is almost five time as much. This shows that that motors are more efficient at a lower speed.

Since motors are more efficient at lower speeds it leads to think that a better solution could be found where 2320g of thrust could be achieved at 30% of maximum throttle. There are motors that can achieve this, but to do so a much bigger motor with propeller is necessary. The weight of the motors would also increase a lot more relatively to the rest of the drone and a new final weight estimation has to be much higher than originally. It is therefore irrelevant to go lower then 50% of maximum throttle and that is also why most of the motor producers not list the specifications below 50%.

2.2 Endurance

In our case endurance translates directly into flight time when considering drones, and is also an important parameter that is affected by size and weight. The flight time depends on how much total power is consumes, and on how big the power capacity of the battery is. If Figure 2.1 is taken into consideration again it can be seen that current consummation at 50% throttle is 3,8A × 4 equals 15,2A. If for example a 5000 mAh battery is used, the flight time can be calculated to:

$$\frac{5000\text{mAh}}{15,2\text{A}} \times 60 = 19,7\text{min}$$

If this is compared to a design with the same motors and battery capacity but where the drone is heavier and hovering is achieved at 65% of maximum throttle, the new flight time is calculate to:

$$\frac{5000\text{mAh}}{29,6\text{A}} \times 60 = 10,1\text{min}$$

In other words, if the throttle value is increased by 15%, the flight time is reduced by almost half. But 15% extra throttle lets us also increase the total weight from 2323g to 3520g, nearly $\frac{1}{3}$ more.

2.3 Discussion

The important parameters such as size, weight and endurance are connected in an evil circle. A bigger drone is heavier and therefor consumes more power resulting in less endurance, whereas a smaller drone is lighter and has more endurance, but is not able to lift the same payload.

In the end it all depends on the total weight, and the requirements you have for the drone design. If size is more important than endurance, a much smaller design can be made by using smaller motors and propellers that achieve hover at $65-70\%$ of maximum throttle. However, if endurance is more important, the design should be modeled around motors with a propeller that can achieve hover at 50% since this is the most efficient.

The most important feature to consider when designing a drone is to reduce weight where ever it is possible. Since weight affects all these parameters negative, it is desirable to design the lightest possible drone to get the best end results.

Chapter 3

Design Concept

The main goal for this thesis is to build a drone with the features needed for an indoor inspection scenarios. The idea is to come up with design concepts that fulfill these features, and compile them together into one complete drone platform. Tests will then be consulted, and potential iterations have to take place before a finished product is achieved.

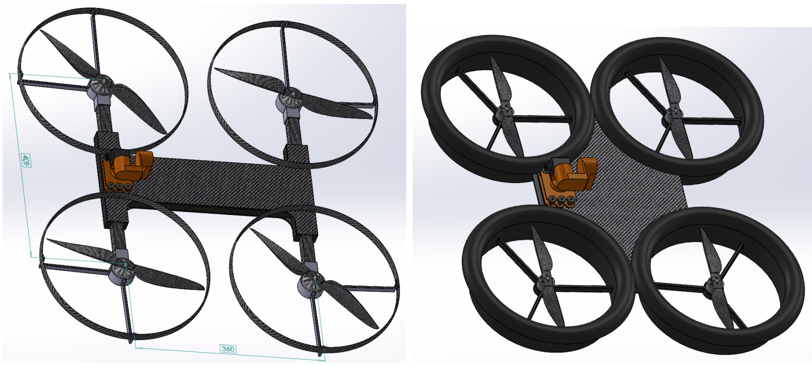
The main features that have to be considered for the drone are listed below. They are listed as they were told by Scout Drone Inspection.

- Size: Keep the design as small as possible.
- Weight: Since some electrical components still are undecided on, an overall estimate should be between $2 - 2,5$ kg.
- Practical: Free space is needed in front to place components.
- Practical: Keep the design "neat and tidy" considering cabling, electronics, etc.
- Look: It should be something new and eye catching.

Since there is no other specific requirement on size then keeping it as small as possible, T-Motor's MN3510 KV700 with 12" carbon fiber propellers will be used because they where found from previous work to give the smallest combination where hover could be achieved at 50% throttle, and thereby get maximum flight time with this weight estimation.

3.1 Choosing the Correct Drone Platform

From previous work, two main Drone-Platform ideas where created. The goal was to build a drone that would have a total wight, including all components, of in between $2 - 2,5$ kg. This was solved by constructing two design's where the right combination of motor and propeller size would be able to accomplish this.



(a) Design 1 (b) Design 2

Figure 3.1: Two Design Ideas

Design 1 was build around a propeller size of 12". This was the smallest propeller size acceptable to fulfill the task. It was designed with a honeycomb structured drone body which is extremely stiff and lightweight. This is a good alternative for structures that are exposed to bending forces.

Design 2 is a more experimental idea. It was also designed with a honeycomb structured drone body, but this design was build around the physical phenomenon called duct effect. Duct effect lets you reduce the size of the propeller by adding a "Duct" (see Figure 3.1b) around the propeller which also create lift when the propellers spin.

Since the uncertainty of how much lift duct effect could add was to big, the conclusion from previous work was to build physical models and test them. However, if a certain amount of lift could not be surpassed with added ducts, the design would no longer be useful. Because there are to many uncertainties with design 2 it was taken out of consideration, and it was concluded to use design 1 as a base for the final design.

3.2 Re-Design

Design 1, which main purpose was a simple and easy to build design, had a flaw. The drone is going to be equipped with electronics, sensors, a gimbal etc, and most of these components need to be mounted on top and as close to the front of the drone as possible. It is therefore desired to have as much free space as possible in front of the drone so these components can be placed to achieve the best results. From Figure 3.1a the area where the propellers spin is illustrated with a circle. This area has to be clear of components and therefor "takes up" space and opportunities for component placement. A simple solution would be to extend the arms, resulting in more space. However, another aspect of the design is to keep it as small as possible. This led to the idea of mounting the front motors upside down.

3.2.1 Upside Down Motors

If the front arms are rotated by 180° it would result in the propellers spinning under the body of the drone. This would generate more free space on top of the drone, as well as giving us the possibility to shorten the arms since there are no electronics present underneath.

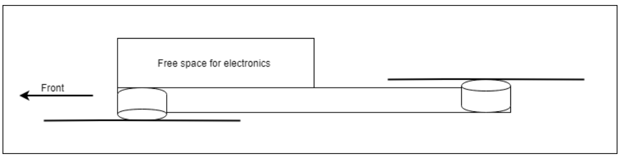


Figure 3.2: "Free Space" Generated by Flipping the Front Motors

Figure 3.2 gives us a visual picture of what a design with flipped front motors would look like, and where the free space is generated.

The Flight Controller, which is the brain of the drone, has predefined what number each motor has, and what way they have to rotate. Figure 3.3 shows which way each motor has to rotate when seen from above. Motor 1 and 4 rotate clockwise, whereas motor 2 and 3 rotate counter clockwise. By flipping the front motors (2 and 4) the direction of rotation is changed.

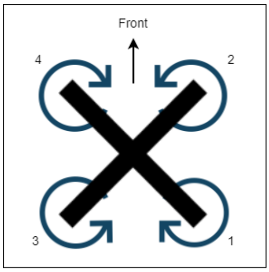
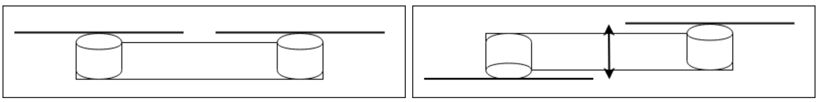


Figure 3.3: Motor Label and Direction

It is important to maintain the correct rotation and therefore this has to be kept in mind when soldering the electronics together.

3.2.2 Compacter Design

A typical drone with four propellers is designed such that all propeller discs are aliened at the same level. This means that if you see the drone from the side, all propeller discs are at the same height. Figure 3.4a shows a typical drone where the propeller discs are aligned.



(a) Propellers Aligned

(b) Propellers not Aligned

Figure 3.4: Difference

By flipping the two front motors a vertical distance between the propeller discs is created. This can be seen in Figure 3.4b. This vertical distance is equals to two times the distance from propeller disc to drone body, plus the thickness of the drone body. If we consider a uniform mass distribution, the center of gravity (COG) is located in the middle on the arrow seen in the figure. It is desired to build the drone as compact as possible, and have all parts as close to the COG to minimize the moment of inertia. From Newtons second law for rotations it is known that:

$$\Sigma\tau = I\alpha$$

$$\Downarrow$$

$$\alpha = \frac{\Sigma\tau}{I}$$

Where τ = torque, I = moment of inertia, α = angular acceleration. From the equation it is seen that angular acceleration depends on the moment of inertia. A compact drone would result in more components being closer to the COG, reducing the moment of inertia.

To maneuver a drone in the air it needs to tilt. For this to happen, two motors need to spin faster then the other. The slower the angular acceleration is the longer it takes to tilt the drone. From Table 2.1 it is seen that a throttle increase from 50% to 65% nearly doubles the current consumption. Hence, if we have a slower angular acceleration, two motors have to spin faster for a longer time and more power is consumed. It is therefore desired to have a compact design where the heaviest components are placed as close as possible to the COG.

This resulted in a design where the drone was split into two parts at the middle, and the front part was attached on top of the back part. This is illustrated in Figure 3.5.

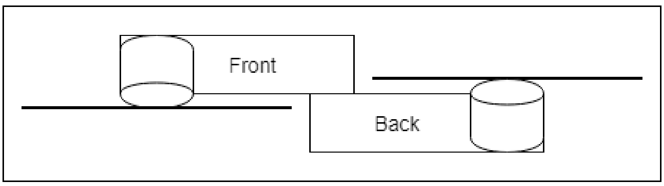


Figure 3.5: Two Level Design

By doing so, the vertical distance of the propeller discs has been reduced by the thickness of the drone body, and a smaller and compacter design is achieved. The remaining distance is needed to give the propellers clearance to rotate freely without interfering with the drone body. This new design gives the drone two levels. The idea is to have the electronics with camera and gimbal mounted on top of the front part, whereas to mount the battery pack on top of the back part closer to the COG.

3.2.3 Two Level Concept

The main idea was to use a sandwich structure for the drone body, where the core material was a honeycomb structured material. This structure would result in a light and extremely stiff body. Because the new concept splits the drone body into two pieces and mounts them together as seen in Figure 3.5, the benefits of using such a sandwich structure would no longer be needed. The weakest point of structural integrate will appear inn and around the area illustrated with the red circle in Figure 3.6.

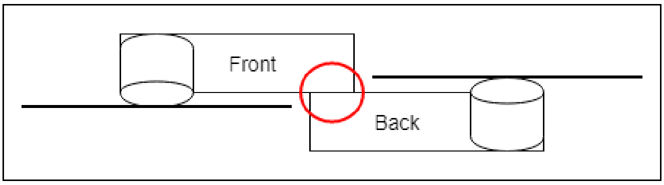


Figure 3.6: Weakest Point of Structural Integrate

The challenge is to find a way to mount the two parts together into one assembly, and still have it as solid and stiff as possible. The first idea of using big bolts that go thought the whole structure was discarded fast since they would add relative much weight, as well as long time exposure to vibrations would make the assembly rickety. Another idea was to glue the two parts together, however the exposure to different elements could result in de-lamination of the glue over time.

Both ideas had flaws that could probably be reduced by increasing the overlap of the two parts, but this would again result in a bigger and heavier design. The result was not to have two separate parts, but use one single carbon fiber plate in the middle. This means that both front and back part would share the same plate.

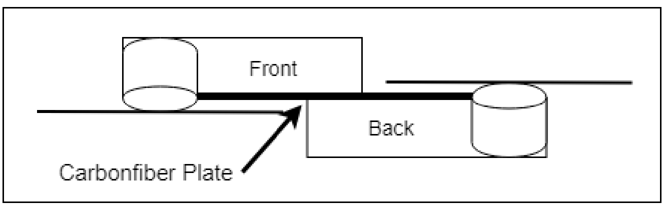


Figure 3.7: One Carbon Fiber Plate

The thick black line in Figure 3.7 illustrates the carbon fiber plate that works as the connection between both parts into one assembly. By choosing the correct thickness, a stable and stiff drone body can be achieved.

3.2.4 Sandwich Structure

As told in 3.2.3, the benefits of having a honeycomb structured drone body is no longer needed. By changing out the core material with thin walls that go around the edge of the body leave us with the same drone design, but generates empty space inside the structure. This empty space gives the opportunity to place electronics and cabling inside, and thereby giving the drone an overall "neat and tidy" look. The walls will be custom made for each edge of the drone, and they will act as a support and fasting area for the carbon fiber plates.

3.2.5 Angled Back Arms

The last big design concept is to do something with the position of the back motors. Since the distance between the front motors could be reduced due to flipping them upside down, it is desired to reduce the distance between the back motors as well. The easy solution would be to reduce the length of the back arms resulting in a smaller distance, however free space is needed for battery placement and therefor this solution is no good.

After some time, the concept of angling the arms backwards was thought of. By doing so, more free space above the drone body is obtained as well as reducing the distance between the back motors. This can be seen in Figure 3.8.

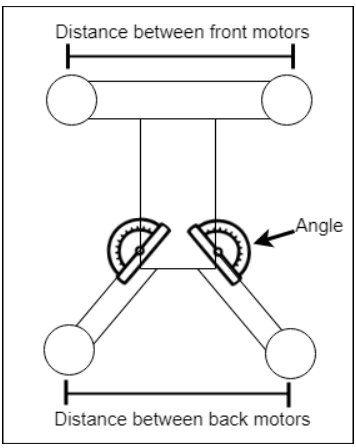


Figure 3.8: Angled Back Arms

The right combination of arm length and angle is important to find, so most free space is obtained as well as keeping the design to a minimum.

3.3 Discussion

The goal was to come up with design concepts that would implement the desired features listed above. By flipping the front motors space was created above the drone which gives us more opportunities for component placement as well as reducing the length of the front arms. The back arms where also angled to reduce the total width of the drone.

The design was split into two levels to give it a better look and make it more compact. This lets us use walls instead of a solid core, creating space inside of the structure for storage and cabling. Overall a new and eye catching design concept was created. There is nothing out on the marked that looks the same as this, so it will be interesting to see if the finished product is functional and does what it is designed for.

Chapter 4

Construction in Solidworks

The next phase in building the drone is to construct all design concepts, and compile them together into one assembly. This is an important phase in the building process since it is a good way to get a visual picture of the finished product, and where potential problems can be reconsidered before building a prototype.

When construction in solidworks takes place, the complete assembly is split into four parts. Each part is worked on separately before they are combined into one. This gives the process structure, as well as parts can be improved on separately without rebuilding the whole design.

The first part is the middle plate seen in Figure 3.7. This is the main part that will give the drone its appearance. The second part will be the Front seen in Figure 3.7. It will contain everything that is located above the main part. The third part will be the opposite of part two. It is the Back in Figure 3.7 and will contain everything underneath the main part. At last we have part four. It will be the arms with the motor holders. This assembly will be called motorarms to easier describe all parts included. They will be constructed at last since the length of the arms depend on the drone body design.

4.1 First Iteration

The first iteration is going to take all the design concepts from Chapter 2 and implement them together into one assembly. There will not be any emphases on how parts are connected, or on where to place holes for wires etc. Concrete dimensions and such are still not clear because not all electrical components have been decided on, but it is known that T-Motor's MN3510 motors with 12" carbon fiber propellers are going to be used. With this in mind a overall first iteration can be constructed.

4.1.1 Main Part

This part is going to be based on a relative thick carbon fiber plate since it will be absorbing most of the forces. The front of the plate will have a T-shaped form as in the original design seen in Figure 3.1a. This is to extend the overlap over the arms for more support. The back of the design will have a V-shaped form to achieve an angle. The result is shown in Figure 4.1.

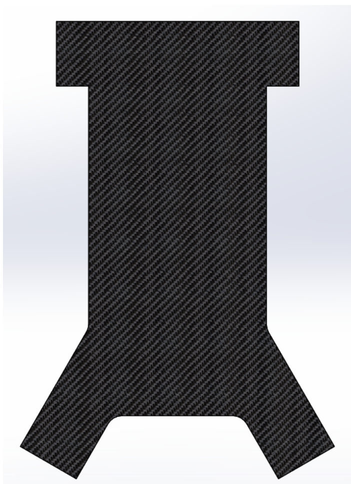
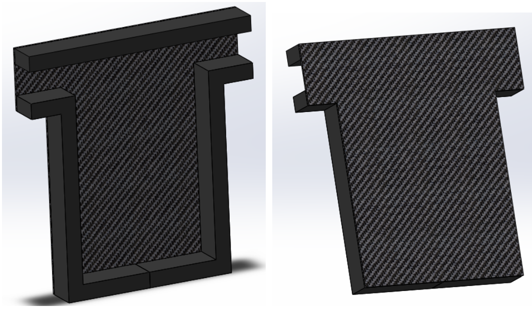


Figure 4.1: Main Part: Iteration 1

It can be seen that a roughly shape has been created. It also has the desired features that was aimed for. The dimensions are not complete, but they are adjusted easily when more components are sett on.

4.1.2 Front Part

The second part is going to have the same shape as the front of the main part. It will also take its base in a carbon fiber plate, but it is only going to hold the weight of the electrical components so a thinner plate can be used. Thin walls will also be created to work as a spacer between the two parts. The height of these will be the same as the thickness of the motorarms.



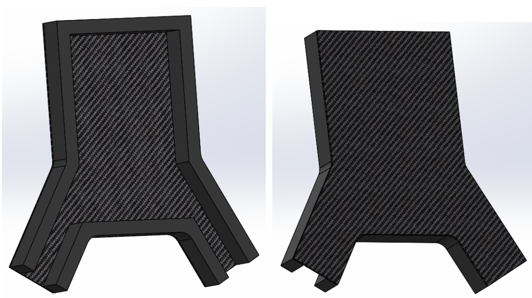
(a) Seen from Below (b) Seen from Above

Figure 4.2: Front Part with Walls: Iteration 1

Figure 4.2 shows how the front part looks with walls. It is also seen that there has been cut away some of the wall structure on each side on the top. This is where the motorarms will slide into the assembly. It is also seen that there is empty space inside the part. This would not be achieved if a sandwich structure with a solid core was used. Now the space can be used for the placement of different electronic components that are needed.

4.1.3 Back Part

The back part, which is located underneath of the main part, will be constructed as the front part. It is a thin carbon fiber plate with walls that surround the edge, except of where the motorarms slide into the assembly.



(a) Seen from Above (b) Seen from Below

Figure 4.3: Back Part with Walls: Iteration 1

Like the previous figure, free space is achieved by using walls instead of a solid core. Notice that the labels have been changed. Figure 4.3a is seen from above since it will be placed underneath the main part, whereas Figure 4.2a is seen from below because it will be placed on top of the main part.

4.1.4 Motorarms

As already known, we will be using T-Motor's MN3510 700KV motors for this drone. The motors are going to be connected to the drone body via carbon fiber rods. Because carbon fiber is relative time consuming to produce, pre-fabricated rods will be used. These come in either square or round shapes, and they can be found in different sizes. We will be using square shaped rods since they are easier to orientate correctly.

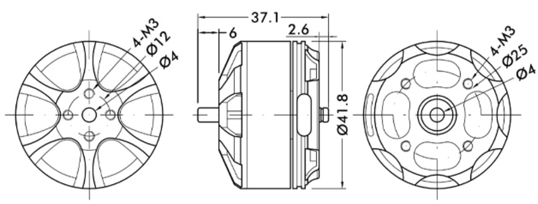


Figure 4.4: MN3510 Dimensions [4]

Figure 4.4 shows the dimensions of a MN3510 motor. With these dimensions a 20 mm × 20 mm square hollow carbon fiber rod is the best alternative to use for the arm thickness. This information is used as a base in the construction of the motor holder.

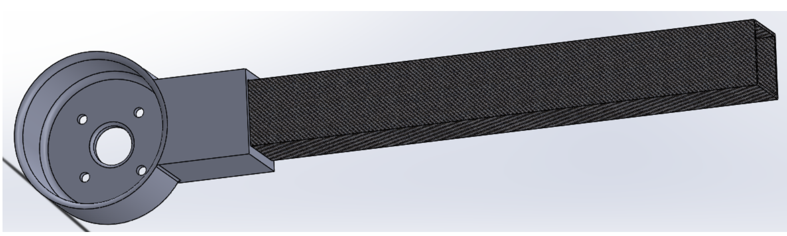


Figure 4.5: MN3510 Motor Holder with Carbon Fiber Rod

Figure 4.5 is a motor holder that will fit our motor. The mounting holes for the motor have been orientated such that the cables connecting to the motor are aligned with the carbon fiber rod, and can therefore go through it for installation.

4.1.5 First Assembly

For the first assembly, all parts that have been constructed are mounted together to see a complete design. Replicas of T-Motor's MN3510 and T-Motor's 12" carbon fiber propellers are also present in the figure to get a better understanding of the design.

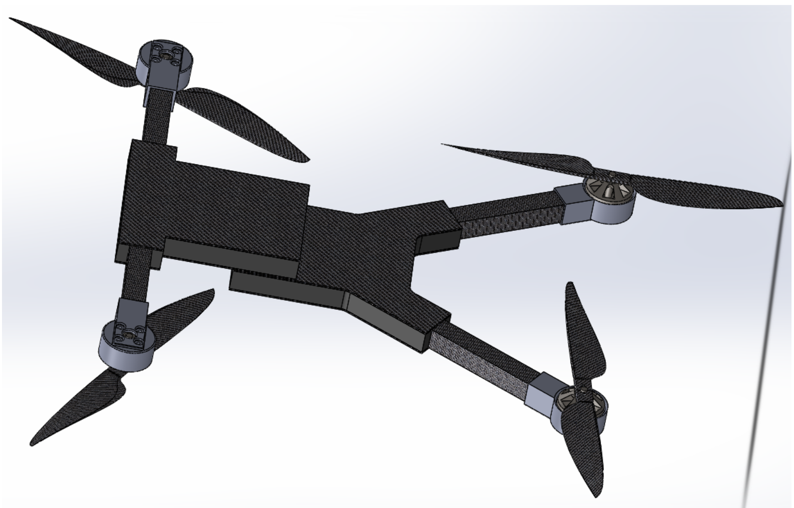


Figure 4.6: Complete Design: Iteration 1

Figure 4.6 shows us our first complete assembly. The goal was to create a two leveled design with flipped front motors and angled back arms. It is clearly seen that this was achieved.

There are no dimensions present in this figure. This makes it hard to visualize the overall size of the drone, but since there are still uncertainties of what type of electrical components that are going to place on the drone, most of the dimensions are still unknown and have to be adjusted for later.

4.2 Second Iteration

The first iteration gave us a design that included all concepts from Chapter 2. Since not all electrical components where decided on, a overall model was made without emphases on dimensions but with good interaction between all concepts.

The main focus of the second iteration is to implement new components that Scout Drone Inspection has come with, and make the design ready for a prototype production. New tasks that have to be implemented are:

- Implement placement for the Printed Circuit Board (PCB).
- Make place for a 4s 5000 mAh LiPo battery.
- Make space for a gimbal in front of the drone.

A physical copy of each component was given to create a model of them in solidworks. This is done to be able to see them implemented in a complete design, as well as making sure that the drone dimensions are correct compared to these components. Each component (left), and its solidworks model (right) are shown below in the following figures.

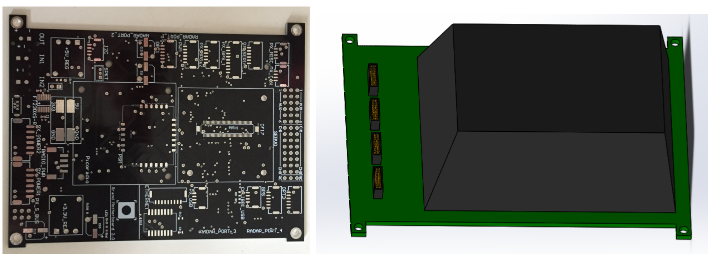


Figure 4.7: PCB and its Solidworks Model

Figure 4.7 is the PCB. It is seen that the actual PCB has no components soldered to it. To illustrate them a black box was placed on top of it. This was done to be sure that parts will not interfere with the PCB when its finished.

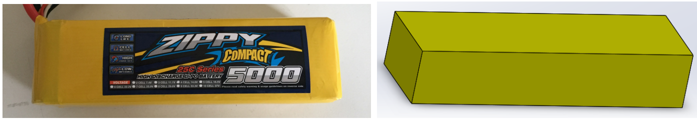


Figure 4.8: Battery and its Solidworks Model

Figure 4.8 shows a simplified rectangular box of the actual battery. It has the same dimensions as the battery, and it will mainly be used to check that the propellers have clearance to it.

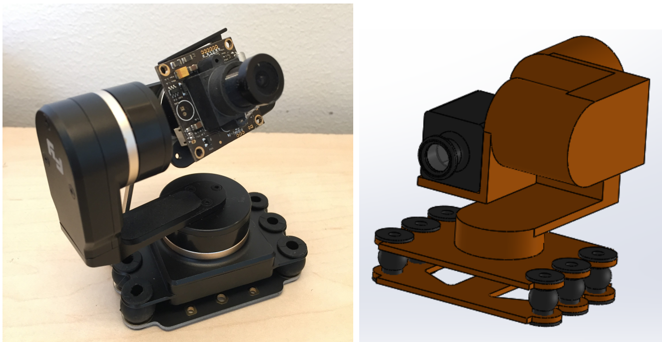


Figure 4.9: Gimbal and its Solidworks Model

Figure 4.9 is the same solidworks model as from the previous work. Since the gimbal has to rotate freely and needs free line of sight, no obstacles can be placed around it. It is therefor not important to have an exact copy of the gimbal or camera, however the mounting plate for the gimbal has to have the same dimensions because mounting space for it is needed on the drone.

Table 4.1 was made to show the dimensions of the three components that have to be implemented. This gives a better understanding of the size.

Component	Length (mm)	Width (mm)	Height (mm)
PCB	116	88	2
Battery	155	45	34
Gimbal Plate	76	60	2

Table 4.1: Component Dimensions

4.2.1 Wall Construction

Before the iteration process of each part is taking place, the construction of the walls will be shown here. Each wall will be constructed the same way, but the shape of the wall depends on the edge it will follow.

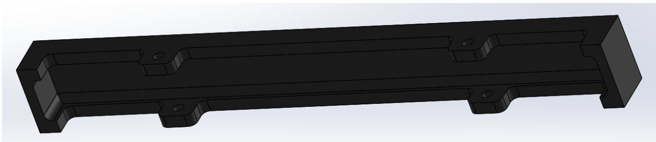


Figure 4.10: Wall Construction

Figure 4.10 is the constructed wall that will be placed in the front. It is a straight wall since the front of the drone has a straight edge. Each wall is 3 mm thick, and has a 3,5 mm thick lip on top and bottom. They are constructed such that 13 mm threaded spacers can be placed between extended lips, thus letting a carbon fiber plate be fastened to it from top and bottom. This is illustrated in Figure 4.11.

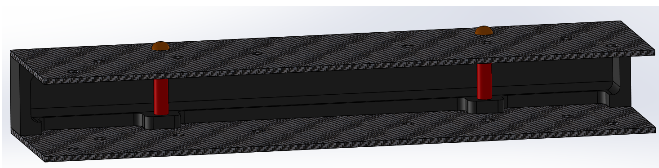


Figure 4.11: Wall Assembly

The parts that are colored red are the threaded spacers. They are placed inside the extended lips on the wall. A carbon fiber plate is hold in place with a M3 screw on each side, making up the new sandwich structure. Each wall will have between two and four extended lips depending on how large the carbon fiber plates that are mounted to it are. The height of the walls is 20mm because that is also the thickness of the motorarms. They will thereby fit inside this structure.

4.2.2 Main Part

The front on the new main part will have the same T-shape as before. It will be sized such that the PCB and the gimbal plate would have enough space to be placed on top of it.

It is also desired to integrate the battery into the drone. This is to make it more compact, less bulky and getting it closer to the COG. The idea is to let the battery rest on top of the back plate, and as far inside of the drone as possible. A rectangular hole was therefor cut into the back of the main part, inside the V-shape. This can easily be seen in Figure 4.12. The hole is big enough to fit the battery.

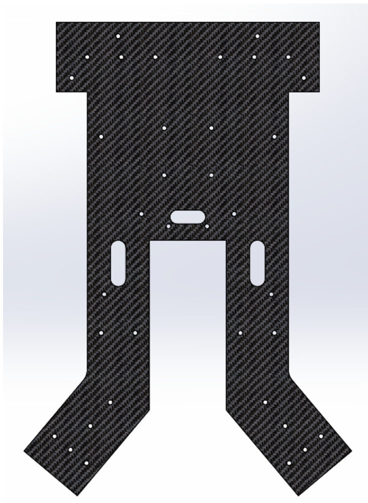


Figure 4.12: Main Part: Iteration 2

A lot of small holes are also present on the main part. They have a diameter of 3,1 mm, and are for mounting purposes only. Most of them are for fastening the walls and the motorarms to the part, whereas some are for mounting electrical components. We can also see three elliptic holes. They where made for treading the motor cables through them. The hole placements have been rearranged some times to find the best spots for the screws so they do not collide with other components, but this figure shows the final placements for them.

The thickness of the carbon fiber plate is still debatable. It is desirable to have the main part as stiff as possible so when it is cut into its shape we are not able to physically bend it with our hands, but it is also necessary to not over dimension the thickness due to the additional dead weight added. The solution will be to order multiple plates with varying thicknesses to do a bending test and see what thickness to go for. Meanwhile a educated guess is done and a 3 mm plate is chosen.

4.2.3 Front Part

This part was originally one plate, but it was split it into two pieces. Combined it still has the same T-shape as before, but it was beneficial for us to split it because there will be electronics inside the drone, and they have to be checked on a regular basis. It is therefor easier to remove a plate that only covers them instead of removing the whole plate that also keeps the motorarms in place.

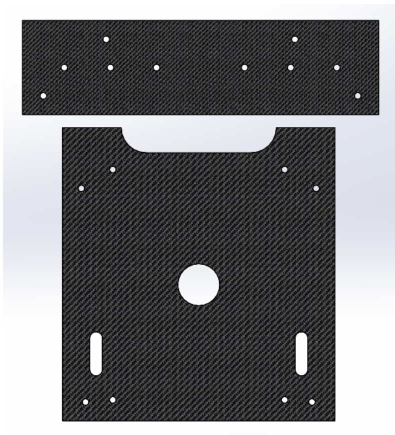
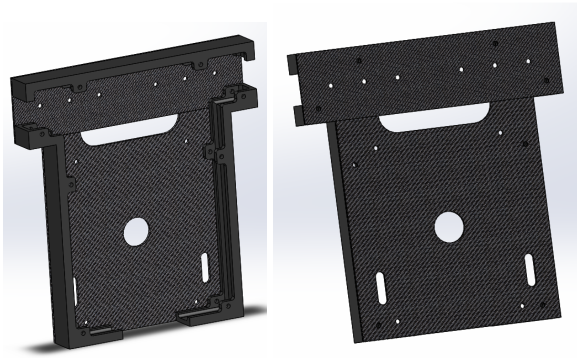


Figure 4.13: Front Part: Iteration 2

Figure 4.13 shows the two plates. The top plate will be mounted permanently since it holds the motorarms in place. The lower plate is the plate that can be removed and will only be mounted with four thumb screws. It is sized the same as the main part, meaning that the PCB will fit on top of it. The smaller holes are again 3,1 mm in diameter, and are placed such that they mirror the holes on the main part. The bigger holes are made to thread different cables up to the PCB.

Figure 4.14 shows us how the walls are supposed to be mounted onto the carbon fiber plate. The assembly is as desired from iteration 1, but it is seen in Figure 4.14a that there is a gap between the lower walls. This was made so that the battery has space to slide inside the drone.



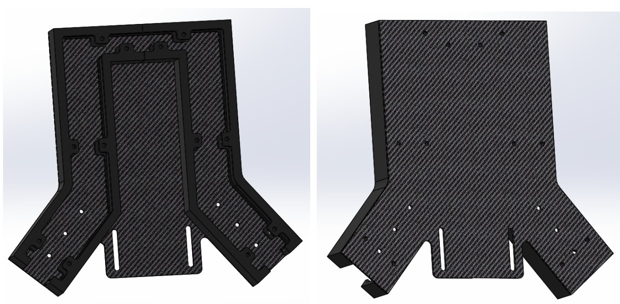
(a) Seen from Below (b) Seen from Above

Figure 4.14: Front Part with Walls: Iteration 2

The plates that will be used for this part and the back part have the same thickness. They will be thinner than the main plate since they are not part of the core structure. They are therefor chosen to be 2 mm thick, but this can be changed if another thickness is more beneficial.

4.2.4 Back Part

There have not been made any significantly changes to this part except that the part was made longer in the middle to support the battery. This is seen in Figure 4.15.



(a) Seen from Above (b) Seen from Below

Figure 4.15: Back Part with Walls: Iteration 2

It is also seen that the walls have been modified to surround the battery instead of the plate's edge. This enables space for us to integrate the battery inside the drone, thereby getting it closer to the COG. There are also made two long holes for a strap to hold the battery in place during flight.

4.2.5 Motorarms

During the modeling process it was found out that radars had to somehow be mounted to the drone. These radars are for collision avoidance to the surroundings and are therefore required to be mounted as close to the surroundings as possible. This led to placing them onto the motorarms since that is the furthest place out.

A design was made where the radar mount was integrated into the motor holder. It seemed that this would result in the best solution because it lets us 3D print a complete part that holds both the radar and motor in place. The need for gluing or screwing two separately parts together was thereby avoided. This part can be seen in Figure 4.16.

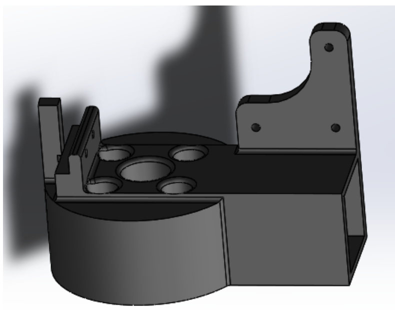


Figure 4.16: Motor Holder with Radar Mount

This part was 3D printed and used for the prototype, but it appeared that this solution was not good. The structure of the 3D printed plastic that made up the radar mount was to weak. It took little time before most of the radar mount broke off during handling.

Instead of constructing the radar mount and motor holder as one piece, four small indents are made into a new motor holder design so that a radar mount can be separately constructed with corresponding pins for better connecting when mounted on later. The benefit of having two separate parts is that in case the radar mount breaks it is only necessary to change it instead of the whole motorarm. There is also the possibility to construct a new radar mount and changing it out with the old one without building new motorarms if different radars are to be used later. Since a easy solution to how radars can be mounted to the drone was found, the work of designing the radar mounts was set on hold because having a flyable prototype was more important.

The following pictures of the drone prototype are constructed using the first motor holders with the integrated radar mount. Even though the radar mount broke off, they worked perfectly well for holding the motors. The new motor holder with four indents is a better solution and will be used in the future for other models. It is shown in Figure 4.17. The thickness of the bottom was also increased a bit to elevate the motors giving the propellers more clearance to the drone body.

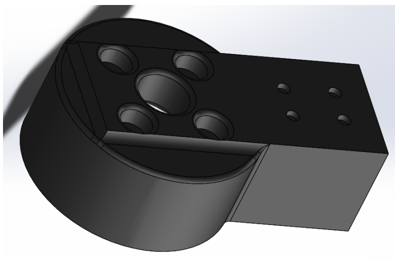


Figure 4.17: New Motor Holder with Four Indents

To find the correct length of the front arms, a model of the constructed parts was assembled in solidworks and the motorarms with motor and propellers were placed into it as well. The length of the arms were then shortened bit by bit to find the shortest possible length before the propellers collided with other components. They were then extended by a bit to have some margins. The length of the front arms was found to be 18 cm each. The length of the back arms depended on the angle. Figure 3.8 shows what angle is meant. From this figure it is seen that an angle of 180° results in the back arms pointing backwards, whereas an angle of 90° results in them pointing outwards. The same procedure as for the front arms was used with different angles to find the best solution.

If a large angle is chosen, somewhere between 150° an 170°, the arms would have to be relative long to avoid collision between the propellers. On the contrary, if the angle would be somewhere between 90° an 120°, they would also need to be relative long so that the propellers would get clearance from the drone body. The angle was therefor set to 140°. This lets us have shorter arms then in the other scenarios, and still avoid collision with components when the propellers rotate. This angle resulted in 18 cm long back arms as well.

4.2.6 Second Assembly

This assembly will contain all features and modifications that have been made in the second iteration process. Motors, propellers, PCB, gimbal and battery will also be included in this assembly to give an overall impression on how the drone will look.

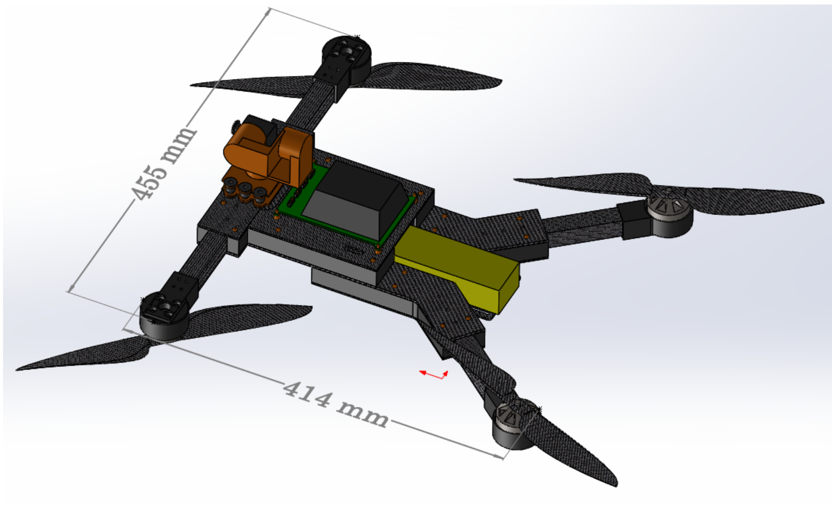


Figure 4.18: Second Assembly

Figure 4.18 shows us our new Design. Dimensions are also illustrated here. They are measured from the edge to edge. It can be seen that the length is 414 mm and the width is 455 mm. The propellers are not considered to contribute to the size since they can easily be removed. The width of the drone can not be reduced more since there needs to be place for one leg in the front. However, you may argue that the length of the drone could be reduced by having a smaller angle on the back arms. This is true, but this would also result in needing to extend the arms so the propellers would not collide with the battery. This would result in making the width even wider, and because the length is already smaller then the width, this is the smallest design. A detailed dimension description of each part can be found in Appendix A.

The biggest and most significant change are all the modifications that had to take place to integrate the battery into the drone. By doing so, a compacter drone design was achieved, leading to a COG placement closer to the middle.

A proper weight estimation is also important to do since the finished product has to be within a total weight of between $2 - 2,5$ kg. Solidworks has a feature that calculates the weight of each part if a mass density is given to it. The walls and motor holders will be created by a 3D printer with a standard ABS plastic. This mass density is already a default property included in solidworks.

Solidworks has different mass densities for carbon fiber varying from what producer it is from, so to get a proper weight estimation the mass density of the plates that are going to be used should be calculated and manually included in solidworks. A 4mm × 300mm × 400mm plate from Hobbyking® [2] was therefor ordered, and the weight was measured to 792g. The mass density was then calculated to:

$$\frac{0,792kg}{(0,004 \times 0,3 \times 0,4)m^3} = 1650\frac{kg}{m^3} \tag{4.1}$$

It can be assumed that the mass density of the carbon fiber is the same independent on the thickness of the plate and this will therefore be used on all carbon fiber parts to get a weight estimation. Solidworks knows the volume of each part and the weight is therefore automatically calculated. The weight on the rest of the components is known.

Table 4.2 shows us the weight of each component present in Figure 4.18. It also divides all components into sections. The first section is our drone body estimate. These are all part needed to build an empty frame with no electronics. It is also here where design modifications can be made to reduce weight. The second section consists of the motors, propellers, ESC, cables and PDB. This weight is known. Our third section is called payload. This is the section where components are still unknown, and will be added when decided on. This is why a drone platform is constructed around $2 - 2,5$ kg so there is room for extra. The last section is the battery which weighs 444g.

Component	Total parts	Weight per part (g)	Total weight (g)
Drone Body Estimate			
Motor Mount	4	22	88
Motor Arms	4	22	88
Walls	7	20	140
Front Plate Small 2mm	1	25	25
Front Plate Big 2mm	1	55	55
Main Plate 3mm	1	164	164
Back Plate 2mm	1	84	84
M3 Screw 10mm	40	0,3	12
Spacer 13mm	20	0,4	8
Total			**664**
Motor, Propeller, ESC, Cables and PDB			
T-Motor MN3510 KV700	4	117	468
T-Motor 12" CF Prop	4	14	56
ESC	4	4	16
Cables and PDB	NA	NA	170
Total			**710**
Payload			
Gimbal with Camera	1	211	211
PCB with Components	1	90	90
Total			**301**
Power Supply			
4s 5000 mAh Battery	1	444	444
Total			**444**
Total Weight			**2119**

Table 4.2: Weight Estimation

Solidworks estimated the drone body to 664g. The weight of the other components are known, and if this is added to the estimation we get a total weight of 2119g. This gives room for extra payload before the weight limit of 2500g is reached.

4.3 Discussion

The goal was to create a "ready to build" model that included all design concepts from Chapter 3 into one complete assembly. This was done in two iterations. The first iteration focused on compiling all design concepts into one functional model. Having two levels with space for components, angling the back arms, and making the overall size fit T-Motor's MN3510 KV700 motors with 12" propellers.

The second iteration focused on specifying each part so it can be manufactured. The core components such as motor, propeller, gimbal, battery and PCB where used as base to get the correct dimensions for all parts. Hole placements for cables, motorarms and wall mounting where also made. The biggest change was the cutout for the battery. Since the battery is the heaviest part and we now are able to place it closer in the middle to the COG, the weight distribution is more centered. This results in all four motors working at the same RPM while hovering, whereas a unbalanced drone would result in two motors consuming more power to stay hovered.

A table with the weight of all components including a estimation on the drone body was made. The total weight was calculated to 2119g. Knowing that almost all main components are present in this estimation leads to think that the weight limit will be held even after adding radars and a complete cover.

Chapter 5

Building Process

After the second iteration on the drone design, the clear signal from Scout Drone Inspection was given to build a prototype. The building process is probably the easiest of them all, but it is definitely the most time consuming. Ordering parts, waiting for 3D prints and being dependent of others takes time, and it is therefore very important to do things correctly the first time.

5.1 Requirements

The building process requires machines and tools that are not found in a normal house hold, but with the cooperation of the mechanical workshop at the institute of cybernetics all the necessary equipment was provided. A Computer numerical control (CNC) machine will be used for cutting out the parts in carbon fiber, and a 3D Printer will be used to create all parts in plastic. There will also be used a soldering iron to connect all electrical components, and other standard tool to complete the process.

5.1.1 CNC Machine

A computer numerical control, also called CNC is a machine that guides a drill bit automatically by the help of way points fed to the machine using a computer-aided design (CAD) software. In our case solidworks is this software and also used to create components. The component file is then "translated" into way points the machine can read. A carbon fiber plate is then mounted in place, and the machine is started. The components a CNC machine can produce depends on how many axis it has. Since only plates are cut out a 2-axis CNC machine is required.

5.1.2 3D Printer

A 3D printer is like a original printer, but it can print 3-dimensional. It uses the same method as a CNC machine where it automatically guides a nozzle by following way points to build a part. The plastic which is fed thought the nozzle is called filament. A 3D printer builds a part by applying layers of filaments upon another. If parts have overhang, meaning that a new layer would start in mid air, a support has to be build first. Our 3D printer has two nozzles where one is for building the part, and the other for building the support. The support material is water based, and can therefore be removed by washing it in water. This lets us print any type of modeled part.

5.2 Drone Body

The first thing to to was to order carbon fiber plates for the drone body. 300 mm × 400 mm plates with thicknesses 1,5 mm, 2 mm, 3mm and 4 mm were ordered from Hobbyking®. The stiffness of each plate was physical tested by bending them with our hands. It was seen that the 3 mm plate was nearly impossible to bend, whereas the 2 mm plate had more flex to it. It was therefor decided that the 3 mm plate was going to be used for the main plate, which was guessed to begin with, and a 2 mm plate for the other parts. Each shape was then cut out in the desired thickness using the CNC machine. Since carbon fiber easily splinters when cut into, each edge had to be sanded down to make it smooth.

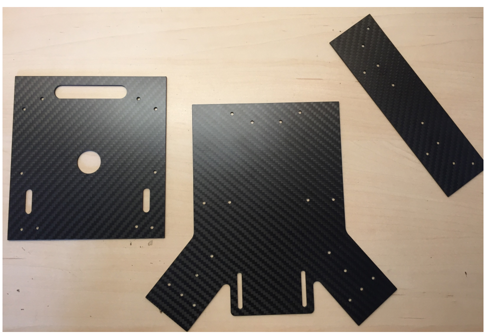


Figure 5.1: Carbon Fiber Cutouts

Figure 5.1 shows the front plates and back plate that have been cut out. The main plate was also cut out, but is not present here. The next phase was to 3D print the walls and motor holders. They can be seen in Figure 5.2.

Figure 5.2: Walls and Motor Holders

Now that all parts have been produced, the assembling process can begin. 13 mm spacers where placed in between the walls where the lip extend. The spacers (red) and the extended lip can be seen in Figure 5.3. All walls are fastened onto the corresponding carbon fiber plate using 10 mm bolts (gold) to build up the drone body.

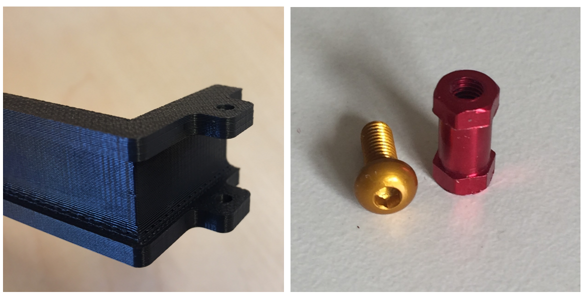


Figure 5.3: Wall Lip, Bolt and Spacer

5.2.1 Motorarms

A 20 mm × 20 mm × 800 mm hollow carbon fiber rod was cut into four 18 cm long pieces. Each piece got a motor holder glued onto using Araldite®. This is a rapid two component epoxy where you mix together 50/50 of each part, and it will bond most elements in about 5 minuets [1].

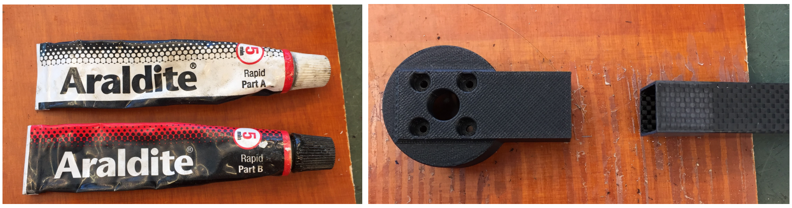


Figure 5.4: Rear Motorarm Assembly

Figure 5.4 shows the Araldite® that is applied to bond the motor holder and carbon fiber arm together. This process is repeated four times. Three holes had also to be manually drill into each motorarm so they could be mounted to the drone body using 30 mm bolts.

5.2.2 Discussion

Figure 5.5: Complete Assembly

Figure 5.5 shows us the complete assembly of the drone. The motors have also been attached since it is done simultaneously with the attachment of the motorarms for easier cable treading. Simple legs have also been made to extend the drone from the ground. The PDB has has been mounted to illustrate size. It is seen that we have managed to build the desired model from solidworks.

One thing that stands out immediately is the extreme stiffness of the drone. It was thought that the main plate had to be extremely stiff since it is the only part that gives stiffen to the whole structure, but it shows that the walls attached in a sandwich structure help create stiffens to the frame. It can therefor be concluded that it is possible to reduce the thickness of each plate and still get the stiffens aimed for. This will also result in a reduced total weight of the drone.

Since all components have been made, the actual weight of the drone can be found, and it can be compared to the solidworks estimation. Table 5.1 is the actual weight of each component. This table lists only the components that solidworks did an estimation of since the weight of the other components were already known.

Component	Total parts	Weight per part (g)	Total weight (g)
Drone Body Actual Weight			
Motor Mount	4	17	68
Motor Arms	4	22	88
Walls	7	18	126
Front Plate Small 2mm	1	25	25
Front Plate Big 2mm	1	53	53
Main Plate 3mm	1	158	158
Back Plate 2mm	1	80	80
M3 Screw 10mm	40	0,3	12
Spacer 13mm	20	0,4	8
Total			**618**

Table 5.1: Actual Weight

It can be seen that the actual weight is 618g compared to solidworks 664g estimation from Table 4.2. It shows that there is a small estimation error in almost each part. The reason for this can be that the mass density of thinner carbon fiber plats is different then for the 4 mm plate which was used to calculate it, or that the consistency in fabricating each plate can differ and thereby give different results. It can also be assumed that the predefined plastic in solidworks has another mass density then the plastic used to print these parts. However, in our case an over estimation was made by solidworks resulted in the final product being lighter then estimated.

If all parts are added together our new total weight of the drone is 2073g. This is less then before and still leaves room for the extra components needed for a finished product before the weight limit is reached. The size was also measured manually and it turned out to be the same as shown in the solidworks assembly.

5.3 Component Wiring

To perform a flight test, all electrical components have to be wired together. Motors, Electronic Speed Controllers (ESC) and Power Distribution Board (PDB) are components that will remain in a finished product, but since the PCB is not completely done a standard F4 flight controller will be used to act as the "brain" for testing. F4 stands for the micro controller unit present on the controller. This is sufficient for the tests that will be conducted.

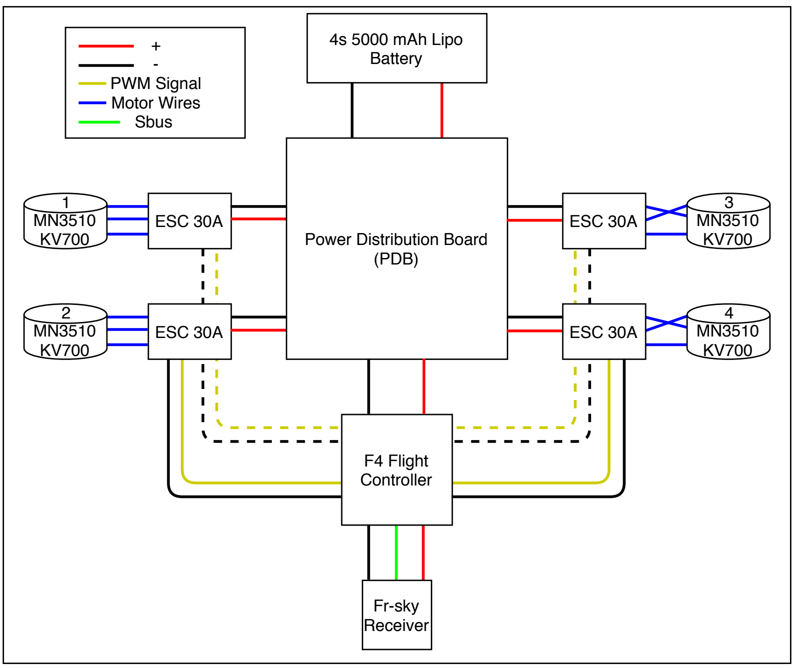


Figure 5.6: Electrical Diagram

Figure 5.6 is a electrical diagram that shows how all electrical components are connected to another in our drone. The biggest component illustrated in this figure is the PDB, and it has as task to distribute the power from the battery. This is illustrated with black ground wires and red positive wires. Since a 4s battery is used, the nominal voltage is 14,8V. Each component has a different voltage requirement, so to give them the required voltages the PDB has various voltage regulators integrated into it. It is also seen that all ESC's are rated to 30A. They have to be rated higher then the maximum possible current consumption one motor can draw. In our case it was seen from Table 2.1 that the maximum current consumed was 16,8A, and a 30A rating was therefor chosen to have some margins for potential current peaks.

All motors are connected to the ESC's by three wires. Since the motors are brushless the rotation occurs by creating a varying magnetic field inside it. This is created by sending signals through these wires in a specific pattern. By crossing two of the three wires the rotation of the motor is changed. From 3.2.1 it was said that since the front motors are turned upside down the rotation for them has to change. That is why motor 2 has no crossed wires whereas motor 4 has. By doing so, the rotations shown in Figure 3.3 are achieved.

It is also seen that each ESC is connected to the flight controller by a ground wire and a signal wire. The flight controller is the "brain" of the drone, so for it to communicate with the ESC's it has to send a PWM signal to them. PWM stands for Pulse-Width Modulation and its main use is to control the power supplied to a electrical device, usually motors. It is very important to connect each PWM wire to the correct pin on the flight controller so that the motor number and flight controller output match.

At last we have the radio receiver. It is connected directly to the flight controller so we are able to control the drone as desired using a remote radio controller. The receiver communicates through a single wired simplex Serial-Bus (Sbus) to the flight controller.

When the PCB is finished, the F4 flight controller installed can be removed and all wires can be reconnected the same way as before to the PCB. This is why all wires and components that are placed permanently are soldered together, whereas wires going to the flight controller have bullet connectors so a change out can be performed easily. There has also been used bullet connectors on the wires connecting from the motors to the ESC's so it is possible to remove all four motorarms if necessary without cutting the wires.

5.4 Mini Drone

During the building process Scout Drone Inspection requested a mini drone. After seeing the actual size and weight of the prototype, it was desired to see if a smaller and lighter drone could be build. Since the original design was build around a final weight of $2 - 2,5$ kg, a smaller drone was requested with the concept of having a known payload of 500g. The payload being the same as for the original design, but with some added weight to compensate for missing components. The benefits of also having a smaller drone are many. It gives us more testing data that can be used for a better estimations on a optimal drone. The optimal drone has a small size, is light weight and has as much flight time as possible.

Since there already exists a functional design there is no need to start from scratch. Our original design will be used and scale down to a fitting size regarding to what motors and propellers are used. This lets us reuse most of the solidworks models by just scaling them down, but some modifications have to be made.

5.4.1 Modified Parts

First of all it is important to find smaller motors and propellers for the mini drone. We will still use T-Motor because our original prototype also uses them, and therefore factory errors can be neglected when testing them against another. By using the theory from 2.1 and guessing the final weight to be roughly 30% lighter then the original, T-Motor's MN2212 KV920 [3] were found to fit the smaller version. Table 5.2 shows the datasheet for these motors together with T-Motor's 9,5" propeller.

Since it almost is impossible to guess the exact weight of the final product, these motors are a good choice because they let us hover with a throttle value of in between $50 - 65\%$ of maximum if the final weight is between $1172 - 1904$g. This is a large gap which probably will result in achieving it.

These motors are smaller then our original motors, therefore they consume less current. Thus if we are able to hover at these throttle values the flight time is not reduced compared to the original design, however the size can be reduces because of the smaller propellers.

Throttle	Current (A)	Power (W)	Thrust (g)	RPM	Efficiency ($\frac{g}{W}$)
50%	2.1	31.08	293	4260	9.43
65%	4	59.2	476	5300	8.04
75%	5.6	82.88	605	5960	7.30
85%	7.4	109.52	742	6000	6.78
100%	10.3	152.44	918	7350	6.02

Table 5.2: MN2212 KV920 Datasheet with 9,5" Propeller

Thinner carbon fiber rods can be used for this design because the motors are smaller. Figure 5.7 show the new motor holder attached to the carbon fiber arm. It was found that a 15 mm × 15 mm hollow carbon fiber rod is a relative size compared to these motors and will therefore fit well. There has also been reduced some material on the motor holders to reduce the overall weight. They still have four indents on the back with the same dimensions as the original design so radar mounts can be mounted later on. The new length was found to be 14 cm due to smaller propellers. This will result in a much smaller design.

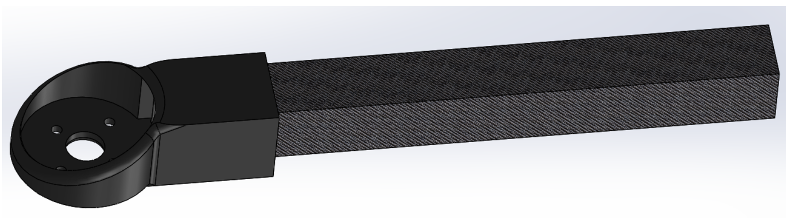


Figure 5.7: MN2212 Motor Holder

Thinner arms result in lower walls. Since the walls depend on the thickness of the arms they will now be 15 mm high instead of 20 mm. The thickness of the walls can also be reduced to 2,5 mm to save weight. Other than that they remain the same.

The last part that had to go through a makeover was the front plate. Since the height of the walls has been reduced, the overall thickness of the drone body has shrunken. This means that the battery will no longer fit inside the drone. A hole was therefor cut out so that the battery can be placed the same way. This is seen in Figure 5.8.

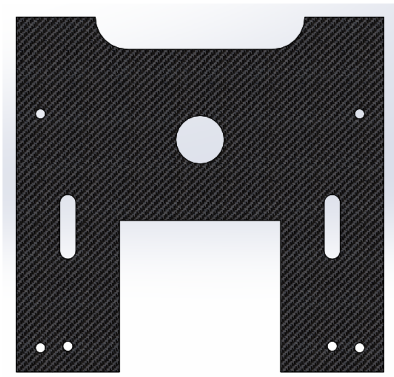


Figure 5.8: Front Plate with Battery Cutout

5.4.2 Mini Drone Assembly

A complete assembly of the mini drone can be seen in Figure 5.9. Replicas of T-Motor's MN2212 and 9,5" propellers have been made to give the model an overall finished look. It can be seen that the length is 321 mm and the width is 350 mm. This is 105 mm smaller then the original size, roughly $\frac{1}{4}$. We were able to reduce the width of the mini drone even more then only due to the propeller size by shaving of the edges of the back plate. This prevented the propellers from colliding into the edges and thereby the arms could be shortened more. Detailed dimentions on all parts for the mini drone can also be found in Appendix A.

The main plate is now reduced to a 2 mm thickness, whereas the other plates are reduced to a 1,5 mm thickness. This was done because it was seen that thicker plates were unnecessary to obtain stiffness.

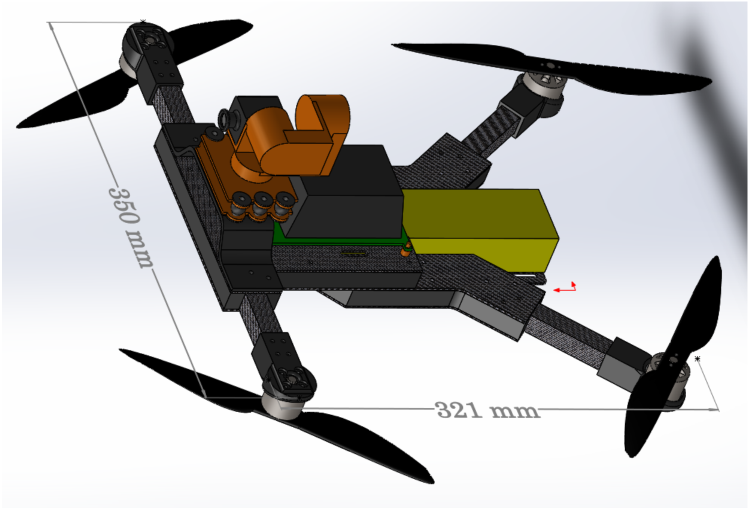


Figure 5.9: Mini Drone Solidworks Assembly

Because the mini drone has a smaller body, the gimbal had to be placed higher to give space for the PCB. A simple mount was constructed for that purpose. It is also seen that these propellers are colored black. This illustrate that they are plastic propellers and no longer carbon fiber propellers. Except for this and the modifications explained above everything is as before.

5.4.3 Discussion

The process of building and soldering the mini drone together is done exactly the same as the process of building and soldering the original drone. The only difference is that the spacers have been reduced to 10 mm, and the bolts to 8 mm so they fit our new walls. Figure 5.10 shows use the build mini drone. It is seen that simple legs have been constructed here as well to extend it from the ground. The PCB is also placed to illustrate size compared to the bigger drone.

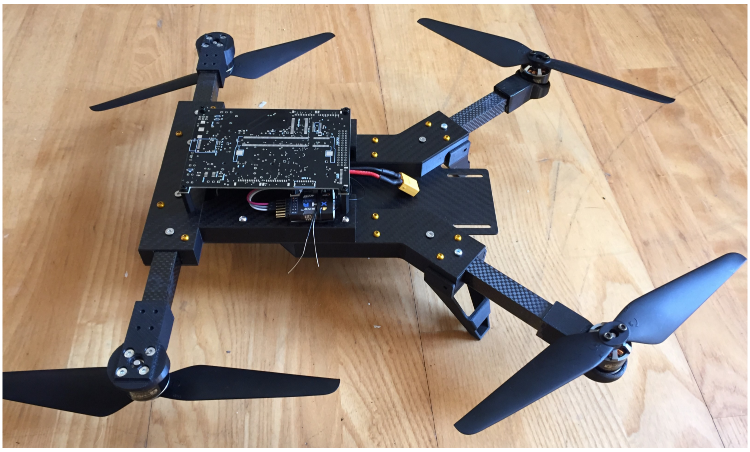


Figure 5.10: Mini Drone

Thinner carbon fiber plates have been used in this build, and the drone still feels solid and stiff. Even though a 2 mm carbon fiber plate was used, which was found to be more flexible then the 3 mm plate, the sandwich structure with the walls again shows that it actually helps create stiffness. The conclusion for this is that it is possible to reduce all carbon fiber plates to a 1,5 mm thickness on both the mini drone and original drone. The overall construction with the walls is stiff enough, and weight can therefore be saved if 1,5 mm plates are use.

Table 5.3 shows the weight of each part of the drone body, and the weight of the smaller motors and propellers. It can be seen that the total weight of the mini drone with motors is 728g. If the weight of the battery is added from Table 4.2, and the desired payload of 500g is added the total weight is 1627g. This lets us fly with a throttle value of between 50 – 65% of maximum, which was aimed for.

Component	Total parts	Weight per part (g)	Total weight (g)
Mini Drone Body Actual Weight			
Motor Mount	4	8	32
Motor Arms	4	12	48
Walls	7	10	70
Front Plate Small 1,5mm	1	14	14
Front Plate Big 1,5mm	1	23	23
Main Plate 2mm	1	70	70
Back Plate 1,5mm	1	51	51
M3 Screw 8mm	40	0,2	8
Spacer 10mm	20	0,3	6
Total			**322**
Motor, Propeller, ESC, Cables and PDB			
T-Motor MN2212 KV920	4	67	268
T-Motor 9,5" Prop	4	11	44
ESC	4	4	16
Cables and PDB	NA	Na	78
Total			**406**
Total Weight			**728**

Table 5.3: Weight Mini Drone

In comparison, if the weight of the original drone body from Table 5.1 is added to the weight of the motors, propellers ESC's, Cables and PDB from Table 4.2 the total is 1328g. It can be seen that the mini drone is exactly 600g lighter then the original prototype if payload and battery weight is neglected. Since both drones are build around two different concepts they can not be compared directly to another, but flight test can be consulted with the same payloads, and data can be found to help finding the optimal solution regarding size, weight and flight time.

Chapter 6

Testing and Results

Now that there is a "ready to fly" prototype of the drone, tests will be conducted to see how this new design flies. Discussions on how weight affects flight time, and an overall suggestion on size will also be made.

6.1 Flight Performance

Even if this new and innovative design looks cool, it is useless if it does not fly well. Since there are so many different designs out on the marked today that fly, it is easy to think almost anything can perform well. The fact that our design has flipped front motors is something that has not been seen before, and you may wonder if there is a reason for it. However, a flight performance test will be conducted where we will take off and maneuver the drone in all possible ways to see if flaws can be found.

Figure 6.1: Prototype Flying

Figure 6.1 is a photo of the drone while flying. It is impossible to see on a picture how the drone behaves, but you can clearly see that it flies. The drone did surprisingly well. It hovered very nice, and there where no unexpected vibrations. Some small drifting occurred while hovering, but that is probably due to some wind and a poor Inertial Measurement Unit (IMU) calibration on the F4 flight controller for testing. However this can be neglected since a better flight controller will be used, and the drone will operate inside big tanks where there are no winds present.

The drone did also perform good while maneuvering it around. There occurred no unaccepted movements, and the drone leveled itself out quiet fast when the joysticks where released. In other words, it did good flight performance vice. The same goes for the mini drone.

6.2 Weight and Flight Time

To see how the weight affects the flight time, both drones will fly with different loads to have more data for a better conclusion. As of now, not all components are present on the drone, so one payload is going to represent that weight to get a realistic flight time estimation. This payload represents the 301g from the components in Table 4.2, plus additional weight so that the total payload is put to 500g. The second payload will be put to 1000g, whereas the last test will be performed without any payload. To simulate the payloads a small basket with the corresponding weight will be mounted on top of the empty PCB because most of the payload will be located around that area.

The test are performed by using a fully charged 4s 5000 mAh battery, and fly the drone at a steady hover for 5 minutes. It is desired to fly the same each time. The battery is then charged fully up to see how many mAh the charger puts back into it. By doing so, a calculation of the flight time can be made with such battery because LiPo batteries are considered empty at 20% of its total capacity. This means that 4000 of the 5000 mAh can be used. Each test is conducted three times and a average mAh consumed is found.

6.2.1 Mini Drone

Table 6.1 shows the estimated flight time with the different payloads for the mini drone.

Mini Drone	Total Weight	mAh Used	Estimated Flight Time
Without Payload	1172g	680	29,4 min
With Payload (500g)	1672g	1100	18,2 min
With Payload (1000g)	2172g	1475	13,6 min

Table 6.1: Estimated Flight Time Mini Drone

The weight without payload is the weight of the drone body, motors, propellers, ESC's, cables and PDB, and battery. The weight with payload is the same, but with added load of 500g and one with added 1000g. It can be seen that the flight time is reduced if the weight is increased. This means that one parameter is inversely proportional to the other. We can thereby described this model as a simple hyperbola. The formula for a hyperbola is:

$$y_i = \frac{C}{x_i^n}$$

where y = Flight Time, x = Total Weight, C = constant.

To solve this equation, two identical equations are solved for C and n, but with different y and x. If we rearrange the equations and substitute for C we get:

$$n = \frac{ln\frac{y_2}{y_1}}{ln\frac{x_1}{x_2}}$$

where y_1 and x_1 are the weight and flight time for the drone without payload, and where y_2 and x_2 are the weight and flight time for the drone with maximum payload (1000g). These points where chosen to make a model so the final weight can be represented in it because it will most certainly be somewhere in between. Solving for n gives n = 1,249. Rearranging the original equation and solving for C gives us:

$$C = y_1 x_1^n$$

$$\downarrow$$

$$C = 200188 \qquad n = 1,249$$

To test the model, the flight time of the drone with payload (500g) will be predicted and compared to our estimate to see if it matches.

$$y = \frac{200188}{1672^{1,249}} = 18,8$$

The predicted flight time is 18,8 minutes and almost the same as the estimated flight time from Table 6.1. To verify this model even more a test was conducted with a 300g external payload as well to see if this also matches the prediction. The predicted flight time with this payload is 22,1 minutes after using our model, whereas the estimated flight time was found to be 22,5 minutes. Since it is hard to fly exactly the same each time these estimations can vary a bit, but our model is very close and can therefore be used to predict a flight time for T-Motor's MN2212 KV920 with 9,5" propellers with different loads.

6.2.2 Original Drone

Table 6.2 shows the estimated flight time with the different payloads for the original drone.

Original Drone	Total Weight	mAh Used	Estimated Flight Time
Without Payload	1772g	930	21,5 min
With Payload (500g)	2272g	1320	15,2 min
With Payload (1000g)	2772g	1800	11,1 min

Table 6.2: Estimated Flight Time Original Drone

As expected, the flight time is again reduced when the weight is increased and the same model will be used. y_1 and x_1 are the values for "Without Payload", whereas y_2 and x_2 are the values for "With Payload (1000g)". The calculations are done as above, and the new C and n are found to be:

$$C = 1350266 \qquad n = 1,477$$

To verify the model the flight time of the drone with 500g payload is again predicted to see if it matches our estimation from Table 6.2.

$$y = \frac{1350266}{2272^{1,477}} = 14,9\text{min}$$

This time the prediction is 0,3 minutes of the estimation and it can therefore be said that the model does its work again, and can be used to predict the flight time for T-Motor's MN3510 KV700 with 12" carbon fiber propellers at different weights.

6.2.3 Comparison

If the two tables above are compared to another it can easily be seen that the mini drone did better regarding flight time. It can be assumed, since Scout Drone Inspection has said so, that the payload of all the components that will be added to the drone is about 500g. It can therefor be said that the mini drone has both a better flight time estimation and is also smaller in size. Plot 6.2 shows the predicted flight time for both models with our actual estimations represented as x.

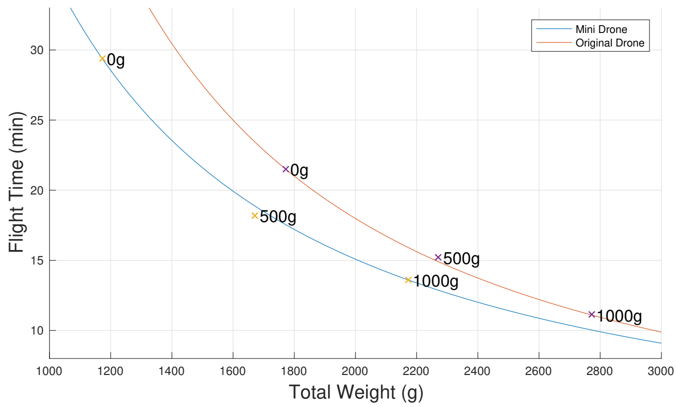


Figure 6.2: Flight Time Plot

The blue line represents the mini drone whereas the red line represents the original drone. It is seen that the mini drone has a higher flight time with a payload between 0 – 1000g compared to the original drone. Predictions of a payload over 1000g can be neglected since it most certain will not exceed this.

It has to be sad that the weight without payload represents only the parts necessary for the drone to fly. It is already known that the mini drone is 600g lighter then the original drone before payload is added. Our original drone uses 2 and 3 mm thick carbon fiber plates, whereas the mini drone uses only one 2 mm plate, and the rest are 1,5 mm. Since the conclusion already has been made that all plates can be dimensions to 1,5 mm, the weight of the original design will be reduced compared to the weight now.

From 4.2.6 a estimation could be made for the weight on the carbon fiber plates by finding the mass density and putting it into solidworks. It was also seen that this mass density gave a close estimate compared to the actual weight. A new estimate can therefore be made to see how much the weight can be reduced on the original drone when only using 1,5 mm carbon fiber plates.

By reducing the thickness of all plates to 1,5 mm a total of 111g was saved according to solidworks estimation. The new weight without payload can therefore be assumed to be 1661g. If the payload of 500g is added to this, a new flight time can be predicted by using our model for the original drone. The new flight time was predicted to be 16 minutes. It is seen that this still is less then the flight time with 500g payload for the mini drone. The flight time of the mini drone will also increased by a tiny bit if the same calculations are done by changing the 2 mm main plate to a 1,5 mm thickness. This shows that the smaller motor are a better choice for the given payloads.

Because the mini drone uses smaller and lighter motors, and the drone is smaller and lighter as well, it can be said that for a payload of in between $0 - 1000$g it is a better design then the original design. However, the original design was created for a total weight of $2 - 2,5$kg so if the maximum weight is used in both models

$$y_{\text{mini}} = \frac{200188}{2500^{1,249}} = 11,4 \qquad\qquad y_{\text{original}} = \frac{1350266}{2500^{1,477}} = 12,9$$

it can be seen that the original design performs better, and is therefore a better choice if only flight time is considered.

6.2.4 Size

There has not been many comments on size, and that is because it is hard to control it. The size of the propellers set a standard on how long the motorarms have to be and thereby setting the overall size. We have been using 9,5" and 12" propellers for the two drone models. We achieved a size of 455 mm with our 12" propellers whereas this could be reduced to 350 mm by using 9,5" propellers. There are probably only some tiny changes like shaving of the edges of the back part that can reduce the size by a bit, but it is the propeller size that plays the biggest role.

The mini drone is 25% smaller then the original drone which led to mounting the PCB and gimbal more compact. If it is decided that more sensors, which are not yet accounted for, need to be mounted to the drone body, it would be more desirable to have the size of the original drone body since there is more free space. A good solution to obtain the best combination of size and flight time might be to combine the original drone body design with the motor/propeller combination of the mini drone.

If this solution was tried, the size could be reduced to around 350 mm like the mini drone. The new weight of the drone body with only 1,5 mm carbon fiber plates would be 618g from Table 5.1 minus 111g that solidworks estimated that could be saved, and minus approximately 60g that could be saved by reducing the motor arms and motor mounts. This gives a total of 447g. If we add the weight of motors, propellers, ESC, Cables and PDB from Table 5.3 and the weight of the battery, the total is 1297g. This lets us keep the original drone body design, but we could reduce the overall size. If we add the 500g of payload to this and use our model for the smaller motors to predict the flight time we get 17,2 minutes.

It all melts down to the most important parameter needed. If flight time and a overall smallest size are more important parameters, the mini drone has the best result for this. However, if large payloads and more component space is needed the overall size has to increase. If the payload results in actual being 500g, and space for extra components is needed, the best solution would be to use the drone body from the original design and the motor/propeller combination from the mini drone. A sacrifice of 1 minute with flight time is nearly nothing compared to the results of getting a reduced overall size by 105 mm and still having the original drone body.

6.3 Discussion

Both drones performed well during the flight tests. They showed no unexpected movements and it can be said that the drone design worked as hoped for.

A model was fount to see the connection between weight and flight time, however the constants C and n have to be calculated for each motor/propeller combination chosen. It was seen that with the expected payload of 500g, T-Motor's MN2212 KV920 combined with the 9,5" propellers performed better regarding flight time. This is also a much smaller design and would be the optimal solution for the given payload with the already existing components. The problem would be if additional components are added to the drone. The free space left on the mini drone is already very limited. It would therefor be necessary to use the original design since it has more space for this, but then again the size would increase. A solution would be to use the original drone body with 1,5mm thick carbon fiber plates to reduce the weight as much as possible and combine it with the smaller motors. This would give a smaller overall size, more space for component placement, and much more flight time then the original design.

However, for the first task, which was to build a $2 - 2,5$kg class drone, the original design performed better if the higher end of the weight scale was reached. The smaller motors are not fit for such weights and flight time will drop faster compared to the bigger ones. But again, compromises can be made if size is more important by using a battery with a higher mAh rating. This would add a bit more weight to the drone, but the flight time would increase more relative to this.

As already said, it all depends on what parameters are more important. The drone design, regardless of small or big, has all features necessary for an indoor inspection scenario. The camera is placed on the best position, the electronics are easy to reach without much disassemble, and the battery is integrated into the design centering the mass as much as possible. The design can be scaled to the optimal solution as desired when all components and parameters are chosen.

Chapter 7

Cover

After two iterations of modeling, and a long building process a functional prototype was made. It has all the desired features that were aimed for, and it performed well during flight tests. However, the need to give it a overall finished look still lacks.

With the cooperation of Inventas, which is a consulting firm that help produce and develop products, a complete finished design was composed. This included a cover that surrounded the electronics and lets the gimbal have free line of sight, as well as constructing legs with matching appearance to the cover. A important feature was also to have a cover where access to the electronics is possible without going through a whole disassemble process.

It started by sending Inventas the complete solidworks model illustrated in Figure 4.18. It was also said that the gimbal had to be placed higher to give space for additional components underneath if needed, and it was explained that the black box on top of the PCB illustrates components such that the cover can not interfere with them.

After some weeks a model of the design was made. The model included three legs with the front leg colored red, and the two back legs colored black. It had also a stand to elevate the gimbal through the cover. The stand is similar to the one from Figure 5.9. This stand was also colored red. At last a cover was modeled with Scouts logo. Scouts logo being red and black, hence the colors. It was found that the best solution for the cover was to produce it from a thin plastic sheet where small cuts are made to create creases. The cover can therefor be folded into its shape and be fastened to already existing screw holes.

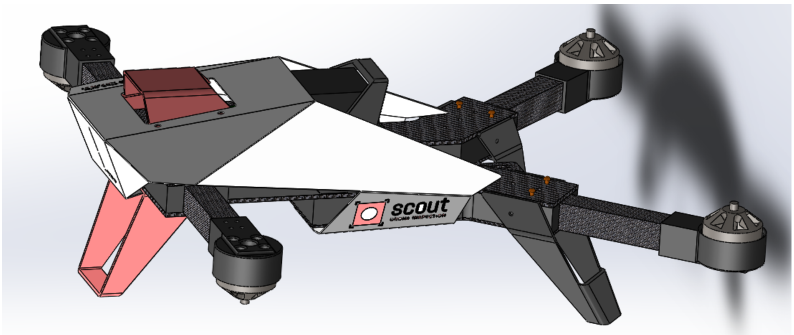


Figure 7.1: Cover

Figure 7.1 illustrates the complete cover with legs and gimbal extension mounted to our solidworks model. This was done to see that all of the components interacted as desired with the already existing components. After some small modifications to the cover it was decided to produce the parts. When the parts arrived they where mounted to the prototype to see the finished result. This can be seen in Figure 7.2 and 7.3.

Figure 7.2: Finished Product with Cover

It can be seen that gimbal with the camera is mounted high and has free line of sight. It is also seen that the electronics are almost covered completely by the cover, but there needs to be done some modifications to this since they need to be covered completely because the chance of drops dripping onto the PCB can occur when flying inside tanks risking a short circuit and potential crash. The placement of the three legs turned out to be great. It was first thought that only one front leg would make the drone unstable, and the risk of falling over during landing was to big. However, the majority of the mass lays centered over the front leg and it required relative much force to make the drone fall over.

The weight of the three legs, gimbal mount and plastic cover was measured to 139g. If this is added to the existing weight the total is 2212g. This still leaves room for the radars before the maximum of 2500g is reached. There has not been created any cover for the mini drone since there are still uncertainties if that is the desired design, but this cover would fit the potential new option with the original drone body and smaller motor/propeller combination.

Figure 7.3: Finished Product with Cover form Behind

The final product looks "neat and tidy", and is something completely new compared to the drones on the marked today.

Chapter 8

Conclusion

The main objective for this thesis was to design and build a drone prototype that has the features needed for an indoor inspection scenario. A functional prototype was build where all these necessary features are included. The structure of the drone body consists of carbon fiber plates. In order to to get a stiff structure it was first thought that relative thick plates were needed, but it turned out that the plates combined with the walls in a sandwich structure is very stiff itself. It was thereby concluded that all plates can be reduce to a 1,5 mm thickness without influencing the stiffness of the structure while saving weight.

During the process it was also requested to build a smaller drone were the main focus was to have a known payload of 500g. This was achieved by scaling the original drone design down, making the new drone 25% smaller in size and 35% lighter. Both drones consulted flight tests where a connection between wight and flight time was found leading to a mathematical function that can predict the flight time for a specific weight or vise versa. This function was used to predicting the flight times for our models and it turned out that the mini drone has a longer flight time with a payload between $0 - 1000$g. Since it also is smaller in size it is a much more desirable model to use.

However, the problem with this drone design is that the body is smaller than the original drone body. This may result in difficulties if more space is needed for potential extra components. A good solution for this would be to build a model that uses the original drone body with 1,5 mm thick carbon fiber plates to reduce weight, and combine it with the motor/propeller combination from the mini drone. This would reduce the overall drone size as well as having the original drone body for maximum component space. By using solidworks weight estimation and predicting the flight time with our model it was found that this solution will give the best balanced results regarding size, flight time and component space.

Although the drone design can easily be scaled to the desired size, it all depends on the properties that are most important. In order to achieve the smallest overall size possible, number one priority is to keep the weight to a minimum. Since the motor/propeller combination has to be scaled after a total weight estimation, it is necessary to keep the weight down if a small design is desired. This is because the propeller size sets the standard on the overall drone size. In other words, weight basically affects all parameters negative so a compromise needs to be found to get the best solution possible.

8.1 Recommendations for Future Work

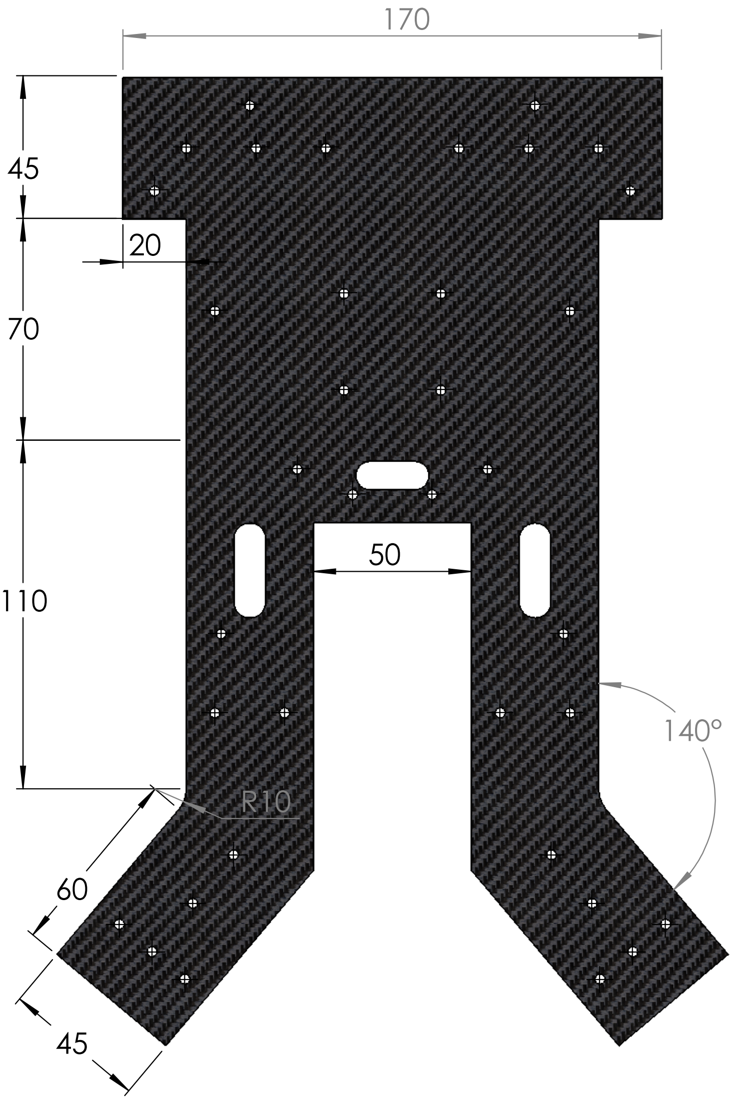
For the future work the solution from above should be build and tested to see how it actual performs. Regardless of this, simple propeller guards should be made to have additional safety from the surrounding objects, and radar mounts have to be constructed as well. This would then be a completely finished result. After this each part can be optimized by shaving away material that not affect structural integrate to get the maximum flight time possible.

Appendix A

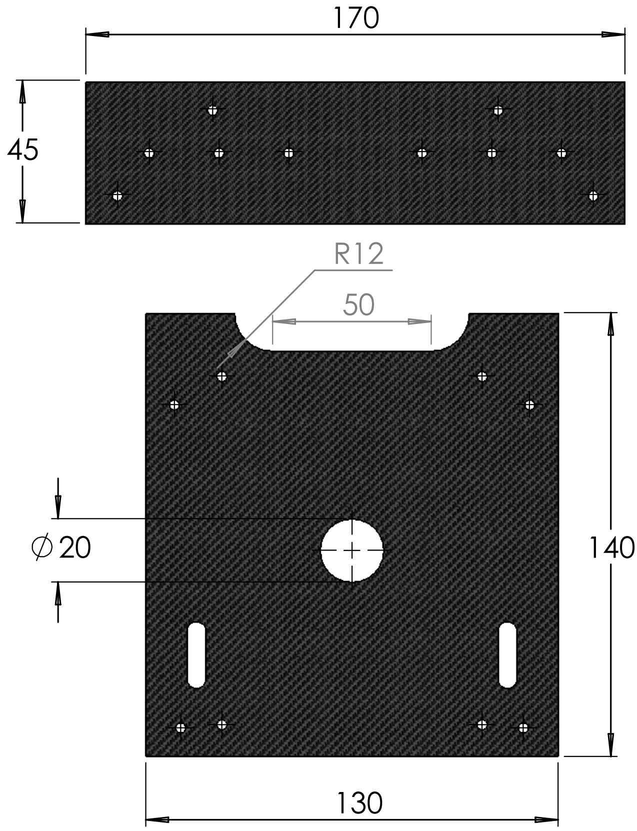
Component Dimensions

The appendix includes detailed dimensions of each part constructed in solidworks. The following parts are listed below. They appear as listed with the parts for the original drone first. All dimensions are shown in mm.

- Main Part
- Front Part
- Back Part
- Walls
- Motorarms
- Main Part Mini
- Front Part Mini
- Back Part Mini
- Walls Mini
- Motorarms Mini



FINISH:		DO NOT SCALE DRAWING	REVISION	
NAME	SIGNATURE	DATE	TITLE:	
			Main Plate	
MATERIAL: Carbon Fiber				A4
WEIGHT:			SCALE:1:2	SHEET 1 OF 1



FINISH:

DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE

TITLE:

Front Plate

MATERIAL: Carbon Fiber

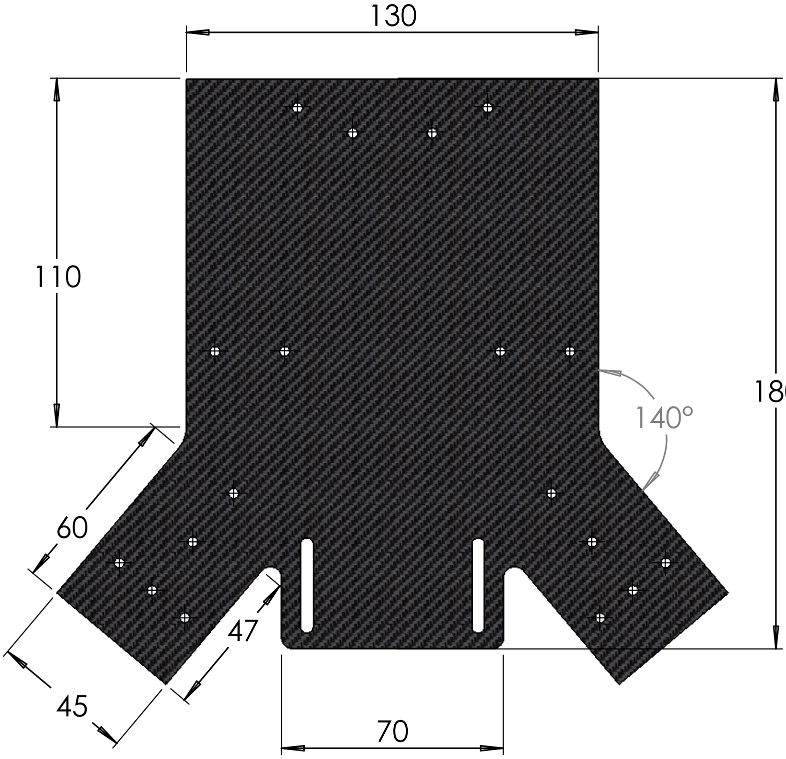
DWG NO.

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



FINISH:

DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE

TITLE:

Back Plate

MATERIAL: Carbon Fiber

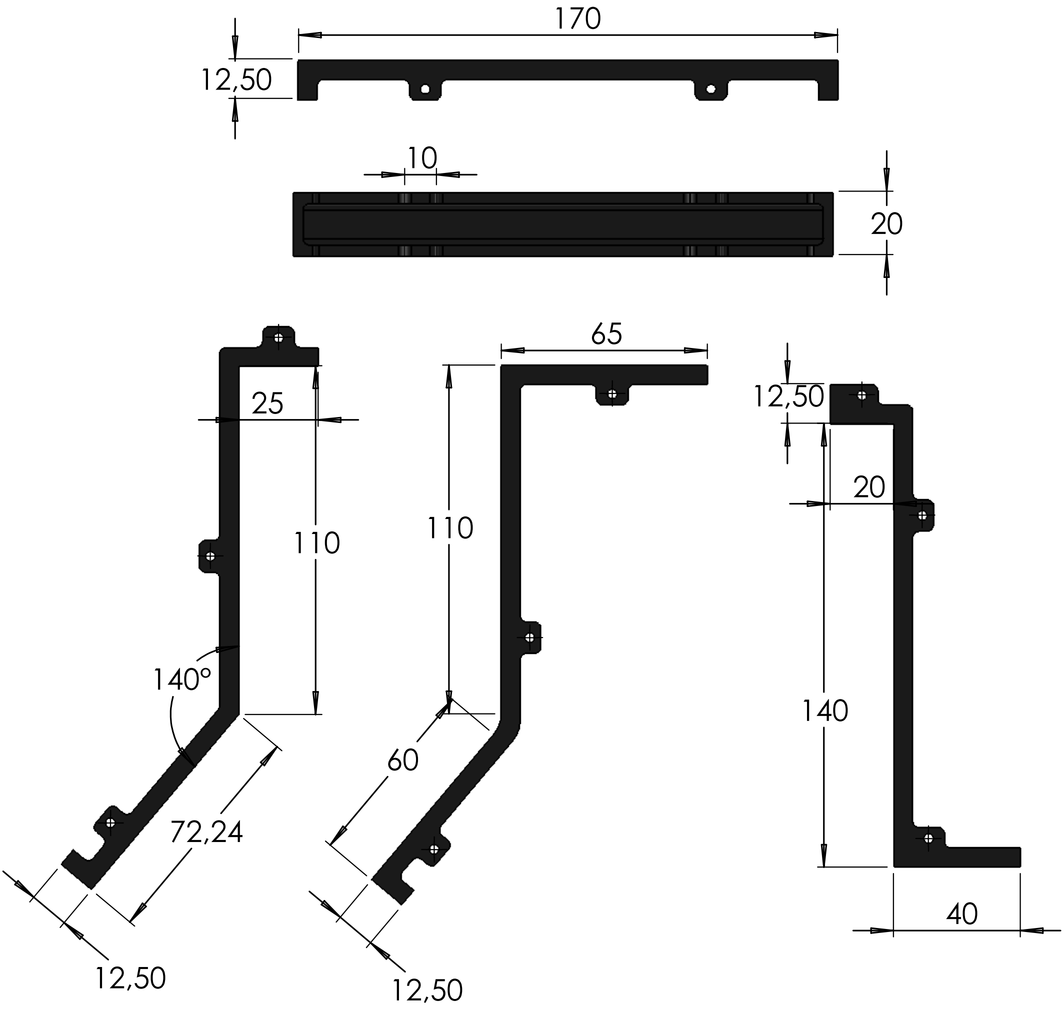
DWG NO.

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



Comment: All walls have the same thickness and height.

DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		

TITLE:

Walls

MATERIAL: ABS Plastic

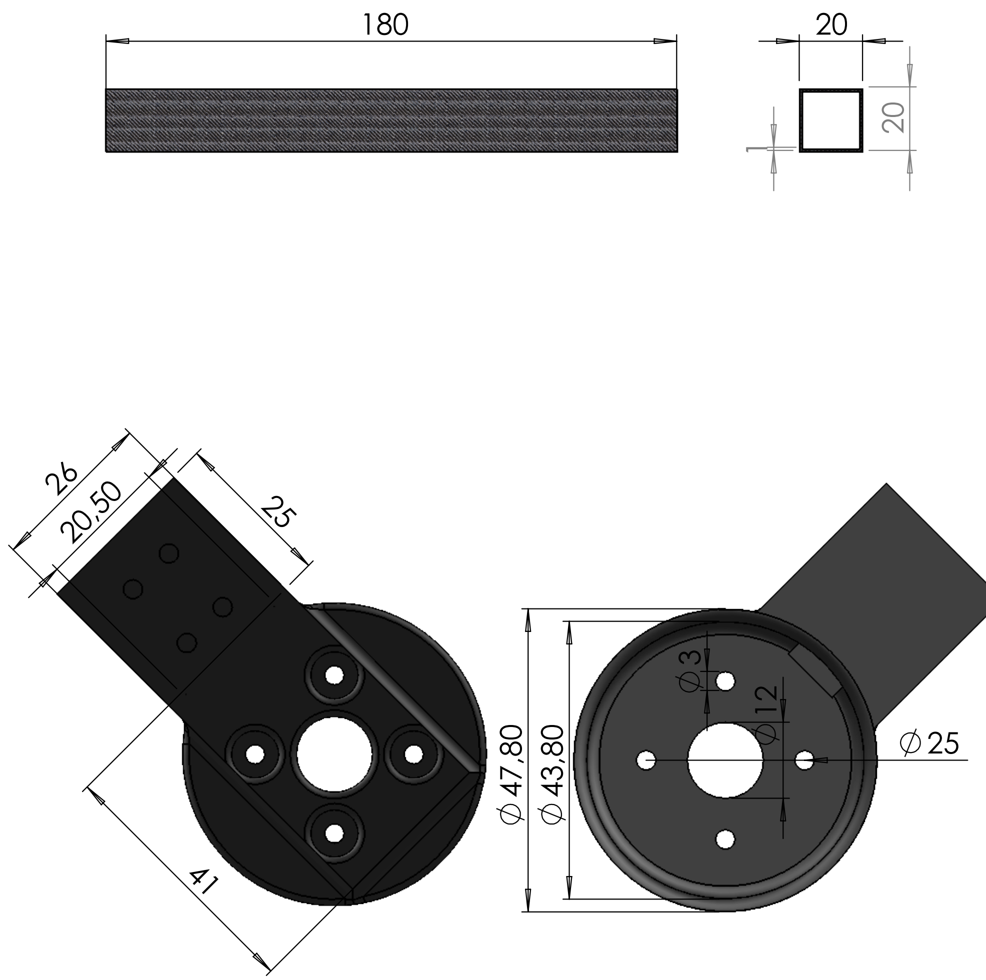
DWG NO.

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE

TITLE:

Motorarm

MATERIAL:

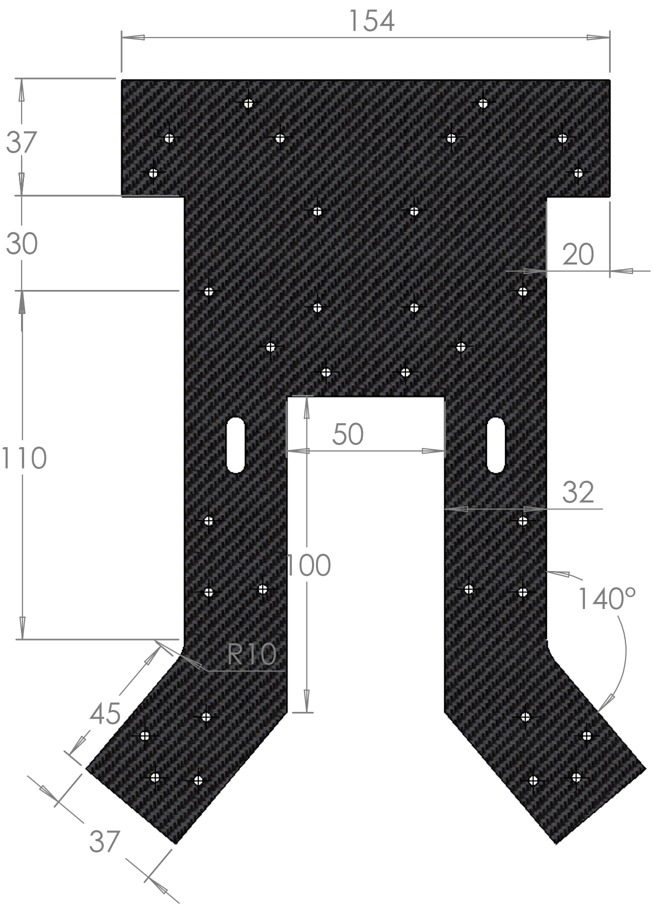
DWG NO.

A4

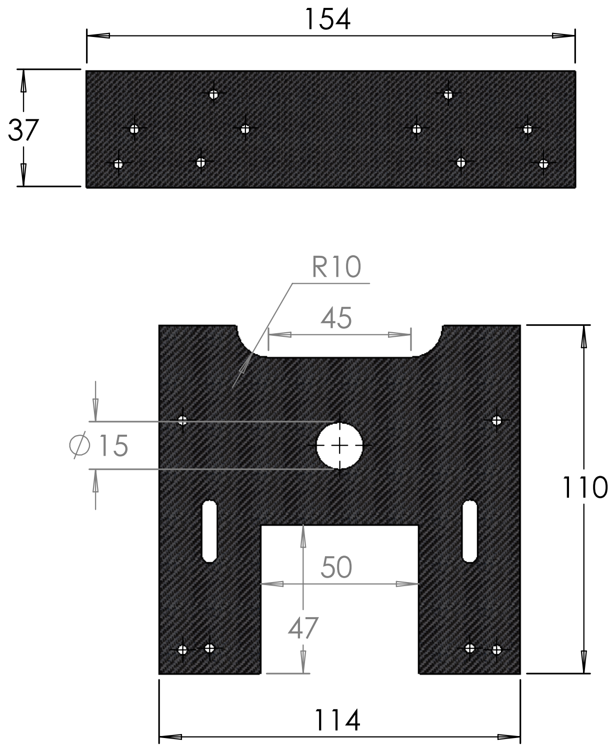
WEIGHT:

SCALE:1:1

SHEET 1 OF 1



FINISH:		DO NOT SCALE DRAWING	REVISION	
NAME	SIGNATURE	DATE	TITLE: Main Plate Mini	
MATERIAL: Carbon Fiber		DWG NO.		A4
WEIGHT:		SCALE:1:2	SHEET 1 OF 1	



FINISH:

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		

TITLE:

Front Plate Mini

MATERIAL: Carbon Fiber

DWG NO.

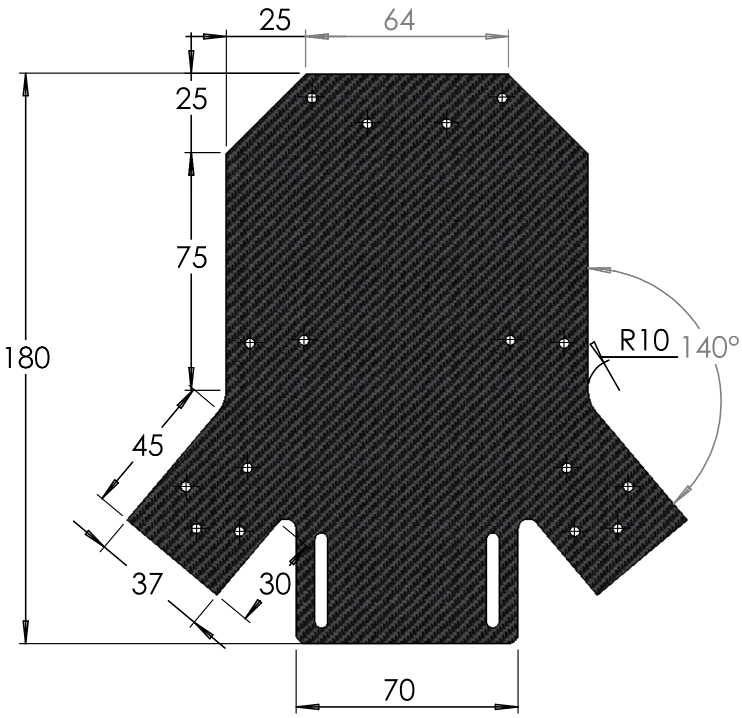
A4

SOLIDWORKS Educational Product. For Instructional Use Only

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



FINISH:

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE

TITLE:

Back Plate Mini

MATERIAL: Carbon Fiber

DWG NO.

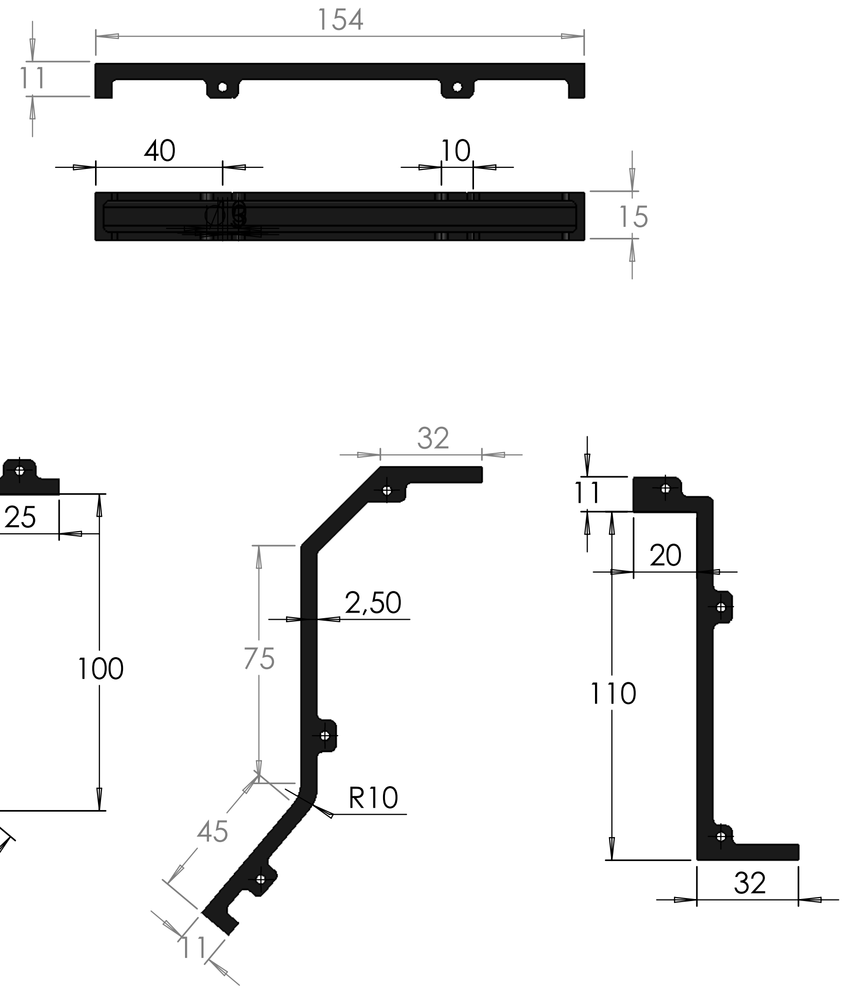
A4

SOLIDWORKS Educational Product. For Instructional Use Only

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



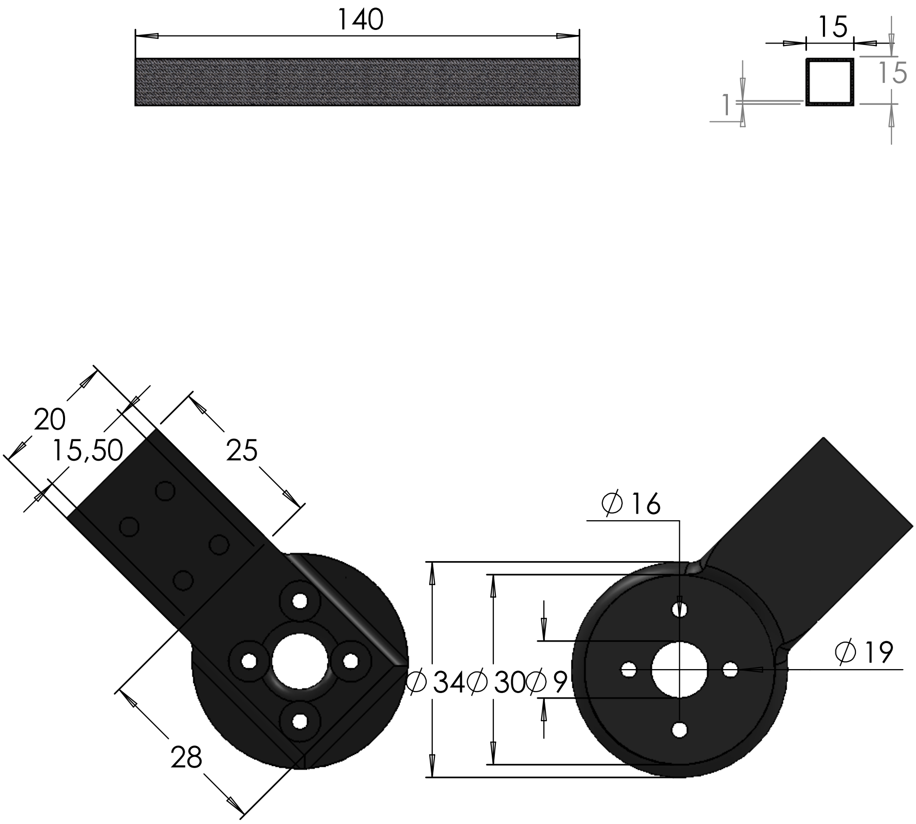
	NAME	SIGNATURE	DATE			TITLE: Walls Mini
				MATERIAL: PLA		DWG NO.
				WEIGHT:		SCALE:1:2

DO NOT SCALE DRAWING

REVISION

A4

SHEET 1 OF 1



DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE

TITLE:

Motorarm Mini

MATERIAL:

DWG NO.

A4

SOLIDWORKS Educational Product. For Instructional Use Only

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

Bibliography

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