Mechanical design, prototyping and evaluating of a 3 DOF manipulator for an Unmanned Aerial Vehicle

G. (Gerjanne) Dekker

BSc Report

Committee:
Dr.ir. M. Fumagalli
Ir. F. Sojoodi Farimani
Dr.ir. R.J. Wiegerink

November 2015

033RAM2015
Robotics and Mechatronics
EE-Math-CS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Contents

1 Introduction

1.1 Introduction

Nowadays inspection and maintenance of Civil Infrastructure comes with many risks and costs. Especially structures that are difficult to access, such as windmills, power plants or tall chimneys, take a lot of effort to maintain. Safety measures are needed to reach these location which come with high costs and often hazardous working environments for the people working on these locations.

To overcome these risks and costs the Aeroworks project is is working on an UAV (Unmanned Aerial Vehicle) that can have physical contact with its environment to perform small maintenance tasks and inspections.[1]

The AeroWorks project is a consortium of ten European universities, including The University of Twente. The University of Twente is responsible for developing the aerial manipulator of the collaborative aerial robotic workers that can perform small physical maintenance tasks in above mentioned environments.

1.2 Previous work

For the AeroWorks project a concept of the envisioned aerial manipulator has been determined by the supervisors of this BSc project. The envisioned range of motion of this manipulator will be translation in the x-y plane and rotation about the x-y-z axes. This range of motion is required to compensate for the movements of the UAV to improve the preciseness of the end-effector

The concept of the manipulator can be seen in figure 1. The manipulator will consist of 2-DOF in series on top and 3-DOF in a parallel structure of 6 links.

This gives the end-effector the required 3 rotational and 2 translational DOF.

One of the advantages of a parallel structure is that it has a high structural stiffness compared to serials structures. Therefore it has the possibility to achieve high operational speeds. The drawback of a parallel structure is the reduced workspace and the analysis of the workspace is more complex because its a closed system. [2]

The main advantage of this parallel structure for the design of this prototype is that the motors can be connected close to the base and that it can be easily be lightweight while still being relatively rigid in the z-direction.

1.3 Project goal

The goal of this project is to design, built and test the manipulator described in section 1.2. This project will only focus on the parallel structure with

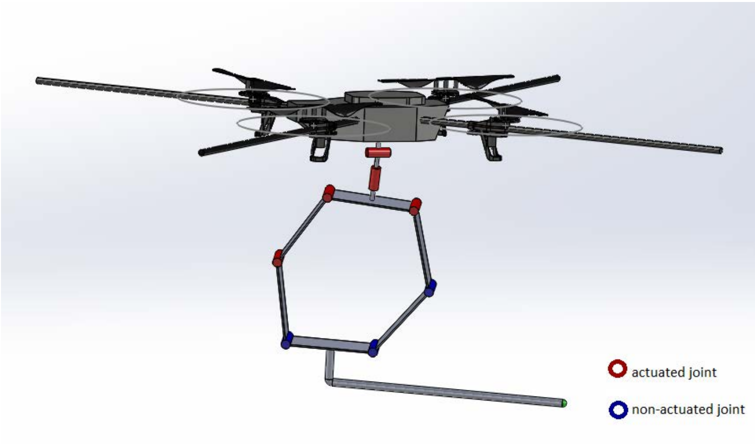


Figure 1: Basic concept of the manipulator

3 degrees of freedom. The 2 serial degrees of freedom will be designed and tested by the supervisors of this project.

The Manipulator should compensate for the disturbances of the UAV. Especially when an UAV gets near walls or ceilings the UAV gets less stable. To find out how much compensation is needed for these disturbances, tests should be performed with a manipulator connected to the UAV. These tests will result to requirements for the workspace and speed of the manipulator. To perform these tests first a prototype is needed. This project is focussed on designing and building this prototype, this will be done by designing two prototypes.

The first prototype will be a fast prototype to find out what the main problems are of this design. To make the prototype cheap and easy to produce 3d-printers and laser cutters will be used to produce the parts.

After evaluating prototype 1, a new design will be made for a second prototype in which problems of the first prototype will be solved. For the second prototype other manufacturing methods can be used if necessary to make the prototype more durable.

1.4 Report Outline

This report is split in two main parts, First Prototype 1 will be discussed, starting with requirements and the design, following by the realization and evaluation of prototype 1. The second part discusses additional requirements and the design of Prototype 2. In the end conclusions and future work are discussed.

2 Prototype 1

In this section first the requirements of the first prototype are stated, following by the Design of the prototype. Then the realization and evaluation discussed.

2.1 Design requirements prototype 1

Since this project only focusses on the design of the manipulator, only the design requirements will be stated in this section. The requirements for the control of the manipulator will be stated by other members of the Aeroworks project.

2.1.1 Weight

The manipulator will be connected to A UAV with a maximum payload of 1000 grams. Therefore the manipulator should be as light as possible. The lighter the manipulator the more force can be used by the end-effector to perform small tasks. The aim is a weight below 500 grams for the parallel structure, the base joints and the end-effector together.

2.1.2 Modular design

The design of the manipulator should be modular with as many same parts as possible. Furthermore, complexity should be avoided as much as possible. This to make the prototype easy to assemble.

2.1.3 Placement of motors close to the base

Relatively to the other components motors are quite heavy, placing them close to the base results to lighter moving parts while moving the structure, which decreases the inertia and therefore the torque needed by the motors. For the first prototype multiple types of actuation of the joints should be considered to find out how the joints can be actuated on the most convenient way with adding as less inertia as possible to the structure.

2.1.4 Producible parts

Parts like the joints will first be produced using a 3d-printer, however they also should be easily producible on a milling and/or turning machine. This to make sure the material of the part can be changed if the materials turn out to be not strong or rigid enough.

2.1.5 Workspace

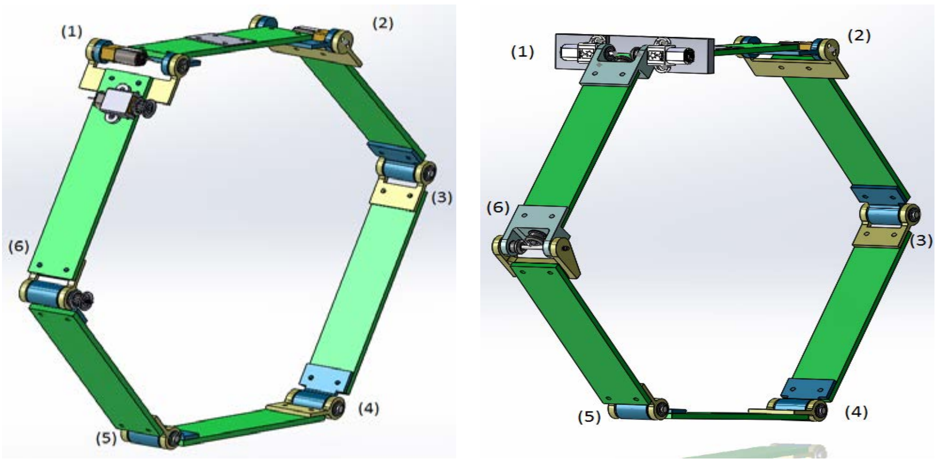
As stated in section 1.3 the requirements of the workspace are not clear. The workspace should be sufficient to compensate for the disturbances of the UAV while the manipulator wants to touch a certain point. The size of the required workspace will be determined after tests can be performed. The reachable workspace of the structure is determined by the link length and the joint angles. The link lengths can be easily changed if the workspace is not sufficient, however the joint angles are more difficult. Therefore the reachable angles of the joints should be maximized.

2.2 Design of prototype 1

This section will present the design of the first prototype. First the total structure will be presented to get an indication of the whole structure following with more details about the different components.

2.2.1 Total Structure

The total design of the structure can be seen in figure 2. Two designs have been made, one with a pulley system and one with a differential mechanism. All joint positions has been numbered to make clear which joint is discussed in this section, these number can be seen in figure 2. For both designs joints (1), (2) and (6) are actuated and joints (2), (3) and (4) are non actuated. The choices for the different parts are mentioned in the following sections.



(a) Design with pulley (b) Design with differential mechanism

Figure 2: Joints (1), (2) and (6) are the actuated joints, joints (3),(4) and (5) are the non actuated joints.

2.2.2 Motors

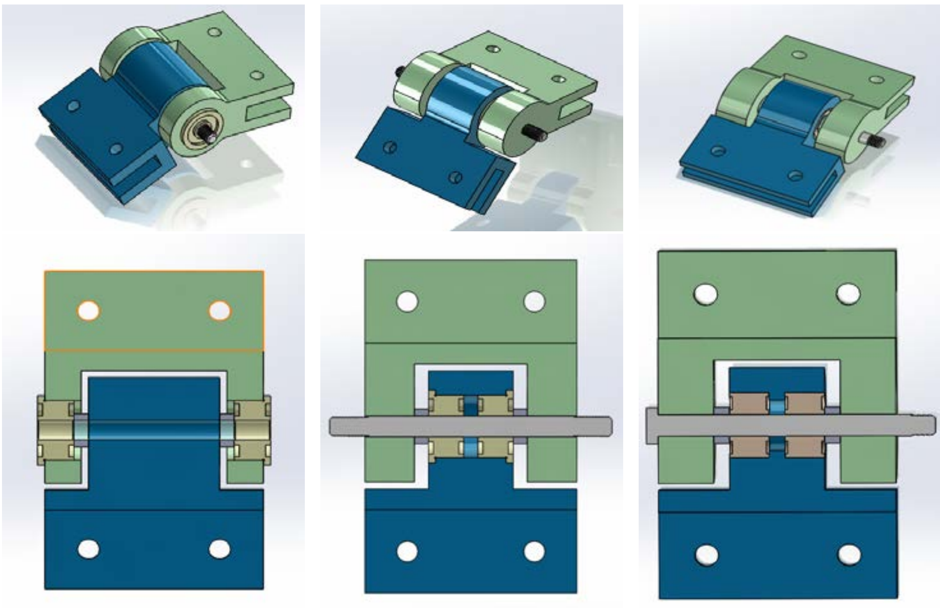
The motors that will be used for the prototype are Pololu Micro Metal Gearmotors. The main advantage of these motors are that they are relatively cheap and they were already available at RaM. Different gearboxes can be used to adjust the torque of the shaft. The size of these motors is 10 by 12 by 29.5 mm, which allows the motors to be placed inside the joints. With the gearbox ratio of 1:1000 the torque provided by these motors is 0.9 Nm which is expected to be sufficient to tilt the joints.

2.2.3 Plates

The plates connect the joints as can be seen in figure 2 and determine mainly the size of the prototype. The size of the plates for prototype 1 is 150 by 30 by 3 mm. This size has mainly been chosen because it seemed like a right size for the manipulator with respect to the UAV. For the design of prototype 2 an analysis of the workspace will be taken in account to reconsider this size. The material chosen for this plates is Polyoxymethylene (POM). This is a thermoplastic with high stiffness and can be cut precisely by the laser cutter. Furthermore it was already available at RaM.

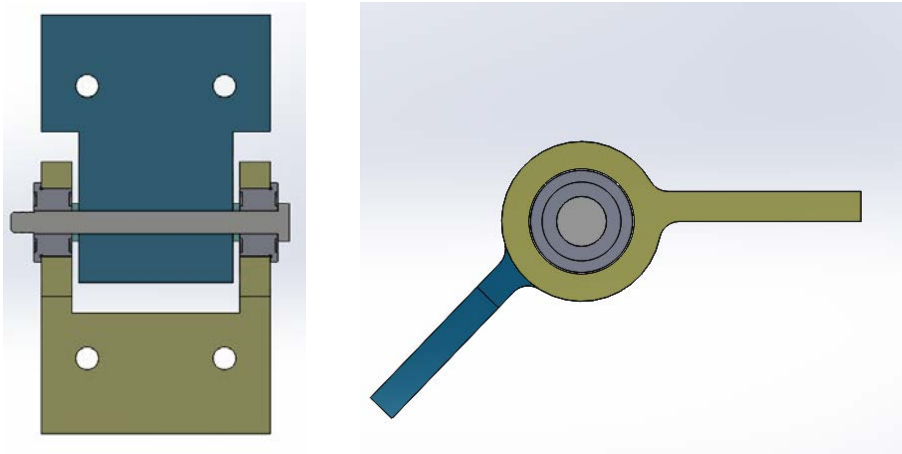
2.2.4 Non-actuated joints

The non actuated joints are located at positions (3), (4) and (5) as shown in figure 2. The most important part of all the joints is the bearings. With proper bearings the joint will move smoothly. To make sure one sort of bearing can be used in the whole design the inner diameter of the bearing has to be 3 mm since the diameter of the motor shaft is 3 mm. For the same reason the axes of the joints has been chosen with a diameter of 3 mm.Three designs have been made with two different types of bearings as you can see in figure 3.



(a) (b) (c)

Figure 3: (a) Joint with flanged bearing on the outside. (b) Joint with flanged bearing on the inside. (c) Joint with bearing without flange on the inside.



(a) (b)

Figure 4: Non-actuated joint (a) Cut through. (b) Side view .

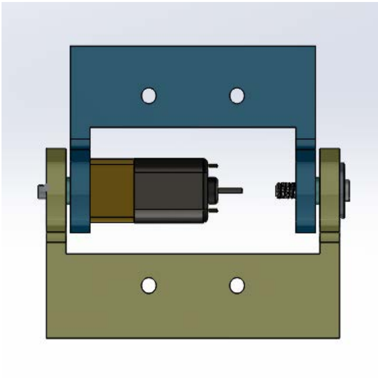
The main criteria to choose one of these joints is that is should be easy to assemble and easily producible on a milling and turning machine. To make it easier to produce these joint parts it is better to have the flanges on the bearing instead of a flange in a joint, therefore joint 3c was not chosen. Furthermore joint 3a is much easier to assemble than joint 3b. this because if the flange is on the outside of the joints you can easily assemble the axis and spacers and place the bearings in last. These were the main reasons joint 3a has been chosen. As can be seen in figure 3 in this design the plate will be clamped within two parts of the joint part which can lead to internal stresses in the joint part. To reduce stresses the double plates on the joints have been reduced to one plate, as can be seen in figure 4. The place of the lower part of this plate has been chosen at the height of the centreline to maximize the workspace of the joints, now the joint can close completely if it moves inwards. To make sure the joint is exactly determined spring spacers will be used as spacers between the two joint parts.

2.2.5 Actuated joints

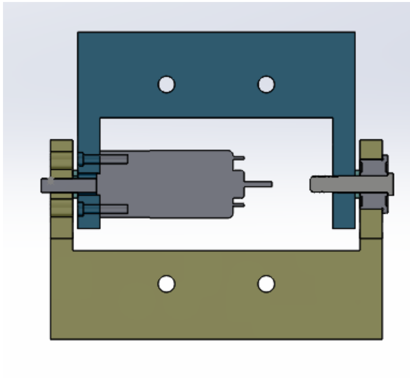
In total there will be three actuated joints in the structure at position (1), (2) and (6) as shown in figure 2. Preferably all motors are positioned as close as possible to the base, This to move as less mass as needed to decrease inertia.

Motor in joint

The easiest way to actuate a joint is to place the motor right in the joint. For this reason a joint is designed with the motor placed in the joint. This joint is wider than the non-actuated joints because the motor has to fit in completely to make it possible to assemble the joint. The design of this joint can be seen in figure 5.



(a)



(b)

Figure 5: Joint with motor

This joint can be used for joint positions (1) and (2), The joint part with the motor connected to it will be connected directly to the base so the motor does not add any inertia to the system.

This joint can also be used for joint position (6), however this will increase the inertia around the axis of joint position (1) significantly. The inertia added by placing the motor inside joint 1 can be approximated by assuming it to be a point mass rotating around the axis of joint (1).

$M_{motor} = 30$ grams. $x_1 = 174$ mm

$$I = M \times x^2 \tag{1}$$

$$I_1 = M_{motor} \times x_1^2 = 908 \times 10^3 g/mm^2 \tag{2}$$

In the following part it will become clear that this Inertia can significantly be decreased by placing the motor closer to the base. For this reason placing the motor in the joint has not been chosen as an option for actuating joint position (6).

Pulley and timing belt

To drive joint (6) there are different possibilities. One of these is to use a pulley and timing belt. Now the motor can be placed much closer to the base using a bracket as can be seen in figure 6.

An approximation of the inertia for this placement of the motor can be calculated with equation 1.

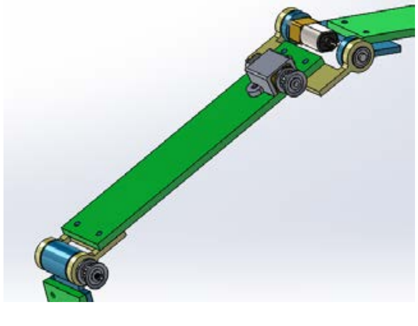


Figure 6: Pulley system

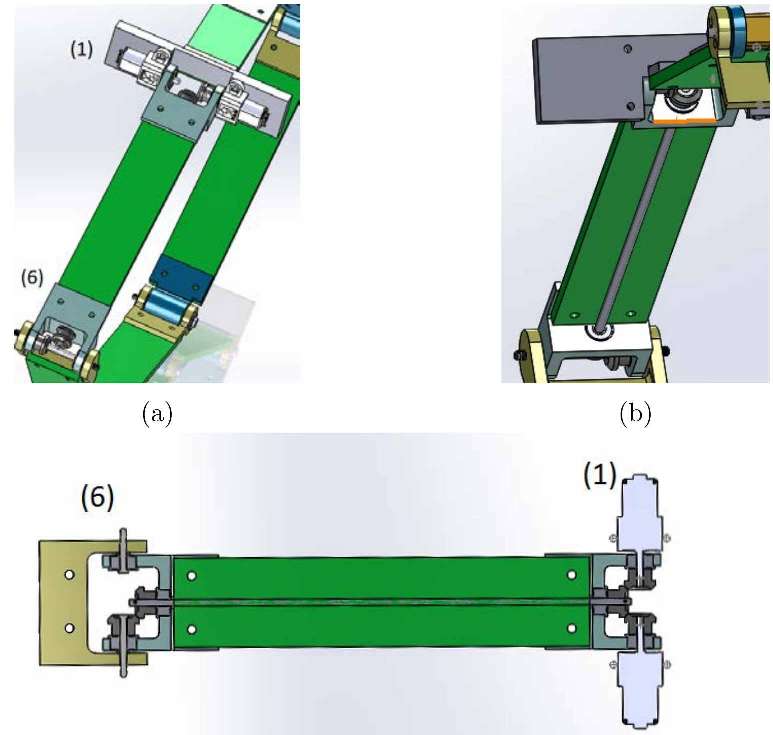
M_{motor}= 30 grams. x_2= 30 mm.

$$I_2 = M_{motor} \times x_2^2 = 27 \times 10^3 \; gmm^2 \quad (3)$$

The inertia added to the systemby the motor placed at 30 mm of the axis of joint(1) is about 3 % of the inertia of placing the motor directly in joint (6). Using this solution for actuating joint (6) decreases the Inertia significantly, therefore this has been chosen as one of the options for actuating joint (6).

Differential Mechanism

Another solution for actuating joint (6) is a differential mechanism. This is a mechanism with bevel gears. Both motors are placed at joint postition (1). The motors will be connected to gears, which will be connected to the gears in joint (6) with a rod. Figure 7 shows this design and how to place the gears to make this mechanism work. If the motors move in the same direction they will move joint (6). if they move in opposite directions they will move joint (1).



(a) (b) (c)

Figure 7: Differential mechanism

This is an elegant solution because it allows all motors to be placed directly to the base leading to no added inertia of a motor placed at joint(6). For this reason the differential mechanism has been chosen as one option for the actuation of joint (6), and therefore also as an option to drive joint (1).

2.3 Realisation and evaluation of prototype 1

In this section the realisation and evaluation of the first prototype will be discussed. First al components used will be listed, following by the realisation and evaluation of the different components of the design.

2.3.1 Materials and components

The following materials are used for building the prototype.

amount	component	aaterial	part number	supplier	method of manufacturing
6	plates	Polyoxymethylene (POM)	-	RaM	laser cutting
12	printed joint parts	Polylactide (PLA)	-	RaM	3d-printing
20	bearings	stainless steel	CSFL 603ZZ7	Misumi Europe	-
2	pulley	polycarbonate - glass filled	778-4803	RS components	-
1	timing belt	rubber	778-5086	RS components	-
5	bevel gears	POM	21-6036	RS components	-
3	Pololu micro metal gearmotor	-	3080	Pololu Robotics and electronics	-
3	Pololu bracket	plastic	989	Pololu Robotics and electronics	-

The bolts, nuts and spacers used to assemble the structure are commonly used and widely available. Therefore they are not discussed in this table.

2.3.2 Building the prototype

As described in section 2.2.1 there are two options for actuation of joint position (6). To test both options one prototype will be built with two modules for the actuation of joint position (6). During the building of the prototype several problems already occurred, therefore the building process will be described at the evaluation of the modules.

2.3.3 Evaluation of the plates

The plates of prototype 1 are laser cut out of POM. This made them simple to produce. One mayor drawback is that these plates have a high flexibility. After these plates had been cut in the dimensions of 150 by 30 by 3 mm. The plate bends about 10 degrees if you clamped one end and apply a force of 5 Newton on the other end. To overcome this flexibility another material will be needed for the plates. Carbon fibre is one of the strongest plate materials with a relative low weight. This material was also easy to access within the University of Twente. Plates of the dimensions of 150 by 30 by 2.5 mm were cut of a carbon fibre material. These plates showed less than 1 degree of bending when applying a force of 5 N at one end. This while the weight of this plates is 18.8 grams versus 19.4 grams for the POM plates. Therefore the material of the plates was changed to carbon fibre.

2.3.4 Evaluation of the non actuated joints

The non actuated joints were easy to assemble. The bearings fitted well in the printed parts. A normal bolt has been used as the shaft for this joint. The only problem that occurred was the play of the parts. Due to flexibility in the joint material spring spacer were needed. pictures of these non actuated joints can be seen in figure 8. The outer joint part does bend a little to the inside mainly due to the material, but is not expected to give any problems. Overall The joint moves smoothly.

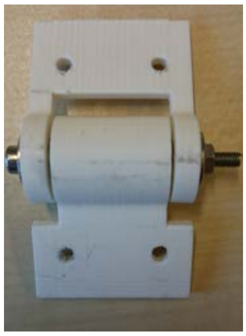


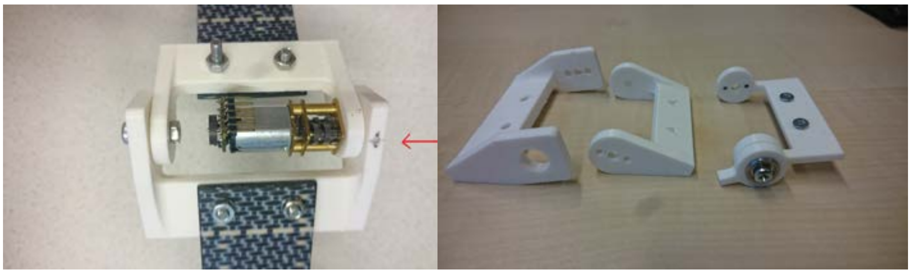
Figure 8: non actuated joint

2.3.5 Evaluation of the actuated joints

Motor in joint

The actuated joints with the motor placed in the joint, as shown in figure 9a, gave many problems in the building phase. The first problem was that the joints broke easily. This because PLA is relatively weak with respect to for instance aluminium. The joint parts had been designed for producing out of aluminium, but if they are made using a 3d-printer the whole design of the joint parts should be thicker and more. Therefore the design of these joints has changed during the building process which can be seen in figure 9 b.

The main problem of these joints was fixing the shaft to the joint. Many ways have been tried, but most of them broke after some time due to the weak material PLA. In the end a pin was put through the shaft, but then still after some time moving the joint, play returned because joint material wear of and the pin started to move inside joint. This problem will have to be solved in the next prototype.



(a) (b)

Figure 9: (a) motor placed inside the joint, the arrow indicates the point where the motor shaft is fixed to the joint.(b) on the left new design of the joint parts, on the right the old design.

Pulley system

The joint with the pulley system is just a normal joint, with a longer shaft and a motor assembled to the plate with a bracket. The main problem of the pulley system is tensioning the belt. Tension has been created by cutting the belt and shorten it with a belt clam. The problem however was that the shaft of the motor bent easily when the belt was tensioned as can be seen in figure 10. Clearly the motor shaft could not endure the force needed for the belt to tension it properly. This flexibility in the motor shaft led to a too loose belt for moving joint (6) properly. Under torque the belt showed to be too loose.

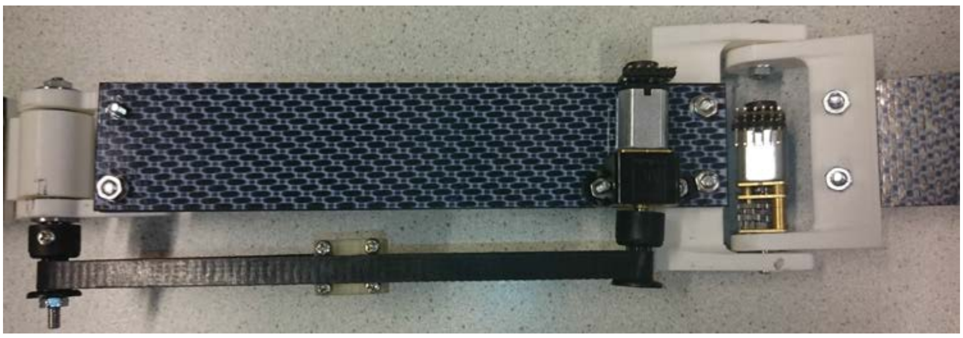


Figure 10: Pulley mechanism

Differential mechanism

The differential mechanism gave some difficulties in connecting the gears to the shafts and connecting the shafts to the joints. After moving the structure the connections often loosened which resulted in the differential mechanism failing. After pinning the shafts to the gears and to the joints this problem was fixed.

Due to the material of the differential gears, POM, the gears wear of after some time moving the differential mechanism, which resulted in the gears skipping teeth at the gears inticated in figure 11. This clearly indicates that stronger and better suitable gears are needed for the differential mechanism to perform as required.

Furthermore the workspace of the upper differential design was not a large as needed, it should be at least able to move an angle of 180 degrees and be able to move completely inwards. This last part was not possible due to a design error, it could only move inwards to an angle of about 30 degrees with the base plate.

Figure 11: Differential mechanism

2.3.6 Evaluation of the total structure

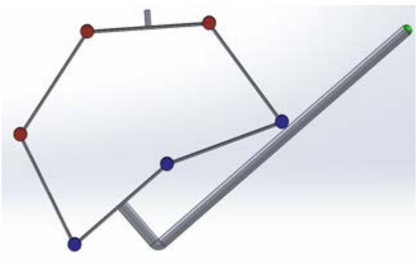
The total structure can be seen in figure 12. As mentioned in section 2.3.5 both the pulley mechanism and the differential mechanism did not perform smoothly at this point. However the differential mechanism has been chosen for the evaluation of the total structure, since the pulley system is not suitable for this prototype with the current motor shaft. Furthermore it is a elegant solution which allow us to place all motors directly at the base.

One of the main problems while connecting the whole structure was that play in the upper joints with a small angle, resulted in much larger play at the end-effector due to relative long arms. Since the actuated joint with the joint in the motor was not properly connected to the joint, this led to such play. While holding al motors locked, this play resulted in the end-effector still being able to move over an angle of about 20 degrees. To minimize this angle the next prototype should have less play in the joints and shorter links if the workspace allows it.

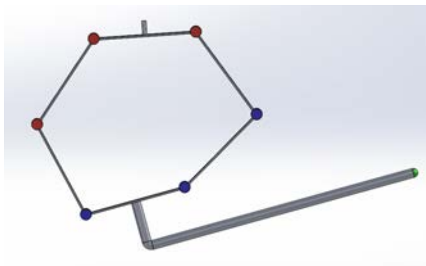
Another problem of this structure not mentioned before is that the po-

Figure 12: Pulley mechanism

sition of joint (4) is not completely determined. This joint can be in two positions at a certain configuration of the motors. An example can be seen in figure 13. To overcome these two possible configurations of the end-effector at certain motor angels, a physical end-stop has to be designed to prevent the joint from moving inward, leaving only one possible configuration of the end-effector at certain motor angels.



(a)



(b)

Figure 13: Two posibble configurations of the end-effector at fixed motor angels

The weight of the parallel structure including all motors is 390 grams. this is below the weight of of 500 grams. However this requirement of a weight below the 500 grams was for the parallel structure together with the base joints and the end-effector. The weight of all these parts together is 600 grams.

After connecting all motors, the motors were able to move the whole structure. This indicates that the motors deliver enough torque to lift all joints. For this reason these motor can be used again in the next prototype.

Initially more test were planned for this prototype, like measuring the precision. But due to the play in the actuated joint as described in section 2.3.5 This was not possible.

3 Prototype 2

After evaluating prototype 1 it became clear that there were to many weak points still present, to really test the structure. therefore Prototype 2 will also be a fast prototype still with 3d-printed parts, however some parts can be made out of aluminium if they can be easily manufactured.

3.1 Requirements of prototype 2

The evaluation of Prototype 1 led to some additional requirements. The requirements of the first prototype still apply to this prototype.

3.1.1 Workspace

As stated in the requirements of the first prototype the end-effector should be able to compensate for the movement errors of the UAV. This errors are not exactly clear but an indication has been made based on previous work, where this workspace was $5 \times 5 \times 5\ cm^3$ [3]. In this previous work the manipulator did not have to perform small maintenance task, but only had to touch a wall. However it will be used as an indication. which leads to a desired workspace of the end-effector of$5 \times 5\ cm^2$ since the parallel structure is only two dimensional.

3.1.2 Weight

The weight of the parallel structure should be <300 grams, This because the weight of the combination of the end-effector, parallel structure and the base joints together should be <500 grams. The estimation of the weight of the end-effector and the base joints is 200 grams, based on the first prototypes of these parts.

3.2 Design of prototype 2

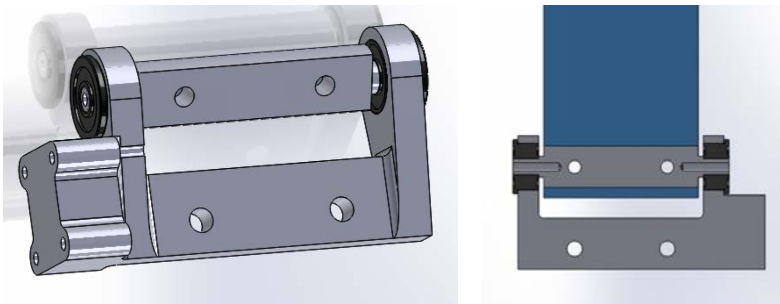
In this section the design of the different components of prototype 1 are redesigned. Also an analysis for the link lenghts and static balancing and are discussed.

3.2.1 Non-actuated joints

To decrease the weight of these joints and to minimize flexibility of the system, by having large joints. the shaft and one joint part have been combined in the new structure as can be seen in figure 14.

The inner part of this joint will be produced from aluminium. Because aluminium is still light weight, but can be manufactured more precise and the holes can be properly tapped on the sides to be able to connect the outer joint part to the inner joint part with a bolt. The outer joint part will be 3d-printed. As described in section 2.3.6 a physical stop is needed for joint (4) to make sure it's position is known. This physical stop is can be seen in figure 21.

To know the angle of these joints at any time, absolute encoders will be added to the non actuated joints. These absolute encoder are magnetic rotational encoders from Farnell (article number: AMS AS5045-ASSU). The boards for these encoders have been designed by Eamon Barret, working For Ram. This board can be connected to the outer joint part. To the bolt exactly at the axis, used to fix the outer joint parts to the inner joint part, a magnet will be fixed, this magnet will rotated when the joint rotates. Now the encoders can measure the angle of the joint at any time, which will help for the motor control part. The boards for these encoders have been designed by Eamon Barret, working for RaM.



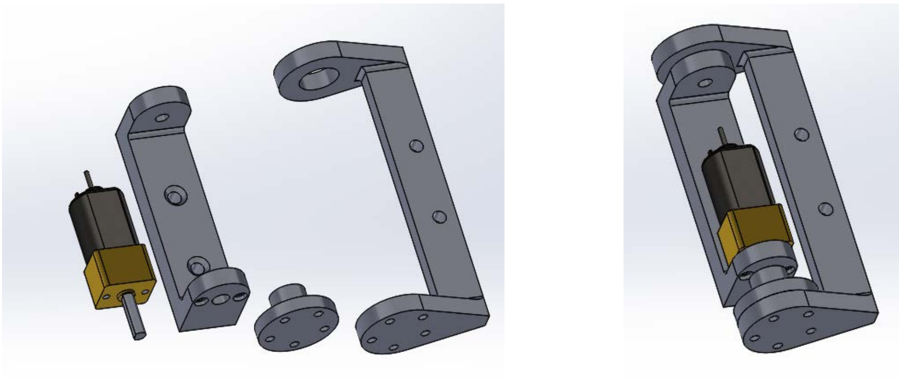
(a) (b)

Figure 14: Non actuated joint

3.2.2 Actuated joints

Motor in joint

The main problem of the actuated joint was the connection of the shaft to the moving joint part. To ensure no play will arise at this connection a adapter has been designed as can be seen in figure 15. This adapter will be made out of aluminium to make it possible to firmly connect it to the motorshaft. the other side of the adapter will be fixed to the outer joint part using 5 bolts. Furthermore the motor now hangs directly under the base plate, since this creates some was more convenient for the differential mechanism motors.



(a) (b)

Figure 15: (a) exploded view of the joint with the moter in the joint. (b) Assembled view of the joint with the moter in the joint.

Differential mechanism

In prototype 1 the upper joint was not able to move in completely. Therefore this design has changed the position of the motors to directly under the base plate, which creates enough space for the joint to move completely inwards. Furthermore the long rod that connects the gears of both joints has been changed to two flanges with a pipe in-between to decrease flexibility. The same sort of adapter as was used for the motor in the joint has been used again to connect the gear with the moving joint.

(a) (b)

Figure 16: (a) differential mechanism (b) cut through of differential mechanism

3.2.3 Analysis of link lengths

To reduce the weight of the structure and the torque in the actuated joints the lengths of the links should be reduced with respect to prototype 1. This length can be determined using the the requirement for the workspace of of $5 \times 5\ cm^2$. Assuming the end-effector will be placed at the middle of the bottom link at point P. Point P should be able to move within the workspace of $5 \times 5\ cm^2$ at any angle α of the link. In figure 17 a sketch of the structure with point P and the desired workspace can be seen.

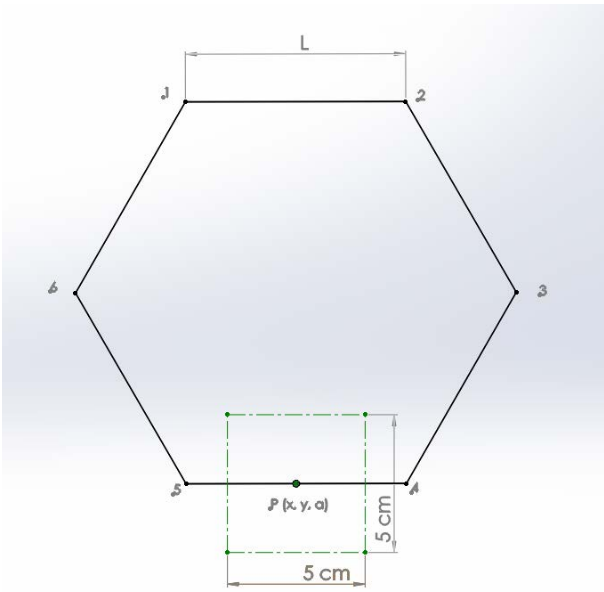


Figure 17: Point P is the point where the end-effector is connected. The dotted square is the desired workspace of point P.

The outer boundaries of the workspace are the corners of the workspace of 5 by 5 cm. If you place point P at the a corner of the workspace. All positions points 4 and 5, the edges of the link, can reach are on a circle with diameter L around point P. This circle can be seen at figure 18. The positions points 4 and 5 can reach with respect to the base plate are within a circle with a radius of 2L, since both points are connected with two links to the base, around points 2 and 1. This is also shown in figure 18.

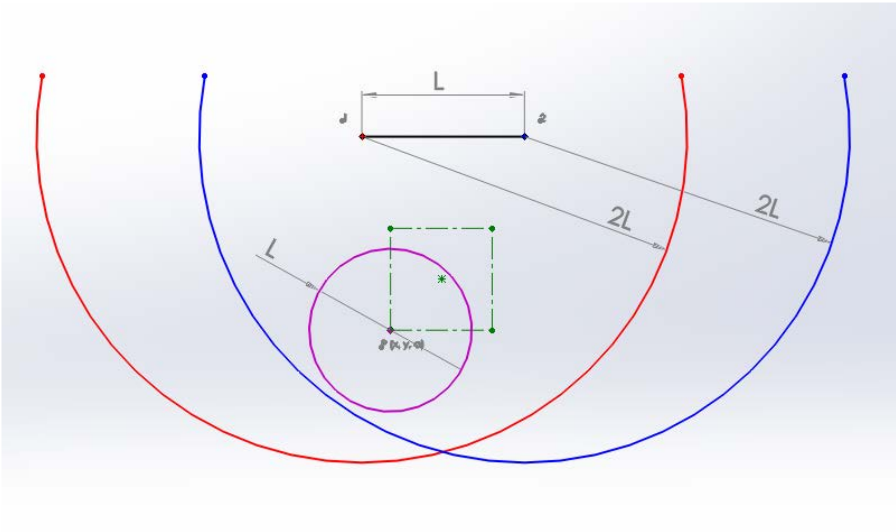


Figure 18: Small circle: Positions points 4 and 5 can reach with respect to Point P. Large circles: Positions point 4 and 5 can reach with respect to the base.

To determine the minimum link length al outer positions of points 4 and 5 should be determined, this leads to a square with rounded edges around the workspace of 5 by 5 cm. This can be seen in figure19. To ensure the bottom link can move within the workspace at any angle of the link This outer square should fit within both circles of 2L, and should not cross the base link.

This Analysis has been implemented in SolidWorks using variable lengths, which showed that for a link length of 6.88 cm the workspace would be exactly 5 by 5 cm. To add at safety buffer the link length has been chosen to be 8 cm. This leads to a minimum workspace of 5.81 by 5.81 cm.

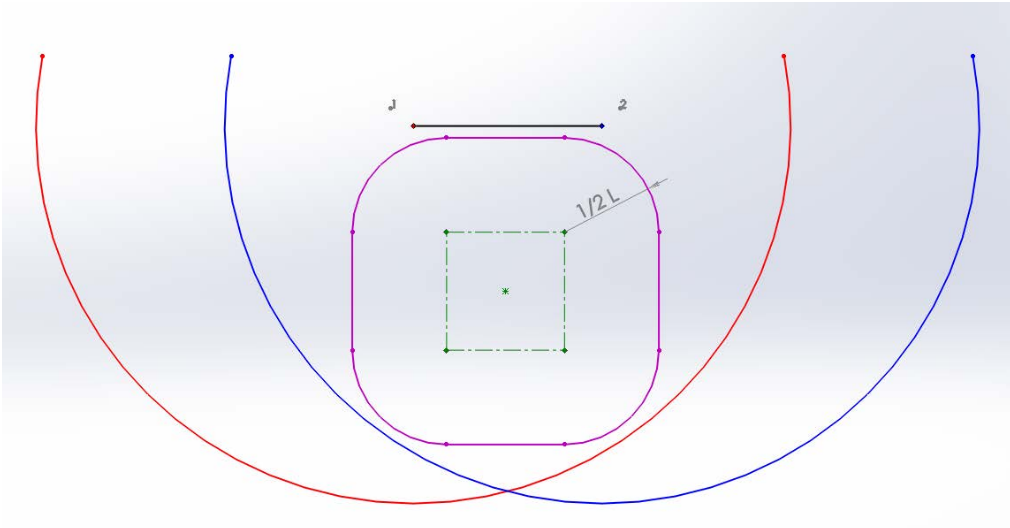


Figure 19: Square with round edges: positions points 4 and 5 can reach while point P is within the square.

3.2.4 Static balancing

To minimize the motor torque needed to lift the joints, springs could be added to the structure. If the spring is connected to the UAV directly above the joint, The spring force (F_s) will compensate for the force of the gravity (F_g) if the joint is in an angle of 90 degrees. In any other angle F_s will also compensate for F_g and help lift the link. This will decrease the torque needed of the motor to lift this link.

To calculate the best variables for this configuration and minimize the torque some assumptions are made. For this calculation a simplified structure is used of a base link with 1 link attached. The center of mass if at L/2. The distance between the joint and the points of the spring are attached (a and b) are variable, however a is somewhere on the moving link. b is directly above the joint. k is the spring stiffness and c is the relaxed position of the spring. This simplification is shown in figure 20.

The equation for the Torque is now derived as:

$$T = m\,g\,\sin(\theta)\,\frac{l}{2} - F_s\,a\,\sin(\beta) \tag{4}$$

Where

$$F_s = k\,\sqrt{a\sin(\theta)^2 + (b + a\,\cos(\theta))^2} - c \tag{5}$$

$$\beta = \theta - \arctan\left(\frac{a\,\sin(\theta)}{b + \cos\theta}\right) \tag{6}$$

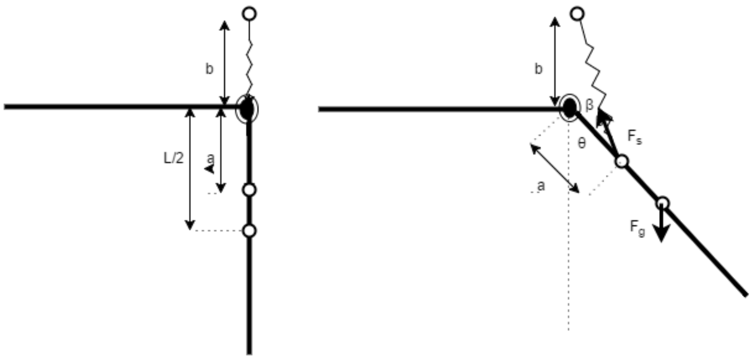


Figure 20: Base and side joint with spring

Now filling in equation 5 and 6 in equation 4 gives:

$$T = m\,g\,\sin(\theta)\,\frac{l}{2} - a\,\sin\left(\theta - \arctan\left(\frac{a\,\sin(\theta)}{b+\cos\theta}\right)\right)\,\left(c - k\,\sqrt{a\sin(\theta)^2 + (b + a\,\cos(\theta))^2}\right) \tag{7}$$

To find the lowest torque needed by the motor the maximum torque should be found. This can be done by solving $dT/d\theta = 0$. Now this maximum Torque should be minimized by finding the right variables for a, b, c and k. To do this is a recommendation for future work.

3.2.5 Total design

The total design of prototype 2 is shown in figure 21.

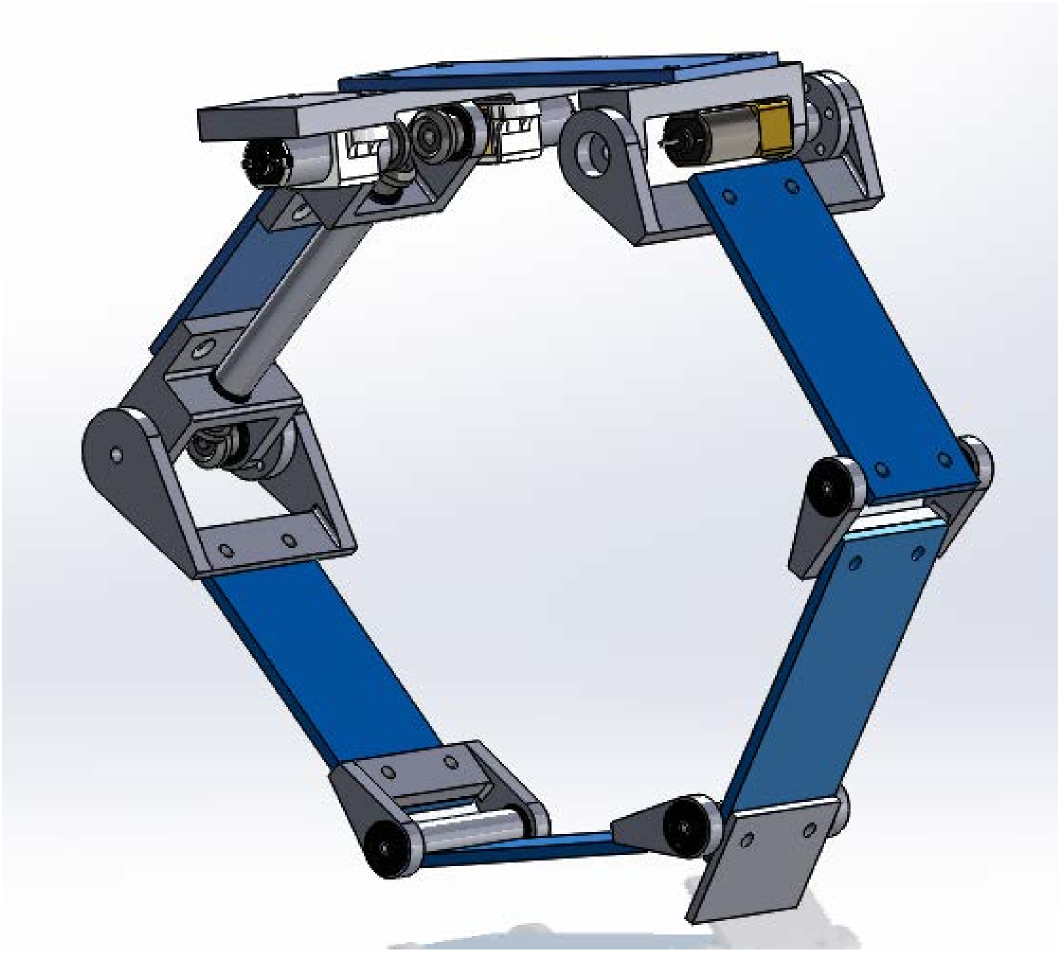


Figure 21: Total design of prototype 2.

3.2.6 List of components

In this section all components used will be listed. in table 1 all components that have been purchased are listed, in table 2 all components that have been designed are listed. in Appendix A detailed drawings of the designed components can be found.

Amount	Component	Supplier	Article no.
3	Pololu Micro Metal Gearmoter	Pololu	3080
13	Bearing	Misumi Europe	CSFL 603ZZ7
5	Bevel gear	Conrad Electronics	547237 - 89

Table 1: Components purchased

Part group	Amount	Part name	Material
Plates	3	Plate 1	Carbon fibre
	1	Plate 2	Carbon fibre
	1	Plate 3	Carbon fibre
	1	Plate 4	Carbon fibre
Non actuated joints	3	NA-1	Aluminium
	3	NA-2	PLA
Motor in joint	1	MI-1	PLA
	1	MI-2	PLA
	1	MI-3	Aluminium
Differential mechanism	1	DIF-1	PLA
	2	DIF-2	PLA
	1	DIF-3	PLA
	2	DIF-4	Aluminium
	1	DIF5	Aluminium

Table 2: List of designed components

4 Conclusions and future work

This section summarizes all conclusions from this report and gives possible continuations of this project.

The first prototype has been designed, built and evaluated as stated in the project goal. Many weak points were discovered during the building and evaluating phase. One of the most influencing problem on the whole structure was the play in the actuated joint. This was also the main reason precision tests could not be performed.

The second prototype has also been designed, the design looks promising, it is overall smaller which decreases the weight and reduces play. An adapter has been designed to connect the 3d-printed joints with the motor shaft to reduce the play in the actuated joints. However before any real conclusions can be drawn for this manipulator the prototype should be first built and tested.

The right variables for the static balancing could be calculated to minimize the torque needed by the motors. If these variables are found they could be added to the structure.

Some recommendations for testing the prototype are setting requirements for, and testing of the preciseness and speed of the manipulator. Afterwards the two serial degrees of freedom and the end-effector should be connected to the parallel structure. Then the whole manipulator together with the end-effector can be tested

This project focussed mainly on the design of the manipulator, however the control part should also be optimized. The position of the UAV together with the position of the joint angles should be implemented in the control code to control the position of the end-effector.

If all previous steps have been performed, the control of the manipulator should be connected to the control of the UAV. Then the manipulator can be tested while connect to an UAV to find out if the workspace of 5 by 5 cm and the speed of the manipulator is sufficient to compensate for the disturbances of the UAV.

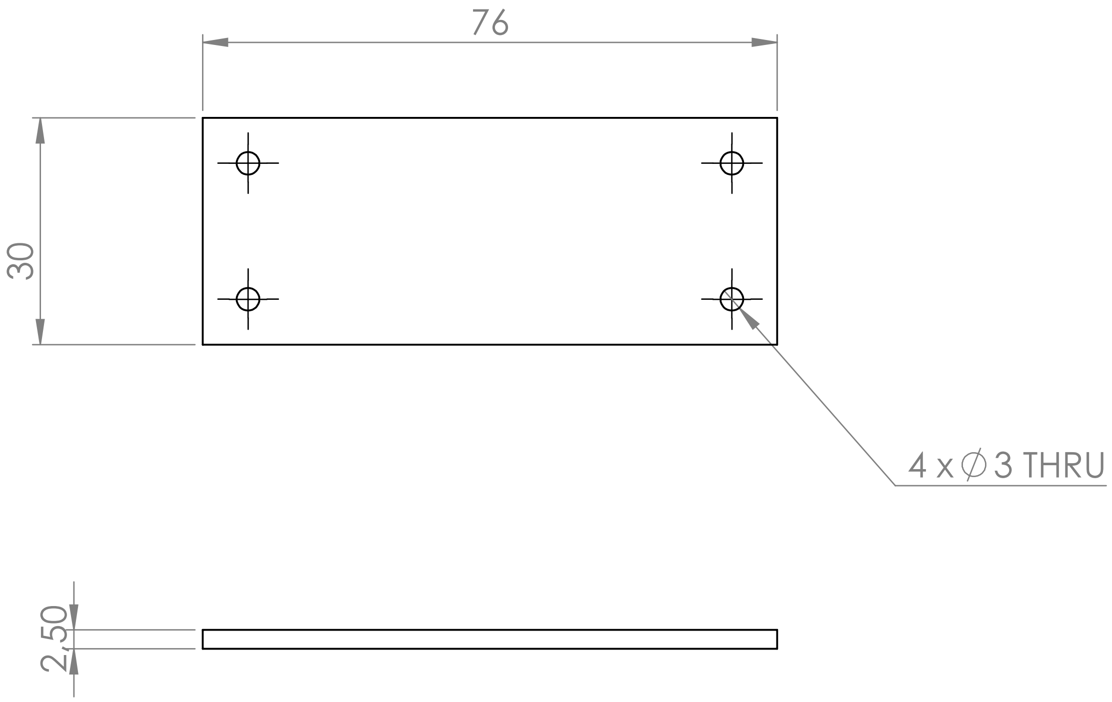
References

[1] AEROWORKS. AEROWORKS official website, 2015.

[2] G. Oriolo B. Siciliano, L. Sciavicco, L. Villani. Robotics - Modelling, Planning and Control.pdf, 2009.

[3] a Q L Keemink, M Fumagalli, S Stramigioli, and R Carloni. Mechanical design of a manipulation system for unmanned aerial vehicles. {*IEEE*} *Int. Conf. Rob. Aut.*, pages 3147–3152, 2012.

A SolidWorks drawings Prototype 2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

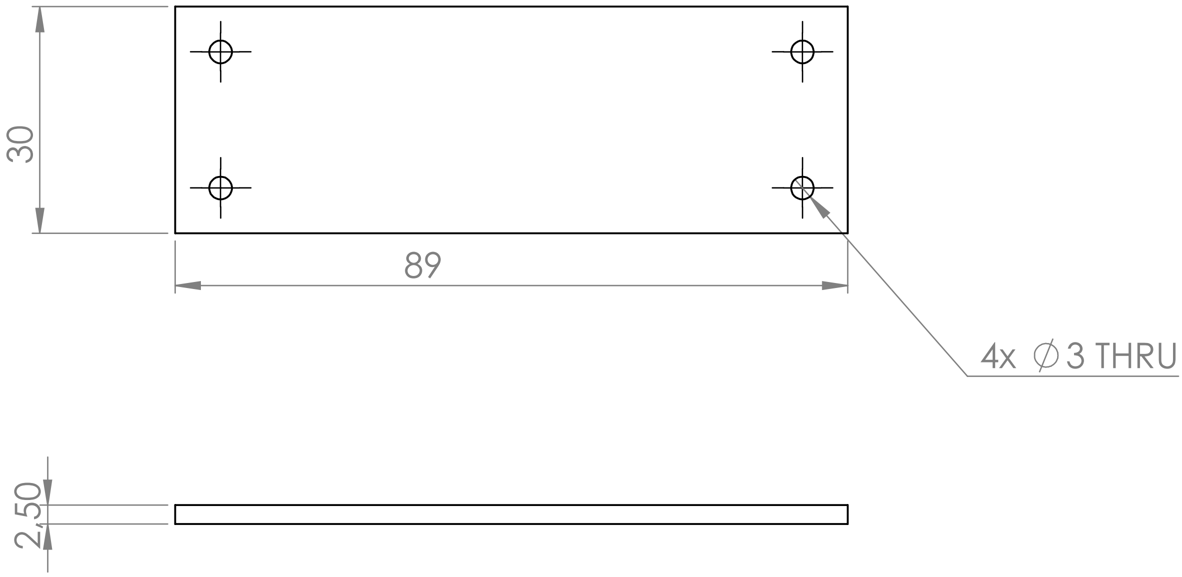
DWG NO.

Plate1

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

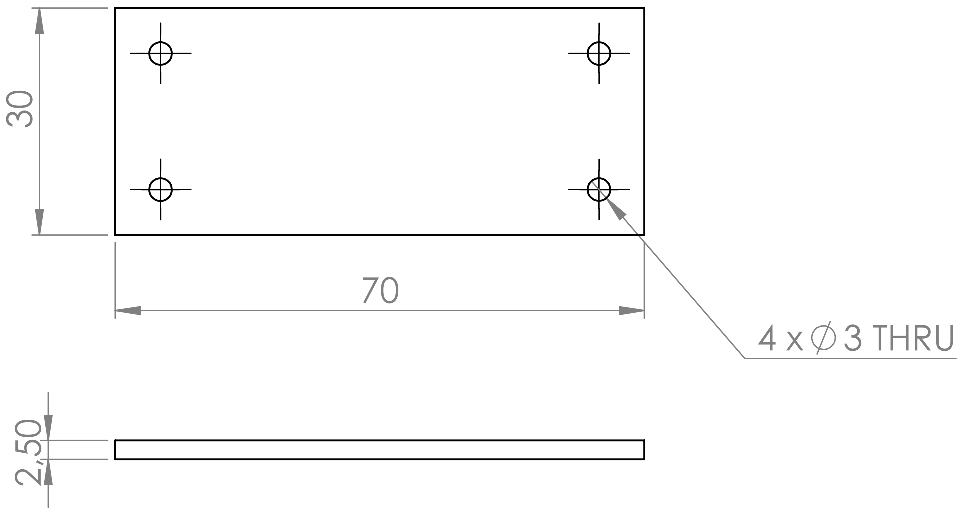
WEIGHT:

DWG NO. Plate2

A4

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

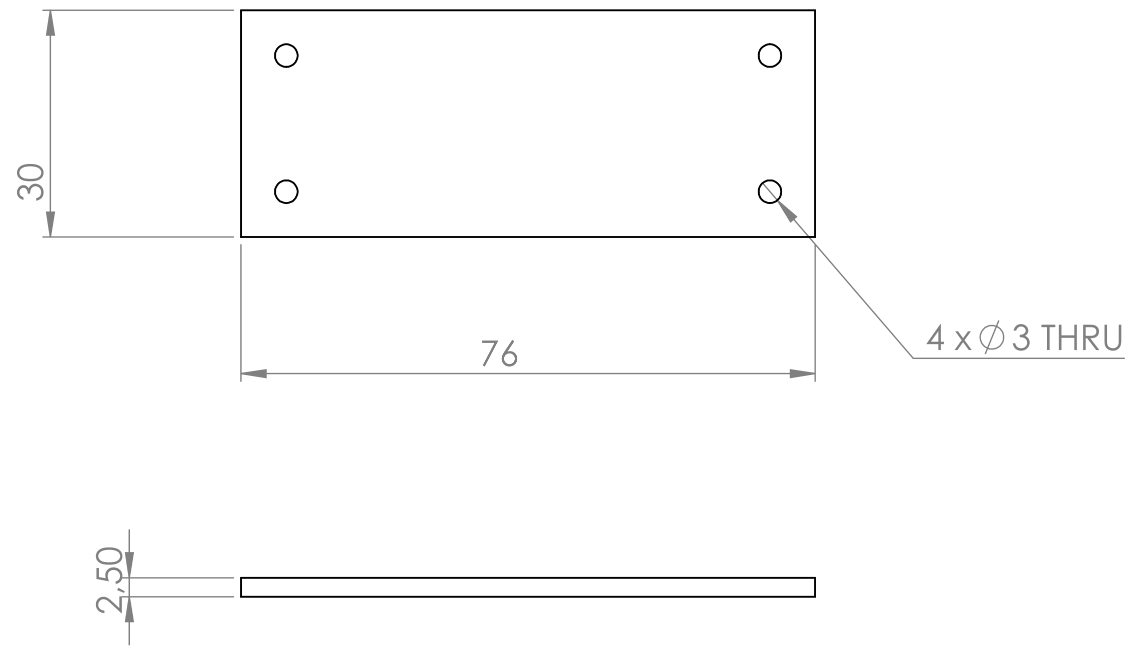
DWG NO.

Plate3

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

MATERIAL:

WEIGHT:

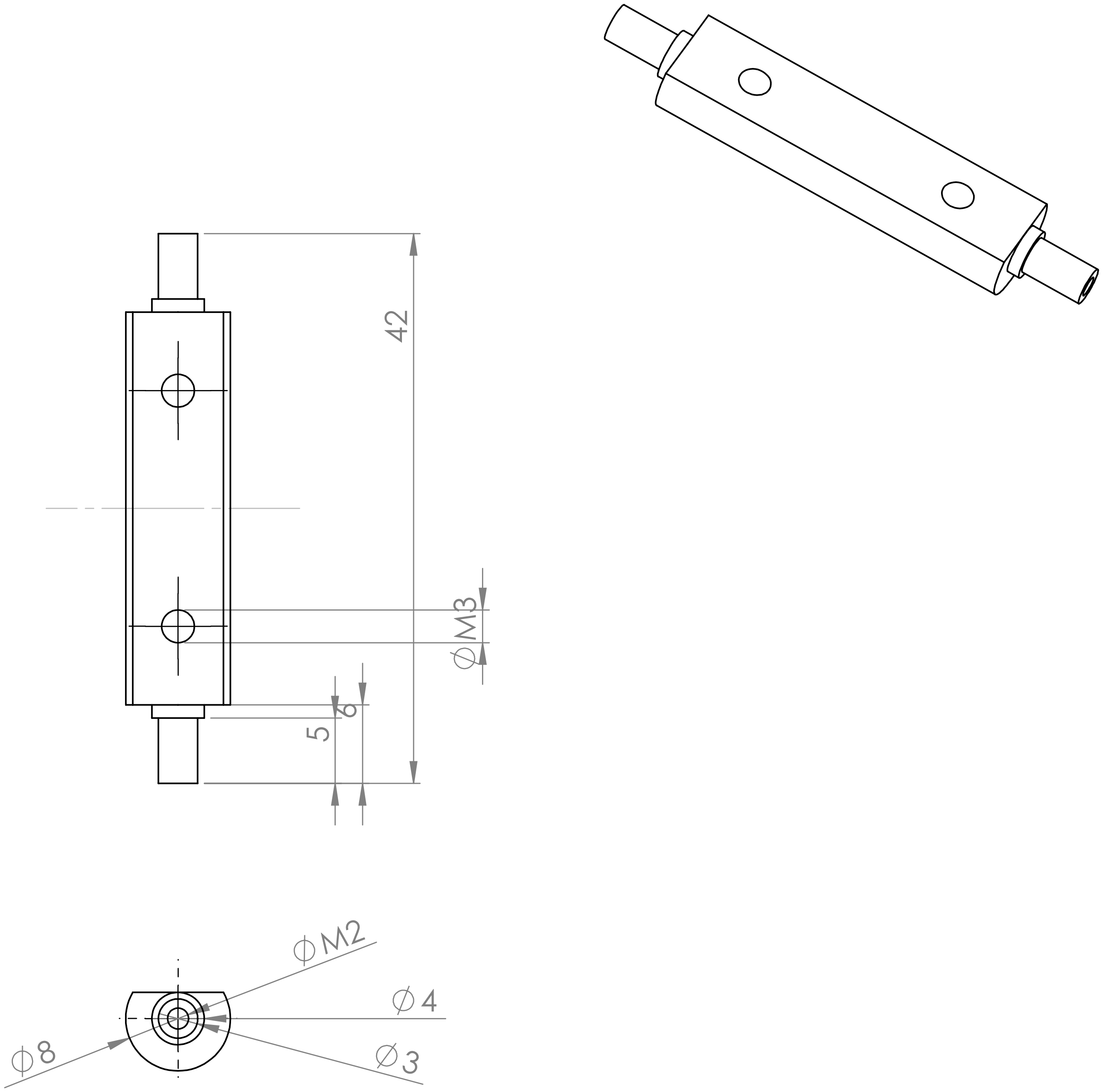
DWG NO.

Plate4

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

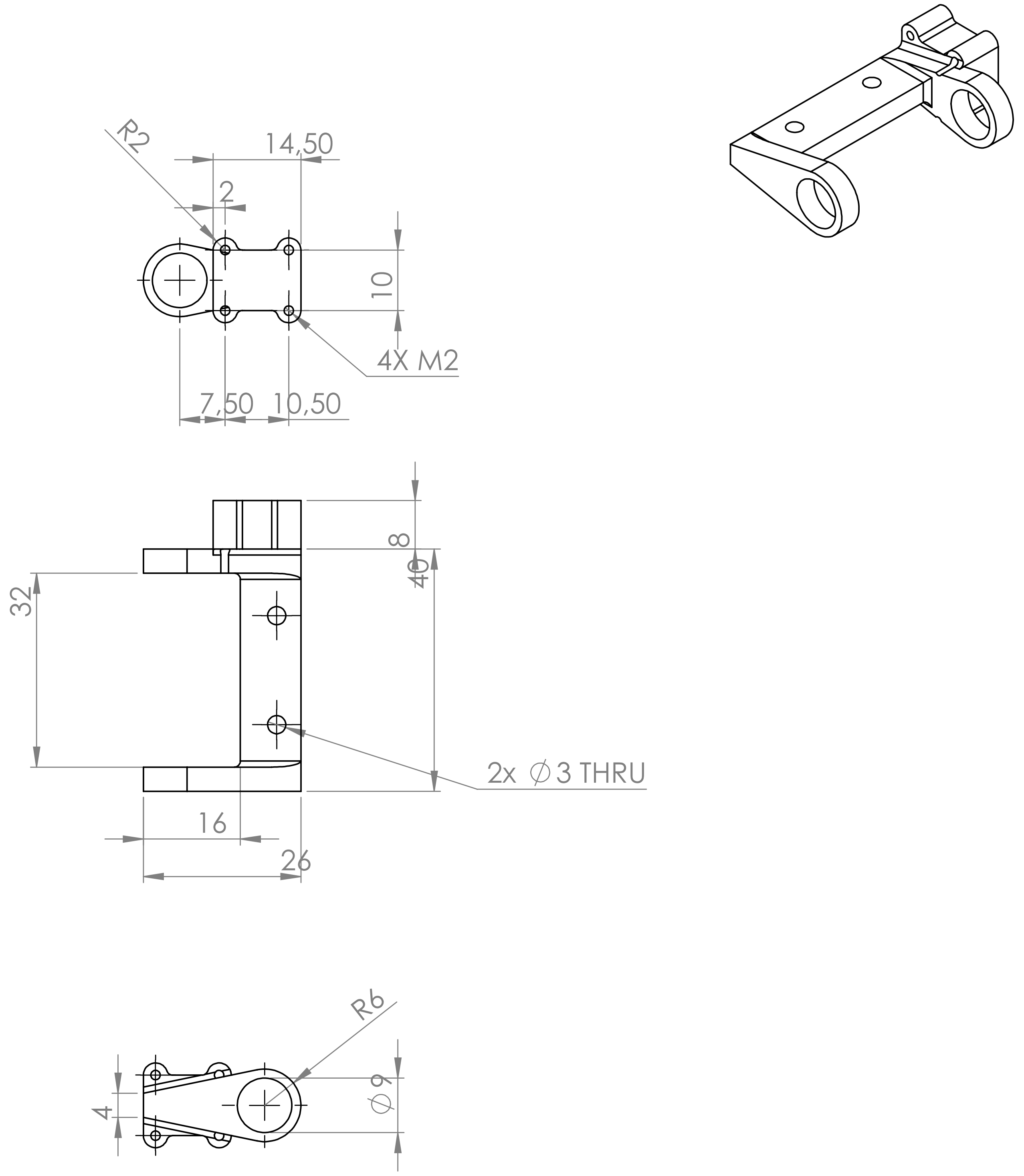
WEIGHT:

DWG NO. NA-1

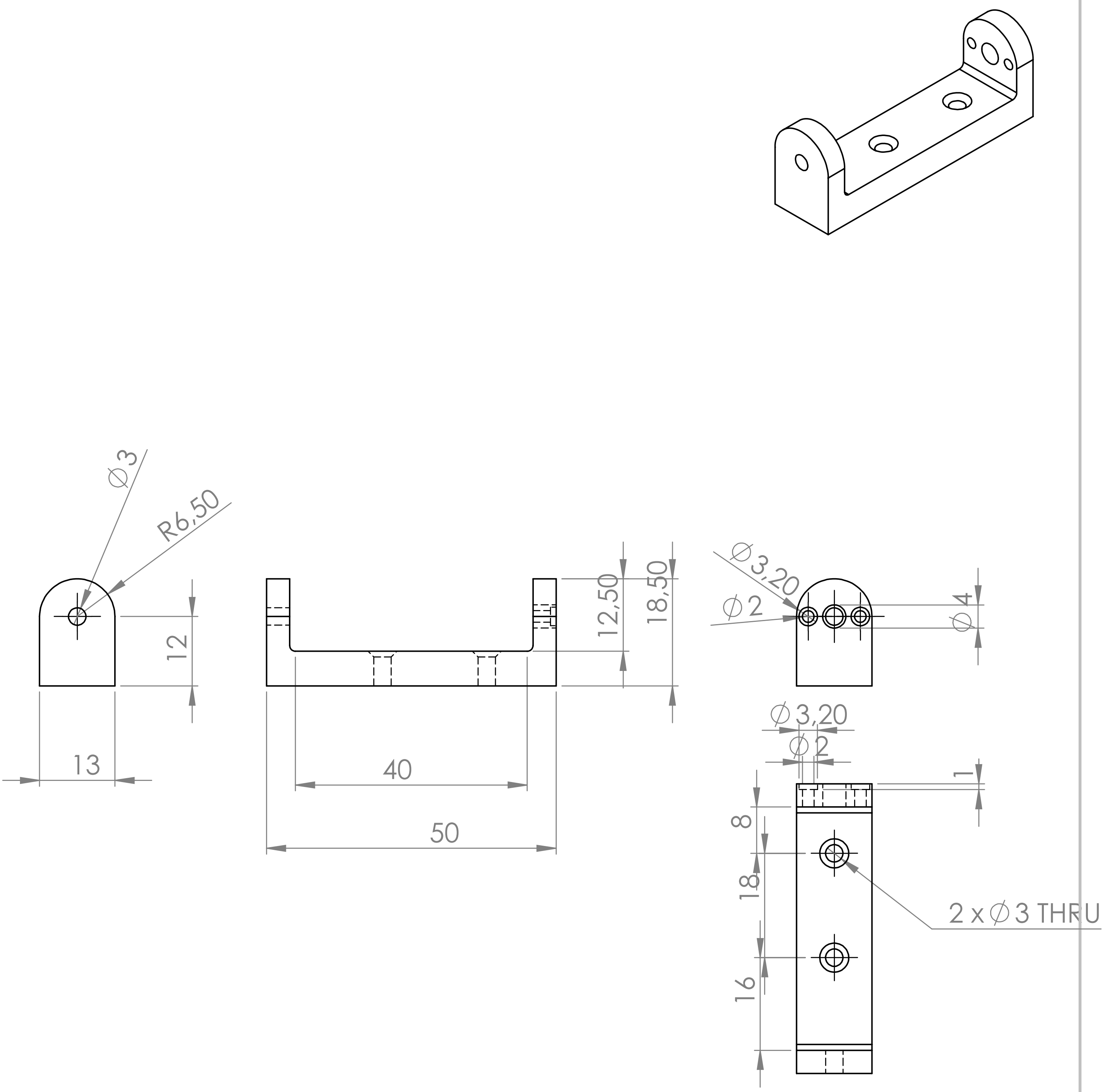
A4

SCALE:2:1

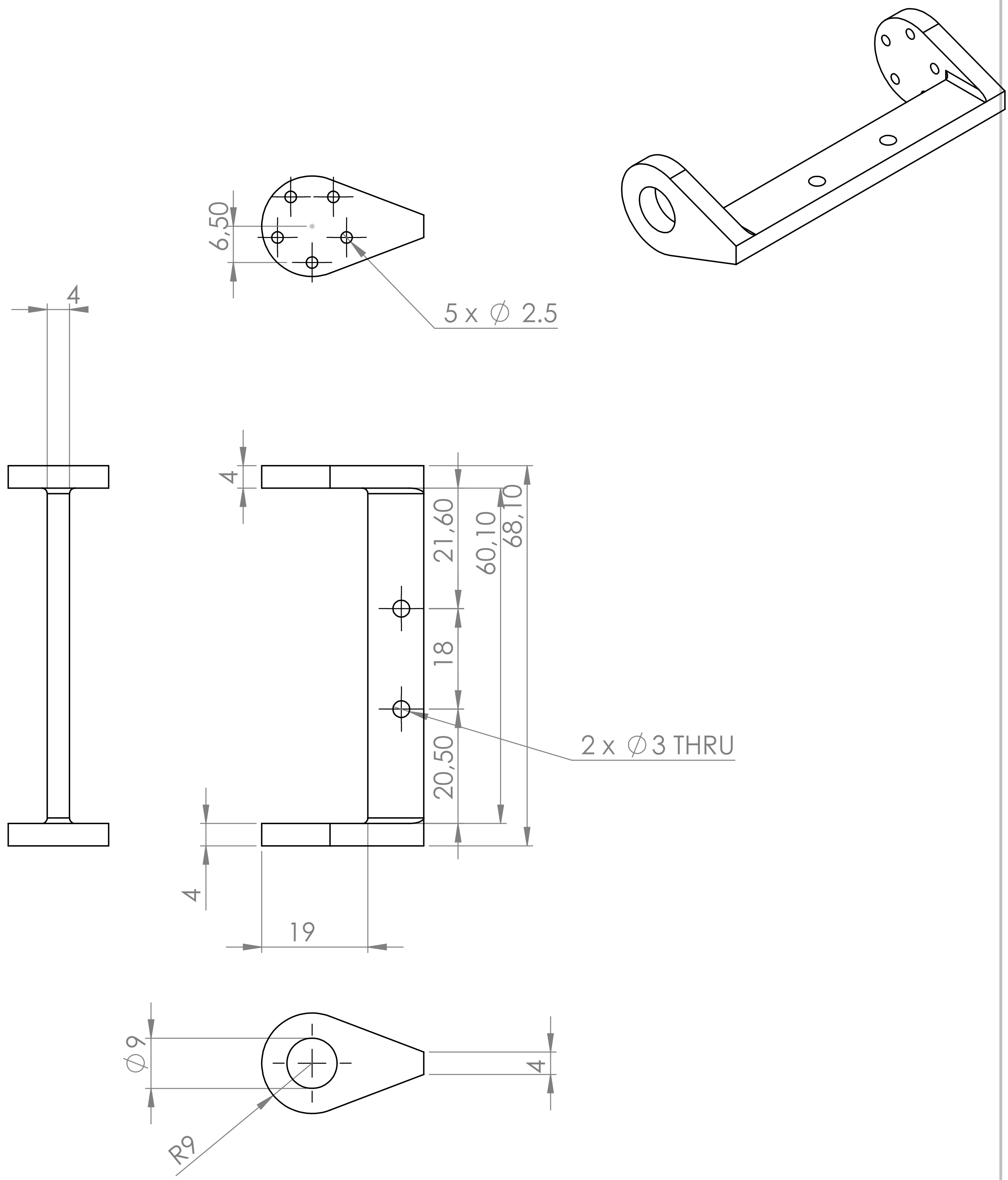
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:				DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. NA-2	A4
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:				DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE				TITLE:	
DRAWN								
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL:			DWG NO. MI-1	A4
				WEIGHT:			SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

MATERIAL:

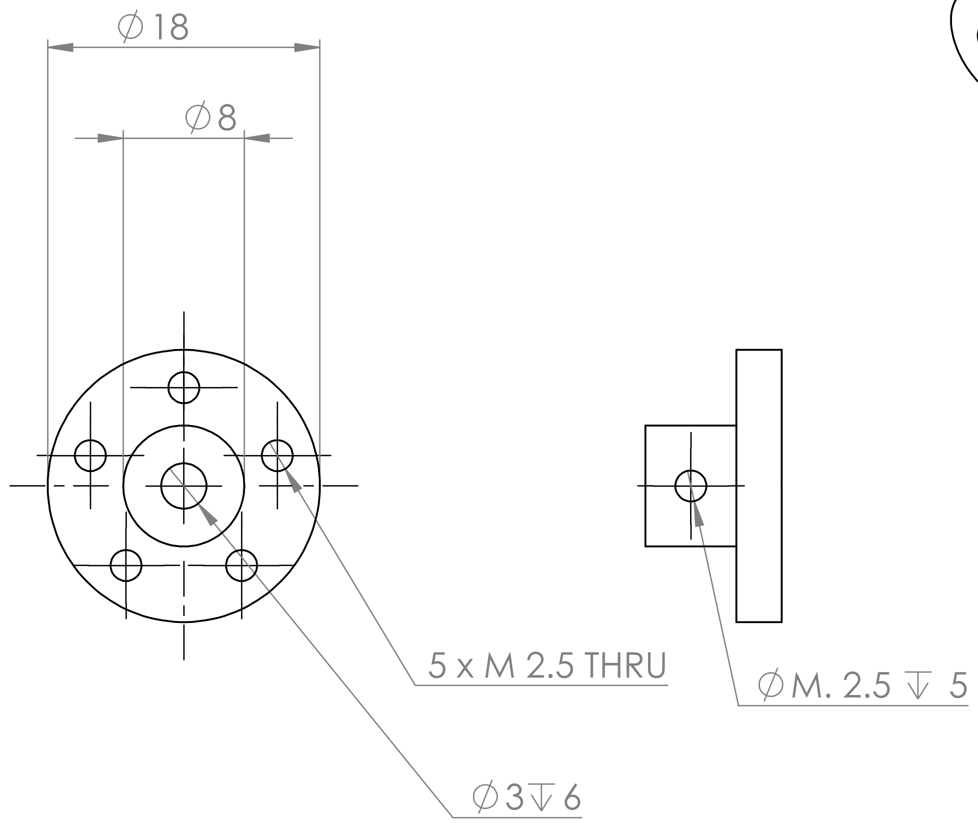
WEIGHT:

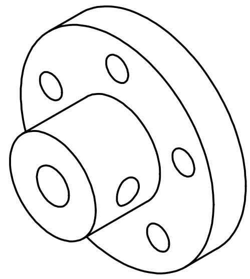
DWG NO. MI-2

A4

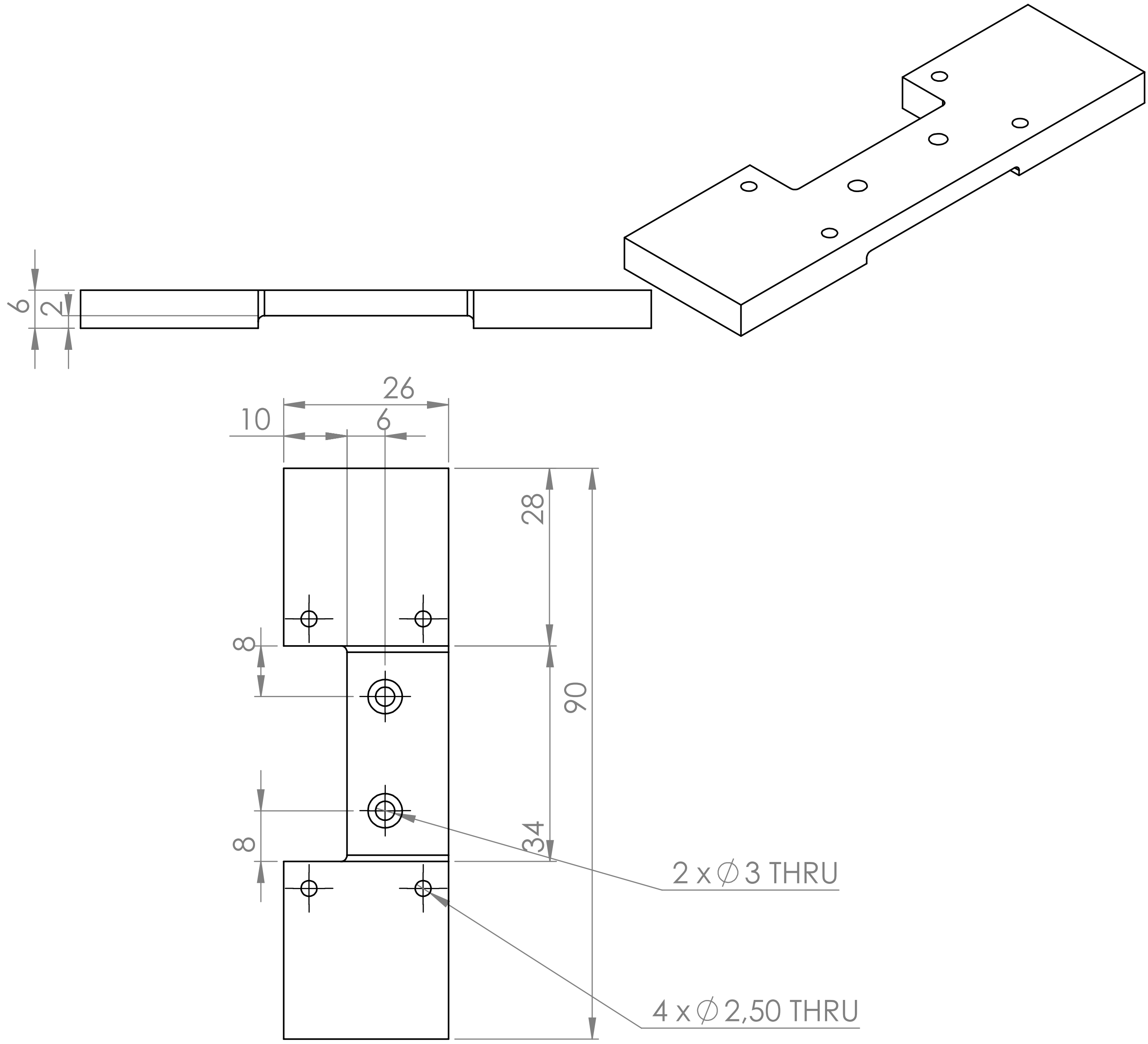
SCALE:1:1

SHEET 1 OF 1

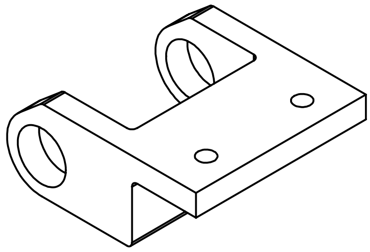


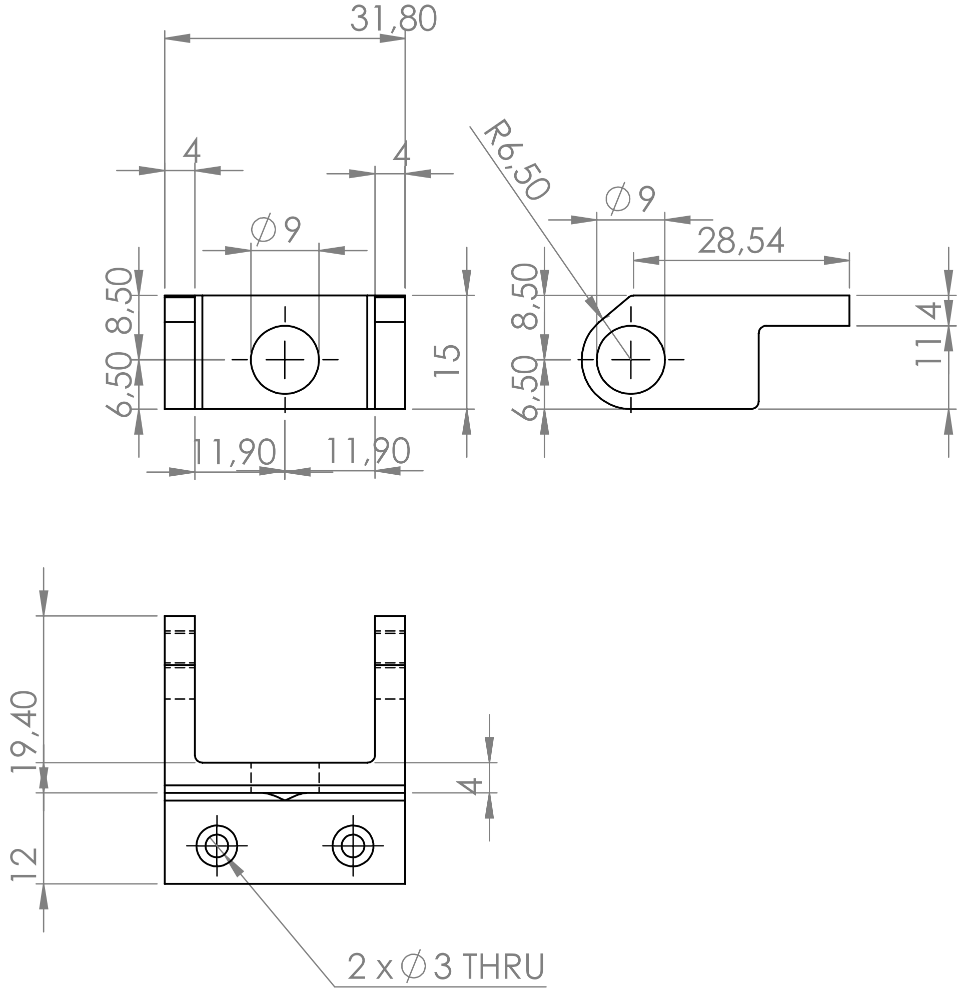


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	DWG NO. MI-3
					A4
				WEIGHT:	SCALE:2:1
					SHEET 1 OF 1



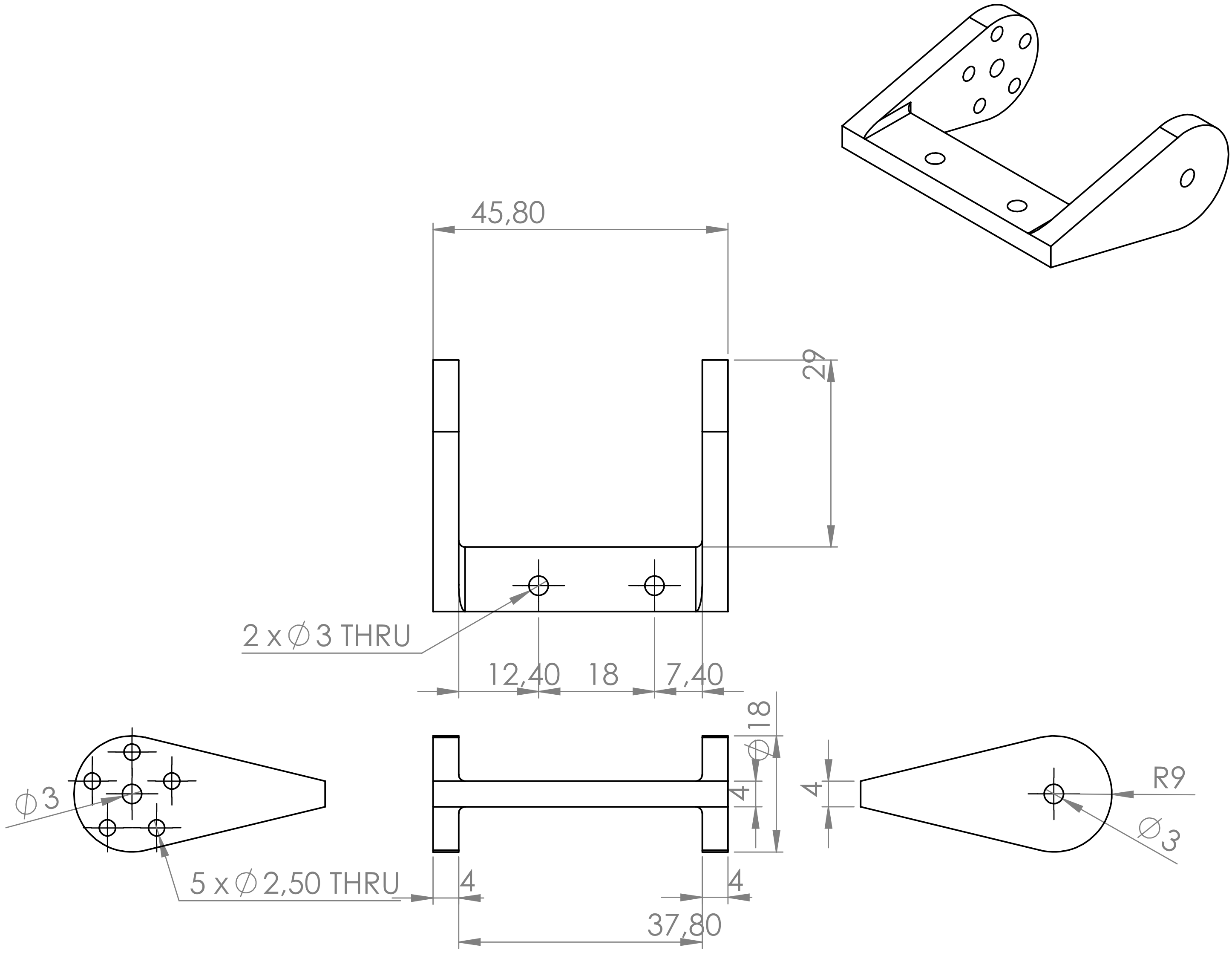
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION		
	NAME	SIGNATURE	DATE			TITLE:
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:		DWG NO. DIF-1 A4
				WEIGHT:		SCALE:1:2 SHEET 1 OF 1



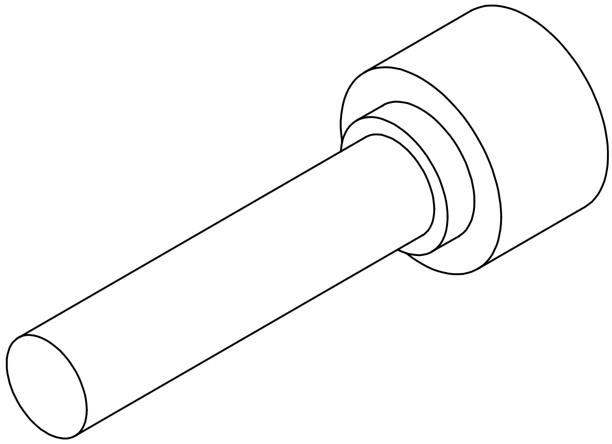


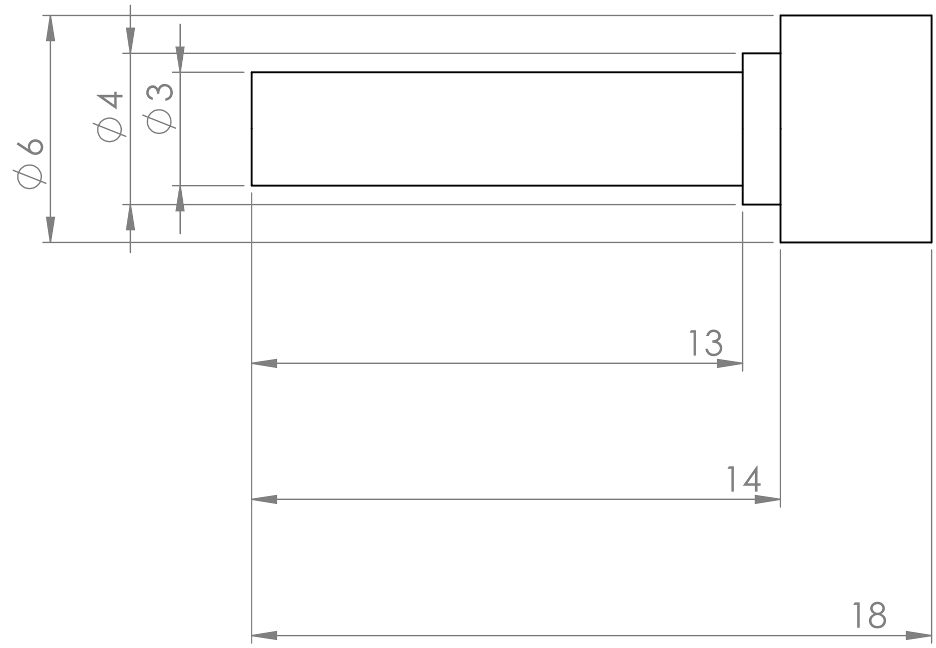
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE				TITLE:
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:			DWG NO. DIF-2 A4
				WEIGHT:			SCALE:1:1 SHEET 1 OF 1

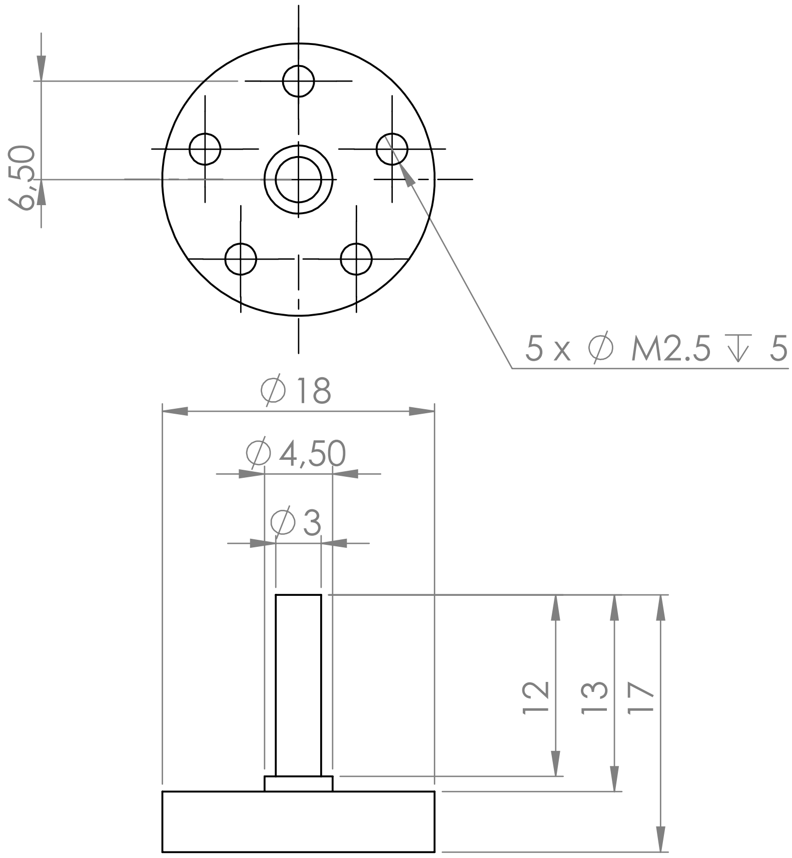


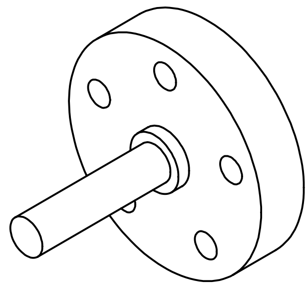
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:				DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. DIF-3	A4
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION
	NAME	SIGNATURE	DATE			TITLE:
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:		DWG NO. DIF-4 / A4
				WEIGHT:		SCALE:2:1 / SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				MATERIAL:
				WEIGHT:

TITLE:

DWG NO. DIF-5

A4

SCALE:2:1

SHEET 1 OF 1