

B.Sc.Eng. Thesis
Bachelor of Science in Engineering



Tether Control for Unmanned Aerial Vehicle

Creating a Platform for Tethered Control of UAVs

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Kongens Lyngby 2015



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Tether Control of Unmanned Aerial Vehicle

Tøjr-styring til ubemandet luftfartøj

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Project period: 2014-09-01 to 2015-01-23

ECTS: 15

Education: BSc.

Field: Electrical Engineering

Class: Public

Remarks: This report is submitted as partial fulfilment of the requirements
for graduation in above education at the Technical University of Denmark.

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Summary

Unmanned Aerial Vehicles or UAVs is getting more common in everyday life, both as hobby project and industrial applications. The aim of this project is to propose a solution to extend flight time for UAV's in an industrial application using a tether cable connection. It is desired to develop a platform, that handles the mechanical part of winching and storing the cable, and the electrical part of using the cable as position reference for the UAV, and using the cable for communication with the UAV. Using a hexacopter(a 6 rotor UAV) with lifting capabilities of about 3kg and a 50m light weight cable ensures the UAV to be able to lift the cable. Two methods of winching and storing the cable is analysed, and one selected for prototyping. Two electrical measurement devices are developed to measure position references for position control of UAV. This work does not deal with the position controller for the UAV. A Ethernet link from the Ground Control Station to the UAV is established through a regular Ethernet over power line adapter. Both Ground Control Station and the UAV are designed to run on Beaglebone Black, the actual flight controller is a PixHawk. The system design and prototype is analysed and discussed for further development on this project.

Preface

This bachelor thesis was written at the department of Automation and Control at the Technical University of Denmark in fulfilment of the requirements for acquiring a bachelor degree in Electrical Engineering.

This project is an innovation project, that pushes the boundaries of the relative low cost technology. There is an old Danish saying that "Deep fall, high flying". Innovation project is about being willing to take a high risk, of falling deep, to achieve results no one thought was possible. If every innovation project succeeded, it's is not innovation - but only a further development of known technology. To achieve an innovative goal, you have to set a goal 110 per cent higher of what you expect to achieve and afterwards be fair in sentencing if missing the target.

Kongens Lyngby, January 16, 2015



Peter Juhl Savnik (s113556)

Acknowledgements

A special thanks to my two academic advisers, for always seeing the possibilities rather than the impossibilities in this project. Thanks to Søren Hansen for introducing me to "a real world problem" that is very relevant today. Thanks to Christian Andersen for always having time to help me problem solving or introduce me to programming concepts, even then it got late in the evening. It has been very supportive to see that you both share a huge personal interest in this project.

Thanks to all friends and family who has supported me though this project and helped me having time for this project to become a success.

Thanks to Martin Meister from DTU Skylab team for helping out with the mechanical work and supplying materials for this project. Then mechanic from the institute only saw problems Martin always saw possibilities and guided me towards a solutions. It has been a long battle for me, without any mechanical experience, to master such a underestimated expertise, both the manufacturing part and documentation.

Thanks to RS Components for sponsoring electrical and mechanical components for this project.

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CHAPTER 1

Introduction

Unmanned Aerial Vehicles, also commonly known as UAVs or drones, have for long time only been used for military, research and hobby purposes - but recently have a wide range of industrial applications seen the potential in using UAVs for industrial purposes. Flying UAVs have been implemented in a variety of applications such as monitoring, photography / filming, surveying the landscape and much more.

In some applications the system must be capable of operating for a long period of time. In this cases there is a need for a constant power supply via a cable. This project is about developing a platform for tether control of UAV with a cable. A solution must not be limited to solving a single problem but as a platform for the implementation of tethered drones in a wide range of applications.

1.1 Previous work

Several attempts to build a tethered UAV have been seen before, several design concepts have been panted across the world - yet there is no commonly known commercial system available for sale. It is a great curiosity because most UAV systems have started to be tethered in some degree.

For this project a UAV from microcopter with a PixHawk is provided. The UAV and the PixHawk has in previous work been set up and are working.

While this thesis was written Mikkel Wahlgreen has designed a power supply system [Wah14] that attempts to meet the requirements described in this design requirement specification and Claudia G. Walls is working on a position controller for the UAV.

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1.2 Problem formulation

The objective for this project is to analyse and propose mechanical and electrical design for a platform for tether control of UAV. The designs has to be analysed and through the analysis one design must be selected to be prototyped and tested.

1.3 Problem limitation

- The UAV must be capable to be airborne significantly longer time than a battery powered alternative.
- It is assumed the anchor point of the UAV has significantly greater mass than the UAV lifting capabilities.
- The power supply may be optimized by using both a cable and a battery. The UAV do not use 100 per cent of it's power at all time, but cable and power converters must be dimensioned so it can deliver 100% power when needed. Therefore it can be imagined that the UAV take off and land on the battery, and then the battery is recharged in air by the cable. This thesis only investigates the case without battery.
- This project will not cover the position control in the PixHawk.

1.4 Example of use case

In Denmark agriculture grain production constitutes 35 per cent of the total area, or 1,495,000 hectares with a value of 29.4 billion. kr. Producing increasingly more with less resources. The Agriculture puts a strong focus on optimizing production through research and innovation[Fø13].

A well-known problem in cereal production is when the farmer harvests in the forest, there is often young wild hiding in the grain. Their natural instinct of danger is to hide even more or pretend to be dead. This means that when the farmer harvests his field, the animal is not moving away from the machine. This results in a large number of young deer which are hit by farmers machinery. It has economic consequences for the farmer, because the harvested grain is destroyed, materiel damage can happen to the equipment resulting in down-time and, not least it is an unpleasant experience for the farmer.

A research group at DTU Automation has proposed a solution with a tether UAV flying in front of the vehicle and with a vision system can detect any obstacles such as animals or stones.

1.5 Outline of this thesis

This thesis is divided into 2 main chapters, excluding the introduction. Chapter 2 investigate the presented problem through deeper analysis - resulting in a design requirement specification. Chapter 3, Prototyping, using the design requirement specification from the analysis chapter to develop both mechanical and electrical components. All practical information for replicating this work is located in the appendix.

CHAPTER 2

Analysis

2.1 Background

It is desired to develop a platform for tether control of UAV. Such a platform can have many applications in the industrial world - which also raises a number of requirements for reliability and robust design.

The project has several issues which needs to be addressed in the analysis in order to make a design requirement specification. This analysis will cover the issues and the solutions of the issues will be addressed in the prototype chapter

2.2 Platform for Tethered UAV

A platform for tether control of UAV must have 3 basic elements; the UAV, a power line and a ground station. The ground station supplies the power line with power and keeps track of the cable. The UAV must be able to land and take-off from the ground station. The power line must be light enough for the UAV to lift it. The ground station must assure that the power line is not touching the ground by releasing or pulling cable.

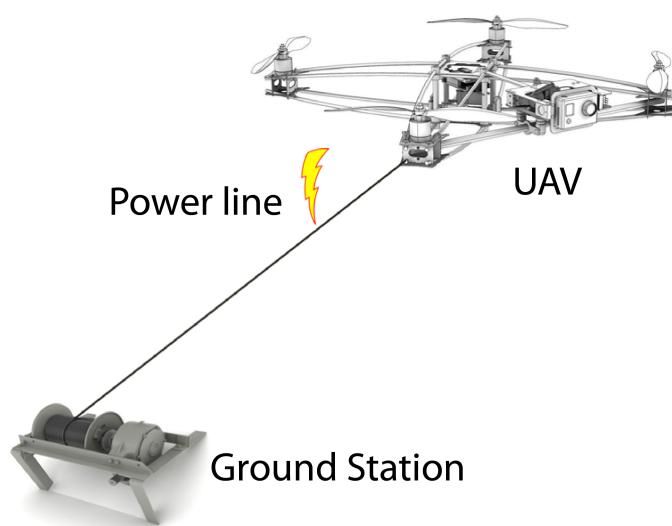


Figure 2.1: Illustration of key elements for a platform for tethered UAV

2.3 Power line

Every cable has an electrical loss, and this factor contributes significantly when the cable is long and has a low cross-sectional area. It is wanted to have a cable that is as long as possible, but the UAV can only lift a limited amount of payload. The cross-sectional area and the length has a big impact on the weight. Investigating the electrical loss in the cable results in the cable specification requirements.

2.3 (2) Ind- It is assumed the UAV requires 500 watt at 12 volt when using maximal thrust. To be on the safe side a tolerance of 10 per cent is added, ending up with supplying the UAV with 550 watt. The loss in the cable can now be calculated as following. P is the power in Watt, U is the voltage in Volt, l is the cable distance in meter, ρ is the electrical resistivity in $\Omega \cdot m$ and A is the cross sectional area in m^2 . The current $I[A]$ through the wires is given by the power divided with the voltage.

$$I = P/U \quad (2.1)$$

The resistance $R[\Omega]$ per unit length is to be determined by the electrical resistivity $\rho[\Omega \cdot m]$ divided by the conductors cross sectional area, A .

$$R = \frac{\rho}{A} \quad (2.2)$$

The voltage drop $U_{drop}[V]$ per unit length is to be determined by the current times the resistance.

$$U_{drop} = I \cdot R \quad (2.3)$$

The voltage drop depends heavily on the current going through the wire. It is favourably to have a high voltage and low current to minimize the voltage drop. It is a commonly known method used in power supply systems all over the world. For a low voltage the percent of voltage drop is very high, as illustrated on figure 2.2.

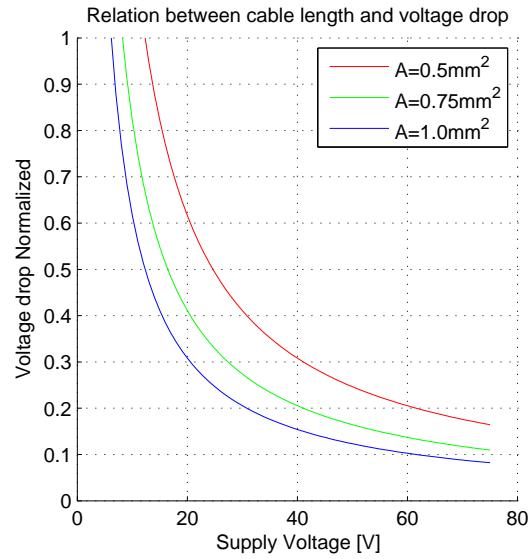


Figure 2.2: Relationship between Voltage drop and cable length per Ampere over a 50m cable. A is the cross-sectional area of the conductor.

In order to avoid the Low Voltage Directive [PCTU06] the DC voltage must be less or equal to 75 volt. For this application 75 volt DC is easily achieved with standard components and therefore set as the power transmission voltage.

The cable loss $P_{loss}[W]$ per unit length is now given by

$$P_{loss} = I^2 \cdot R \quad (2.4)$$

The loss in the cable needs to be minimal. A known method to minimize the loss on the cable is to step up the voltage. This is because of the fact the loss depends on the current squared times resistivity and independent of the voltage.

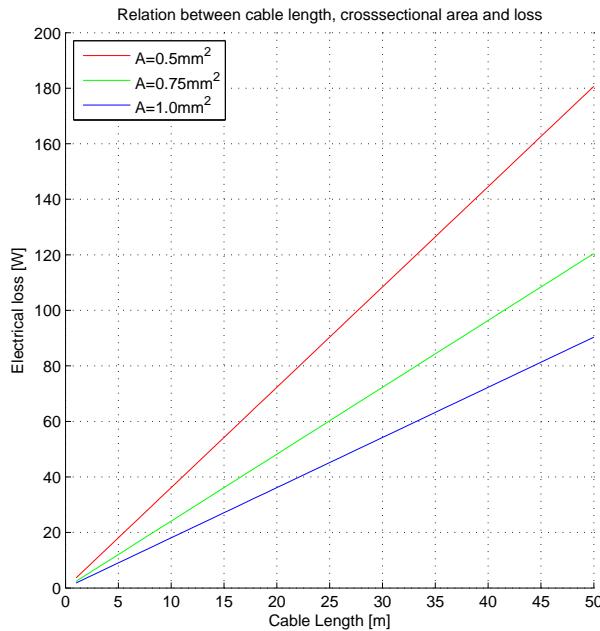


Figure 2.3: Relationship between cable length, cross-sectional area and loss. Calculated with copper resistivity and for both + and GND conductor cores.

2.3 (3) Check

From figure 2.3 it is seen that electrical loss is the conductor also depends on length and cross-sectional area of the conductor. The electrical loss is converted to heat in the cable.

undregning om den der lobbelt

2.4 Tension force in the Cable

In a simplified model the weight of the cable will only drag the UAV on one axis, towards the ground station. On the UAV there is one loadcell mounted, measuring the force in the direction of the tension. The output of the loadcell will enable the ground station to decide if it should roll cable out or in. However this simplified model assumes the UAV to be perpendicular to the cable at all times. That will in the real world only be true when it hovers directly over the ground station. As the UAV goes to one of the sides it will try to maintain horizontal pitch/tilt. The cable will try to drag it in the direction of the ground station, making giving the UAV a steady force to work against. Because of aerodynamics the UAV will tilt in some extend to work against the tension. If this tilt gets too large the UAV will lose its lifting capability and therefore stall and crash towards the ground.

2.4 (4) deiner udtryk

Modelling the tension in the free hanging cable

Modelling the cable in the real world has a great complexity and in order to make a robust design we must assume the surrounds are not ideal. The ideal case is the cable is hanging as a direct line, as seen on figure 2.4. Only at the anchor point the cable touches the ground. Worst case scenario is all cable is lying on the ground, except what is directly underneath the UAV. It can be assumed that the cable will be in between the direct line and worst case. The maximal position error will be the difference between the direct line and worst case line, calculated to approximately 14.65 meters or 29.3 per cent.

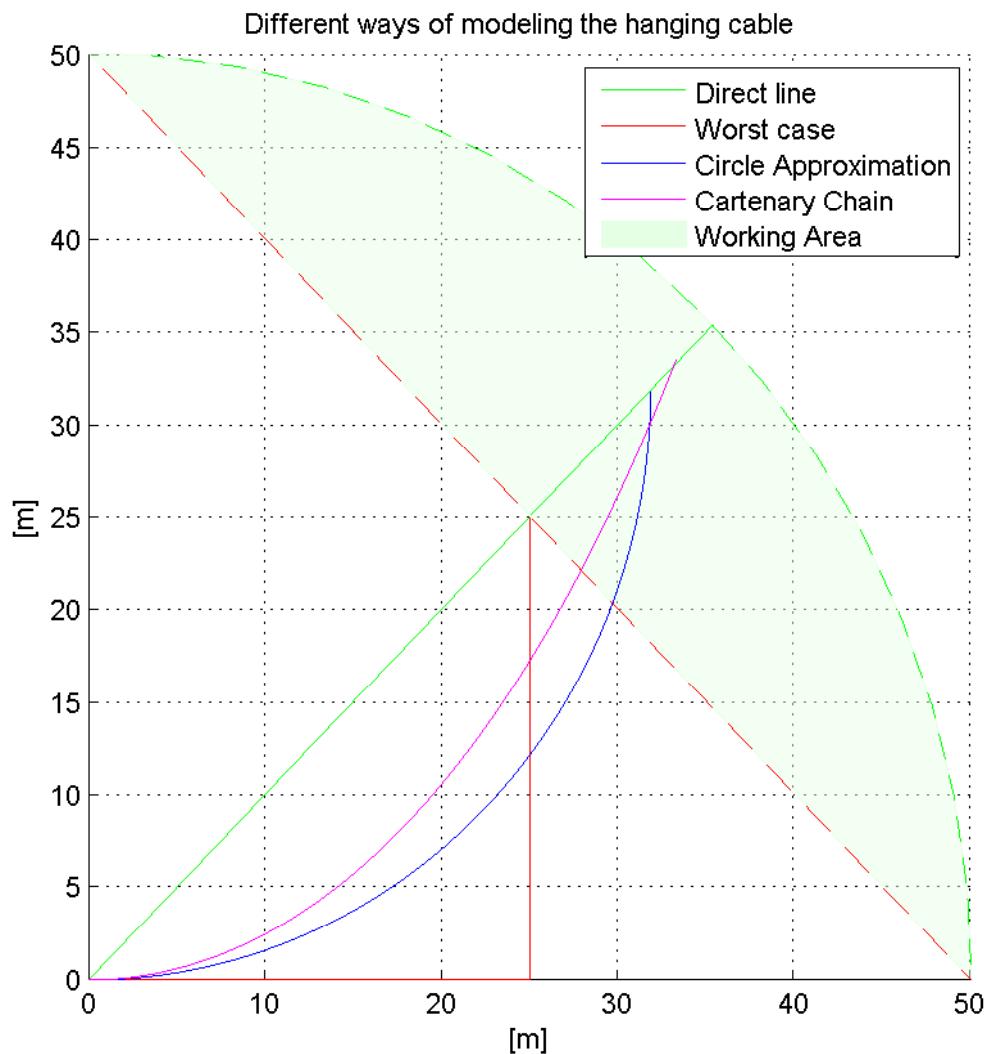


Figure 2.4: Diagram showing 4 ways of approximate the cables position. The direct line the the ideal case. The area between the ideal and worst case is the actual working area where it's assumed the position of the UAV to be. Position estimation using a circular shape and catenary chain to approximate the position.

Both the direct line and worst case is possible, but highly unlikely in the real world. A cable hanging between two points will have a curved shape from the sag. If the curve from the sag can be described as an circle, the cable will curve uniformly over the entire length. This assumes the cable has no mass, but in the real world it has. The catenary chain is close to an parabolic shape but describes the curve of a freely hanging chain with the weight uniformly distributed[Whe33]. The catenary equation has the form

$$y = a \cdot \cosh\left(\frac{x}{a}\right) \quad (2.5)$$

The catenary chain assumes the cable is so flexible that any force exerted by the chain is parallel to the chain. This set a requirement for the bending radius for the cable to be much less than the length of the cable. The weight of the cable pulls the UAV down and towards the anchor point. Let the point c be the anchor point to the ground and r be a force vector at the anchor point on the UAV. r must be at a higher point than c . The force T_0 at point c is tangential to the curvature thus only has a x component. The force T at point r is tangential to the curvature at point r and can be described as

$$T = T \cos(\phi) + T \sin(\phi) \quad (2.6)$$

ϕ is the angle between the x axis and the force vector and T is the magnitude of the force. The cable weight is represented as λ per unit length. g is the gravitational force and s is the length of the cable. The downward force is therefore $-y\lambda gs$

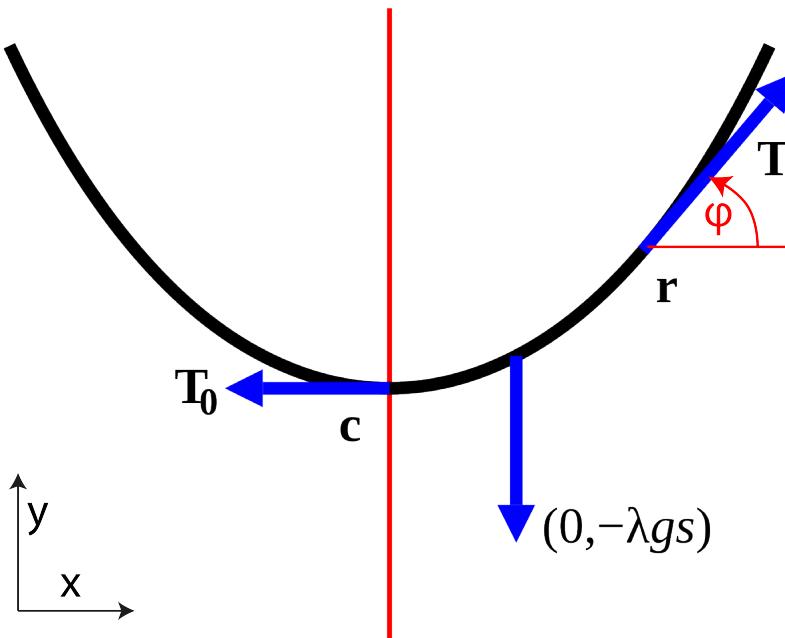


Figure 2.5: Catenary Chain Force diagram displaying forces acting from anchor point c to point r . T_0 is the tension at anchor point c and T is the tension at point r . Note the y axis in this diagram will correspond to the height later denoted as z .

In this analysis the cable is in equilibrium thus the sum of the tree forces is zero. Splitting up the sum in x and y components gives:

$$T \cos(\phi) = T_0 \quad (2.7)$$

$$T \sin(\phi) = \lambda g s \quad (2.8)$$

This gives the expected force at T as a function of either the force at the anchor point or the cable length and ϕ .

$$T = \frac{T_0}{\cos(\phi)} = \frac{\lambda g s}{\sin(\phi)} \quad (2.9)$$

To be able to model the cable using the catenary chain 4 parameters must be available; The tension at anchor point T_0 , the angle at the UAV ϕ and the length of the cable.

This model excludes all cases where either the UAV is below the anchor point or the cable partially is below the anchor point.

Horizontal Angular Force Measurement

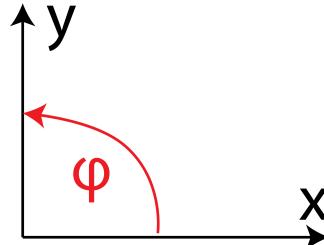


Figure 2.6: Coordinate system for horizontal measurement device.

For measuring the horizontal angle, ϕ , relative to the Ground Control Station and the UAV; a 2-axis measuring device is needed. The two axis must be perpendicular to each other. In that way a scalar of two unit vectors \hat{x} and \hat{y} can represent the tension from the cable in a combination of each direction. From the length scaled of the scaled vectors \overline{XY} and \overline{Y} the angle phi can be found.

$$\phi = \text{atan}2(Y, X) = 2 \cdot \arctan \frac{\sqrt{X^2 + Y^2} - X}{Y} \quad (2.10)$$

ϕ is the angle from the positive \hat{x} -direction and increases counter clockwise.
The length of \overline{XY} is given by:

$$\overline{XY} = \sqrt{X^2 + Y^2} \quad (2.11)$$

The length og \overline{XY} corresponds to the total tension in the cable in ϕ direction.

Tree Dimensional Force Measurement at the UAV

The UAV has 3 degrees of freedom in space, thus a tree axis measurement devices is needed in order to measure the total force T . The measurement device must measure the force relative to the UAV, thus if the UAV tilted to one side, by roll or pitch, it will not be adjusted in the angular calculation of θ .

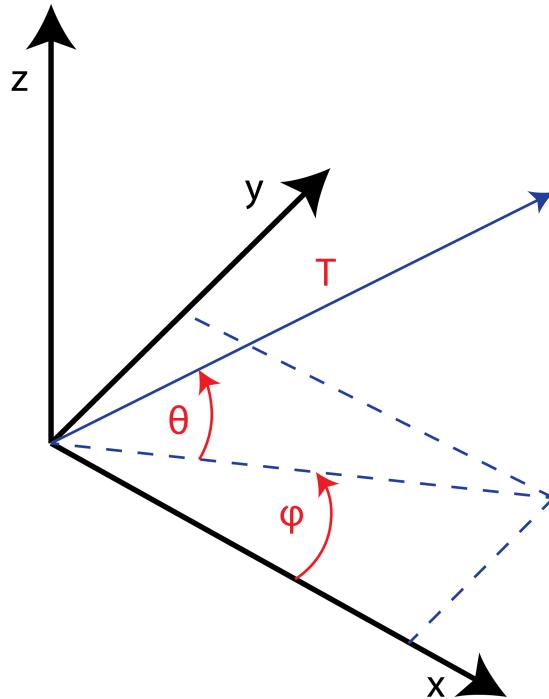


Figure 2.7: Diagram showing the force T the UAV have to withstand from the cable.

Calculating the total force from the tree axes using the same method as in the horizontal measurement device.

$$T = \sqrt{x^2 + y^2 + z^2} \quad (2.12)$$

To determine the direction of the total force the angle between x- and y-axes is denoted as ϕ and the angle between the xy-plane and z-axis is denoted as θ . ϕ is derived as in the horizontal force measurement device.

$$\phi = \text{atan2}(x, y) \quad (2.13)$$

θ is derived as the inverse cosine to the force in the z-direction over the total force.

$$\theta = \cos^{-1}\left(\frac{z}{T}\right) \quad (2.14)$$

Loadcell

The loadcells used in this project is a single-point loadcell. The choice of loadcell was determined by the availability/flexibility to easily create multidimensional measurements and the cost. A loadcell is basically a strain gauge(flexibly resistor pattern) that will change resistance when bended, mounted on a flexible material. In this case a block of Aluminium is cut out and a strain gauge is mounted. When the aluminium is exerted with a force or weight it will bend slightly, causing a small change of resistance in the straingauge. The change of resistance can be measured by a Wheatstone bridge, as the one on the Phidget bridge.

The calibration of the loadcell is very important to obtain a value that fits the theory. The calibration converts the measured voltage to the measured force.

$$F = K_f \cdot (V_{in} - b) \quad (2.15)$$

$$W = K_w \cdot (V_{in} - b) \quad (2.16)$$

F and W is the expected force and weight. K is a gain value depending on whether the output unit is force or weight. The offset b will vary between individual loadcell, even from the same batch. V_{in} is the voltage reading from the Phidget bridge.

When dealing with multiple loadcells there are two ways of configure them electrical wise. First is to measure each loadcell individual and second to measure all together. The first one has the advantage of being able to measure each loadcell individually, but the disadvantage of using many inputs and each loadcell needs to be calibrated individually. Second one has the advantage of only using 1 input on the bridge and all cells can be calibrated together, but the disadvantage of all loadcells need to be of same type and size and not being able to measure each loadcell individually. In this project the information of direction of tension is important and because of that measuring each loadcell individually is the best solution. [Phi12]

Data Connection

The measurements from both the Ground Station and the UAV is used as position references in the position controller on the UAV. Thus the data must be sent to the PixHawk flight controller with as little delay as possible.

2.5 Design Requirement Specification

- Supply the UAV with 12 volt DC and 500 watt
- The weight of the cable must not be greater than the lifting capability of approximately 3kg.
- The system must not be subject to the Electrical Safety: Low Voltage Directive, and therefore keep any voltage under 75 volt DC [PCTU06].
- Given the cheap cost of UAVs today, the solution must keep a low material cost.
- Measuring the total horizontal force at the anchor point.
- Measuring the total force and direction at the UAV.
- Measuring the length of the free hanging cable.

CHAPTER 3

Prototype

The ground control platform must have some physical dimension due to the size of the UAV used in this project. The dimension of the UAV used will effect the dimension and choice of construction of the ground station. In dimensioning and designing the ground station the primary focus is on making an industrial and robust prototype.

3.1 Landing platform / Helipad

The landing platform or helipad is a 60cm x 60cm wide plate with a hole in the middle. Dimensioning of the size mainly relies on tolerance on the presision of landing the UAV. The UAV only needs 30cm x 30cm space for the landing gear, but in case a big wind gust comes in just before landing/take-off, the UAV can slide off the platform if the platform is too small. On figure 3.1 the helipad is seen from the top.

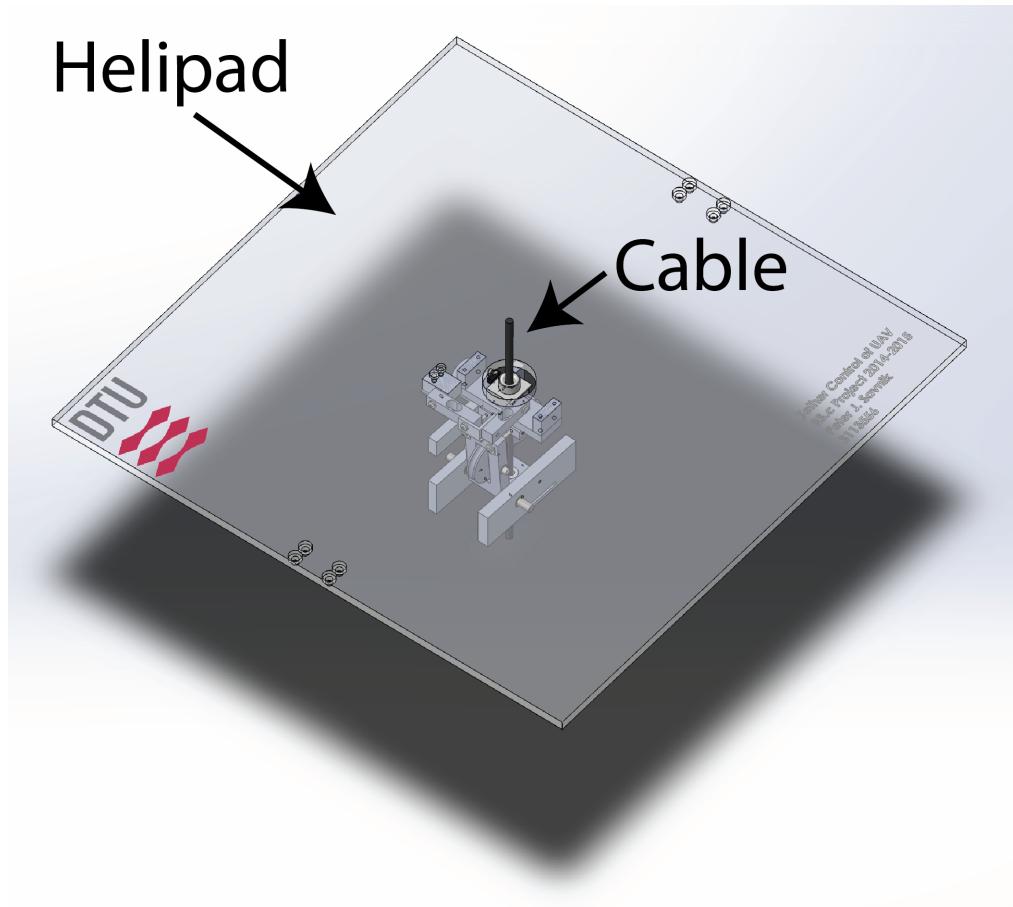


Figure 3.1: Illustration of Helipad with a hole in the middle for the cable.

3.2 Messuring the horizontal angle

In order to precisely determinate where the UAV is positioned relative to the helipad on a horizontal plane a coordinate system on figure 3.2 is introduced. x and y are cartesian coordinates corresponding to the measurements of loadcell 1 and loadcell 2 from figure 3.3. ϕ is the angle, starting at the positive x direction and increases in positive direction of rotation.

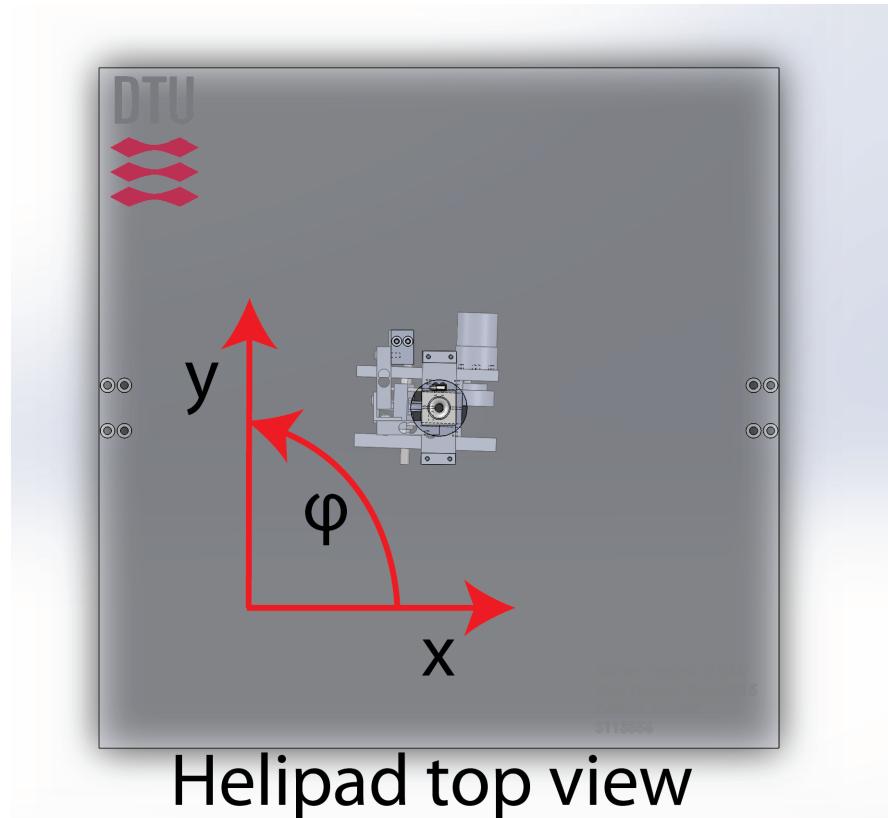


Figure 3.2: Helipad seen from top view with coordinate system.

To measure the horizontal angle between the ground station and the UAV to loadcells are used, perpendicular to each other. One end attached to the ground station and the other end attached to a cable though hole made in Teflon. Then the UAV is exactly direct over the hole, no force will be measured, but at the UAV moves to one of the sides it will create a cable tension that results in a force in x- and y- direction. Combining the x and y force can be translated to an angle.

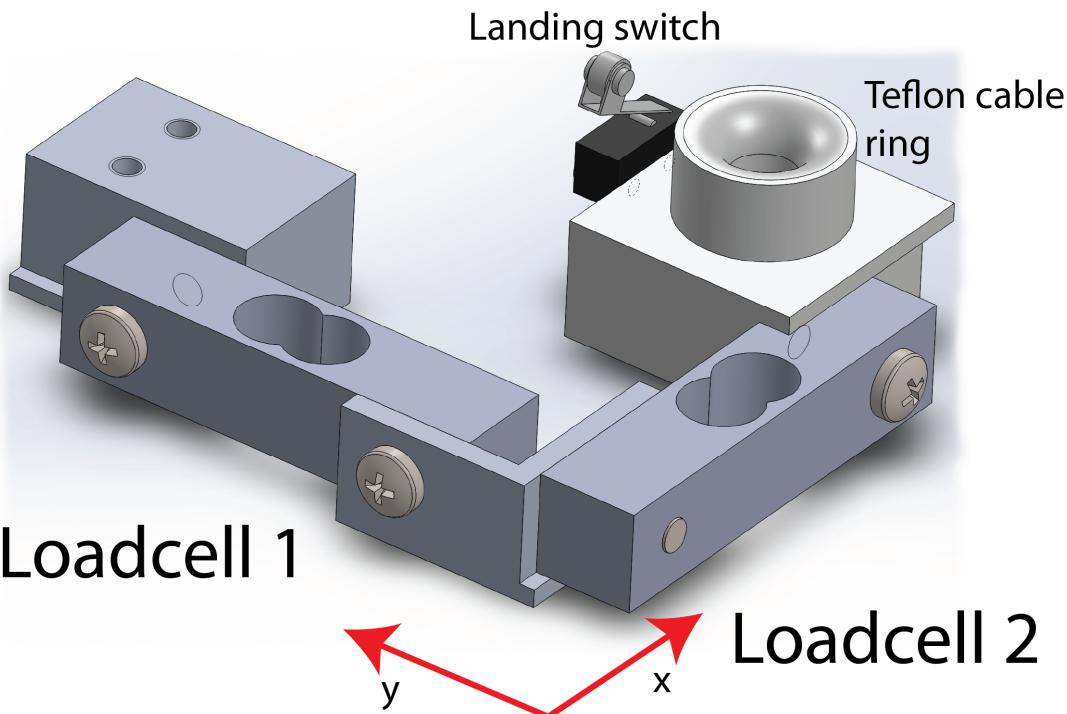


Figure 3.3: Configuration of 2 loadcells, for measuring the cable drag in x and y direction. Loadcell 1 measures in x-direction and loadcell 2 in y-direction.

The UAV can lift about 3kg payload and therefore exert 3kg thrust to the cable and the measuring device must be able to withstand such a force without permanently bending. Two 5kg loadcells from Phidget Inc is assessed to be the best match for the job with regard to what's available in the projects price range.

Testing

First off is calibrating the loadcells. First measurement is without any forces acting in x and y direction in order to determine the offset of each loadcell. The offset for x is found to -455.9787 and the y offset to -511.2618 .

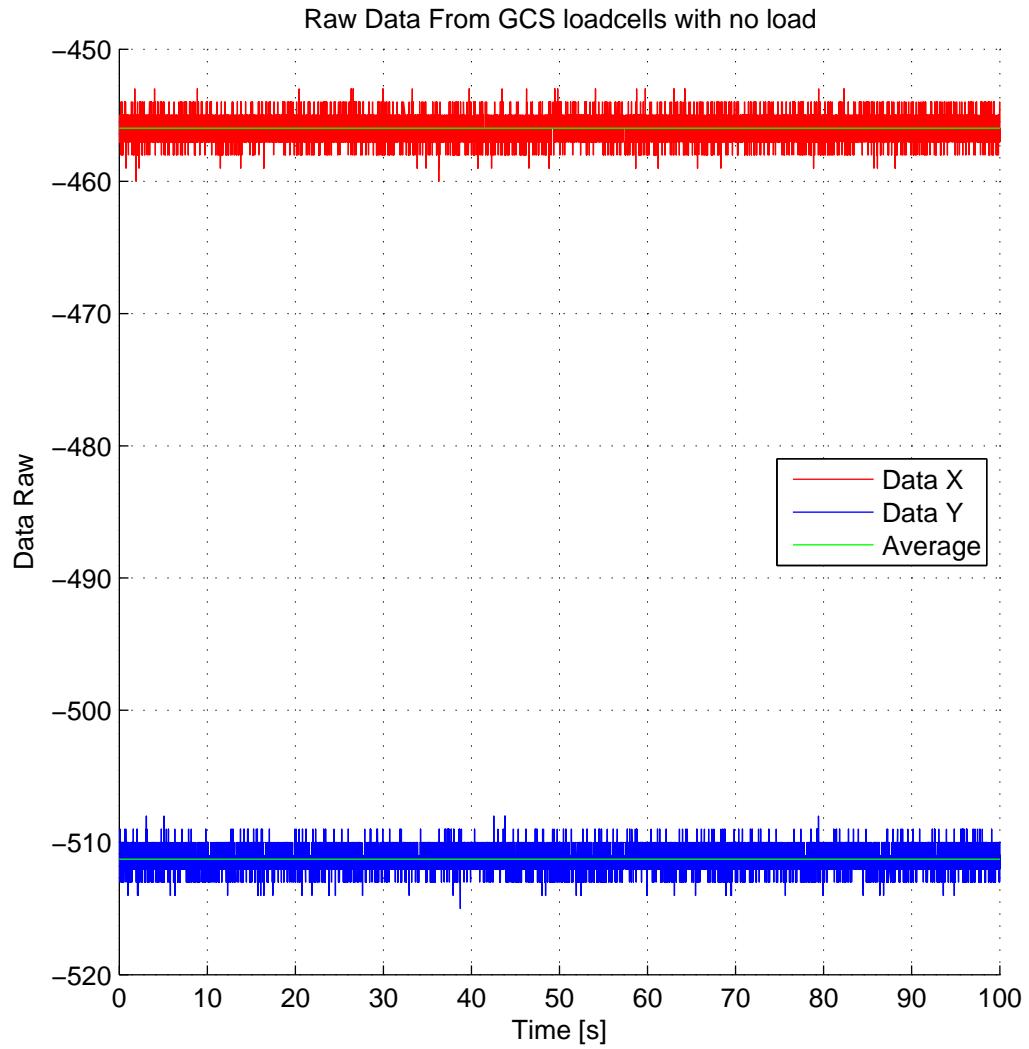


Figure 3.4: Raw input data from loadcell x and y. The average line is the calculated offset used for calibration. Measured without load in any directions.

Next 1000g of load is put on the loadcell with a rope through the Teflon ring first purely in positive x direction and next in purely y direction, in order to determine the gain factor K_x and K_y . K_x is found to 0.4786 and K_y to -0.5134. Afterwards the calibration is tested by applying 600g of force in x-direction and then checking the result.

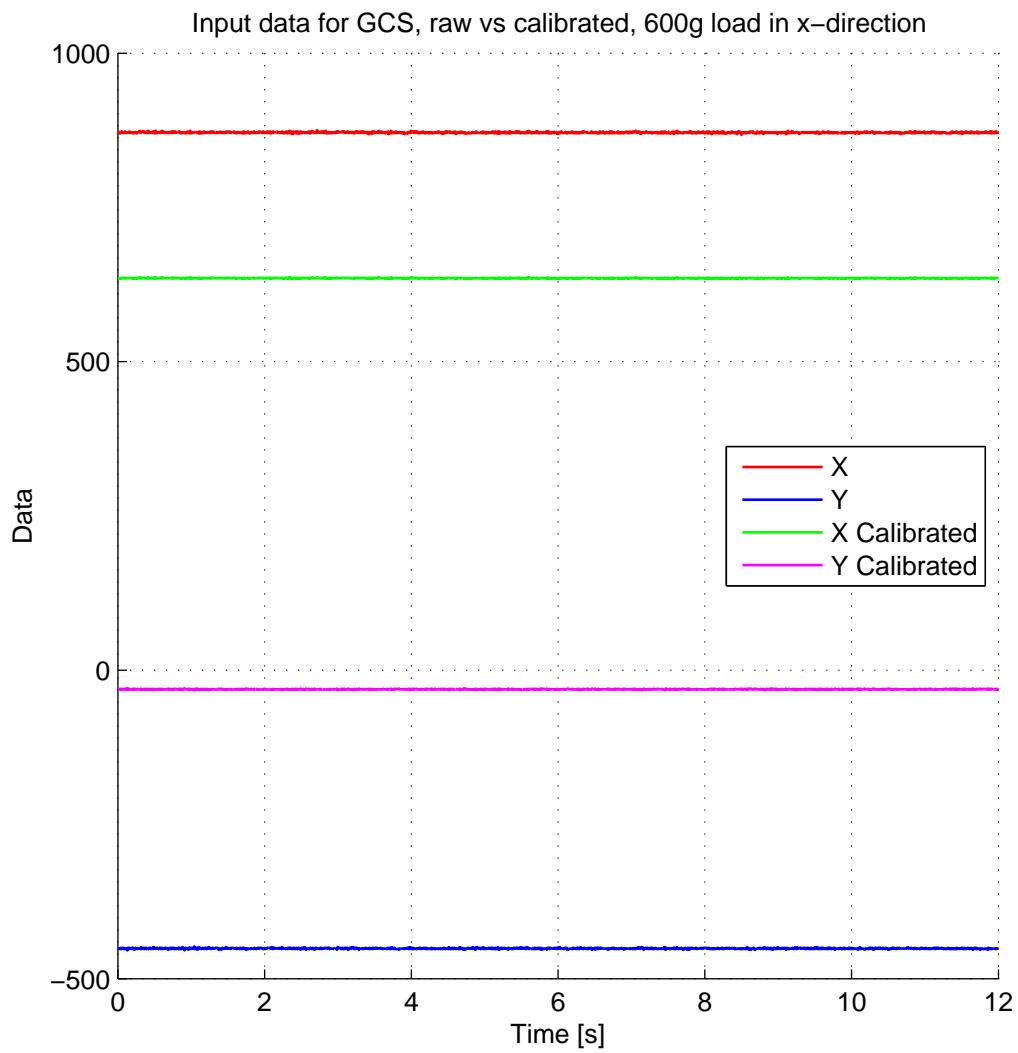


Figure 3.5: Comparing raw data to the calibrated values. The x-calibrated values are between 633g and 636g, then the force applied was 600g. The 33 – 36g difference is most likely caused by the limitations of precision from the spring load. The y-calibrated data is ranging from -29g to -32g. It is expected the precision can vary $\pm 75\text{g}$ around the zero balance.

Second test is done by applying a known force in a combination of x and y direction. For this test ϕ is set to 45 degrees and the total force is 1kg. On figure 3.6 it is seen that the data slightly decreases over time. This is probably due to tolerances in the manufacturing process enabling the loadcell to move slightly over time.

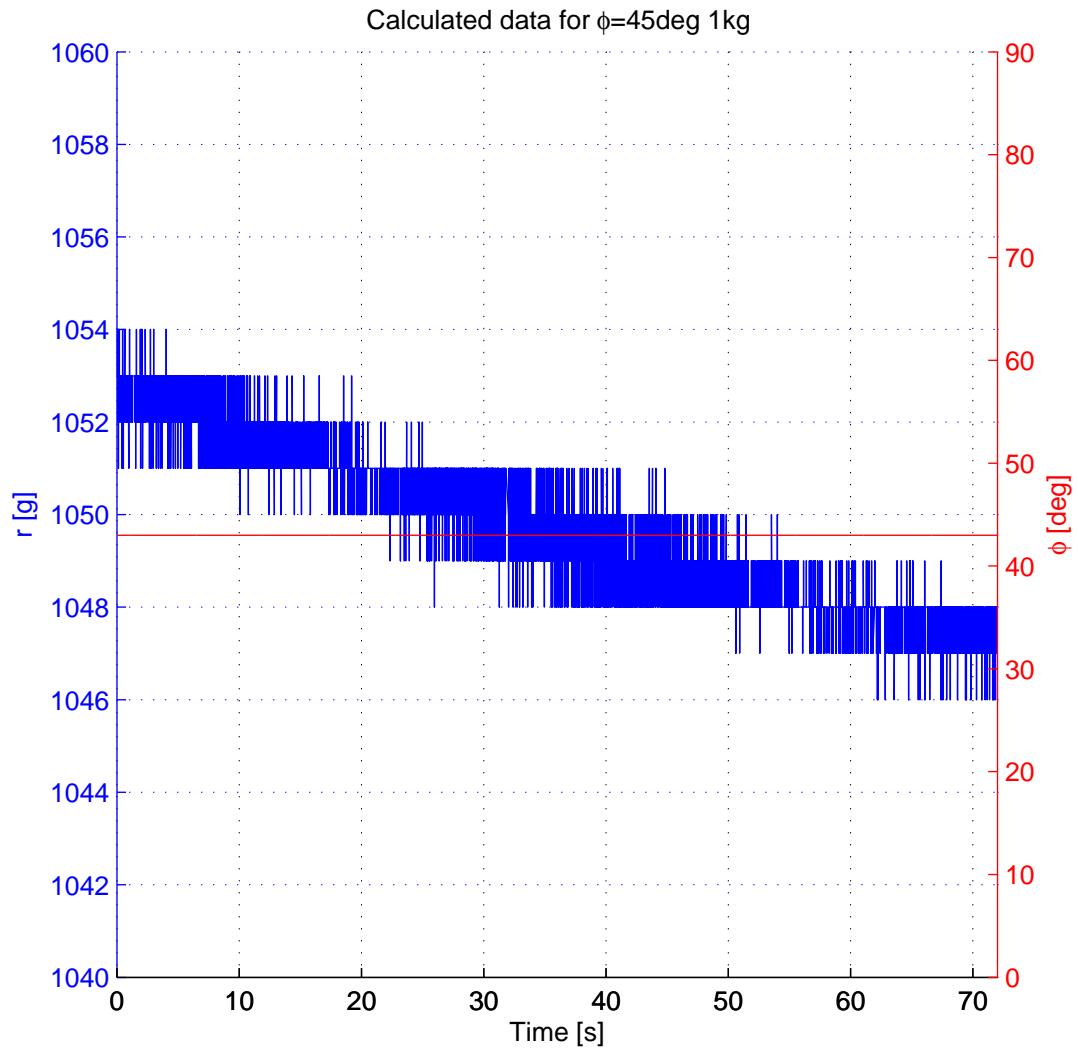


Figure 3.6: This test combines both x and y direction, therefore the force is calculated into the variable r , equivalent to T_0 from the analysis chapter. Notating at around 1kg of load the data drift slightly towards 0.

On figure 3.6 it is seen that the data slightly decreases overtime. This is probably due to tolerances in the manufacturing process enabling the loadcell to move slightly over time or it can be caused by the spring load is permanently bending. Taking a closer look at the data on figure 3.7 showing this phenomena applies to both x and y loadcell. Because it applies to both loadcells the calculated angle ϕ is constant, thus the drift the data is still valid and results in an accurate angle.

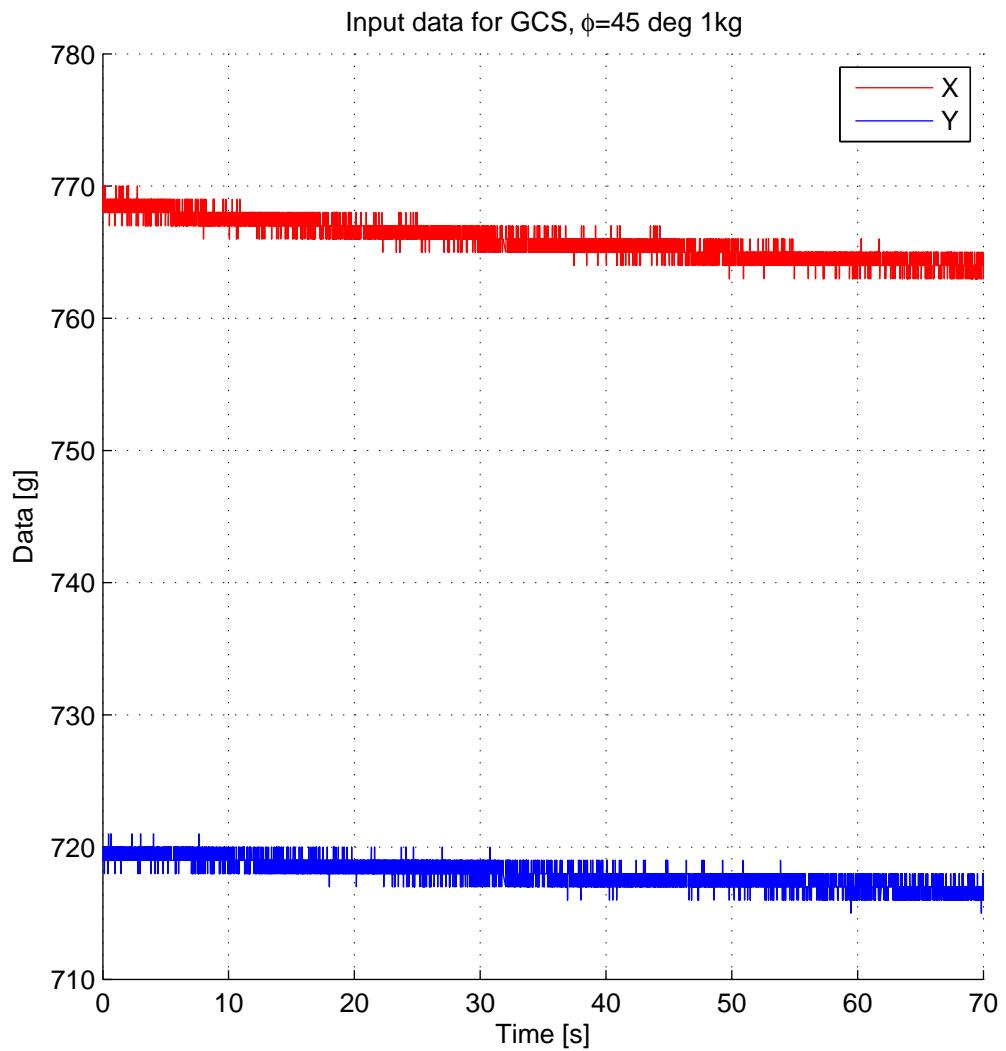


Figure 3.7: Showing the calibrated data from x and y loadcell then 1kg of load is applied with $\phi = 45$ degrees.

Second test was done keeping the ϕ angle and the tension constant and varying the θ angle. It is expected as θ approach 90 degrees the measured force will be approaching 0.

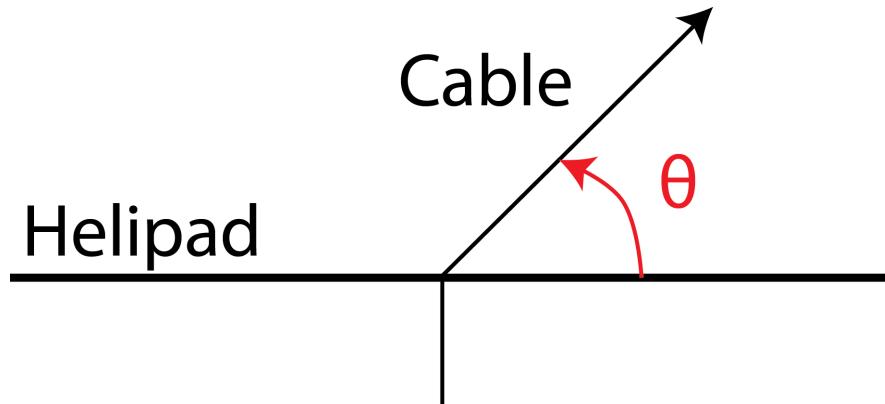


Figure 3.8: Testing the horizontal measuring device by keeping ϕ constant and varying θ .

At $\theta = 45$ degrees and 1kg of load the measured result is very close to the expected result.

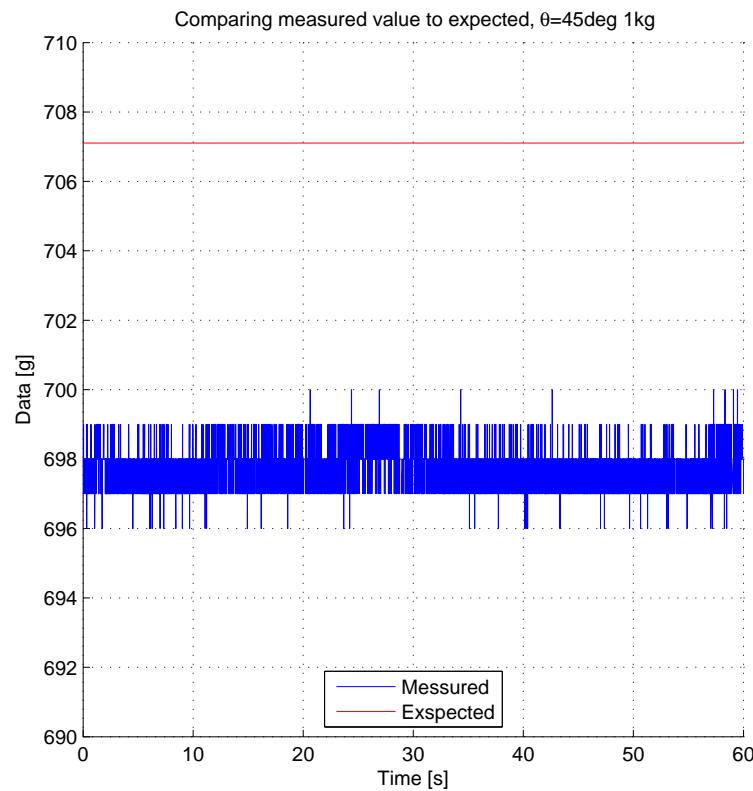


Figure 3.9: Comparing the measured load to the theoretical value. Showing slightly less than expected.

At all previous tests the load has only been anchored in the Teflon ring, but in the real setup the cable are anchored in the winch instead. This mean the measured force is now

only a component of the total force. From figure 2.5 T_0 only has an x-component, but when the cable now is anchored in the winch the total force equation change to

$$\sum T - \lambda gs + (T_{0,x} + T_{winch,y}) = 0 \quad (3.1)$$

Hence the measurement device only measures $T_{0,x}$, $T_{winch,y}$ is unknown. This test will show how much $T_{winch,y}$ influences. On figure 3.9 the measured values are slightly higher than expected. At $\theta = 0$ the overshoot is 13 – 17g and at $\theta = 45$ the overshoot is 28 – 32g, which is within what's in the first test was discussed as due to limitation in precision.

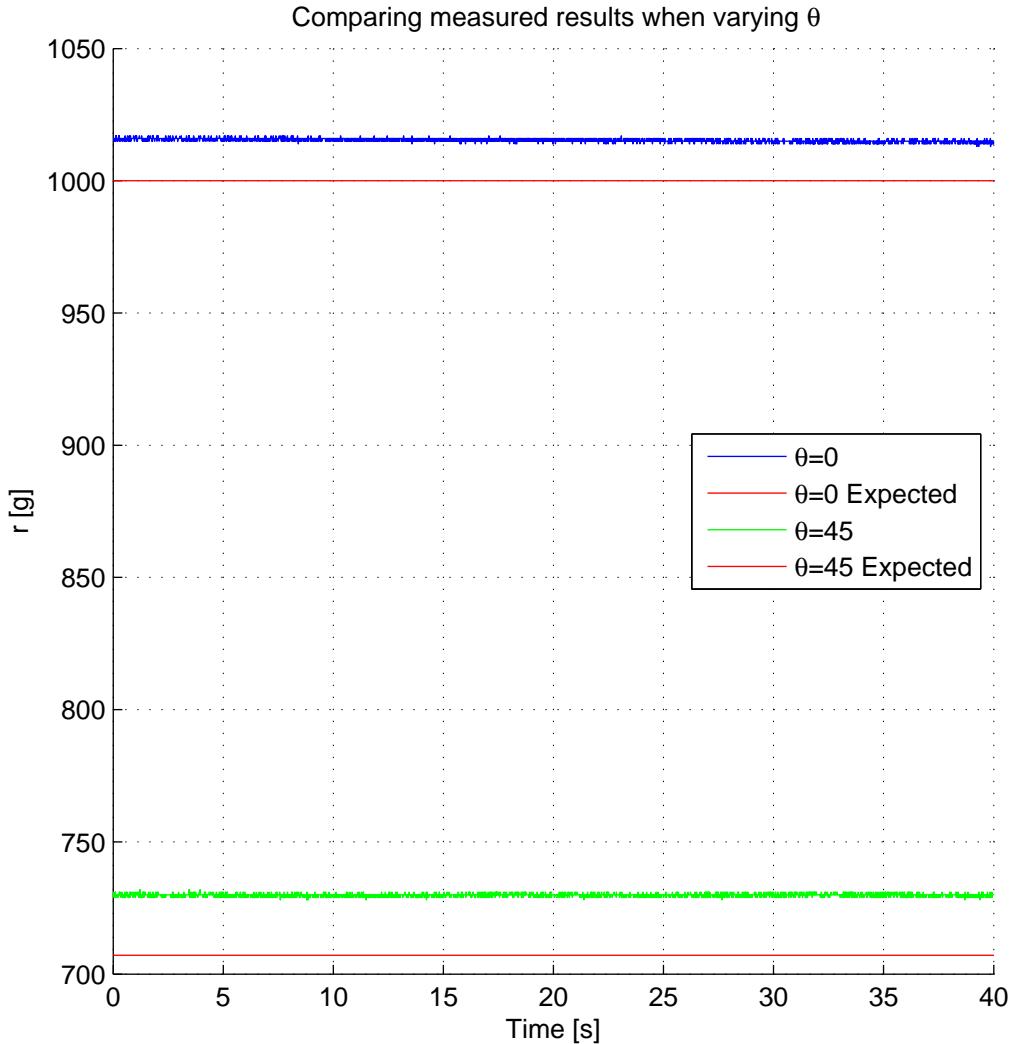


Figure 3.10: Comparing measured results to the theoretically expected when varying θ and 1kg load. The results is a little higher than expected, but comparing to figure 3.9 this result is unexpected.

Summary

The prototype is able to measure the force in x- and y-direction, ϕ and r can be calculated with good results. Higher precision might be possible with more precise testing equipment. The 5kg loadcell has a zero balance at $\pm 75g$. Any values close to this range must be considered as very unreliable. The force in $T_{winch,y}$ is quite small and can therefore be ignored.

3.3 Winching and storing the cable

There are several ways to keep the cable when it's not rolled out, 2 commonly used methods are on a cable drum or in a winded pile. The critical parameters here is the flexibility of the cable, diameter of the cable and heat tolerances. Because the cable is stored tightly together, heating from the cable resistance has to be given a thought in the cable storing design.

Storing cable on a drum

Storing cable on a drum is a very practical and commonly known method to store cables in a organised way. The benefits of this design is that the drum it self can be used as a winch to winch in the cable. But the minimum diameter of the drum is given by the cable minimum bending radius for flexible installation and that sets a physical minimum for the drums outer diameter. The larger the diameter the greater the force needed for rotating the drum. To assure smooth windings the drum can move from side to side. Due to physics the movement from side to side will come natural, if the friction is low enough; in practise this concept works often but is not robust and that is why motorized guidance is needed. In theory the rotation of the drum can be used as a feedback for how much cable is rolled out, but in practice this will be a source to a large margin of error. Further more this design is very dependent on the cable all ways has tension. If there is no or too little tension on the cable it will loosen from the drum.

On figure 3.11 a cable drum is put under the helipad and the horizontal measurement device.

3.3 (5)
ance

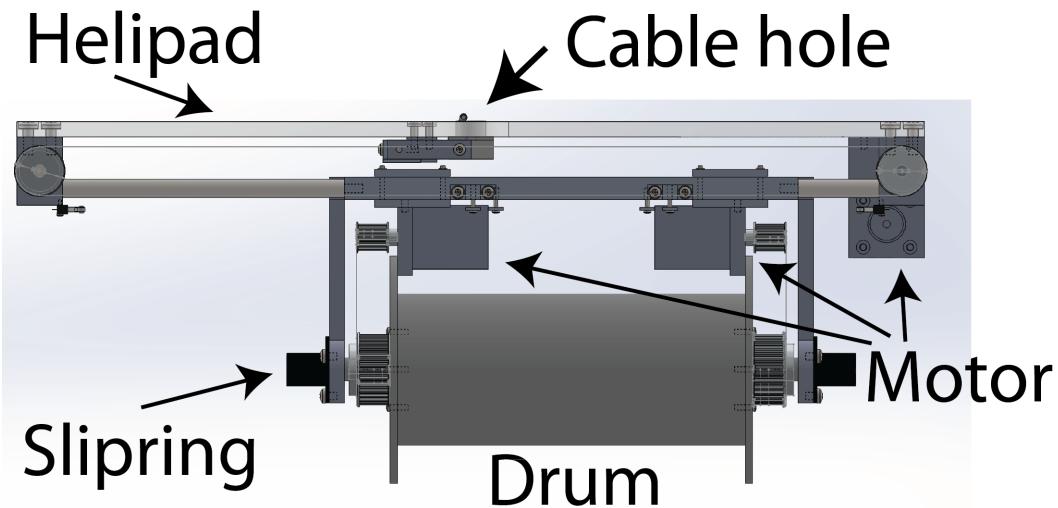


Figure 3.11: Cable drum design. The drum can rotate to winch in/out the cable, and also move from side-to-side to assure smooth windings.

With all wire wounded in and the UAV on maximum throttle there is assumed to be 500W running through the cable with a electrical loss of around 120 Watt, which is transformed into heat. 120 Watt of heat will give rise to heating up the cable drum. This is a known cause of electrical fire, when a cable drum gets too hot and melts. Therefore a series of pretests where performed to address how big a problem this would bee and too incorporate the result in the design of the system.

The worst-case test with full load over long time was performed at indoor environment with room temperature on 24 degree Celsius. The coil was excited with 75V DC and 30A just over an hour. The inner diameter of the coil is 10cm and is made of 2mm thick PVC pipe.

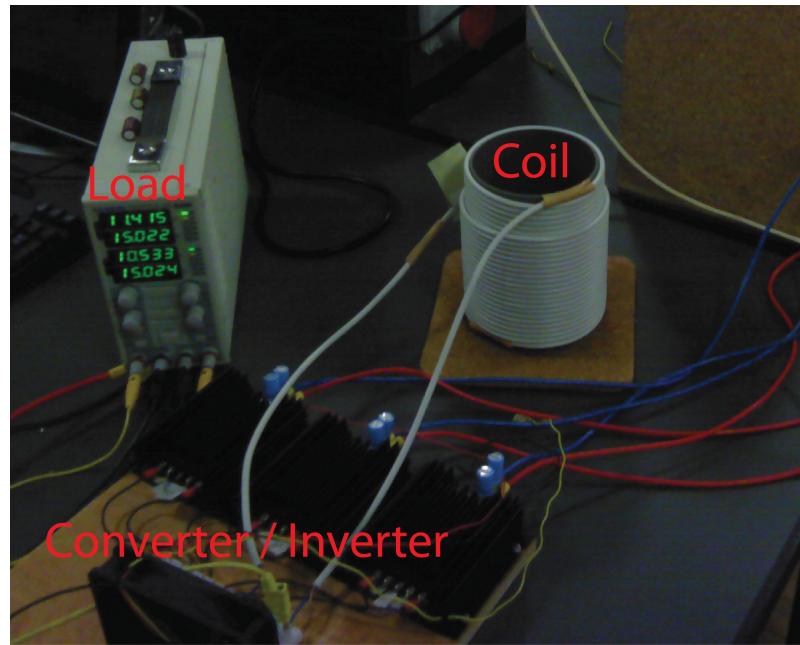


Figure 3.12: Heat test setup showing the coil, the test load and power Converters.

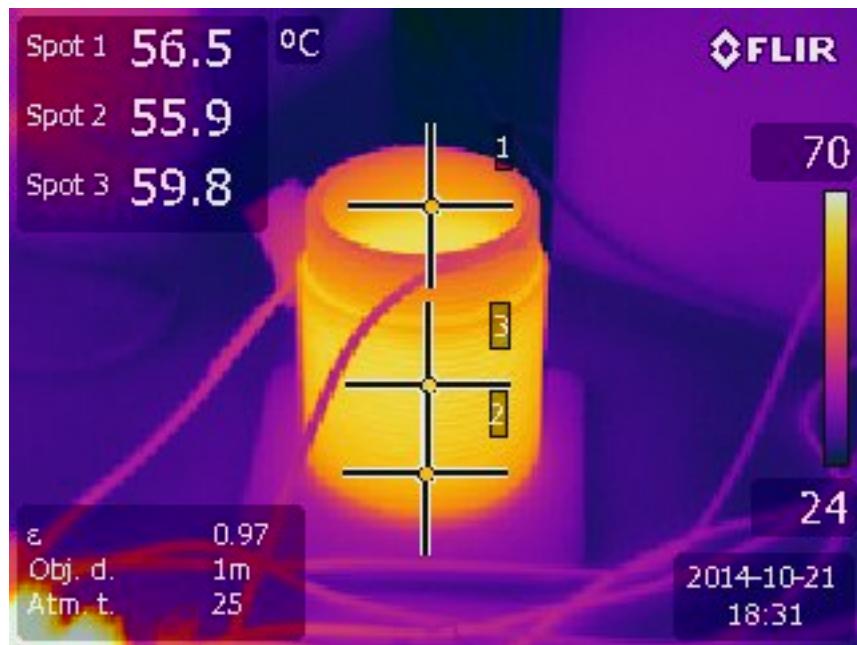


Figure 3.13: Heat test of 20m standard household cable¹winded in 2 layers with 75V DC and 30A. Spot 1 is inside the coil, spot 2 is the lower side of the outer coil and spot 3 i at center of the outer coil. On the lower left corner thermometer calibration constants is displayed.

¹House hold cable with unknown origin, cross-sectional area 0.75mm², Max voltage 230 AC, Max current 10A

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The Simple Winch

Sometimes simple is better. The simple design has a motorized toothed wheel and an encoder wheel pushing the cable against the motorized wheel. The encoder wheel turns only when the cable is moving, and the slip is minimal making it a very robust feedback for the motor controller. The encoder wheel is pushing the cable toward the motor wheel with a spring, that assures small imperfections in the cable does not make it slip. two simple screws adjust the spring tension. For storing the cable a box underneath collects the cable.

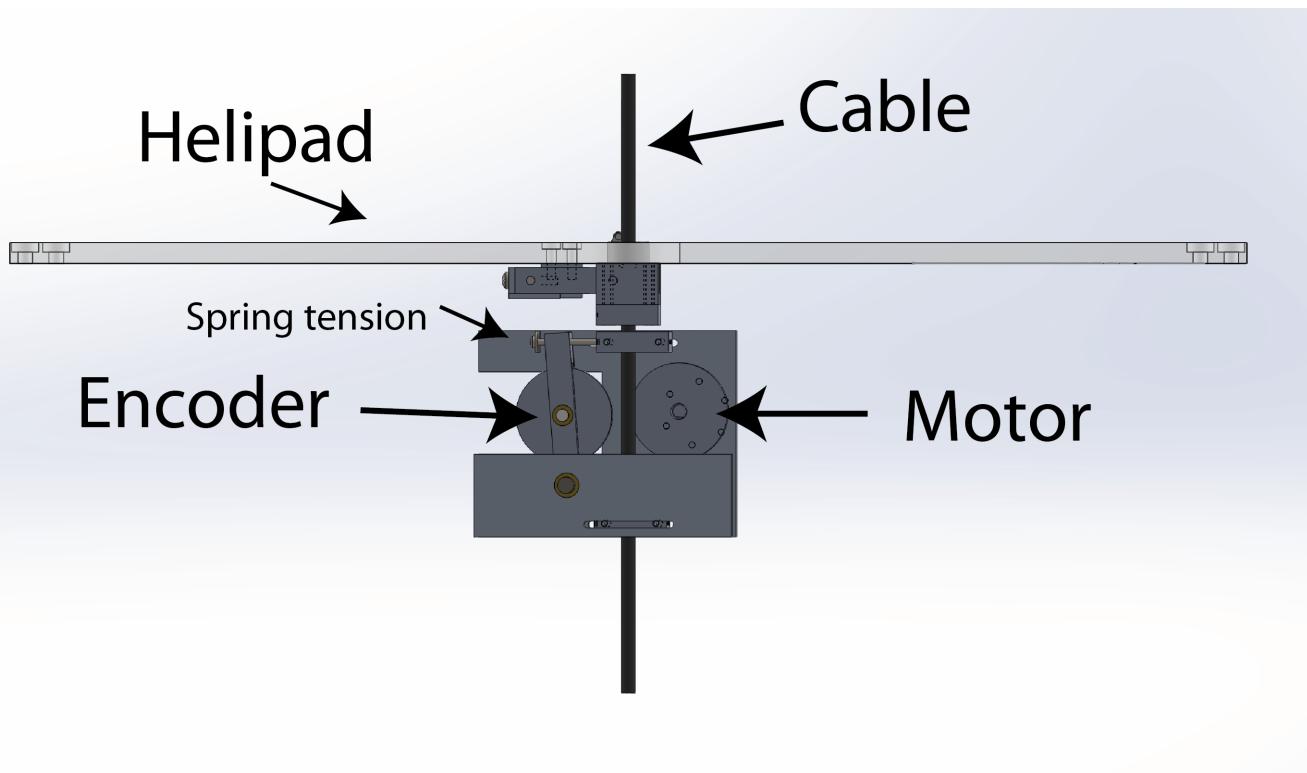


Figure 3.14: The Simple Winch only has one motor and an encoder wheel pushing the cable towards the motor wheel. Two springs adjust the tension.

Summary

Both concepts are mature enough to be prototyped and tested, but due to the time frame of this work there is only time for manufacturing and testing one design. Based on the lower mechanical complexity of the simple winch, the simple winch is the chosen design.

3.4 Cable Connection point on the UAV

Connecting the cable to the UAV have several issues to address. First a 3-axis measurement device is needed to measure how much the cable tension is and in tree directions - x, y, and z directions. The loadcells used is of same type as in measuring the horizontal angle in section 3.2 on page 14. In z-direction the maximal force applied to the loadcell is the UAVs lifting capability on approximately 3kg. Hence the choise of loadcell is a 5kg loadcell.

In x- and y-direction the force applied by the cable or the UAV is not expected to exceed 0.5kg, thus two smaller 0.78kg loadcell is used to measure the x- and y-directional force.

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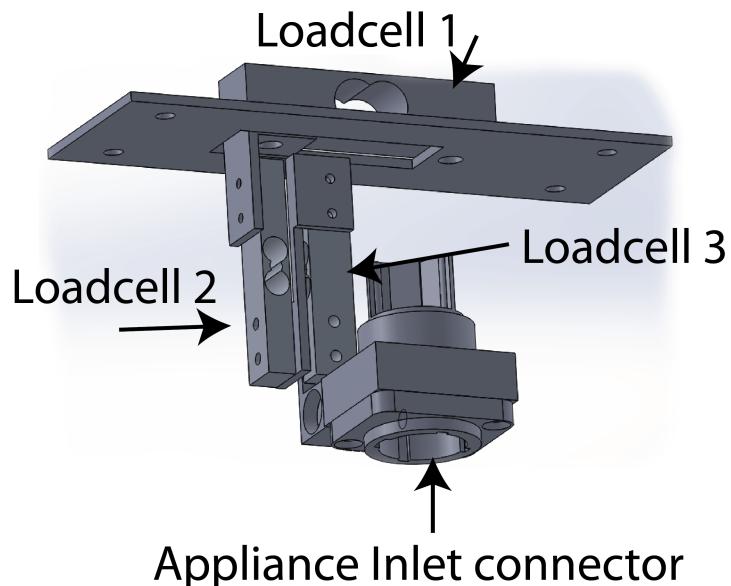


Figure 3.15: 3-axes measuring device for the UAV with appliance inlet connector.

Second an appliance inlet connector for easy plug-in and unplug is wanted. The connector must be capable to withstand the weight of the cable and the force applied of the UAV.

3.5 Electrical Design

From an electrical view there are 2 separate systems, Flight Control System on the UAV and Ground Control Station. The system reading the sensor data on the Ground Control Station has to feed the UAV with the measured data hence the UAV's position controller is running on the UAV.



Figure 3.16: Neutrix True One appliance connector system.

Ground Station

The ground station sends data to the UAV system and decides whether to roll cable in or out based on the wanted position. The control of feeding the cable is done by comparing the load on the UAV system to what is expected by the weight of the rolled out amount of cable. If the load is higher than expected more cable are rolled out and vice versa.

UAV System

The system on the UAV measures a 3-axis loadcell connected to a Phidget Bridge. The Phidget Bridge are interfaced via a Beaglebone Black.

Data Connection using Ethernet over Power line

To connect the UAV to the Ground Station an Ethernet over power line system is used. Ethernet over power line operate by adding a modulated carrier to the wiring system, intended to work on 110-230 volt AC with frequencies in 50-60 Hertz. The AV500 Nano² system from TP-Link supports speeds up to 500Mbps and works without any configuration needed. Stripping the housing from the electronic and soldering 2 wires on to parallel connect the component to the 75 volt system.

²Model number: TL-PA411KIT.

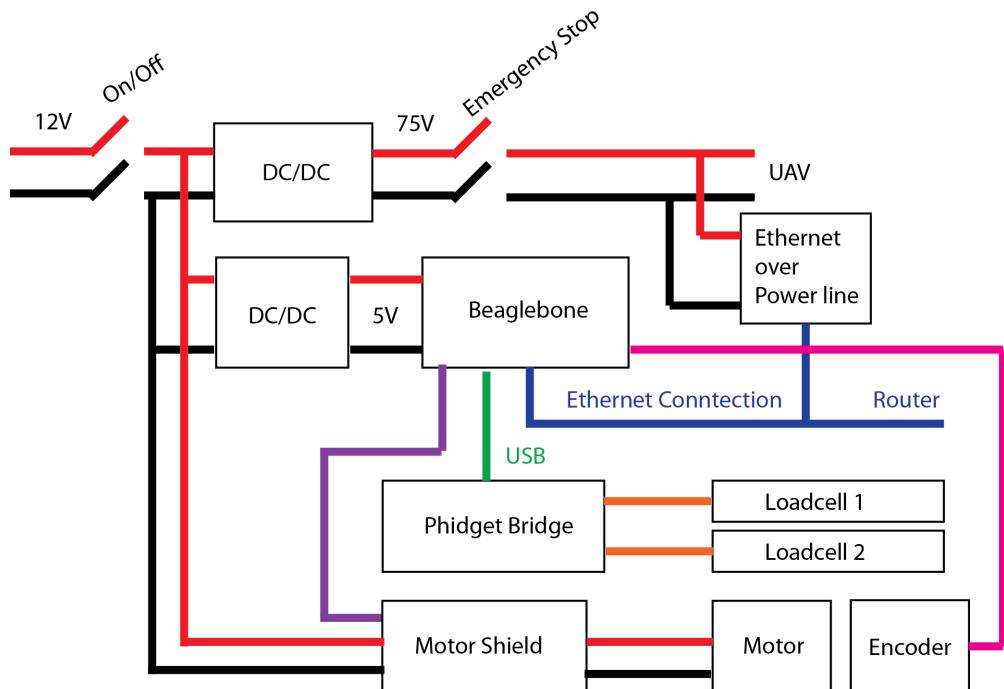


Figure 3.17: Ground Station electrical overview.

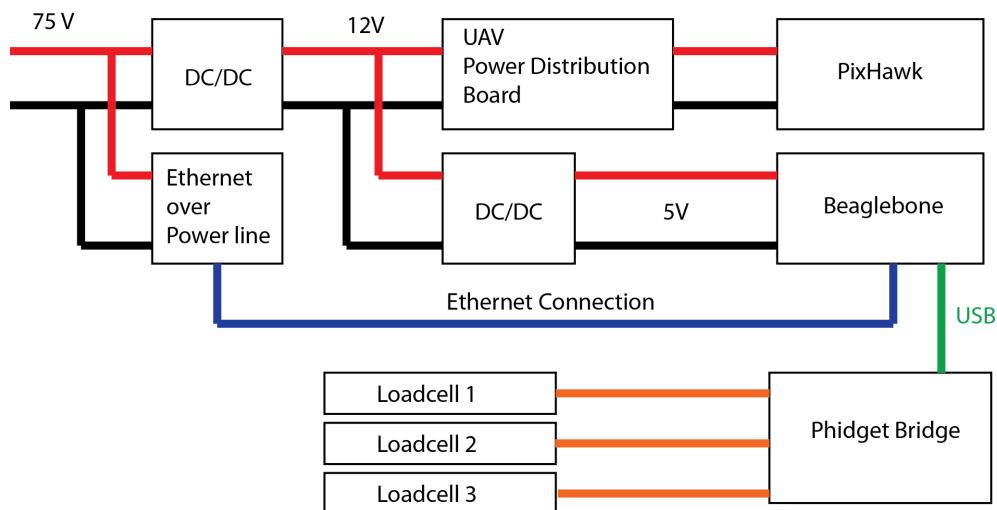


Figure 3.18: UAV electrical overview.

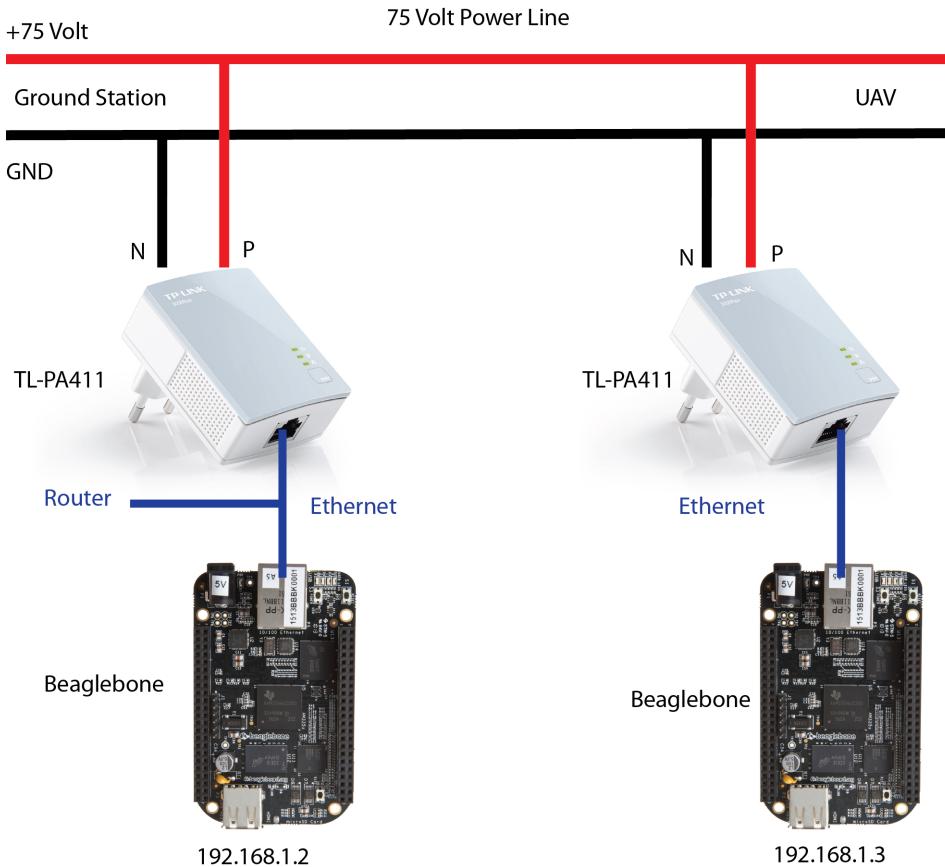


Figure 3.19: Ethernet over power line setup. Two TL-PA411 is connected to the 75 volt powerline creating an Ethernet over power line connection to the UAV.

3.6 Software Design

All software for measuring and controlling is implemented in the real-time software framework Robot Hardware Daemon, RHD. RHD is the real-time hardware abstraction layer for the Mobotware platform, developed at DTU. RHD is a plugin-based platform that allows easy integration with sensors and actuators. RHD creates a synchronized database with read/write variables that can be shared between plugins and/or accessed by other software applications.

Ground Control Station

The objective of the Ground Control station software is to measure the horizontal force, fetch steering reference signals from joystick or other controller, control the cable winch, and make the calculated control signals available in the variable database. On figure 3.20 a graphical overview of the plugin structure is shows the periodic run sequence and plugin variable dependency relationship. The speed variables are created in the plugin tcuav, and not the joycontrol hence the joycontrol module estimates the steering method

by variables available. This also mean the initialization of joystick must be performed after initialization of tcuav.

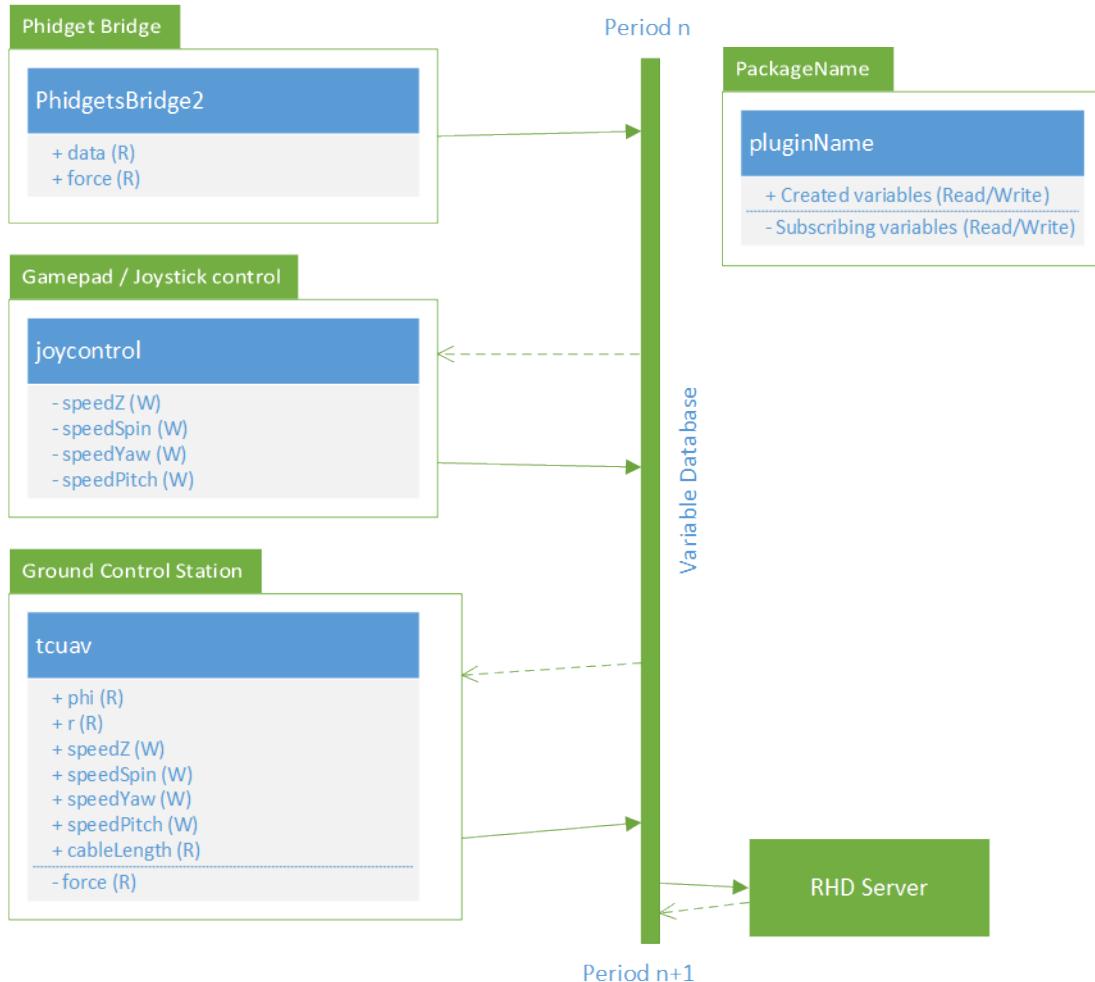


Figure 3.20: Ground Control Station software overview based on the RHD plugin structure showing plugin sequence for one sample period.

Flight Control System

The objective of the Flight Control System is to measure the force from the 3-axes loadcell system, establish a link connection to Ground Control Station and fetch control variables, and make control variables available to the PixHawk(UAV Flight Controller).

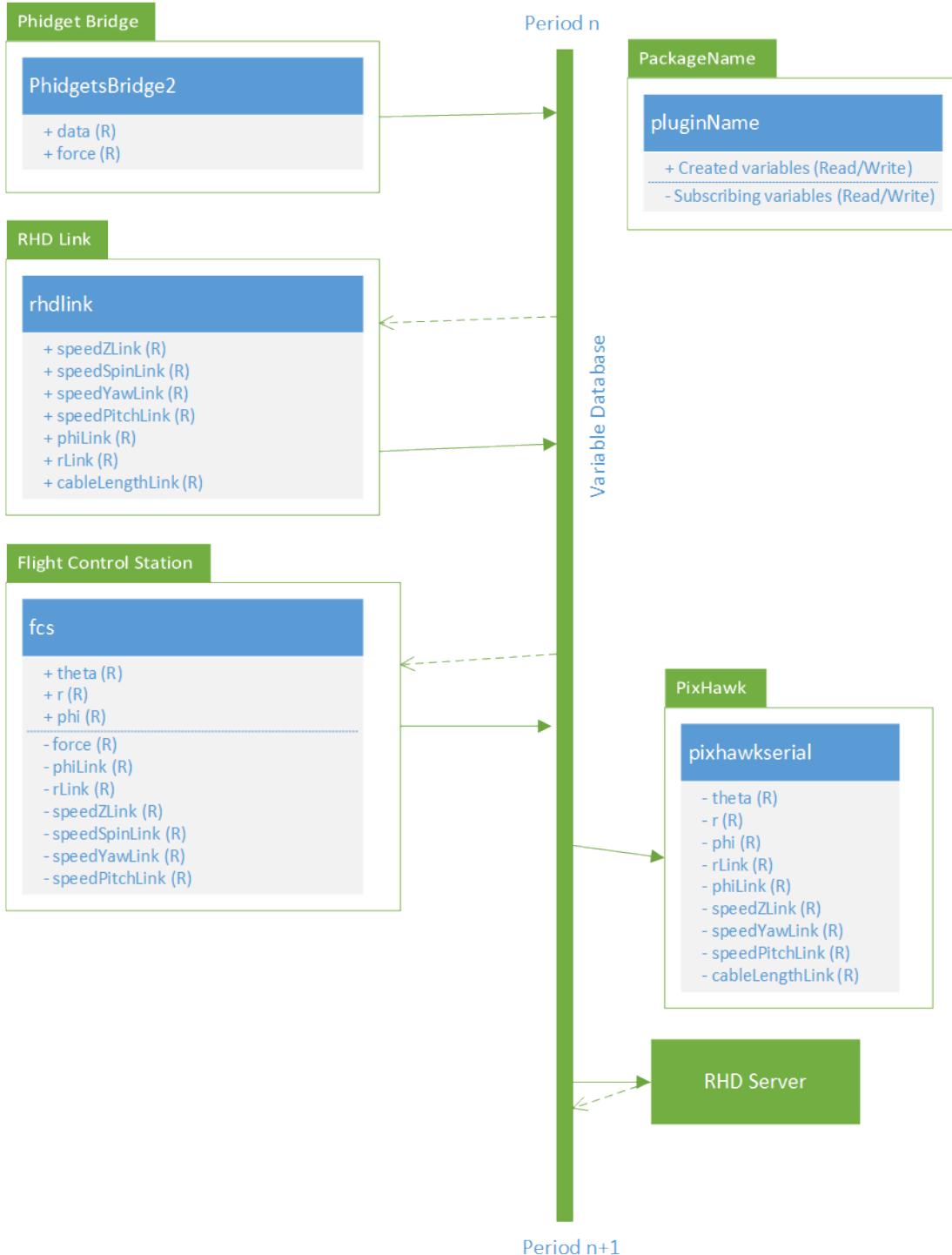


Figure 3.21: Flight Control System software overview based on RHD plugin structure showing plugin sequence for one sample period.

CHAPTER 4

Conclusion

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4.1 Further Work

There is no doubt this work can be improved and develop further.

Rearange loadcells on UAV

The loadcells on the UAV can be rearranged to ensure the center of gravity and the cable connection coming closer to each other, and thus improves the UAV's stability.

Power system

At the moment the power supply system are only able to deliver 400W insted of 500W over only 20m of cable. The limiting factor is in the converters/inverters system developed by another student project. A way of solving this problem is to combine the power supply from the cable with a on board battery. When the UAV not are using all the power it can recharge the battery and when extra power is need is can be delivered in combination with the battery.

RHD Link

Serial connection to PixHawk

APPENDIX A

Symbols and Acronyms

A.1 Acronyms

BBB	Beaglebone Black
CAD	Computer Aided Design
DTU	Danish Technical University
FCS	Flight Control System
GCS	Ground Control Station
RHD	Robot Hardware Daemon
UAV	Unmanned Aerial Vehicle
XML	Extensible Markup Language

A.2 Symbols

Units are as following, unless otherwise stated.

U	Voltage
I	Current
R	Resistance
ρ	Electrical resistivity
A	Surface area
P	Power
W	Watt
F	Force
K	Constant
b	Offset
T	Tension force
λ	Cable Weight per unit length
g	Gravitational constant
ϕ	The angle from x axis in positive rotational direction.

APPENDIX B

Beagle Bone Setup

This project used a BeagleBone Black edition revision C with Debian distribution from 2014-05-14 running.

Setting up is done by cloning the git repository at <https://github.com/savnik/rhd> that contains all code needed¹.

```
1 git clone https://github.com/savnik/rhd
```

Inside the folder rhd/ a setup file found basic containing all setup that is needed. The setup is explained in parts below.

```
1 cd rhd/  
2 ./setup
```

B.1 usblib

For communication with the Phidget bridge the usblib are needed and in this project version 1.0.9 is used. The library can be downloaded from <http://www.libusb.org/>.

B.2 libphidget

The Phidget bridge comes with a library for interfacing the Phidget bridge easy. For this project version 2.1.8.2014 is used. The library can be downloaded from Phidgets website <http://www.phidget.com/>.

It is very important to setup the rules using the 99-phidgets.rules file, otherwise the RHD plugins can't connect.

B.3 Networking

Connecting the Beaglebone to the Ethernet is straight forward using the RJ45 plug, but in this setup the RJ45 plug is already used in connection to the UAV. There fore it is needed to bridge the network connection via USB. Beaglebone natively support

¹In order to bridge the usb network connection see Networking below.

a network connection through USB, but needs some configuration to connect to the internet through the USB cable².

On the Beaglebone run following command:

```
1 /sbin/route add default gw 192.168.7.1
2 echo "nameserver 8.8.8.8" >> /etc/resolv.conf
```

First line tells the Beaglebone to go through 192.168.7.1 when trying to connect to the internet and second line tell the Beaglebone to use google name-server.

On the host computer (Ubuntu):

```
1 sudo iptables -A POSTROUTING -t nat -j MASQUERADE
2 sudo echo 1 | sudo tee /proc/sys/net/ipv4/ip_forward > /dev/null
```

B.4 GPIO

Setting up the GPIO is done through the device tree source file. This file shows an example on 4 GPIO pins that is setup to Output or Input, and the internal pullup/pulldown settings.

```
1 /dts-v1/;
2 /plugin/;
3
4 /{
5     compatible = "ti,beaglebone", "ti,beaglebone-black";
6     part-number = "DM-GPIO-Test";
7     version = "00A0";
8
9     fragment@0 {
10         target = <&am33xx_pinmux>;
11
12         __overlay__ {
13             pinctrl_test: DM_GPIO_Test_Pins {
14                 pinctrl-single,pins = <
15
16                     0x070 0x07 /* P9_11 OUTPUT MODE7 - M1EN */
17                     0x078 0x07 /* P9_12 OUTPUT MODE7 - M1NA */
18                     0x031 0x07 /* P9_13 OUTPUT MODE7 - M1NB */
19                     /* No PWM */
20                     0x040 0x27 /* P9_15 INPUT MODE7 - M1CS */
21
22                         /* OUTPUT GPIO(mode7) 0x07 pulldown, 0x17
23                         pullup, 0x?f no pullup/down */
24                 /* INPUT   GPIO(mode7) 0x27 pulldown, 0x37 pullup, 0x?f no
25                 pullup/down */
26             };
27         };
28     };
29 }
```

²<https://github.com/anujdeshpande/BBB-workshop>

```

24      >;
25  };
26  };
27  };
28  };
29
30  fragment@1 {
31  target = <&ocp>;
32  __overlay__ {
33    test_helper: helper {
34      compatible = "bone-pinmux-helper";
35      pinctrl-names = "default";
36      pinctrl-0 = <&pinctrl_test>;
37      status = "okay";
38    };
39  };
40  };
41 };

```

Compiling a Device Tree Source file (.dts files) can be done like this:

```
1 dtc -O dtb -o DM-GPIO-Test-00A0.dtbo -b 0 -C DM-GPIO-Test.dts
```

It is a little tricky because ”-O” is for output format, dtb is for Blob format, ”-o” is output file DM-GPIO-Test-VERSION.dtbo, ”-b” physical boot cpu 0 and the input file DM-GPIO-Test.dts³.

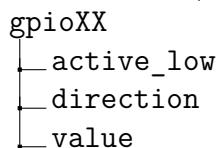
The device tree blob object can be loaded on boot or by

```
1 echo DM-GPIO-Test > /sys/devices/bone_capemgr.9/slots
```

A list over active device tree blob object is obtained by

```
1 cat /sys/devices/bone_capemgr.9/slots
```

Writing, reading and some level of configuration is done by normal unix input/output method, writing/reading to/from a virtual file located at /sys/devices/gpio/.



³<http://web.mit.edu/freebsd/head/contrib/dtc/Documentation/manual.txt>

B.5 PWM

Using the PWM output from the Beaglebone is not "out-of-the-box". In order to enable the PWM module a Device Tree Blob Object (.dtbo file) needs to be loaded in the cape slots. Beaglebone comes with a default Device Tree Blob Object file that supports the PWM module. The Device Tree Blob Object files can be found in /lib/firmware/. For this project the default Device Tree Blob Object file for pin 14 was used⁴.

Accessing the PWM module is like normal unix input/output method, writing to a virtual file. The PWM modules virtual files is at /sys/devices/ocp.3/

```
pwm_p9_14
├── duty
├── period
├── polarity
└── run
```

B.6 SPI

To enable the SPI interface on the beaglebone follow instructions from http://elinux.org/BeagleBone_Black_Enable_SPIDEV. Using the SPI interface can only be done by disabling the HDMI interface because they use the same pins. Because of the long cable connection (over about 10cm) the communication speed needs to be slowed down.

B.7 Wire connections

Encoder wiring:

Encoder Cable Pin	AMS AS5045B Pin	Beaglebone Pin
1	16 VDD 5V	5/6 P9
2	7 VSS	1/2 P9
3	12 PWM	
4	11 CSN (Chip Select)	
5	6 Index	
6	10 CLK	31 P9
7		
8	9 DO (data out)	29 P9
9	8 PDIO	
10	1 MagIn	
11	2 MagDec	

⁴/lib/firmware/bone_pwm_P9_14-00A0.dtbo

Motor Driver wiring:

Cable pin	Motor Driver Pin	Beaglebone pin
Blue	Green GND	P8 1 GND
Green	Blue VSS 5V	SYS 5V
Yellow	Yellow Encoder Channel A	P8 7
Orange	Orange Encoder Channel B	P8 8
Red	Red Motor 12V	Motor Driver M1+
Black	Black GND	Motor Driver M1-

B.8 General notes

The Device tree blob object can be loaded at boot in the uEnc file, but it seems to be root of many booting problems loading the Device tree blob object at boot, therefore it is a better solution to run a shell script after bootup that loads the device tree blob objects. This way the Beaglebone is always able to boot, and in case of bad device tree blob object files it does not prevent the system from booting.

The Beaglebone Debian distribution does unfortunately not include a compiled version of xpad. Xpad is the driver for the joystick and is needed for using the gamepad plugin. The raw files for the xpad driver is available several places on the internet and even through available at the Beaglebone Debian Distribution, but is somehow not included in the latest build from 2014-15-14. In order to compile xpad the header files placed in /usr/src is needed but in they does not come with the distribution. So to use xpad a new debian image is needed to be compiled. The distribution image size is 2Gb and the Beaglebone Back memory size is only 4Gb. The distribution image must be compiled on same type of processor in order to work properly or compiled using a cross compiler. Thus the joystick plugin will be disabled by default in the setup, but can be activated in rhdconfig.xml.

The Beaglebone community is rather small compared to the Arduino or Raspberry Pi community, therefore searching for patches or solutions is generally extensive work and requires a high level of unix skills.

APPENDIX C

Robot Hardware Daemon

RHD (Robot Hardware Daemon) is the real-time hardware abstraction layer for the Mobotware platform, developed at DTU. RHD is a plugin-based platform that allows easy integration with sensors and actuators. RHD creates a synchronized database with read/write variables that can be shared between plugins and/or accessed by other software applications. RHD uses a real-time scheduler to ensure a fixed sample rate. All setup of RHD is done based on a XML configuration file, containing all parameters and plugins specific to the robot. Plugins are intended to be general and works across robots, and all "magic" variables are placed in the configuration file.

This project has been implemented as a configuration in RHD and plugins for hardware has been developed. To run the program type in:

```
1 rhd trunk/plugins/tcuav/rhdconfig.xml
```

This runs the RHD program and loads the configuration for the Ground Control Station.

C.1 Plugins

PhidgetBridge2

PhidgetBridge2 is build on the initial Phidgets Bridge plugin, only made more flexible by allowing the configuration file to contain all of Phidgets Bridge configuration settings. The Phidget Bridge is a 4 channel amplifier, and is intended for measuring small voltages for example in loadcells.

Configuring the bridge is done by first enabling the wanted channels. The default amplifier gain is 128V/V. The minimum sample time is 10 milliseconds. Calibration constant offset and gain is found by $F_{Expected} = K * (Measured - Offset)$.

```
1 <!-- Phidget Bridge -->
2   <phidgetsbridge2
3     enable = "true"
4     lib="phidgetsbridge2.so.1"
5     debug = "1"
6     interval = "0"
7     updateTimeMs = "10"
8     gain = "128 128 128 0"
9     enableCh = "1 1 1 0"
10    offset = "-290 6050 -90 0"
```

```

11      k = "876 870 360 1"
12      >
13  </phidgetsbridge2>
14
15  <!-- Flight Control System - Tether Control of UAV -->
16  <fcs
17    enable= "true"
18    lib="fcs.so.1"
19    debug = "true"
20    >
21 </fcs>
```

This plugin depends on Phidgets Linux Library. Special installation notes are found in the readme file.

Files:

```

plugins
└── phidgetsbridge2
    ├── 99-phidgets.rules
    ├── Makefile
    ├── README
    ├── libphidget_2.1.8.20140319.tar.gz
    ├── phidgetsbridge2.c
    ├── phidgetsbridge2.h
    └── rhdconfig.xml
```

TCUAV

C.1 (9) Skriv TCUAV or Tether Control of UAV is the Ground Station.

FCS

FCS or Flight Control System is a part of the Tether Control of UAV project. This plugin establish contact to Ground Station via a Socket connection, and exchange information(references) from the ground stations measurements and control parameters, and then sends control parameters in to a PixHawk. It also reads 3 loadcell from a Phidget Bridge to determine the yaw and the force from the cable in x,y and z direction.

It is intended the PixHawk runs it's own position estimator in hard real time, and the control parameters from this plugin in soft real time, because of the variable delay in the feedback from the Ground Station.

Setting up this plugin requires the PhidgetBridge2 to be configured first.

```

1 <!-- Phidget Bridge -->
2   <phidgetsbridge2
3     enable = "true"
4     lib="phidgetsbridge2.so.1"
5     debug = "1"
6     interval = "0"
7     updateTimeMs = "10"
8     gain = "128 128 128 0"
9     enableCh = "1 1 1 0"
10    offset = "-290 6050 -90 0"
11    k = "876 870 360 1"
12  >
13 </phidgetsbridge2>
14
15 <!-- Flight Control System - Tether Control of UAV -->
16 <fcs
17   enable= "true"
18   lib="fcs.so.1"
19   debug = "true"
20 >
21 </fcs>
```

This plugin depends on the phidgetsbridge2 plugin.

Files:

```

plugins
└── fcs
    ├── Makefile
    ├── fcs.c
    └── fcs.h
```

RHDLink

This plugin creates a socket connection to another RHD server(Server) and makes a copy of the variable database on the local machine(Client). The client with this plugin installed can access read and write variables on the other RHD server it is connected to, but the server can not read or write in the clients variable database. The Plugin is based on a copy of librhd.c, with a few alternations in the function and variable names to avoid name conflict. Only one RHD link per RHD server can run without conflicts.

The configuration of the plugin is done in the XML file "rhdconfig.xml" and adding following to the plugin configuration. Substitutting host and port to the corresponding RHD server will access another server weather it's on the local machine or on the network. The access rights can be set as read(r) or write(w), if write both read and write are possible.

```
<!-- *** RHD Link - creates a link to another RHD server *** -->
```

```

2 <rhdlink enable="true"
3   lib="rhdlink.so.1"
4     host="192.168.7.2"
5     port="24902"
6     access="w"
7     debug="true">
8 </rhdlink>
```

This plugin requires the RHD component of Mobotware version 3.583.

Files:

```

plugins
└── rhdlink
    ├── Makefile
    ├── librhdlink.c
    ├── librhdlink.h
    ├── rhdconfig.xml
    ├── rhdlink.c
    └── rhdlink.h
```

Joycontrol

This plugin provides remote override control possibilities using a standard HID Joystick. The plugin is developed by Anders Billso Beck and automatic detect the vehicle steering configuration for wheel based robots. For this project the plugin was modified to be able to detect UAV steering parameters. The plugin detect the steering configuration on which unique control variables it can find in the variable database. UAV steering has unique control variables like yaw, pitch, roll and height.

Files:

```

plugins
└── joycontrol
    ├── Makefile
    ├── joycontrol.c
    └── joycontrol.h
```



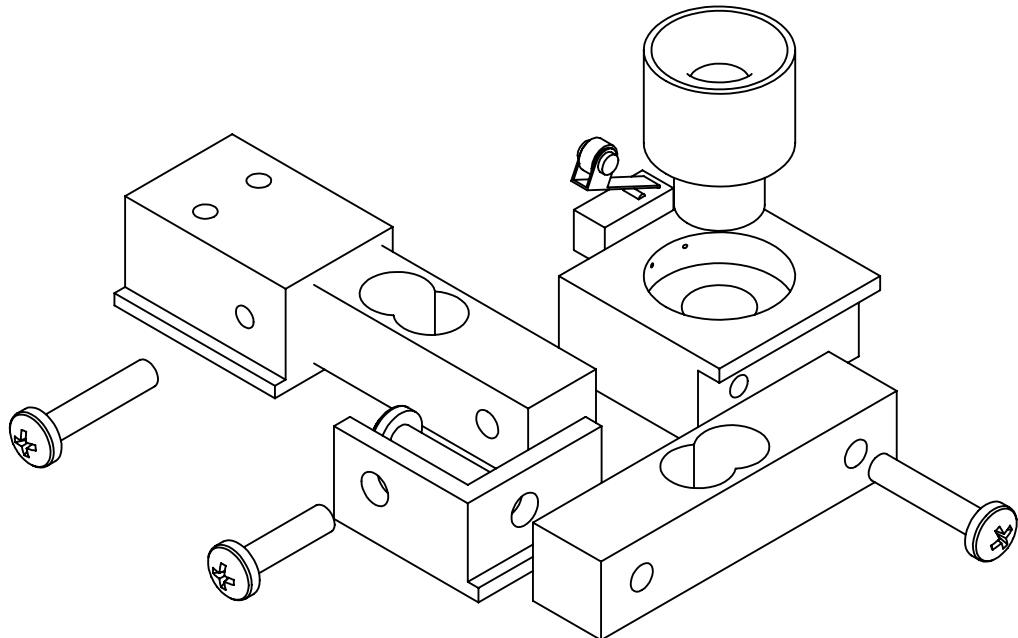
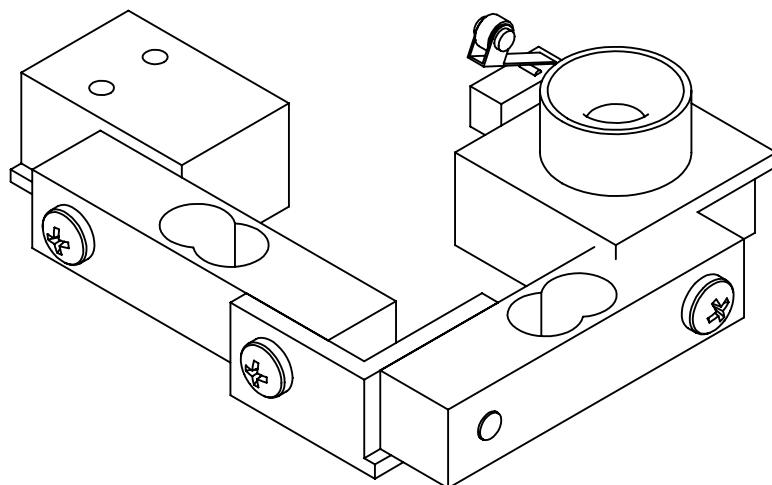
Figure C.1: Implementation of joystick control for UAV control.

APPENDIX D

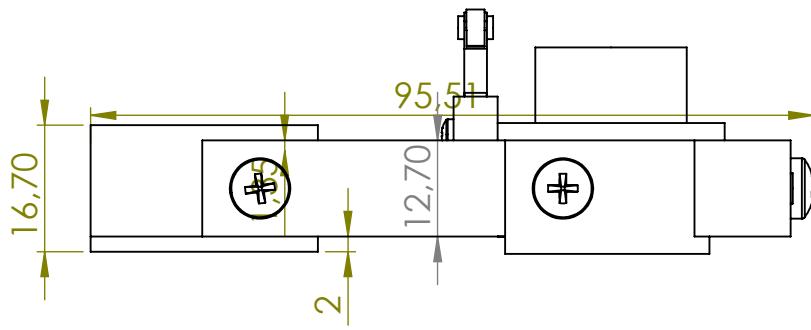
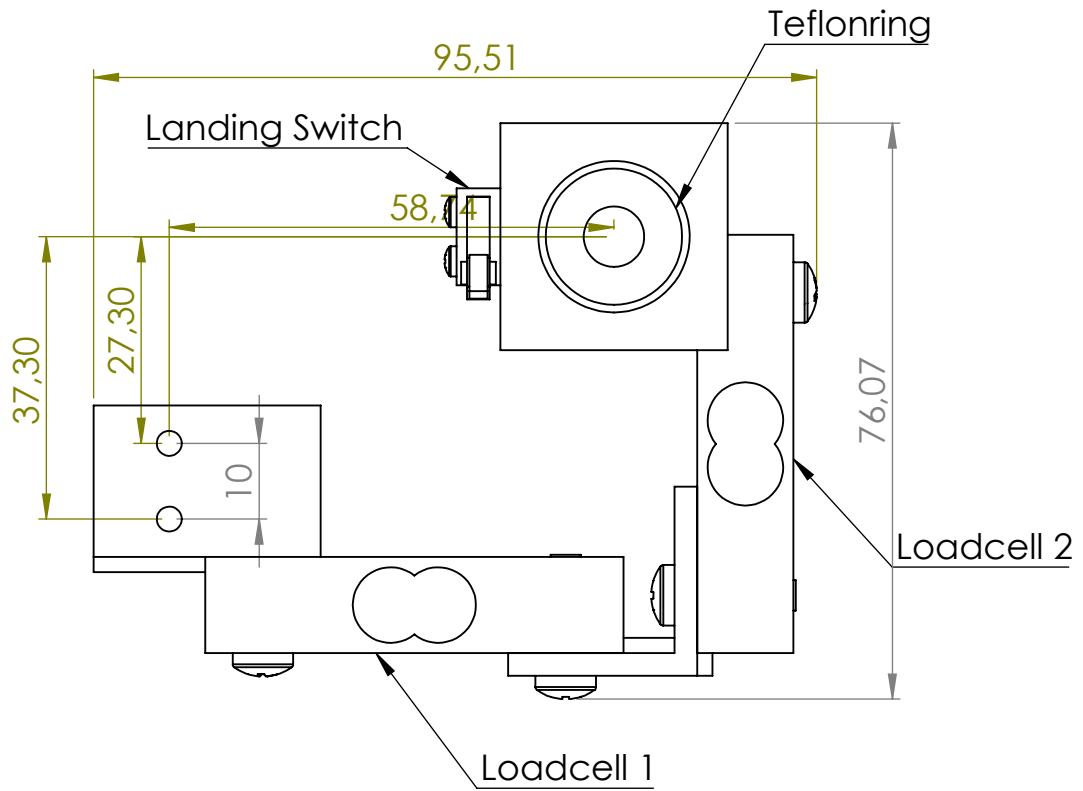
CAD Design

All tolerances are 1/100mm, screws and bolts are in metric units, dimensions are in mm, and the material is aluminium unless other is stated.

Horizontal angle measurement device



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					Peter J. Savnik	
DRAWN	NAME	SIGNATURE	DATE			
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APP'V'D				TCUAV		
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Q.A.				WEIGHT:	SCALE:1:2	
					SHEET 1 OF 3	

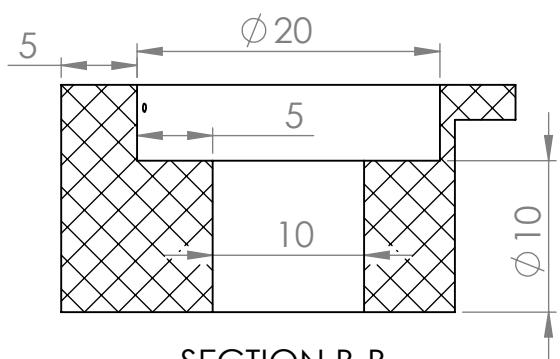
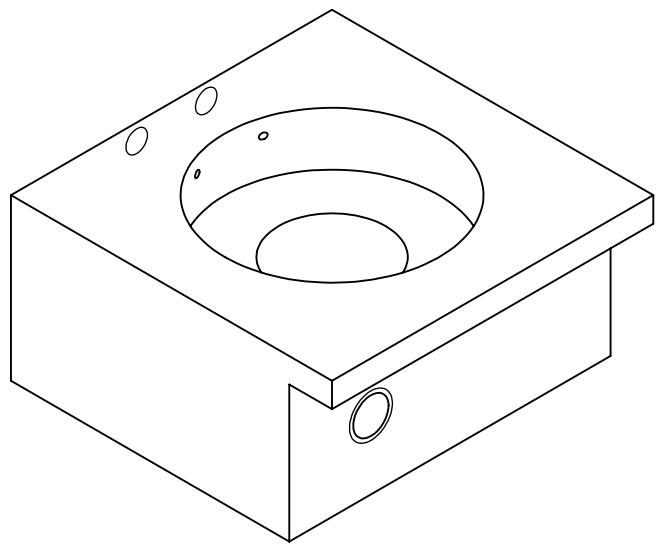
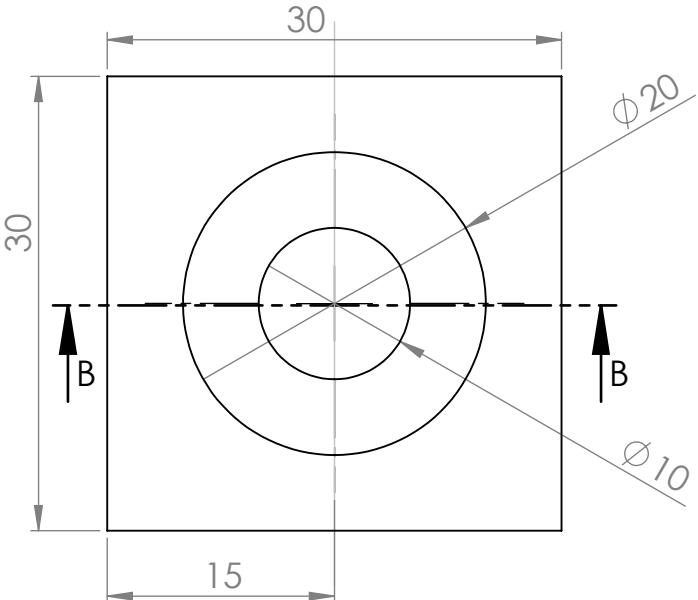


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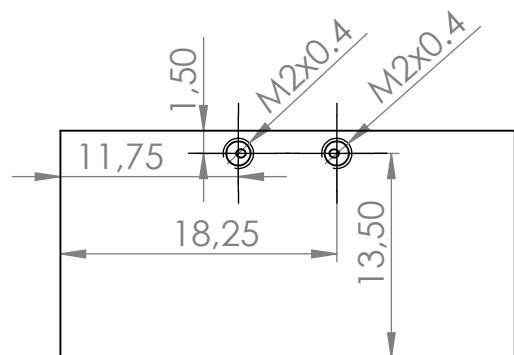
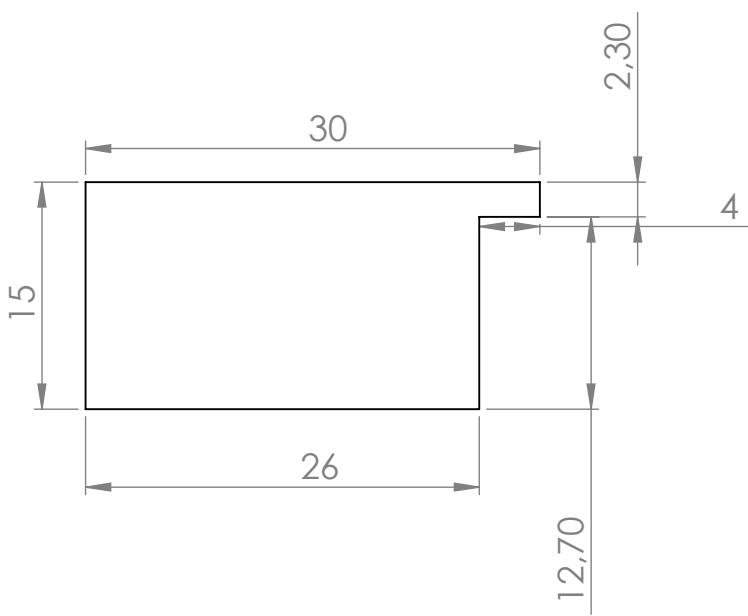
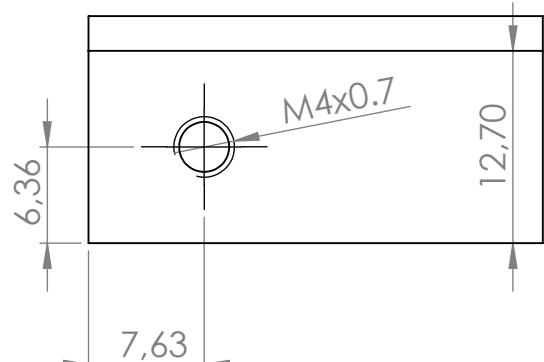
Material List

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2	loadcell-vinkel-fitting		1
3	loadcell-to-toplevel-fitting_V2		1
4	loadcell-5kg		2
5	B18.6.7M - M4 x 0.7 x 20 Type I Cross Recessed PHMS --20N		2
6	B18.6.7M - M4 x 0.7 x 16 Type I Cross Recessed PHMS --16N		2
7	teflon-ring-insert		1
8	switch		1
9	B18.6.7M - M2 x 0.4 x 10 Type I Cross Recessed PHMS --10N		2

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								A4			



SECTION B-B
SCALE 2 : 1



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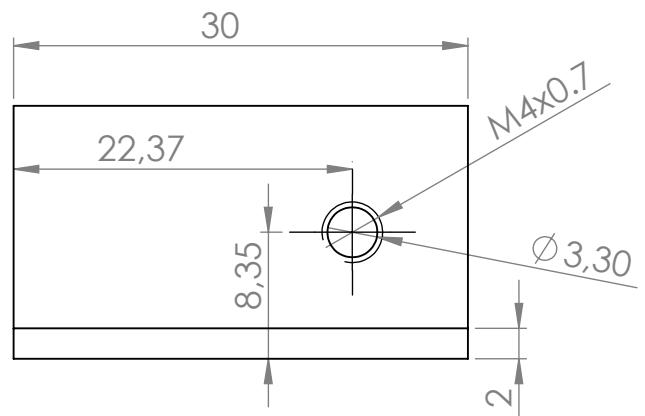
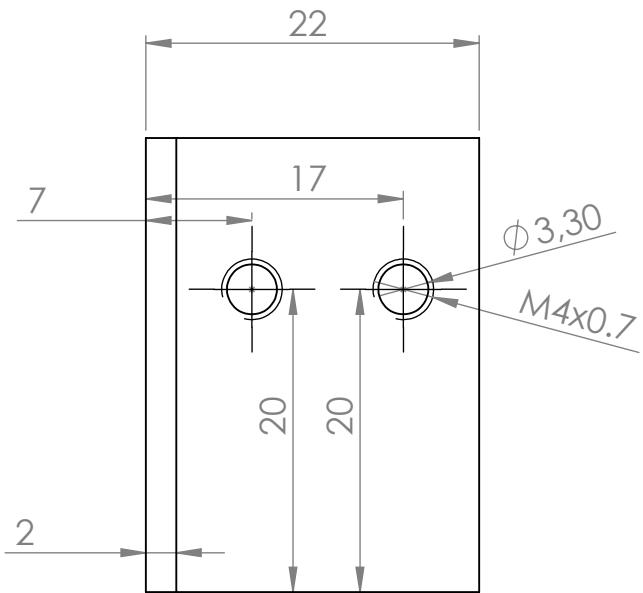
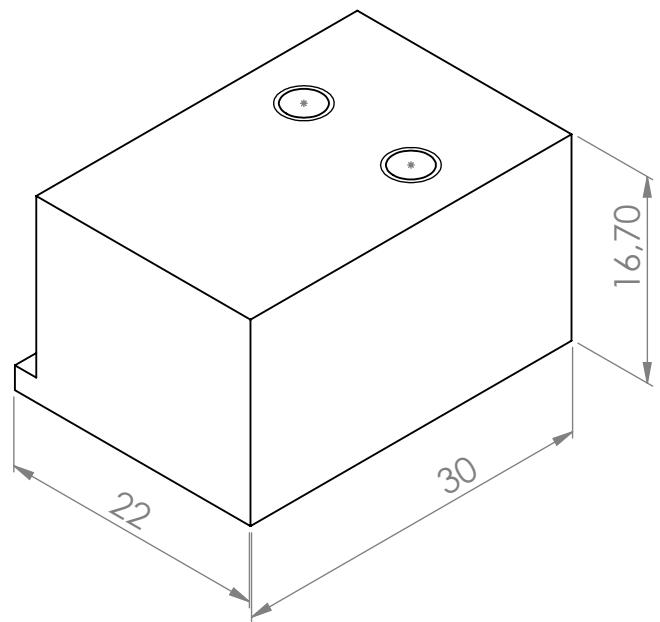
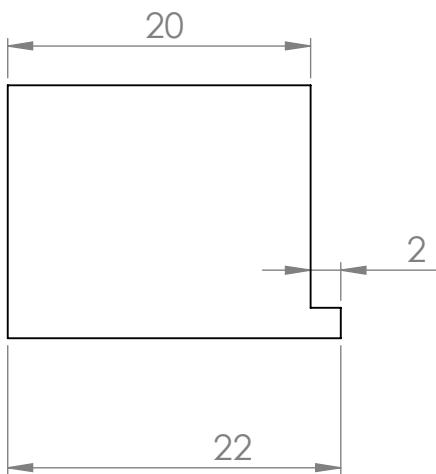
cable_hole

A4

WEIGHT:

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SHEET 1 OF 1



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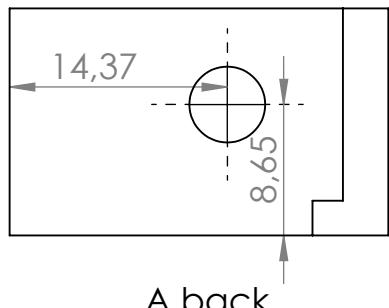
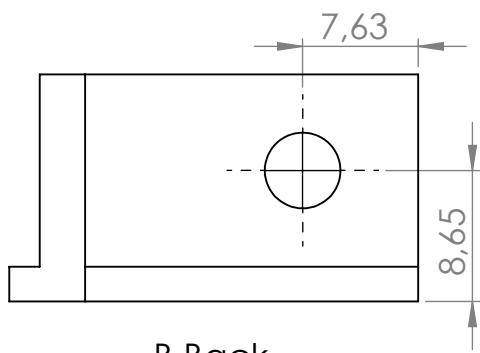
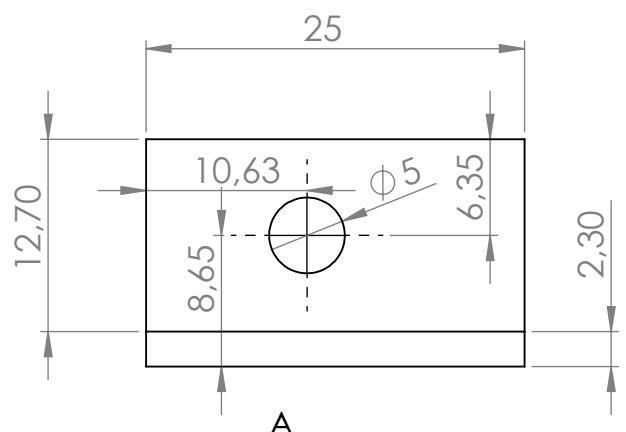
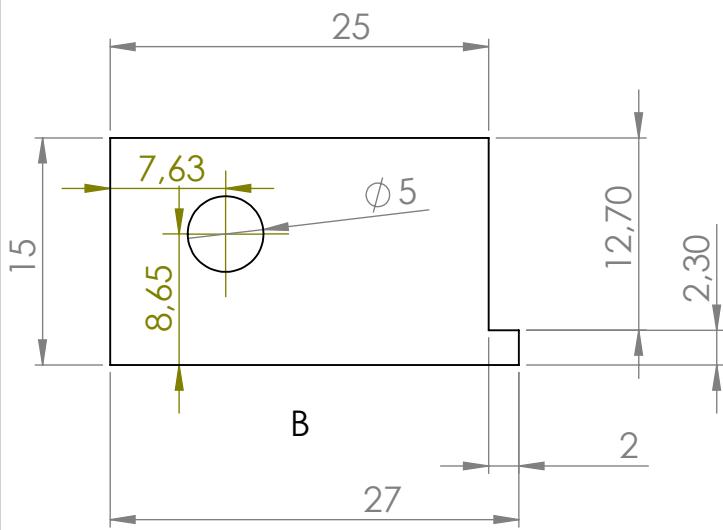
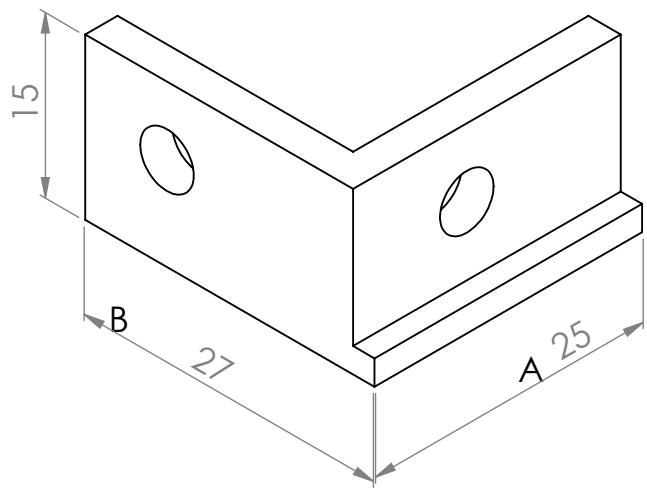
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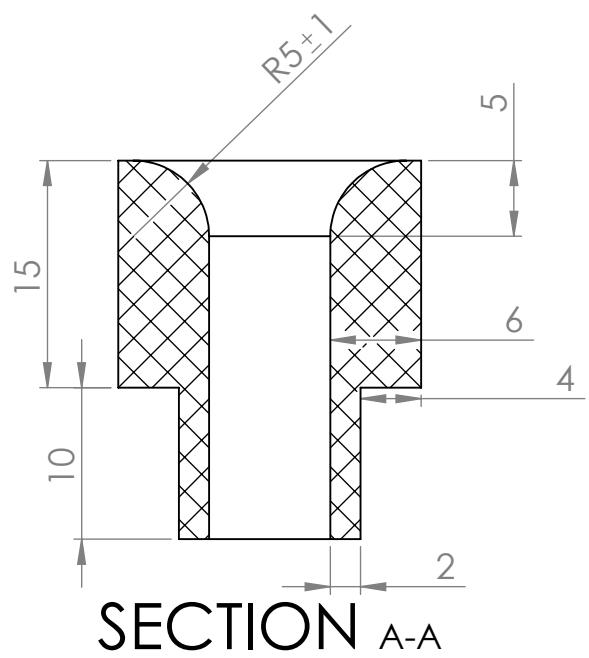
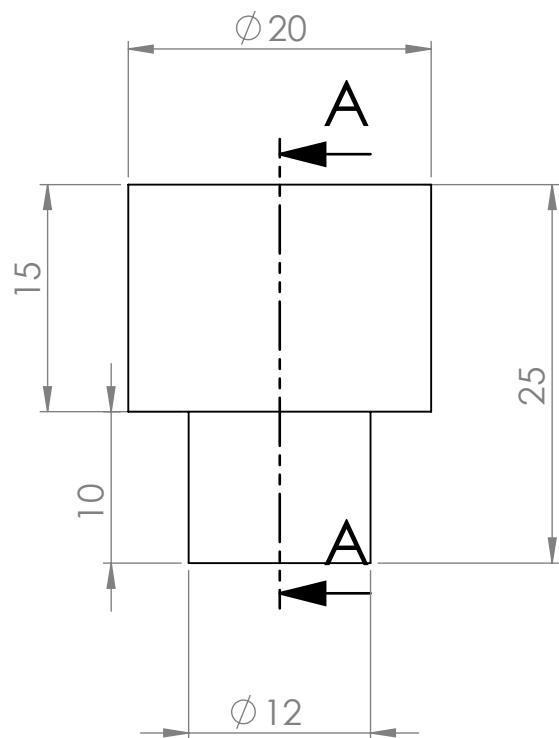
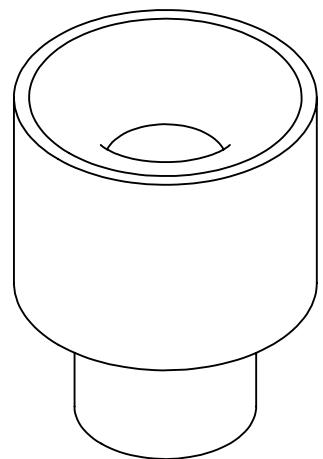
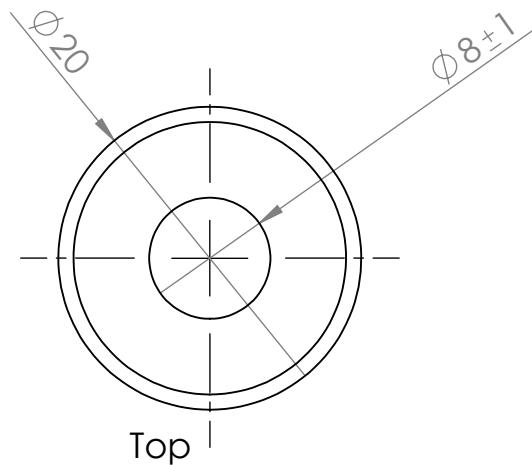
SHEET 1 OF 1

loadcell-to-toplevel-fitting



B Back

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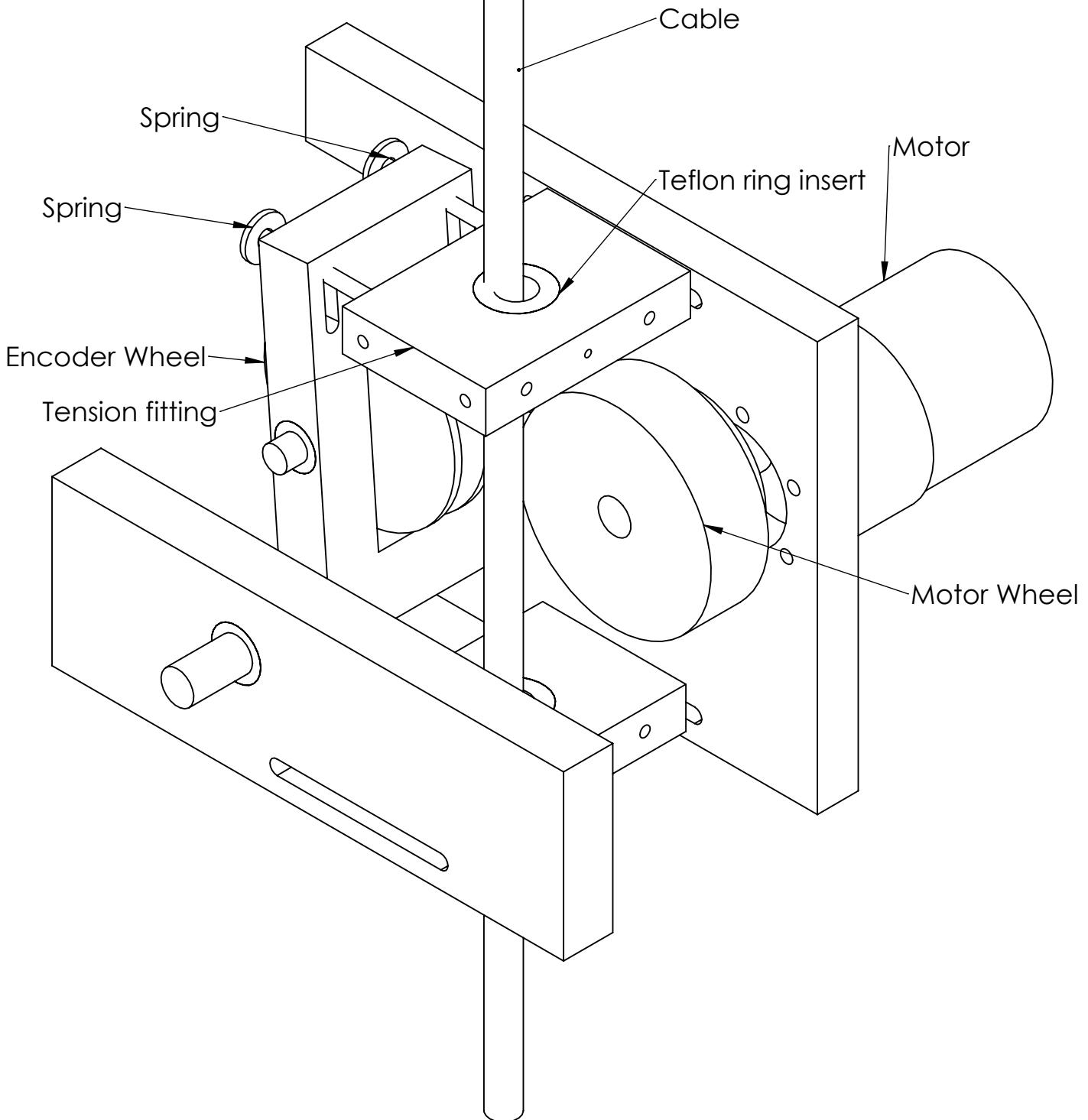


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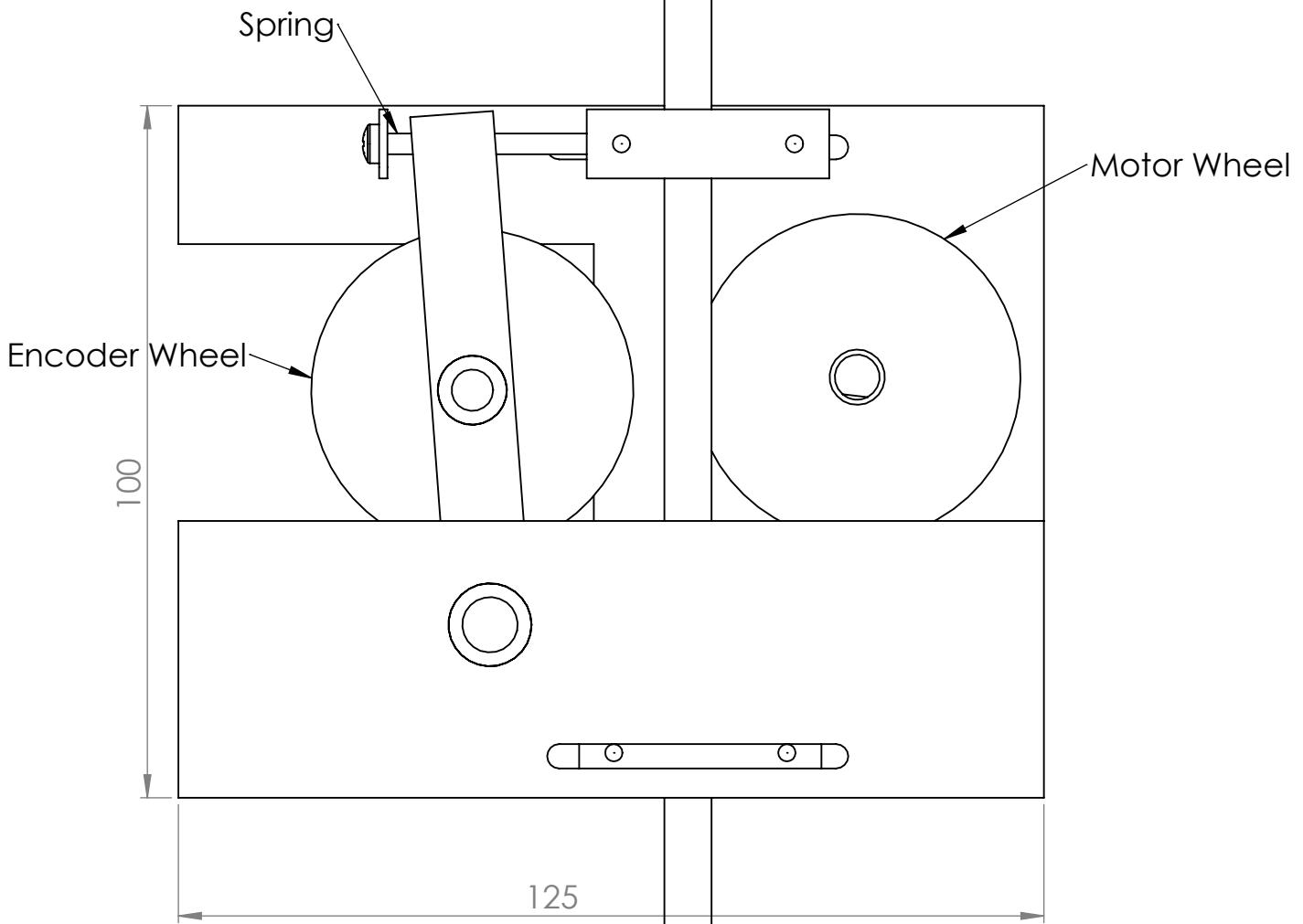
The Simple Winch

The simple winch is inspired from 3D printer extruder mechanism. The is pushed between two wheels. One wheel is motorized and fixed in position and second is pushing towards the motor wheel with a spring tension. The spring assures the second wheel always have contact with the cable, even if there is small variations in cable thickness. Second wheel also includes an encoder. Having the encoder on the second wheel, instead of the motor wheel, assures the rotation is actually from the cable and not because the motor wheel slips on the cable. The springs in this prototype is normal ballpoint pen springs taken from two arbitrary ballpoint pens.

The encoder is a magnetic encoder with a magnet attached at the end of the shaft. The shaft is made of steel, so the magnet will stick.



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					Peter J. Savnik	
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DWG NO.

winch-assembly

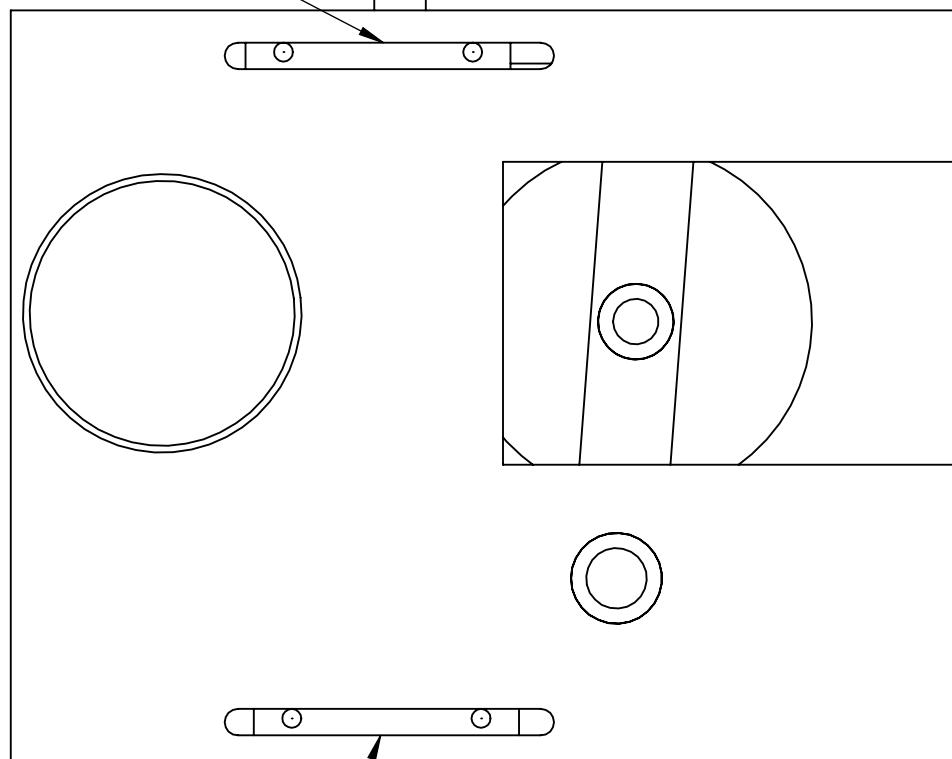
A4

WEIGHT:

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SHEET 2 OF 4

Milled track for adjusting cable position

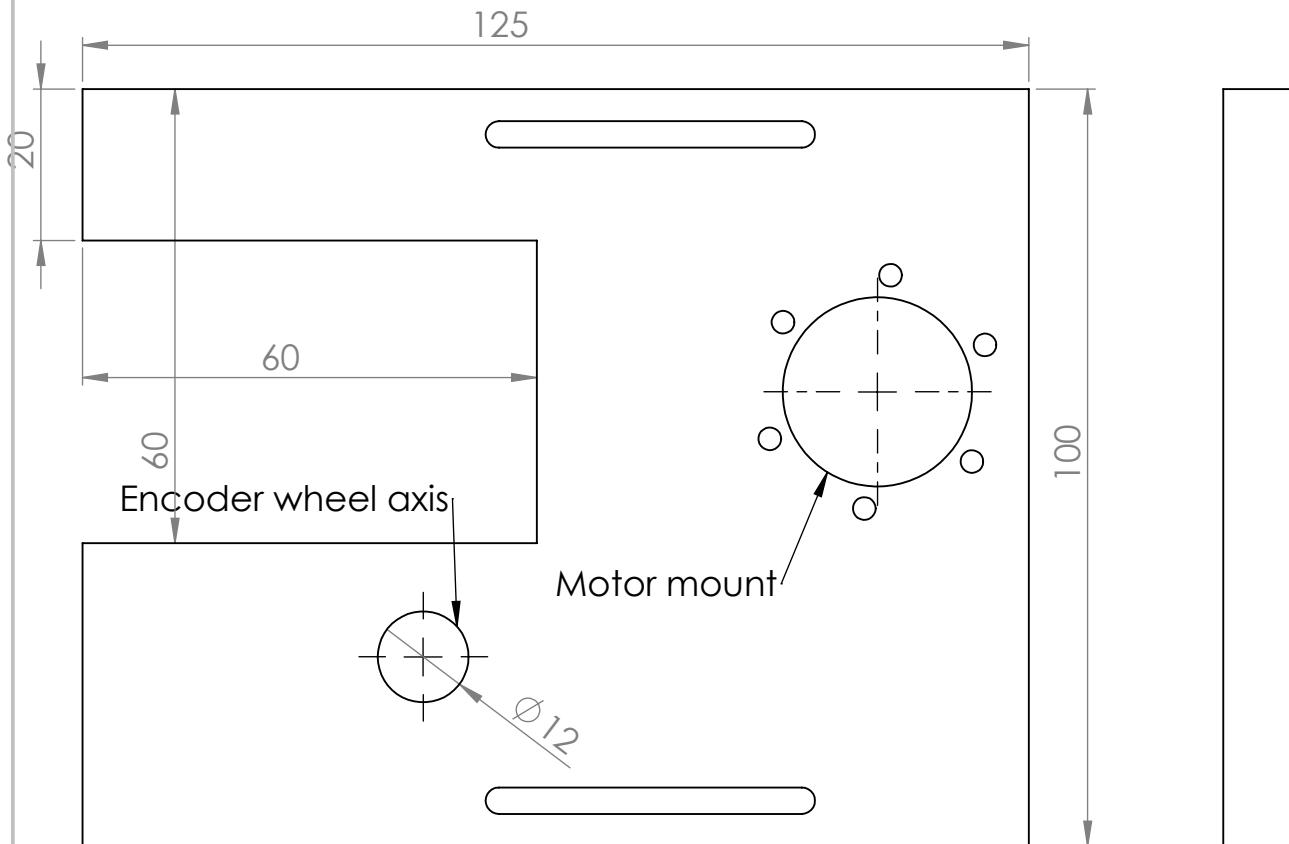
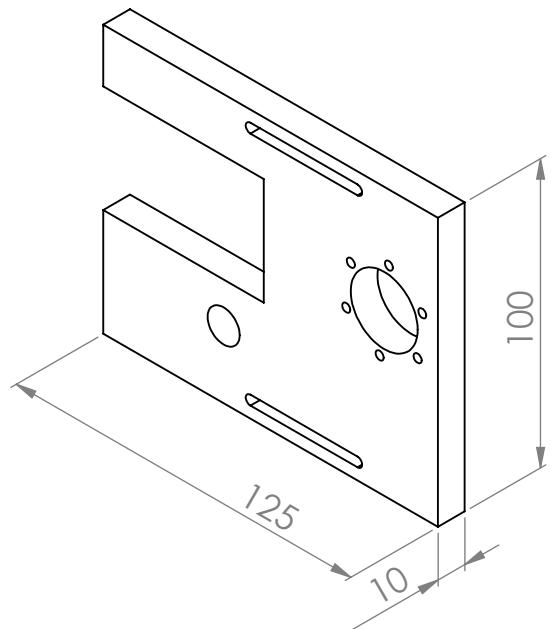


Milled track for adjusting cable position

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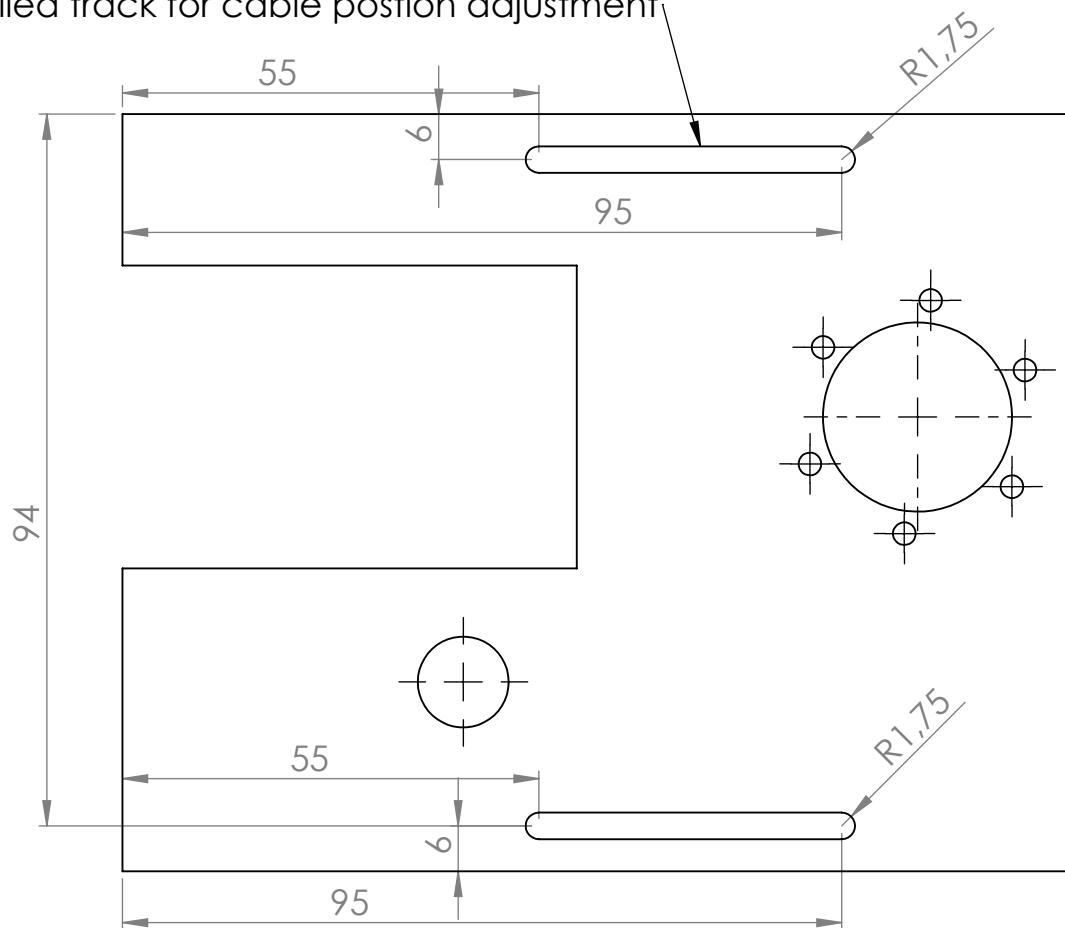
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1	winch-side-plate-motor		1
2	cable		1
3	winch-side-plate		1
4	wheal-1		1
5	T2-5-60		1
6	tension-fitting		2
7	B18.6.7M - M3 x 0.5 x 30 Type I Cross Recessed PHMS --30N		2
8	axis-holder		1
9	brass-bearing		2
10	smooth-rod-6mm		1
11	smooth-rod-8mm-winch		1
12	brass-bearing-8-12		2
13	B18.22M - Plain washer, 3 mm, regular		2
14	teflon-ring		2
15	Pololu motor		1

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SolidWorks Student Edition. For Academic Use Only.					DWG NO.	winch-side-plate-motor		
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				WEIGHT:			SHEET 1 OF 4	

Milled track for cable position adjustment



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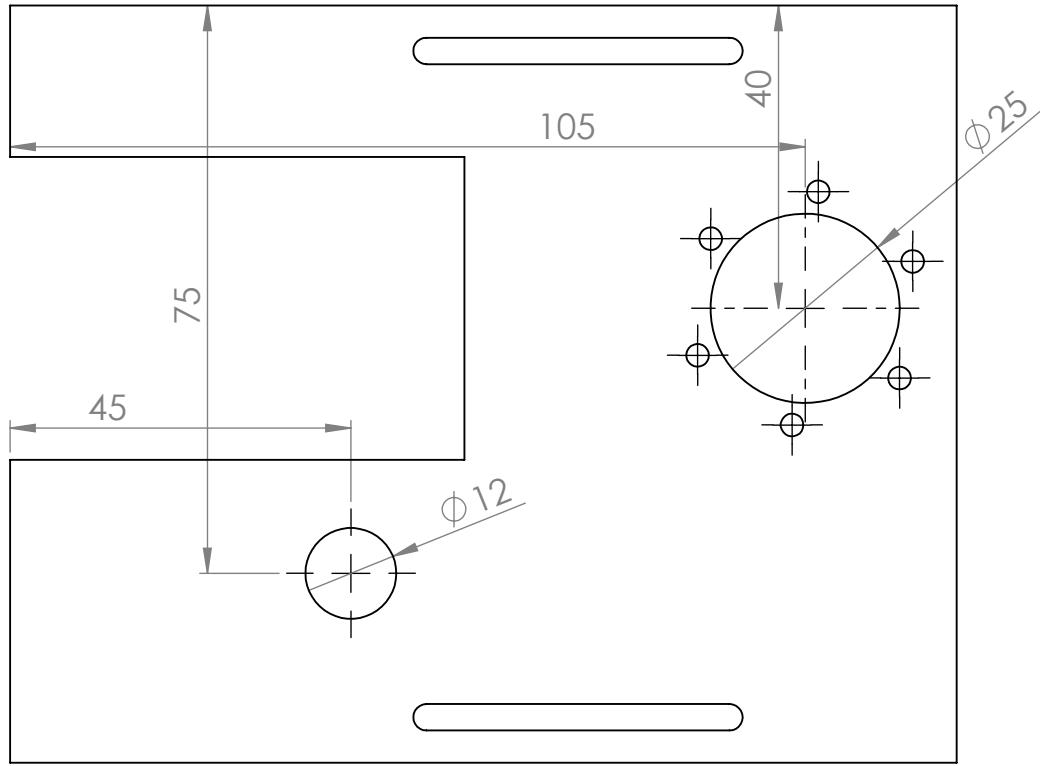
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winch-side-plate-motor

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SHEET 2 OF 4



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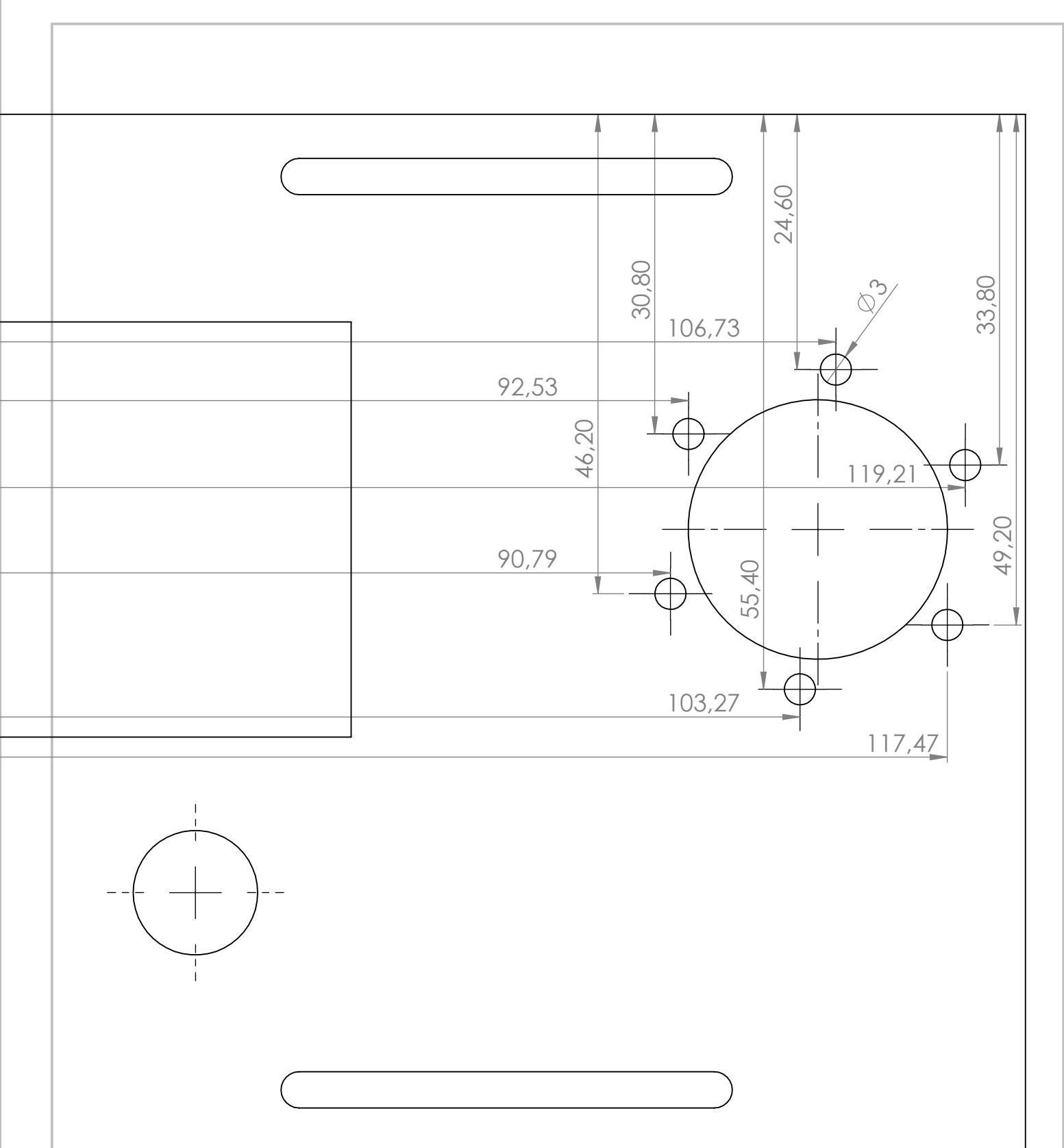
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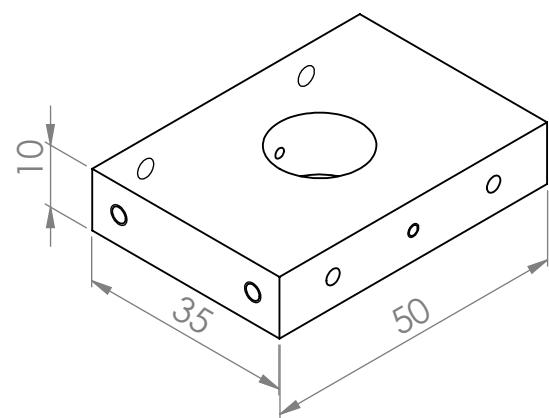
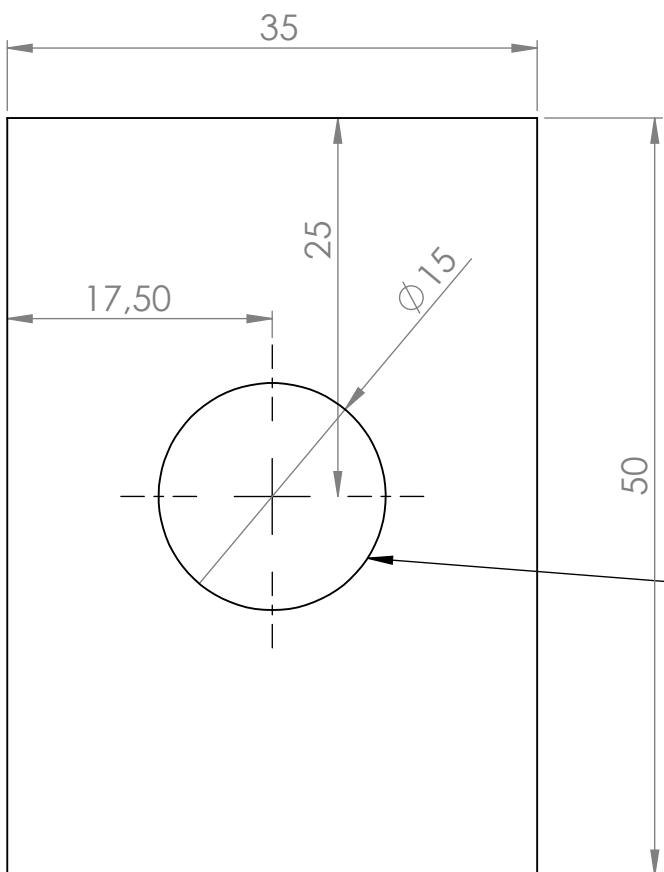
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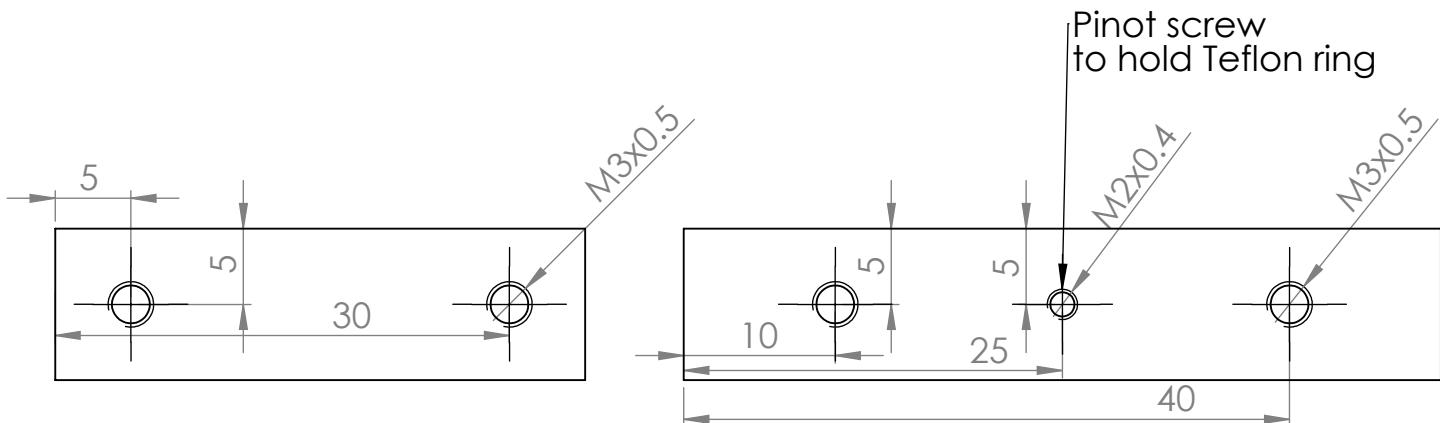
SHEET 3 OF 4



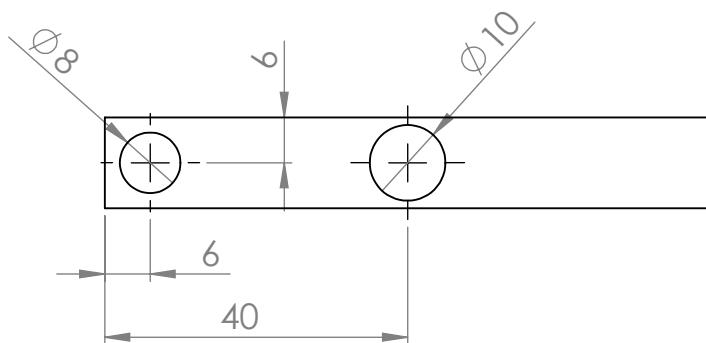
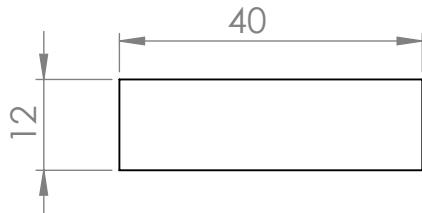
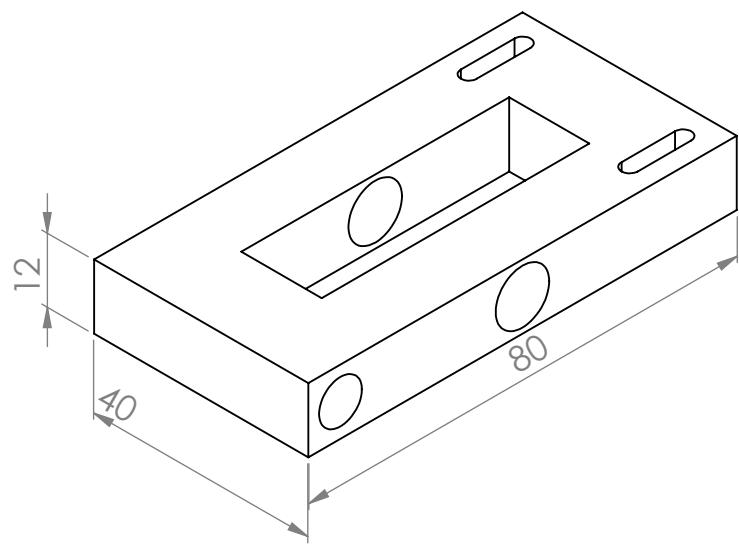
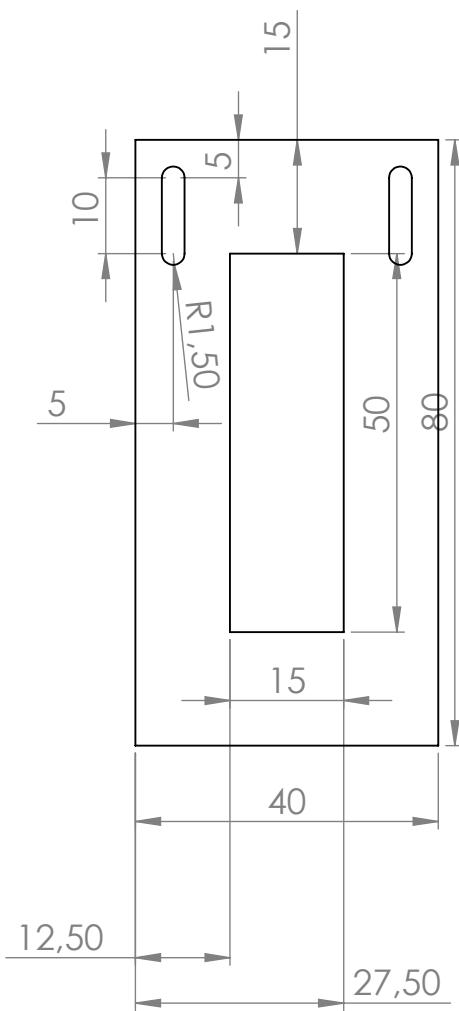
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Hole for Teflon insert



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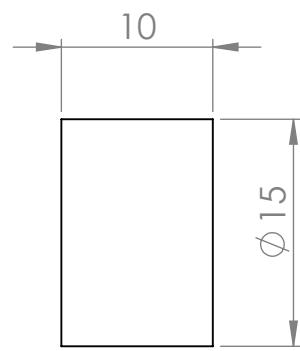
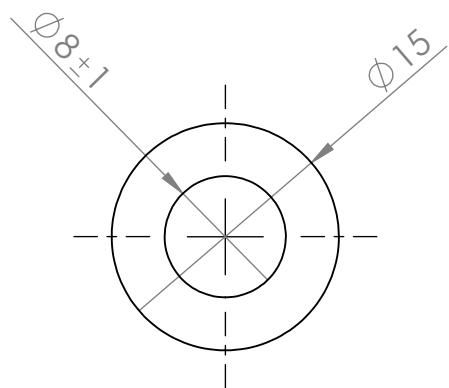
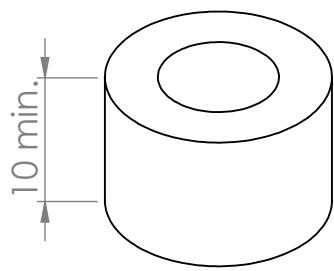
axis-holder

A4

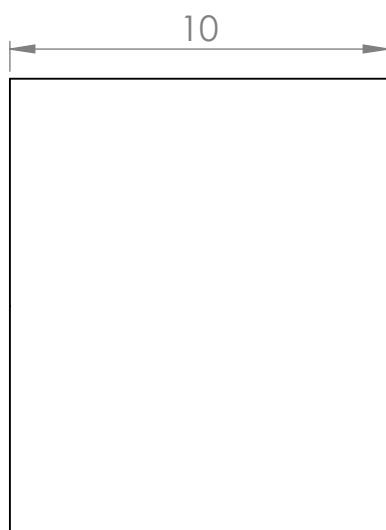
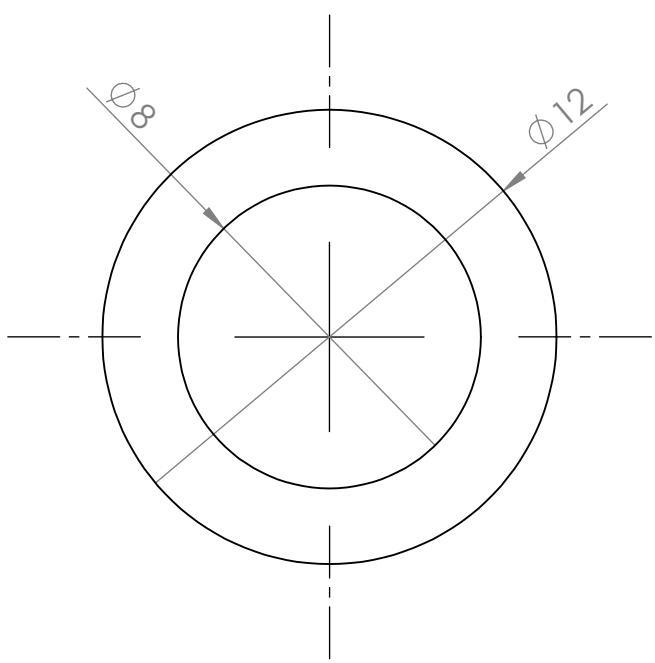
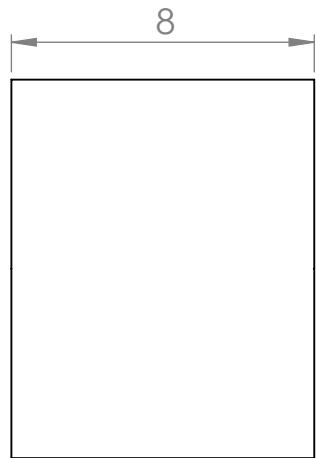
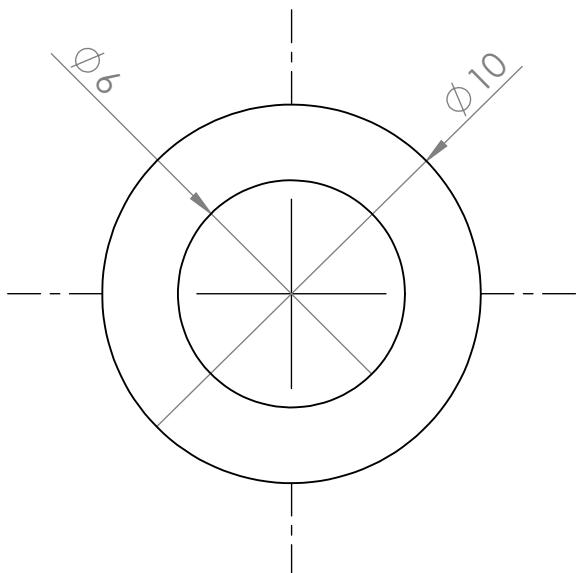
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SCALE:1:2

SHEET 1 OF 1

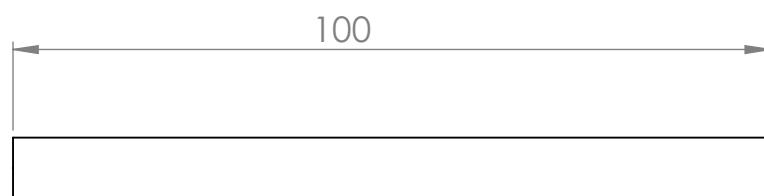
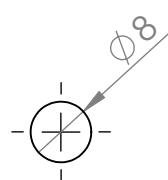
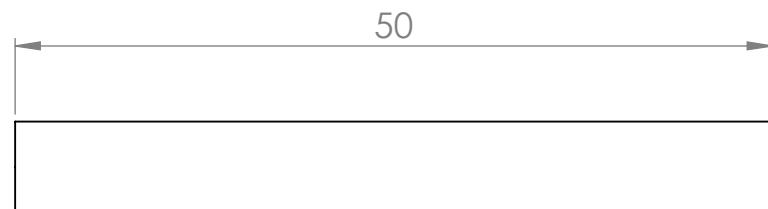
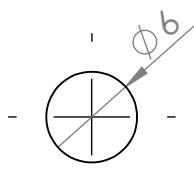


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DRAWN	NAME	SIGNATURE	DATE					
CHK'D						TITLE:		
APP'D								
MFG								
Q.A.	SolidWorks Student Edition. For Academic Use Only.					DWG NO.	teflon-ring	
						SCALE:2:1	SHEET 1 OF 1	
				WEIGHT:				A4



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION
DRAWN	NAME	SIGNATURE	DATE					
CHK'D					TITLE:			
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.				MATERIAL: Brass		DWG NO.	
Q.A					WEIGHT:		SCALE:5:1	SHEET 1 OF 1
								A4

Smooth rods



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH: Polished			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN	NAME	SIGNATURE	DATE				
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.			LATERAL			
Q.A					DWG NO.	smooth-rods	
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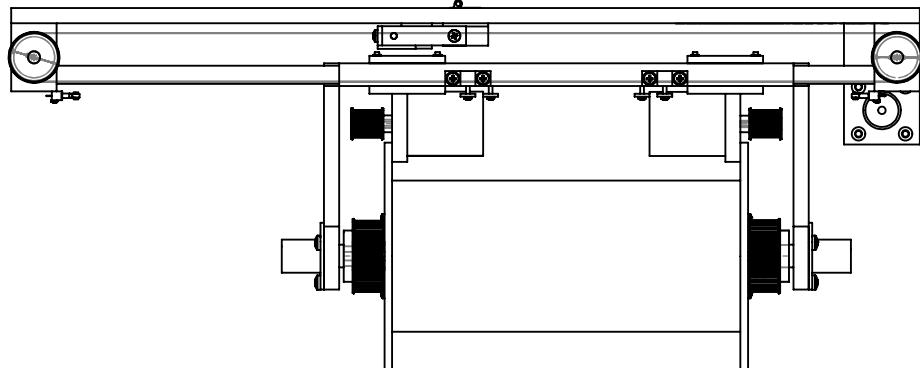
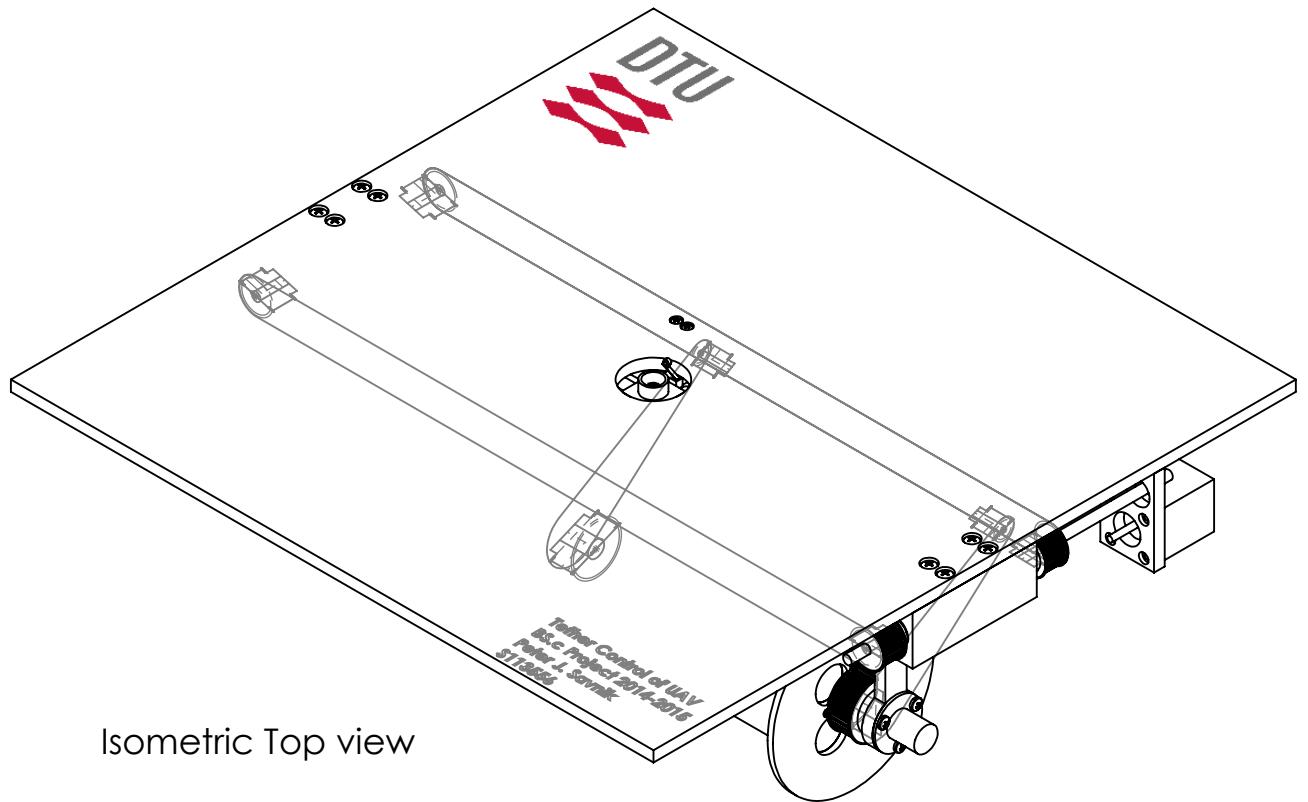
The Cable Drum

The Cable Drum is the most developed and complex prototype of the two winching methods. It has 3 motors, 2 to turn the drum around and 1 to move the carrier from side to side. Again it is very much inspired of open source 3d printers¹. Every thing can be mounted to the bottom of the helipad.

The power is connected to the drum through 2 slips rings. The slip rings can't carry any payload since they are made of thin plastic.

The drum has 4 big holes in the vertical direction to help passive heat dissipation from the cable.

¹Reprep open source 3d printers, www.reprap.org.



Front view

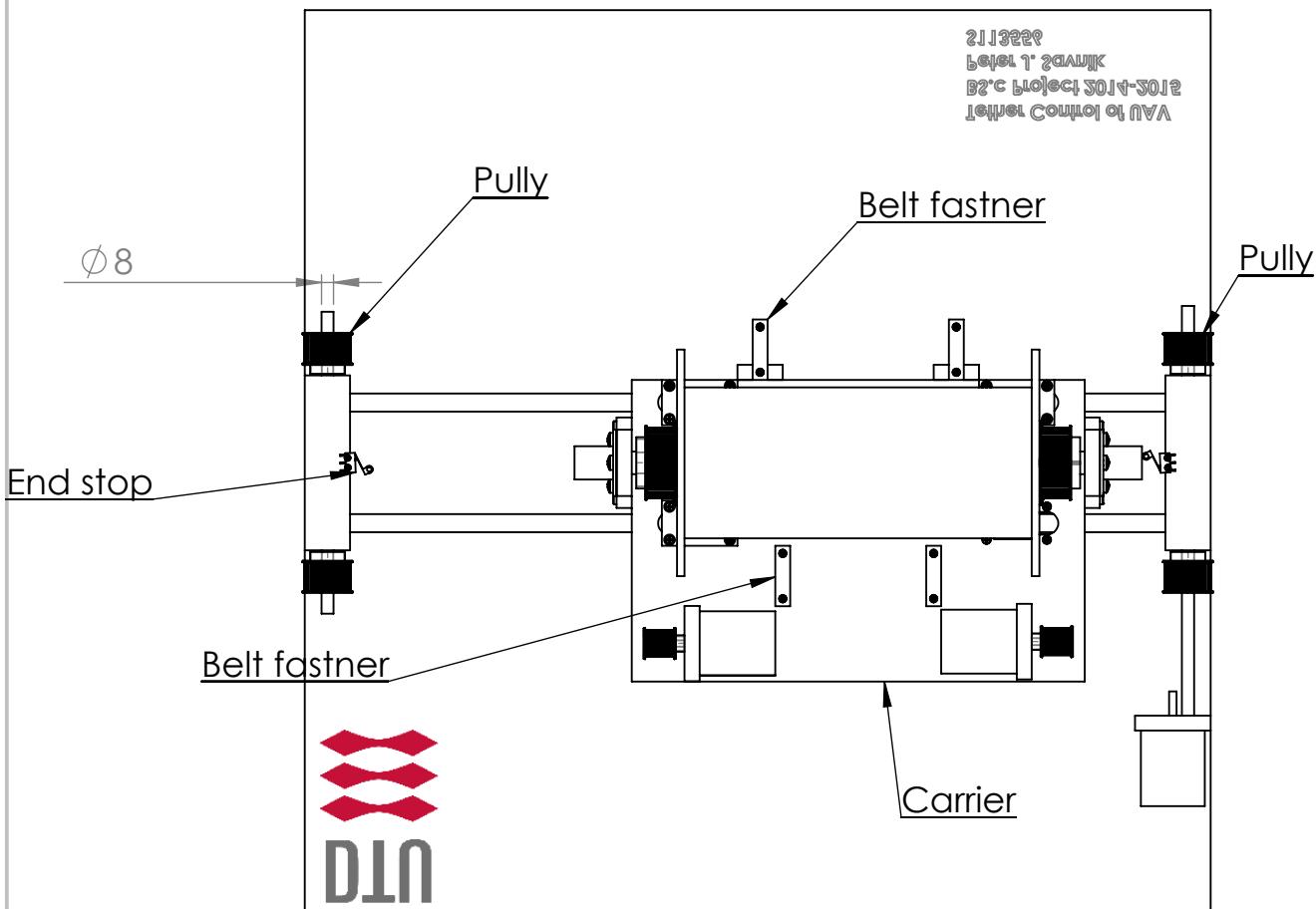
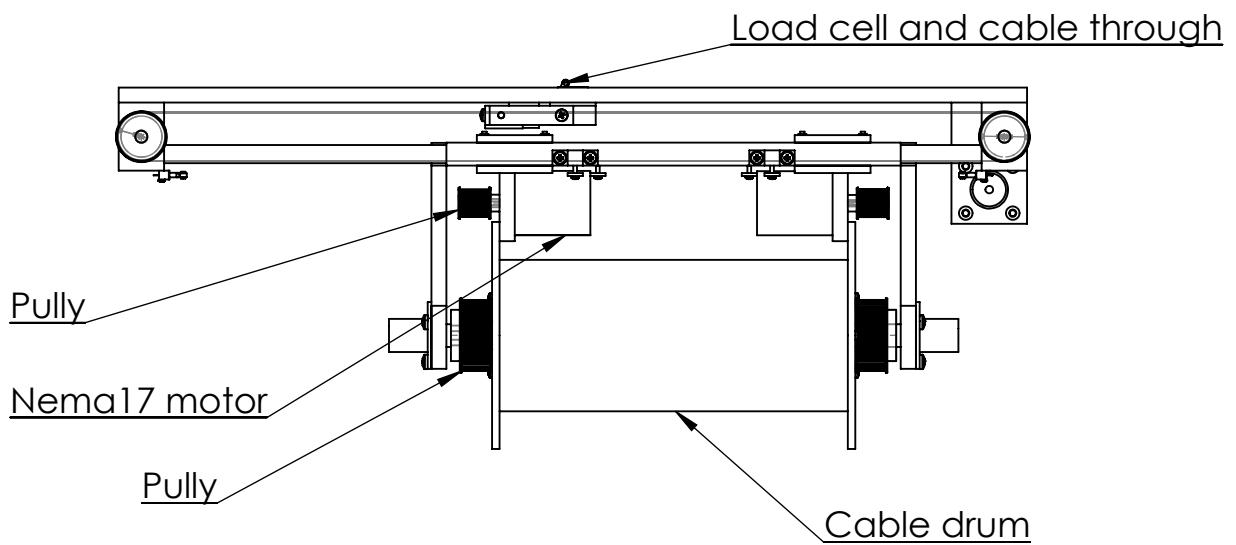
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DRAWN	SIGNATURE	DATE						
CHK'D						TITLE:		
APP'D								
MFG								
Q.A.						DWG NO. main_assembly		
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						SHEET 1 OF 4		
						A4		

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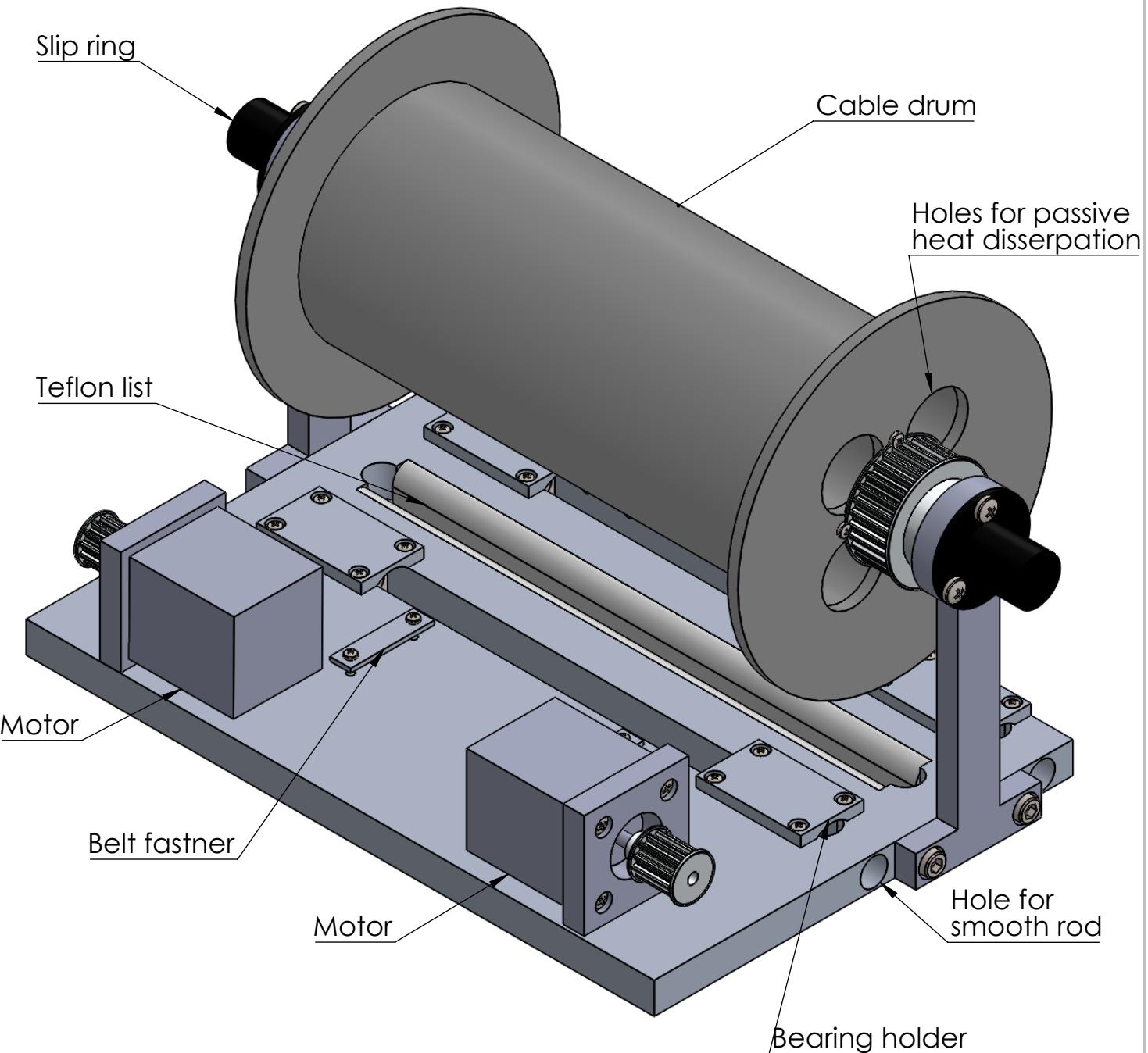
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SHEET 1 OF 4

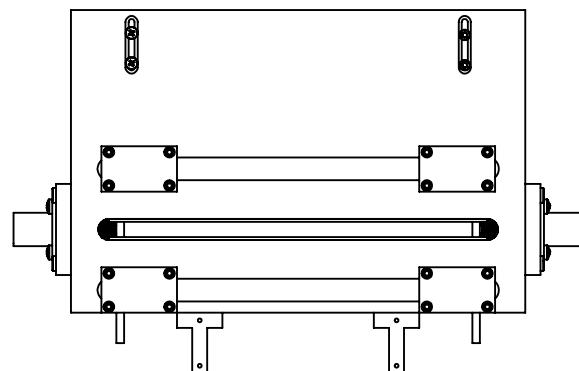
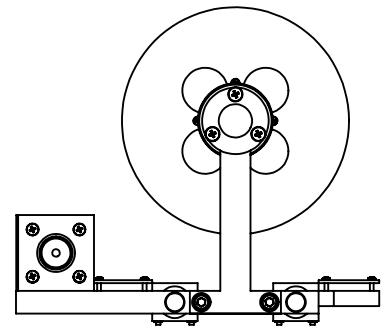
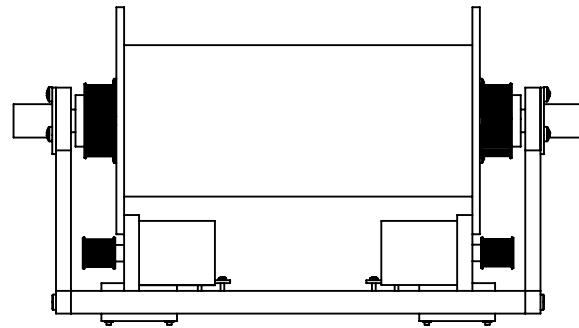
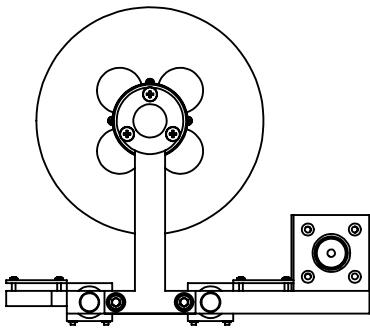
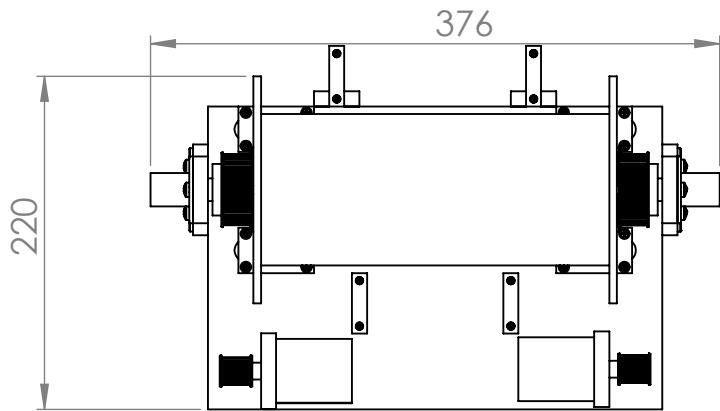


Bottom view

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DRAWN	NAME	SIGNATURE	DATE			TITLE:		
CHK'D								
APP'VD								
MFG								
Q.A	SolidWorks Student Edition. For Academic Use Only.				MATERIAL	DWG NO.	main_assembly	A4
						SCALE:1:20	SHEET 2 OF 4	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 3
Peter J. Savnik							
DRAWN	NAME Peter J. Savnik	SIGNATURE	DATE		TITLE:		
CHK'D							
APP'D							
MFG							
Q.A.							
SolidWorks Student Edition. For Academic Use Only.							
				DWG NO.	drum-carrier-assembly		
				WEIGHT:	SCALE:1:10		
					SHEET 1 OF 10		



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

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

DRAWN Peter J. Savnik

CHK'D

APP'D

MFG SolidWorks Student Edition.
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Q.A.

TITLE:

DWG NO.

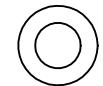
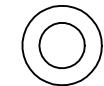
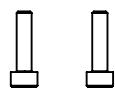
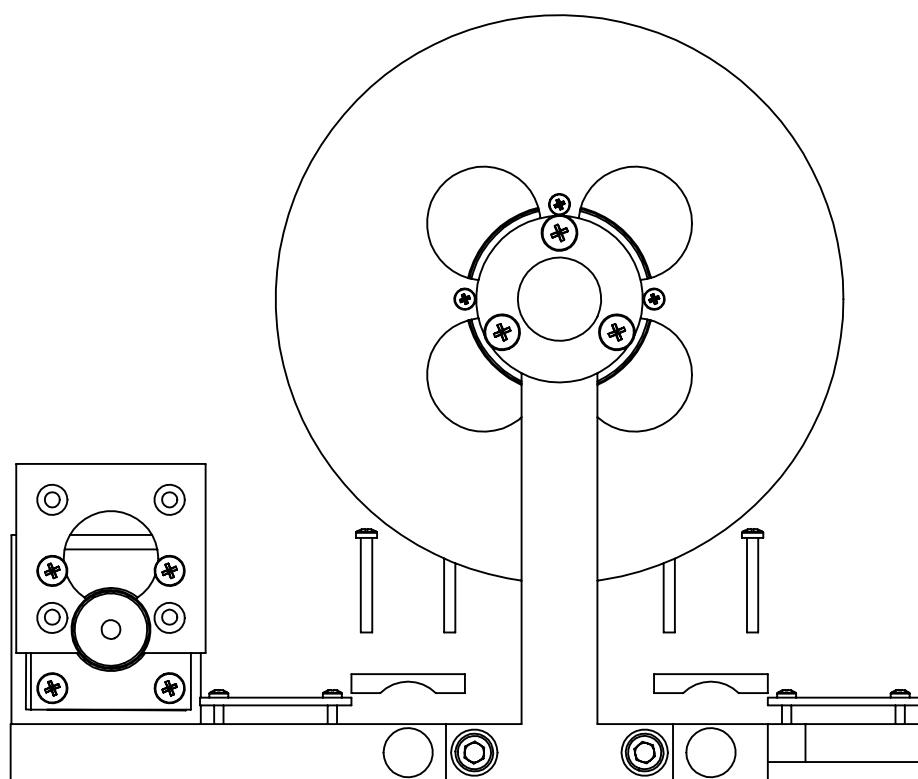
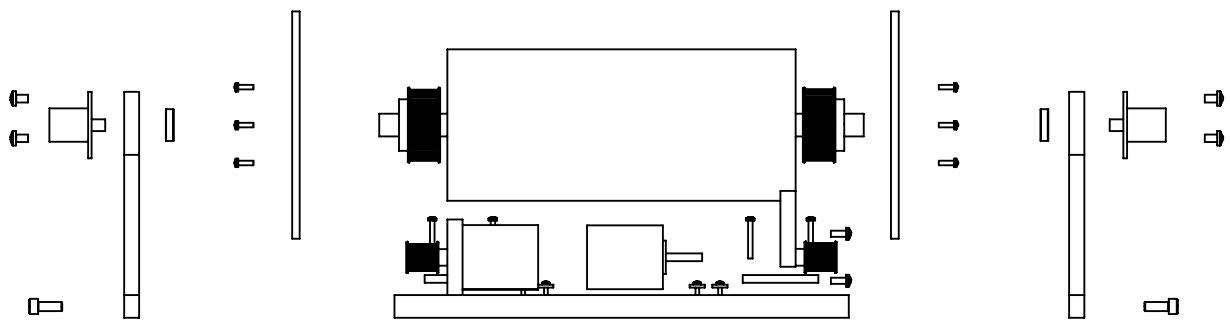
drum-carrier-assembly

M4

WEIGHT:

SCALE:1:10

SHEET 2 OF 10



UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

DRAWN Peter J. Savnik

CHK'D

APP'D

MFG SolidWorks Student Edition.
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Q.A.

TITLE:

DWG NO.

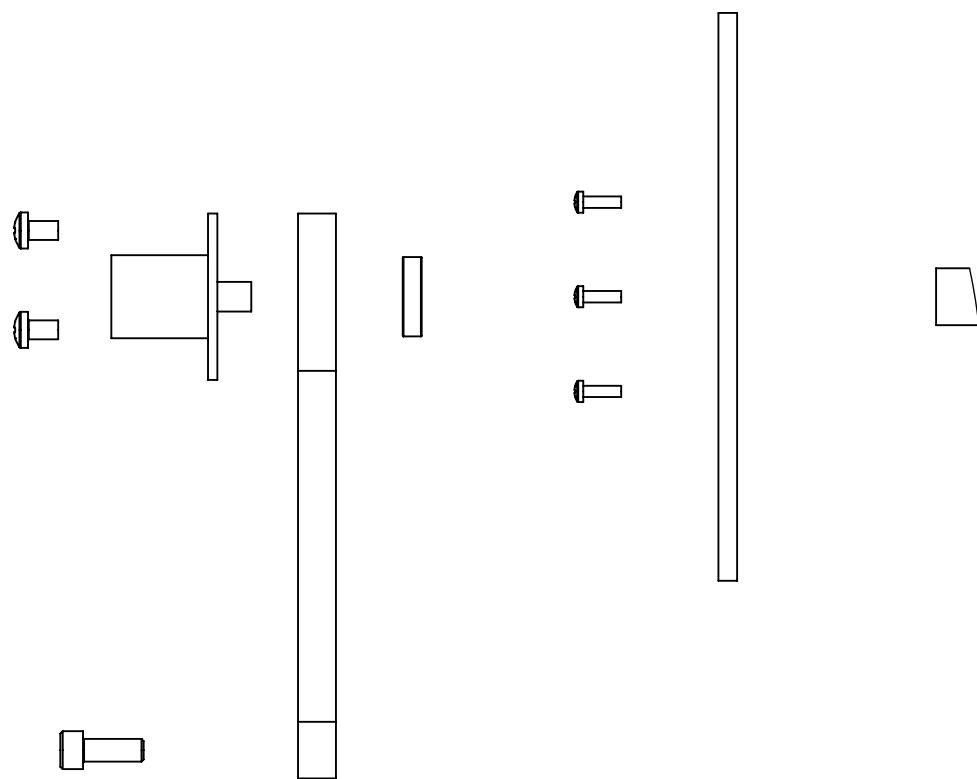
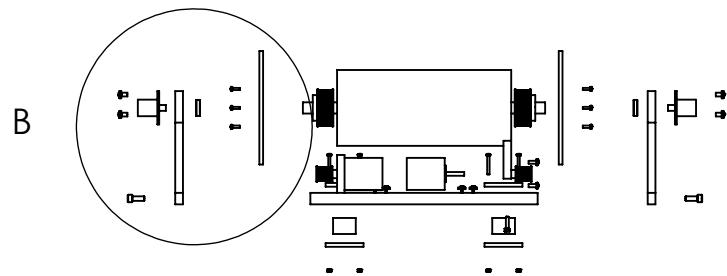
drum-carrier-assembly

M4

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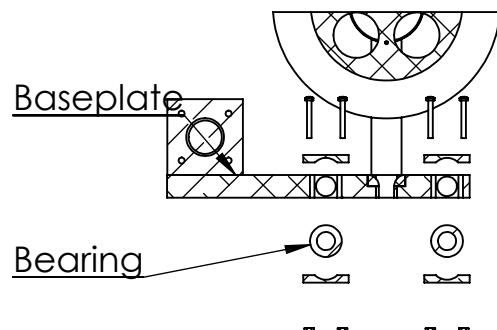
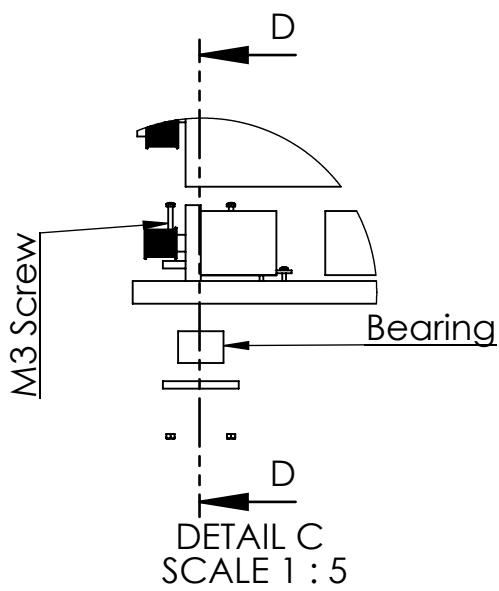
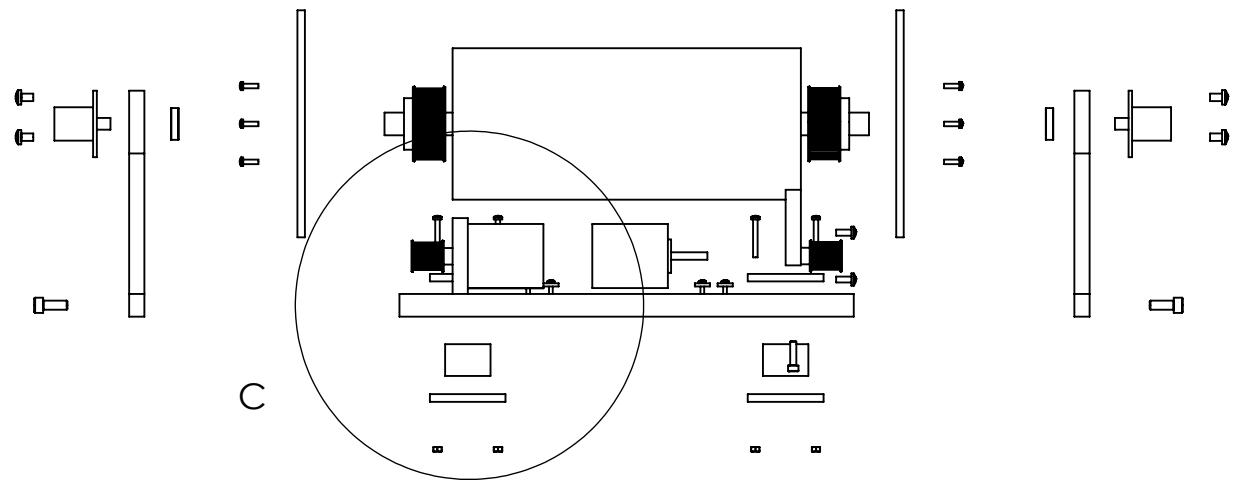
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SHEET 3 OF 10



DETAIL B
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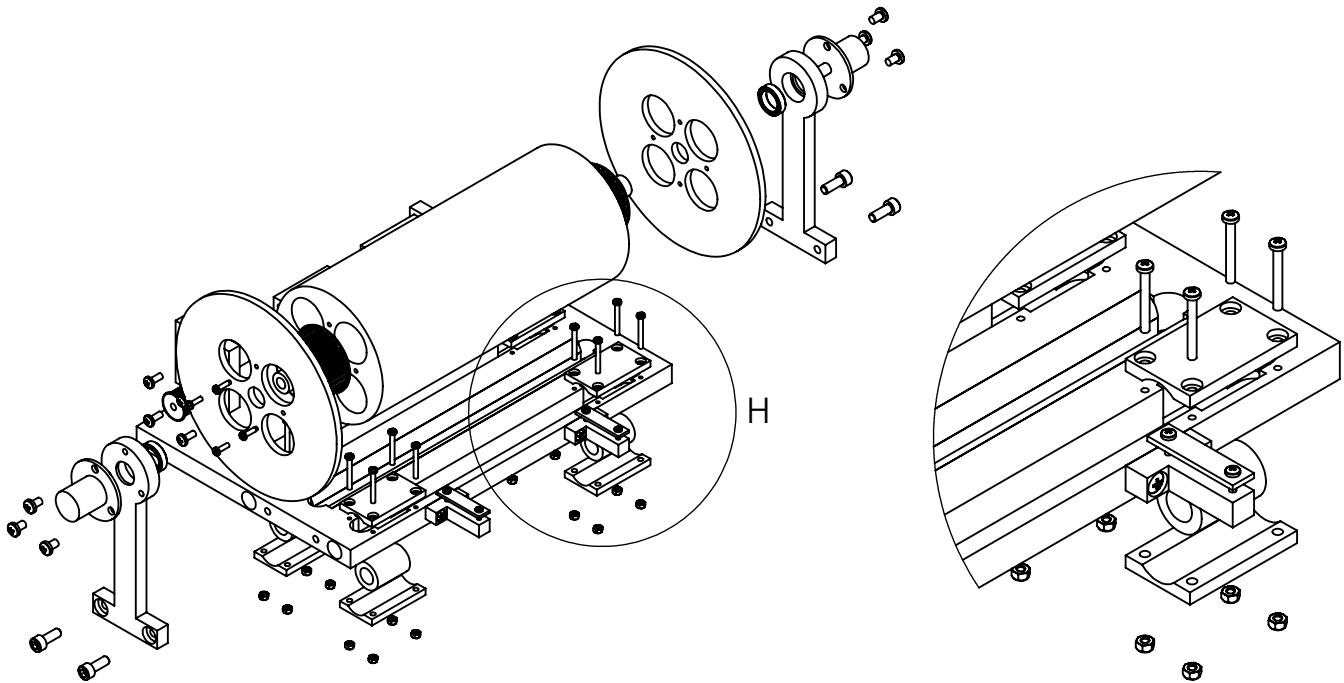
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DRAWN	Peter J. Savnik	SIGNATURE	DATE			TITLE: SolidWorks Student Edition. For Academic Use Only.	
CHK'D							
APPV'D							
MFG							
Q.A					DWG NO.: drum-carrier-assembly	SCALE:1:10	SHEET 4 OF 10



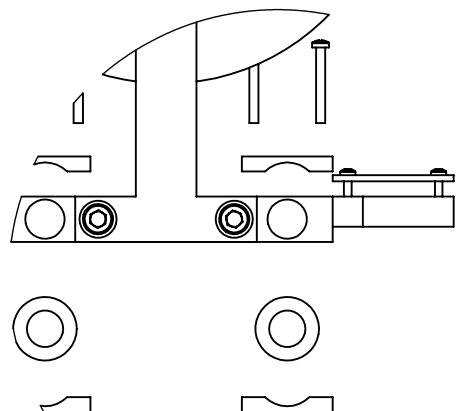
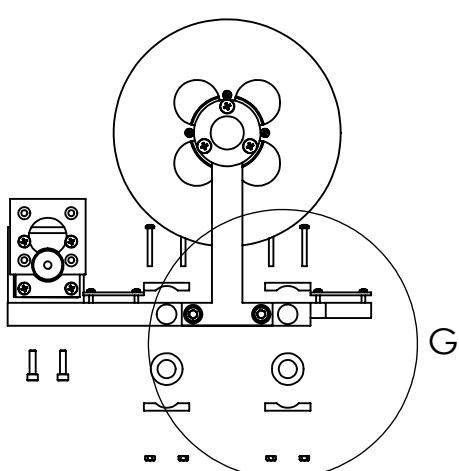
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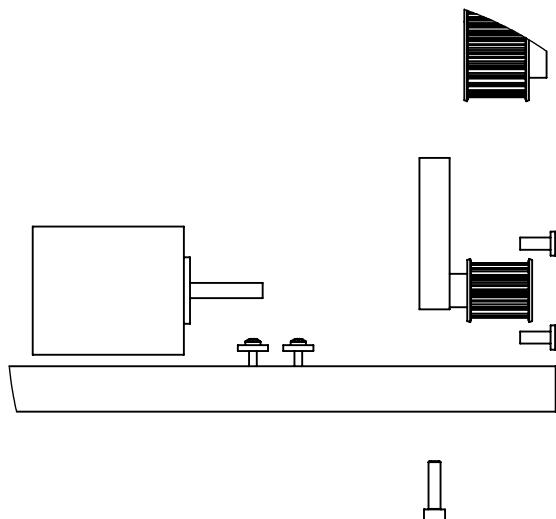
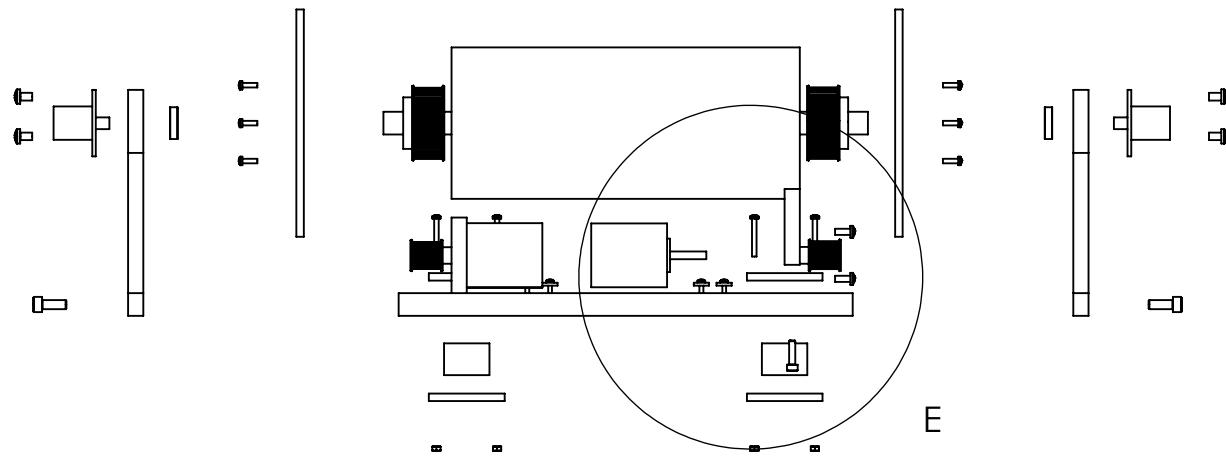
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DRAWN	Peter J. Savnik	SIGNATURE	DATE			TITLE: Bearing assembly	
CHK'D							
APPV'D							
MFG	SolidWorks Student Edition. For Academic Use Only.						
Q.A							
						DWG NO.	drum-carrier-assembly
						SCALE:1:10	M4
						SHEET 6 OF 10	
						WEIGHT:	



DETAIL H
SCALE 2:5

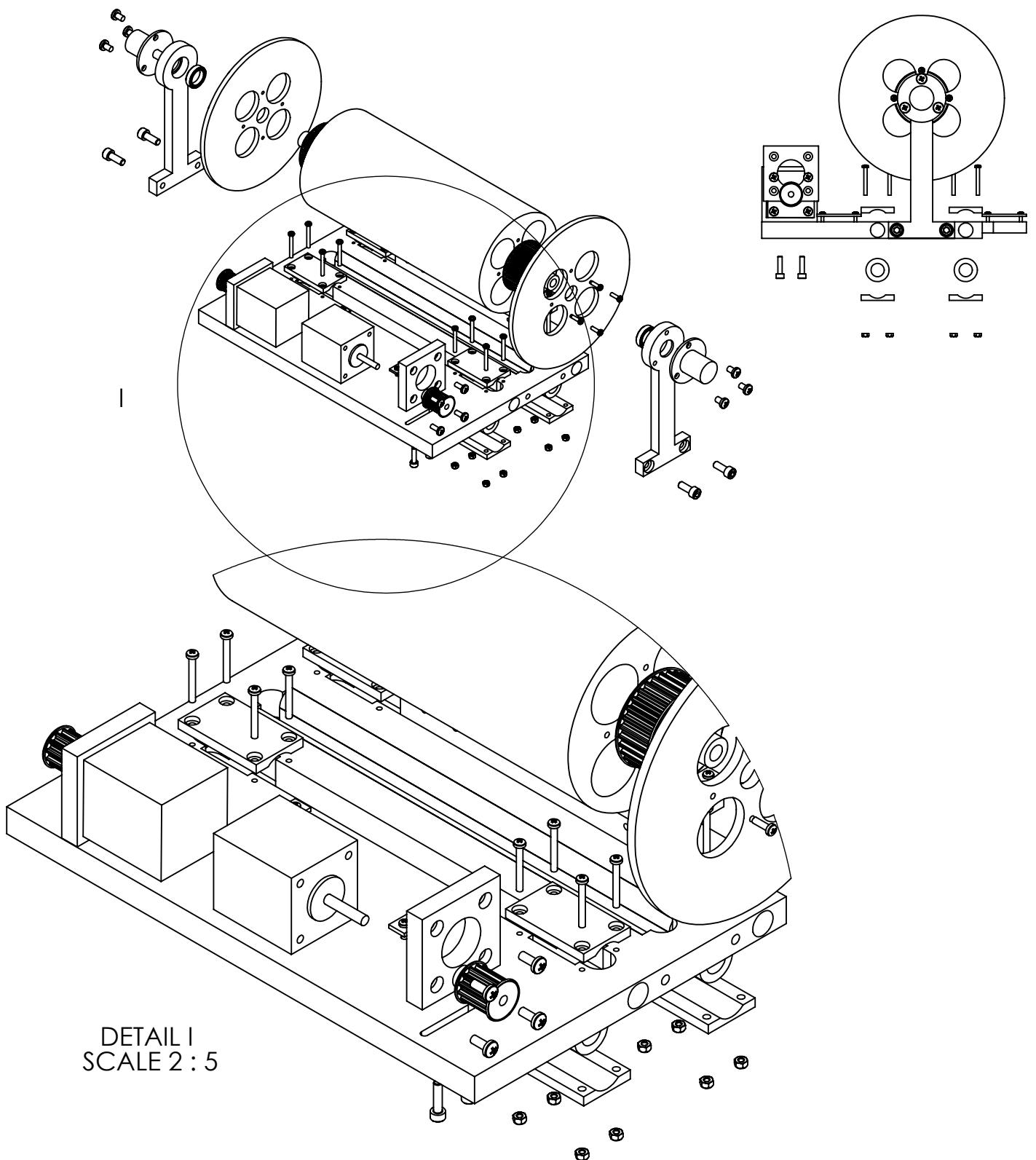


DETAIL G
SCALE 2:5



DETAIL E
SCALE 2:5

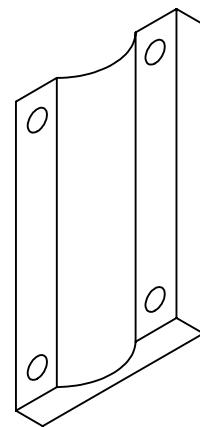
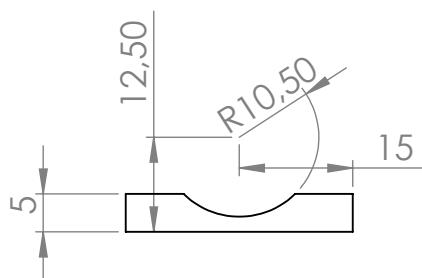
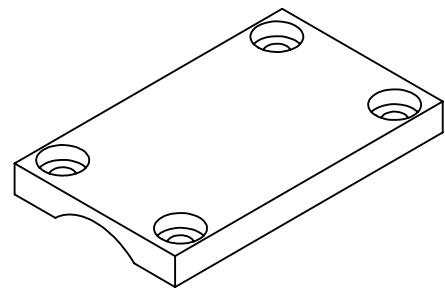
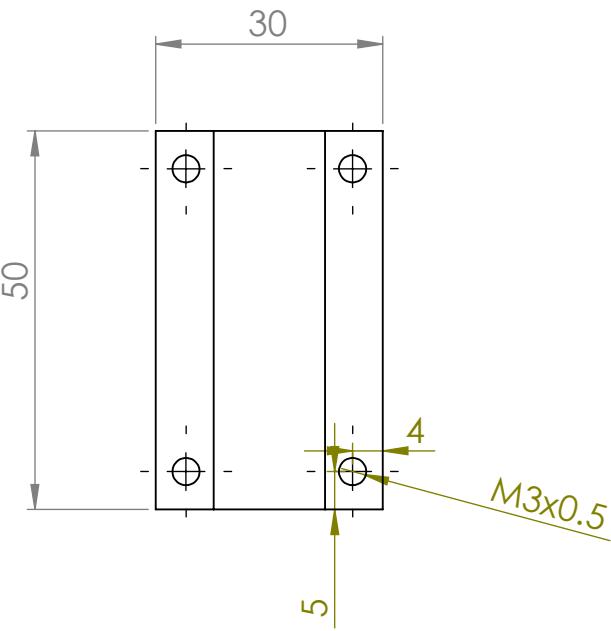
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DRAWN	Peter J. Savnik	SIGNATURE	DATE			TITLE:	Motor assembly
CHK'D							
APP'VD							
MFG	SolidWorks Student Edition. For Academic Use Only.						
Q.A						DWG NO.	drum-carrier-assembly A4
						SCALE:1:10	SHEET 8 OF 10



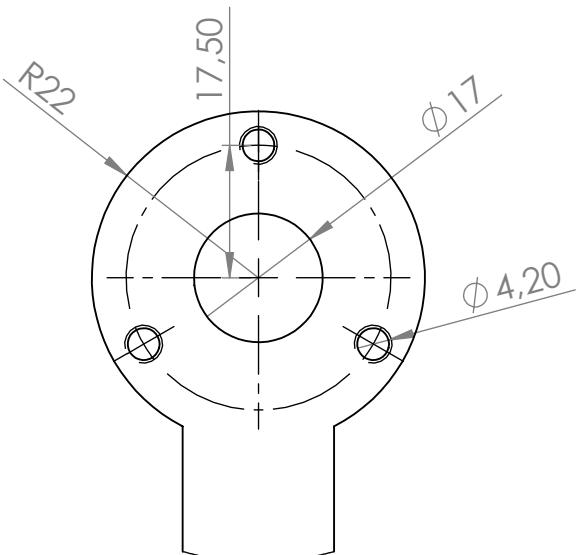
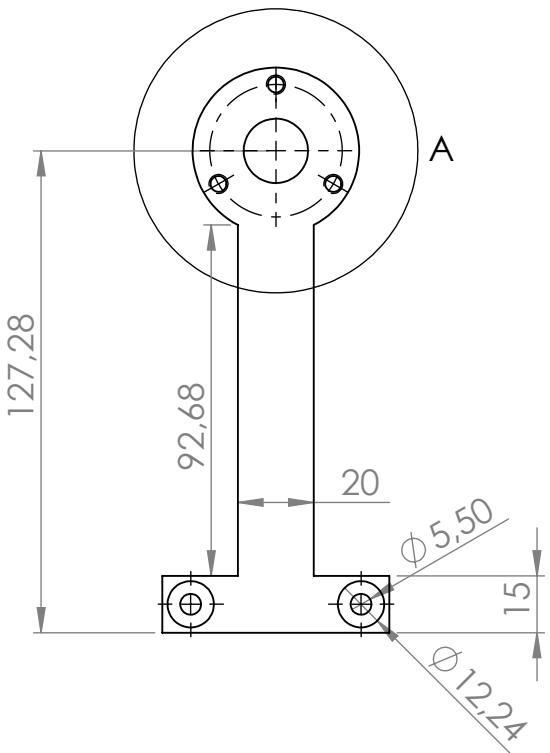
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DRAWN	Peter J. Savnik	SIGNATURE	DATE				
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APPV'D							
MFG	SolidWorks Student Edition. For Academic Use Only.						
Q.A.						DWG NO. M4	
MATERIAL:						drum-carrier-assembly	
WEIGHT:						SCALE:1:10	
						SHEET 9 OF 10	

ITEM NO.	PART NUMBER	Default/QTY.
1	baseplate	1
2	teflon-insert-2	2
3	end	2
4	B18.3.1M - 6 x 1.0 x 16 Hex SHCS -- 16Nhx	4
5	B18.3.1M - 4 x 0.7 x 16 Hex SHCS -- 16Nhx	2
6	AFBMA 12.1.4.1 - 0150-21 - Full,DE,NC,Full_68	2
7	rod	1
8	side	2
9	B18.6.7M - M3 x 0.5 x 10 Type I Cross Recessed PHMS --10N	8
10	B18.6.7M - M5 x 0.8 x 8 Type I Cross Recessed PHMS --8N	3
11	B18.6.7M - M4 x 0.7 x 10 Type I Cross Recessed PHMS --10N	4
12	B18.6.7M - M3 x 0.5 x 25 Type I Cross Recessed PHMS --25N	16
13	slip_ring_with_flange	2
14	ISO 7045 - M5 x 8 - Z --- 8N	3
15	motor-holder	2
16	Nema17motor	2
17	LM12UU	4
18	LM12UU-holder	8
19	AM-M3-N	16
20	teflon-insert	2
21	Pulley-27T5_30-2-Aratron	2
22	Pulley-27T5_12-2-Aratron	2
23	B18.6.7M - M4 x 0.7 x 25 Type I Cross Recessed PHMS --25N	2
24	belt-fastner-bracket	2
25	B18.6.7M - M4 x 0.7 x 13 Type I Cross Recessed PHMS --13N	4
26	belt-fastner-plate	4
27	B18.6.7M - M2.5 x 0.45 x 16 Type I Cross Recessed PHMS --16N	8

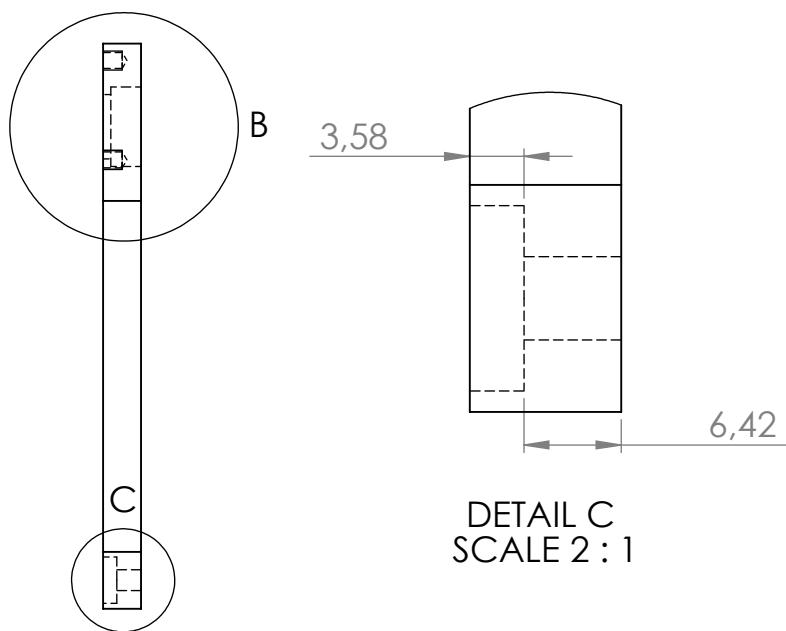
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APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.					DWG NO.	
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						M4	
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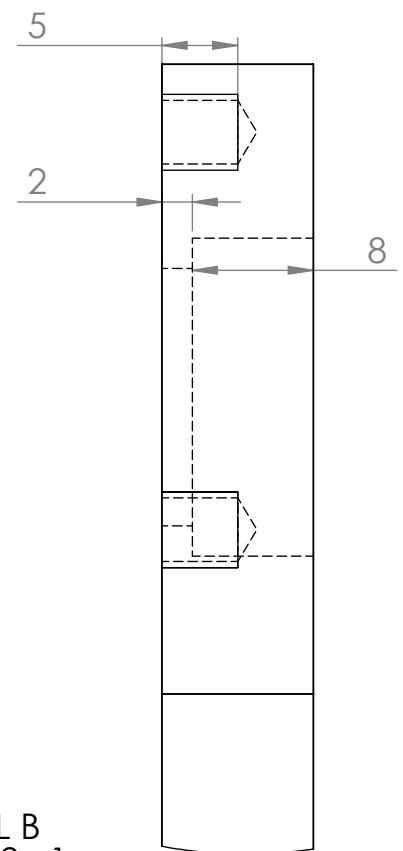
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DRAWN	NAME	SIGNATURE	DATE					
CHK'D	Peter J. Savnik							
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.					TITLE:		
Q.A	MATERIAL: Alu					DWG NO.	LM12UU-holder	
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DETAIL A
SCALE 1 : 1



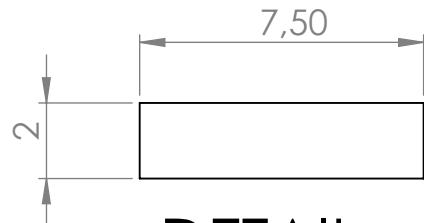
DETAIL C
SCALE 2 : 1



DETAIL B
SCALE 2 : 1

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TOLERANCES: LINEAR: ANGULAR:								
DRAWN	NAME Peter J. Savnik	SIGNATURE	DATE					
CHK'D								
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.			LATERAL Alu				
Q.A						DWG NO. end		A4
				WEIGHT:		SCALE:1:2		SHEET 1 OF 1

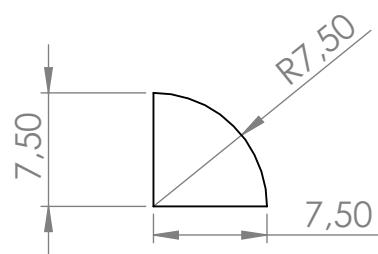
(-)
A



DETAIL A

SCALE 5 : 1

(D)
B



DETAIL B

SCALE 2 : 1

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

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

DRAWN

NAME

SIGNATURE

DATE

TITLE:

CHK'D

APP'D

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Teflon

MFG

Q.A

DWG NO.

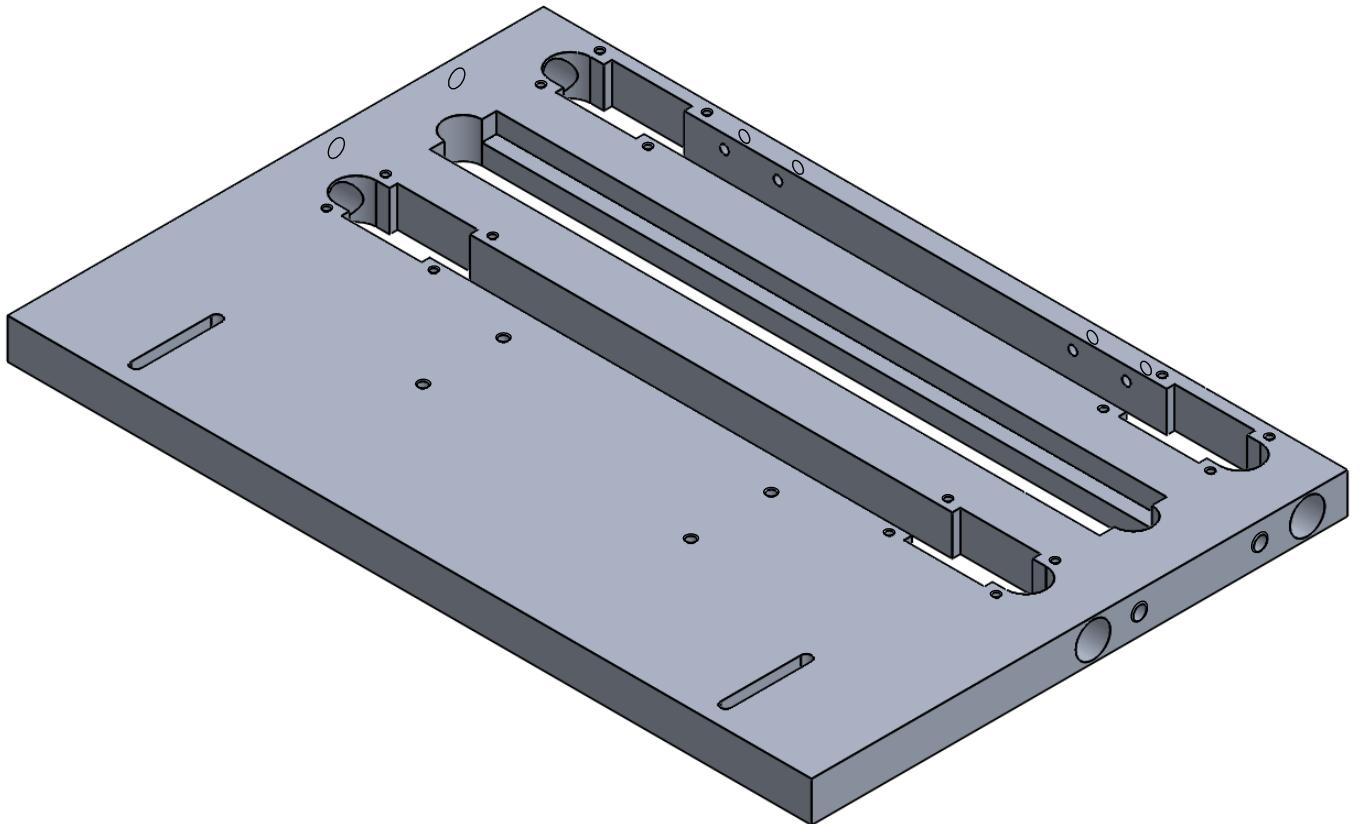
teflon-inserts

A4

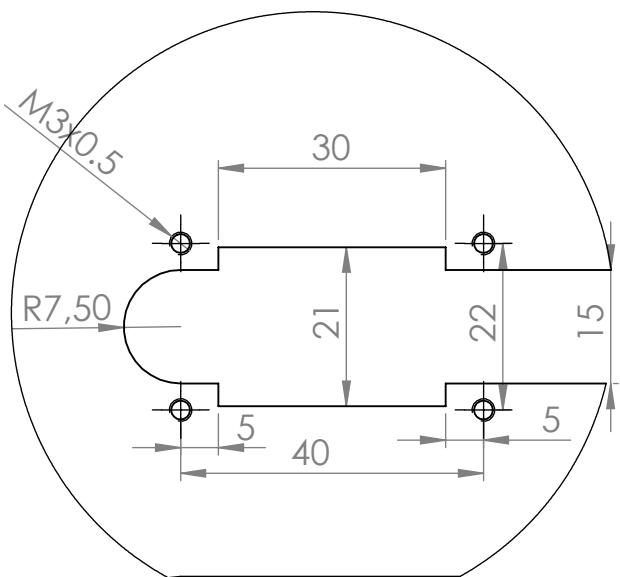
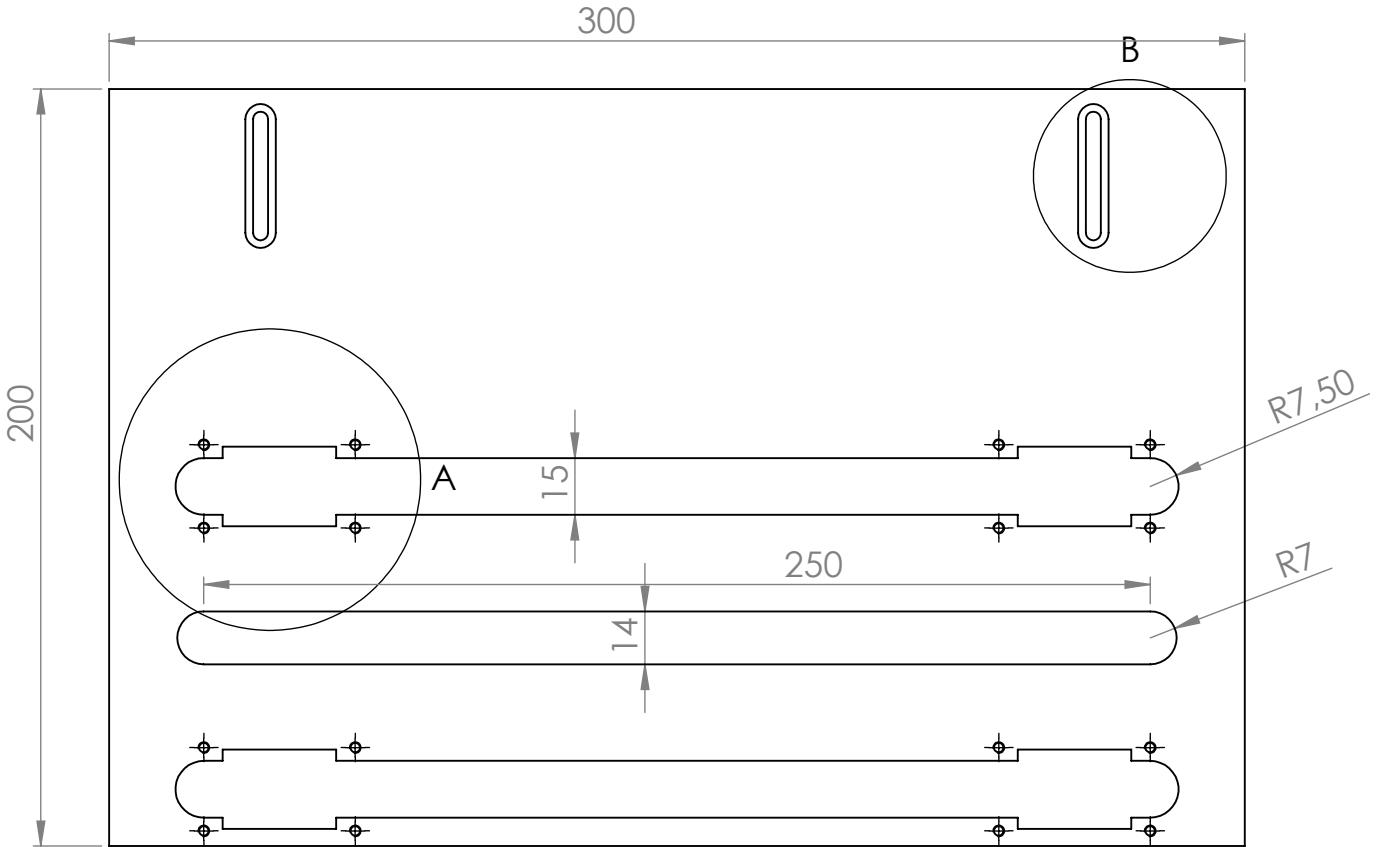
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SCALE:1:5

SHEET 1 OF 1

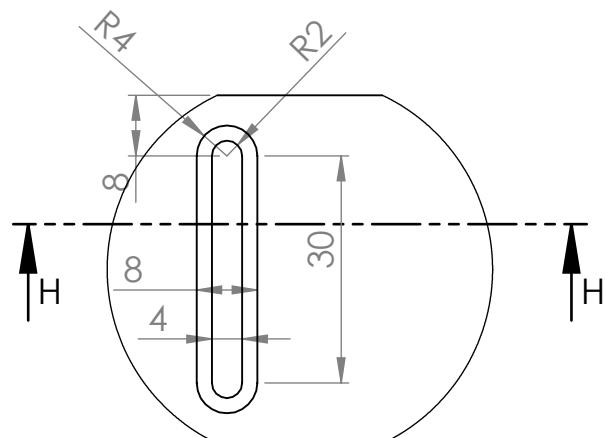


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DRAWN	Peter J. Savnik	SIGNATURE	DATE			TITLE: Baseplate for carrier		
CHK'D								
APPV'D								
MFG	SolidWorks Student Edition. For Academic Use Only.							
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						SCALE:1:5	SHEET 1 OF 5	
							A4	

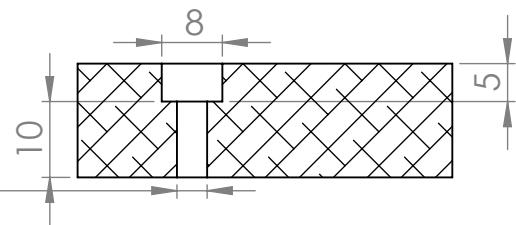


DETAIL A
SCALE 1 : 1

Bottom view

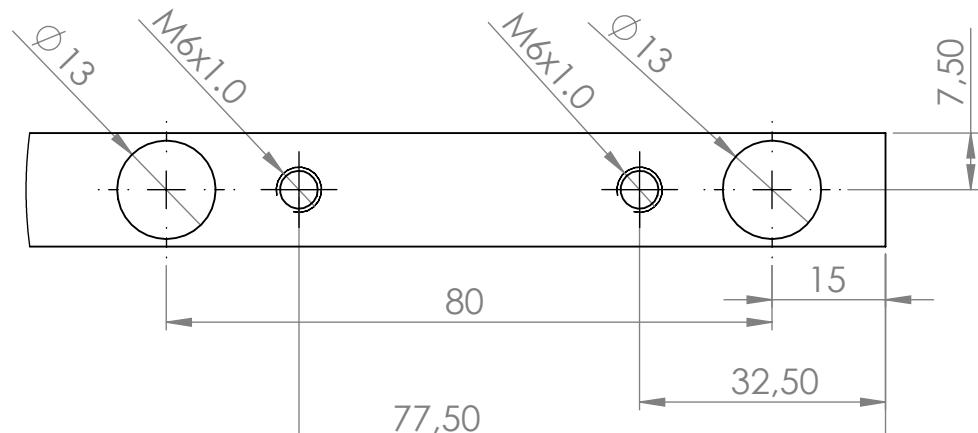
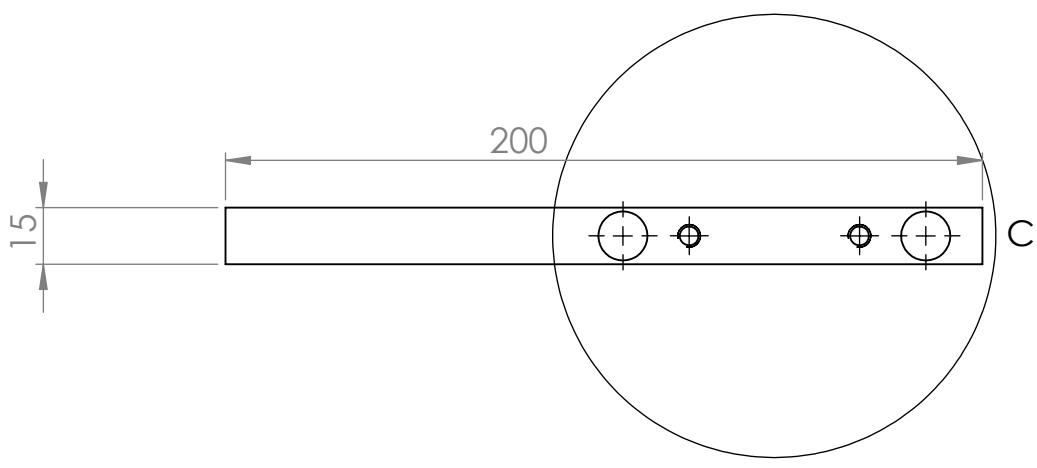


DETAIL B
SCALE 1 : 1



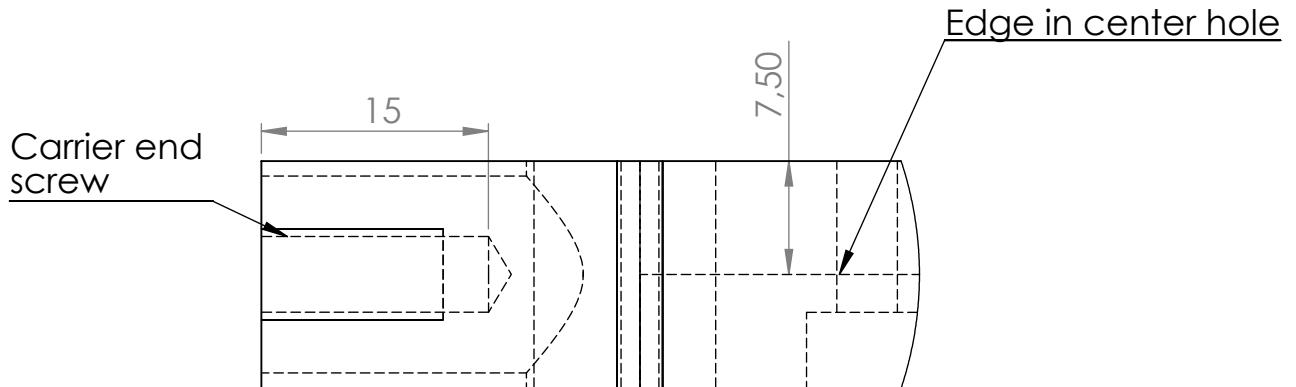
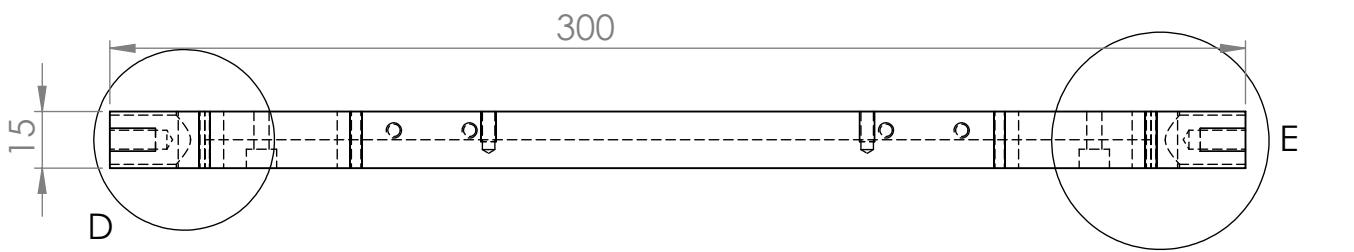
SECTION H-H
SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
SURFACE FINISH:						3
TOLES:						
LINEAR:						
ANGULAR:						
DRAWN	NAME	SIGNATURE	DATE		TITLE:	
Peter J. Savnik						
CHK'D						
APP'D						
MFG	SolidWorks Student Edition. For Academic Use Only.				DWG NO.	
Q.A					baseplate	A4
					SCALE:1:5	
					WEIGHT:	
					SHEET 2 OF 5	

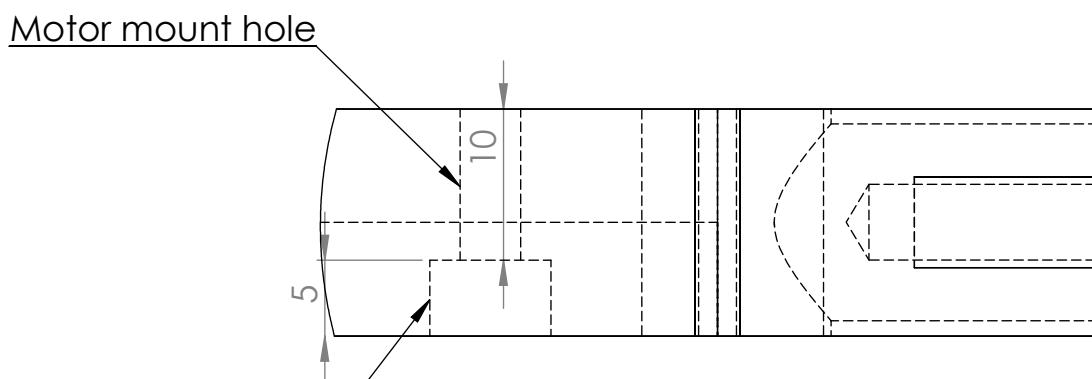


DETAIL C
SCALE 1 : 1

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DRAWN	NAME	SIGNATURE	DATE					
DRAWN	Peter J. Savnik							
CHK'D								
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.							
Q.A.						DWG NO.	baseplate	
							A4	
				WEIGHT:		SCALE:1:5	SHEET 3 OF 5	

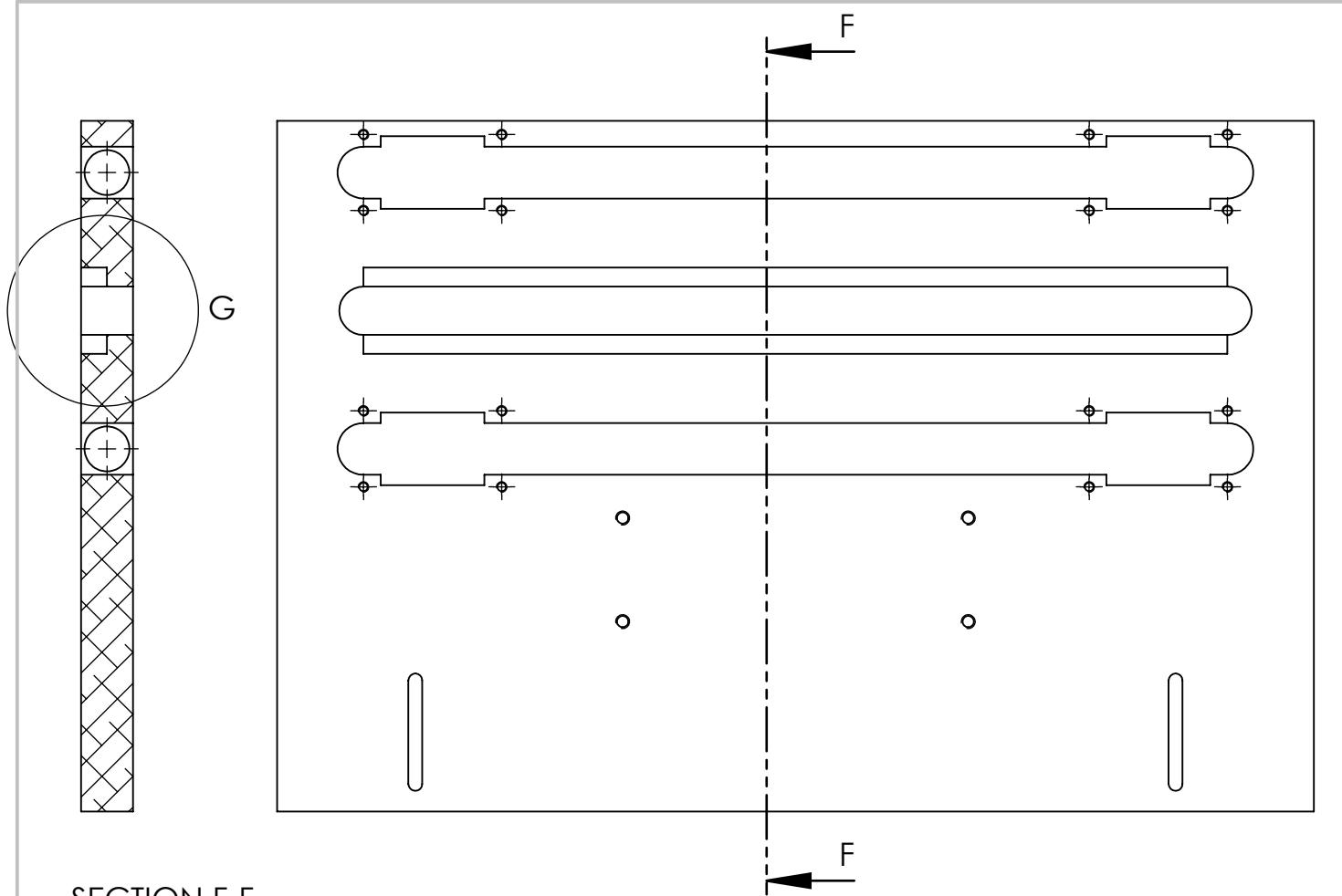


DETAIL D
SCALE 2 : 1

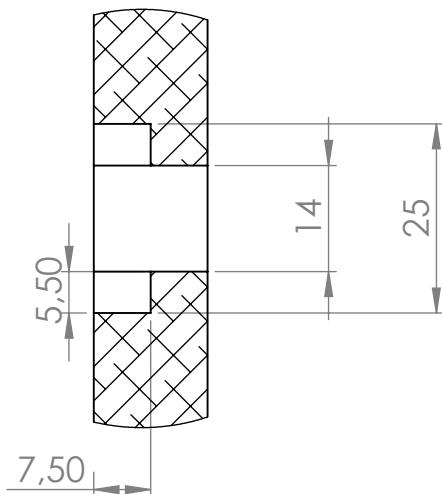


Motor mount screw sink DETAIL E
SCALE 2 : 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	3
	NAME	SIGNATURE	DATE			TITLE: SolidWorks Student Edition. For Academic Use Only.	DWG NO. baseplate	A4
DRAWN	Peter J. Savnik							
CHK'D								
APPV'D								
MFG								
Q.A								
						WEIGHT:	SCALE:1:5	SHEET 4 OF 5



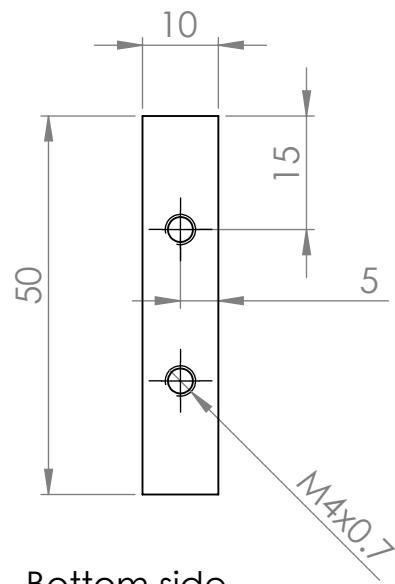
SECTION F-F
SCALE 1 : 2



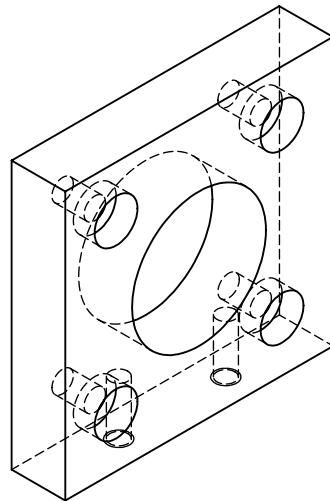
DETAIL G
SCALE 1 : 1

Center hole

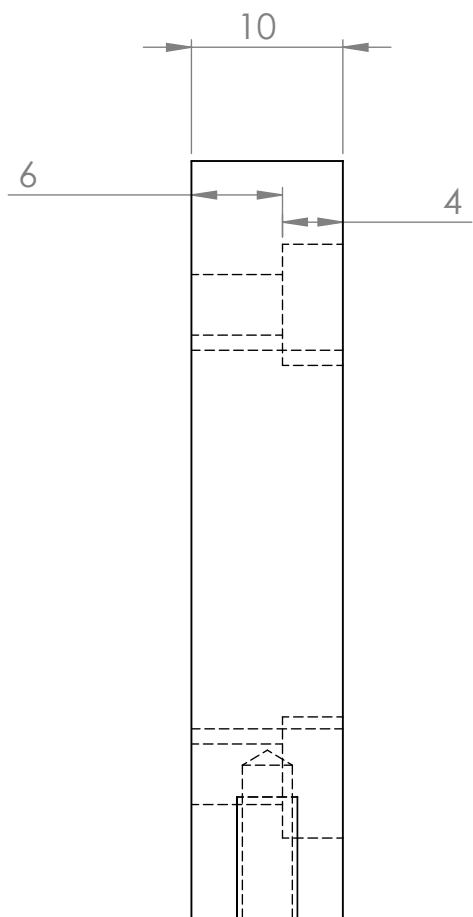
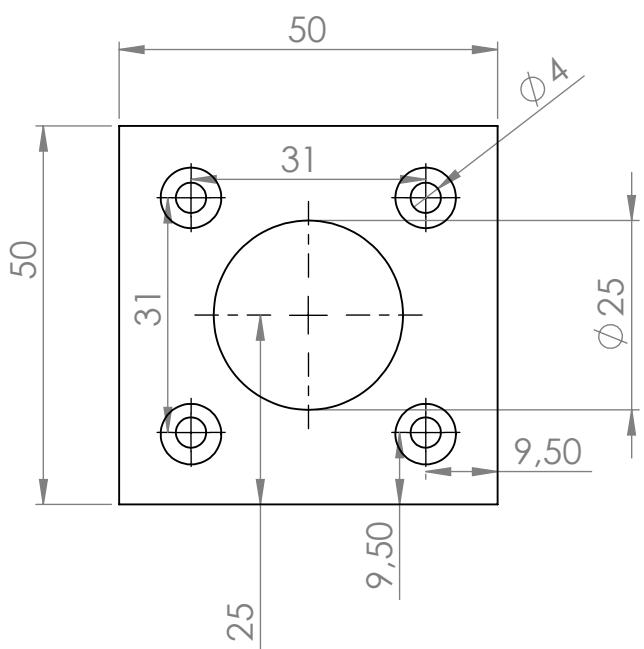
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DRAWN	NAME	SIGNATURE	DATE				
DRAWN	Peter J. Savnik						
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.						
Q.A					DWG NO.	baseplate	
							A4
					WEIGHT:	SCALE:1:5	
						SHEET 5 OF 5	



Bottom side



Front View



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

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

3.1

Motor holder for Nema 17 stepmotor

DRAWN

Peter J. Savnik

SIGNATURE

DATE

TITLE:

CHK'D

APP'D

MFG

Q.A

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AlU

DWG NO.

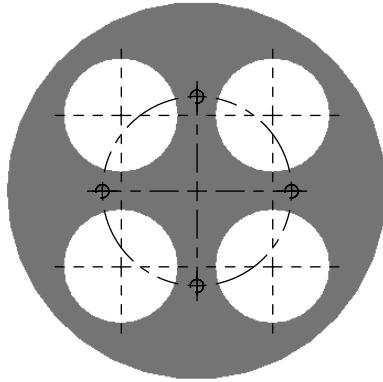
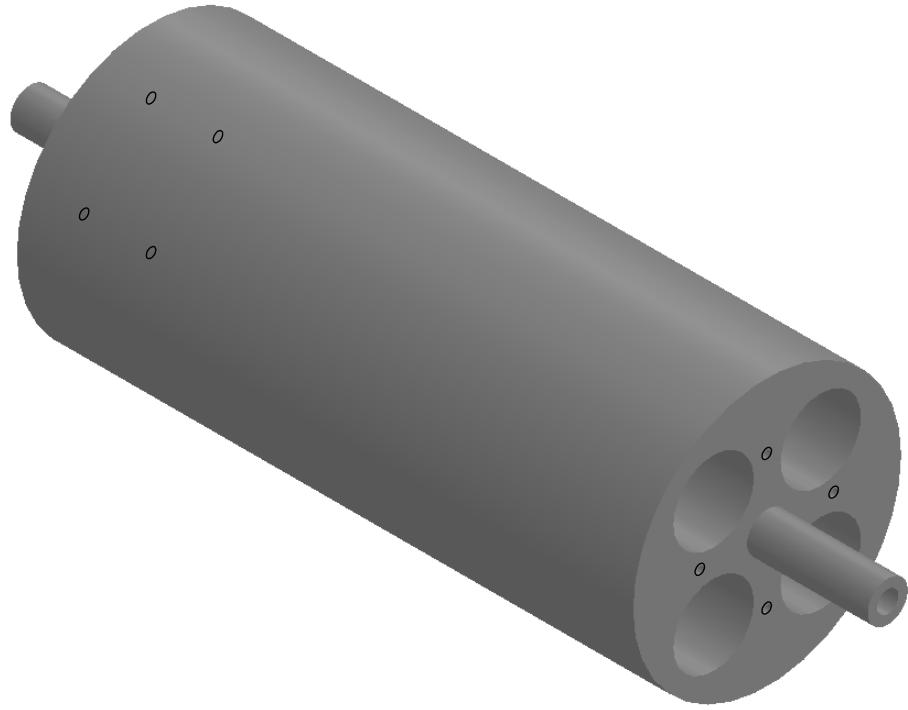
motor-holder

A4

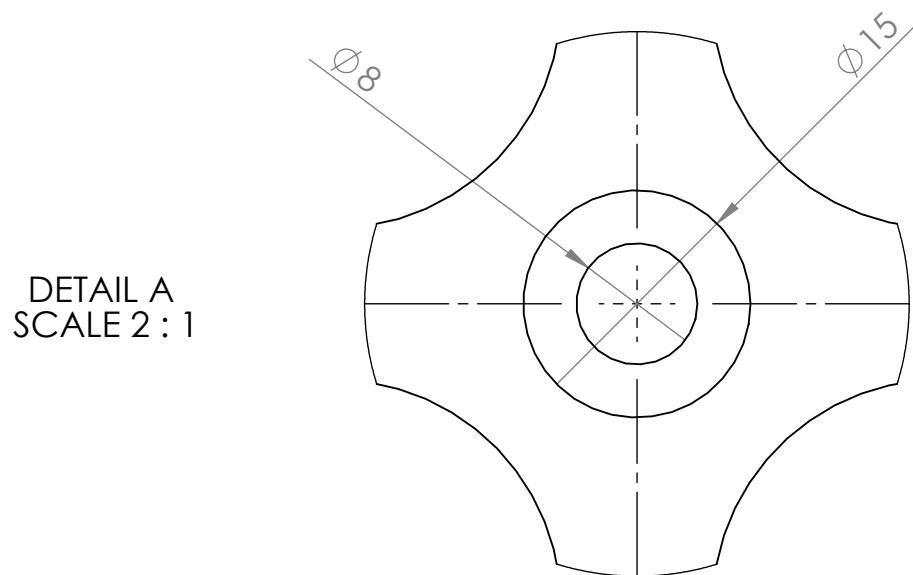
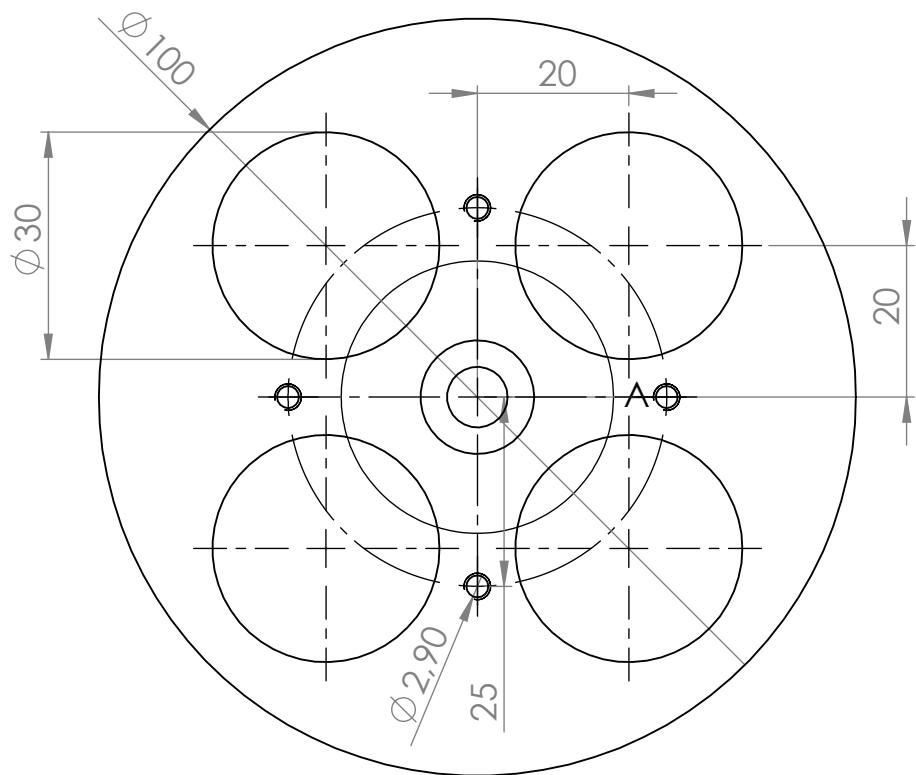
WEIGHT:

SCALE:1:1

SHEET 1 OF 1

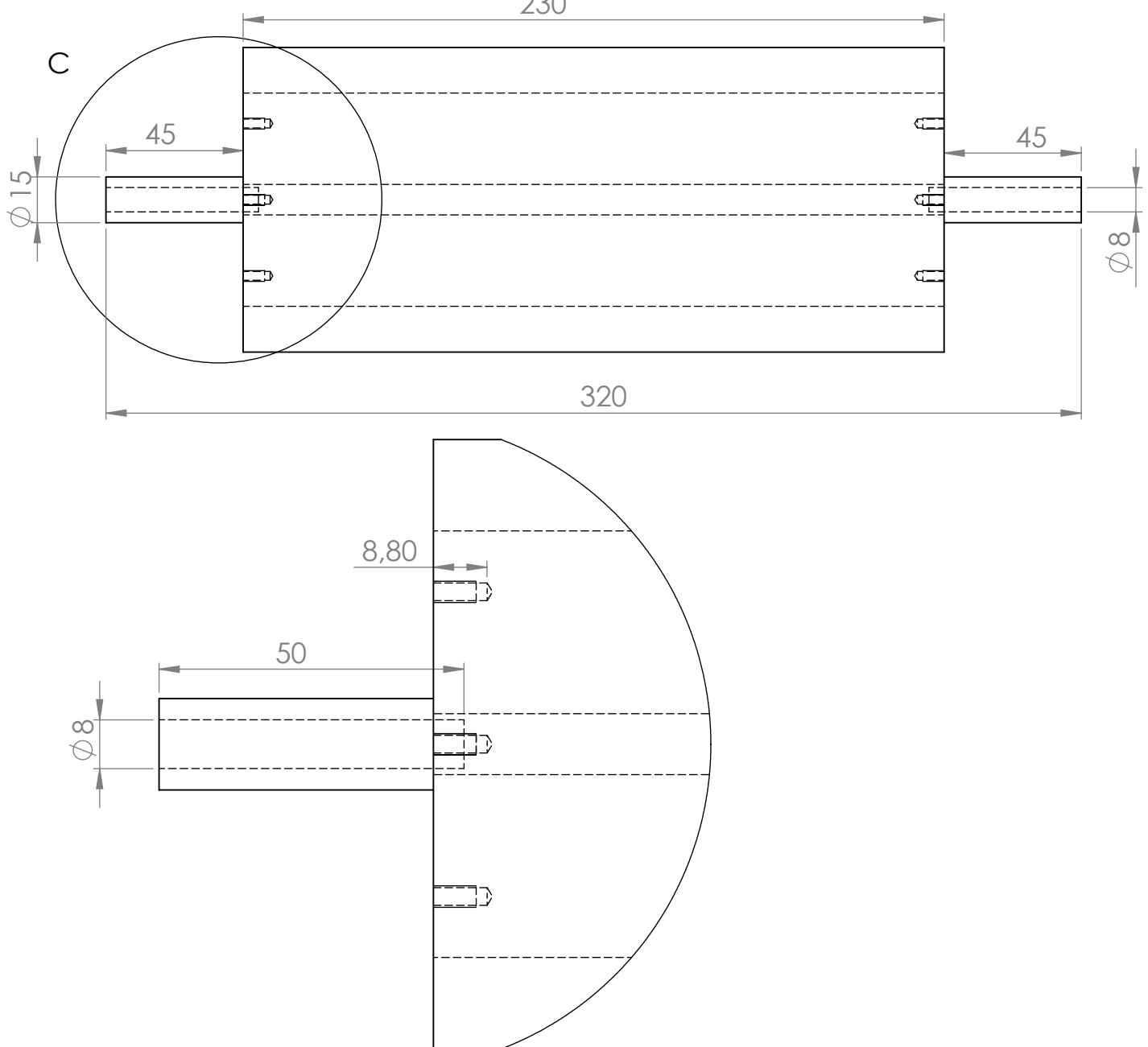


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DRAWN	NAME	SIGNATURE	DATE					
CHK'D								
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.			LATERAL POM		TITLE:	Drumroll rod	
Q.A					DWG NO.		rod	A4
				WEIGHT:		SCALE:1:5	SHEET 1 OF 3	



Side view

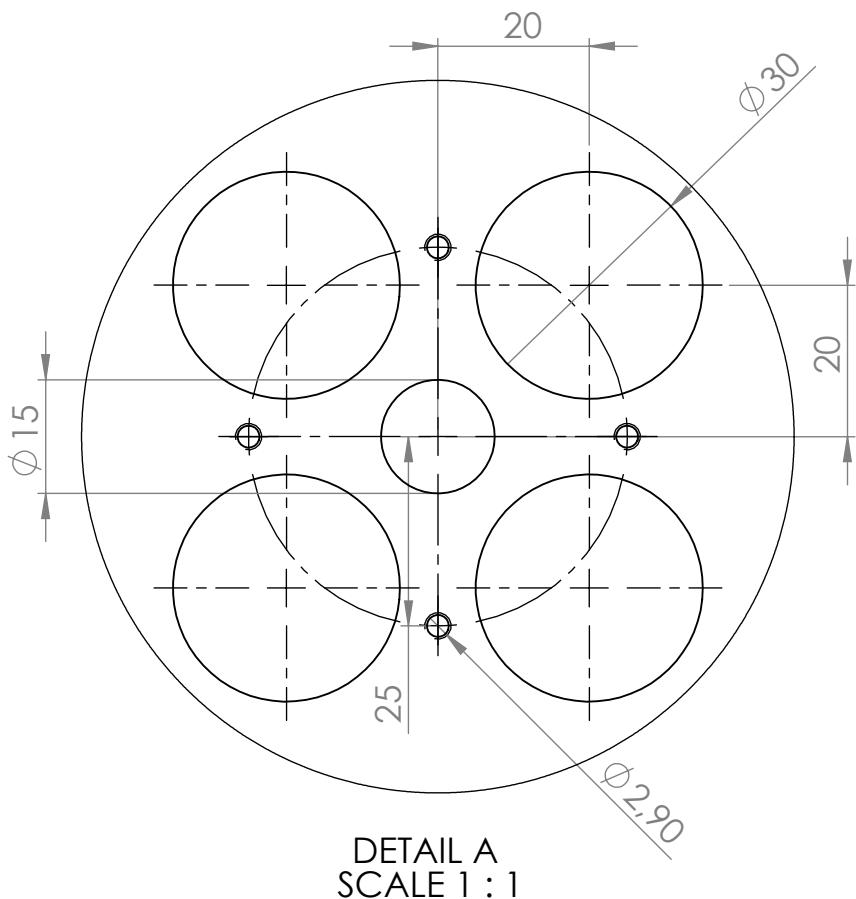
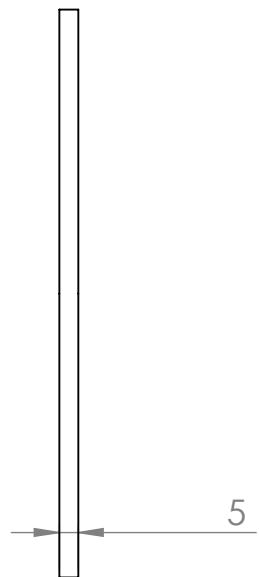
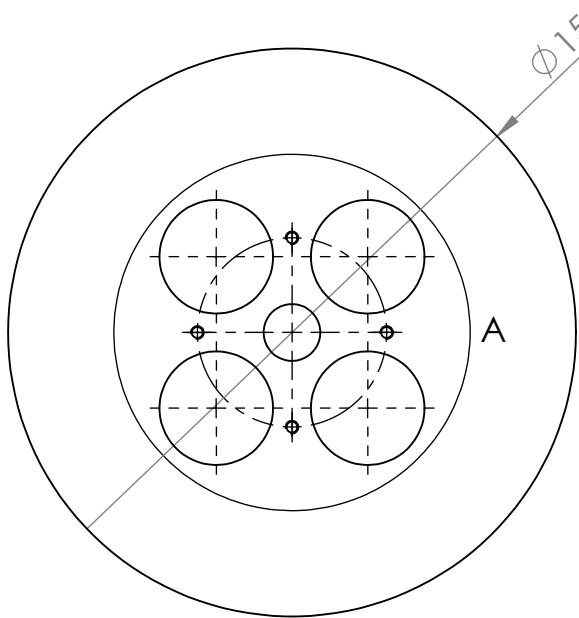
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DRAWN	Peter J. Savnik	SIGNATURE	DATE			TITLE:	DWG NO.	A4
CHK'D								
APP'D								
MFG								
Q.A	SolidWorks Student Edition. For Academic Use Only.							
						rod		
						WEIGHT:	SCALE:1:5	SHEET 2 OF 3



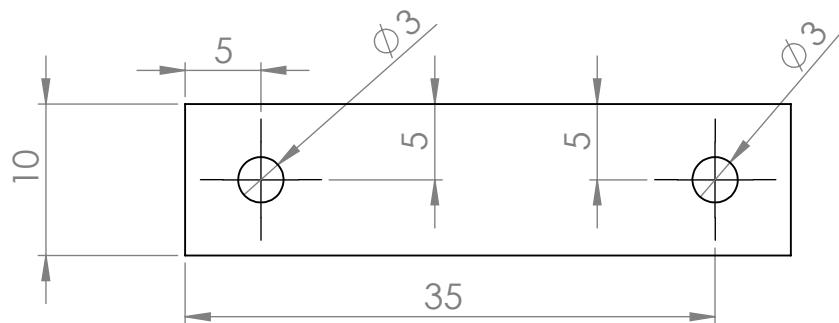
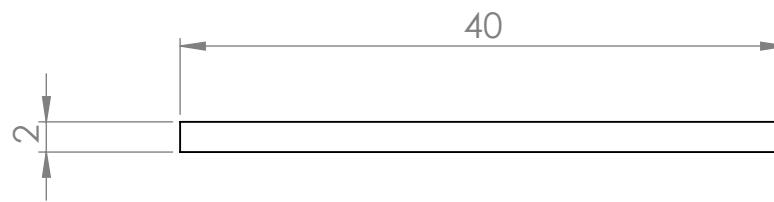
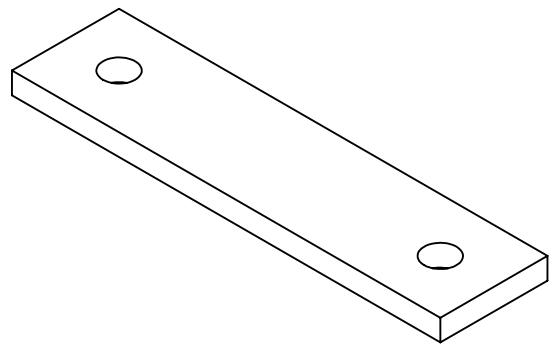
DETAIL C
SCALE 1 : 1

Front view

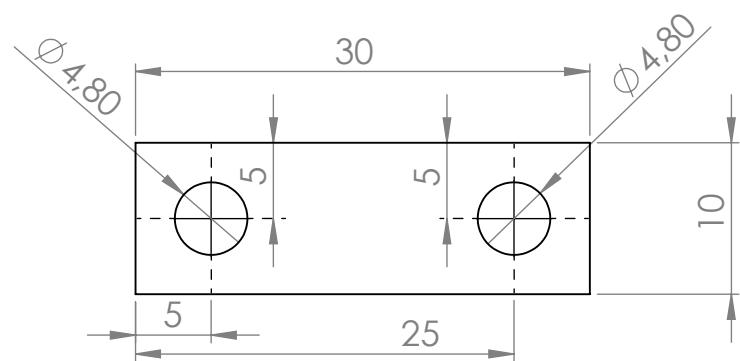
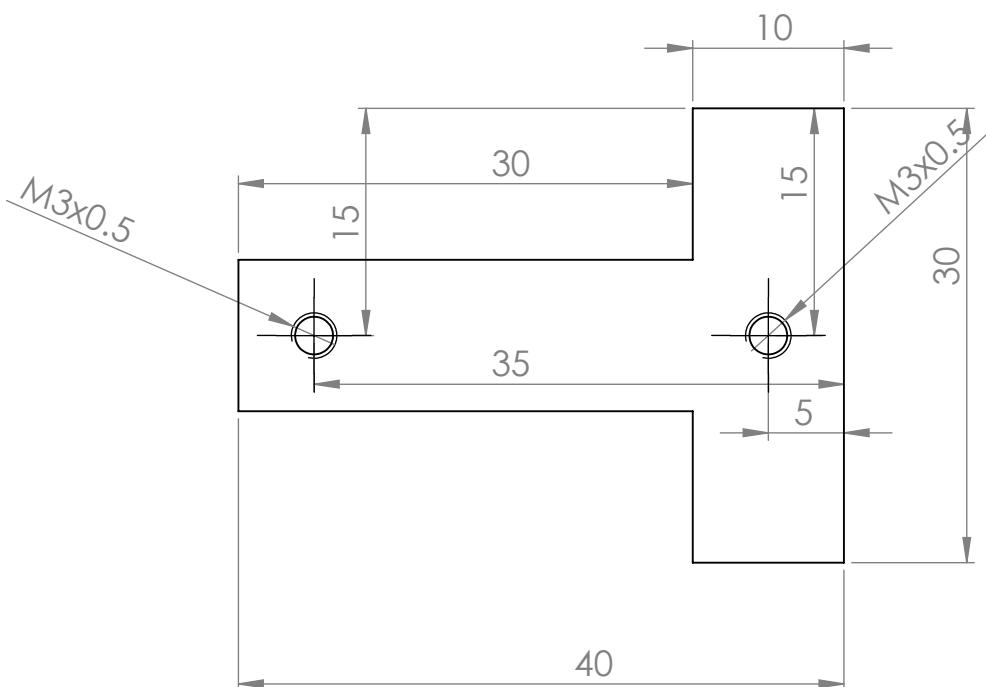
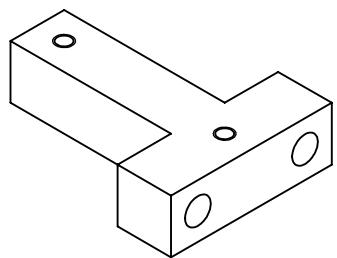
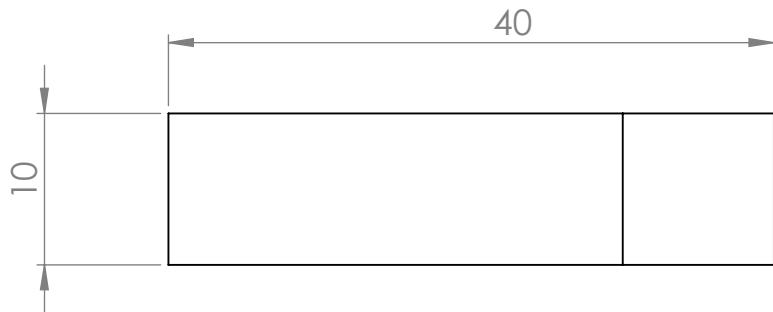
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	3
DRAWN	NAME	SIGNATURE	DATE					
CHK'D								
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.							
Q.A						DWG NO.		
						POM	rod	A4
						WEIGHT:	SCALE:1:5	SHEET 3 OF 3



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	3
DRAWN	NAME	SIGNATURE	DATE				
CHK'D	Peter Savnik						
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.				TITLE:	Side Dish for drumroll	
Q.A	LAYER				DWG NO.	side	
	Acryl						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
DRAWN	NAME	SIGNATURE	DATE				
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.			LATERAL MATERIAL Alu	TITLE:		
Q.A					DWG NO.	belt-fastner-plate	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

DRAWN

NAME

SIGNATURE

DATE

TITLE:

CHK'D

APP'D

MFG

Q.A

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DWG NO.

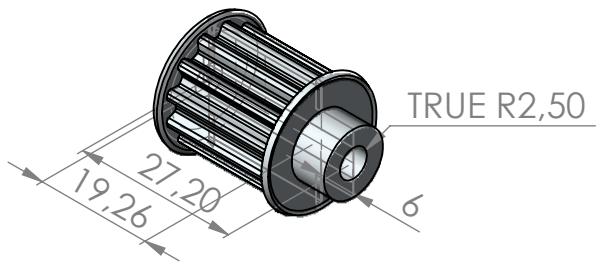
belt-fastner-bracket^{A4}

WEIGHT:

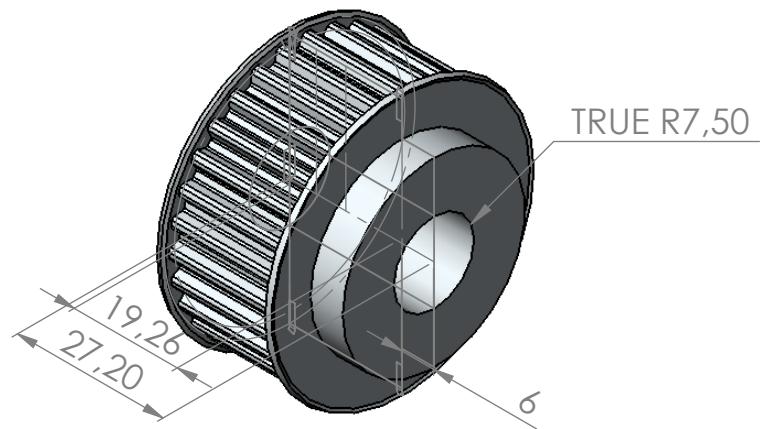
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SHEET 1 OF 1

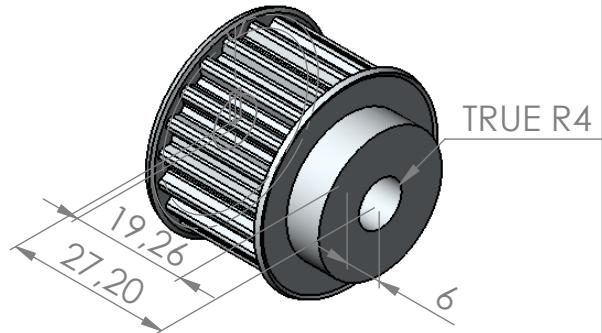
27T5 12-2



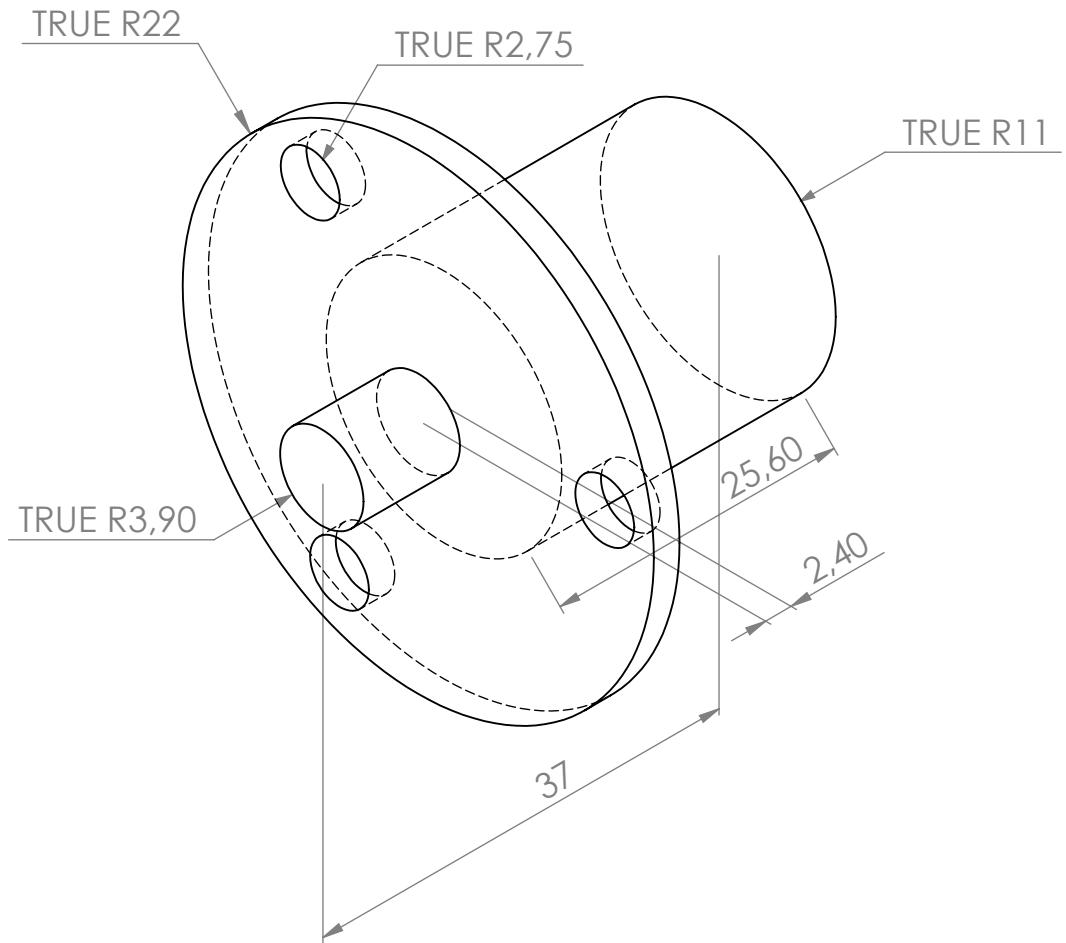
27T5 30-2



27T5 20-2



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DRAWN	NAME	SIGNATURE	DATE			TITLE:		
CHK'D								
APP'D								
MFG	SolidWorks Student Edition. For Academic Use Only.							
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							A4	

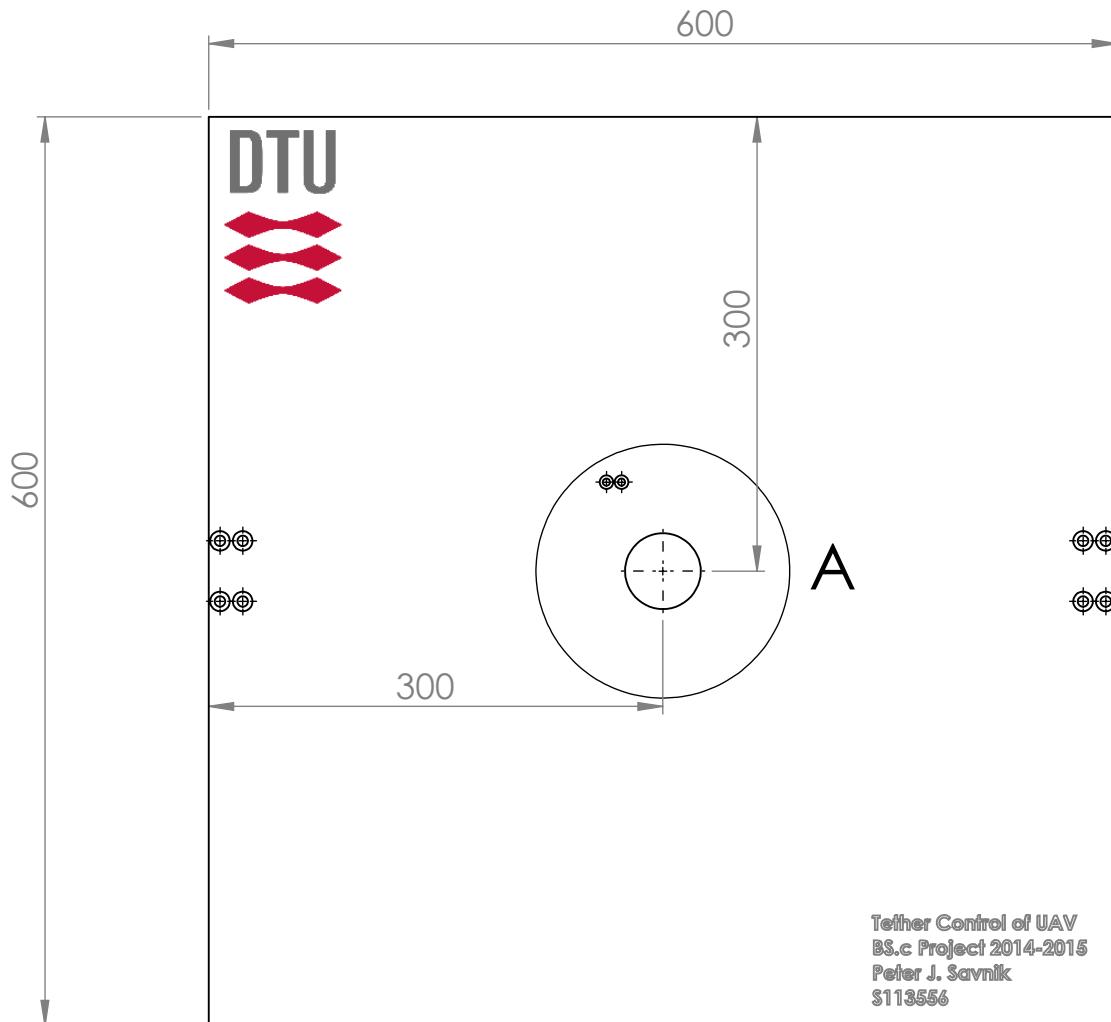


Slipring with flange from Adafruit

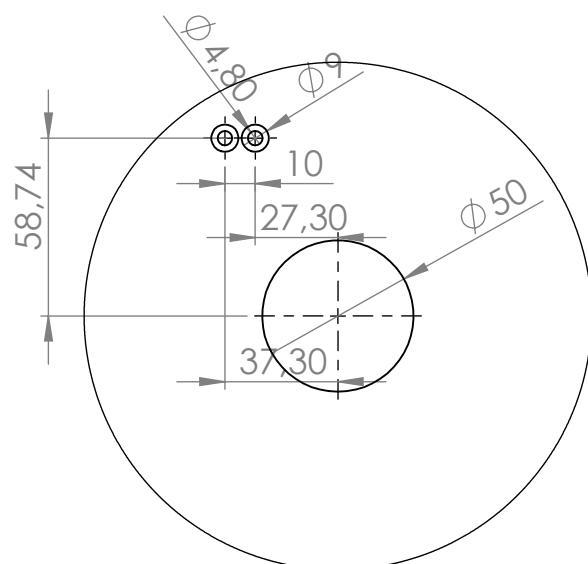
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DRAWN	NAME	SIGNATURE	DATE			TITLE:	
CHK'D							
APPV'D							
MFG							
Q.A	SolidWorks Student Edition. For Academic Use Only.				DWG NO. slip_ring_with_flange^{A4}		
			WEIGHT:	SCALE:1:1		SHEET 1 OF 1	

Helipad

The Helipad is the platform where the UAV land and take off. In the middle of the platform a hole for the cable is made. Next to this hole two counterbore holes fits to mount the horizontal measurement device underneath.



DETAIL A
SCALE 2 : 5

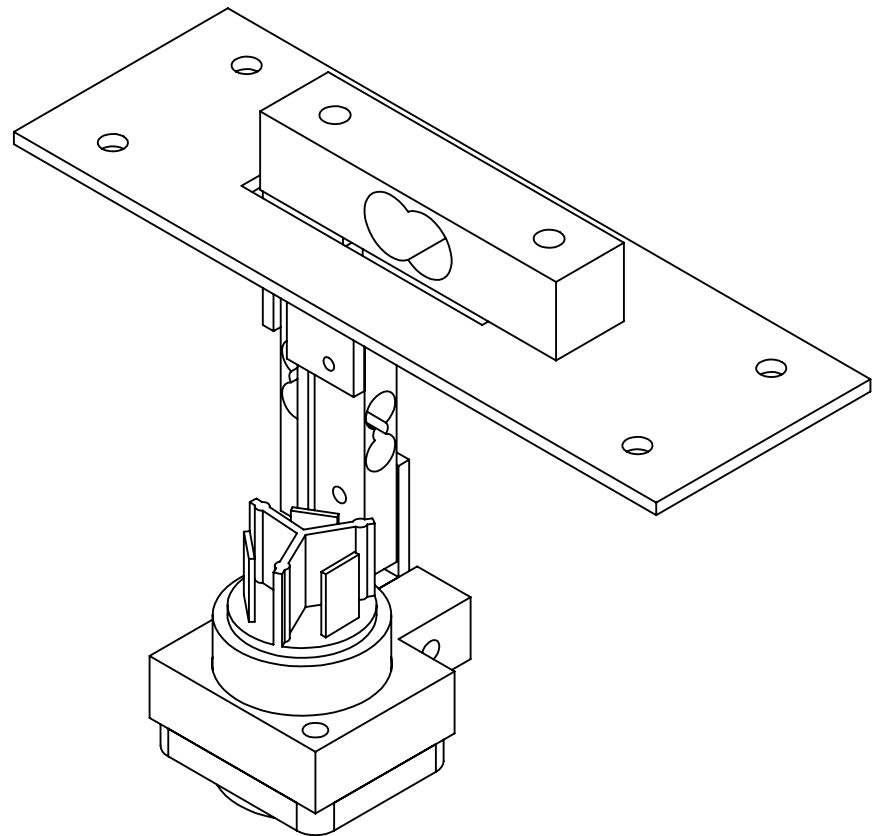


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APP'D						
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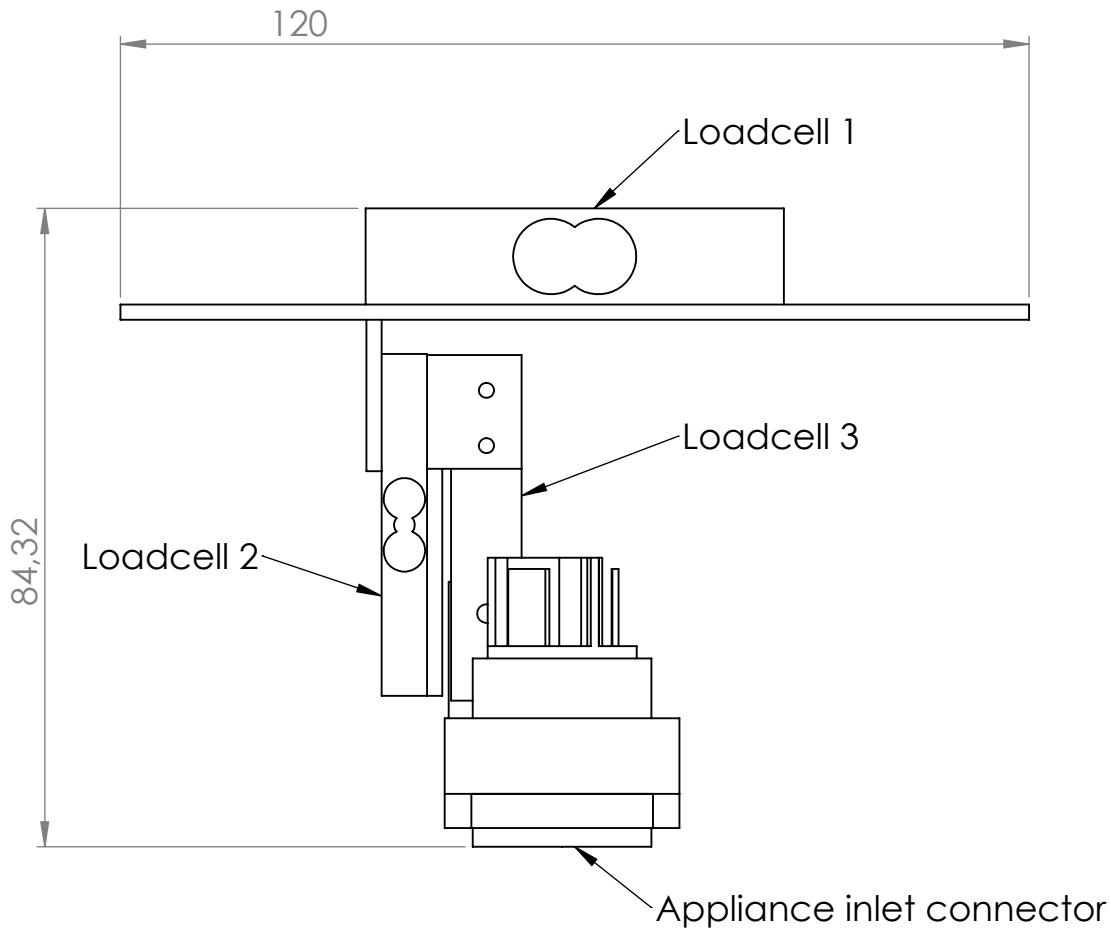
toplevel

D.1 UAV

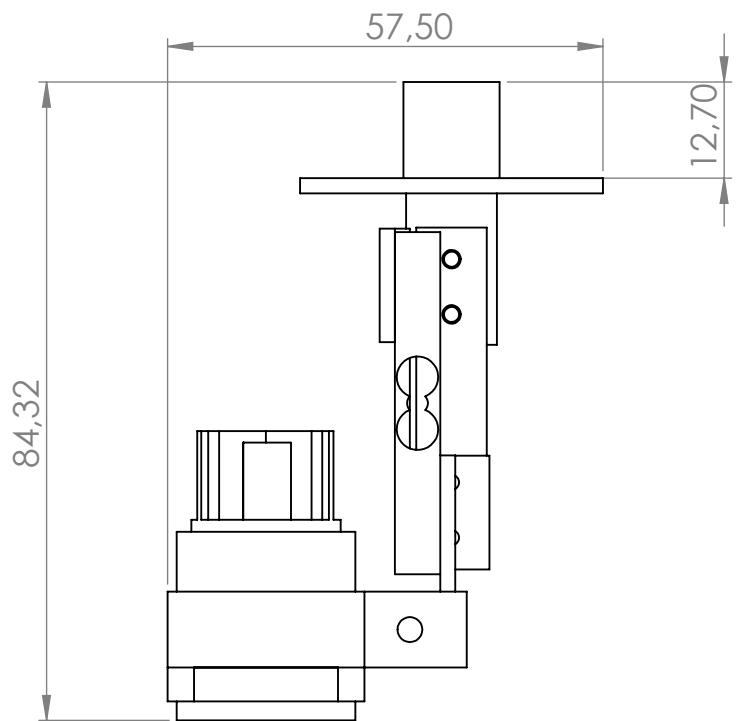
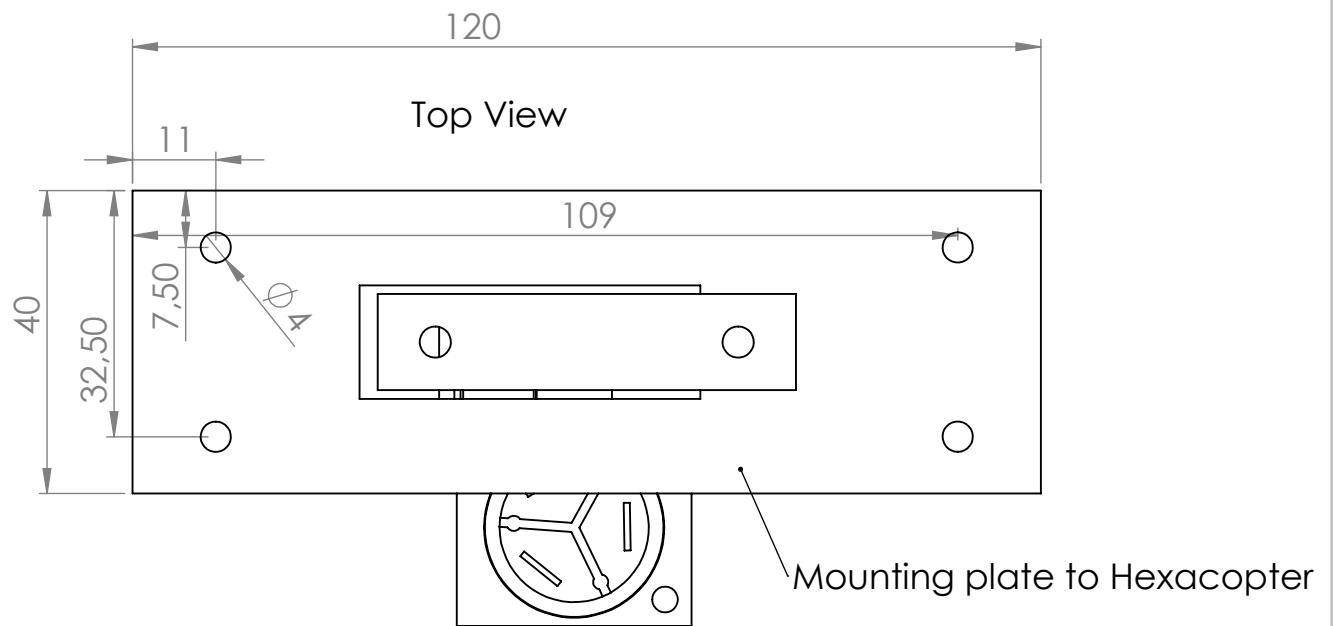
The mechanical configuration on the UAV was partially made from a previous project, but was rebuild to fit a Neutrix powercon true connector and slightly adjusted in the configuration height.



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 4.2
						Peter J. Savnik	
DRAWN	NAME	SIGNATURE	DATE		TITLE: TCUAV		
CHK'D							
APP'V'D							
MFG	SolidWorks Student Edition. For Academic Use Only.			MATERIAL:	DWG NO. hexa-assembly		
Q.A.							
		WEIGHT:		SCALE:1:2	SHEET 1 OF 4		
					A4		



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION
DRAWN	NAME	SIGNATURE	DATE					
CHK'D					TITLE:			
APP'V'D								
MFG	SolidWorks Student Edition. For Academic Use Only.				DWG NO.		hexa-assembly	
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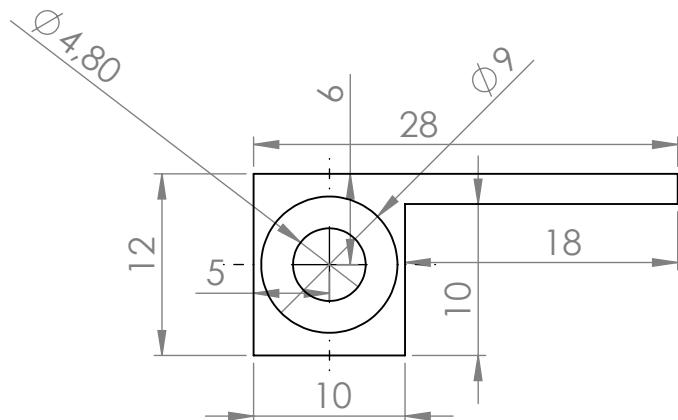
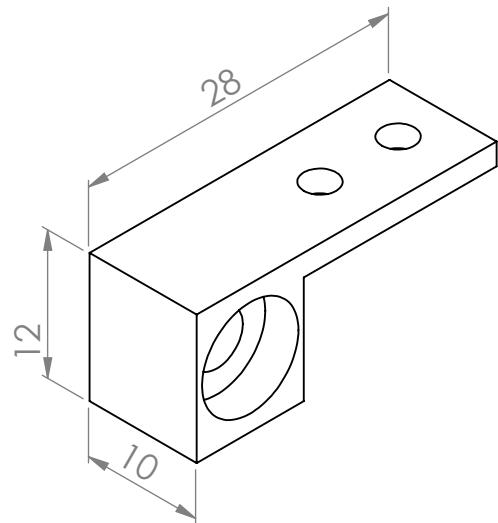
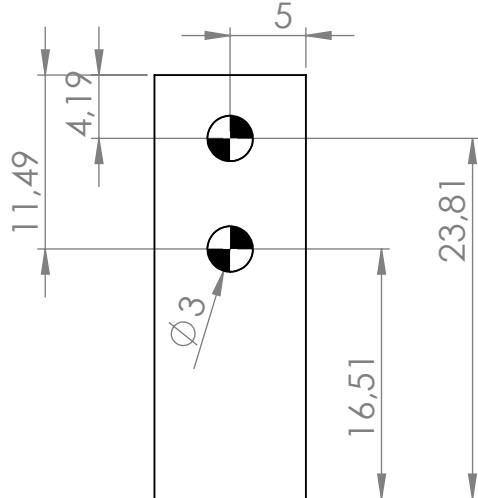


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DRAWN	NAME	SIGNATURE	DATE				
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.			MATERIAL:		TITLE:	
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						A4	

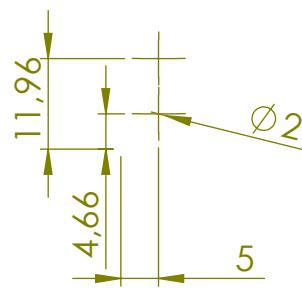
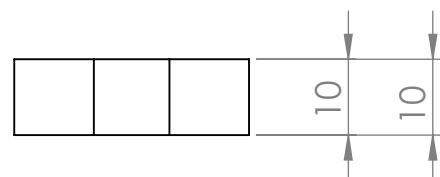
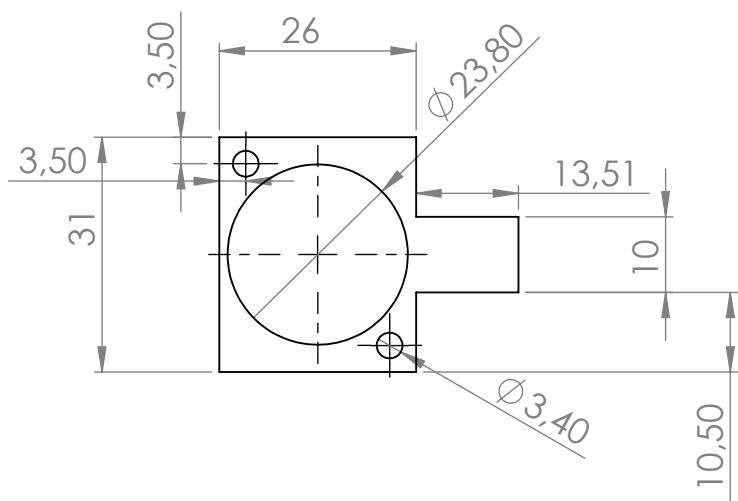
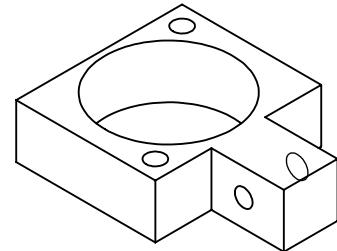
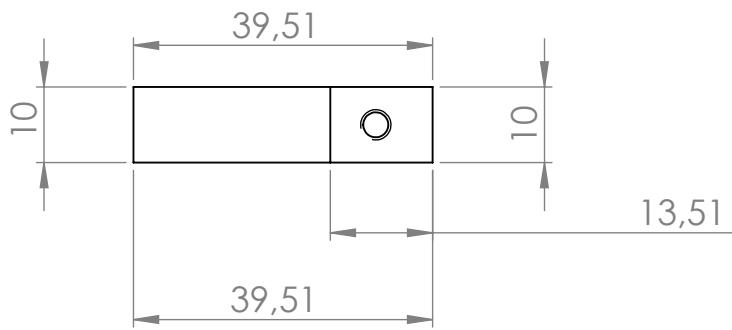
Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	mount-plate		1
2	loadcell-5kg		1
3	fitting-5kg-to-075kg		1
4	loadcell		2
5	fitting-075-to-075		1
6	Neutrix-powercon-true		1
7	powercon-fitting		1
8	powercon-to-loadcell		1

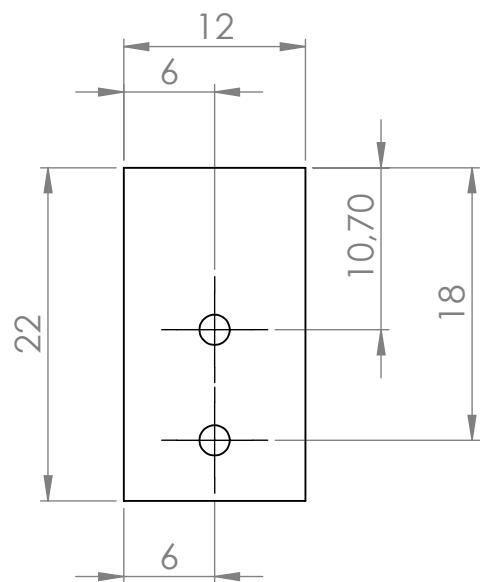
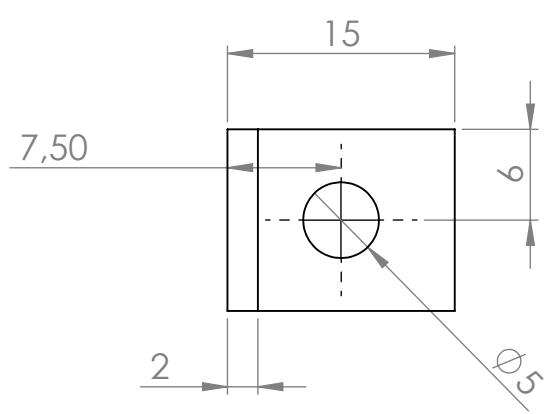
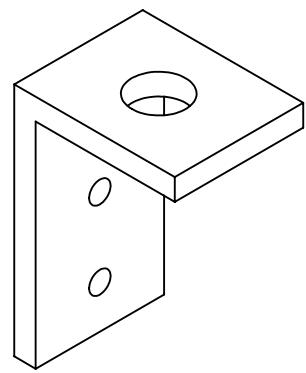
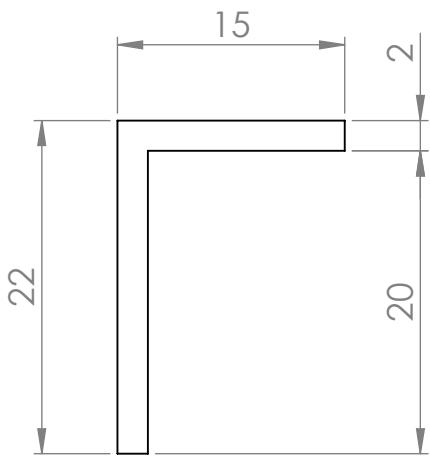
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DRAWN	NAME	SIGNATURE	DATE					
CHK'D					TITLE:			
APP'D								
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			WEIGHT:			SCALE:1:2	SHEET 4 OF 4	



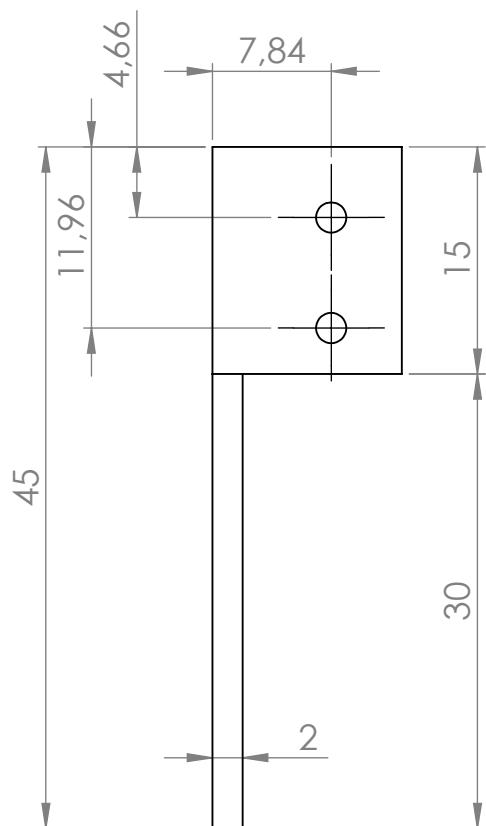
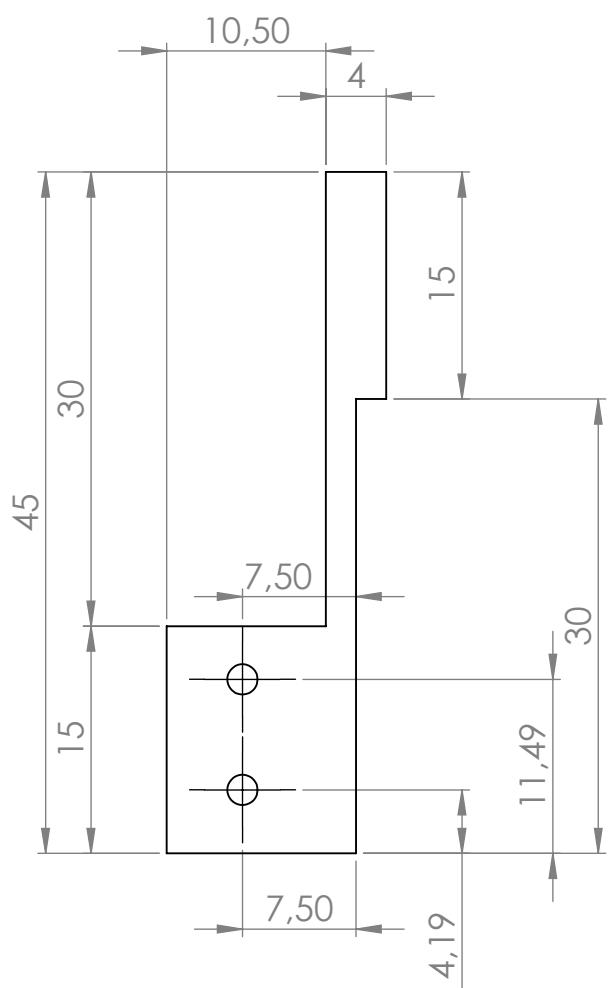
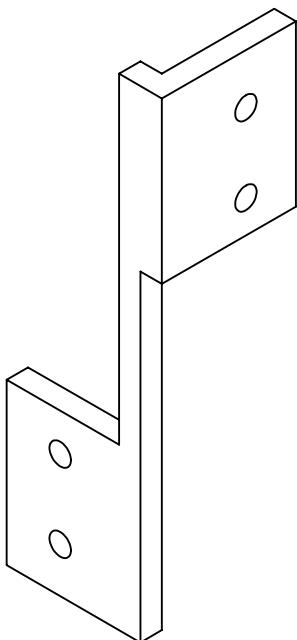
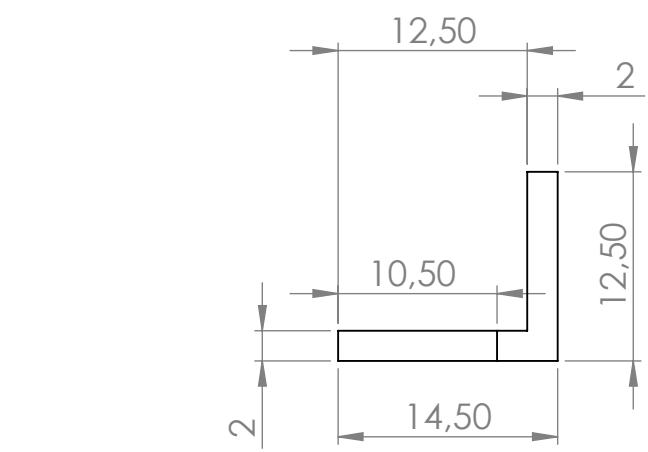
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DRAWN						TITLE: SolidWorks Student Edition. For Academic Use Only.	powercon-to-loadcell
CHK'D							
APPV'D							
MFG							
Q.A							
WEIGHT:					SCALE:2:1	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION
DRAWN	SIGNATURE	DATE					
DRAWN					TITLE:		
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.				DWG NO.		
Q.A					powercon-fitting		A4
					SCALE:1:1		SHEET 1 OF 1
			WEIGHT:				



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN	NAME	SIGNATURE	DATE		TITLE:		
CHK'D							
APP'D							
MFG	SolidWorks Student Edition. For Academic Use Only.				DWG NO. fitting-5kg-to-075kg ^{A4}		
Q.A	MATERIAL:				SCALE:2:1	SHEET 1 OF 1	
	WEIGHT:						



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

FINISH:

DEBUR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

DRAWN

NAME

SIGNATURE

DATE

CHK'D

APP'D

MFG

Q.A

TITLE:

**SolidWorks Student Edition.
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DWG NO.

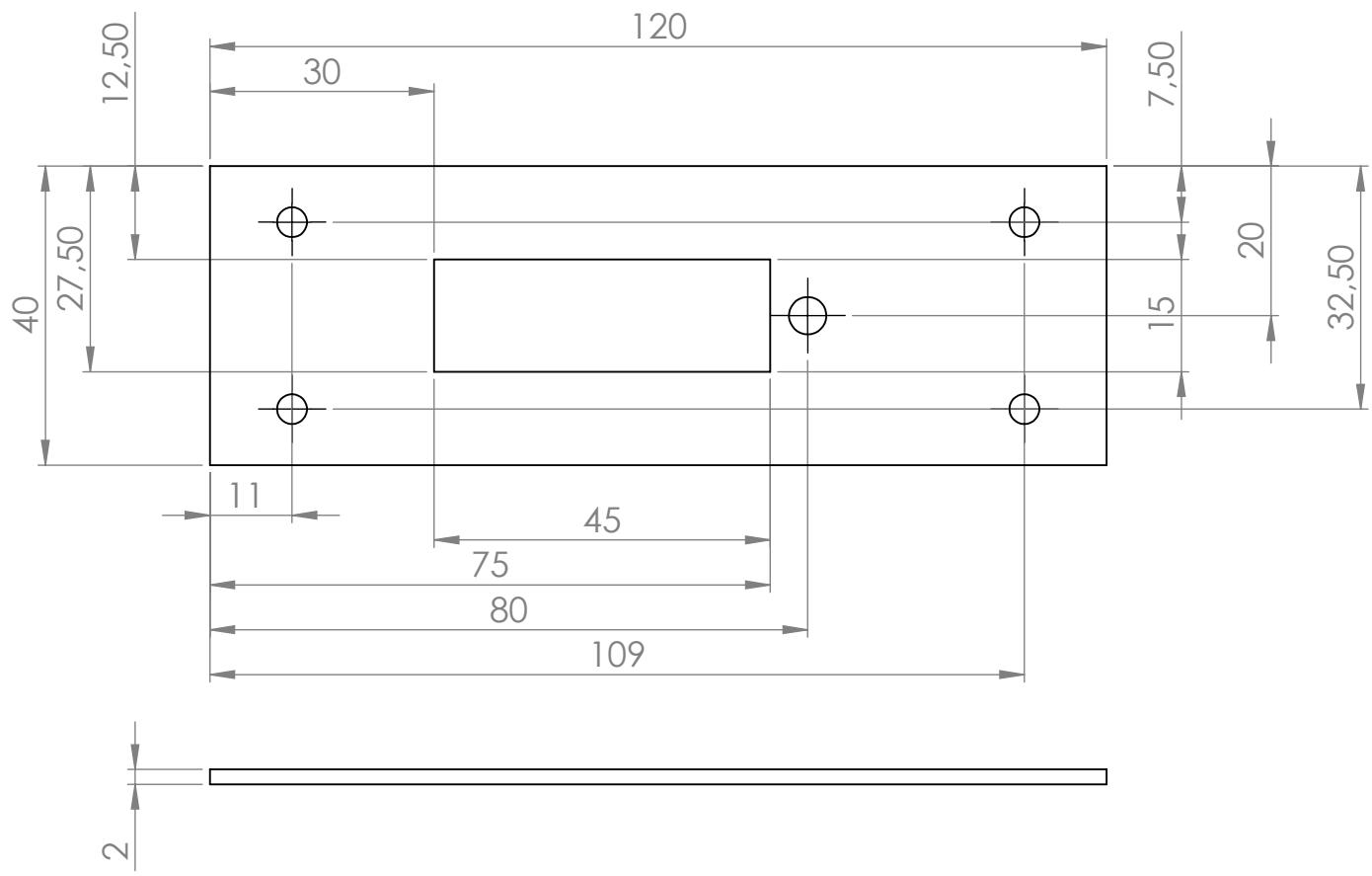
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A4

WEIGHT:

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SHEET 1 OF 1



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