Robocon 2015
Mechanical Team Documentation

Robotics Club, IIT Delhi

Abstract

The annual Robocon competition is an international robotics competition whose national round is held in Pune and is organized by DD and ABU. The theme for Robocon 2015 is Robominton and problem statement is to play a doubles game of badminton with two robots competing with two other robots for a game five points long. The project required a team of students to develop a pair of manual or autonomous badminton playing robots. The robots must follow a stringent set of rules regarding the dimensions, weight and other aspects and should be able to play in a normal sized badminton court with normal rackets and shuttlecocks. The winner of the national round will represent India in the International Robocon held in Indonesia.

Following the relative success of the 2014 IITD Robocon team, the 2015 Mechanical team has focused its energies to the development of more refined and robust systems for the different components and mechanisms used in the robots. Looking at the problems faced by past teams from IITD, the teams have been able to implement several new design strategies and features for this year.

The following document contains the chronological design process that each mechanical subgroup followed to arrive at a complete subsystem design. Then the document covers the integration of the subsystems into a complete robot and then the fabrication of the robots. Finally the testing and final results of the two robots are presented. This document fully chronicles the steps that were followed by the Mechanical design team from the initial group formation to the final testing of the 2015 robots.

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Chapter 1

Theme

The motif of the Robocon 2015 theme is badminton's doubles game. The highlight of this game is how the two robots hit and hit back shuttle by collaborating each other. The longer the rally continues the more exciting the game becomes. The flow of the game is as follows:

- The first server will be decided by a lottery before the game.
- Each team must preload six shuttles that will be provided by the referee. Teams can decide how many shuttles to preload to each robot.
- Service will be delivered by both teams taking turns. When delivering a service, the robot must drop the shuttle vertically using free-fall. The robot that delivers a service must hit the base of the dropped shuttle with a racket. At the moment when the robot delivers a service, the area from shaft to head of the racket must be facing downward lower than horizontal. The racket and the shuttle can come in contact only once per service.
- A rally ensues if the opponent robot is able to return the shuttle. Else, if the shuttle lands in the service zone of the opponent's court successfully, the service team wins a point.
- The contest field is a regular size wooden doubles badminton court. The field is surrounded by a wooden fence.

1.1 Mechanical requirements of robots

- Each team must make two robots.
- Robots cannot be separated.
- The maximum dimension of a robot when fully extended excluding the racket must fit in a cylindrical tube with diameter of 1,200mm and height of 1,500mm.
- The weight of each robot must be under 25kgs. However, if the robot is controlled by cable, the weight of the cable and controller will be included in the total weight.
- There is no limit in the number of rackets that each robot can hold.
- Robot must not jump using propellers.
- The two robots must fit in the robot box with dimension of 1,600mmW X 1,000mmD X 1,400mmH for shipping.
- It is allowed to operate robot using compressed air filled in PET bottle and so on. However it must be under 6 bar of compressed air.
- It is strictly prohibited to use dangerous energy source such as high pressure gas and explosives.
- Robots must be designed in the way that the rubber (or similar) bumper surroundings come in contact first with the object in case of a crash.
- Only commercial racket can be used that has been made based on the regulations set by the Badminton World Federation. The purchased racket shouldn't be transformed. However, the handle of the racket or shaft can be remodeled so that it won't be detached from the robot during the game. The racket should be attached using plural methods so that in case one fixing is broken the racket doesn't fly away.

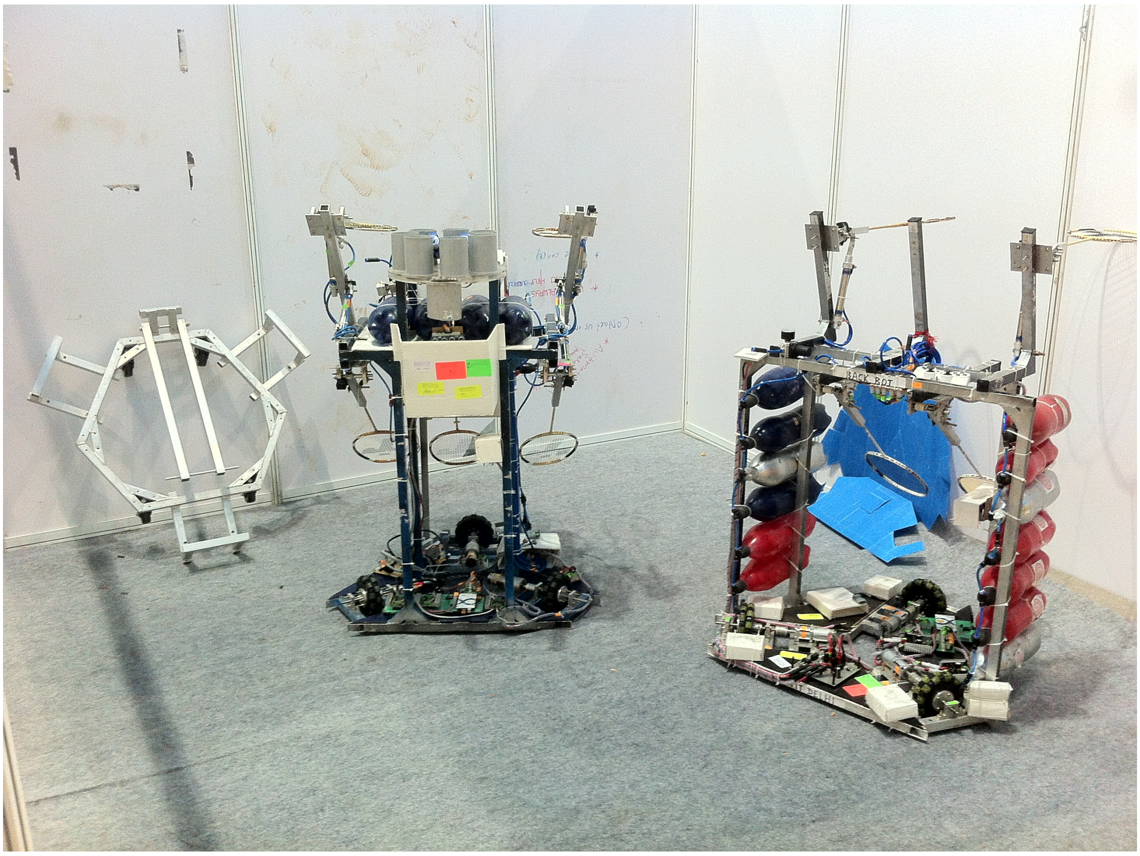


Figure 1.1: After the competition, 7th position in India and winner of Best Innovative Design Award

Figure 1.2: The 2015 IITD Robocon team

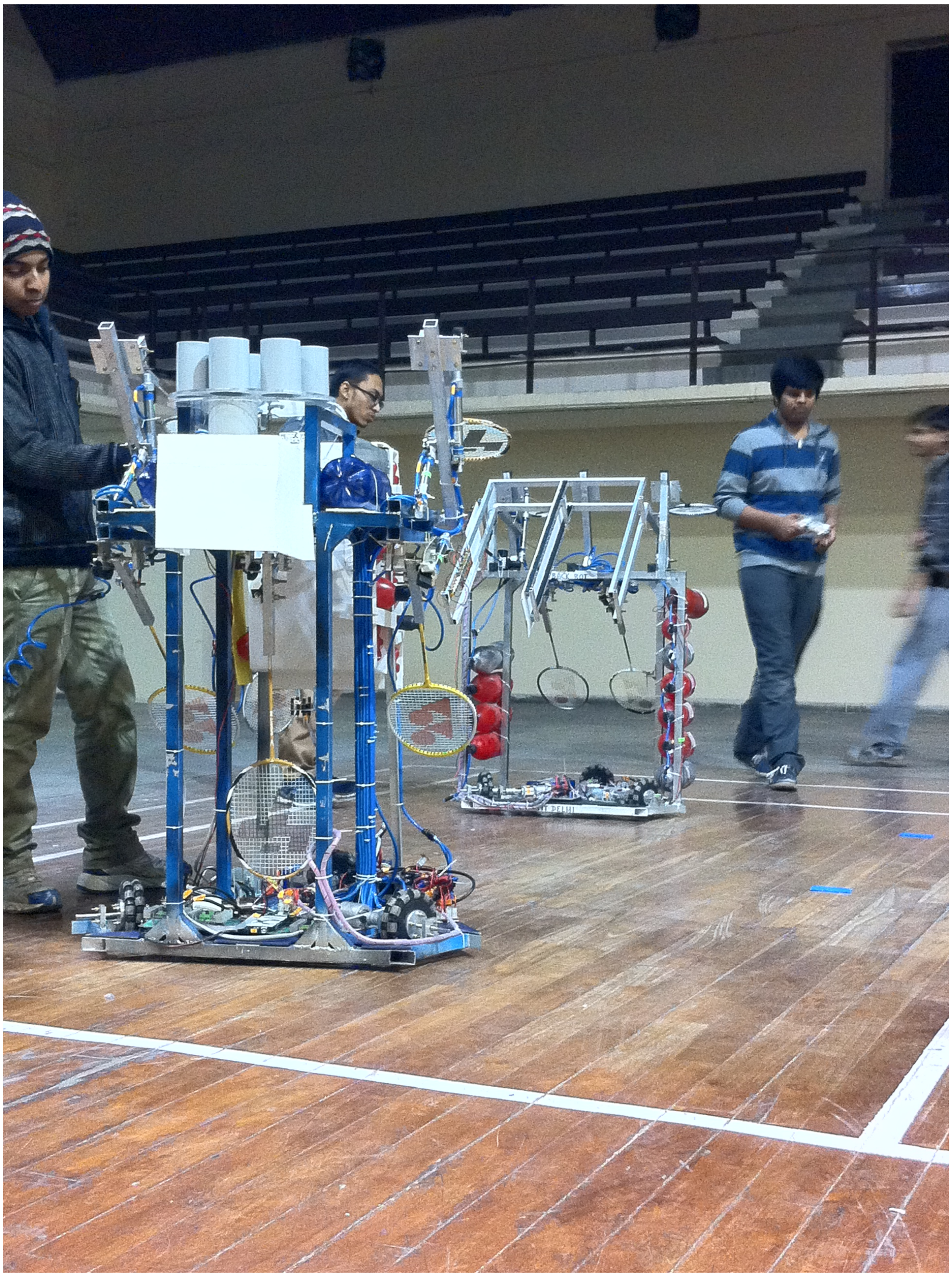


Figure 1.3: Robots in action during a practice session

Chapter 2

Mechanical System overview

The mechanical design team comprised of three 3rd year and seven 2nd year students. The range of experience has led to a very productive and educational experience.

The 2015 Mechanical Design Team consists of our faculty advisors: Subir Kumar Saha, Sunil Jha, Kolin Paul, Jitendra Prasad Khatait and Dharmender Jaitly

Mechanical team members:

1. Rishabh Agarwal (Team Leader)
2. Himanshu Patel
3. Rahul Kumar
4. Harshit Chauhan
5. Jyotirmoy Ray
6. Kuldeep Singh Rathore
7. Nalin Bendapudi
8. Saurabh Sinha
9. Shivam Agarwal
10. Shubham Kumar Prajapati

2.1 2015 Mechanical Organization and Structure

The team followed a parallel process where different subsystems of the design were completed simultaneously and the integration was done on the main chassis immediately. The team also worked in parallel with the electrical group regarding the wiring and position and mounting of sensors. The team had also established a schedule and a budget to help organize the tasks that needed to be accomplished within the year.

Chart of Robotics Club.jpg

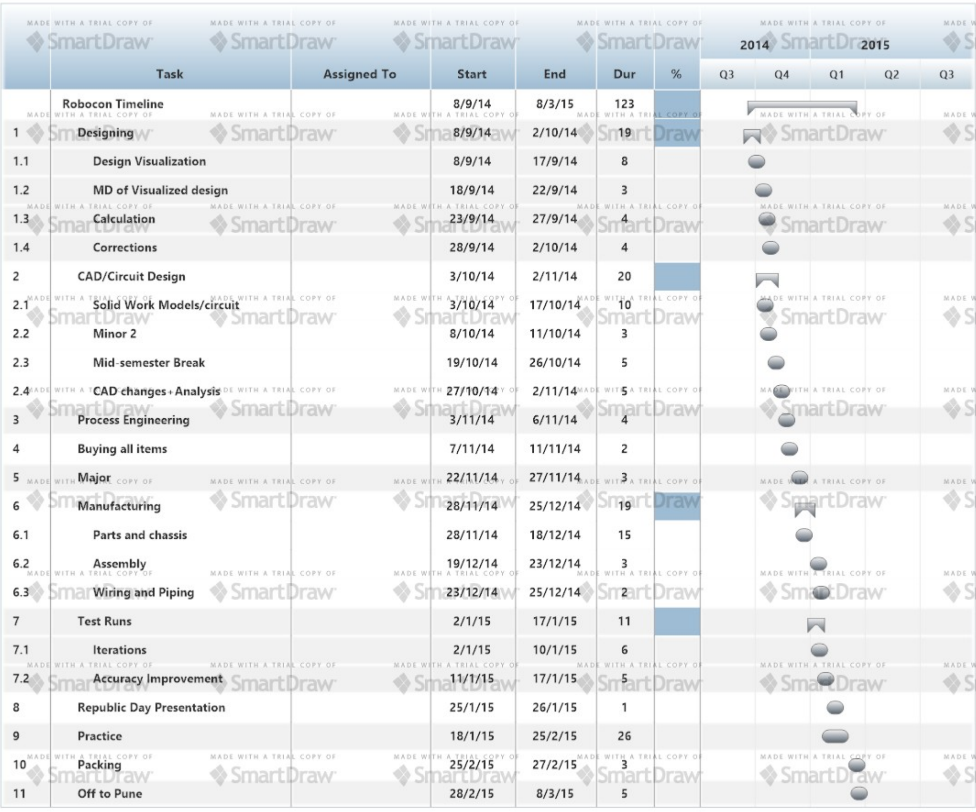

	Task	Assigned To	Start	End	Dur	%
	Robocon Timeline		8/9/14	8/3/15	123	
1	Designing		8/9/14	2/10/14	19	
1.1	Design Visualization		8/9/14	17/9/14	8	
1.2	MD of Visualized design		18/9/14	22/9/14	3	
1.3	Calculation		23/9/14	27/9/14	4	
1.4	Corrections		28/9/14	2/10/14	4	
2	CAD/Circuit Design		3/10/14	2/11/14	20	
2.1	Solid Work Models/circuit		3/10/14	17/10/14	10	
2.2	Minor 2		8/10/14	11/10/14	3	
2.3	Mid-semester Break		19/10/14	26/10/14	5	
2.4	CAD changes+Analysis		27/10/14	2/11/14	5	
3	Process Engineering		3/11/14	6/11/14	4	
4	Buying all items		7/11/14	11/11/14	2	
5	Major		22/11/14	27/11/14	3	
6	Manufacturing		28/11/14	25/12/14	19	
6.1	Parts and chassis		28/11/14	18/12/14	15	
6.2	Assembly		19/12/14	23/12/14	3	
6.3	Wiring and Piping		23/12/14	25/12/14	2	
7	Test Runs		2/1/15	17/1/15	11	
7.1	Iterations		2/1/15	10/1/15	6	
7.2	Accuracy Improvement		11/1/15	17/1/15	5	
8	Republic Day Presentation		25/1/15	26/1/15	1	
9	Practice		18/1/15	25/2/15	26	
10	Packing		25/2/15	27/2/15	3	
11	Off to Pune		28/2/15	8/3/15	5	

Figure 2.1: Gantt Chart of Robotics Club

2.2 Mechanical Team structure

During the initial design conceptualization phase, just after the problem statement was released, the entire club was divided into four teams with the task of coming up with a solution to play badminton with robots. Also each team had to demonstrate one of their mechanisms as a Proof of Concept demonstration.

Finally the mechanical team was broadly divided into three teams for the drive, the shuttle hitting mechanism and the shuttle dropping mechanism.

2.3 Mechanical Design Team goals

From the combination of the design ideas and POCs of the four teams formed initially, a set of requirements were passed onto the mechanical sub-groups that set the goals for the design team. Each of these goals are reviewed below:

2.3.1 Omnidirectional drive

The drive system was integral to the movement of the robots on the badminton court. In addition to the drives being quick and able to cover the length of the court fast enough to intercept the shuttle, the system also needs to be agile and able to change direction quickly. Thus the following objectives were given to the drive group:

- Design drive with holonomic capabilities (i.e. 3 degrees of freedom)
- Maximize drive speed and acceleration
- Improve traction and prevent slipping of wheel

2.3.2 Hitting mechanism

The hitting system had to ensure that the rackets used to hit the shuttle are moving at the optimum speed and angle so that the shuttle can cross the net after being hit and land inside the court. Therefore the objectives of the hitting mechanism were:

- Study flight of shuttlecock and find optimized angles for hitting
- Design mechanism for actuating racket

- Mounting racket without violating the rules as said in the rulebook
- Ensure racket doesn't break or fly off while playing in the field

2.3.3 Dropping mechanism

The dropping mechanism was integral to the service subsystem and it had to be able to contain six preloaded shuttlecocks and drop them one by one vertically. The objectives of the dropping mechanism were:

- To drop a single shuttlecock when required while securely containing the remaining shuttles
- Make system reliable and less prone to failure by jamming

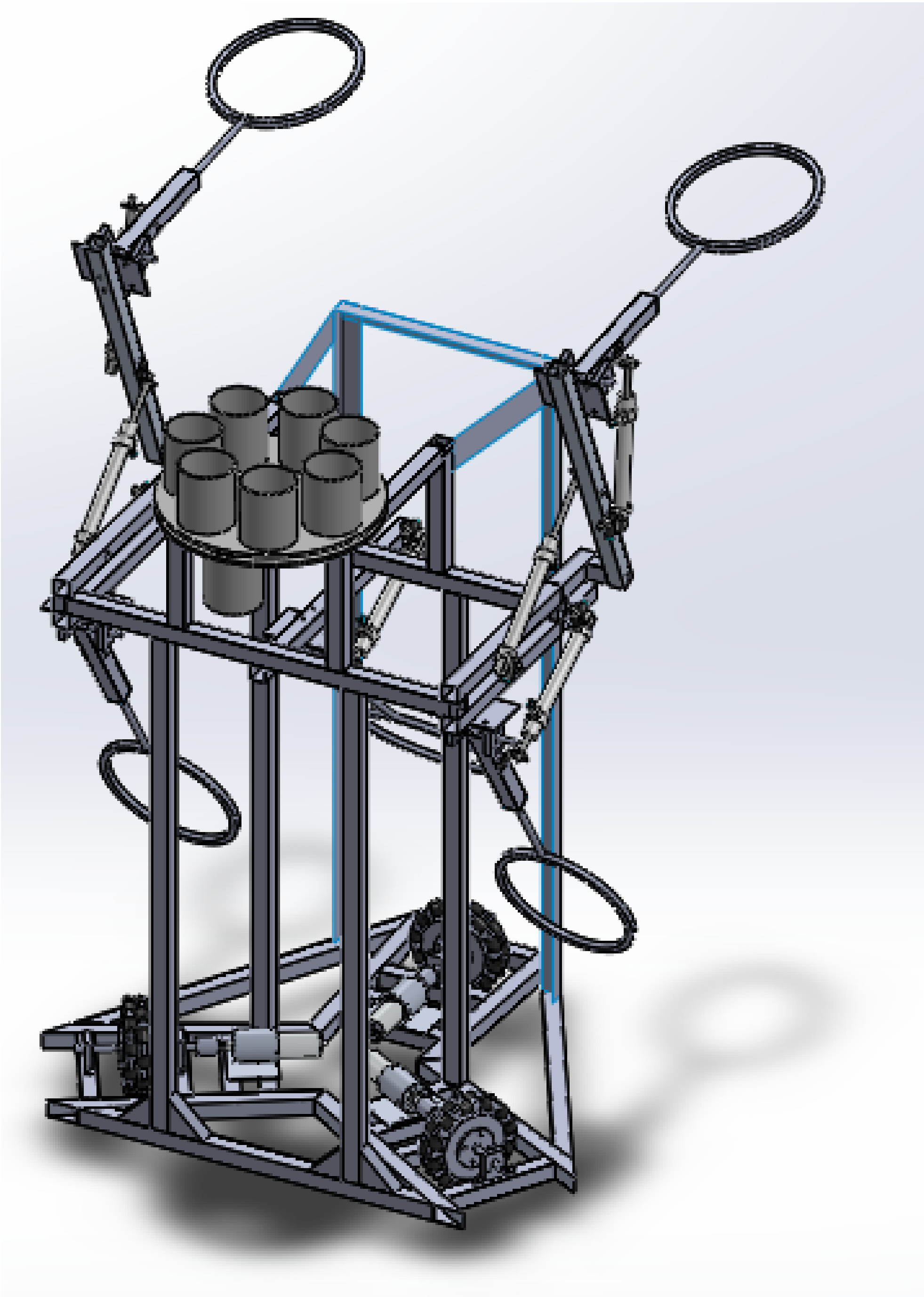


Figure 2.2: Front robot CAD rendering (isometric view)

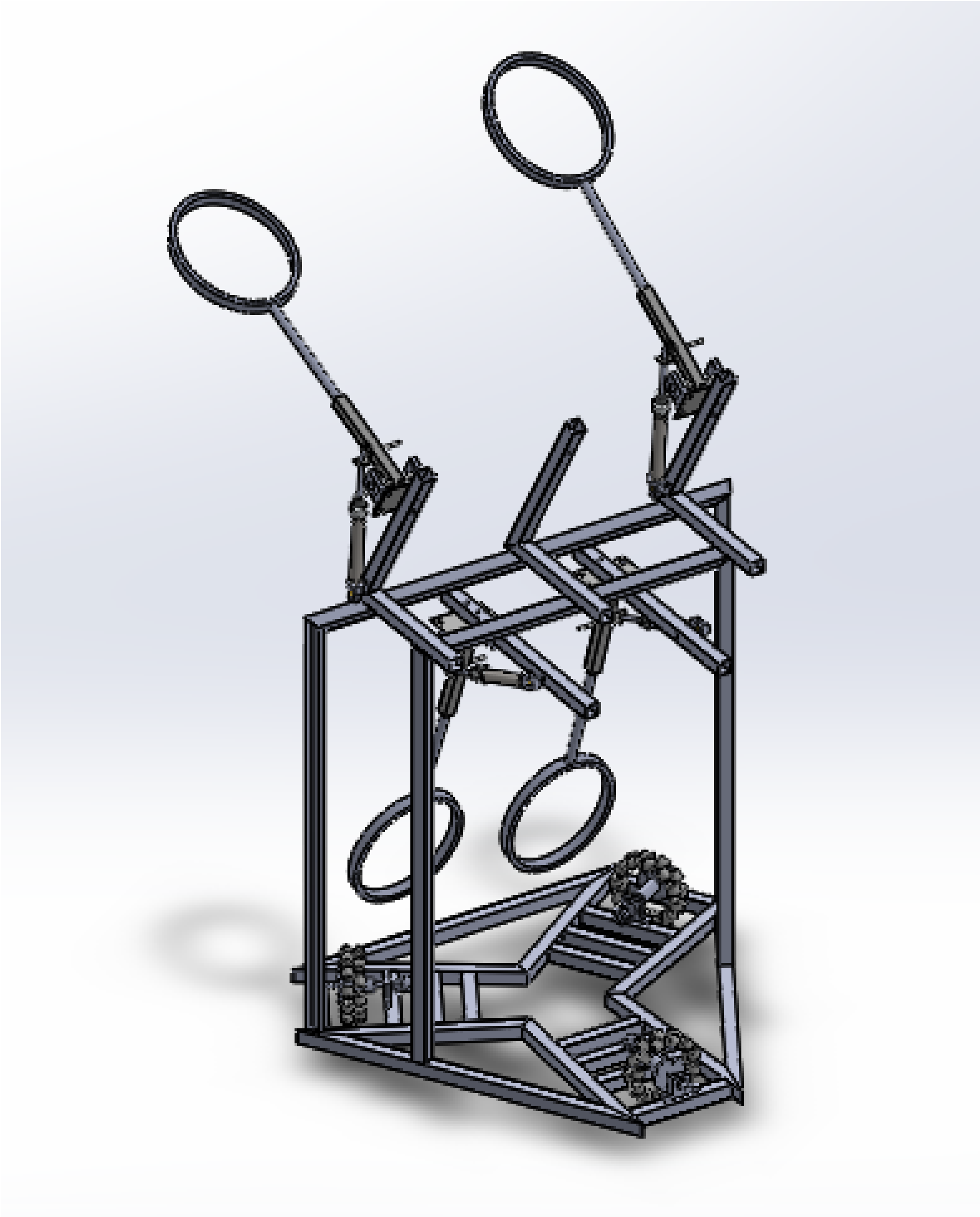


Figure 2.3: Back robot CAD rendering (isometric view)

Chapter 3

Omni-Directional Drive Documentation

3.1 Introduction

The omni-directional drive is the component responsible for the movement of the robot in the badminton court. Omni-directional or holonomic drive implies that the robots have three degrees of movement in the horizontal plane: two translational degrees of freedom and one rotational degree of freedom. This system is perhaps the most critical system of the robot, for without it, the robots would be incapable of moving about the playing field. Further, the omni-directional design removes any kinematic restrictions on the drive system. Hence it is more intuitive to control the robot while playing badminton as one has the freedom to accelerate the robot in any direction at any time.

3.2 Preliminary design

During the summer camp of 2014, a preliminary design was developed for a three wheel holonomic drive system. This section documents all the analysis, design done in the process of achieving a preliminary design.

3.2.1 Proposed ideas

The following are the two designs that were proposed for the base of the chassis. The second chassis was selected owing to its lighter weight and lesser number of welds.

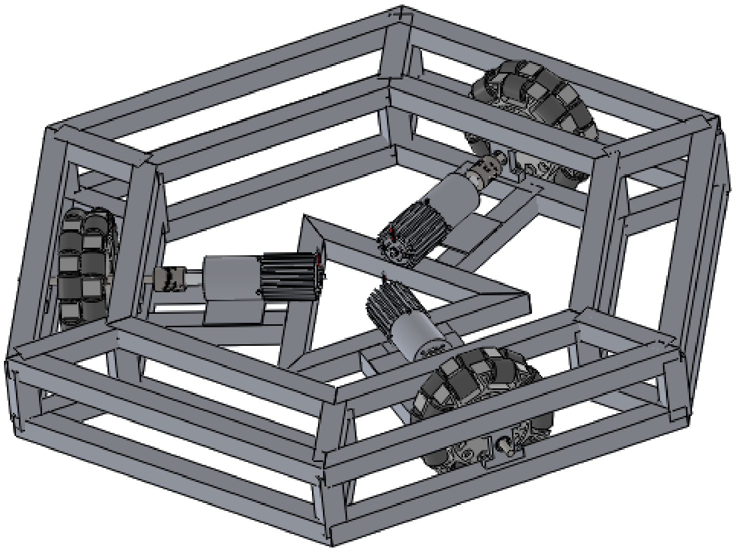


Figure 3.1: Double layered hexagonal chassis design

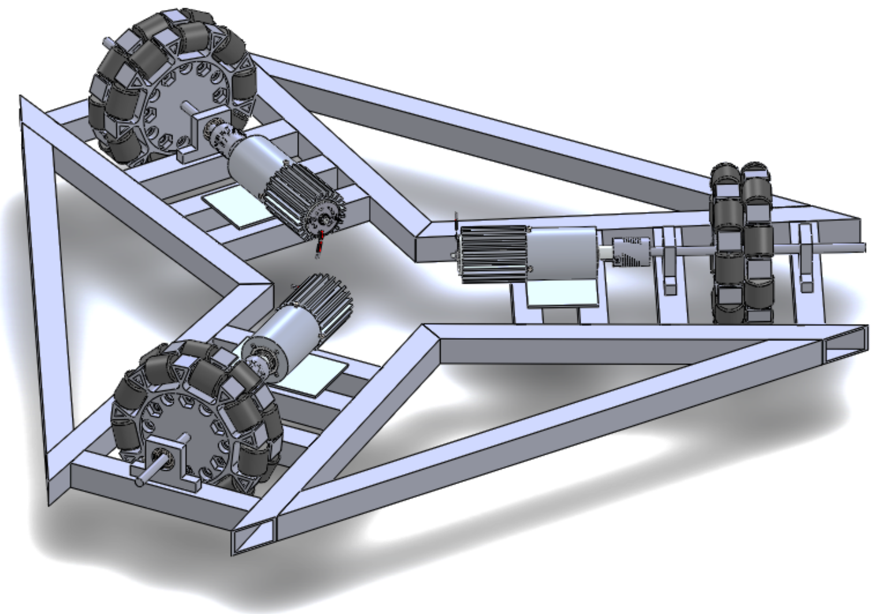


Figure 3.2: Single layer triangular chassis

3.2.2 Major design objectives

Based upon experiences from past years Robocon robots, the major goals for the drive system are:

- Design base to stay within dimensional limits
- Ensure symmetrical distribution of weight on wheels
- Reduce ground clearance for greater stability of robot while moving with high acceleration and speed, especially while changing directions
- Minimize weight of system for faster acceleration

Additionally, we also want to improve the pneumatic piping by integrating it to the "channel flow" in the chassis. Doing so makes the piping neater and makes troubleshooting and repair work easier and faster.

Our last goal was to make the drive and the chassis more robust and in less need for alternations and maintenance. To ensure this, we custom built housings for the bearings, and iterated the design of the wheel hub and shaft for the best possible design.

3.2.3 Simulation

Stress and deflection analysis was done on the frame of the chassis subsequently by applying loadings in different cases using SolidWorks 2014.

Simulation results: The simulations show that the maximum stress generated in the chassis and the maximum displacement due to the forces are well within the limit of the material properties of Aluminum 7000, which is used to manufacture the chassis.

The simulation results are shown in *Figures 3.4, 3.5, 3.6 and 3.7.*

3.3 Design Parameters

For a holonomic drive, there are a number of design parameters that we have to work with. An alteration in any one of these may significantly help or hurt achieving design objectives. These parameters include:

- Motor and wheel selection
- Number of wheels
- Wheel orientation

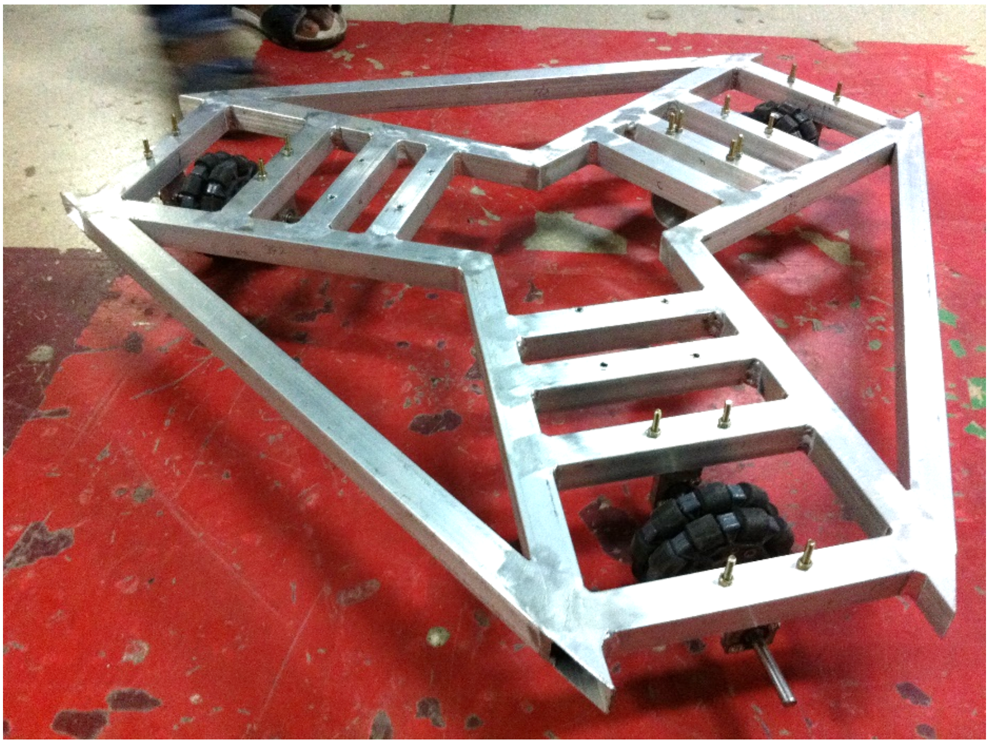


Figure 3.3: Drive base after welding

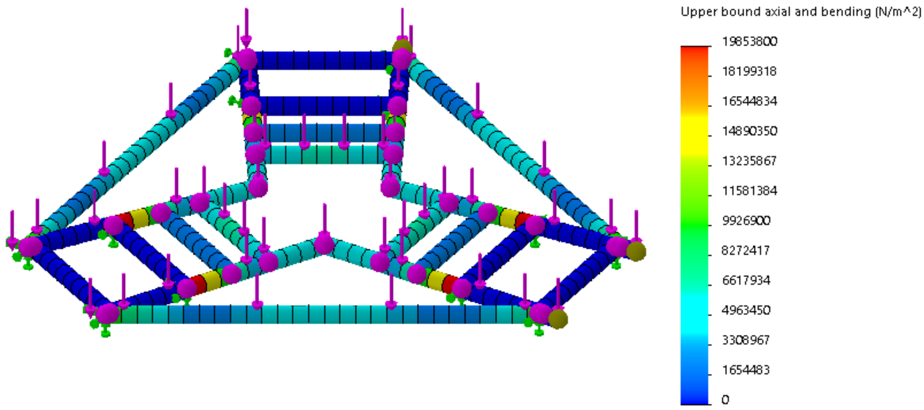
3.3.1 Increased acceleration and velocity

The following are the factors influencing the speed and acceleration of the robot:

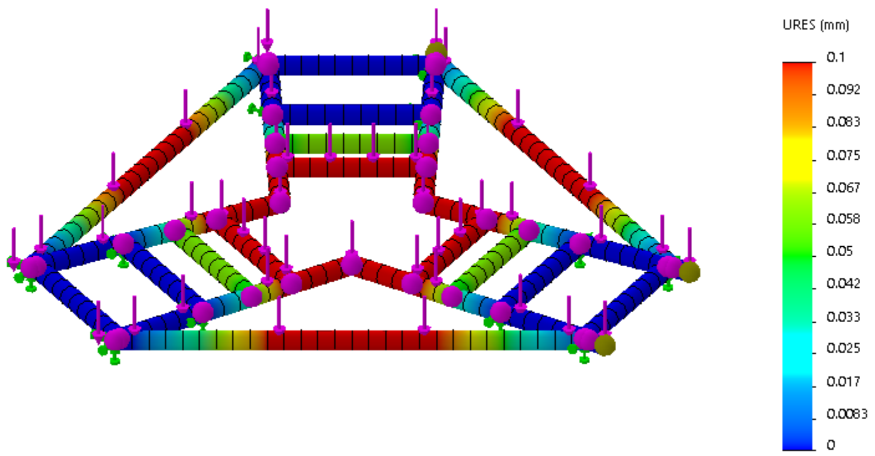
- Our robots are friction limited. Thus we need to increase the effective friction with the surface to increase the acceleration proportionally.
- Decrease the weight of the robot. Hence use motors with better power to weight ratio.
- Lower the center of mass , thereby allowing us to accelerate more quickly without tipping of the robots.

3.3.2 Three vs four wheels

The odds were stacked in favor of the three wheel holonomic drive from the beginning because attempts to manufacture a four wheel chassis with no suspension system in previous years had led to loss of contact of one of the

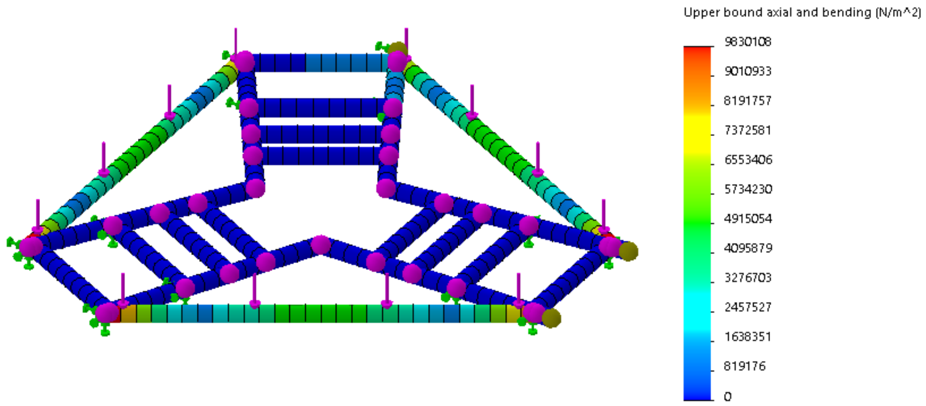


(a) Upper bound axial and bending stress

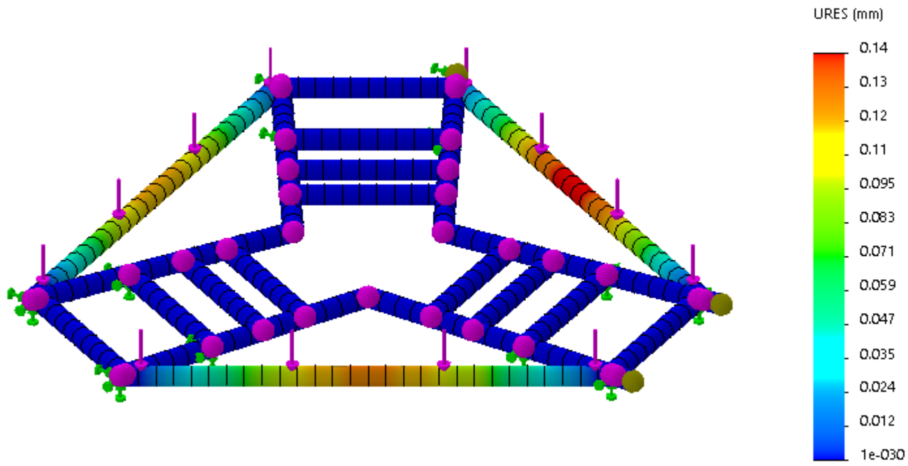


(b) Maximum displacement

Figure 3.4: Loading only on triangular elements

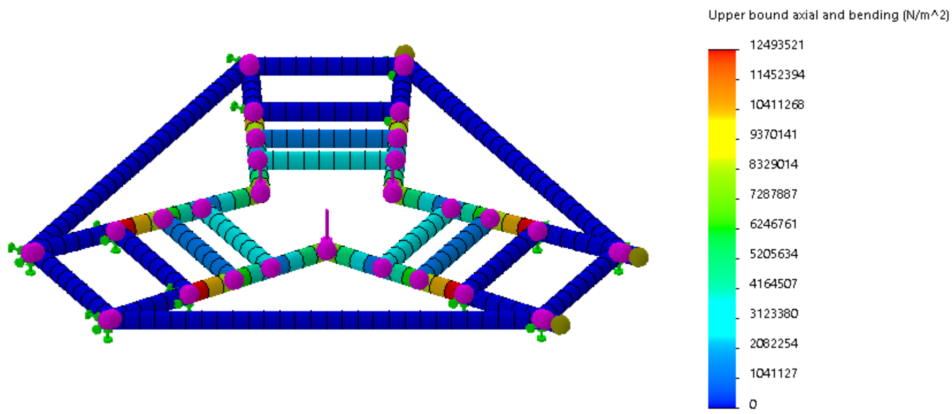


(a) Upper bound axial and bending stress

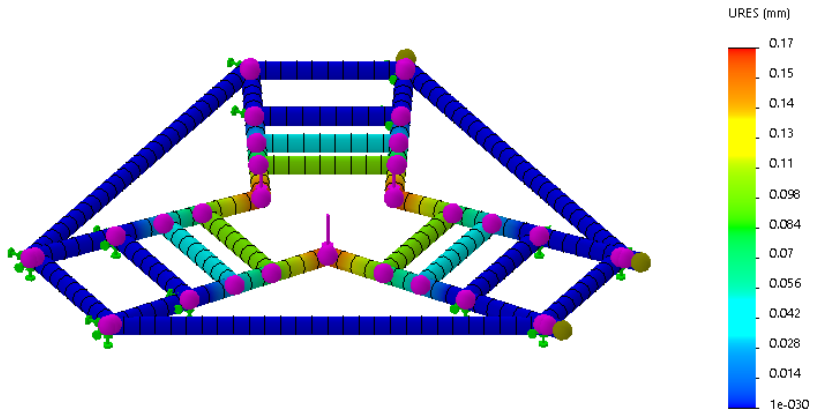


(b) Maximum displacement

Figure 3.5: Loading only on outer edges

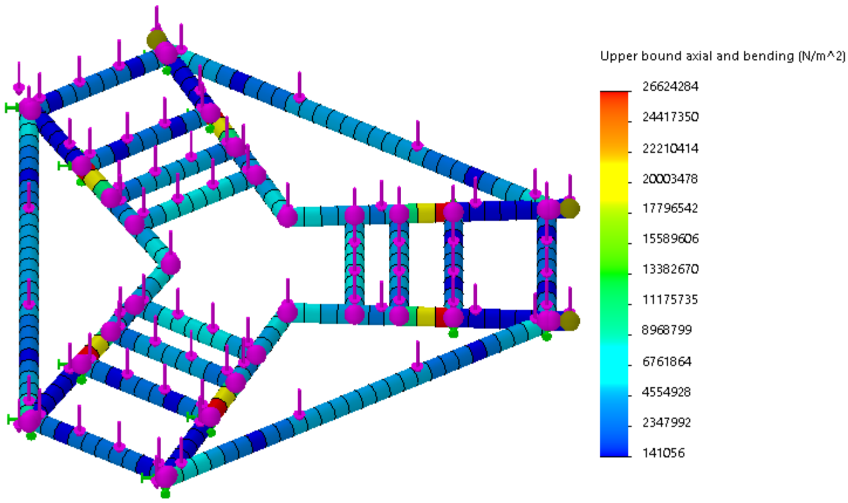


(a) Upper bound axial and bending stress

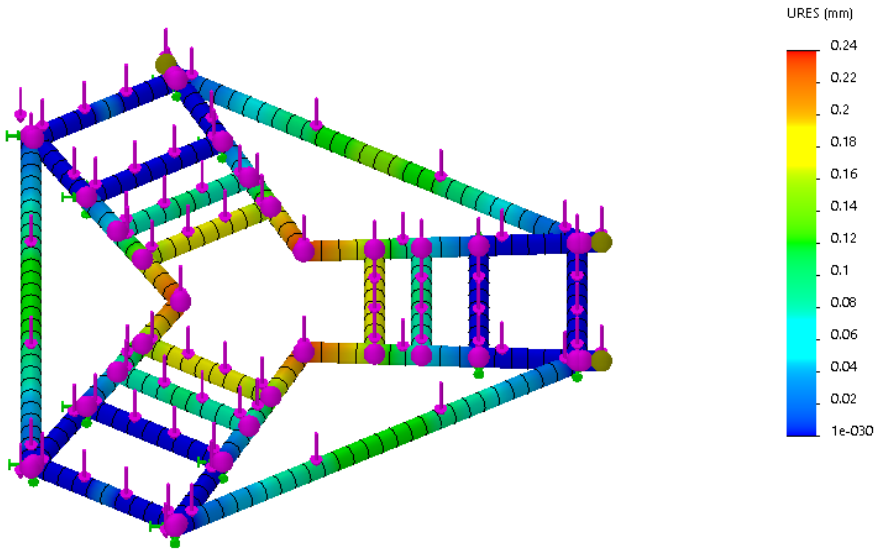


(b) Maximum displacement

Figure 3.6: Loading only on inner joint



(a) Upper bound axial and bending stress



(b) Maximum displacement

Figure 3.7: Uniform loading on entire chassis

wheels with the ground. Hence a four wheel system required the design of a suspension system which the design team felt would be risky to attempt for the first time just before the competition.

However, under the assumption that the robots are friction limited rather than power limited, a four wheel drive will always have proportionally better acceleration than a three wheel drive, which is required by the design objectives.

Finally we decided to focus on improving the tried and tested three wheel drive instead of the alternate option.

3.4 Initial design, analysis and testing

Having established how to meet the design objective, the next step is to identify which ideas were feasible to help us meet the objectives.

3.4.1 Increasing acceleration and speed

Being a major design goal of 2015, this section details the factors that went into increasing the speed and acceleration, and the results.

The effect of robot weight

One of original ideas to increase our acceleration was to reduce the weight of the robot. From a theoretical standpoint, Newton's Laws state that the force required to accelerate a given mass at a given acceleration is equal to force times acceleration. Thus, a heavier object would take more force than a lighter object to obtain an equal acceleration. However, classical theory of static friction states that the maximum force that can be applied to a static body is proportional to the normal force. Using equations, we can express this relationship:

$$F_{max} = \frac{\mu m g}{3}$$

Hence we find that the maximum acceleration of the robot is proportional to the coefficient of friction times gravity. The constant of proportionality k is related to the number of wheels, the positioning of the wheels with respect to the chassis, and the direction of acceleration.

$$a_{max} = k\mu g$$

This analysis tells us that if our robots are friction-limited, and assuming the coefficient of friction to be a constant, then the mass of the robot is irrelevant.

Hence in previous years' drives, the motors and wheels were indeed slipping, and the potential torque that could be applied by the motors was much greater than the torque at which they slipped.[1]

However an important aspect in this analysis is that the a_{max} in the equation is the maximum acceleration achieved by the robot instantly in any direction. However the velocity of the robot does not change instantly, and hence while changing directions rapidly, it is observed that the response time of the robot is significantly high for playing on a badminton court. To solve this problem, we had to use dead weights strategically placed near the wheels to increase the normal reaction on the wheels. This is because

$$\Delta v = a\Delta t$$

Hence to achieve the same Δv in lesser time, a should be greater.

Coefficient of friction

Regardless of what number of wheels is chosen, how they are oriented, and how mass transfer comes into the picture, the easiest way to increase acceleration is to increase the effective coefficient of friction with the ground. As long as the robots are friction limited, increasing the coefficient of friction will proportionally increase the maximum acceleration of the robots. The wheels used in the robots were omniwheels were bought off the shelf and hence the coefficient of friction could not be altered. The rollers on the wheels were made of rubber and hence μ was sufficient ($\mu = 0.8$ in datasheet).

Wheel layout and orientation

Given a direction and magnitude of acceleration, for three wheel systems, there is a one-to-one correlation with the motor inputs. Only one combination of motor torques give the desired acceleration. This is because number of wheels is equal to the number of degrees of freedom.

In order to derive the relationship between the motors' torques and the movement of the robot, we need to analyze the geometry of the problem.[3]

We can compute the x and y components of the robot's acceleration, by considering the respective components of each force:

$$\begin{pmatrix} a_x \\ a_y \\ \dot{\omega} \end{pmatrix} = \frac{1}{M} \begin{pmatrix} -\sin\theta_1 & -\sin\theta_2 & -\sin\theta_3 \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 \\ \frac{MR}{I} & \frac{MR}{I} & \frac{MR}{I} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix}$$

Where I is the moment of inertia of the robot about its centroid and R is the distance at which the wheels are mounted from the centre. The relation arrangement.png

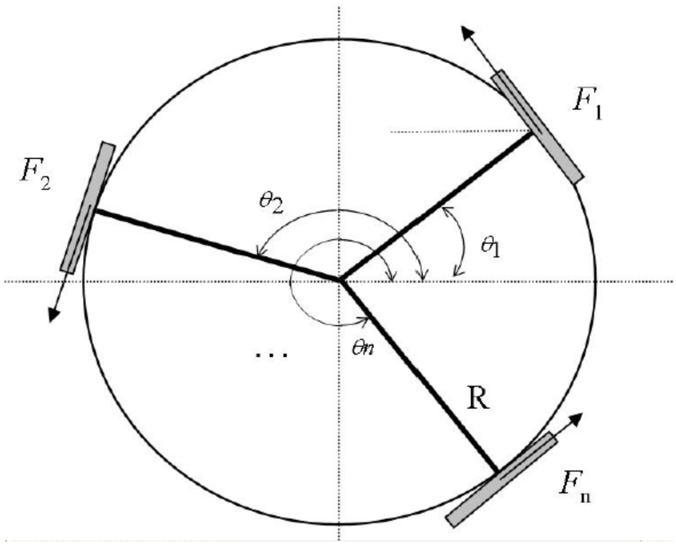


Figure 3.8: Arrangement of 3 wheels and distribution of forces

[3]

between the Euclidean (absolute) and the motor speeds are: For the two standard symmetrical orientations of the drive, the values of $(\theta_1, \theta_2, \theta_3)$ are $(0°, 120°, 240°)$ and $(30°, 150°, 270°)$.

Velocity is maximum in the x direction for the $(0°, 120°, 240°)$ orientation and acceleration is maximum in the x direction for the $(30°, 150°, 270°)$ orientation.

For the robot, based on the assumption that the robot needs to cover a maximum distance of the breadth of the court in the time taken by a shuttle to return back to the robot, the $(30°, 150°, 270°)$ orientation was selected for the chassis.

3.4.2 Motor and wheel selection

At the beginning of the designing, it was a forgone decision that the motor used in previous years Robocon would be used for one of the robots. The 2014 motors were Maxon motors and had consumed a sizeable portion of the budget. Also these motors were still in good working condition and extensive work had been done on its control during the summer camp. However, the main reason that we want to use this motor is that the required character-

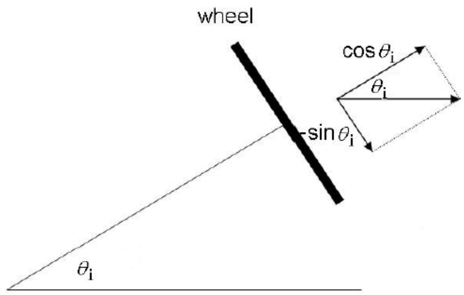


Figure 3.9: Velocity Diagram of an omniwheel: Rotation of large and small wheels, when the robot moves sideways with speed 1. The main wheel rotates with speed $-\sin\theta$, the small wheels with speed $\cos\theta$

[3]

drive.png

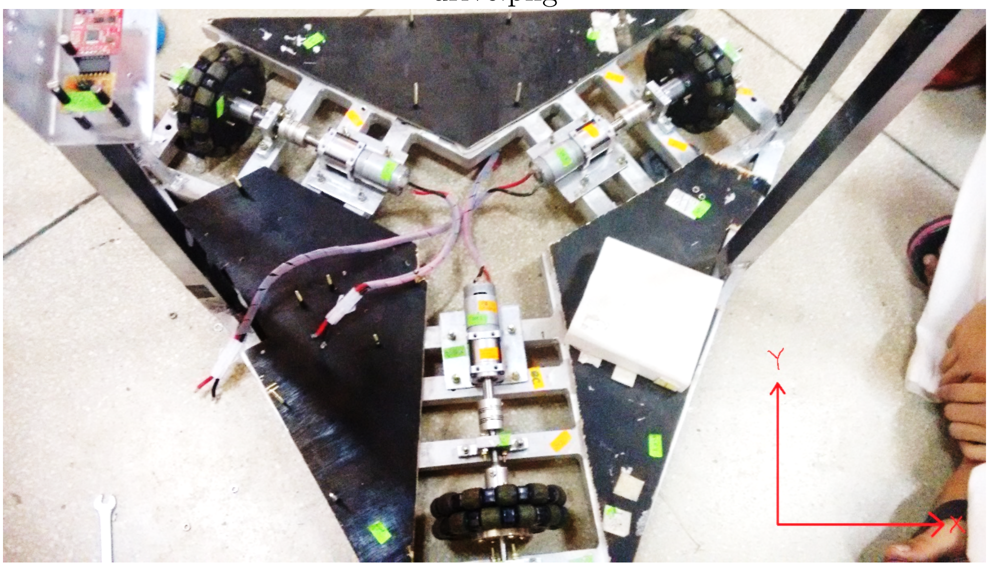


Figure 3.10: Final orientation of drive in robot

istics are comparable. For the set of motors for the other robot, we selected Banebot motors with the required characteristics.

Speed torque calculations

For orientation of the robot in $(0°, 120°, 240°)$ configuration, let required velocity and acceleration of robot be v and a in x-direction. For a single wheel inclined at 60° to velocity vector, the velocity diagram of the wheel is as shown in *Figure 3.11.* Therefore the velocity of the wheel perpendicular

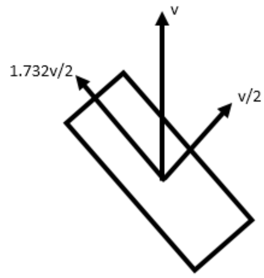


Figure 3.11: Velocity diagram of a single omniwheel, with reference to *Figure 3.9*

to its axis is $\frac{\sqrt{3}v}{2}$.

Assuming no slipping, $\omega R = \frac{\sqrt{3}v}{2}$ or,

$$\omega_{motor} = \frac{\sqrt{3}v}{2R}$$

Similarly, from the force diagram, if f_r is the frictional force on wheel in the direction along its axis and f is the frictional force perpendicular axis, then net force on the robot is $\sqrt{3}f - (1+\sqrt{3})f_r$. Since orthogonal rollers are small compared to the wheel, f_r is much lesser than f is assumed.

$$a_{wheel} = \frac{3f}{2m_{robot}}$$

Again, assuming no slipping, $\alpha = \frac{3f}{2m_{robot}R}$

If each motor applies torque T on each wheel, then

$$T - fR = I_{wheel}\omega$$

(Assumption: Motor rotor inertia is negligible wrt wheel inertia)

For maximum torque,

$$f = \frac{\mu m_{robot} g}{3}$$

assuming equal distribution of normal forces on the three wheels.

Solving,

$$T = \mu g R(\frac{m_{robot}}{3} + \frac{m_{wheel}}{4})$$

Here, based on previous year's drive model calculations,

$$\mu = \mu_s(1 - S_k) + \mu_k S_k$$

where S_k is the slip ratio.

Hence the stall torque of the motor should be greater than the calculated T. Required values:

$$R = 68mm, v_{robot} = 3m/s, m_{robot} = 25kg, m_{wheel} = 0.6kg, \mu_s = 0.3, \mu_k = 0.25, S_k = 0.7$$

Thus, $\omega_{motor} = 365rpm, T_{motor} = 1.5Nm$

The motors that were finally used for the robots were the following:

1. Front robot:

   Maxon Motor with planetary gearhead

   Values of the drive at max. available voltage

   - Max. load speed 457 min-1
   - Continuous torque 2041.2 mNm

   Values of the drive at nominal voltage (18V)

   - No load speed 7200 rpm
   - Nominal speed 6640 rpm
   - Nominal torque (max. continuous torque) 120 mNm
   - Stall torque 1980 mNm
   - Max. output power 115 W

   Mechanical data

   - Max. permissible speed 12300 rpm
   - Max. axial load (dynamic) 7 N
   - Max. force for press fits (static) 22.6 N
   - Max. radial load 65.3 N

   Gearhead data

   - Reduction 21:1
   - Max. continuous transferable output 240 W
   - Max. short-time transferable output 300 W
   - Max. continuous torque 7.5 Nm
   - Permissible intermittent torque 11.3 Nm
   - Max. permissible radial load 150 N

2. Back robot:

   Banebot motor with planetary gearhead

   Performance

   - No load speed 19300rpm

- Stall torque 486.2mNm
- RPM - Peak Eff 17000rpm
- Torque - Peak Eff 62.4 mNm

Gearhead data

- Reduction 26:1
- Maximum torque 47Nm

Wheel selection

The omniwheels that were available in the club at the beginning of the designing phase were of the diameter 100mm or smaller. Since the planning team felt that the robots will have to move large distances on the court swiftly, the precedence was to better the maximum velocity of the robot. Hence omniwheels of a larger diameter of 136mm were procured for the robots. The source of the omniwheels is Vietnam based vendor, www.roboconshop.com.

- Number of Rollers : 12
- Diameter : 136mm
- Shaft Bearing diameter : 10mm
- Plate material : ABS
- Axial width : 19mm
- Roller material : Soft Rubber
- Roller diameter 19mm
- Roller bearing : Bearing
- Net weight : 250g
- Load capacity : 15kg

3.4.3 Wheel hub and shaft design

The new wheels delivered from Vietnam were assembled into double layered omniwheels for better wheel stability and less bumpier rolling motion. The hub and the shaft, key components in the drive, had to be redesigned after preliminary testing.

Hub design

The initial wheel hub was a flange welded to a shaft with a through hole to accommodate the wheel shaft. the hub was fixed to the wheel via interference fit and through bolts in the flange. However after just the initial testing, the hub broke at the welded joint. It was hence observed that the welded joint had to transmit the motor torque from the wheel to the ground and hence shear stresses developed caused the failure of the joint. So the hub was again manufactured , though from a single block of aluminum so as to avoid shear stresses in welded joints.

Shaft design

The shaft for the wheel was supported by double bearings and coupled with the wheel hub through a key. The main parameters of the shaft design were the material to be used and the diameter of the shaft.

The diameter of the shaft was restricted to either 8mm or 12mm owing to the standard sizes of the bearings. Approximating the length of the shaft to be 150mm from the CAD models, a fatigue analysis was done to determine the material properties of the shaft required. The corrected endurance strength for a SS304 shaft of diameter, d=8mm was 111.97MPa, under the case of a three point bending load. The mean and alternating stresses in the 8mm shaft, assuming the robot to weigh 25kgs, were 67.23MPa and 61.02MPa respectively. Hence the factor of safety for a 8mm shaft came out to be approximately 1.5.

However, during testing the drive, a couple of bent shafts caused eccentric loading on the bearing housings and on the motors. Hence, we decided to change over to 12mm shafts to reduce further risks. However, as the bearings had been procured and their housings had already been manufactured for 8mm diameters, the shaft was was manufactured on a lathe keeping its middle portion near the wheel 12mm thick and the portions near the ends to be 8mm thick. the transition from 12mm to 8mm was smooth via a fillet to avoid stress concentrations near sharp corners. Also, as stainless steel is not workable on a lathe, we had to use mild steel(MS) for the redesigned shafts. However, this design compromise did not affect us adversely in the course of the testing and the competition.

3.4.4 Bearing housing design

The housings for the bearings were a major source of problems in last years Robocon designing. Since off the shelf housings were used until then, the bearings often used to come out of their housings due to moments perpendicular to the shafts axis. The bearings were then hammered in again, causing extensive damage to the roller ball bearing elements. Hence after working on it during the summer vacations, the team decided to design and manufacture custom housings. A representative drawing is shown in Figure 3.11

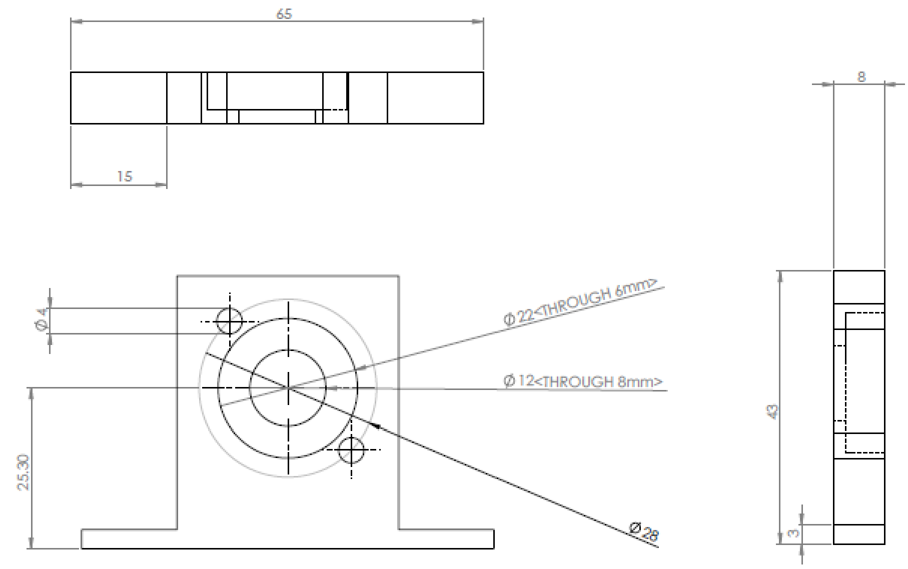


Figure 3.12: Drawing of a bearing housing

The redesigned version of the housing had two threaded holes beside the bearing for screws that prevented the bearing from coming out of its housing. Also the steps on either sides of the were initially 3mm thick which which causd the steps to bend after usage over time. Hence the thickness was later increased to 5mm. In total six bearings housings of two types (owing to the two types of motors used) were required to be mounted on the robot at a time.

3.4.5 Miscellaneous components

Motor mounts

The motor mounts were required to fix the motors to the chassis and required two different designs for the two motors. The mount for the Maxon motor was the same as the one used last year and consisted of a cylinder welded to a plate. the plate was attached to the chassis channels via bolts and nuts. The Banebot motors required simpler mounts with a plate simply fixed underneath the motor via four screws through countersunk holes.

Spring couplers

The spring couplers were critical to the smooth functioning of the drive and hence had to be checked before every practise session or match for deflections arising in it. the spring couplers were off the shelf models with 12mm holes on one side and 8mm holes on the other. The 12mm holes fitted onto the motor shafts via keys and the 8mm holes fitted onto the shafts via interference fit. The amount of deflection in the coupler indicated the amount eccentricity in the motor wheel unit and the eccentric loadings on the bearings as a consequence.

Battery holders

As LiPo batteries were used to power the robot, holders were made according to their dimensions using sheet metal and were fixed to the channels of the chassis in the space available.

Holder for IMU

An IMU was required to be mounted on the robot rigidly to its chassis. This sensor provided feedback about the yaw position of the robot and hence was used to control the orientation of the robot and ensure the robot always faces the net while moving on the court, irrespective of asymmetric distribution of normal and frictional forces on the three wheels. Also the magnetometer on the IMU required an environment free of magnets and ferromagnetic materials for proper functioning. Hence the IMU was mounted a little high up, away from the DC motors, using aluminum sheet and plastic spacers.

3.4.6 Components placement and accessibility

The various circuits including the power board, the drive board, the voltage regulator, the drive components like the motor and bearings, the batteries and the dead weights in the case of the back bot, had to be arranged in the limited space available in the chassis while ensuring that the volume footprint is minimum as the underhand rackets swing closely above the chassis according to the design.

Also the components needed to be accessible so that any debugging or repair and replacement work could be done easily without disturbing the other components. Hence a lot of effort went into the positioning of the components on the chassis base and the wiring and piping of the components.

3.5 Manufacturing, testing and revision

3.5.1 Manufacturing practises used

The entire chassis was made of $1inch \times 1inch$ square aluminum channels $2mm$ thick. Since there was no aluminum TIG or MIG welding facility on campus, we had to get it done from an outside machine shop. The hub and shaft were manufactured using a lathe machine and the bearing housings, owing to the number of identical pieces to be made, was made using a CNC milling machine. This also allowed us to learn how to operate a CNC machine. The rest of the work, mostly related to the assembly of the components was done in the club premises itself. In the final days of the the testing, a decision was also taken to use stainless steel nuts and bolts for all fixtures as they were less susceptible to failure and made the entire system more robust.

3.5.2 Motivation for testing

After completing the 2015 robots, it was the desire of the entire team to see if it could actually play badminton, and if so, how well. In particular, since the robots were to be manually controlled, the operators needed all the practice they could get. More importantly, however, the robot needed to be tested in order to determine what needed to be redesigned and remanufactured. If any portions of the robot failed during testing, it is reasonable to assume they will fail during competition.

3.5.3 Drive system test

Since the drive system has only one function – to move the robot about the playing field – only one function exists to be tested. The drive was run continuously everyday for almost two months and hence most possible mechanical problems were brought up and components were redesigned. The velocity and acceleration of the robots were also observed and translation, rotation, and various combinations were performed non-stop for durations up to twenty minutes. The operators were able to place the robots effectively across the court.

3.5.4 Problems encountered

- During the practice sessions, the team felt that the acceleration of the robots, especially the front robot could have been greater to move more effectively across short distances. Hence, acceleration could have been prioritized over velocity during the design phase.
- Failure of various components like hub, shaft, housing and regular occurrence of deflections in the spring couplers.
- Tipping of front robot while changing direction rapidly because of the placement of heavy components much above the chassis base. The COM of the front robot could have been lowered than what it was.

3.6 Future consideration and goals

During the design process, many ideas are dismissed for various reasons. Below is a list of ideas that were dismissed but merit future research, and other goals that the 2015 team recommends to the 2016 team:

- Design and manufacturing of a four wheel drive with suspension
- Detailed analysis of wheel traction and how frictional forces act on the wheels, especially for omniwheels
- Analysis and control of a mecanum drive
- Development of more efficient drive systems like swivel drive and belt drive systems
- Use of DC brushless motors for their space efficiency and their high power to volume ratio

Figure 3.13: The skeletal chassis of the robots after welding

Chapter 4

Hitting mechanism documentation

4.1 Introduction

The hitting mechanism had the job of actuating the mounted badminton racket to hit the incoming shuttlecock, and not just hit it but hit it at the right angle and speed for maximum range. Hence the main objectives of the team was to analyze the trajectory of a shuttlecock, determine the optimum hitting angles, and design an actuating mechanism for the racket. The mechanism was to be modular and contain one racket each, hence each robot had the same number of actuating mechanisms as the number of rackets.

4.2 Shuttlecock trajectory analysis

There was substantial work done regarding estimating the flight of a shuttlecock. Previous work reveals that from the terminal velocity of a shuttlecock, an equation of trajectory could predict the trajectory of a shuttlecock, and it is shown that air drag force is proportional to the square of a shuttlecock velocity. Additionally, the angle and strength of a stroke could also influence trajectory.[4, 5]

A plot of the trajectory based on the drag force proportional to the square of the velocity was modeled in Simulink and plots obtained. *Figures 4.1, 4.2* and *4.3* are screenshots of the same.

The final equation of the trajectory used for our analysis was the based

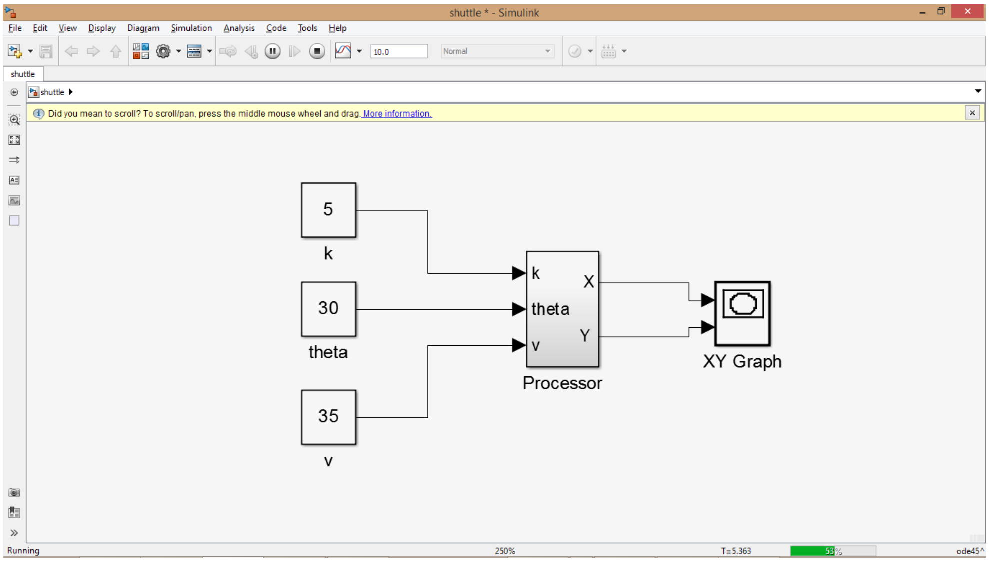


Figure 4.1: Simulink model for plotting shuttle trajectory (Part 1)

on the same assumptions in [4] and their final equation used.

$$y = \frac{v_t^2}{g} \ln \frac{\sin[\frac{v_t}{v\cos\theta}(e^{\frac{gx}{v_t^2}} - 1) + \tan^{-1}\frac{v_t}{v\sin\theta}]}{\sin[\tan^{-1}\frac{v_t}{v\sin\theta}]}$$

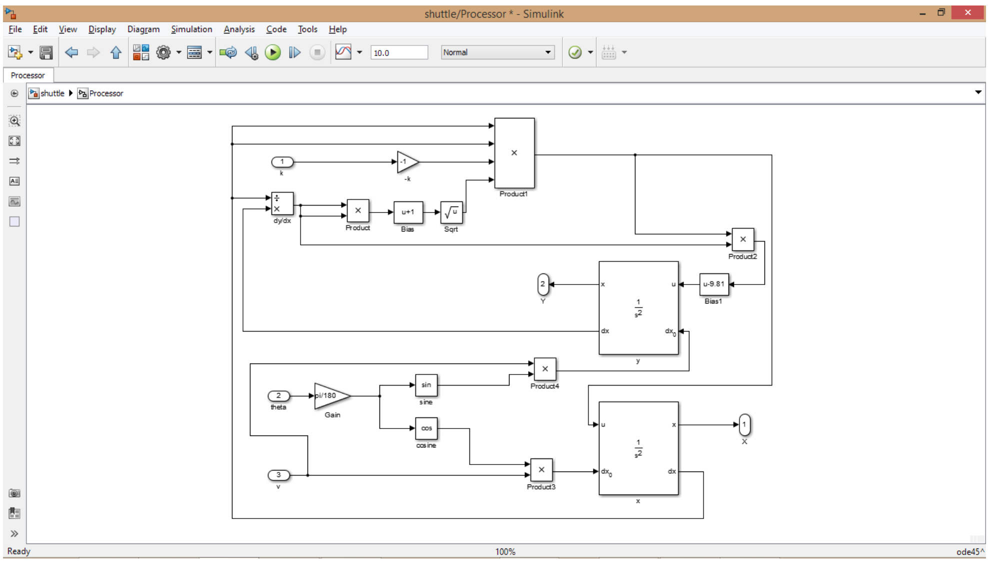


Figure 4.2: Simulink model for plotting shuttle trajectory (Part 2)

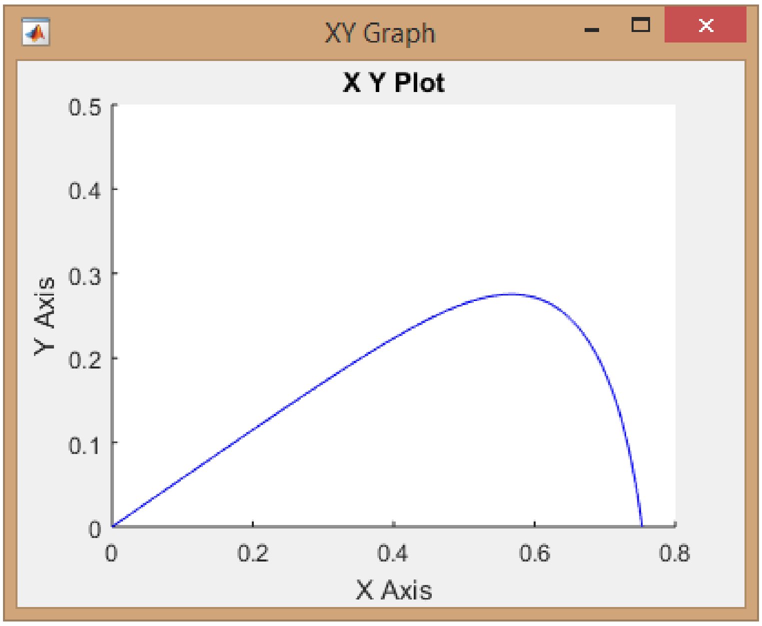


Figure 4.3: Sample solution of Simulink model

where v is the initial velocity of the shuttle and v_t is the terminal velocity of the shuttlecock.

$$v_t = \sqrt{\frac{2mg}{\kappa\rho}}$$

where κ is the coefficient of drag, ρ is the density of air and m is the mass of the shuttlecock. κ was found to be $9.7 \times 10^{-4} m^2$.[5]

4.3 Optimization of hitting velocities and angles

Since the approximate equation of trajectory of the shuttlecock had been determined, three parameters were available for optimizing the trajectory. The three parameters were the initial velocity of the shuttle, the angle at which it is hit and the height from the ground at which it is hit.

The final values for the front robot's top and bottom rackets and back robot's top and bottom rackets were then finalized on the basis of maximum range of shuttle and minimum time of flight.

MATLAB was used to determine the final values and the plot of the trajectory after iterations with different values.

4.4 Synthesis of hitting mechanism

4.4.1 Kinematic analysis

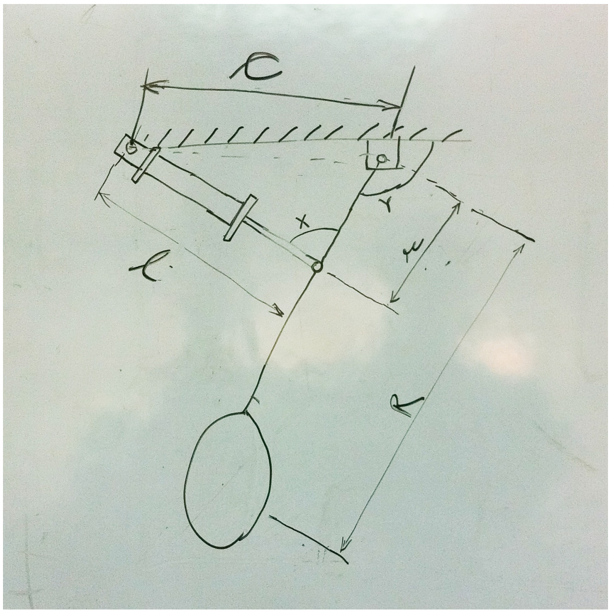


Figure 4.4: Representation drawing of RPRR mechanism for hitting system

The aim of the mechanism is hence to impart a velocity of $30m/s$ to the shuttlecock. By equations of collision,

$$racket\ head\ speed = \frac{shuttle\ speed}{1+e} = \frac{30}{1+0.8}m/s = 16.67m/s = u$$

$$\omega_r = \frac{u}{R}$$

where R is the length of the racket.

Also it is assumed that the coefficient of restitution between racket and shuttle is 0.8

$v_{piston} = 0.8m/s$ for 20mm bore piston and $1.5m/s$ for 16mm bore piston.[9]

$$r \sin X = \frac{v_{piston}}{v_{piston}}(1+e)R$$

where is X is the transmission angle.

$$Y = X + \sin^{-1}(\frac{r}{c}\sin X)$$

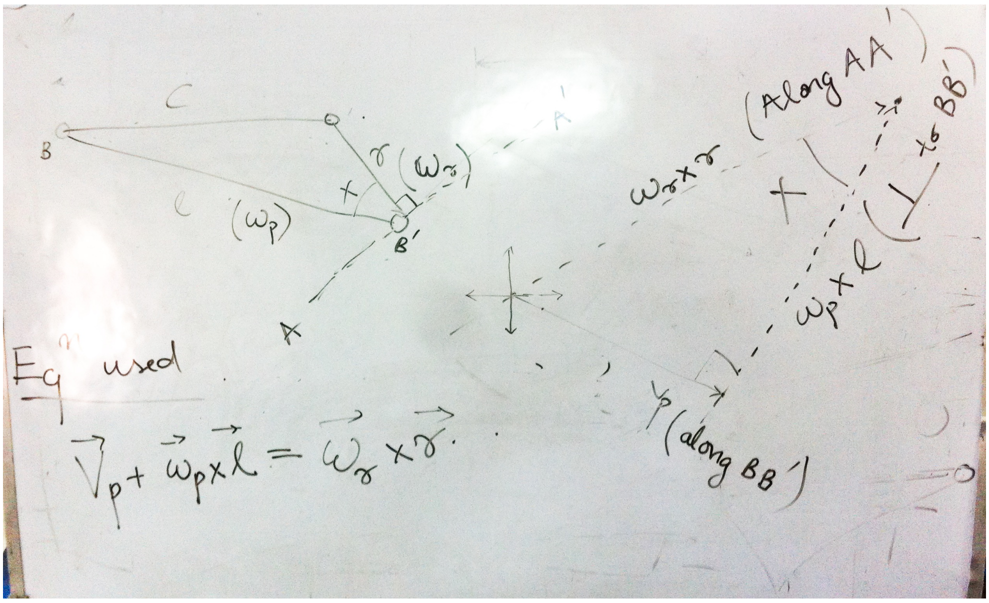


Figure 4.5: Velocity diagram of RPRR hitting mechanism[2]

4.4.2 Dynamic analysis

$$Fr = I\alpha$$

$I =$ moment of inertia of racket assembly $= 1.8 \times 10^{-2} kgm^2$(Calculated from SolidWorks CAD model).

$$\alpha_{average} = \frac{2\alpha_{max}}{\pi} = \frac{\omega^2}{2\theta}$$

$$r = \frac{\pi}{2}\frac{\omega^2}{2\theta}(\frac{P}{I}\pi(\frac{bore}{2})^2)^{-1}$$

where P is the working pressure and is taken to be 4.5bar in the calculations. Hence,

$r = \frac{12.05cm}{\theta}$ for 16mm bore and $\frac{7.7cm}{\theta}$ for 20mm bore.

For a shuttle speed of $25m/s$, $r = 10cm$ for 16mm bore and $7cm$ for 20mm bore.

Transmission angle X, $r \sin X = \frac{v_{piston}}{v_{shuttle}} \times 1.08$

4.4.3 Synthesis

Referring to *Figure 4.6*,

$$\cos\alpha = \frac{r^2 + l^2 - c^2}{2rl}$$

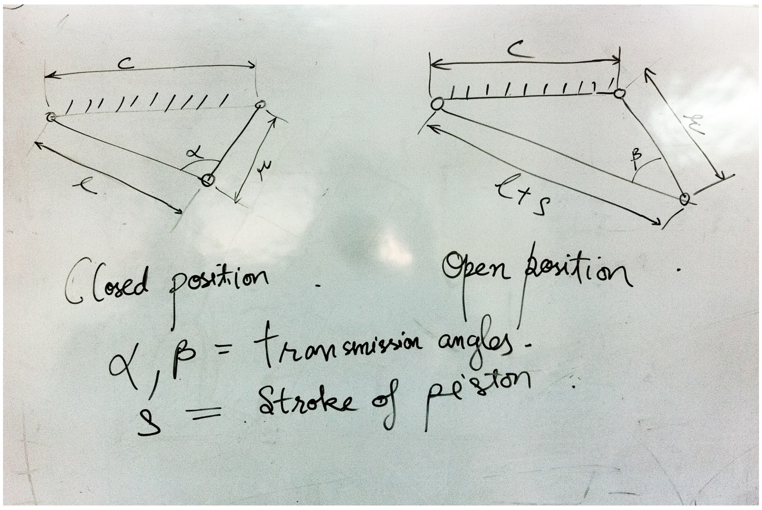


Figure 4.6: Various configurations of mechanism

$$\Rightarrow c^2 = r^2 + l^2 - 2rl\cos\alpha$$

$$\cos\beta = \frac{r^2 + (l+s)^2 - c^2}{2r(l+s)}$$

$$\Rightarrow 2r(l+s)\cos\beta = (l+s)^2 - l^2 + 2rl\cos\alpha$$

Finally,

$$r(\cos\beta - \cos\alpha) + \frac{rs}{l}\cos\beta = s + \frac{s^2}{2l}$$

From the known data, stroke of the piston, s is 100mm.

Also, for the piston bores of 16mm and 20mm, l is known to be 200mm and 240mm respectively and r is 10cm and 7cm respectively.

Next, since transmission angle should be considerably more than β[2], $\beta \approx 10^\circ$

$$c = \sqrt{r^2 + (l+s)^2 - 2r(l+s)\cos\beta}$$

Using these equations, the design had been calculated.

4.5 Final values for bottom arm and service arm

All variables nomenclature is with reference to *Figure 4.4*

For 16mm bore,

$$r = 10cm$$

$$c = 19.7cm$$

$$\beta \approx 10^\circ$$

$$l = 20cm$$

For 20mm bore,

$$r = 7cm$$

$$c = 23.1cm$$

$$\beta \approx 10^\circ$$

$$l = 24cm$$

4.6 Analysis of front robot top arm

The top arm of the robot arm was intended to be designed differently from the rest of the arms as the design and strategy team wanted to use the racket for both flat (or smash) shots and toss shots. This is in contrast to the other rackets which were intended for a single type of shot only. For eg. the back robot top racket was for hitting lofted toss shots from the back only and the bottom rackets of both the robots were intended for underhand shots only.

Hence the front robot top rackets had a modified design of the original RPRR mechanism with two piston actuators. This was for the two different modes that the racket required.

In the representation drawing in *Figure 4.7*, for piston 1, let the length be l_1 and stroke be s_1. Similarly for piston 2, the length is l_2 and stroke is s_2. Also, $AD = l$ and $\gamma_1 = \gamma_2 + \theta$.

Following the same variable nomenclature as in *Figure 4.7*, if section BDE is the same as that of the underarm, then the unknowns are s_1, l, y, γ_1 and θ.

From the MATLAB optimization process, the ideal value of θ for

- flat shot $\Rightarrow \theta = 0^\circ \Rightarrow \gamma_1 = \gamma_2$
- toss shot $\Rightarrow \theta = 30^\circ \Rightarrow \gamma_1 = \gamma_2 + \frac{\pi}{6}$

Then following a analysis similar to the one for the underarm rackets, γ_1 and γ_2 were determined for both cases of pistons with 16mm and 20mm bore.

Again after solving the equations using MATLAB, it was found that no such mechanism was possible unless the line segment in the drawing,AF was horizontal. After it was done the calculations were done again till we got our final design of the mechanism.

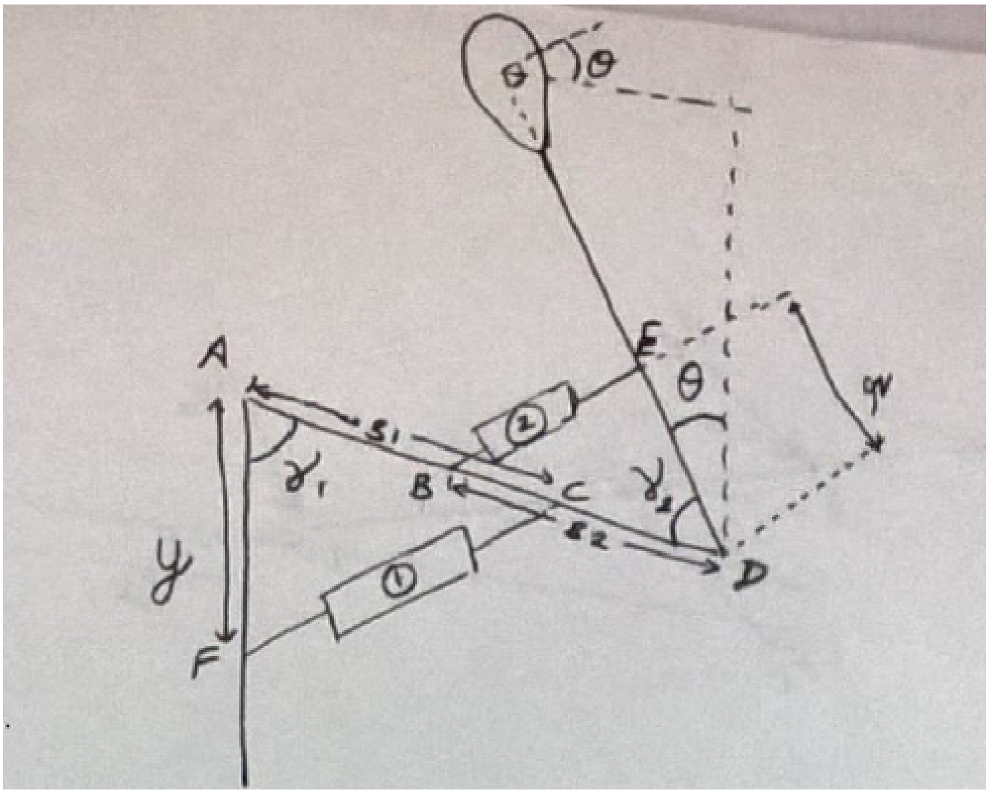


Figure 4.7: Representation drawing of front robot top arm

4.6.1 Final values for front robot top arm

All variable nomenclature is with reference to *Figure 4.7*.

For 16mm bore piston,

$$r = 10cm$$

$$s_2 = 19.7cm$$

$$y = 29cm\ (horizontal)$$

$$s_1 = 20cm$$

$$l_1 = l_2 = 20cm$$

$$s_1 = s_2 = 10cm$$

For 20mm bore piston,

$$r = 7cm$$

$$s_2 = 23.1cm$$

$$y = 29cm\ (horizontal)$$

$$s_1 = 20cm$$

$$l_1 = l_2 = 20cm$$

$$s_1 = s_2 = 10cm$$

In the mechanism, only one geometric parameter could not be determined from the equations. The line segment BC in *Figure 4.7* is the distance between the end point of piston 1 and the starting point of piston 2. Hence, it was reasoned that this parameter could be changed later to make the setup more dynamically stable and set to a value of $5cm$.

4.7 Pneumatic circuitry and components

One of the main advantages of the actuating mechanism design was that all the pistons used were of the same configuration and hence it was easier to procure the pistons and assemble them without mixups. Based on the availability of pistons in the market, their dimensions and prices, we settled for the Janatics pneumatic pistons with bore $20mm$, stroke $100mm$ and length of piston in closed position $20cm$, as per our design requirements.

Control valves

The control valves attached to the pistons were of two types: variable flow and constant flow. Since during the "power stroke" of the piston when the racket goes to hit the shuttle, we require the piston to open at its maximum speed, constant flow valves were fixed at the front outlet of the piston. Whereas, since we did not require the racket to to back to its original speed at high speed, variable flow valves were fixed to the other outlet with the flow adjusted to be minimum, hence causing the racket to slowly fold back to its original position.

Quick exhaust valves

Quick Exhaust Valves or QEVs were the result of a search through pneumatic companies' product catalogs for a component that would help our pistons open faster, so as to impart more velocity to the shuttlecock. The QEVs from SMC Corporation enabled the the exhaust air from the pistons to be released to the atmosphere before reaching the exhaust port in the manifold, which was quite a distance away from the pistons and were connected by narrow pipings.

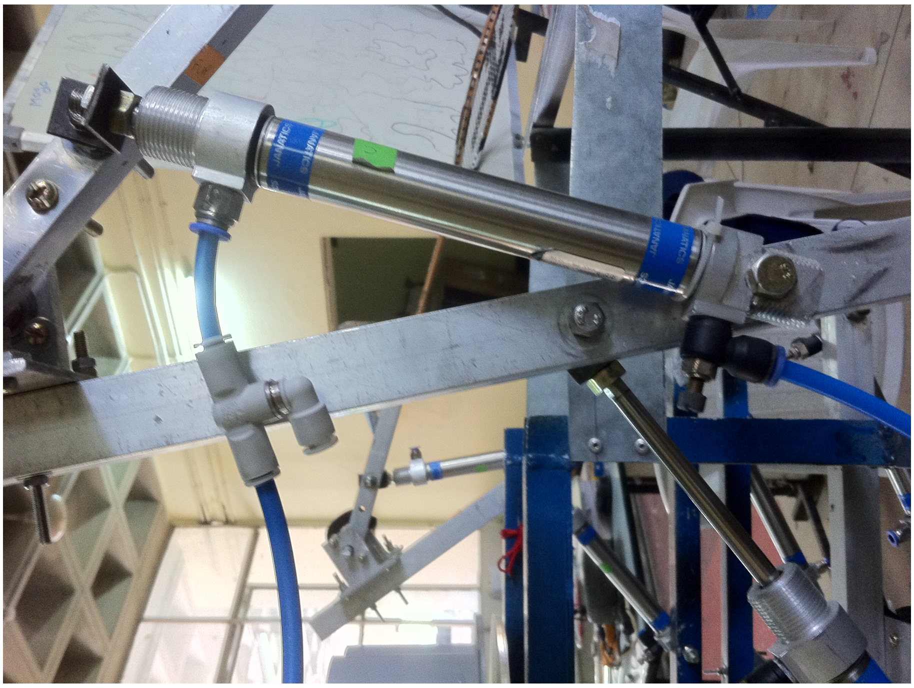


Figure 4.8: Piston with two control valves and a QEV attached

Pressure gauges

The two robots together had three independent compressed air storage compartments between them, one each for the back and front robots' rackets and one exclusively for the service racket. This was done as the service was critical during the game and we could not afford one wrong service out of the six per game due to loss in pressure.

As the rules required the maximum pressure to be $6bar$, we attached three pressure gauges, one digital and two analog, to continuously monitor the state of the storage bottles and refill them in time.

4.8 Manufacturing, testing and revision

4.8.1 Manufacturing processes used

Almost all components of the mechanism were made of Aluminum, with the sole exception of the L shaped component used to connect the piston shaft to the racket channel which was made of MS. Most revolute joints were made using a table mounted rill and the bearing housings were made on a CNC mill. The only welding required was at the joint between the racket channel and the shaft (refer to CAD drawings for a better picture).

4.8.2 Testing and revision

An initial setup was made in our club with only the service racket mechanism mounted and then was tested for range, repeatability and componet fatigue characteristics. A few components and fixtures had to be redesigned including the L connecting piece that was initially made of Aluminum and hence failed in shear. Finally, during the practice sessions, all the rackets

Figure 4.9: A broken L along with another unbroken one, both made of aluminum

were put through their paces and hence, we could even decide the optimum characteristics of the commercial rackets to be mounted finally. The optimum characteristics that we determined were that the racket should be made of carbon fibre and not torsion steel so as to prevent its breaking from fatigue, and also that the clamping of the racket handle in the channel should be such that no part of the wooden portion is exposed.

4.8.3 Problems encountered

The main problems or design defects thta we encountered were:

- failure of L component - they were hence re-manufactured from MS
- breaking of rackets from fatigue due to the large jerk the racket experienced at the end of the stroke
- Lack of damping system for the mechanism
- Collision of the piston shaft with the bearing housing at the end of the power stroke, causing damage to both the shaft and the housing - rubber foam strips were later attached to the housings to absorb the impact
- wearing away of material and subsequent enlargement of hole at the multiple revolute joints, especially at the joint between the piston and racket channel

4.9 Future considerations and goals

Some important areas that still need our attention are

- Usage of damping components alongside pneumatic actuators
- Variable position control of piston instead of the present two position system
- Design of more robust revolute couplings that incorporate at least plain bearings, instead of the present 'bolt-in-a-hole' systems
- Incorporating on-board refilling for the storage systems by mounting smaller compressors

Chapter 5

Dropping mechanism documentation

5.1 Introduction

According to the problem statement, six shuttlecocks need to loaded onto the robots during the game and the serving robot was required to let the shuttle drop vertically i free fall before hitting it with the racket. These conditions required a mechanism that would be able to contain the shuttlecock and release it at the press of a button without pushing it downwards. Also, our team felt it was better to load all six shuttles at once and hence the dropping mechanism should be able to contain six shuttles simultaneously and drop them one by one.

The repeatability of the mechanism was critical to the accuracy of our service during the game.

5.2 Proposed ideas

During the initial design stage, two different ideas were proposed to achieve the required objectives. They were the following:

5.2.1 Coupled cam mechanism

The mechanism consisted of two identical cams coupled to each other via a gear interface. Hence one driving cam rotated clockwise(say), and the other driven gear rotated anticlockwise. The six shuttles were stacked vertically on top of the gap between the two cams the rotation of the cams pulled out one shuttle at a time and let it drop.

Figure 5.1: Coupled cam mechanism

5.2.2 Gun barrel mechanism

As evident from its name, the six shuttles are preloaded into the mechanism the same way as bullets are loaded in a revolver. There are two plates, one on top of the other. The upper plate has seven holes, each a little larger than the maximum diameter of the shuttle, and the lower plate has only one hole. Whenever one of the top holes coincided with the bottom hole, one shuttle was dropped.

5.3 POC and final design

During the initial phase of the designing, when the two mechanisms were proposed, it was decided to build Proof-of-Concept prototypes of both and decide experimentally the better design among the two. The cams for the first mechanism were made using 3D printing method, a fist time for the team.

After the testing of both mechanisms, it was observed that the double cam mechanism took lesser time to release a shuttle compared to the gun barrel. However, the double cam also tended to fail more frequently. Here failure means that two or more shuttles are pulled out of the tube instead of one. On the other hand, the gun barrel, albeit slower, failed less frequently. However, the gun barrel was also prone to failure due to jamming of the shuttlecock between the two parallel plates. The factors that caused this jamming were

- if the top plate rotated at a high speed. The shuttlecock did not have enough time to completely fall out of the mechanism.
- The top plate was not parallel to the bottom plate.

Finally, the gun barrel was selected over the double cam for its reliability.

5.4 Sub components of gun barrel

The sub components of the gun barrel that required attention are:

- the top plate with seven equally spaced holes (acrylic)
- the bottom plate with one hole (acrylic)
- the the motor mount (aluminum sheet)
- the ultrasonic sensor mount (aluminum sheet)
- the motor and plate coupling (aluminum block)
- the component to keep the plates parallel to each other

The average shuttlecock has a maximum diameter between 58mm and 68mm. Hence the holes on the plates have to be greater than 68mm.

Secondly, to keep the two plates parallel, initially a thrust bearing was used in between the plates. However, this setup was unstable because of the large diameter of the plate compared to the bearing. hence, a redesigned mechanism was made with three small castors placed in between the plates.

5.5 Problems faced and solutions

The only problem that we faced to make the mechanism robust and reliable was to ensure that the two plates remained parallel to each other, even after extended use.

As already mentioned, thrust bearings were replaced with castor wheels. However, the "straightness" of the coupler connecting the top plate to the motor also determined if the top plate was mounted in an eccentric fashion or not.

- Initially, a spring coupler was used to couple the top plate to the motor shaft to compensate for any angular misalignment. However, this did not result in a smooth motion of the top plate.

- Next, a shaft was coupled to the motor shaft via a bolt and a flange was welded to the top of the shaft. This flange was fixed to the top plate. Again, due to manufacturing errors, we could not ensure that the flange was exactly perpendicular to the shaft after welding. Hence, inherent angular misalignment could not be avoided in the system.

- The final solution was to manufacture a flange shaft from a single block of aluminum on a lathe. Though this method caused the wastage of a large amount of material, the lathe ensured that the flange was perfectly perpendicular to the shaft.

These iterations ensured that the gun barrel mechanism was the most reliable mechanism in our robot and that the service of the robot had a success rate of $\approx$100percent. Hence the accuracy of the service was also high and later testing showed that the shuttle could be placed within a circle of radius 5cm with high probability repeatedly.

Figure 5.2: Gun barrel mechanism

Bibliography

[1] 2003 Cornell RoboCup Mechanical group Documentation, 2003.

[2] Theory of machines and mechanisms, Ghosh and Mallik

[3] R. Rojas and A. G. Forster, "Holonomic Control of a robot with an omnidirectional drive", *Kunstliche Intelligenz, BottcherIT Verlag*, 2006.

[4] Lung-Ming Chen, Yi-Hsiang Pan and Yung-Jen Chen, "A study of shuttlecock's trajectory in badminton", *Journal of Sports Science and Medicine*, 2009

[5] Masanobu Shibata and Pakorn Amornpatchara, "Deceleration of a Shuttlecock", *ISB Journal of Physics*, 2010

[6] Maxine Kwan, "Designing the World's Best Badminton Racket", Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark, 2010

[7] Kuei-Shu Huang, Chenfu Huang, Shaw Shiun Chang and Chien-Lu Tsai, "Kinematic analysis of three different badminton backhand overhead strokes", National Taiwan Normal University, Taipei, Taiwan, 2002

[8] Gary Currie, "Optimizing racquethead-shuttle interaction for an effective overhead forehand clear in badminton", McGill University Montreal, Québec, 1989

[9] Pneumatic Application and Reference Handbook, Bimba Manufacturing Company

Appendix A

List of components procured and their sources

Component	Source
Aluminum channels, blocks and slabs	Shri Balaji Metals, Shop No. 34, Raghu Shree Market, Ajmeri Gate, Delhi Ph.232323980, M.9899110460 . Mohanshree Metal Works, 26 Raghu Shree Market, Ajmeri Gate, Delhi . Padmavati Metal 10, Raghushree Market, Ajmeri Gate, Delhi . ATCO Aluminium Systems 4, Raghushree Building, Ajmeri Gate, Delhi
Roller ball bearings	Hemkunt Bearings, 43, Shardhanand Marg, G.B Road, Delhi . Kishan Chand Khanna and Sons 328, Inside Ajmeri Gate, Hauz Qazi, Delhi

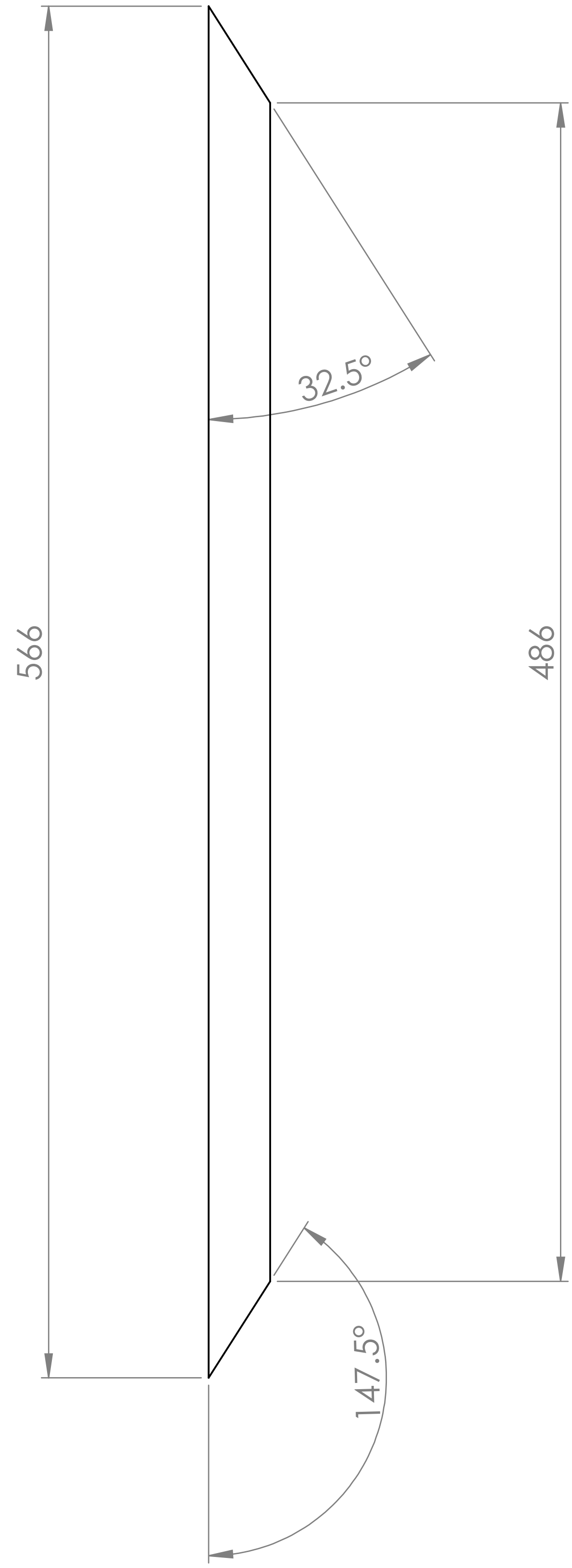
Stainless Steel shaft	MPM Steels, 1/6-B, Asaf Ali Road, New Delhi . R.Kumar and Co., 3602, Chawri Bazar . Girnar Metal and Steel 39,Raghushree market, Ajmeri Gate, Delhi . Rishabh Metals 3, Raghushree Market, Ajmeri Gate, Delhi
Omniwheels (136mm diameter)	Robot Technology Development Company Limited, 24/1A – 102 Street, Ward Tang Nhon Phu A, Ho Chi Minh city, Vietnam *website: www.roboconshop.com/en*
Spring Couplers	Gupta Industrial Corporation 5394, Chowk Niariyan, G.B.Road . Aditya Precitech 235, Vardhaman Tower, Community Centre, Preet Vihar, Vikas Marg, New Delhi
Banebot DC motors	BaneBots LLC 537 W, 66th Street, lovland CO 80538 USA

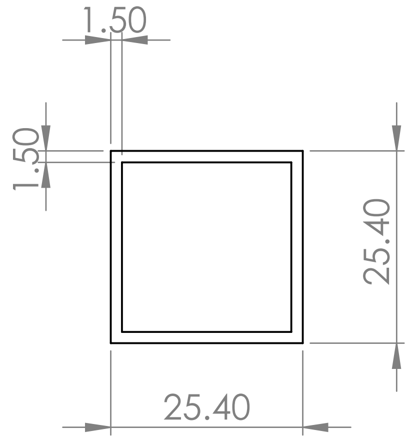
SS fasteners (nuts, bolts and washers)	R.L.Trading Co. 3474,Subzi Mkt, Hauz Qazi, New Delhi . Capital Mill Store, 3996, Ajmeri Gate . New Central Trading Store 141, Ajmeri Gate, Delhi . Aisha Trading Co. 4110, Ajmeri Gate . Tayal Screw India 3435, Hauz Qazi Chowk, Chawri Bazar
Pneumatic piston(20x100)	D.S.Pneumatics Co. Pvt. Ltd, 29-A, Inside Ajmeri Gate, Delhi . J V Automation 467, Maheshwari Building, Ajmeri Gate, Delhi . Nitika Enterprises 3625-A, Chawri Bazar, Delhi
Piping (for pneumatic circuits)	Bittoo Sanitary House 2698, Chuna Mandi, Pahar Ganj . Vishnu Enterprises F-205, Shop No. 3, Munirka Village, N.D . Swastic Hardware Store Shop No. I-E-108/4 12, Gang Nath Market, Munirka . Tiger Rubber Co. 4003, Ajmeri Gate

Pneumatic valve(nrv, 1way, 2way, 3way)	Amba Trading Corporation 4035, Ajmeri Gate . D.S.Pneumatics Co. Pvt. Ltd, 29-A, Inside Ajmeri Gate . Nitika Enterprises 3625-A, Chawri Bazar . Industrial Equipment Corporation 3494, Hira Market, Gali Bajrang Bali, Chawri Bazar
Pressure gauge	Hindustan Hardware and Rubber Goods 4648, Inside Ajmeri Gate
Manifold	Om Prakash Aggarwal and Co. 3630, Chawri Bazar
Acrylic sheet	Jain Plstics, 3043/2, Bhagat singh Street, Pahar Ganj . Kut Solution, 2152, Gali no-2, Chuna Mandi, Pahar Ganj . 0101 Sign India 2147, Gali No-2, Chuna Mandi, Pahar Ganj
Other mechanical inventory (file, spanner, allen key, screw driver, centre punch, etc)	Piyush Trading Co. 3376, Hauz Qazi, Delhi
Hand drill machine	M/S Mukesh Girdhar, 26-A Ajmeri Gate, Delhi
Ties and tape	Shakti Tools and Hardware Store 303, Old Lajpat rai Market, Delhi
Air Compressor and related components	Brij Mohan Aggarwal and Co, 5266-67, G.B Road, Ajmeri Gate,Delhi

Part 1

All dimensions in mm





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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

WEIGHT:

DWG NO. Part1

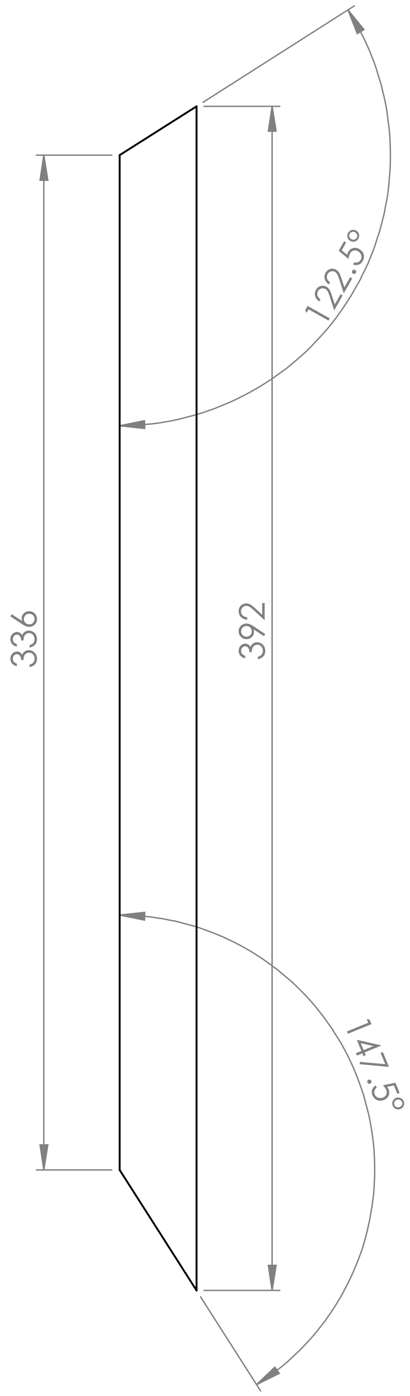
A4

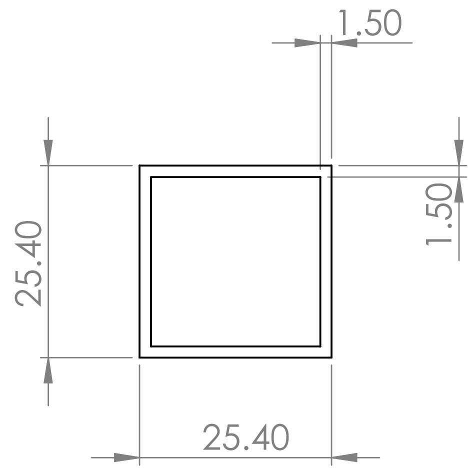
SCALE:1:10

SHEET 1 OF 1

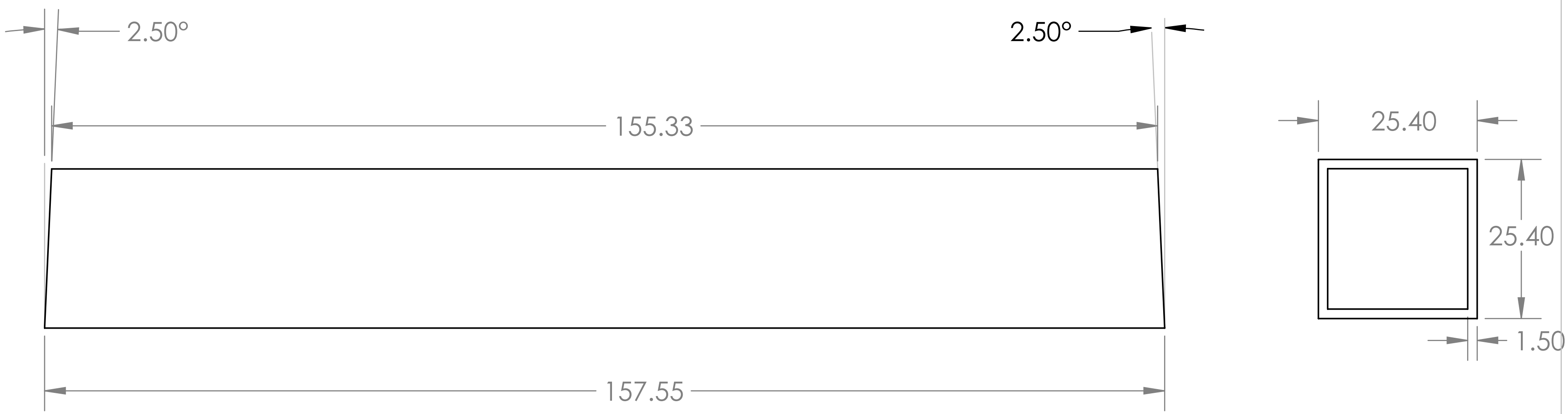
Part 2

All dimensions in mm





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. Part2	A4
				WEIGHT:	SCALE:1:5	SHEET 1 OF 1



All lengths are in mm

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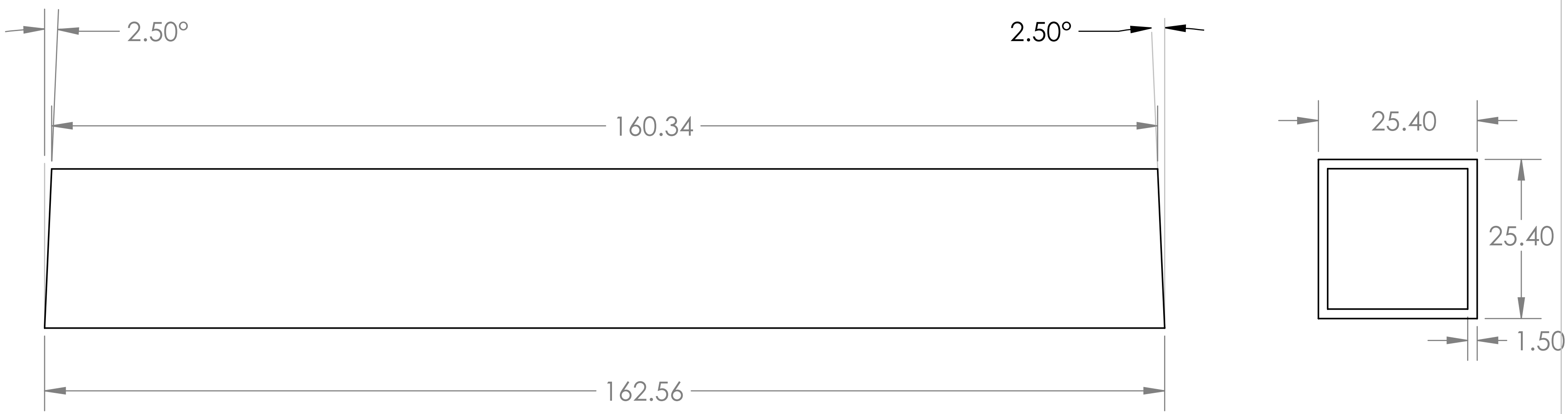
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE A / DWG. NO. Part3 / REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 / WEIGHT: / SHEET 1 OF 1

5 4 3 2 1



All Lengths are in mm

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			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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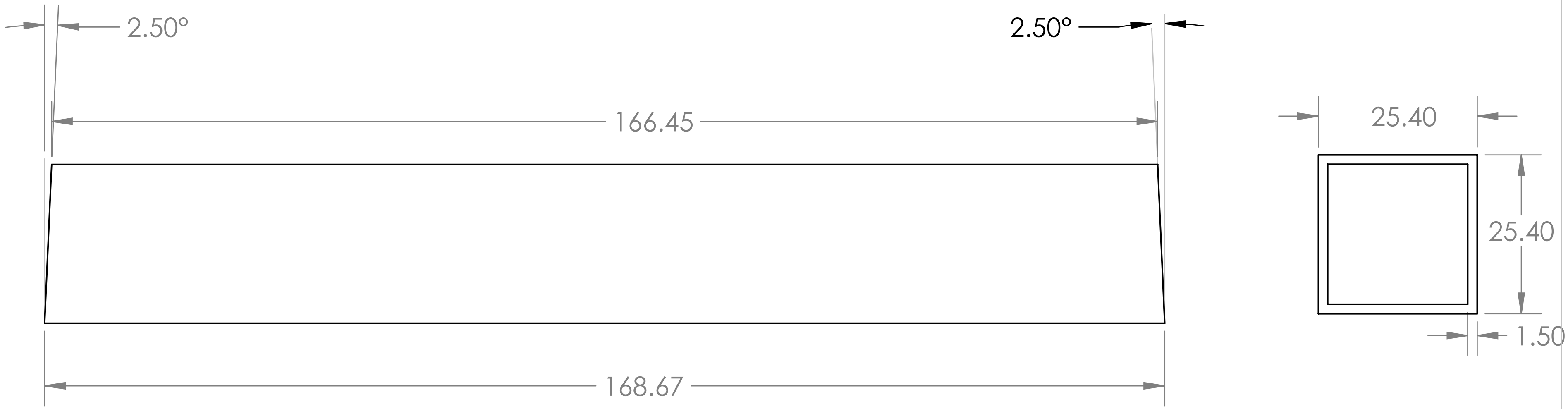
TITLE:

SIZE	DWG. NO.	REV
A	Part4	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



All Lengths are in mm

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			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
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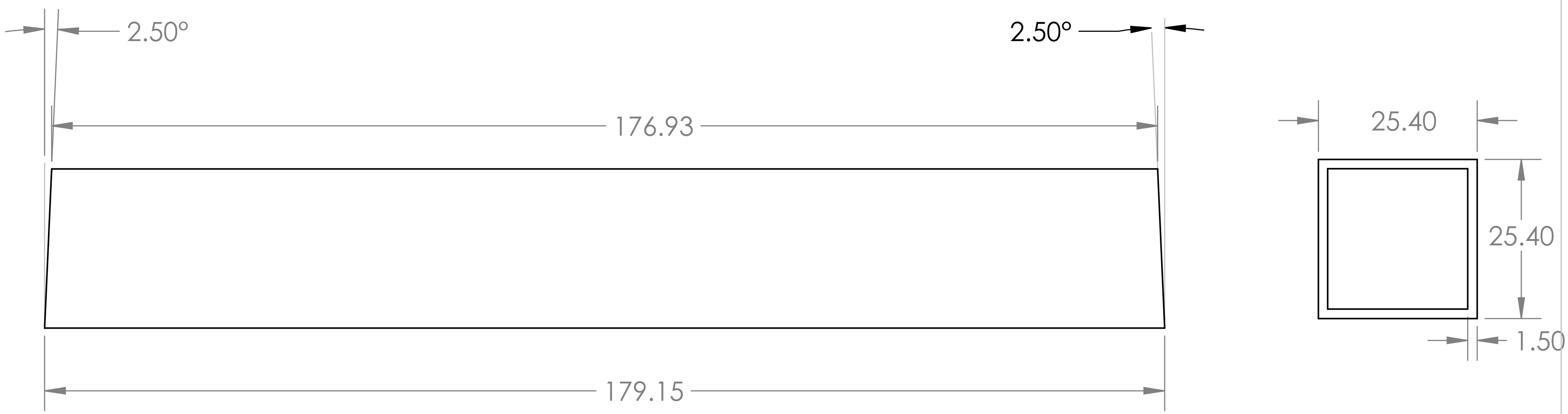

All lengths are in mm

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			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

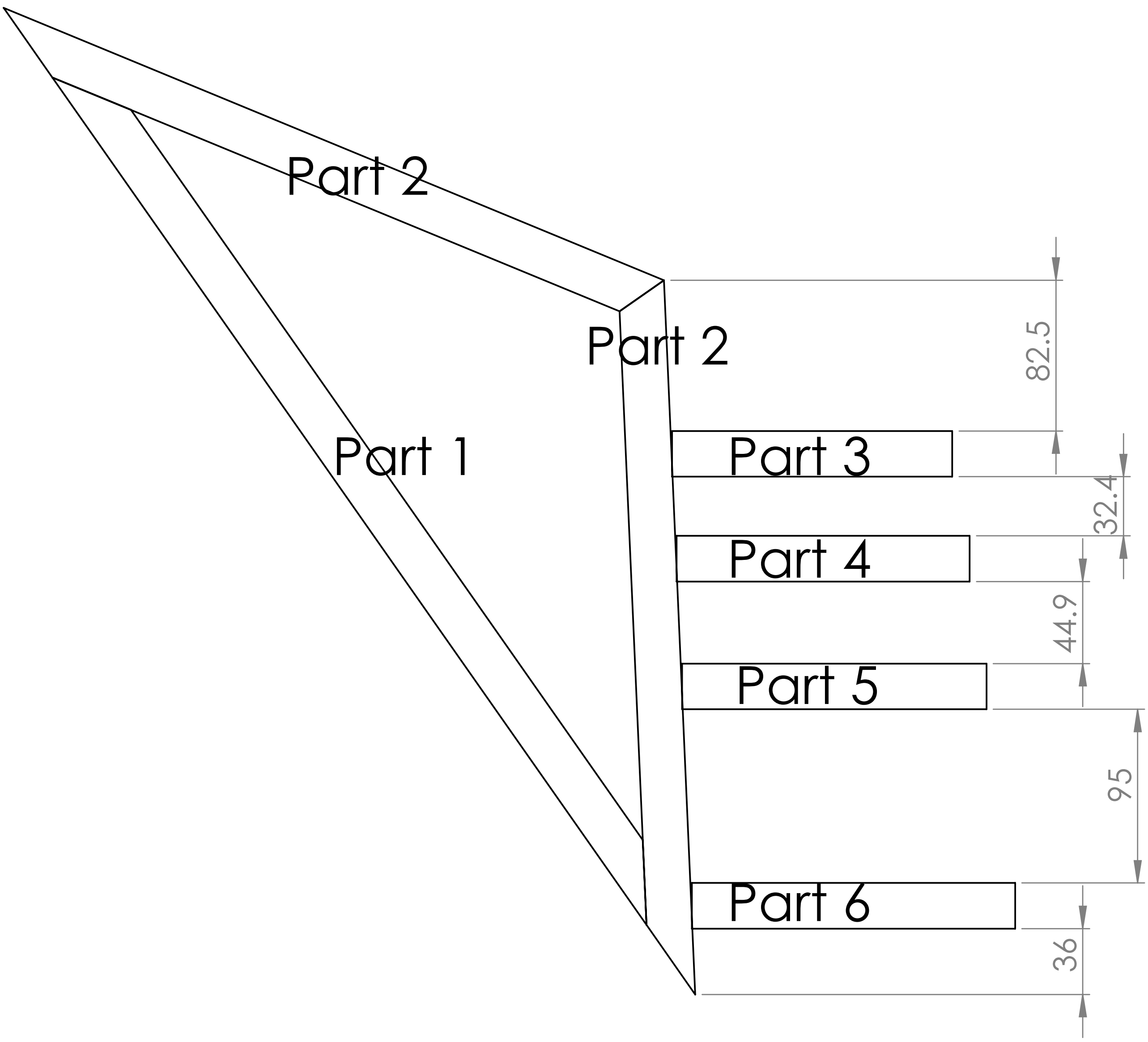
SIZE A | DWG. NO. Part6 | REV

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

Part Connections

All dimensions in mm



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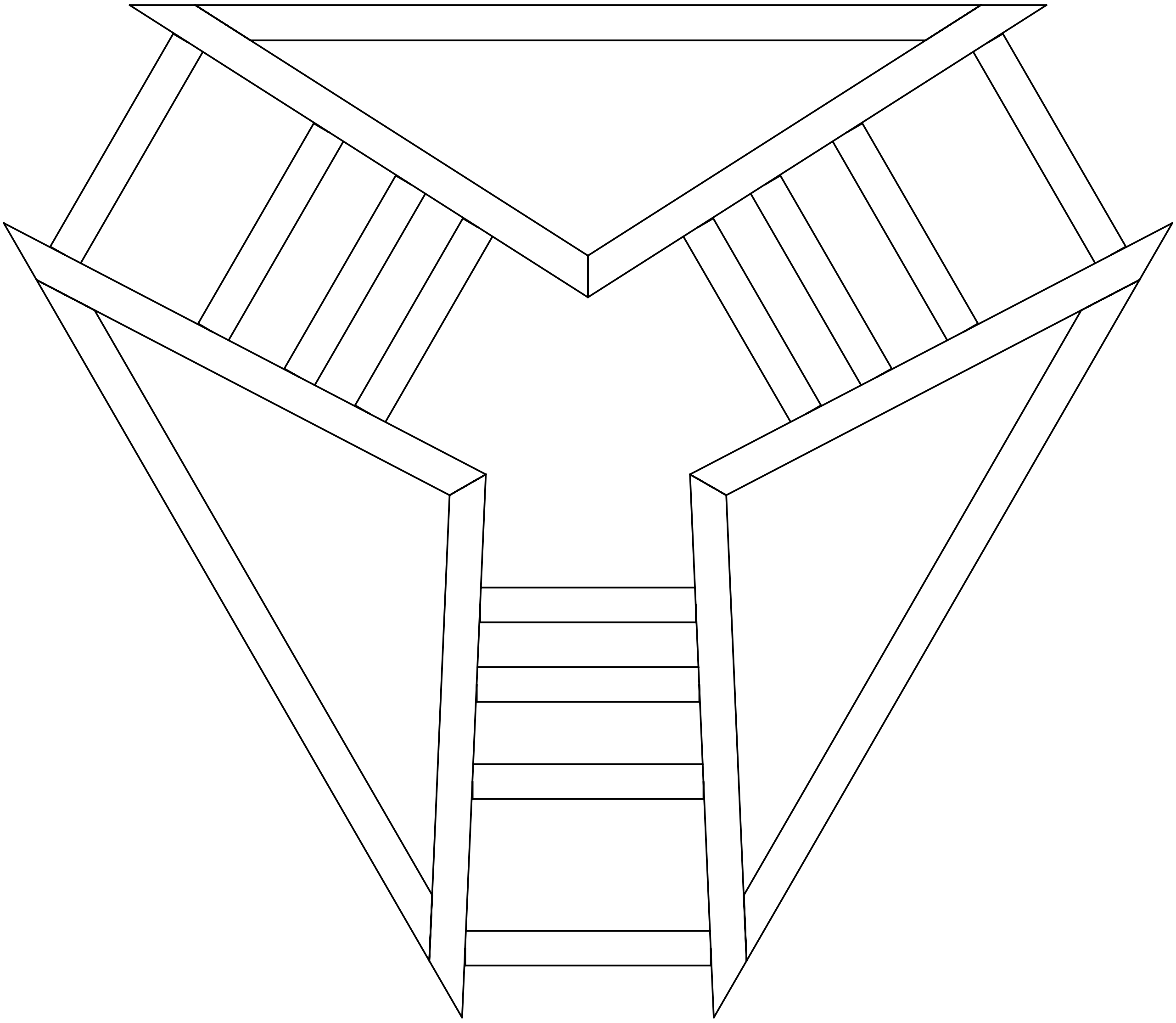
	NAME	SIGNATURE	DATE		TITLE:		
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:	DWG NO. Part_connections		A4
				WEIGHT:	SCALE:1:10	SHEET 1 OF 1	

Total structure of base



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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

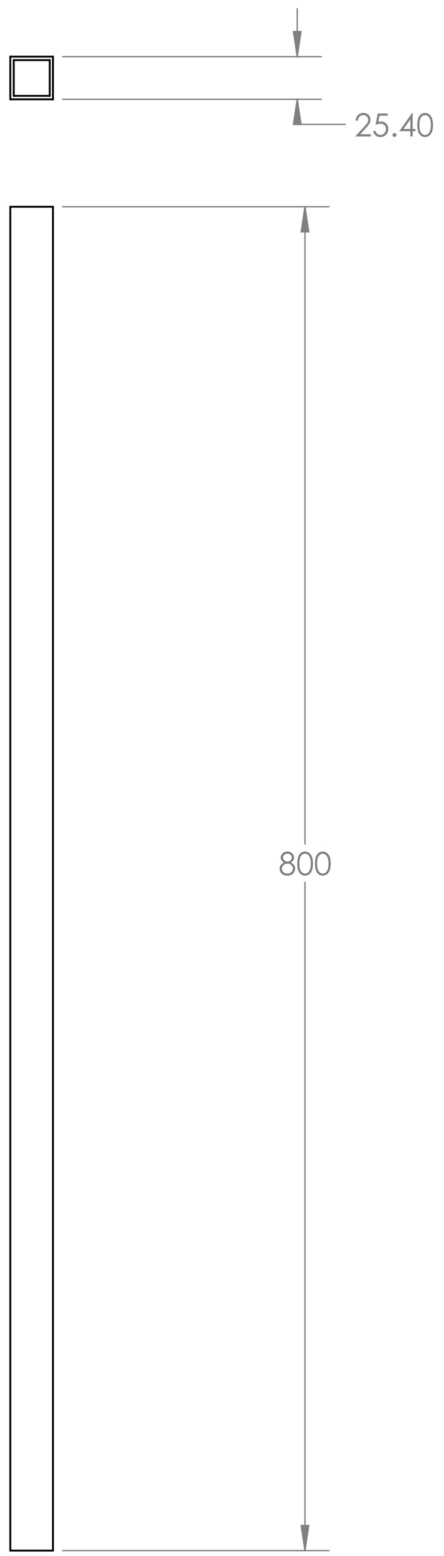
WEIGHT:

DWG NO. chassis no 2

A4

SCALE:1:20

SHEET 1 OF 1



Part 7

All dimensions in mm

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

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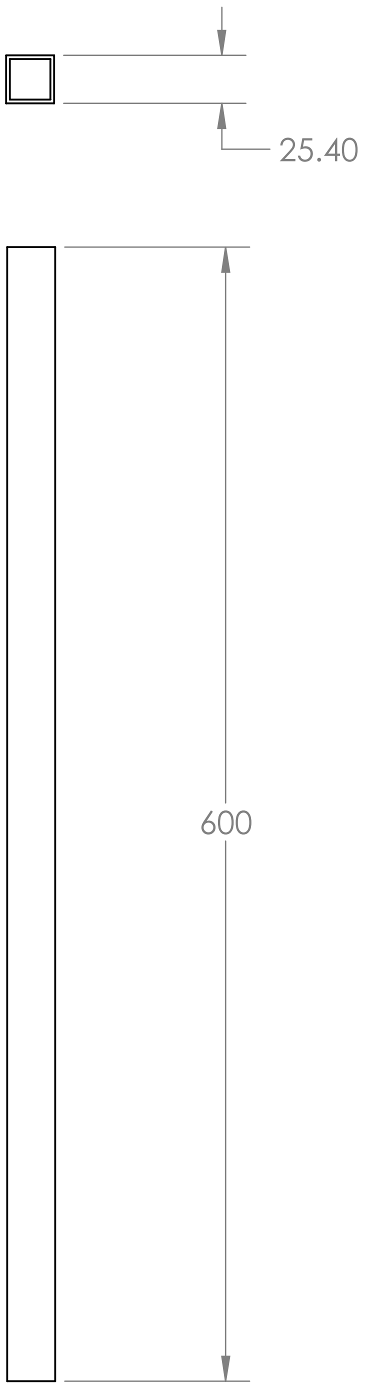
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	
				WEIGHT:	

TITLE:

DWG NO. Part3 A4

SCALE:1:10 SHEET 1 OF 1



Part 8

All dimensions in mm

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DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

DWG NO. Part3

A4

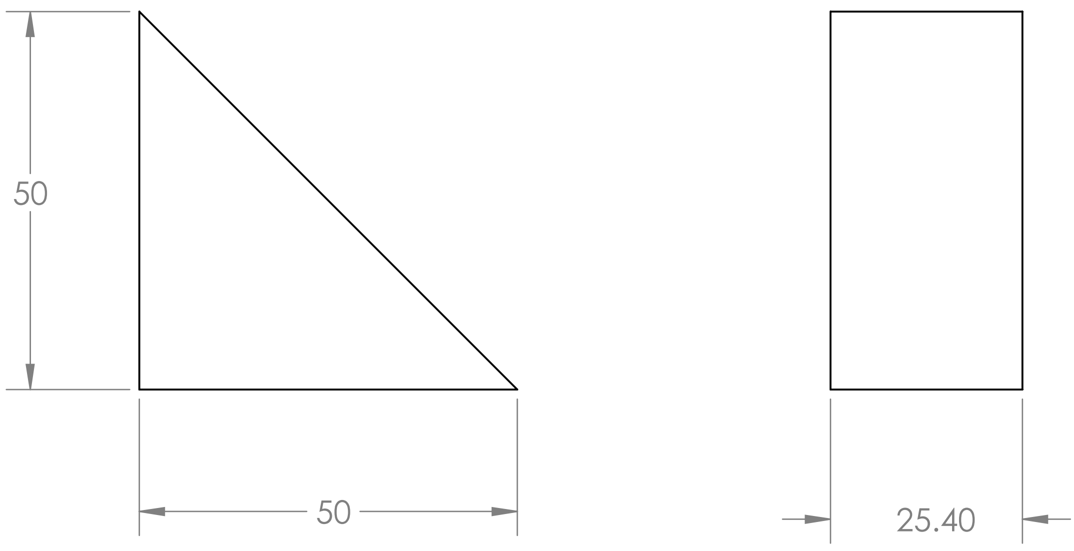
WEIGHT:

SCALE:1:5

SHEET 1 OF 1

Part 9

All dimensions in mm



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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

DWG NO.

Part4

All dimensions in mm

A4

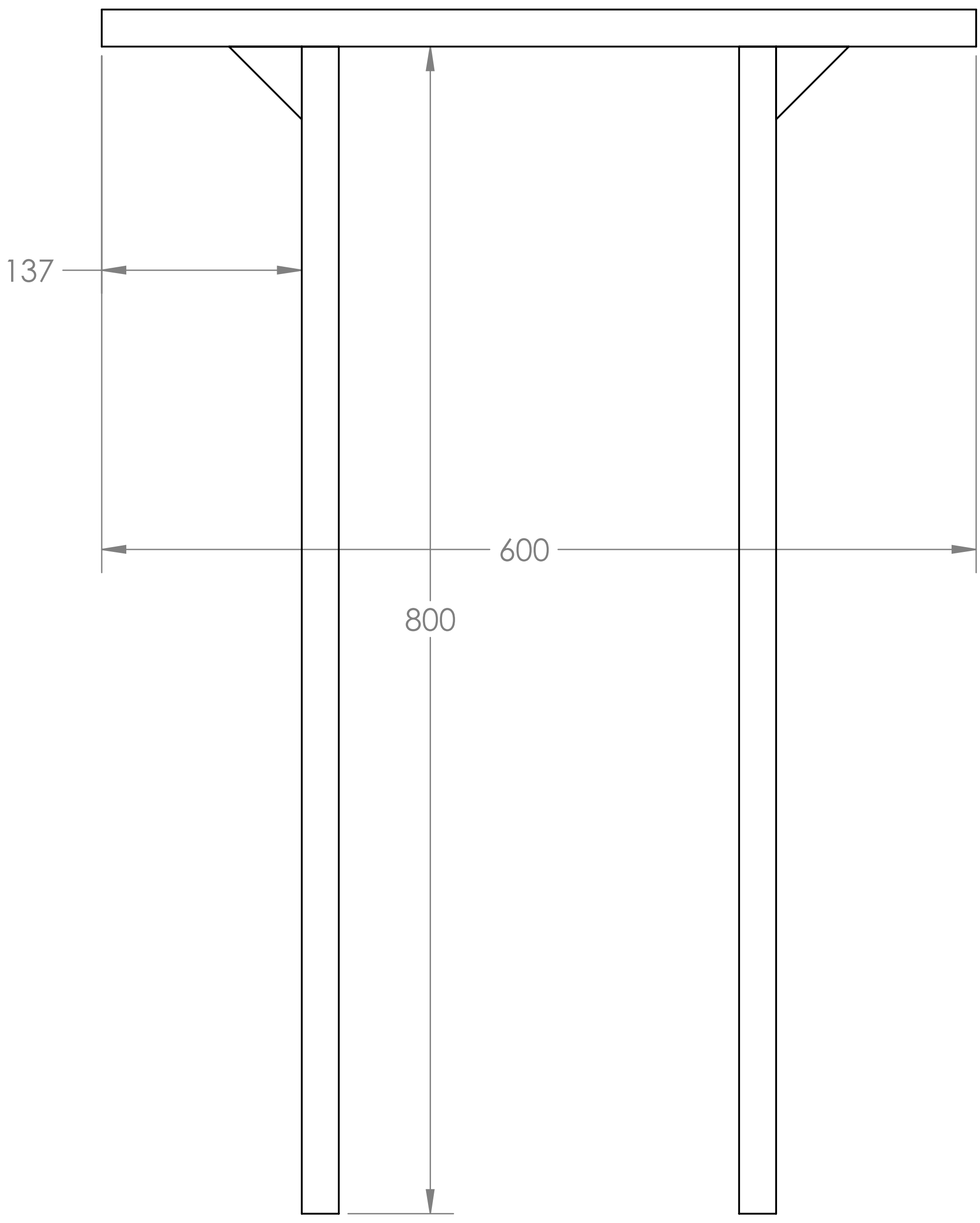
WEIGHT:

SCALE:1:1

SHEET 1 OF 1

part 7 +Part 8+Part 9

All dimensions in mm



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

TITLE:

MATERIAL:

WEIGHT:

DWG NO. 7+8+9

A4

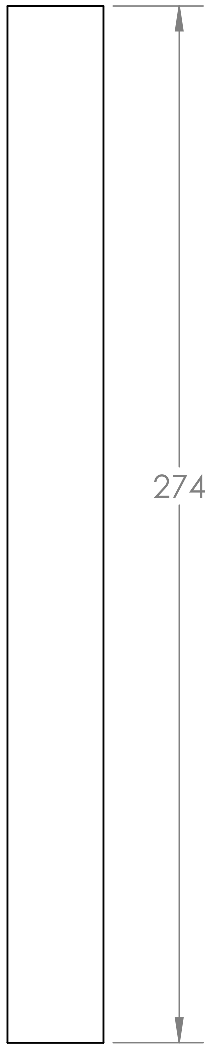
SCALE:1:10

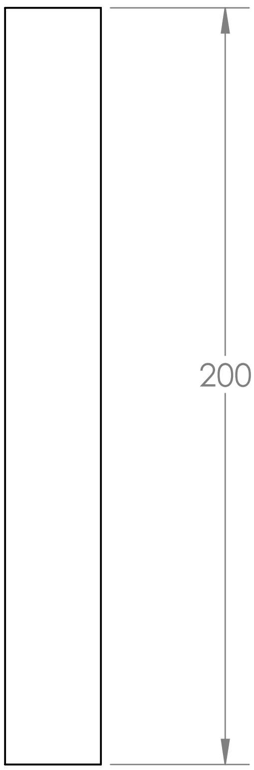
SHEET 1 OF 1

Part 10

Part 11

All dimensions in mm





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LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

WEIGHT:

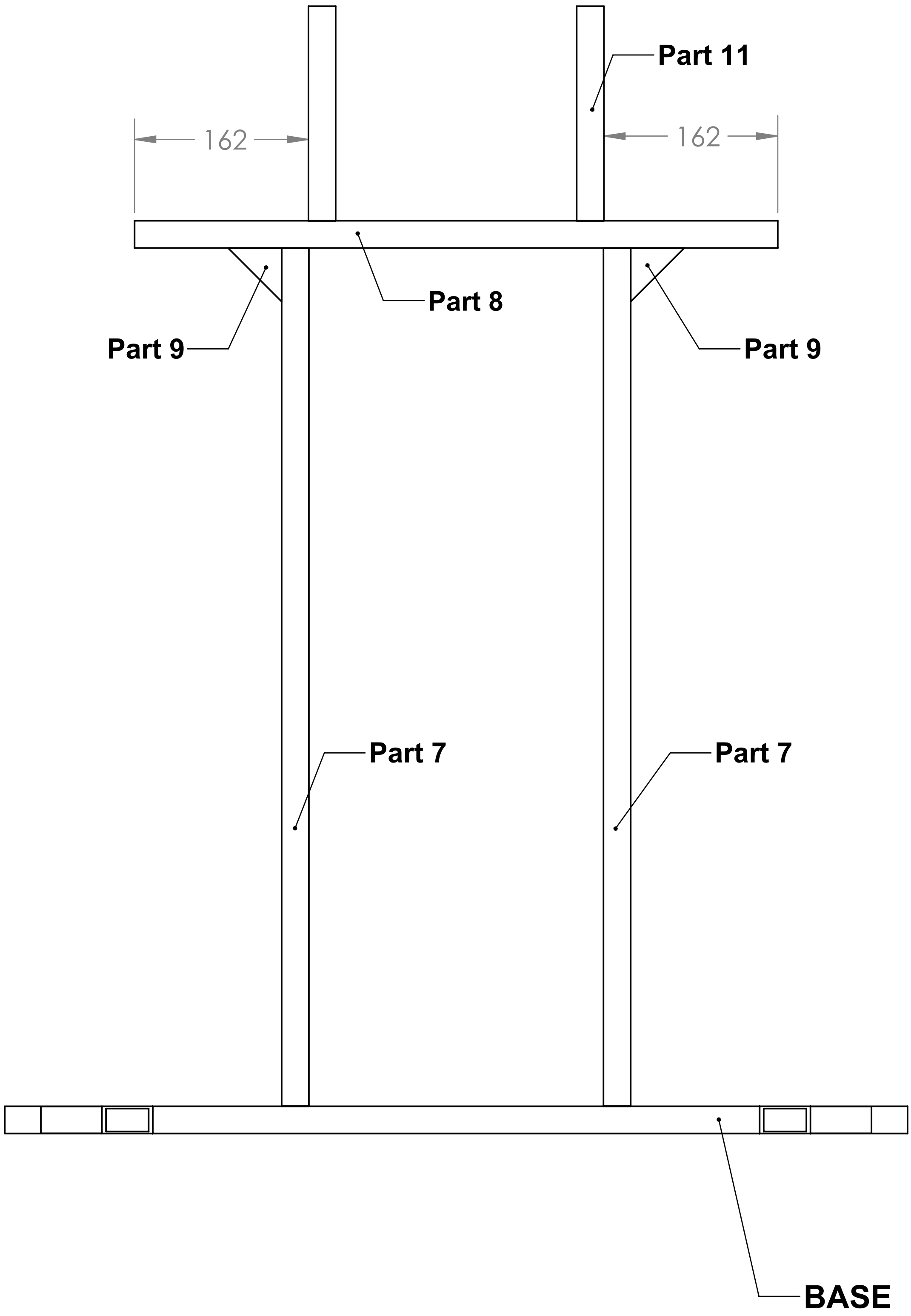
DWG NO. 10p

A4

SCALE:1:2

SHEET 1 OF 1

Total chassis - Front view



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

REVISION

TITLE:

MATERIAL:

WEIGHT:

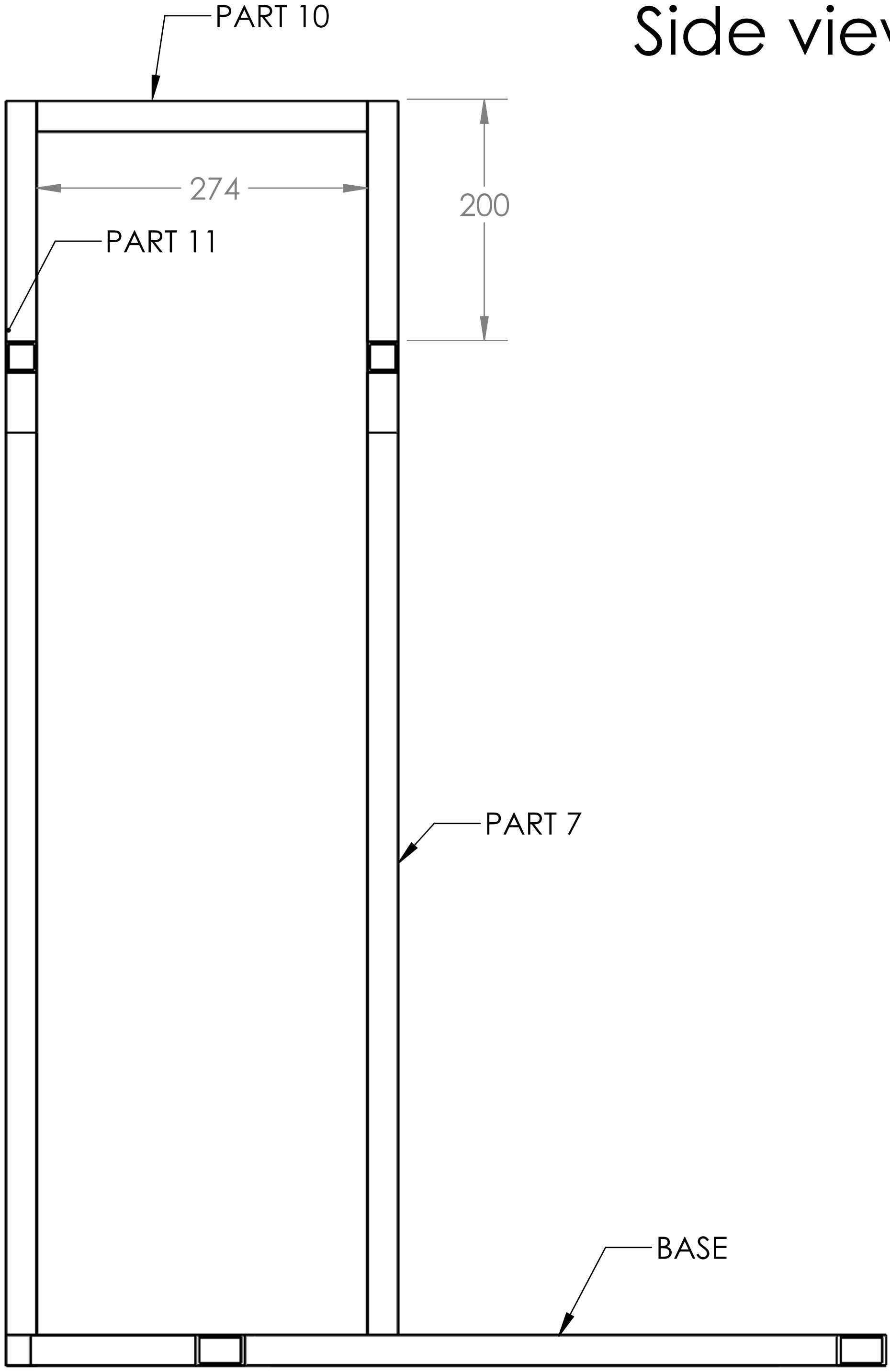
DWG NO. chassis no 2

A4

SCALE:1:20

SHEET 1 OF 1

Total chassis
Side view



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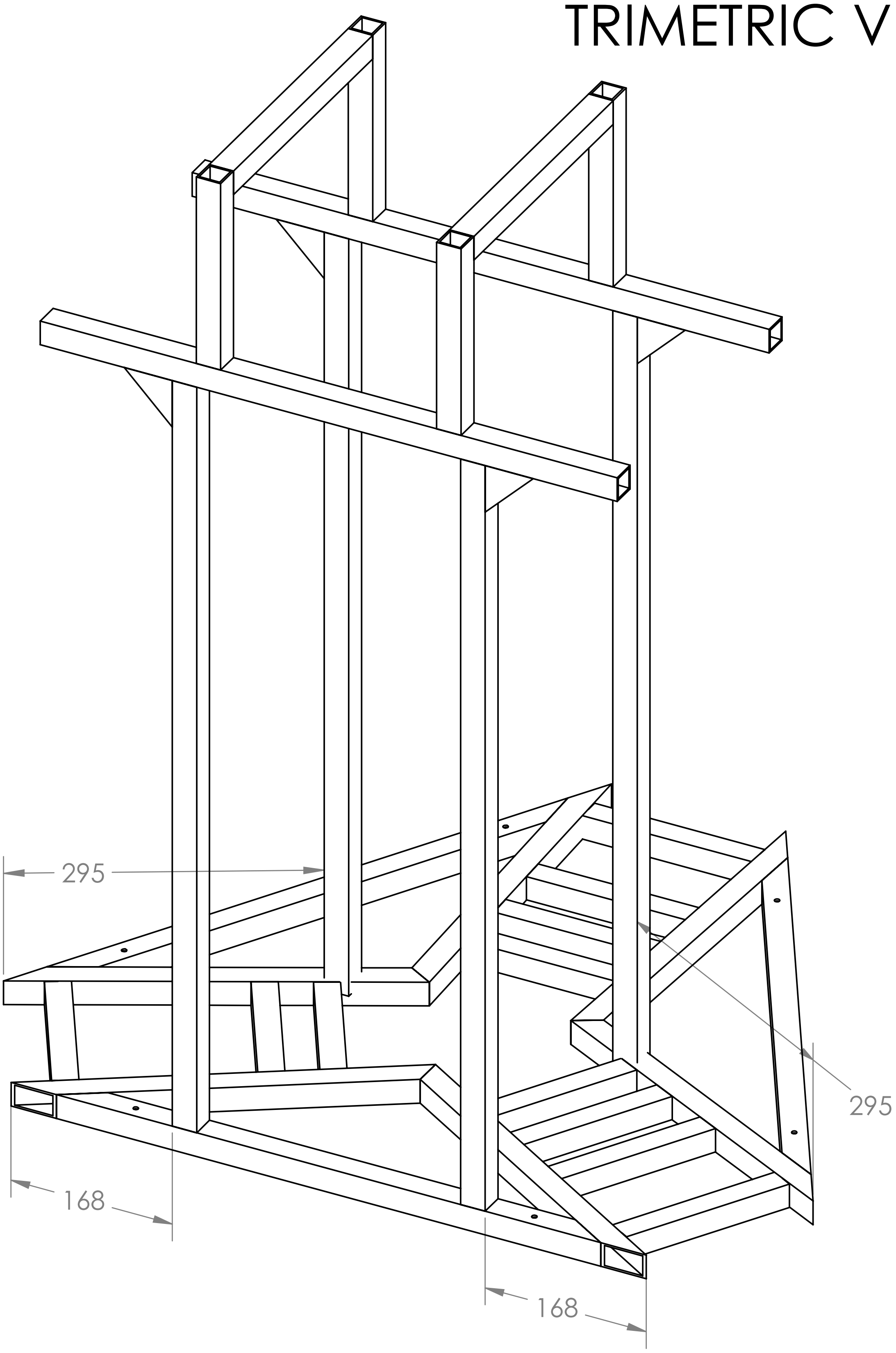
	NAME	SIGNATURE	DATE			TITLE:
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:		DWG NO. chassis no 2 A4
				WEIGHT:		SCALE:1:20 SHEET 1 OF 1

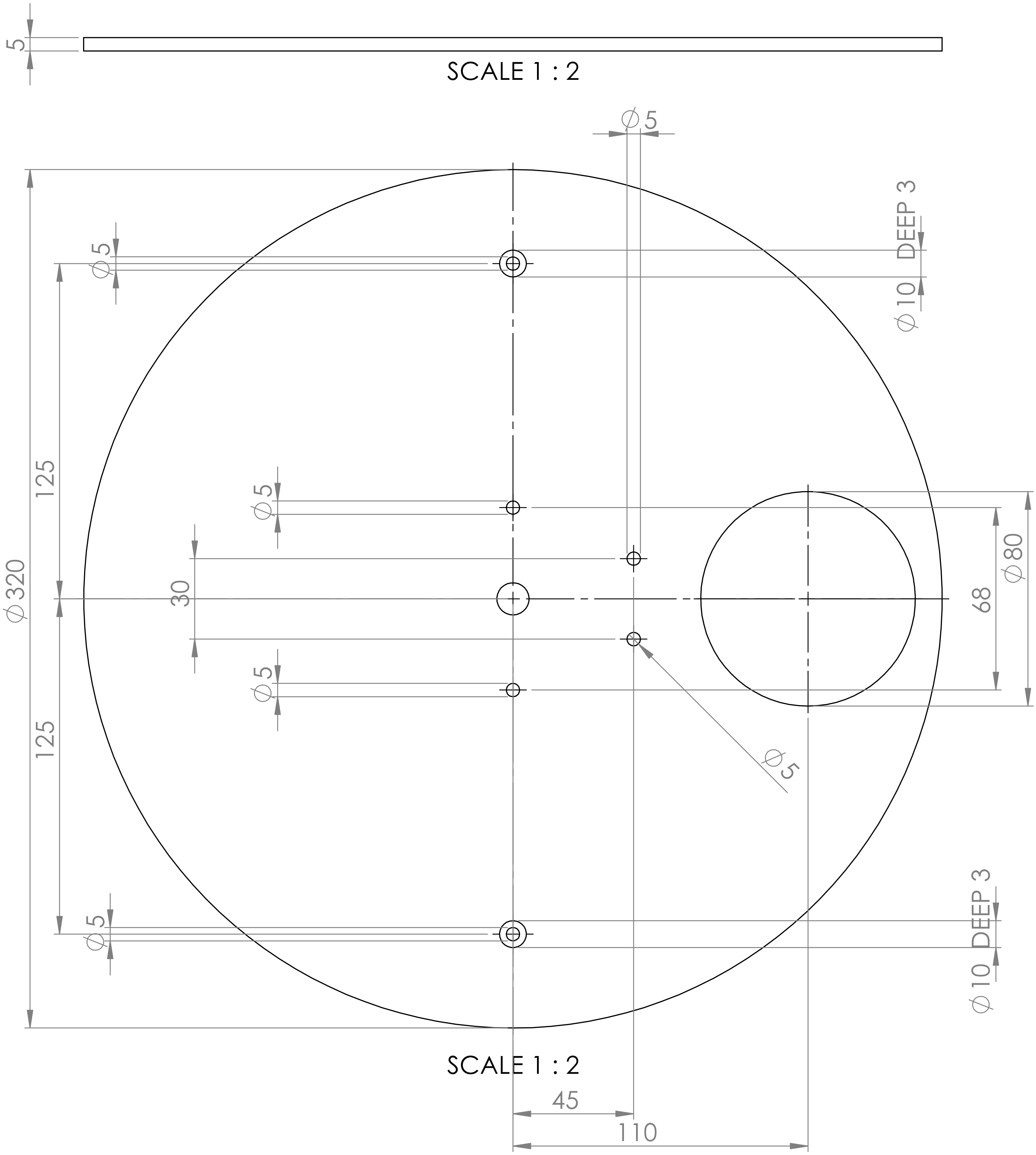
TOTAL CHASSIS TRIMETRIC VIEW



SCALE 1 : 5.7

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. chassis no 2	A4
				WEIGHT:	SCALE:1:20	SHEET 1 OF 1

Gun Barrel Part 1



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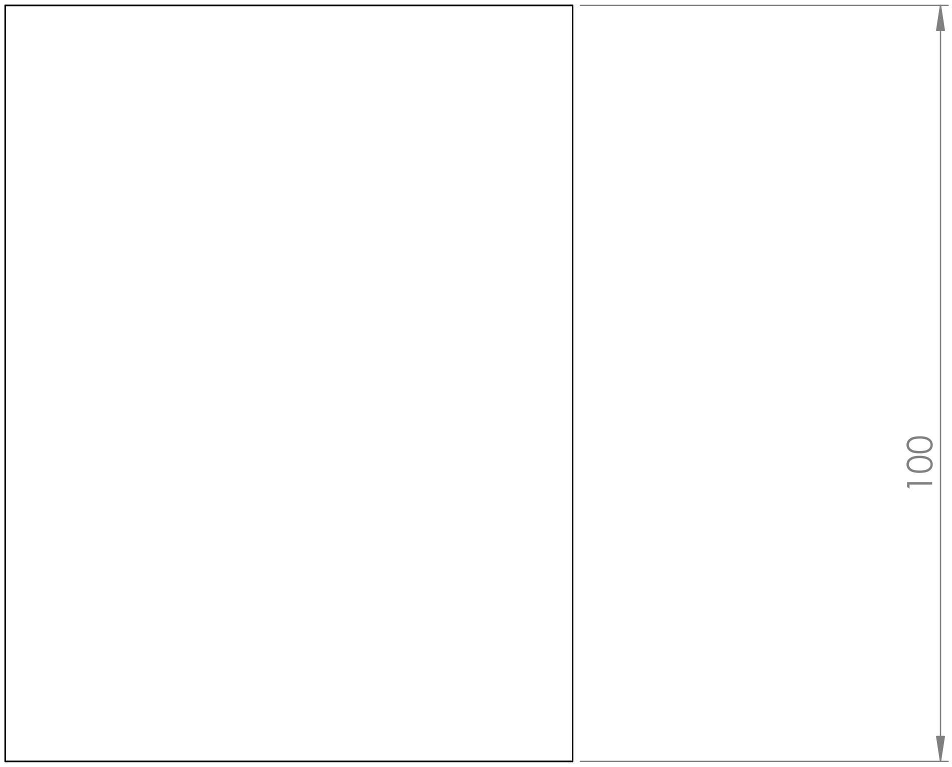
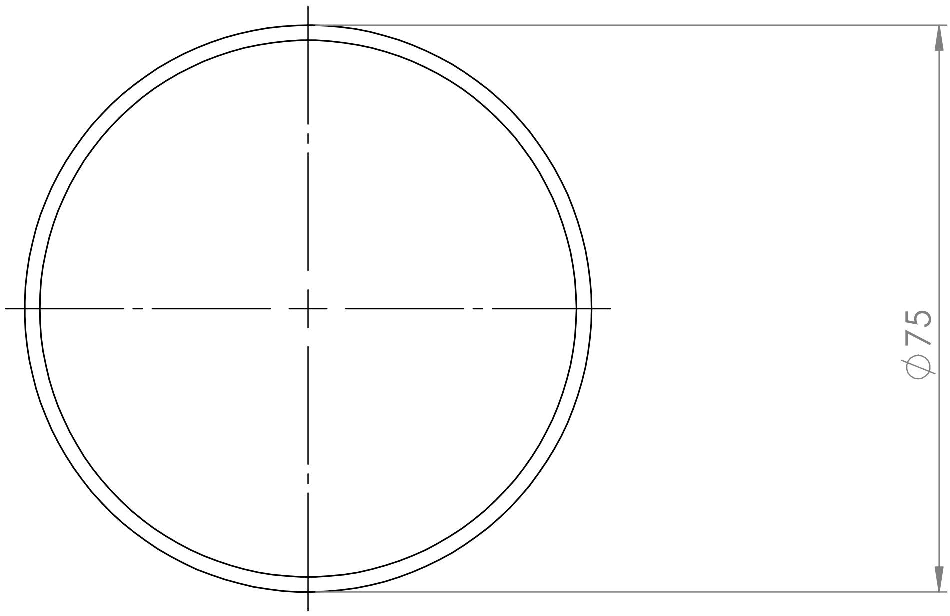
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL:	DWG NO. Gun_Barallel_bottom_plate	A4	
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1	



SCALE 1 : 1



SCALE 1 : 1

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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

MATERIAL:

WEIGHT:

TITLE:

Bottom Plate Cylinder Part 2

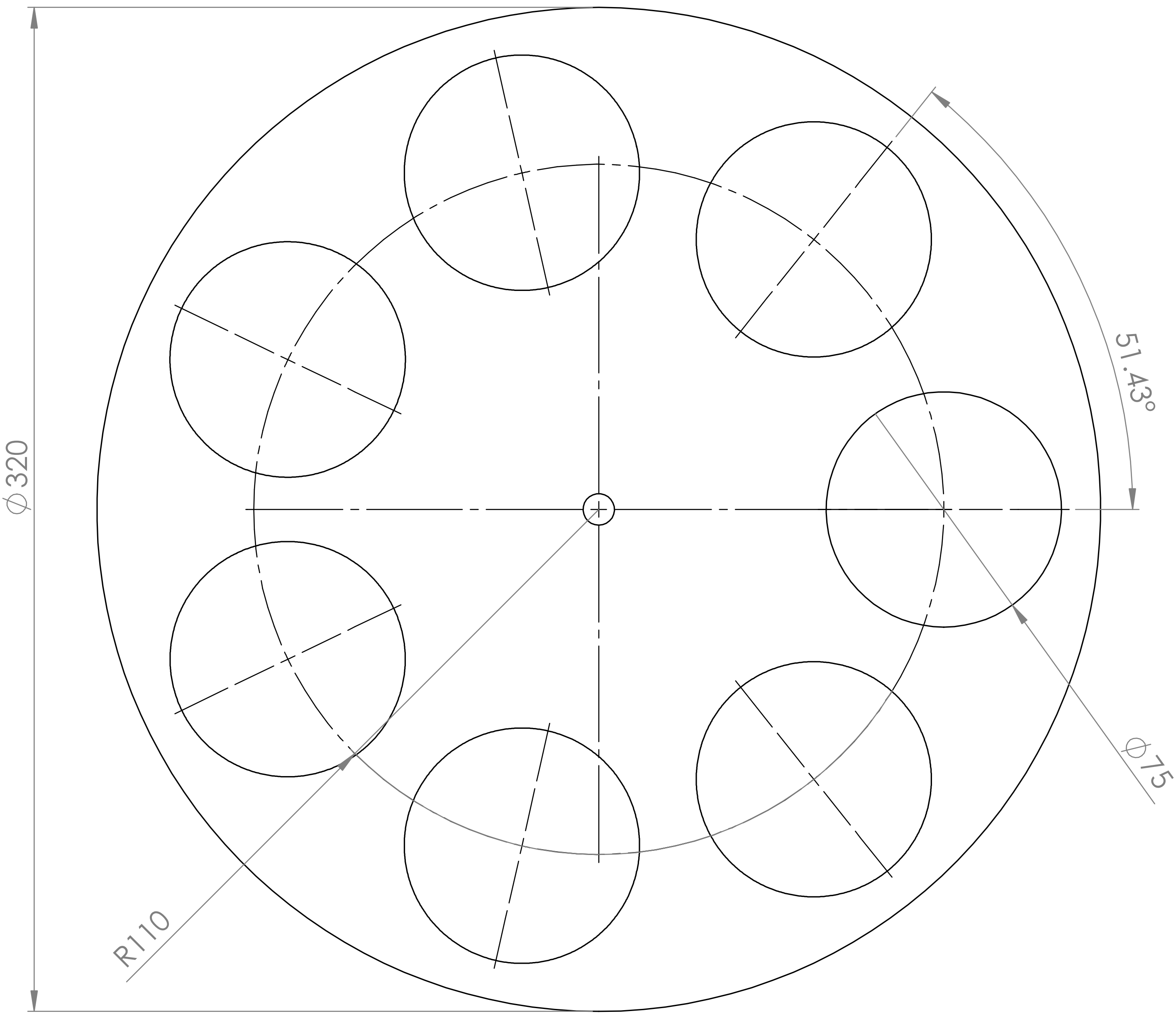
DWG NO. Gun_Barallel_cylinder

A4

SCALE:1:2

SHEET 1 OF 1

SCALE 1 : 2



SCALE 1 : 2

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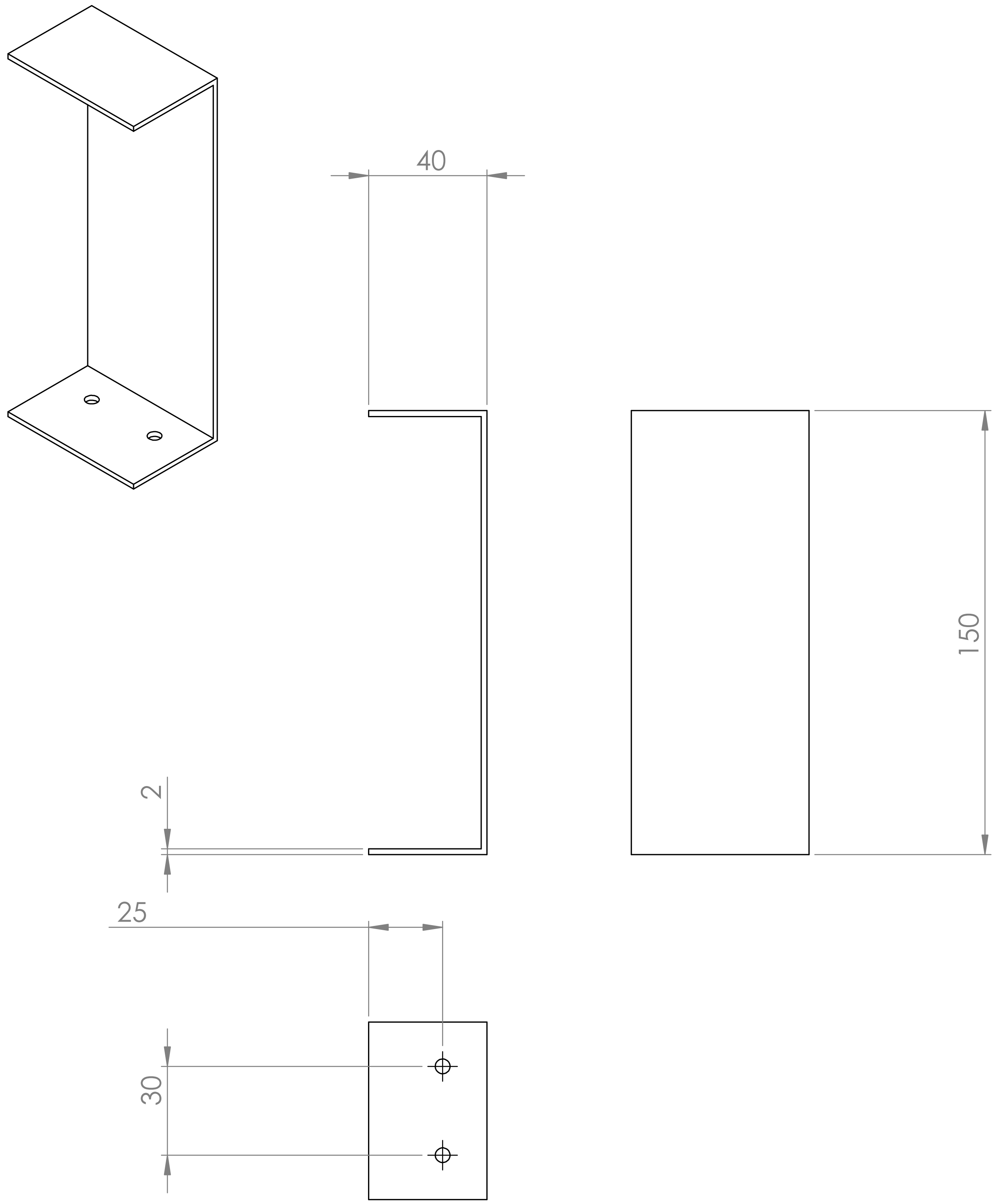
	NAME	SIGNATURE	DATE	TITLE: Top Plate Part 3	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. Gun_Barallel_top_plate	A4
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

MATERIAL:

WEIGHT:

TITLE:

Sensor Support Part 4

DWG NO.

Gun_Barallel_sensor_suppor

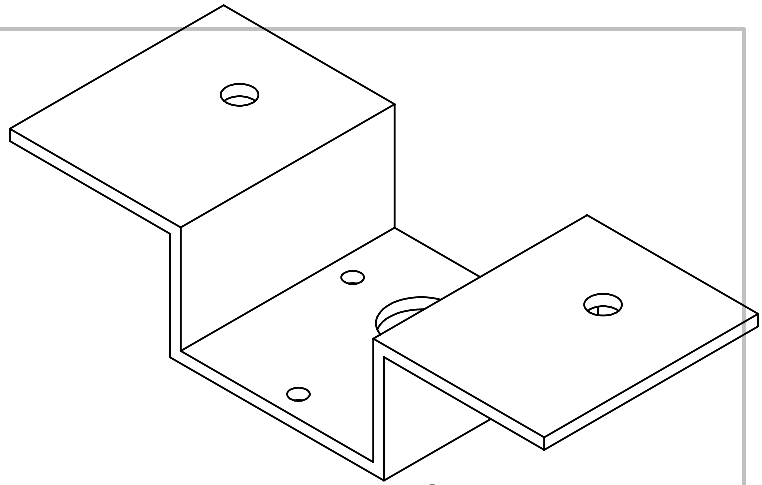
A4

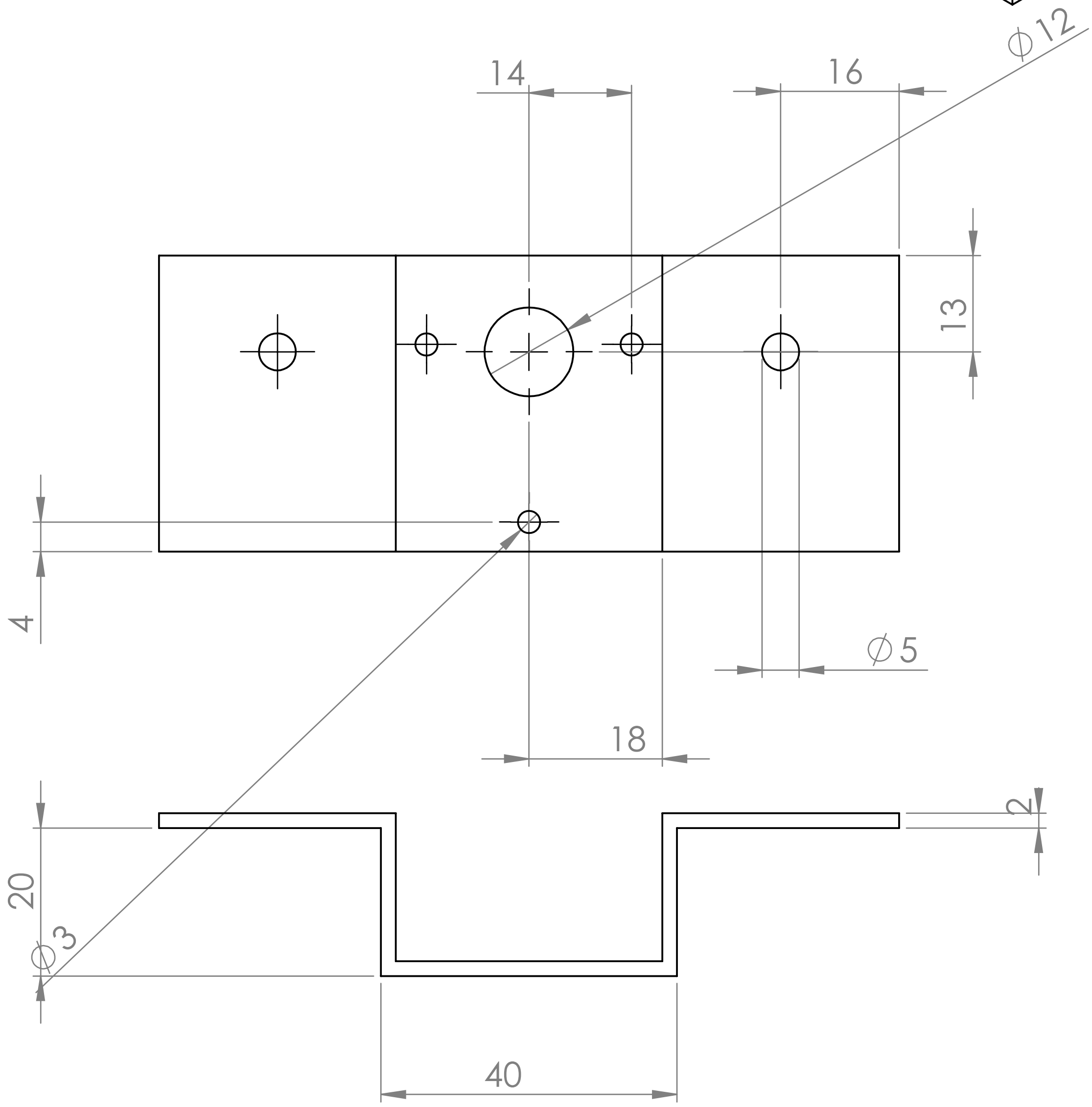
SCALE:1:2

SHEET 1 OF 1

Gun barrel motor support

Part 5





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DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

DWG NO. Gun_Barallel_support

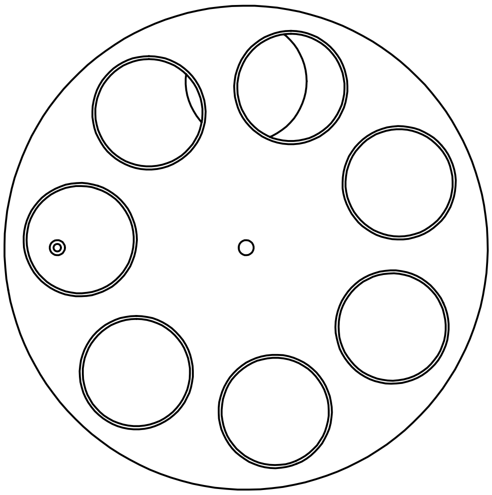
A4

WEIGHT:

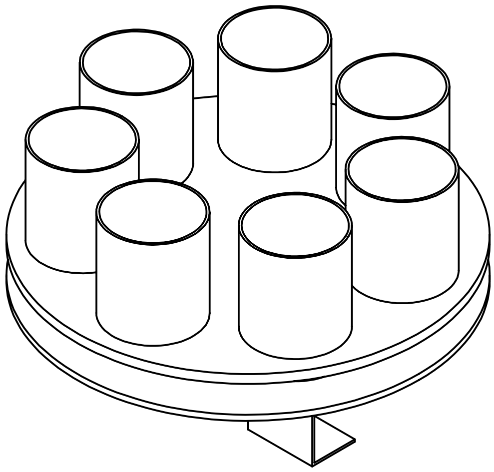
SCALE:1:2

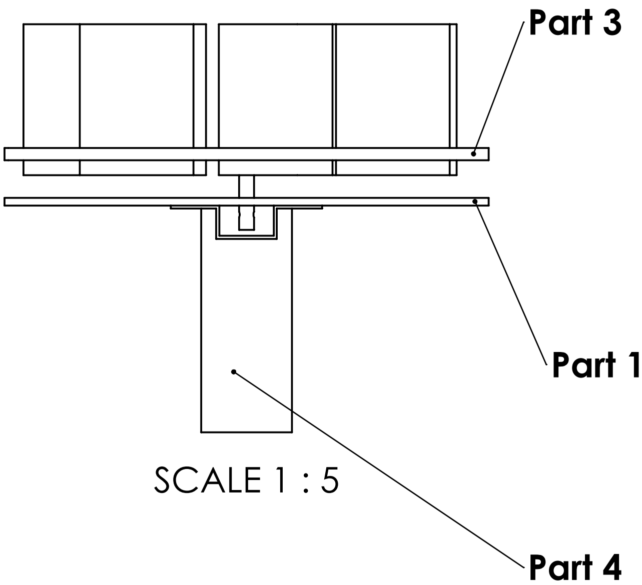
SHEET 1 OF 1

Top

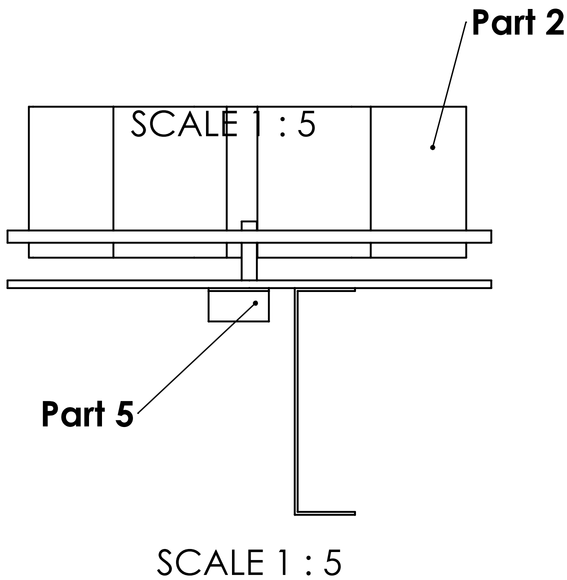


Isometric



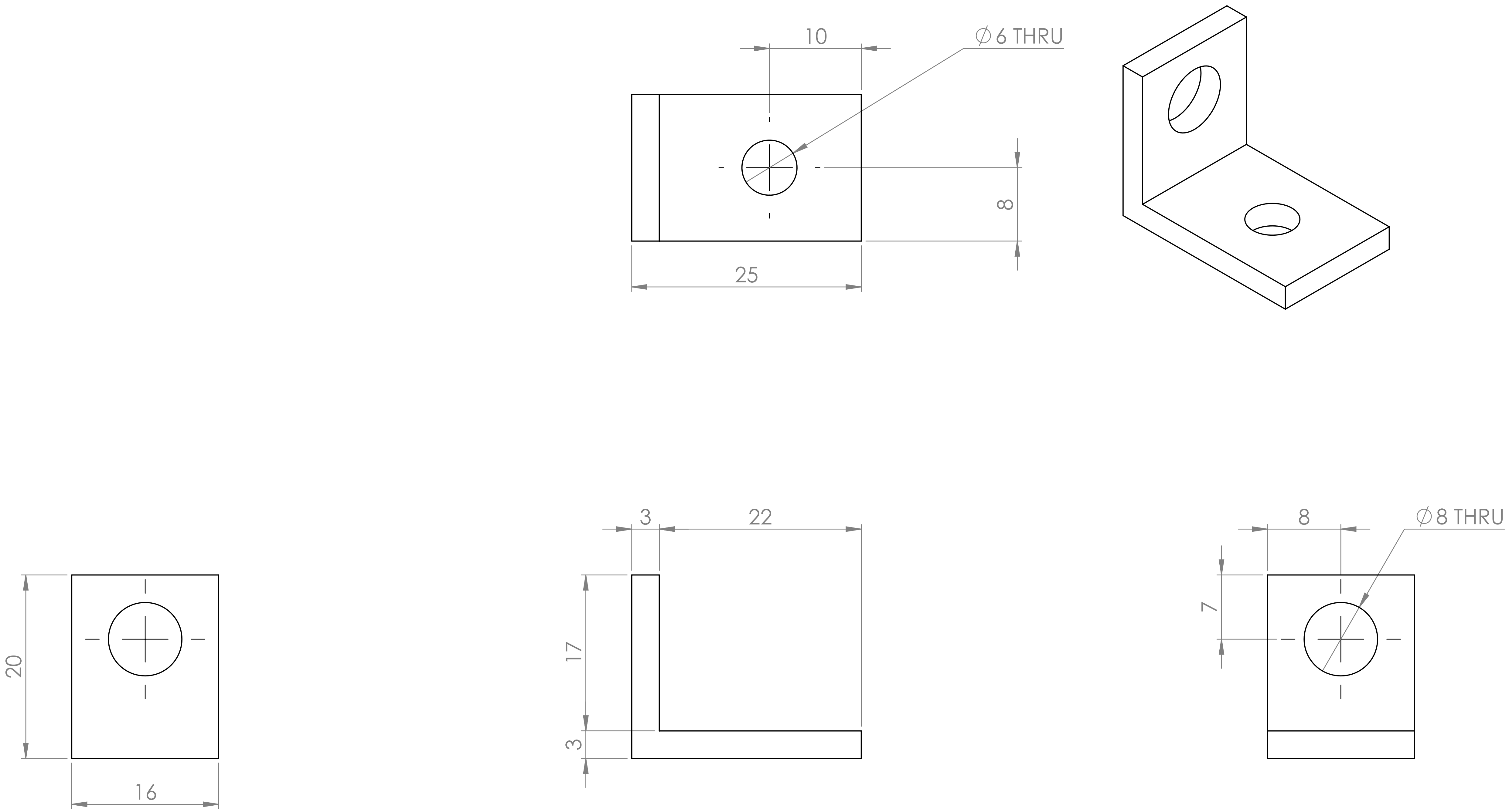


Front



Right

Gun_Barallel_Assembly



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: 0.5 mm
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

MATERIAL: Aluminium

WEIGHT:

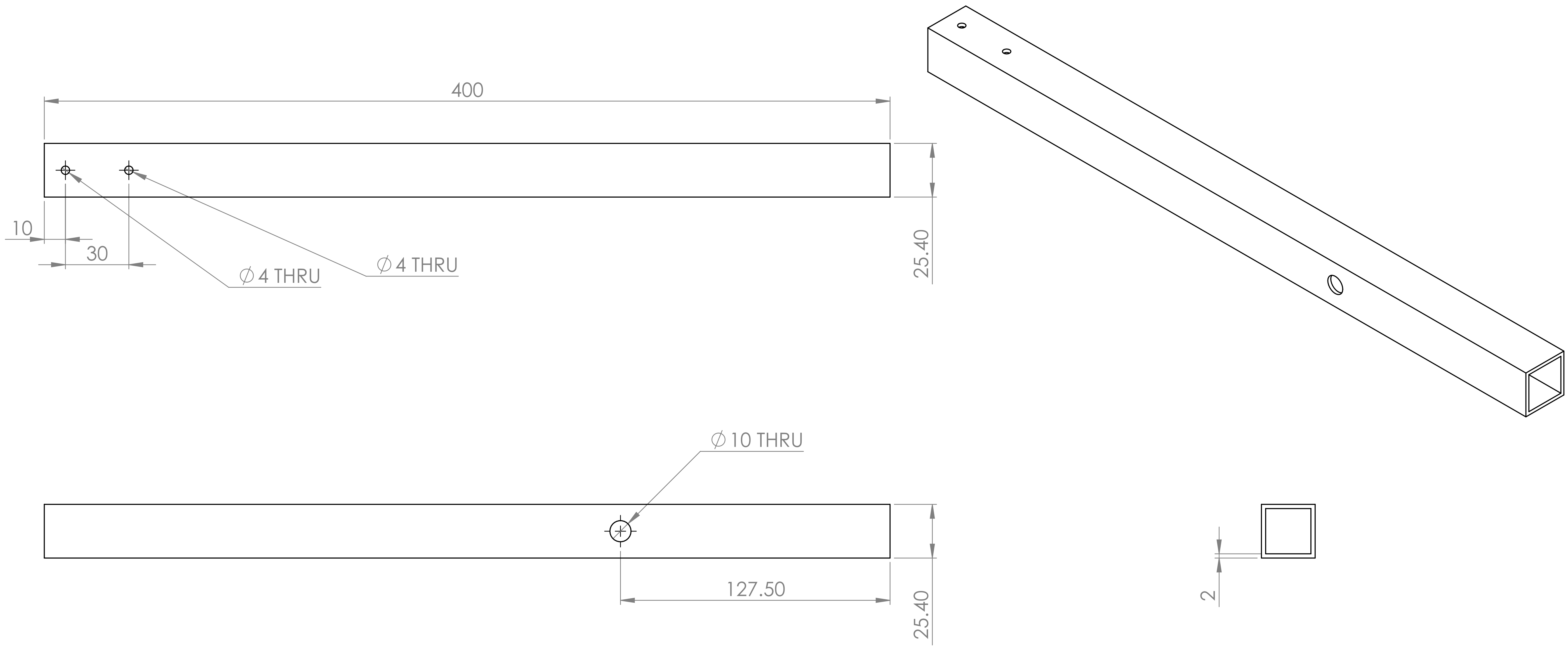
TITLE:

DWG NO. Angle

A3

SCALE:2:1

SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

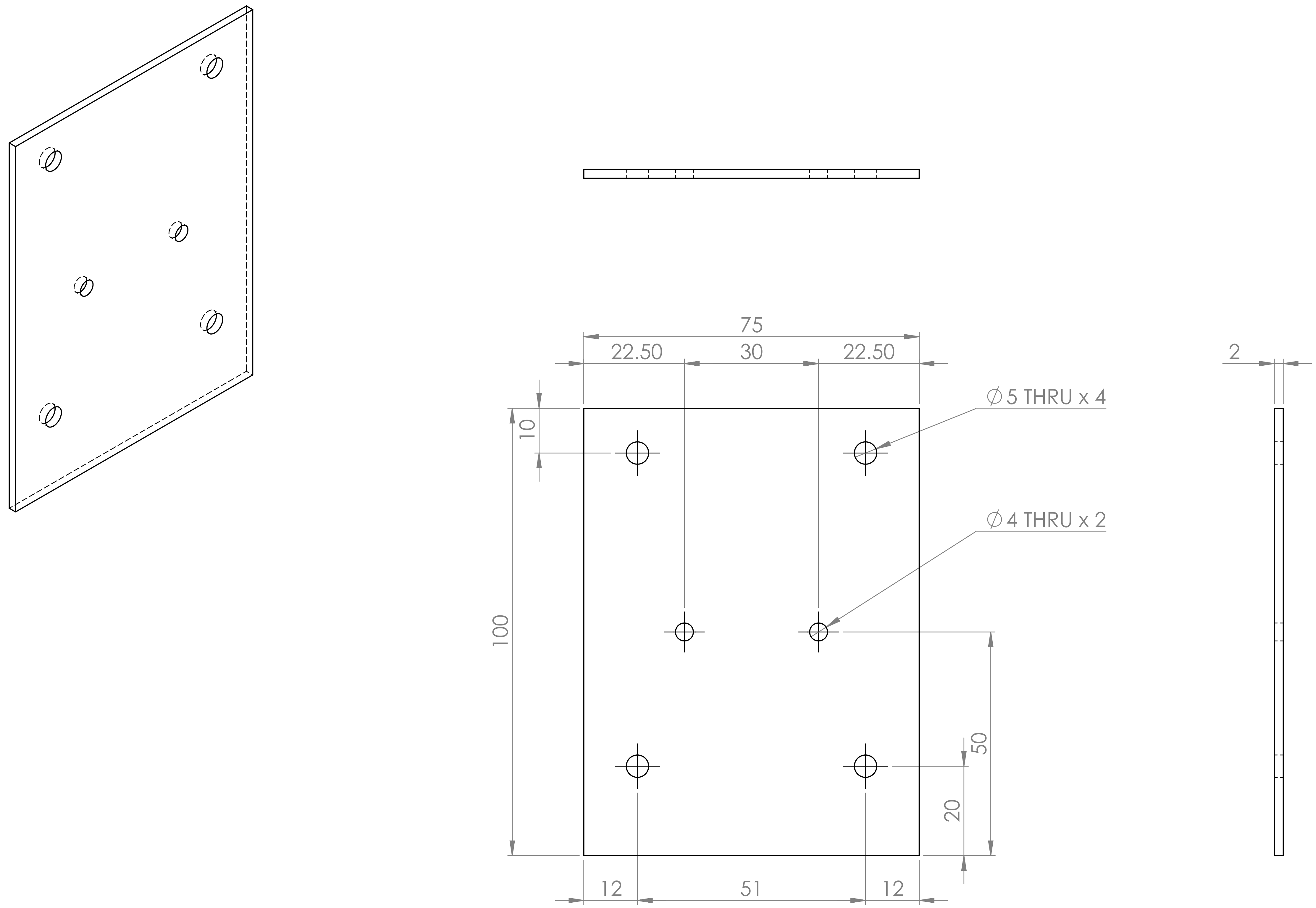
DWG NO. Base_Channel

A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:
Aluminium

WEIGHT:

DWG NO.
baseplate

A3

SCALE:1:1

SHEET 1 OF 1

1	2	3	4

A

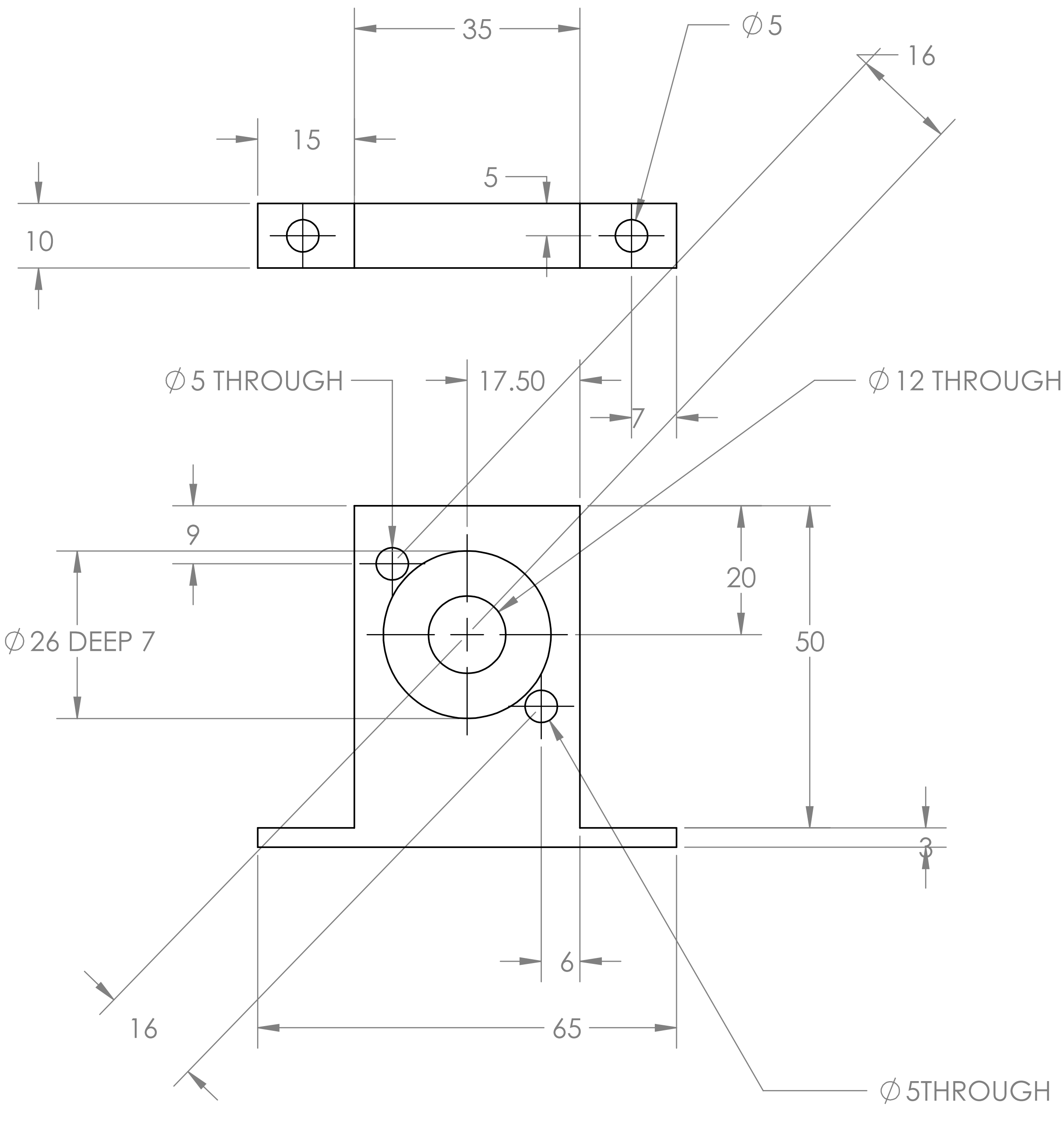
B

C

D

E

F



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

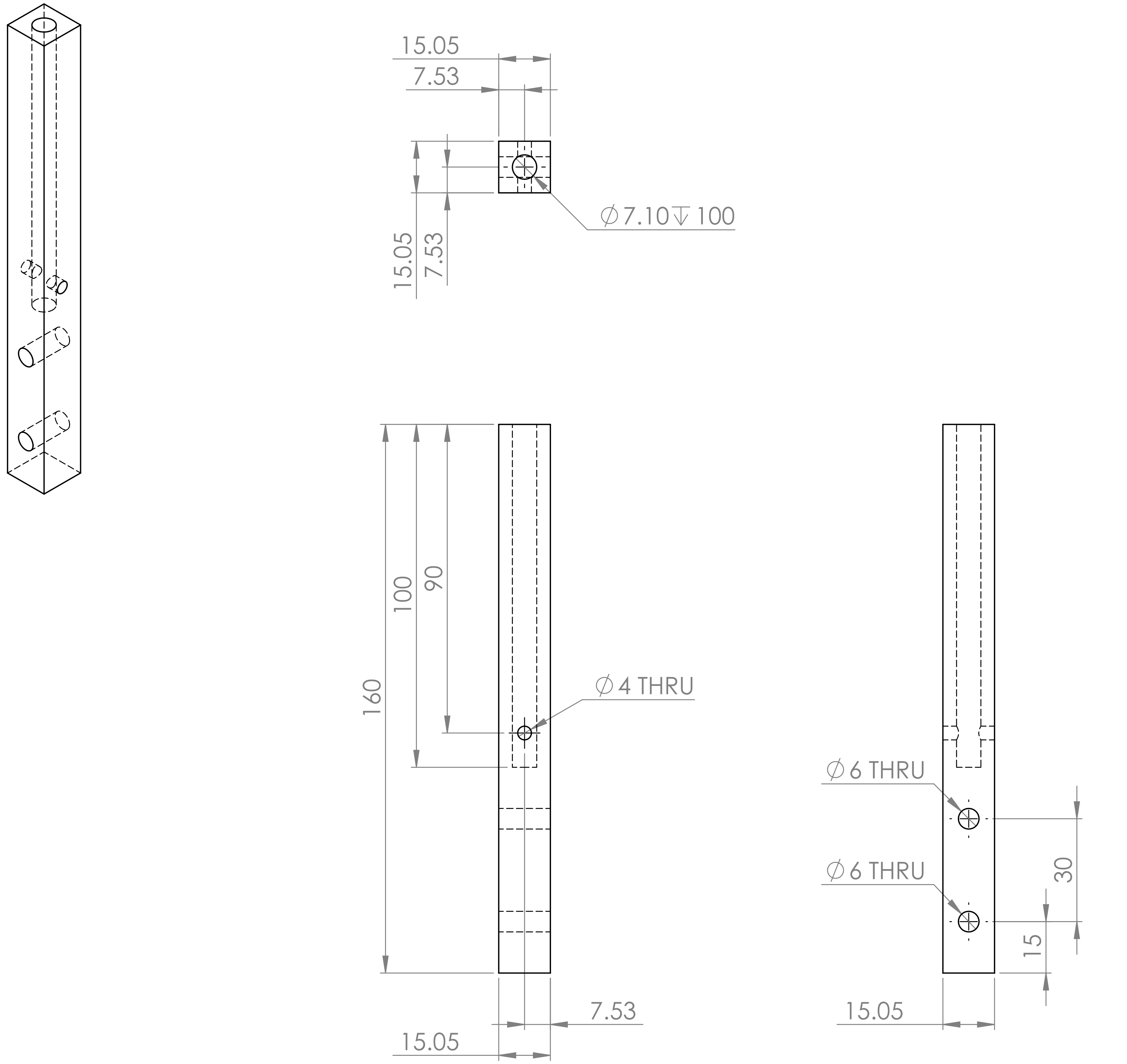
WEIGHT:

DWG NO. bearing-housing

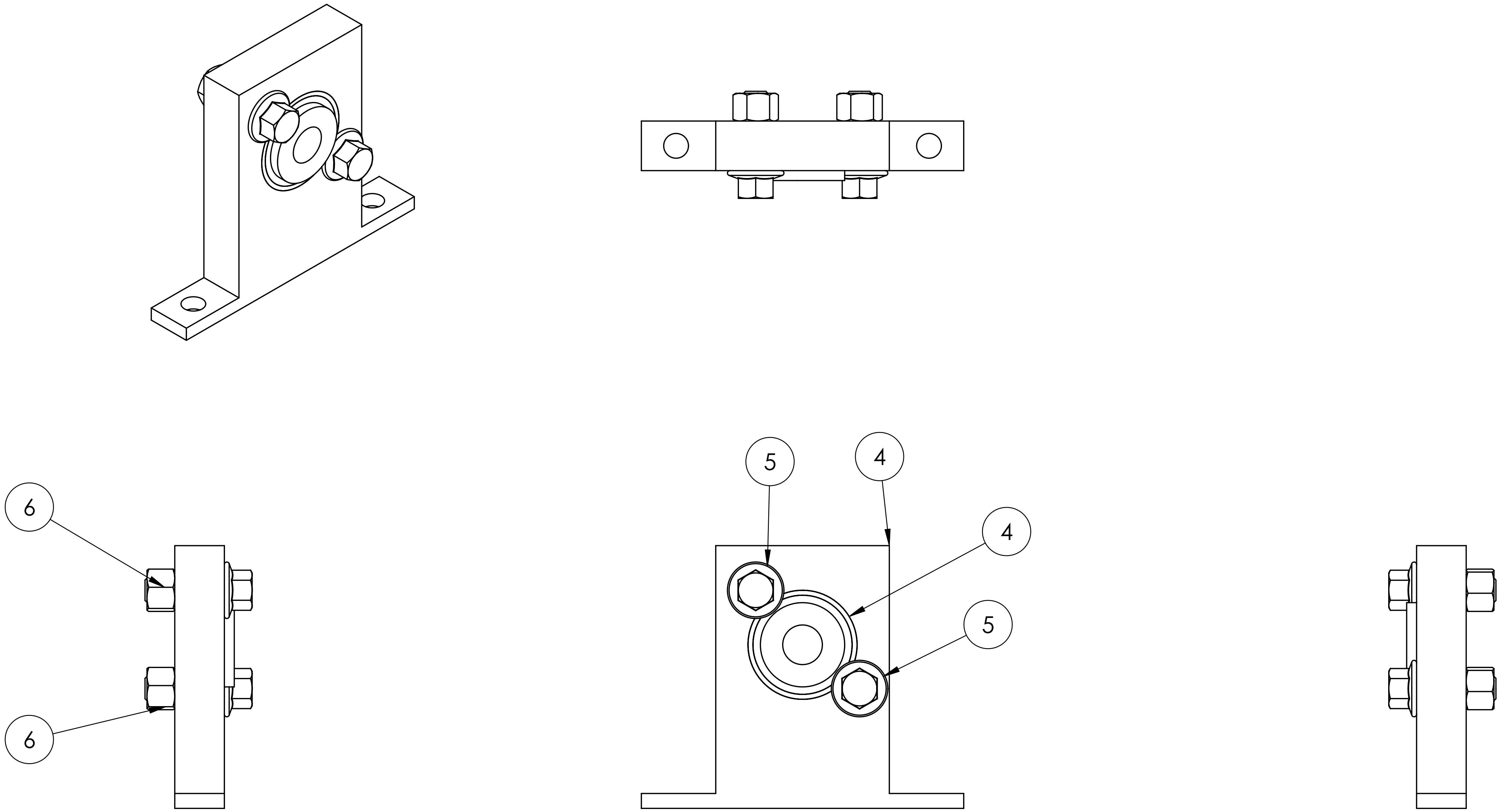
A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: Wood	DWG NO. Racket_Holder		A3
			WEIGHT:	SCALE:1:2	SHEET 1 OF 1	



ITEM NO.	PART NUMBER	QTY.
1	AMANUAL-bearing-inner part-2	1
2	AMANUAL-bearing-outer part	1
3	AMANUAL-bearing-covering-plate	2
4	housing	1
5	ISO 4162 - M5 x 16 x 16-S	2
6	Hexagon Nut ISO - 4034 - M5 - S	2

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

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

TITLE:

MATERIAL:

WEIGHT:

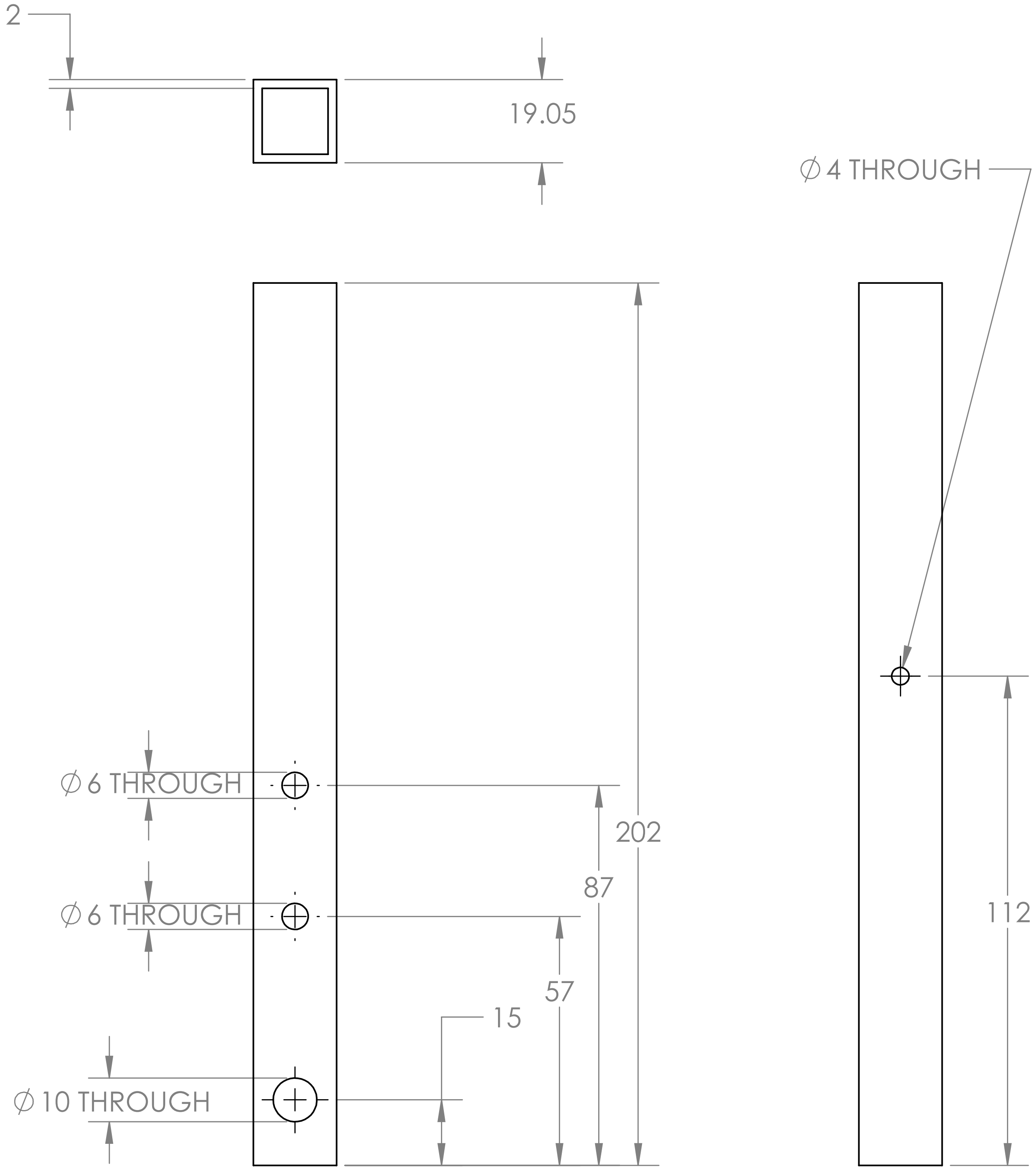
DWG NO.

Bearing_Assembly

A3

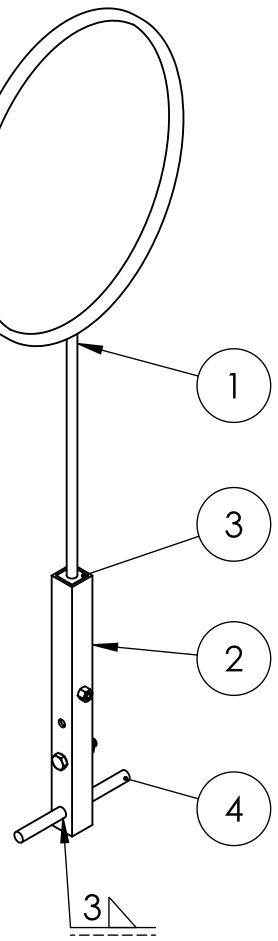
SCALE:1:1

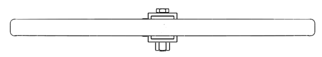
SHEET 1 OF 1

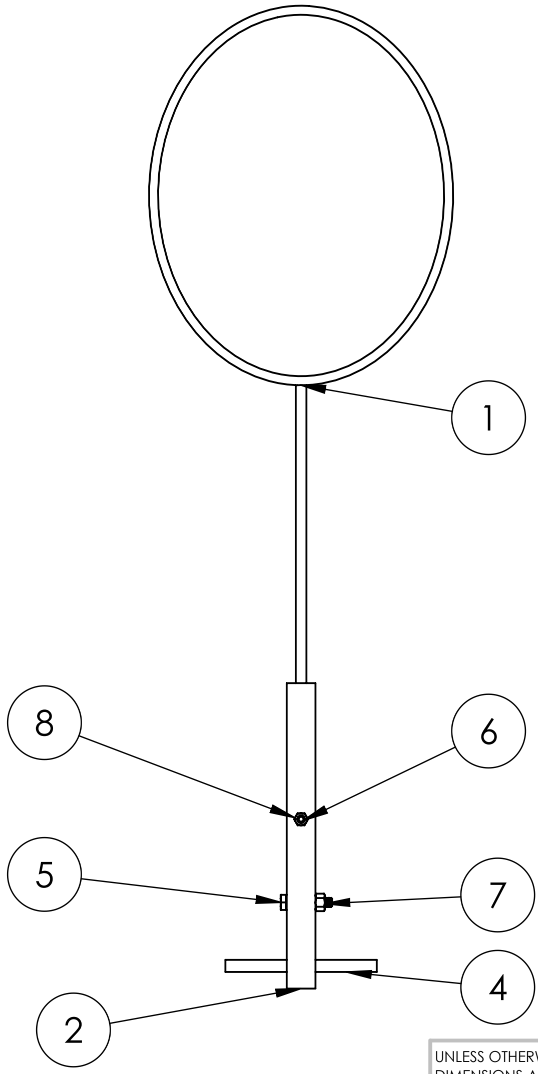


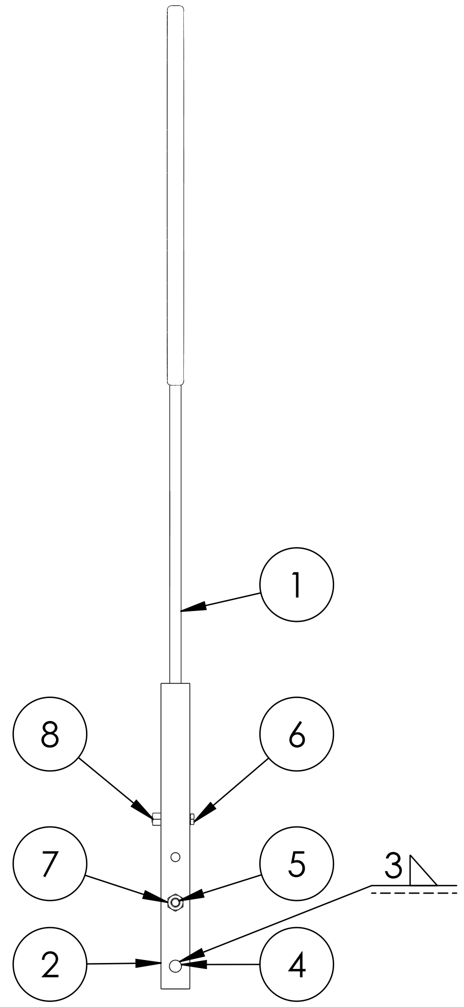
SCALE 1 : 1.5

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









ITEM NO.	PART NUMBER	QTY.
1	Racket	1
2	Racket_Channel	1
3	Racket_Holder (Wood)	1
4	Racket_Shaft	1
5	ISO 4014 - M6 x 30 x 18-S	1
6	ISO 4014 - M4 x 25 x 25-S	1
7	Hexagon Nut ISO - 4034 - M6 - S	1
8	Hexagon Nut ISO - 4034 - M5 - S	1

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

DWG NO.

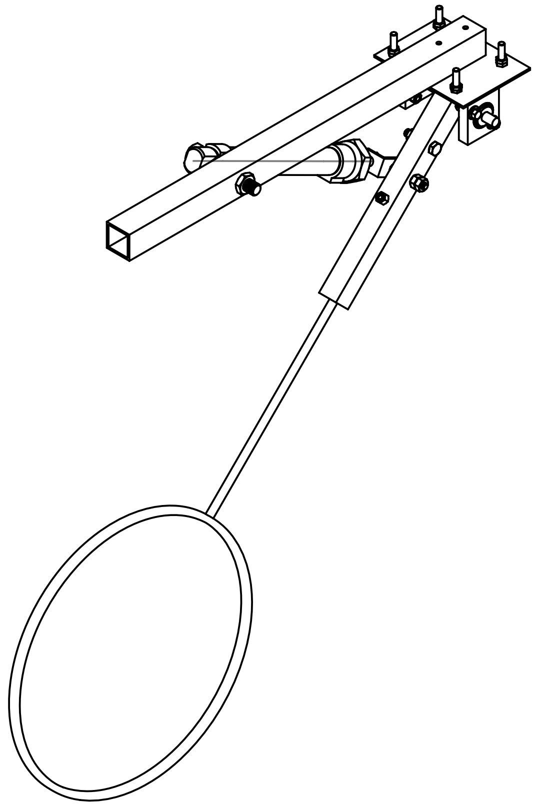
Racket_Arm_Assembly

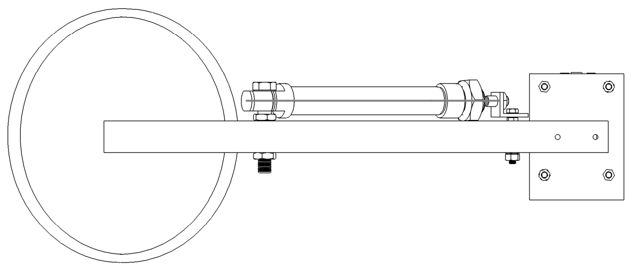
A3

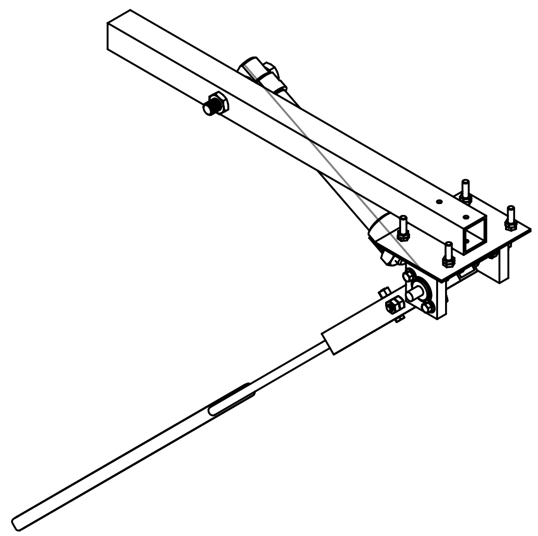
WEIGHT:

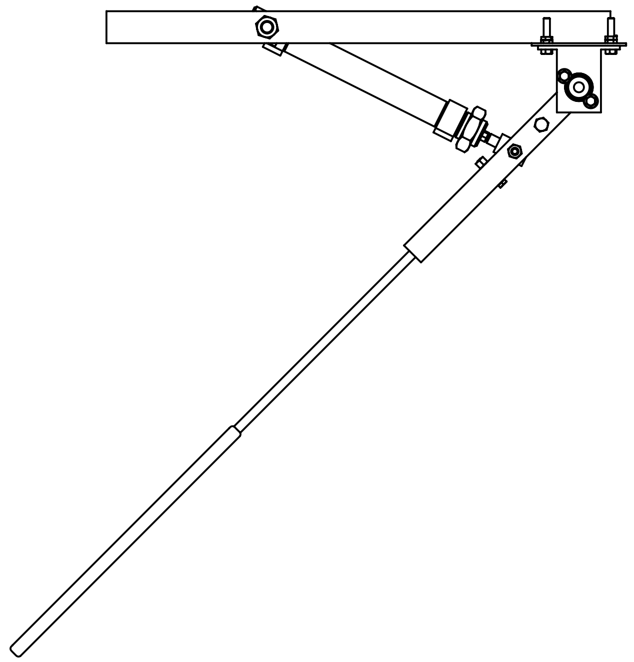
SCALE:1:5

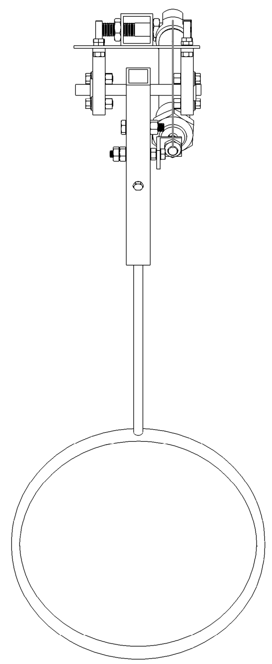
SHEET 1 OF 1











ITEM NO.	PART NUMBER	QTY.
1	channel	1
2	Racket_Arm_Assembly	1
3	A51, A52 Series	1
4	angle	1
5	baseplate	1
6	AMANUAL-bearing	2
7	ISO 4015 - M5 x 25 x 25-N	4
8	Hexagon Nut ISO - 4036 - M5 - N	8
9	ISO 4016 - M5 x 40 x 16-WS	1
10	ISO 4016 - M10 x 65 x 26-WS	1
11	Hexagon Nut ISO - 4032 - M6 - W - N	2
12	Hexagon Nut ISO - 4032 - M5 - W - N	1
13	Hexagon Thin Nut ISO - 4035 - M10 - N	2

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

MATERIAL:

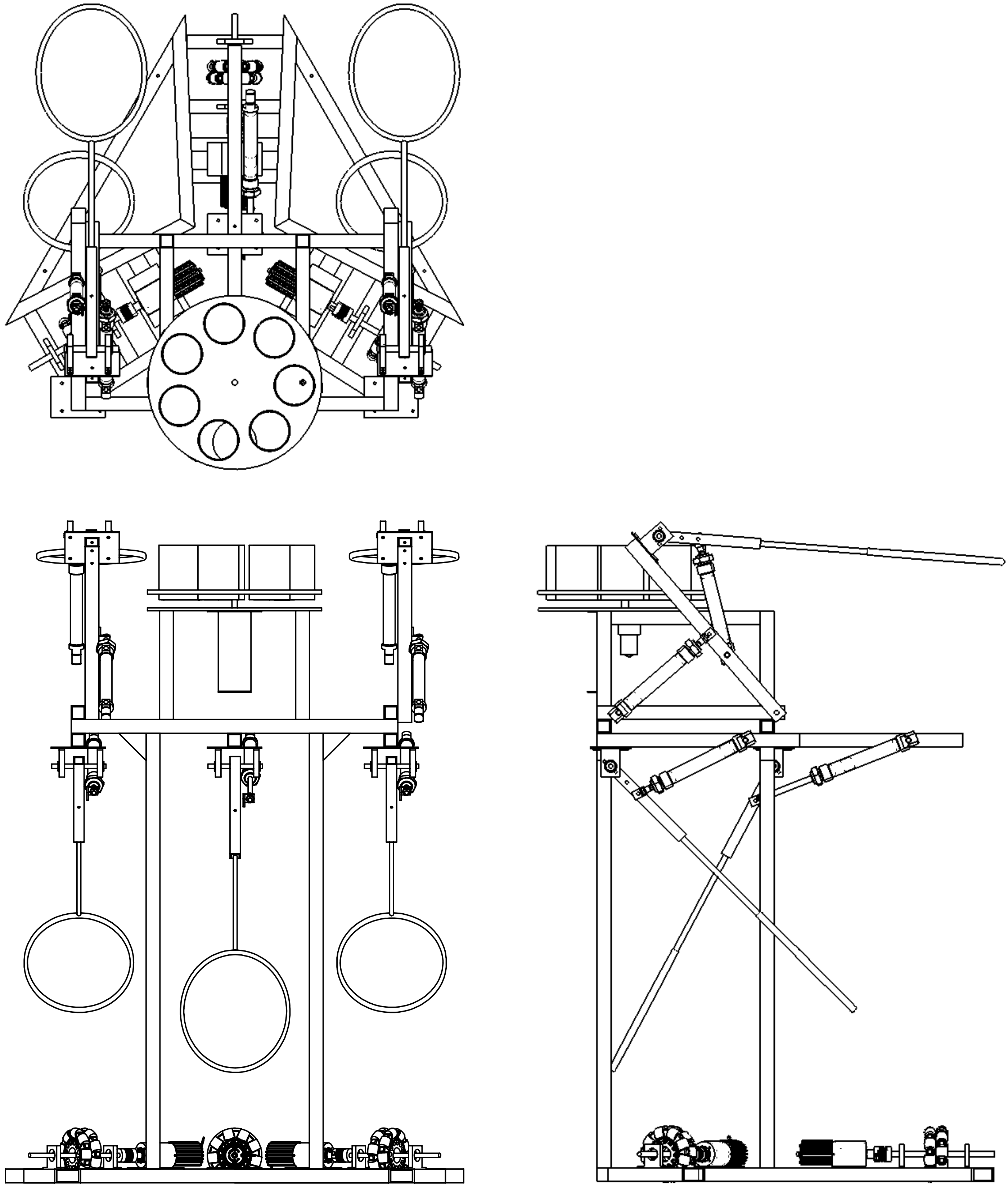
DWG NO. main

A3

WEIGHT:

SCALE:1:10

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

MATERIAL:

WEIGHT:

TITLE:

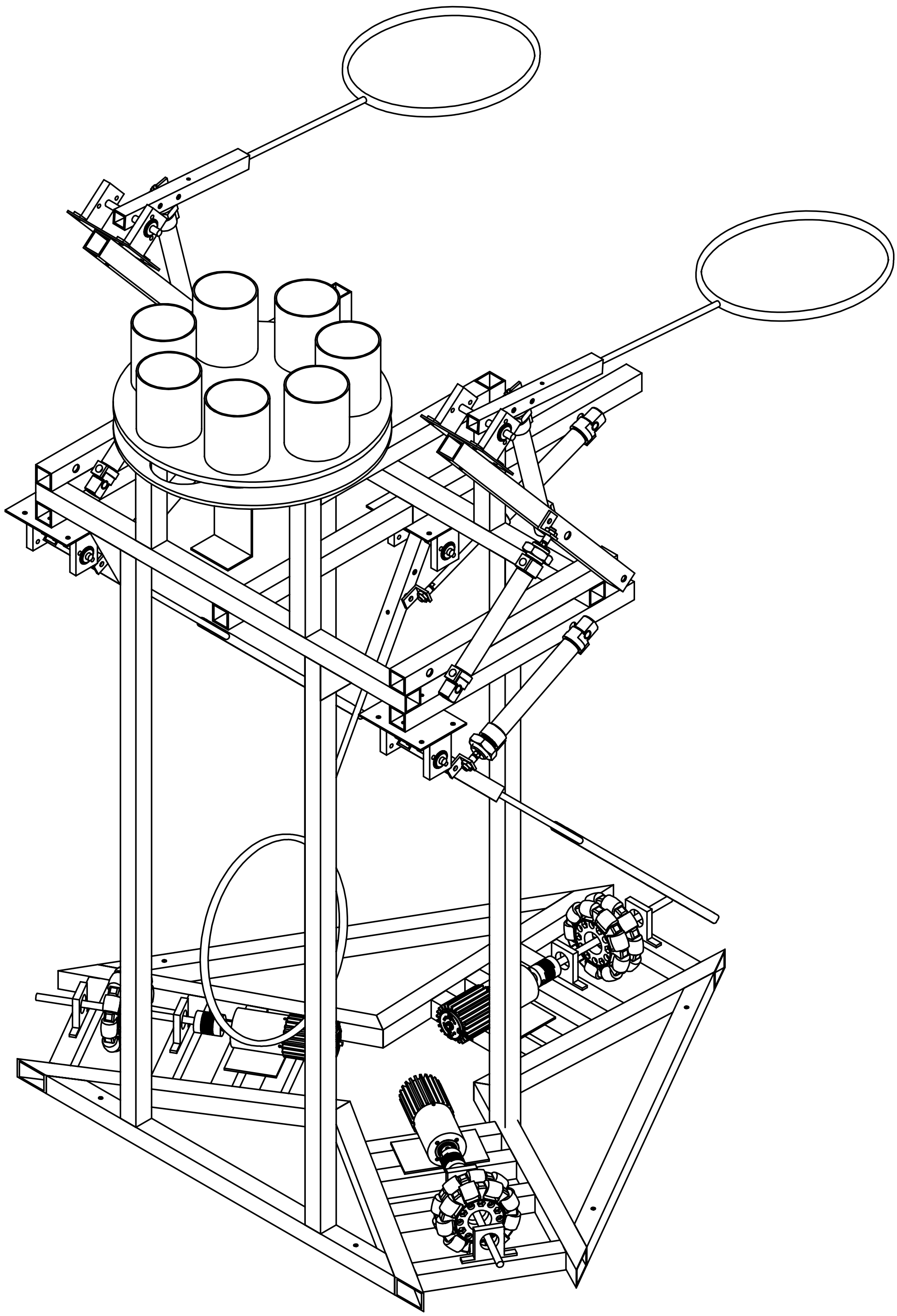
DWG NO.

Final Assembly

A4

SCALE:1:50

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:

SCALE 1 : 7

MATERIAL:

DWG NO.

Final Assembly

A4

WEIGHT:

SCALE:1:20

SHEET 1 OF 1