CID: 02099459

The Design of Rescue MiniRhex

Kang Yang

Nomenclature and Abbreviations

Symbol	Description	Symbol	Description
T_1	Load torque	T_{motor1}	Motor torque
T_2	Acceleration torque	P	Motor power
T_3	Total torque	N_{motor}	Motor speed
F	Force	I_{motor}	Force
R	Leg length	V	Motor voltage
m	Weight	Q	Battery capacity
g	Gravity of Earth	$t_{battery}$	Battery time
F_g	Gravitational force	F_{gear}	Gear force
F_f	Friction force	T_{motor2}	Motor torque before reduction gears
μ	Friction coefficient	r_{gear}	Gear radius
I	Moment of inertia	l_t	Turning cycle
N	Output speed	l	Robot length
v	Speed	a	Angular acceleration
w	Angular velocity	t	The time taken for acceleration

Contents

Introduction

A mini Hexapedal robot (RHex) is a small robot based on the RHex architecture. It features a hexapod with a single, unrestricted rotary actuator per leg. This project aimed to design a rescue MiniRhex to perform search-and-rescue survey tasks in terrain that is too narrow for a person to pass through. The robot needs to meet the parameters shown in Table 1. This report details the design process and decisions leading to the final MiniRhex design.

Metric	Value
Body length	≤ 165 mm
Body height	≤ 40 mm
Body width	≤ 100 mm
Leg length	≤ 50 mm
Leg radius	≤ 35 mm
Weight	≤ 300 g
Turning circle	≤ 165 mm

Payload	≥ 300 g
Speed	≥ 0.5 m/s
Climb Obstacle	≥ 200 mm high
Drop height	≥ 300 mm
Electronics Package	45 x 20 x 10 mm (excl. battery)
BoM cost	≤ 100 GBP (excl. tooling & assembly costs)
Ingress Protection	IP 53 for motor, battery and electronics

Research

At the start of the project, research was done to find out what how RHex move and climb obstacles and what work had already been done and how it could be improved. This research consisted of the work of the original developers of the Rhex at The University of Michigan and McGill University as well as the publication from *X-RHex: A highly mobile hexapedal robot for sensorimotor tasks* (1) *Bionics-based Optimization of Step-climbing Gait in a Novel Mini-RHex Robot* (2) and Kod*lab (3).

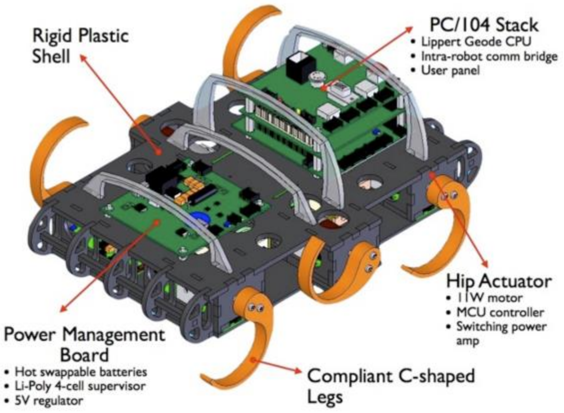

Figure 1 – Annotated diagram from Kod*lab of Rhex iterations showing components and layout. (4)

Through the study, the robot's planar motion is through the simultaneous movement of the front and back legs on one side and the middle leg on the other side. Through the cooperation of six legs, the robot always has three legs in contact with the ground to keep it stable and moving forward.

Figure 2 – Annotated diagram of Rhex loaded legs create a triangle structure while moving (5)

The robot overturns the obstacle by individually controlling two legs of each row, and through the mutual cooperation of each row of legs to overturn the obstacle.

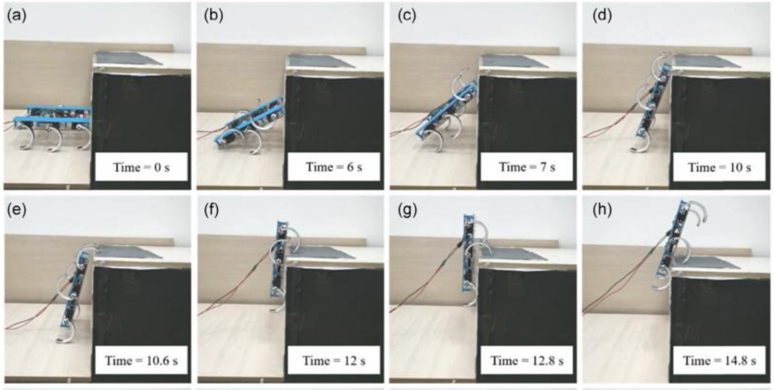

Figure 3 – The Rhex climbs over a 360 mm step with claw-shape legs climbing gait (3)

Limitations and Potential Improvement

Environmental Limitations:

1. The RHex is currently powered by six motors, which are too heavy for MiniRHex’s size.
2. The current chassis is not waterproof, which limits its use in outdoor conditions.
3. The RHex has difficulty climbing high obstacles due to its rigid body.

Manufacturing:

1. The MiniRex would be simpler to construct if more readily available parts and fewer fasteners were used.
2. The MiniRex would be more accessible and easier to produce if the chassis were built using FDM or injection moulding.

Inspiration

Bionics plays a crucial role in the development of robots, as it involves studying biological systems to inform the design of robots. Recently, researchers at the University of Science and Technology of China (USTC) have been exploring using soft materials in robotics. In particular, they have looked to the structural mysteries of the flexible trunk of an elephant to inform the design of a soft arm with similar flexibility and large load capacity. The researchers achieved this by using a honeycomb pneumatic network structure.

The design of MiniRhex can use the similar approach. By softening the body shell and increasing the contact area over obstacles, the robot would be better able to navigate complex terrains. This would increase the robot's ability to pass through difficult areas, making it more adaptable and versatile in a range of environments.

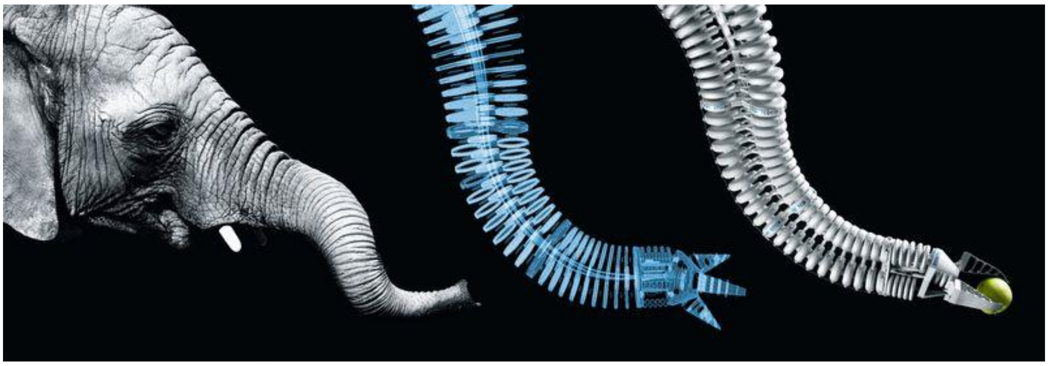

Figure 4 – Elephant trunk-influenced bionic handling assistant (6)

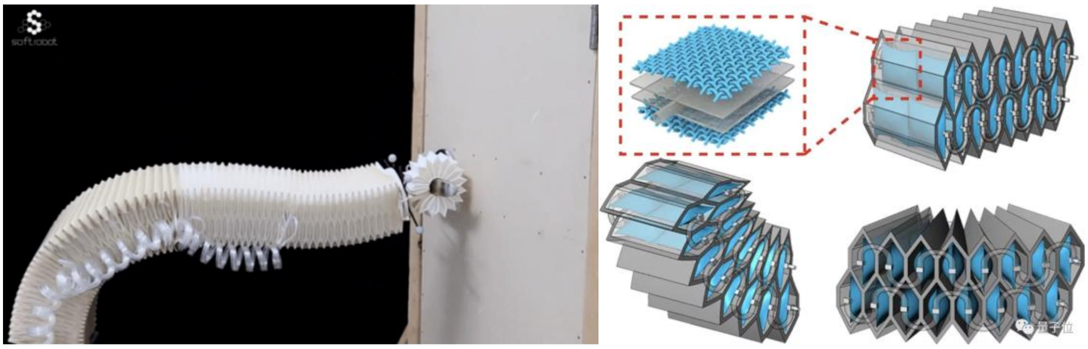

Figure 5 – Elephant Trunk Robot created by USTC (7)

Initial designs & iterative process

Design for the Overall System

The design process begins by deciding how the robot will be driven. Two motors are used to control the movement of each of the robot's three legs on each side, and the three legs on one side always maintain the form with the front and back two legs on the ground and the middle leg in the air.

The robot has two modes, in the planar motion mode, walking is achieved by having two motors move asynchronously. In the climbing mode, the robot's four legs are on the ground and thus climbing by having one side of the motor move half the circumference.

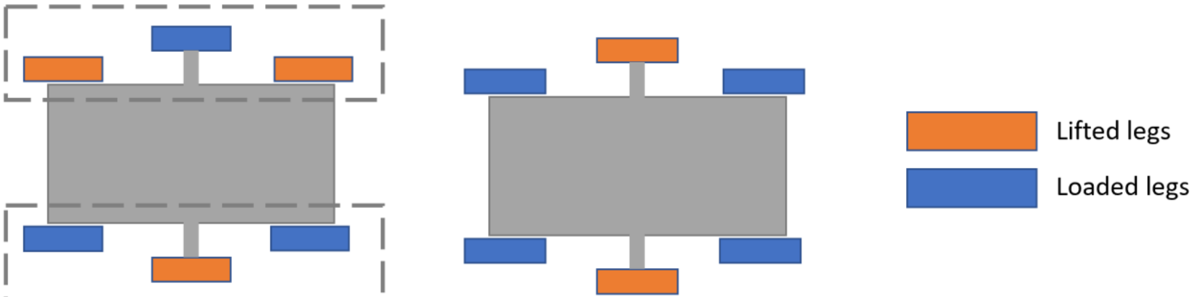

Figure 6 – Planar motion mode (left) and climbing mode (right)

Selection and Iterations of Legs

The C-shaped leg design was chosen for MiniRhex due to its advantages of being more durable, lightweight, and easier to manufacture compared to other leg designs. This decision was based on research (8).

Figure 7 – Compass leg design (left), C-shaped leg design (middle), Hinged four-bar leg design (right)

Figure 8 – Iterations 1, 2,3 for the Rhex's legs

Iterative Development for the Driving Mechanism

The first idea for the driving system was to use five gears to connect the three legs on one side of the robot. But the problem with such a design is that the transmission efficiency is relatively low. Using three bevel gears to drive the legs would reduce the energy loss by a factor of two (the motor is transmitted directly to the legs through the gears).

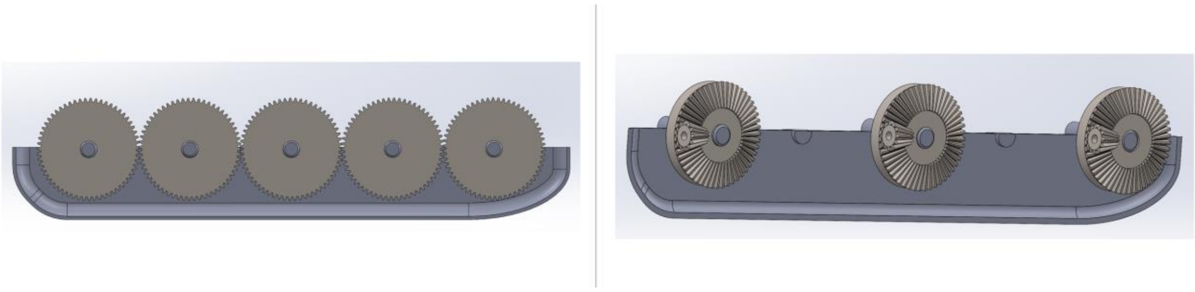

Figure 9 – Iterations 1, 2 for the driving mechanism

Component Analysis

Motor

To determine the required motor first needs to determine the torque. Torque is composed of two components: a load component, which is constant and typically caused by friction and gravity, and an acceleration components.

The load torque components always acts on the motor and can be determined using:

$$T_1 = F \times R$$

The gravitational force is determined by the mass x gravitational acceleration (g).

$$F_g = m \times g$$

Where $\mathrm{m} = 0.6\ \mathrm{kg},\ g = 9.81\ m/s^2$

The friction force, acting in the opposite direction as the conveyor movement direction, is calculated by multiplying the mass of the load with the friction coefficient of the 2 surfaces (hard rubber and concrete):

$$F_f = \mathrm{mg} \times \mathrm{\mu}$$

Where $\mathrm{\mu} = 0.6 - 0.75$ (6)

The maximum load torque required for one leg when the robot is climbing up with only the rear two legs attached to the ground is the torque required to initiate the leg's motion from a stationary position, taking into account the friction force that opposes the motion.

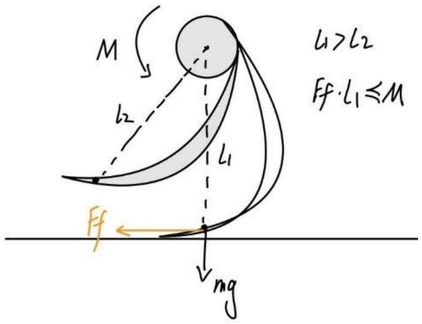

Figure 10 – Free body diagram of the leg

$$T_1 = \frac{F \times R}{2} = \frac{F_f \times R}{2} = 0.11\ Nm$$

For acceleration torque component, it only applies when the motor is accelerating or decelerating.

The moment of inertia of the system:

$$I = \mathrm{m} \times R^2$$

Revolution done by the leg per minutes:

$$rpm = \frac{v}{2\pi R} \times 60$$

The angular velocity:

$$w = \frac{2\mathrm{\pi} \times rpm}{60}$$

The acceleration rate can be defined as the angular velocity over the time taken:

$$\alpha = \frac{\omega}{\mathrm{t}}$$

Where $\mathrm{t} = 1\mathrm{s}$

Therefore the acceleration torque for one leg equals to:

$$T_2 = \frac{\alpha \times I}{2} = 0.0075\ Nm$$

Consider a safety factor of 2, and mechanical losses of 85%, the final torque needed for the robot is:

$$T_3 = \frac{(T_1 + T_2) \times 2}{85\%} = 0.276\ Nm$$

From the calculation above, the optimum motor that delivered the required power could be selected while minimizing size, mass, and cost. The 2206 1500KV outrunner brushless motor supplied by SUNNSKY (6) was found to be the best option. Because of the gears have gear ratio of 1.8 (refer to section 5.7), the enlarged torque emits from the motor is:

$$T_{motor1} = (\frac{9550 \times P}{N}) \times 1.8 = 0.518\ Nm$$

Where $P = 0.12\ kW, N = 4500\ Hz$

The motor torque is larger enough to power the MiniRhex.

Battery

To determine the battery that would be used to power the motor, it is essential for considering weight limitations for the robot, the time of use must be limited so that the battery isn't too heavy. For that reason, the calculations are based for a time of use of around 45 mins.

Determining the current consumption of the motor is done using its output power:

$$I_{motor} = \frac{P}{V} = 428.57\ mA$$

$$\text{Where } P = 3\ W,\ \ V = 7\ V$$

Therefore, for a time of use of 45 min for two motors:

$$Q = (I_{total} \times t) \times 2 = 642\ mAh$$

The battery selected is the Allmax 9V alkaline battery (7) with a capacity of 720 mAh, which is 12% larger than expected, giving the robot more operating time.

Gears

Bevel gears are typically used to transmit power between intersecting shafts. The bevel gear has a gear ratio of 1.8, meaning that for every rotation of the larger gear with 49 teeth, the smaller pinion gear with 27 teeth will rotate 1.8 times. This gear ratio helps to increase the motor torque to the required level.

Nylon gears is chosen due to its lightweight, self-lubrication, , corrosion resistance, durability and low cost.

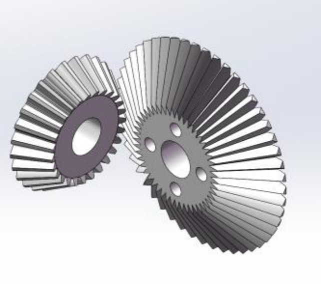

Figure 11 – The bevel gear

Shafts

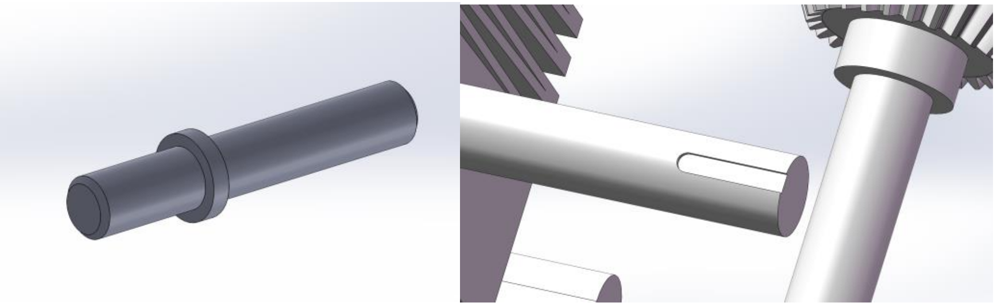

Figure 12 – Iterations 1, 2 for the shaft

Adding a keyway to the improved shaft design allows for better assembly methods by providing a secure and precise connection between the gear and the shaft. The keyway groove ensures that the gear is properly aligned and securely attached to the shaft, which is essential for the proper functioning of the system.

For smaller gears, it's not practical to use a keyway. Using a tap and die set to create screw threads on a shaft is a common method for attaching a gear. The tap creates the threads on the inside of the hole, and the die creates the threads on the outside of the shaft. By threading the gear onto the shaft, it is securely attached and aligned.

Soft Body Structure

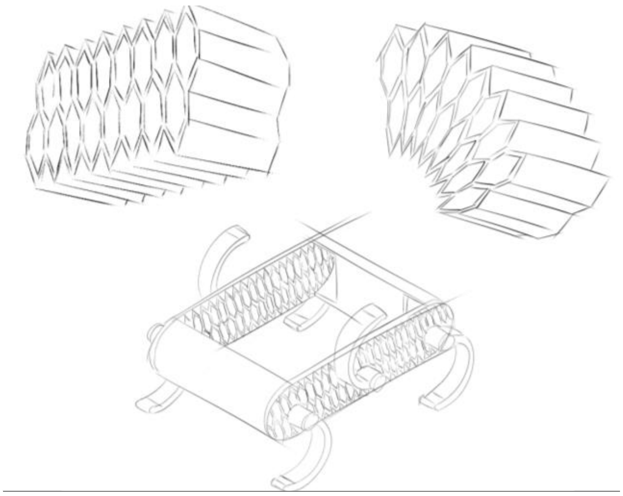

Figure 13 – Initial design sketches

The soft structure shown in the sketch is used as the shell of the robot and is made from a TPU material. The TPU material is selected to soften the robot's shell and give it the ability to deform when going over obstacles. This allows the robot to better fit the terrain, and increases its ability to go over obstacles.

Specifically, the flexibility of the TPU material enables the robot's body to deform and conform to the shape of the terrain, allowing it to maintain better traction and stability when navigating over uneven surfaces. This reduces the risk of the robot getting stuck or toppling over when encountering obstacles, and allows it to move more effectively in challenging environments.

Universal Joints

The purpose of universal joints is to serve the soft body structure by providing a flexible and efficient means of transmitting power and torque between the shafts that may not in a straight line with each other.

Ideally, the robot drive structure can be bent in three places to fit better with the casing. However, because of the size of the robot, the universal joints are very small (see technical drawing GIZ 002) and cannot be purchased directly from the market, but need to contact a custom service, thus increasing the cost of the robot parts.

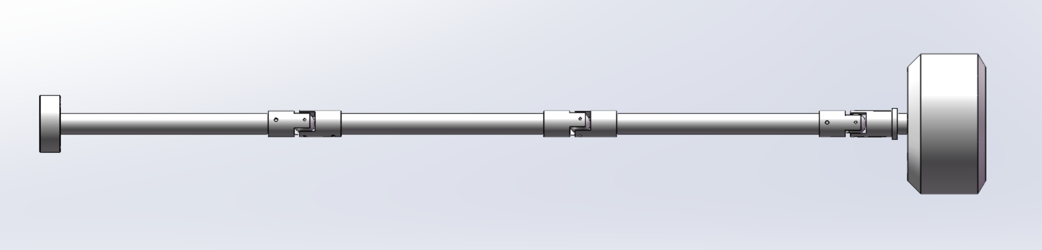

Figure 14 – View of the shafts and universal joints

Ingress Protection

An IP 53 is required for the robot which signifies that the device should be dust protected and resistant to spraying water at any angle up to 60° from the vertical. Firstly, the motor is protected by a plastic transparent case and two rubber waterproof rings are added at the connection between the shaft and the motor. Secondly, add a protective case for the battery and the circuit board, and a layer of waterproof and moisture-proof protective film is attached to the case.

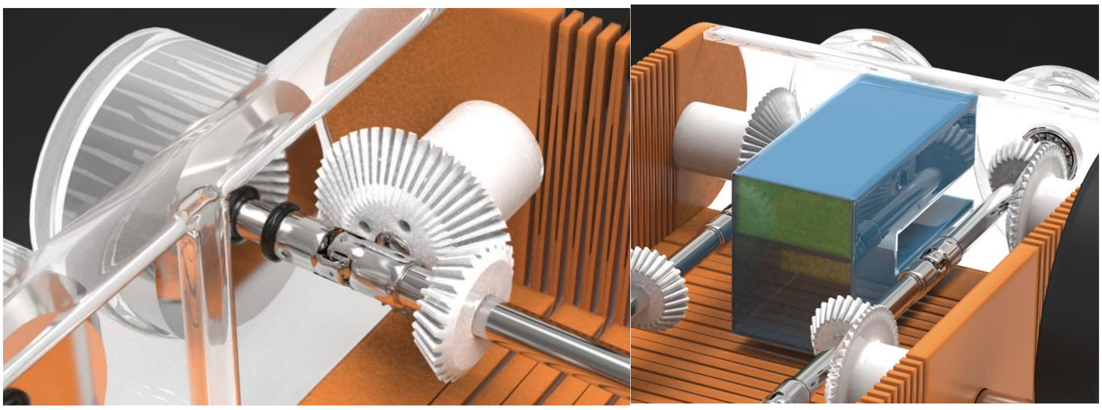

Figure 15 – Ingress protection of the motor, battery and electronics

Engineering Analysis

MiniRhex's Leg

The most likely failure mode for the leg would be fracture. To analyse the possibility of the failure results by the weight and load, Finite Element Analysis (FEA) has been used.

By changing the shape of the legs and increasing the degree of rounding to make the maximum pressure compared to the old version reduced by 26%, and through the graphs can be seen that the large pressure area is much smaller.

ABS and nylon were selected as materials and after FEA analysis, it was decided to choose nylon because it has 10 times better impact resistance than ABS (10), larger tensile strength, results in a safety factor of 6.

Assume the maximum pressure the leg can experience is emitted from the body weight with the load. Therefore through the analysis of FEA, the robot achieves the specification of the 300 mm drop height.

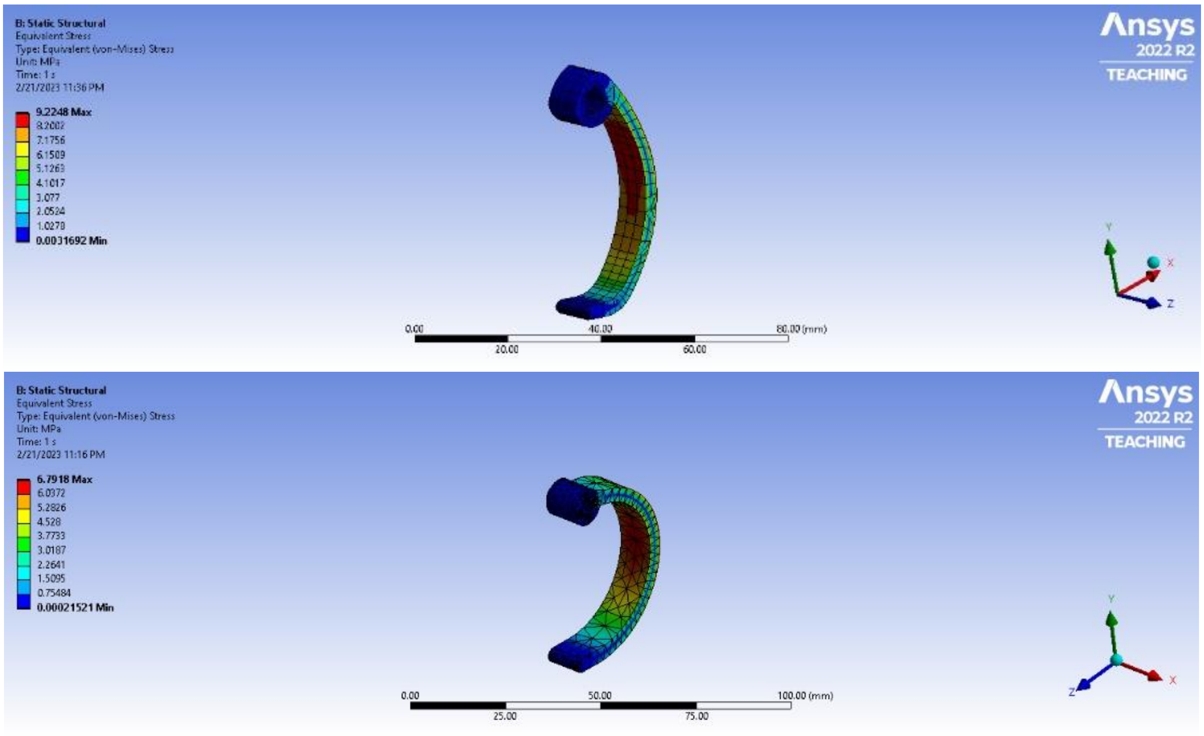

Figure 16 – Equivalent stress distribution across leg section (1st version above, 2nd version below)

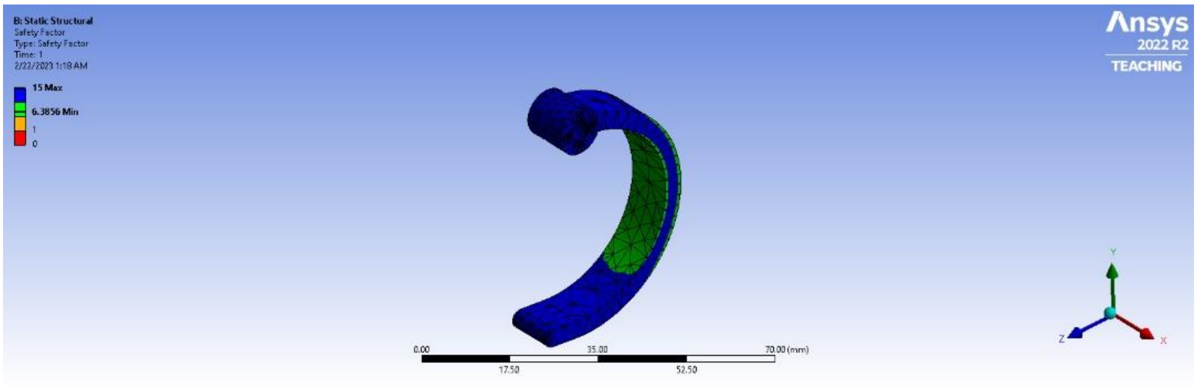

Figure 17 –Safety factor distribution across leg section

Bevel Gear

In bevel gears, the most likely failure mode is tooth bending fatigue.

Bevel gears operate under high loads and varying forces. Tooth bending fatigue occurs due to the repeated bending stresses caused by these forces on the gear teeth, resulting in the formation of small cracks on the tooth surface. Over time, these cracks can spread and eventually lead to gear breakage or failure. (see figure 18)

The force emits from the motor to the gear is calculated through:

$$F_{gear} = \frac{T_{motor2}}{r_{gear}} = 26.182\ N$$

Where $T = 0.288\ Nm,\ r_{gear} = 11\ \mathrm{mm}$

In terms of the material of gears, although nylon gears do not have the strength of steel gears, their lightweight and corrosion-resistant make them the best choice when the application is under relatively low load with slight pressure.

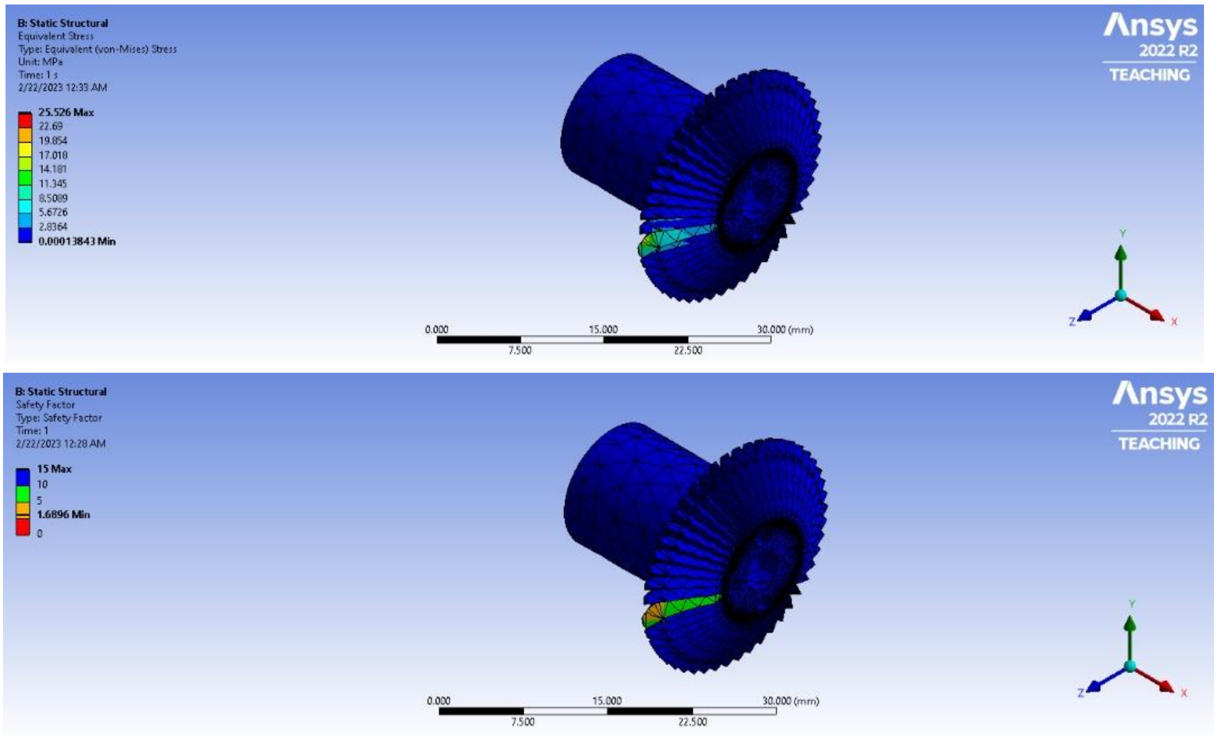

Figure 18 – Equivalent stress and safety factor distribution across leg section

Through the FEA analysis, the Nylon gear has a minimum safety factor of 1.69 at tooth edge of the resulted force.

Turning Cycle

The robot turns by adjusting the motors on the left and right sides to cause a speed difference so that the robot turns, by letting the motor on one side rotate at 0 speed and the motor on the other side rotate to achieve a turn, and a turn radius equal to half the length of the robot's body.

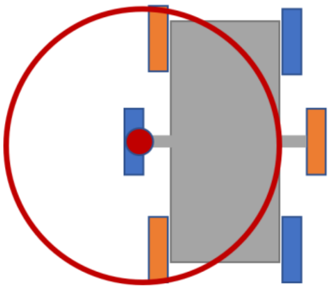

Figure 19 – Turning cycle of the robot

$$l_t = \frac{l}{2} = 82.5\ mm$$

Summary

To ensure that the MiniRhex adheres to the requirements, a bill of material was created that summarised the weights and prices of the component parts. The cost of the raw materials used to make these pieces is used to estimate their costs. Also, pricing of current items are typically taken into account for significant purchases (sourcing components straight from China is substantially less expensive).

Component Group/Name	Quantity within Group/Item Quantity	Combined Mass (g)	Approximate Combined Cost (£)
Battery	1	46	2.49
Wheel Legs	6	30	0.72
Electronics Package	1	15	/
Motor	2	80	26.4
Gears	12	6	7.2
Universal Joints	6	3	12.2
Rubber Seal	4	0.5	0.7
Battery box	1	5	5.2
Plastic Case	2	20	15
Side Case	2	44	1.4
Bearing	2	4	2.92
Shaft	12	16	11.3
Total		269.5	85.53

Table 1 – General component groupings to determine total cost

The following table shows final specification values.

Specification Value	Final Value
Overall Length	165 mm
Overall Width	100 mm
Weight	269.5 g
BoM Cost	£ 85.53
Leg Length	50 mm
Leg Radius	30 mm
Turning Circle	82.5 mm
IP Protection	Minimum IP 53

Table 2 – Final comparison to specification

Conclusion and Further Improvement

Despite the thorough investigation that was done on this design, further advancements would be necessary for it to perform at its best. Testing and prototyping are crucial steps to do in order to determine how well the soft body structure functions and how the body will respond to barriers. Designing the shell and mechanical parts with manufacturing in mind is essential. Overall, the MiniRhex's design was effective in meeting all the requirements outlined in the brief.

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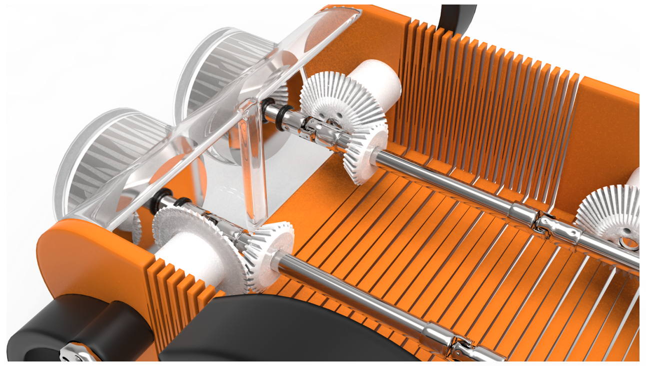
Rescue MiniRhex

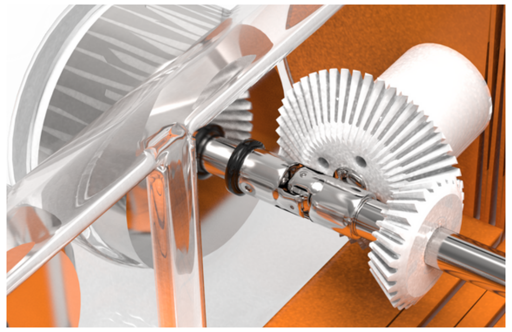
Tiny hero, big impact

Elephant Trunk Structure Shell

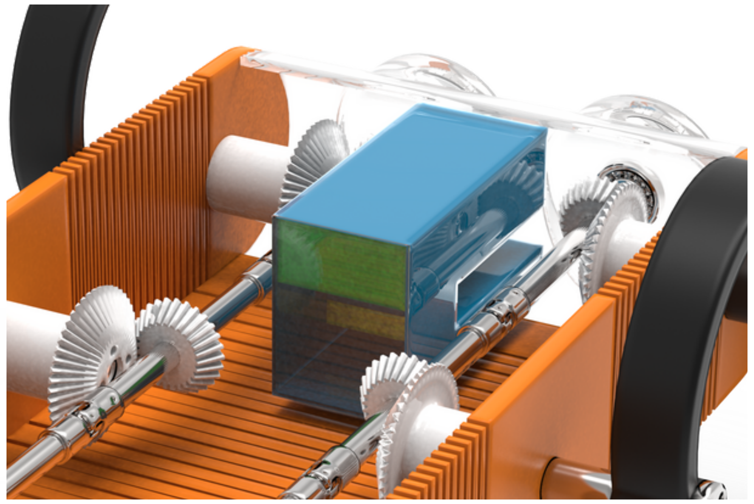
- Adaptive terrain body
- Bionic robot build
- 3D printed TPU body

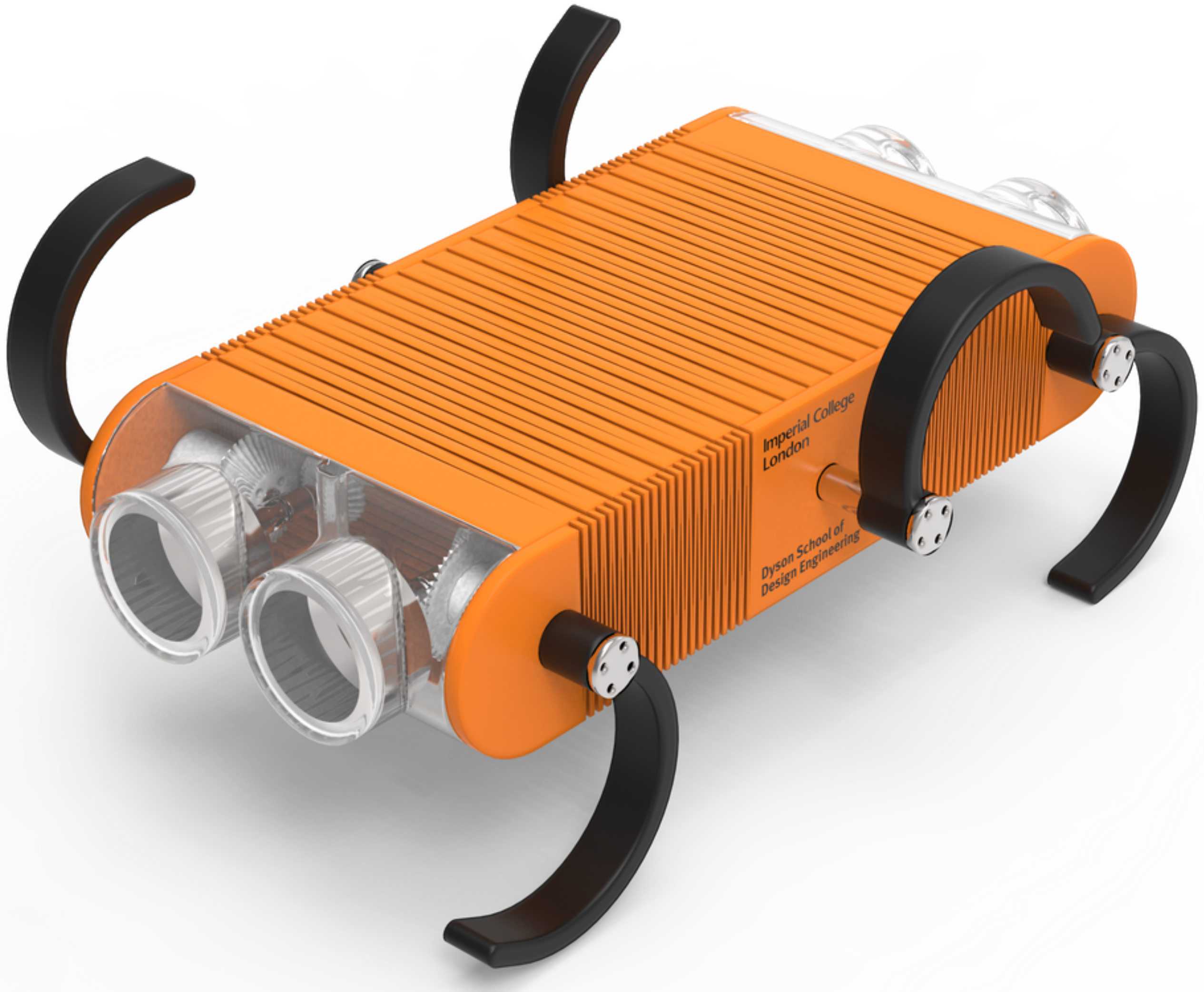


Ingress Protection



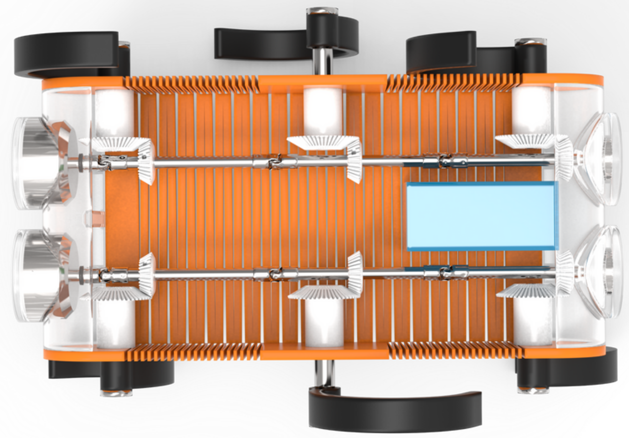
- Minimum IP53 protection
- Waterproof and moisture-proof film applied
- Rubber rings for waterproof, insulated motors

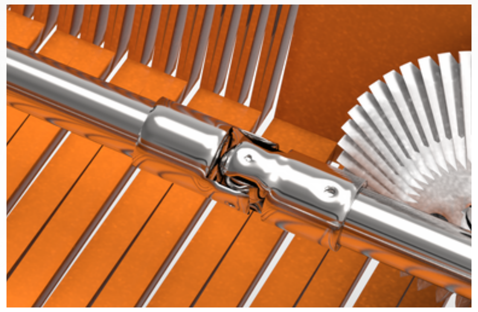




50/45 Weight Distribution

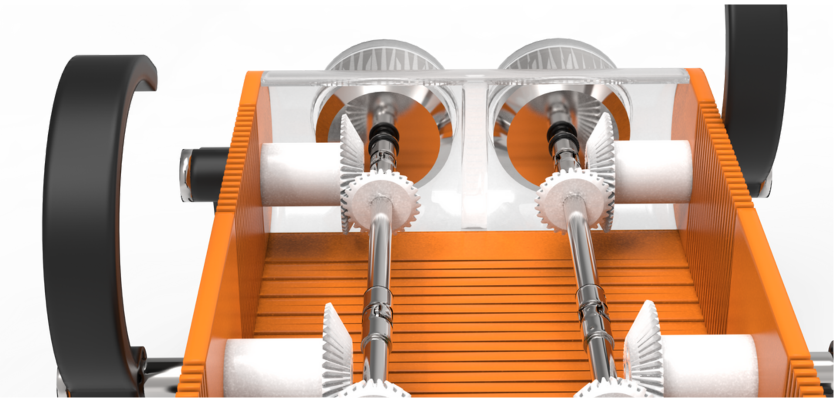
- Effective simplicity in design
- Ingenious transmission design

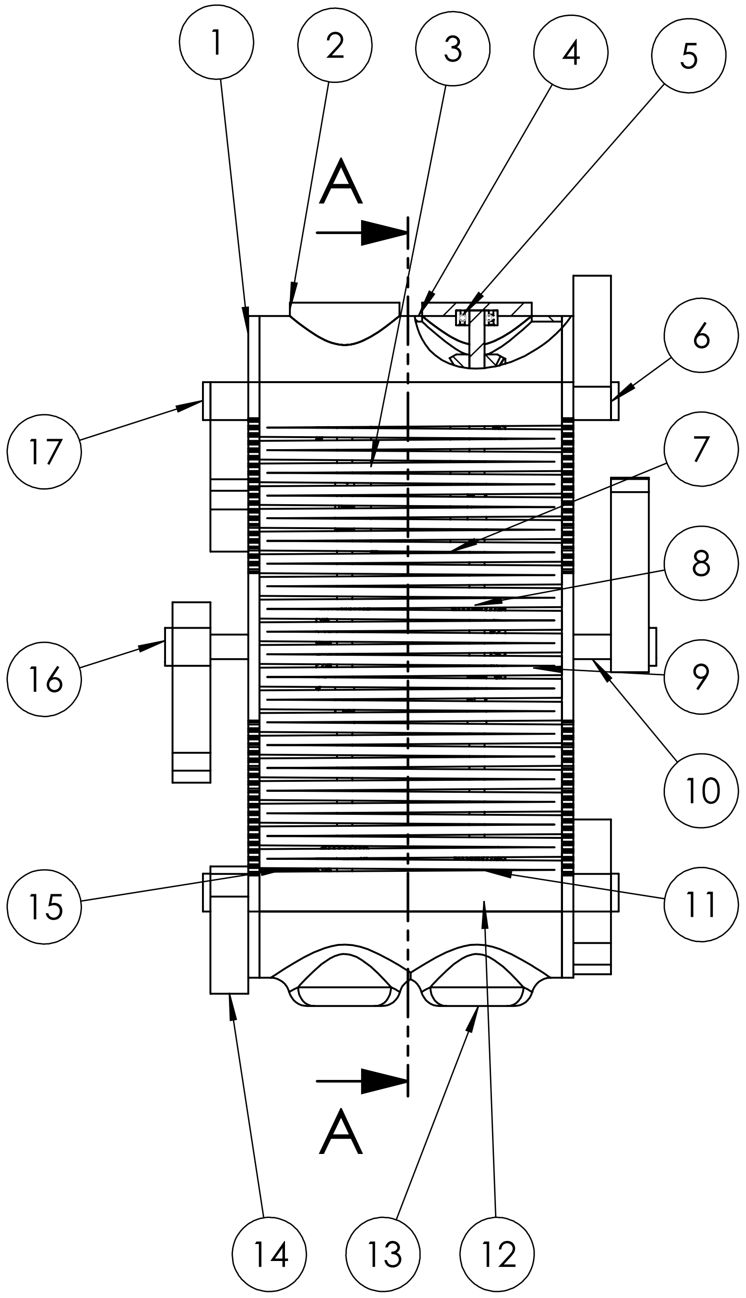


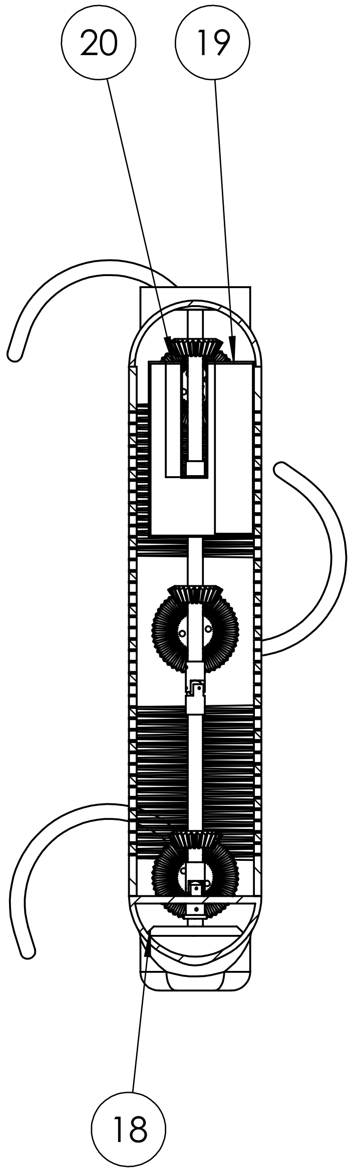


Battery life 45 min +

- Powerful brushless motor
- Battery snap-in design
- Nylon gears boost efficiency.

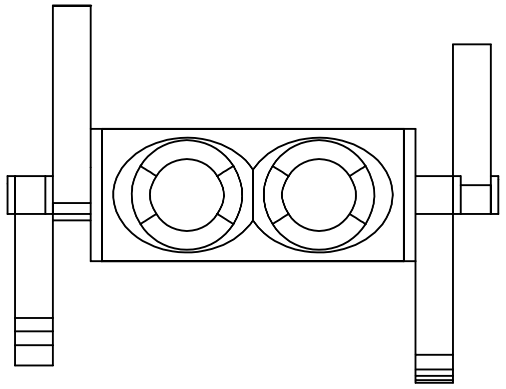






SECTION A-A

ITEM NO.	PART NUMBER	QTY.
1	Side Case	2
2	Bearing Sleeve1	2
3	Battery Case	1
4	Front Case	1
5	Rolling bearings S719-4 GB 292-94	2
6	Leg (Left)	3
7	Battery Cover	1
8	Bevel Gear 27×0.5	6
9	Bevel Gear 49×0.5	6
10	Bearing Sleeve2	2
11	Shaft	6
12	Universal Joint	6
13	Front motor Protector	1
14	Leg (Right)	3
15	Bottom Cover	2
16	Long Shaft for Middle Leg	2
17	Shaft for Leg	4
18	Motor	2
19	Electronics Package	1
20	Battery	1



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General Assembly

MATERIAL:

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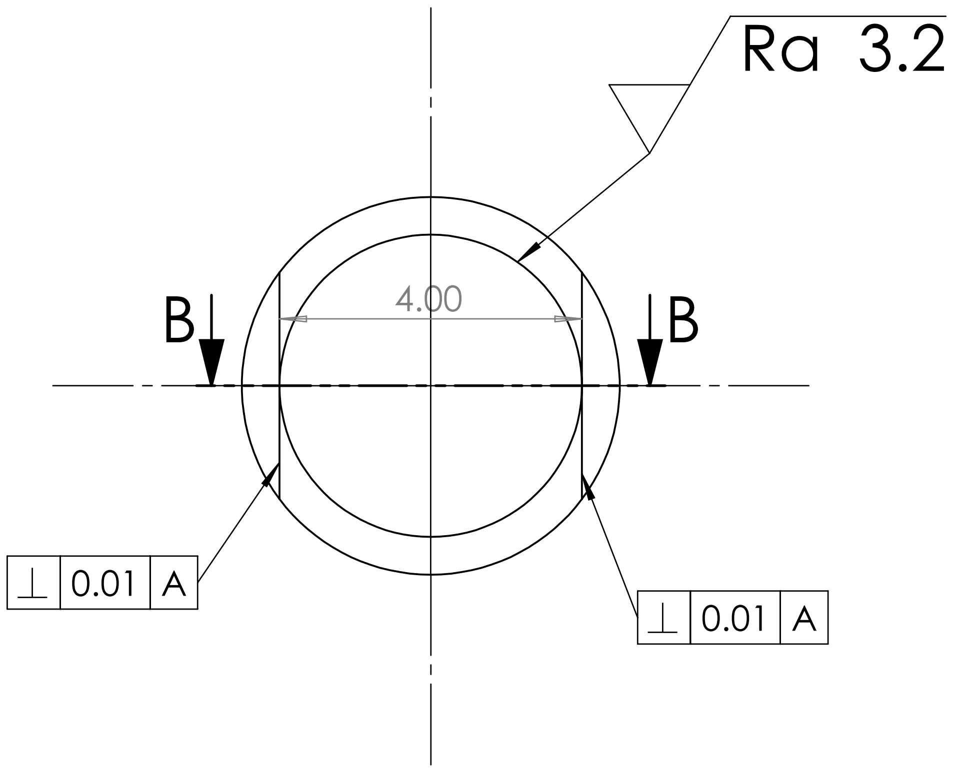
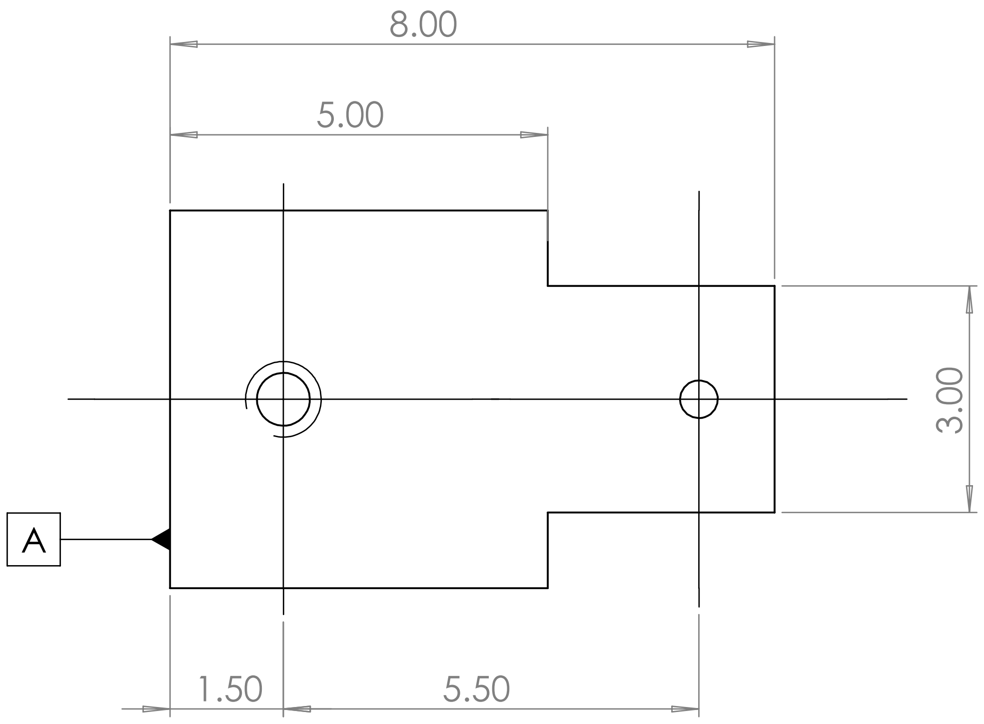
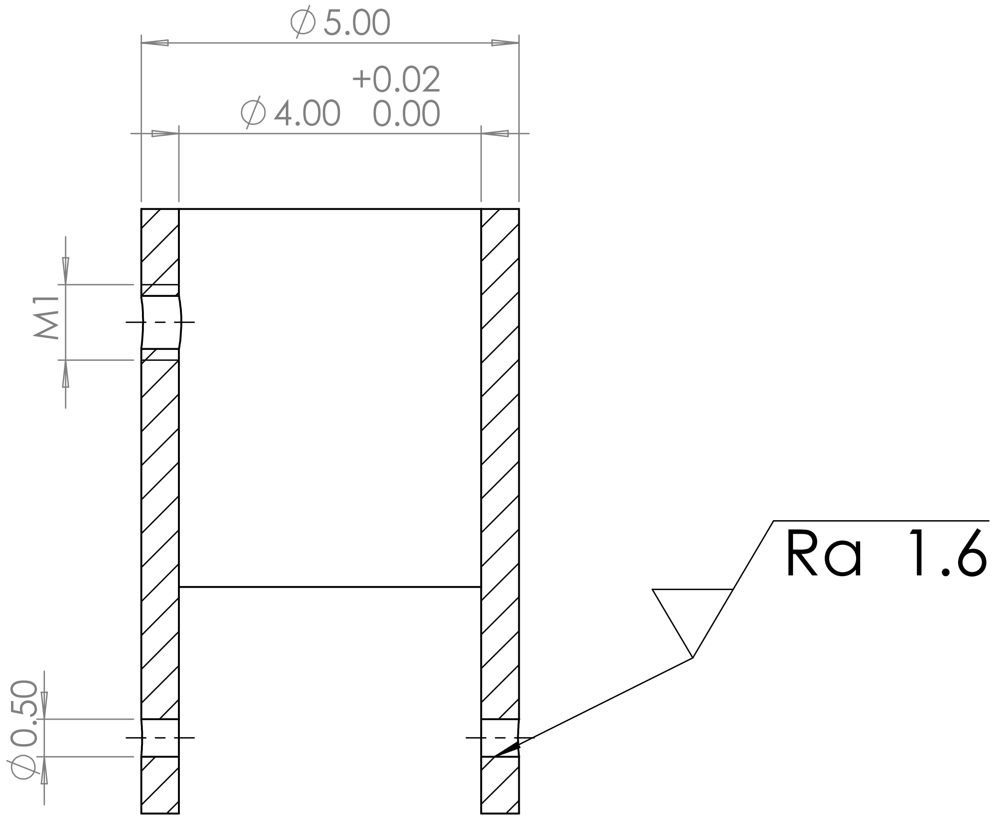
SCALE:1:2

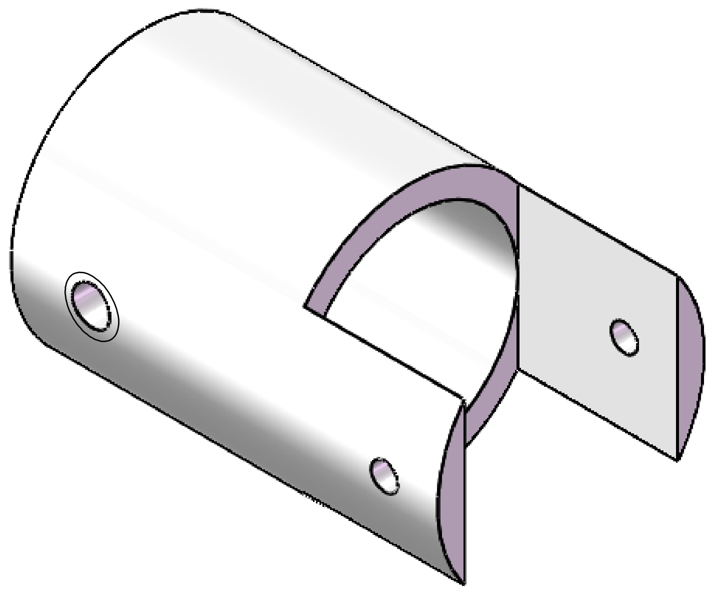
SHEET 1 OF 1







SECTION B-B



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

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

TITLE: Universal Joint

MATERIAL: Material <not specified>

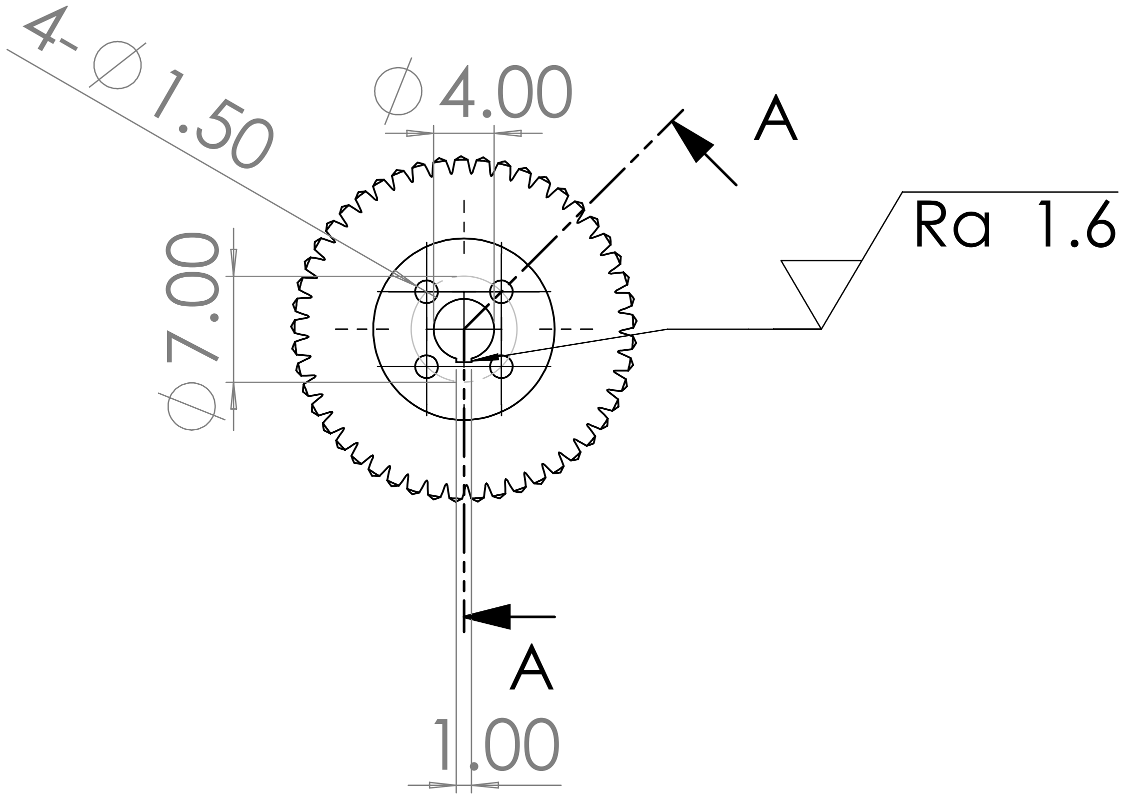
DWG NO. GIZMO 002

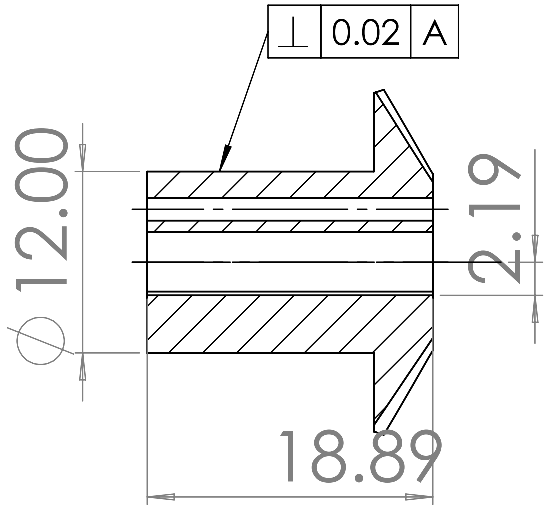
A3

WEIGHT: 0.04

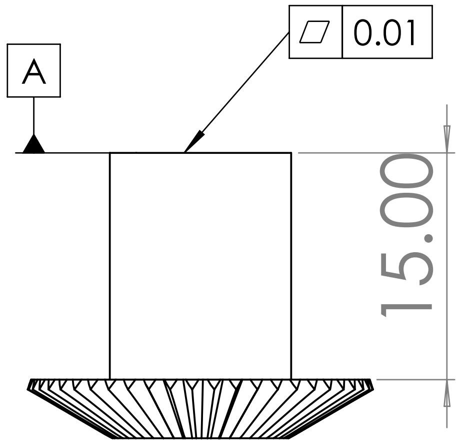
SCALE:10:1

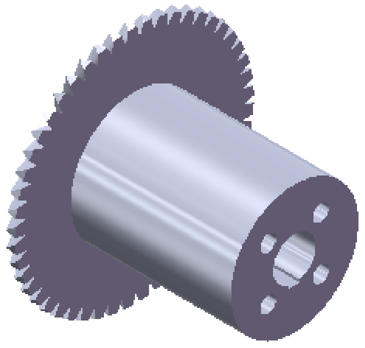
SHEET 1 OF 1





SECTION A-A





The gear on the casing has 49 teeth

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

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

TITLE:

Bevel Gear

MATERIAL:

WEIGHT:

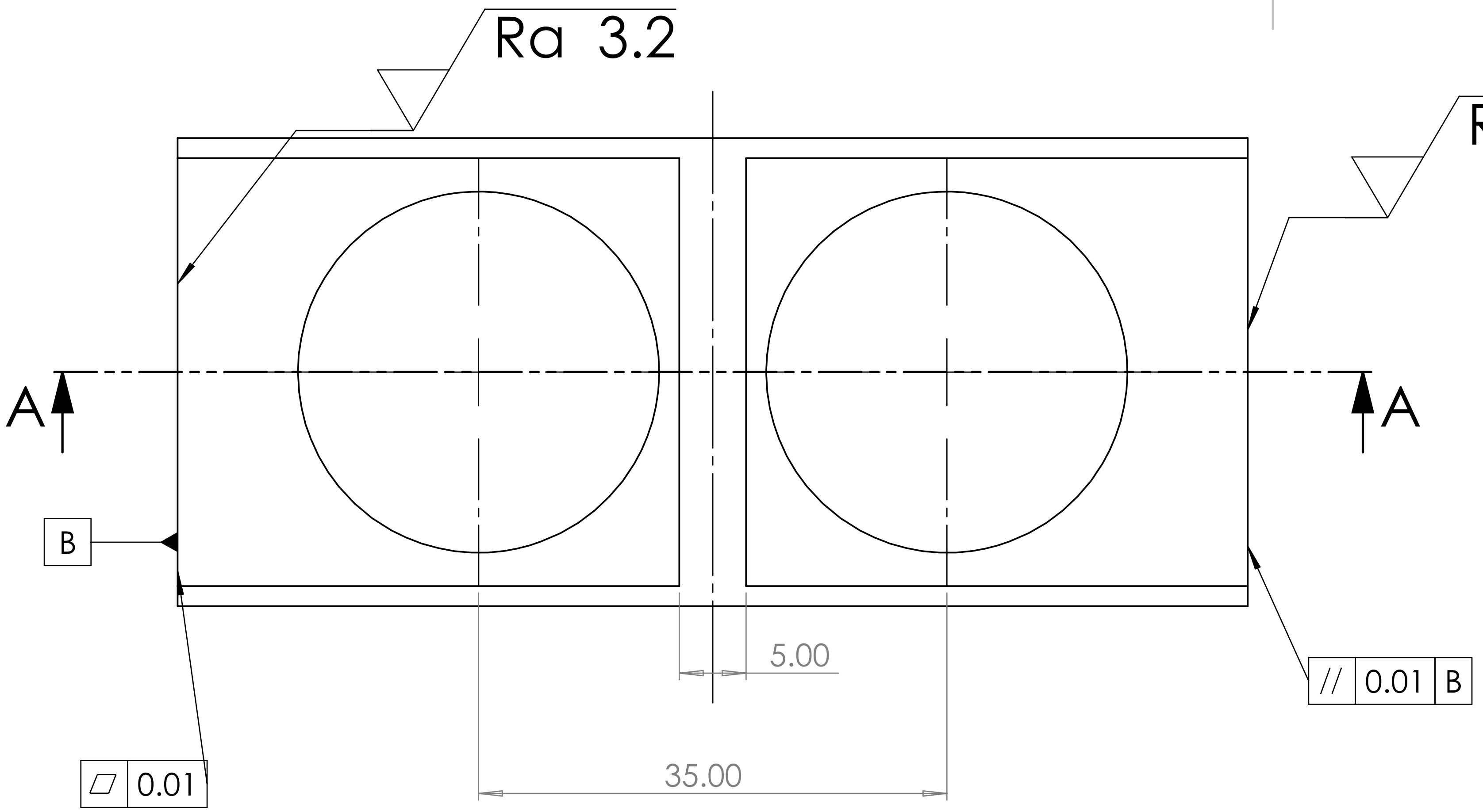
DWG NO.

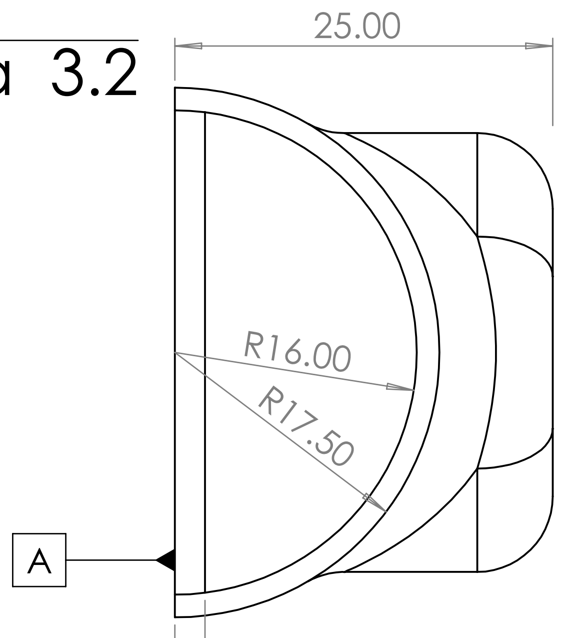
GIZMO 003

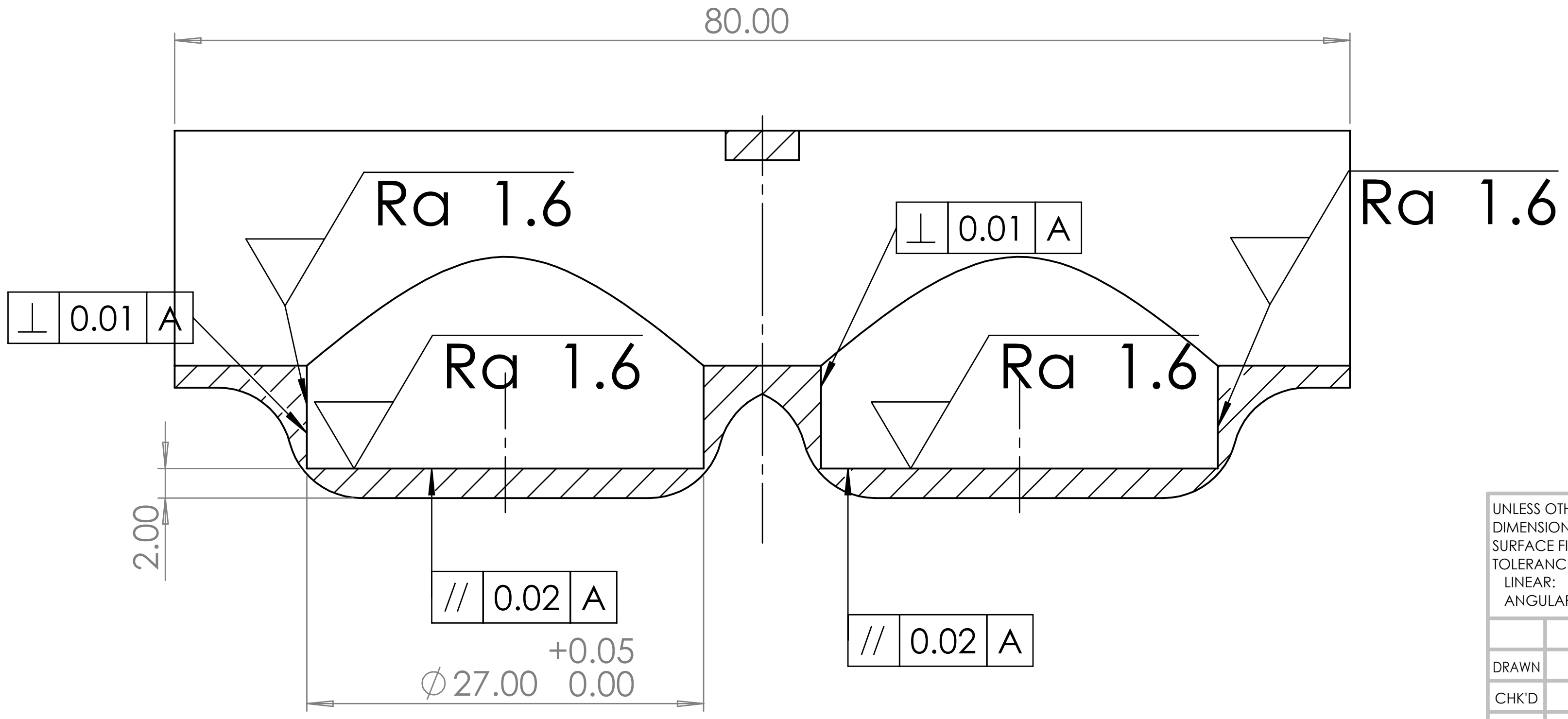
A3

SCALE:1:1

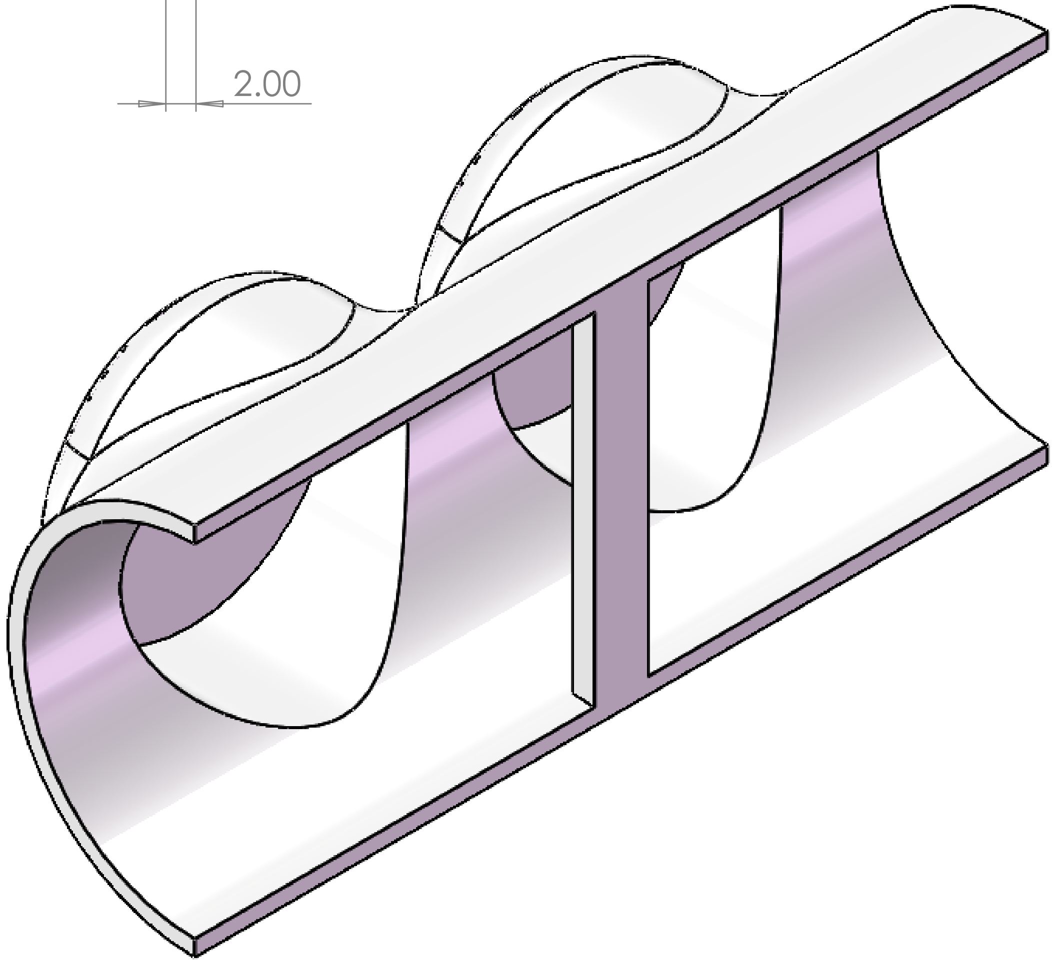
SHEET 1 OF 1







SECTION A-A



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

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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

TITLE:
Plastic Case

MATERIAL:
Material <not specified>

DWG NO.
GIZMO 004

A3

WEIGHT: 8.47

SCALE:2:1

SHEET 1 OF 1