JSR

Monopod Jumping Robot

ABSTRACT

This report looks at the design and development of a Jumping Searching Robot (JSR) which weighs 109.87 g and can jump 300mm vertically and horizontally.

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Gizmo – Term 2

Contents

1. Summary

This report looks at the design process of building a monopedal jumping robot, to search rubble after a natural disaster, such as an earthquake. Jumping is a more energetic efficient way of movement than walking/running[1], and allows the robot to get over obstacles which wheeled/tracked robots are unable to scale. This, along with its small size, would make it much better for searching damaged areas, saving more lives.

The report looks at the how the chassis, power, propulsion, ingress protection, materials and other systems were chosen to meet the specification. Propulsion methods were inspired by organic organisms, which have large jump-distance to size/weight ratios. Finite element analysis, on SolidWorks was carried out on major components to validate the feasibility of the design. When optimizing the design, the main constraint when re-enforcing and redesigning components was the 200g weight limit.

2. Concept development

2.1. Vision

Between 2000 and 2017 there were 22 earthquakes globally above 8.0 on the Richter scale, and 284 above 7.0[2]. This has resulted in hundreds of thousands of deaths in the past 17 years, mostly from buildings collapsing and trapping people (these figures do not account for deaths from tsunamis caused by earthquakes). Response to these differs depending on which country the earthquake effects, due to the economic size and infrastructure of the country. In some countries man power can be a problem, and locating survivors trapped under rubble can take days. Currently there are large, slow, tracked robots which search these areas, but they are very expensive and are limited by there size of where they can search.

A small jumping robot, made from ‘off the shelf’ parts would be considerably cheaper and more versatile. Due to its low cost it would be much more viable for governments to purchase and could search areas which would otherwise be inaccessible to search.

2.2. Design Process

2.3. Product specification

The given product specification is shown in Table 1. These are the minimum requirements which have been set. To meet these requirements, values such as the launch velocity had to be found. These can be found in section 2.5.

Table 1

Metric	Unit	Value
Min Vertical Jump Hight	mm	300
Min Horizontal Jump	mm	300
Mass	g	100-200
Cost	GBP(£)	<100
Ingress protection	IP	<54
Electronics	mm	45x20x10

Must be self-righting

2.4. Wireless Control

There are 3 main standards for wireless control which are WiFi, Bluetooth and FM MHz. Bluetooth is generally very low powered and wasn't designed to work over more than 50m, whilst also not having a high-speed data connection[3]. This makes Bluetooth not very ideal when range is an issue. Previously FM MHz(72MHz) was the most common way to remotely control devices, such as RC planes, but now drones are more popular and have live video streaming, WiFi has become the best way to control a device.

There are 2 main WiFi groups, 2.4GHz and 5GHz. The 2.4GHz has a larger range, but has slower data speeds. Conversely the 5GHz spectrum has much faster data transfer speeds, but works over a shorter range. Table 3 shows the differences of the major spectrums, in regard to their range and transfer speeds[4]. The largest consumer drone company, DJI, uses the 2.4GHz WiFi spectrum. For the JSR an 802.11n 2.4GHZ system will be used, with an additional range extender at the control location. This will allow for live video feed and other information to be sent back to the operator. When having a range extender, this will also boost the signal, helping the data get through fallen walls.

Table 3

Standard		Rate(Mbps)	Max operating range (m)
2.4GHz	802.11b	11	6718
	802.11g	54	949
	802.11n	144	753
5GHz	802.11n	300	114
	802.11ac	866	64

2.5. Power/Energy calculations

To work out the energy required for the JSR some basic calculations were done. Firstly, the speed that the robot leaves the ground at must be determined. This was done initially without air resistance.

$$\max height = \frac{v^2 \times 1}{2g} \quad \therefore v = \sqrt{\frac{2 \times 9.81 \times 0.3}{1}} \quad \text{v = 2.42m/s}$$

The air resistance was then calculated for a JSR with a frontal area of 0.06 x 0.06m.

$$0.5 \times 1.225 \times 0.0036 \times 1 \times 3^2 = 0.02\ \text{N}$$

To account for errors, and loss of energy, the target take off speed was aimed to me 2.6m/s. This was then used in the rest of calculations. To work out the energy required the maximum mass of 200g was used.

$$0.5 \times 0.2 \times 2.6^2 = 0.676\ \text{J}$$

The time over which the leg must extend is determined by the amount that it extends by. This is shown later in the report (3.4.1).

2.6 Extending Legs

A 4-bar linkage system as shown in Figure 1 is a great way to create an extending 'leg' to jump. These however are not actuated rotationally. One possible way is to take inspiration from a combustion engine. Instead of turning linear motion (piston firing up and down) into rotational motion (the crank shaft), you can turn a crank shaft which will then linearly move a 'piston' up and down (Figure 2).
Instead of creating a 4 bar linkage system, a 4+ bar linkage system would have to be created, such as attaching the systems in Figure 1 and Figure 2.

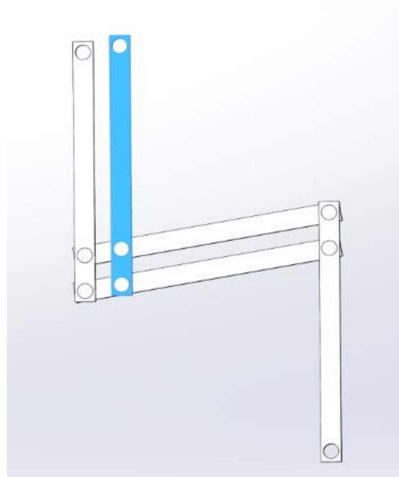


Figure 1

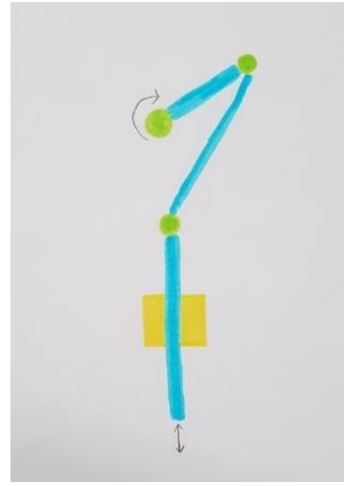


Figure 2

2.6.1 Extending leg model 1

To get a better understanding of how mechanisms behaved some models were developed. These were constructed from laser cut acrylic and steel nuts/bolts. Firstly, a mechanism was constructed which took inspiration from 'extending boxing gloves' and scissor rising platforms. Figure 3 demonstrates how rotation can be utilized to create a 'leg' which extends. One of the main benefits of this system is that just by adding on more scissor joints you can increase the displacement of the leg, with the same amount of rotation. This however requires more joints, at which energy is lost due to friction, and also increases weight. In addition to this it was the least stable feeling of the mechanisms produced and was difficult to omit wobble.

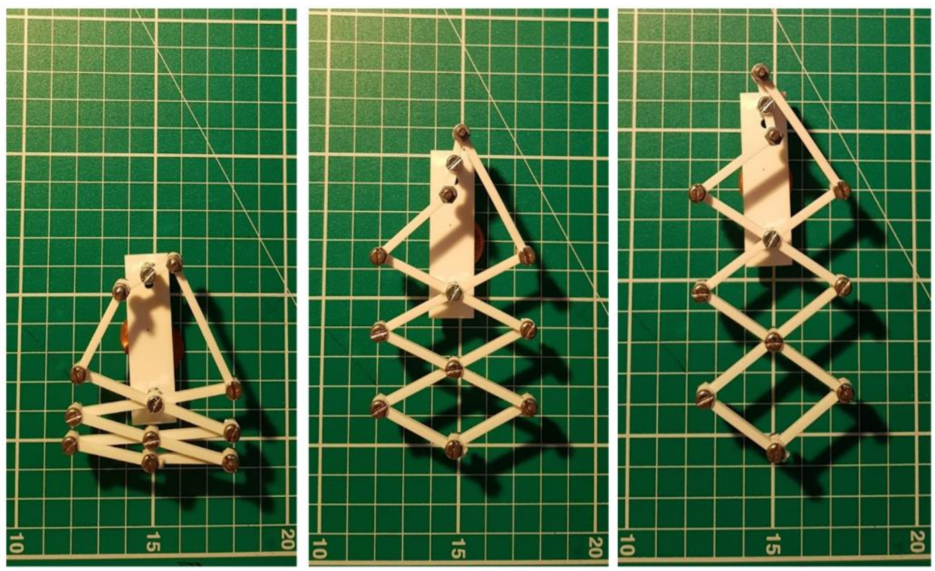


Figure 3

2.6.2 Extending Leg 2

The mechanism in Figure 5 is based on the 4 bar linkage shown in Figure 1 and on the same rotational method used in Figure 3. From fewer members and fewer joints a larger displacement was managed. This is partly due to the members being longer, however it is mostly because when fully extended the members are closer to vertical, than those in Figure 3. This means that there is greater displacement achieved. Another advantage is that there is slightly less rotation required which allows for faster responses to be made. One of the problems discovered with this iteration was the ability to not overlap the top rotation bars, which would allow it to have a greater jump. Another was that the 4-bar linkage could over-extend and get stuck, which would not allow it to reset itself.

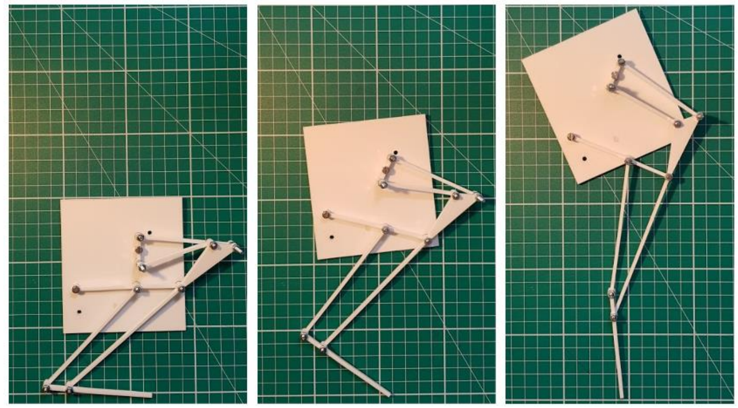


Figure 5

2.6.3 Extending Leg 3

In the third iteration the two linkages which were over extending were made parallel which removed the problem of them getting stuck. The problem with this iteration is that the main arm (with 5 joints) interfaces with other linkages, meaning it can't extend as much. To improve upon this, the main arm was redesigned, and the location where the swing arm was attached was changed. This greatly increased the displacement achievable.

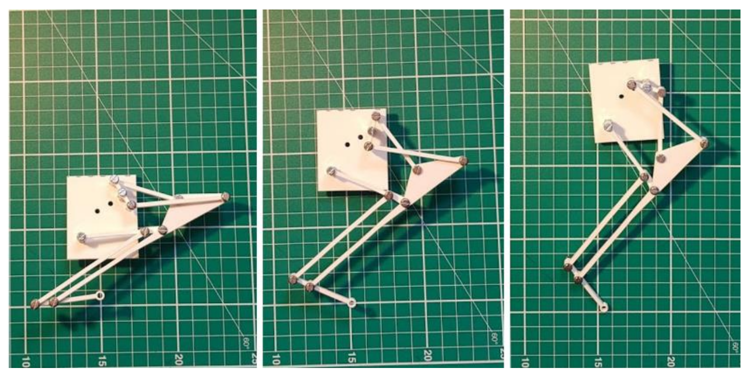


Figure 4

2.7 Material selection

The two most constraining parts of the brief were the weight limit of 200g and the maximum cost of £100. These majorly affect the materials chosen.

2.7.1 Joint Materials

The joints between the linkages need to have as little friction as possible. The most common way of doing this is to use a ball-bearing joint, however due to the small size of the joints this is not possible on the economic scale that has been specified. To overcome this a steel/aluminium pin will be used and separating it from the linkage, a thin nylon insert will be used. Nylon is very hard wearing and has a low coefficient of friction, making it perfect for a live joint[5].

2.7.2 Linkage material

Carbon fibre when cured with the appropriate resin is very stiff and lightweight for its size. It is expensive; however, it is becoming more economically available. To reduce the cost even more, it is possible to manufacture these components alongside larger manufacturing projects. Using the off cuts from large carbon fibre projects, would mean the material would be free, and the only cost would be labour.

2.7.3 Rotation arm

The rotary arm which transfers motion and force from the motor to the linkage system needs to be able to cope with the torque from the motor. A square socket in the component will be used. To keep costs and weight to a minimum, a simple component milled from aluminium will be used.

3. Final Design

3.1 Final Assembly

Property	Value
Dimensions (Crouched)	128mm
Dimensions (Extended)	218mm
Mass (Without Adhesives)	109.87 g
Estimated Cost	£98.03
Total Number of Components	110

3.2 Extending Leg

The leg mechanisms comprises of a 7 bar linkage system, which was developed using an iterative process (shown in 2.6). Figure 6 shows the main components of the system. The rotor (where the two rotor connectors meet) is rotated about 200° which then pushes and pulls on the rotor connectors. These, along with the swing arm, guide the main arm and foot leg from its crouched position to its extended position (as seen in Figure 4). To make sure all of these components are aligned correctly, and to reduce friction, a bespoke system was created (Figure 7). Simple aluminium pins (one outer casing which has been tapped, and one with a threaded screw) were designed. They are much more compact than traditional nuts and bolts, and do not have threading which

Figure 6

cannot scratch the inside surface of the legs. They are also designed so that when fully tightened they are the correct distance appart, which assures that all the joints are tightened to the same amount.

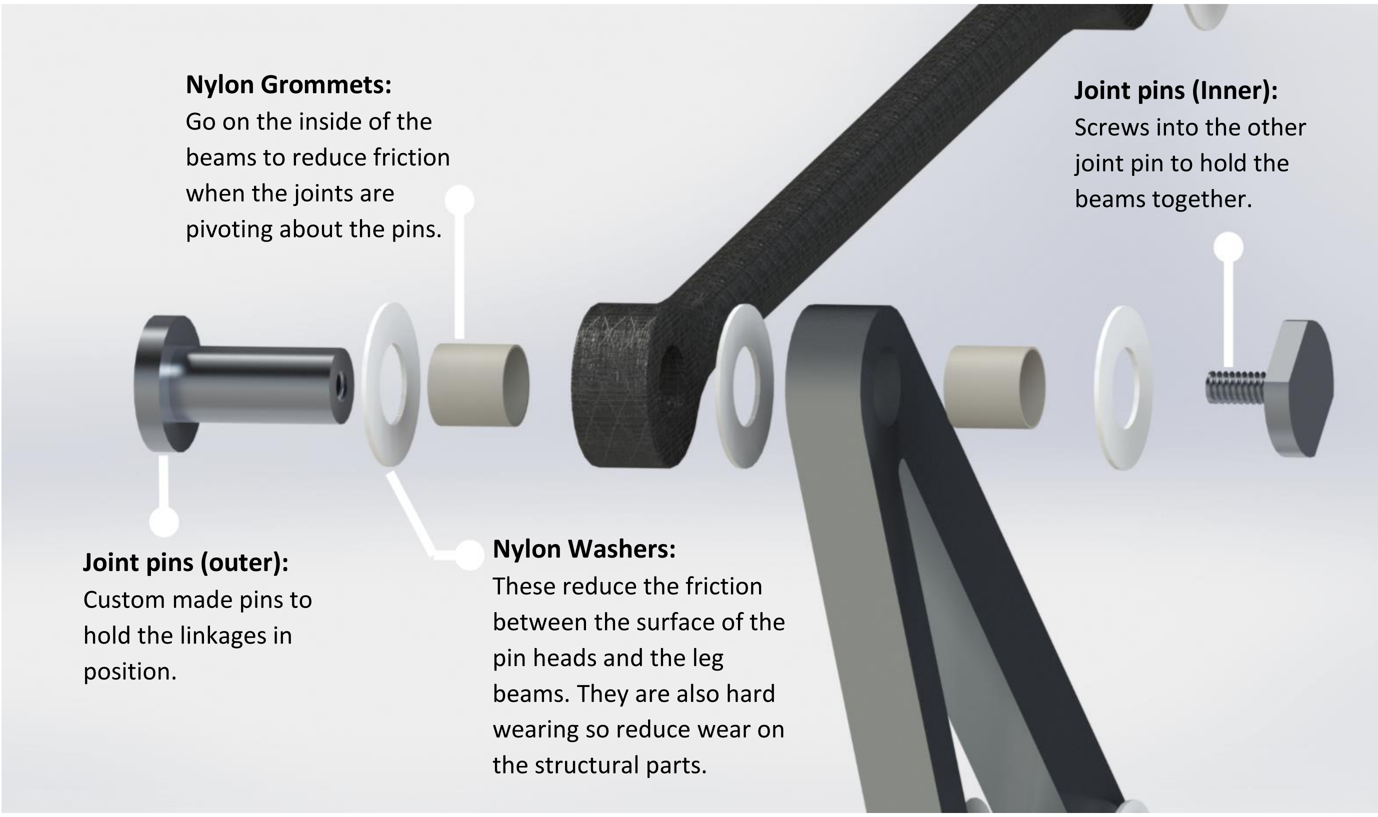


Figure 7

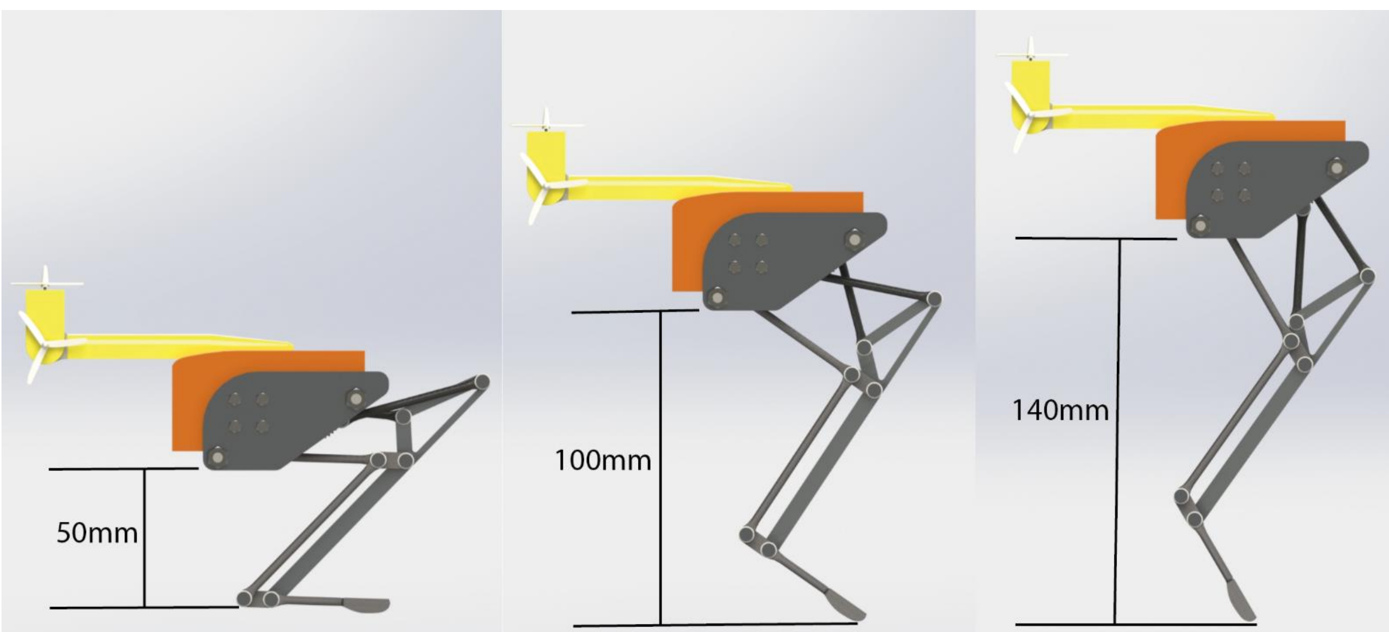


Figure 8

As seen in Figure 8 the total displacement when jumping is 90mm. This is achieved by 200° of rotation from a 20mm long rotor. During this launch the JSR is also propelled forward, which can also be adjusted by the tail rotor system.

3.3 Electrics

3.3.1 Motor

The motor chosen to power the legs is the Turnigy Aerodrive SK3 – 2118. It is a compact brushless DC motor which provides enough power and torque, once geared correctly, to extend the leg of the JSR fast enough.

Aerodrive SK3 - 2118 Specifications	
Weight	17g
Max Current	5A
Max Power	39W
Shaft Diameter	2.0mm
RPM/V	3100
Max torque @ 9900 rpm	0.035N/m
Cost	£11.01

3.3.2 Battery

The motor has a maximum output of 39W, however is only needed in very short bursts of 0.054s (see time and energy calculations in 3.4.1). The specified battery has a continuous discharge of 4.2A at 7.4 volts, however in short bursts can discharge at 11.1V at 6A. This is sufficient for powering the motor, especially as it will only be at 39W for 0.054s.

Storm 7412035-JST Specifications	
Weight	10.3g
Max Current (7.4V) Cont.	4.2A
Max Current (11.1V) Burst	6A
Capacity	0.12Ah
Dimensions (mm)	25x18x15
Cost	£6.16

3.3.3 IMU

To stabilise the JSR, first its position in space must be known. To achieve this there is an inertial measurement unit integrated with the other electrical components. This uses an accelerometer and a 3-axis gyroscope to measure the acceleration and rate of tilt. This information is then processed by a micro-controller which then controls the two motors at the back of the JSR to stabilise it.

3.4 Transmission

3.4.1 Gear Ratios

The motor, under load and full power has an RPM of 9900. To calculate the gear ratio needed, first the RPM of the leg rotor was found. The gear rotor moves through 200° between fully crouched and fully extended. The displacement of the leg is 0.07m, and the take-off velocity must be 2.6m/s.

$$v^2 = u^2 + 2as$$
$$\therefore 2.6^2 = 0 + (2a \times 0.07)$$
$$\therefore a = 48.3\ m/s^2$$

The time taken for the rotor to turn 200° is found by:

$$v = u + at$$
$$\therefore 2.6 = 0 + (48.3 \times t)$$
$$\therefore t = 0.054s$$

This means it takes 0.0972s for 1 full rotation of the rotor. That equates to the rotor turning at 617.3RPM. As the motor turns at 9900 rpm a gear ratio of 16:1 was needed. This was achieved by a gear chain. The primary gear ratio was 3.8:1, and the secondary was 4.2:1, giving a total gearing ratio of 15.96.

3.4.2 Gears

The first gear is made from high speed steel as it must be strong due to the high speed, and low number of teeth (10) on it. The other gears are all made from acetal due to its low density, strength, and low cost. The gears used had a pressure angle of 20°, which is a good compromise between power and smoothness[6]. The second and third gears in the chain were offset by a 1mm spacer, which also connected the two. This also allowed for a small gap between gear 2 and gear 4, meaning that they do not rub on each other.

3.4.3 Shaft Assembly

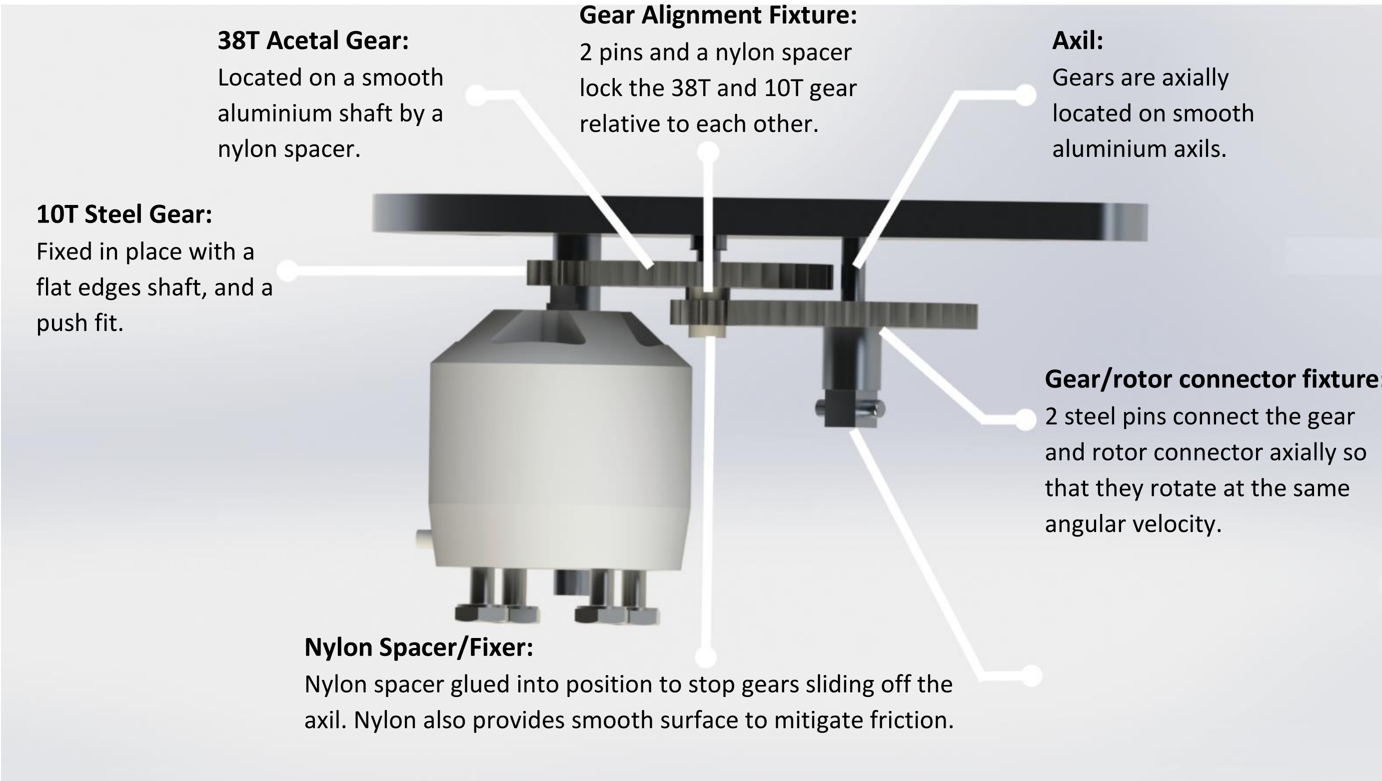


Figure 9

3.5 Stability

To stabilise the JSR a mechanical gyroscope was initially going to be used, however they are expensive, and difficult to package. This would have been linked to a gyroscopic sensor and an accelerometer. Instead inspiration was taken from helicopters. A helicopters tail stabilises it in one axis (yaw), however, by adding an extra propeller working in the Y axis, pitch can be controlled too. Because the centre of mass of the JSR is lower than the axis that the Z axis rotor applies force on, roll of the JSR can be controlled by a combination of the two propellers. If the JSR was to roll towards the left along the axis through the centre of mass force would be applied pushing the tail in the -Z and -Y direction. This would mean that it would no longer be facing in the same direction, however this can be corrected in the Z axis.

To facilitate this system, it is liked up to a micro-controller which has an electronic gyroscopic sensor and accelerometer. This micro controller is linked up to the two motors in the tail to 'push' air in one direction or the other.

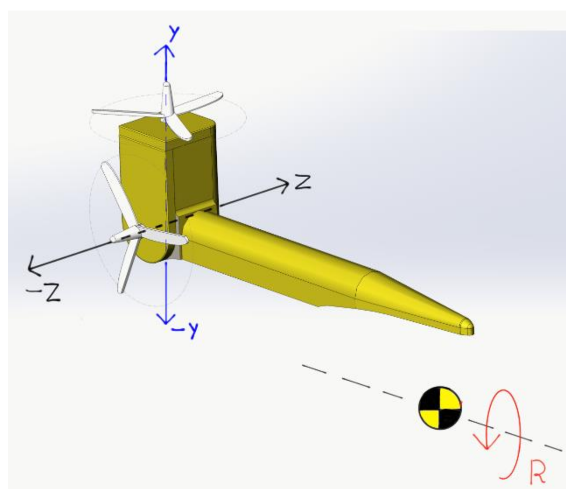


Figure 10

Racestar BR0703 Specifications	
Weight	1.9g
Max Current	1.8A
Operational Voltage	7.4V
Shaft Diameter	1.0mm
RPM/V	8000
Cost	£6.68

3.6 Ingress Protection

To prevent the ingress of water and dust to IP54 several measures were taken. In the main body the electronics, battery and motor were all encased in a 2-part HDPE case. The 2 sides interfaced with each other as shown in Figure 11 and are sealed with glue. This creates a strong barrier against dust and water.

Figure 11

To protect the 2 motors in the 'tail' from weather ingress, the side panels are glued on which seals in the wiring and motors.

On all 3 motor axils, there is little/no gap left. This meant the IP54 standards as it will prevent the majority of ingress of dust and water. These locations are the most likely to let water and dust in. Because water might get in, 3M™ Novec™ Electronic Grade Coating will be applied in case small amounts of fluid did get in, protecting all electronic components from water ingress.

3.7 Chassis/Case

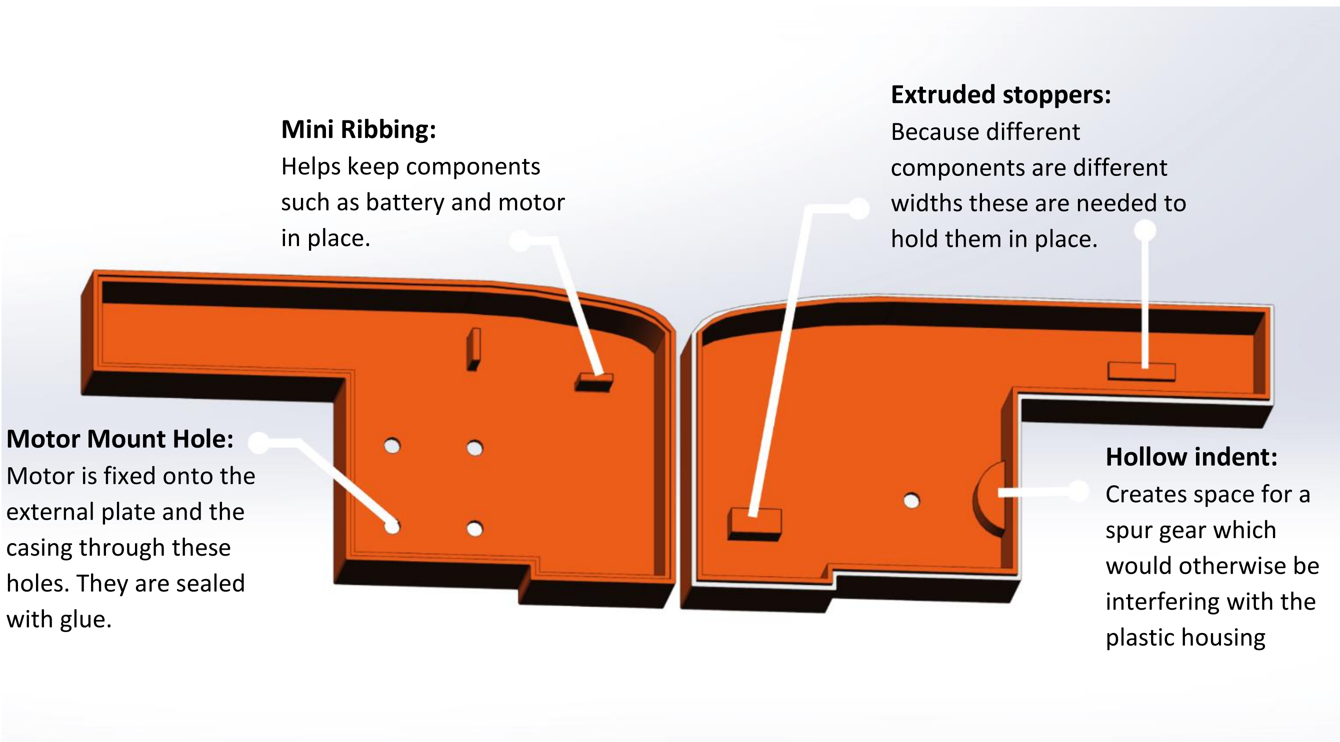


Figure 12

Made from HDPE, the casing is designed to be lightweight, hold components such as the electronics and bettery in place and protect them from the elements. Components are held in place by glue, and by the ribbing and extruded plastic parts.

The chassis is made from 2 aluminium plates. The one which holds the mounting points for the gears and leg assembly swingarm is 3mm thick, whilst the other is 2mm thick, to save weight.

3.8 Optimisation

3.8.1 Optimising the leg displacement

An efficient way of improving the geometry of the baseplate, to force the leg to extend a greater distance was to edit it and then visually inspect the displacement in an assembly. The figures 13-16 below show how the maximum displacement varied when the position of the guide bar was changed (circled in red).

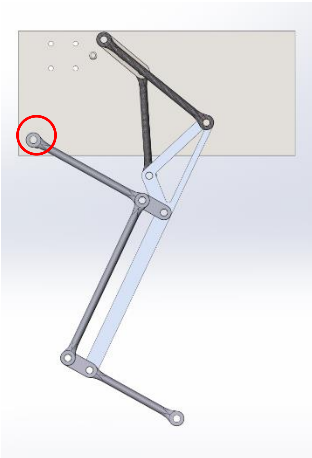


Figure 13

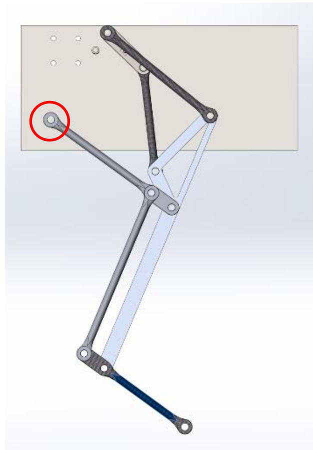


Figure 14

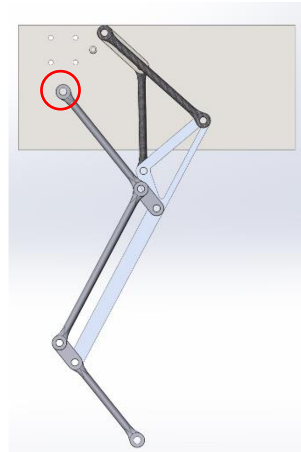


Figure 15

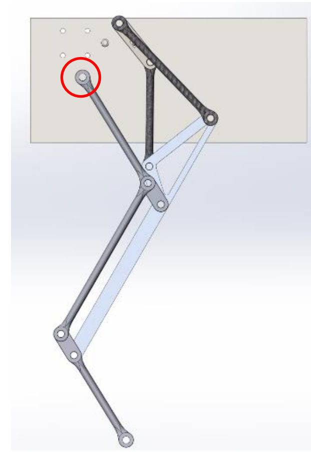
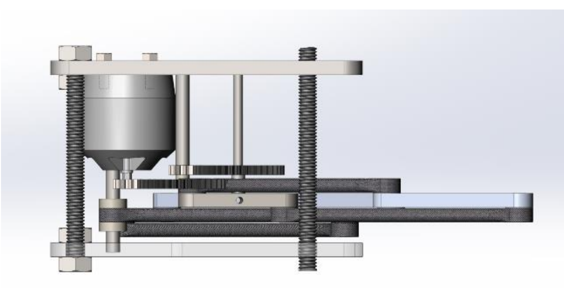
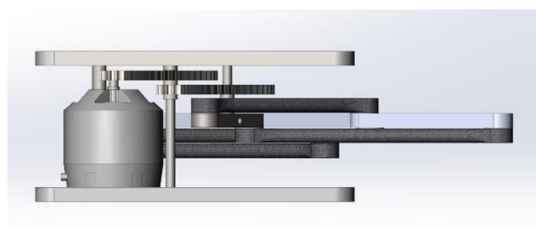


Figure 16

3.8.2 Orientation of components

When looked down on from above, the first iteration the motor sticks out a long way to the left. This throws the center of balance off, and also makes the gearbox 'cage' wide. To improve this the whole gearbox cage and gearing system was redesigned. It made it just under 30% thinner (11mm), which reduced the quantity of material needed, therefore minimising cost and weight.





3.9 Validating

3.9.1 Height

As previously stated the JSR must accelerate at 48.3 m/s² (3.4.1). The total mass of the JSR (with glue) is around 110g,

$$\therefore F = 0.11 \times 48.3$$

So, the force needed at the feet is 5.313N

Torque at the motor is 0.035N, and a gear ratio of 16:1, so torque at the leg rotor is 0.56Nm. The radius of the rotor is 10mm, therefore the force acting on the push arm (downwards) is 56N. Even if you assume only 10% efficiency from motor to foot, then there is still enough force to accelerate the JSR to the required velocity.

N.B. The acceleration calculations were done with 70mm displacement, however JSR has 90mm of displacement, meaning the acceleration can be less, which also reduces the force.

3.9.2 FEA on Leg Joint pins

The maximum force applied to the pins is at the leg rotor, and the carbon fibre connectors. The maximum force that would be applied through the pins is a shear force of 53N. This was modelled in solidworks as a static model, with one half of the pin fixed, and a 53N force applied normally to the pin's surface. This gave a minimum factor of safety of 7.4. Unfortunately the pin could not be made smaller, not due to safety but becase at its size, it becomes increasingly difficult to manufacture any smaller. It should be noted that it was not modelled with the internal screw inserted, which would also give additional support and strength.

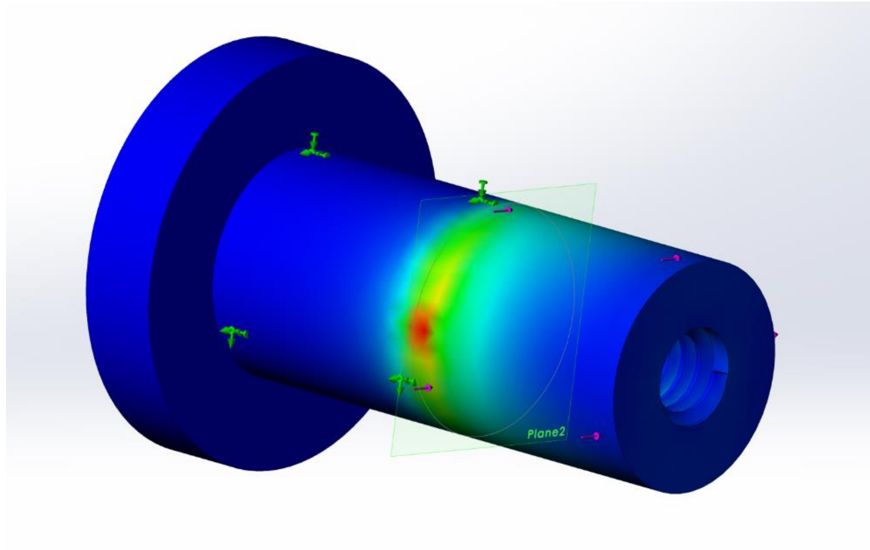


Figure 15

3.9.3 FEA on Gear pins

To model the force on the gear pins, the worst-case scenario was considered, which is if the leg mechanism was to jam, and the leg mechanism was static. This would put 16.5N onto a 2mm long part of the pin. When initially testing the 6mm diameter pin, it failed, so it was adjusted to 8mm. This gave a safety factor of 1.42, however, the probability of this situation occurring is very low, and this is the worst-case situation as in reality the other side of the pin would be able to move. Due to this several components had to be changed to accommodate the new size of pin.

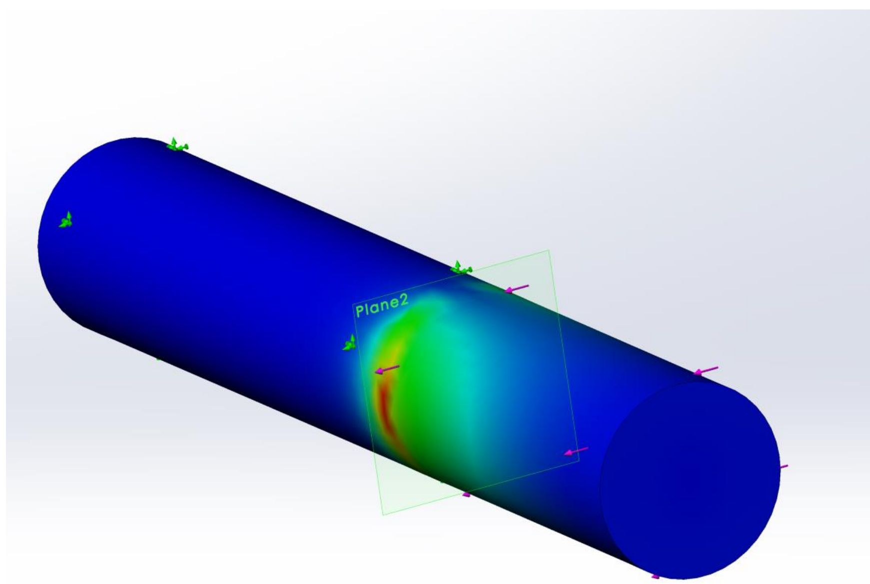
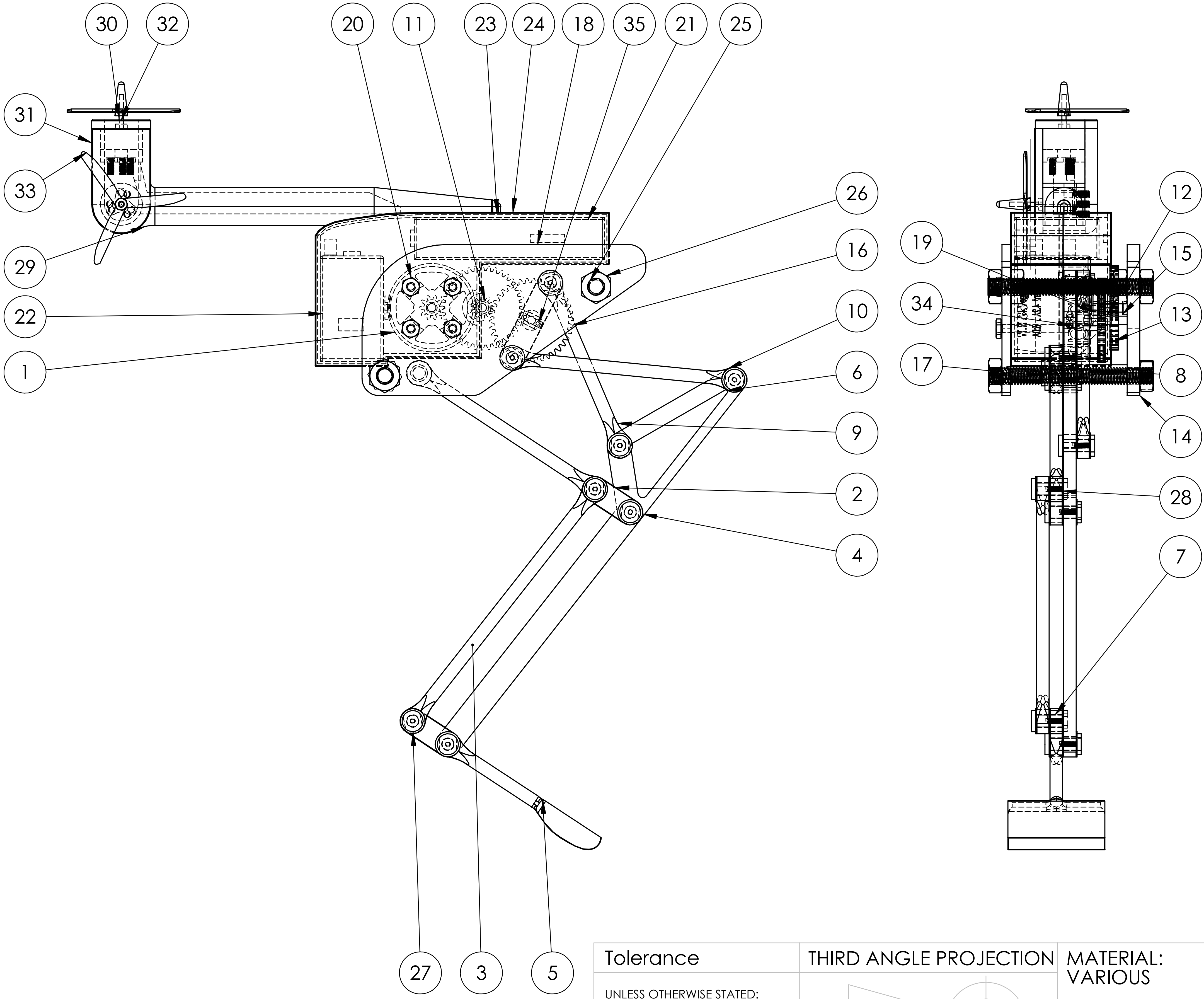


Figure 16

4. General assembly

4.1 Bill of materials

Name	No.	Sub-Assembly	Mass (g)	Quantity	Material	Cost (per item)
Electronics housing (mount)	23	Electronics	4.27	1	HDPE	£0.26
Electronics housing (Shaft)	24		4.23	1	HDPE	£0.27
Motor (main)	1		17	1	Composite	£11.01
Circuitry (inc sensors)	21		8.99	1	Composite	N/A
120 mah Battery	22		10.3	1	Composite	£6.16
Gearbox brace plate	18	Chassis	9.61	1	Aluminium	£3.00
Motor Gear plate	14		15.27	1	Aluminium	£5.50
M4 Studding (39mm)	25		2.88	2	Steel	£3
M4 Nut	26		0.79	6	Steel	£0.10
M2 Bolt	20		2.10	4	Steel	£0.11
Tail Arm	29	Tail	5.34	1	HDPE	£1.12
Tail Top Plate	32		0.39	1	HDPE	£0.34
Tail Side Plate	31		0.62	1	HDPE	£0.34
Mini motor	30		1.90	2	Composite	£6.68
M1.6 screws	36		1.00	6	Steel	£0.03
Rotor	33		0.07	2	ABS	£0.30
Leg Rotor	8	Leg	1.04	1	Aluminium	£1.20
Rotor Pin	34		0.03	1	Aluminium	£0.55
Gear/Rotor Shaft	19			1	Aluminium	£1.25
Rotor Connector arm (short)	9		0.71	1	Carbon Fibre	£3.50
Rotor Connector arm (long)	10		0.85	1	Carbon Fibre	£3.50
Leg Main	6		2.19	1	Aluminium	£3.50
Leg hock	3		1.06	1	Carbon Fibre	£3.50
Leg Swing arm	2		1.09	1	Carbon Fibre	£3.50
Leg bottom joint (foot)	5		3.95	1	Carbon Fibre	£3.50
Nylon Gromit	7		0.00	16	Nylon	£0.06
Nylon retainer	17		0.00	2	Nylon	£0.08
3mm Nylon Washer	4		0.00	24	Nylon	£0.02
Pin casing	27		0.16	8	Aluminium	£1.30
Pin Screw	28		0.06	8	Aluminium	£1.30
10T Spur Gear	11	Gear Box	0.23	2	Steel	£0.40
38T Spur Gear	13		0.55	1	Acetal	£0.28
42T Spur Gear	16		0.68	1	Acetal	£0.30
Gear Spacer	12		0.00	2	Nylon	£0.20
2mm Washer	15		0.00	1	Nylon	£0.02
Alignment Pin	35		0.02	4	Steel	£0.14
		Total components		110	Total Cost	£98.03



NO.	PART NAME	QTY.
1	motor	1
2	leg_swing_arm	1
3	Leg-hock	1
4	3mm_nylon_washer	24
5	leg-bottom_joint	1
6	leg_main	1
7	inner_nylon_grommit	16
8	leg_rotor	1
9	rotor_short_connector	1
10	rotor_long_connector	1
11	10T Spur Gear 0.5M	1
12	gear_spacer	2
13	38T Spur Gear 0.5M	1
14	motor_gear_plate	1
15	2mm_nylon_washer	1
16	42T Spur Gear 0.5M	1
17	nylon_restrainer	2
18	gearbox_brace_plate	1
19	Gear to rotor shaft	1
20	M2 x 16 x 10-N	4
21	electronics	1
22	Battery	1
23	waterproof_mount	1
24	waterproof_sharft	1
25	M4_studding	2
26	M4 Nut	6
27	Pincase	8
28	pinscrew	8
29	tailarm	1
30	minimotor	2
31	side_plate	1
32	top_plate	1
33	rotor	2
34	rotorpin	1
35	steel_gear_pin0_8mm	4
36	10T Spur Gear 0.5M	1

Tolerance

UNLESS OTHERWISE STATED:
LINEAR $\pm$ 0.05
ANGULAR $\pm$ 0°30'

THIRD ANGLE PROJECTION

MATERIAL:
VARIOUS

ALL DIMENSIONS ARE IN MILLIMETRES

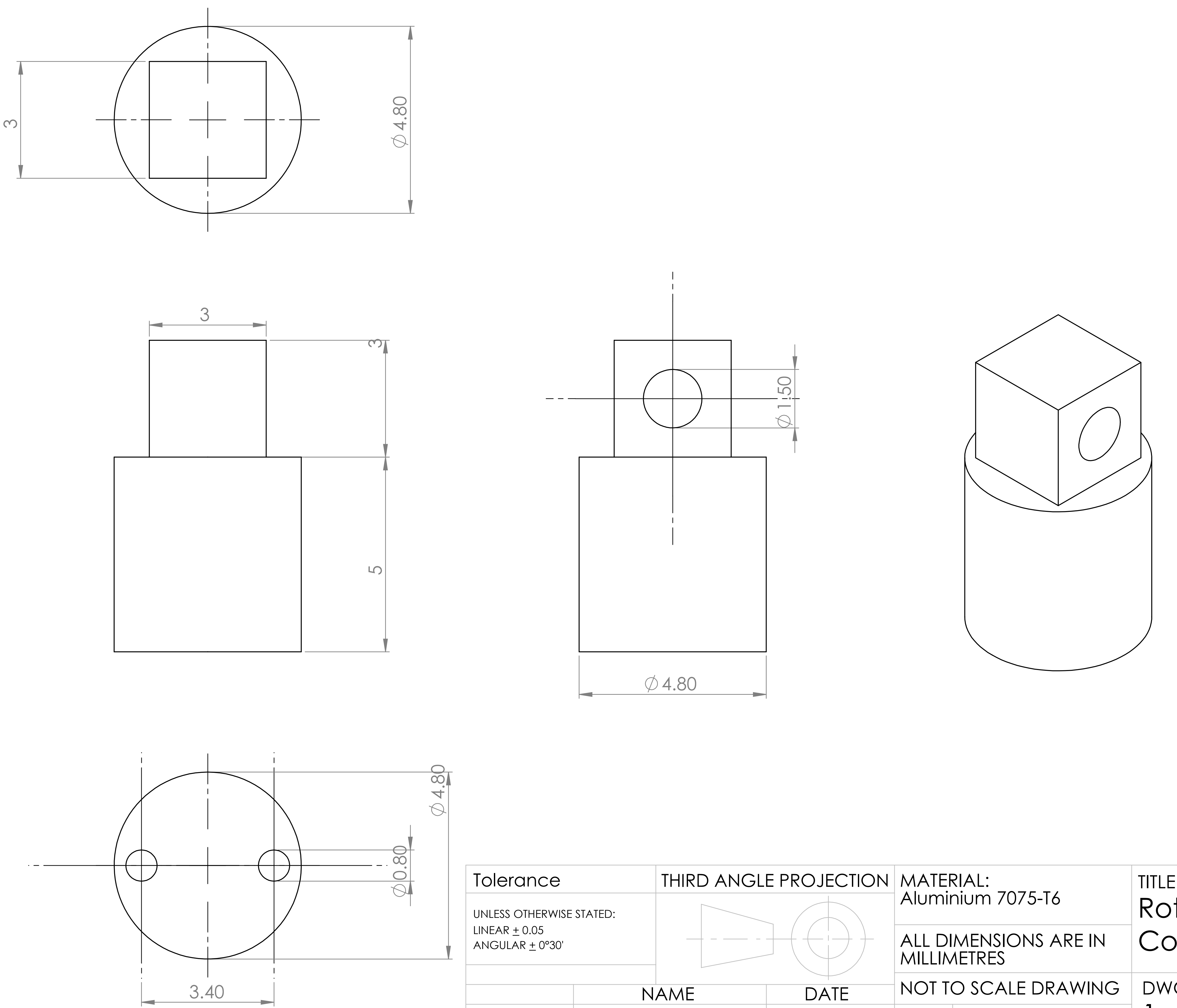
NOT TO SCALE DRAWING

TITLE:
GENERAL ASSEMBLY

	NAME	DATE
DRAWN	ROWAN DIXON	30/04/2018
APPROVED		

A3 SCALE 1:1

DWG No.
JSRFULLASSEMBLY

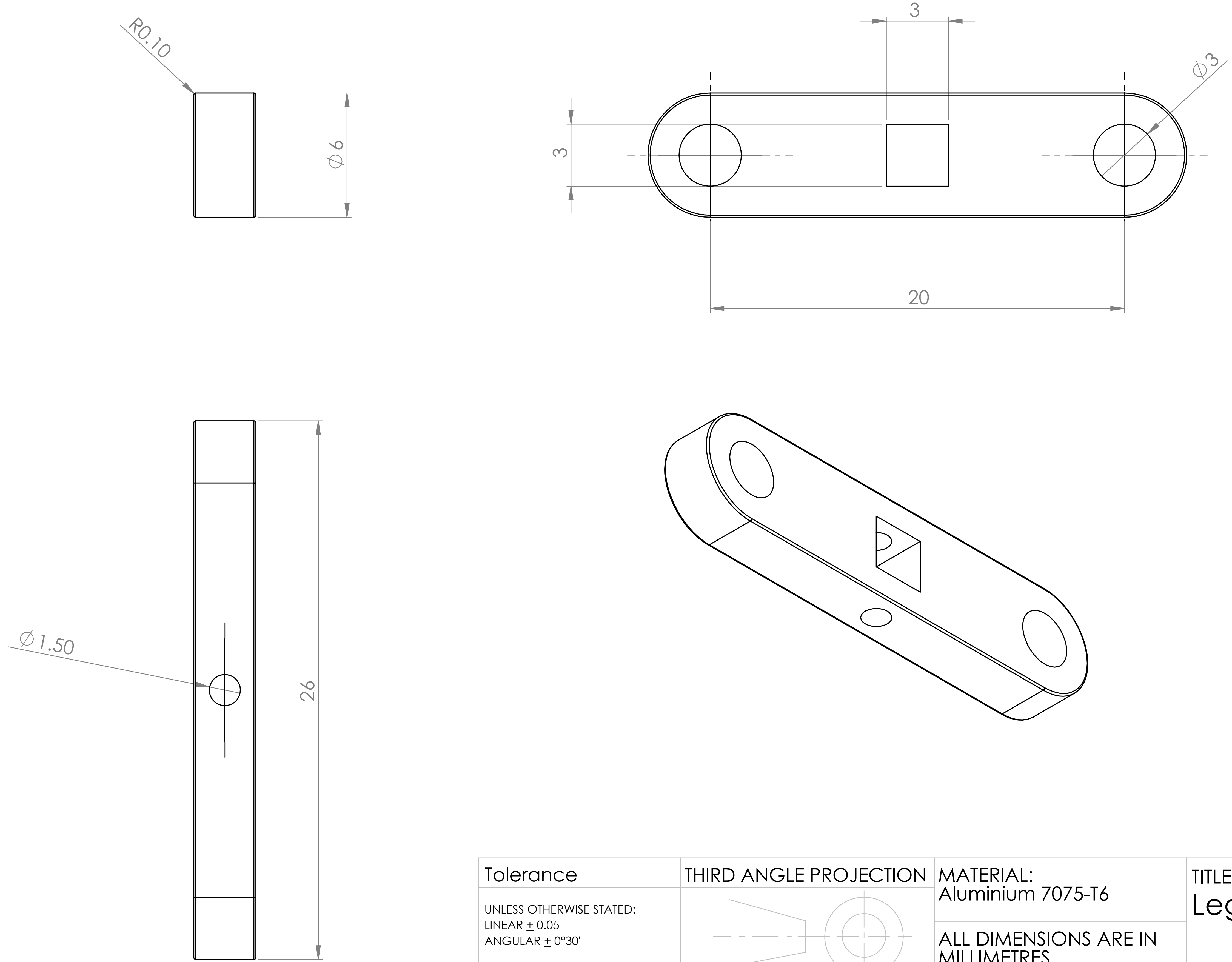


Tolerance	THIRD ANGLE PROJECTION	MATERIAL: Aluminium 7075-T6	TITLE: Rotor-Gear Connector
UNLESS OTHERWISE STATED: LINEAR ± 0.05 ANGULAR ± 0°30'		ALL DIMENSIONS ARE IN MILLIMETRES	
		NOT TO SCALE DRAWING	DWG No. 1

	NAME	DATE
DRAWN	ROWAN DIXON	30/04/2018
APPROVED		

A3 SCALE 10:1

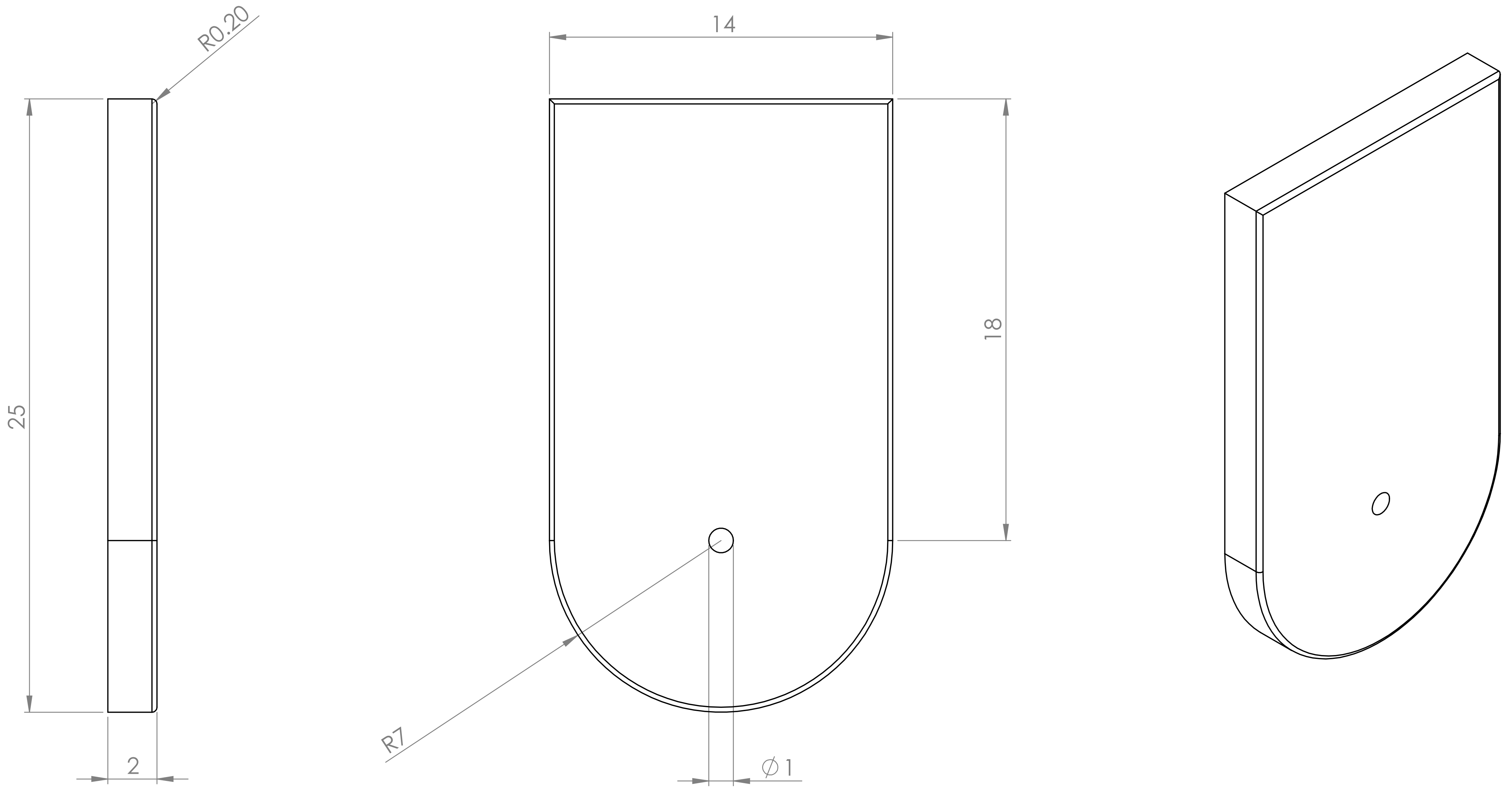
RK



Tolerance	THIRD ANGLE PROJECTION	MATERIAL: Aluminium 7075-T6	TITLE: Leg Rotor
UNLESS OTHERWISE STATED: LINEAR ± 0.05 ANGULAR ± 0°30'		ALL DIMENSIONS ARE IN MILLIMETRES	
		NOT TO SCALE DRAWING	DWG No. 1
		A3 SCALE 5:1	

	NAME	DATE
DRAWN	ROWAN DIXON	30/04/2018
APPROVED		

RK



Tolerance	THIRD ANGLE PROJECTION	MATERIAL: HDPE		TITLE: Side Plate
UNLESS OTHERWISE STATED: LINEAR ± 0.05 ANGULAR ± 0°30'		ALL DIMENSIONS ARE IN MILLIMETRES		
	NAME	DATE	NOT TO SCALE DRAWING	DWG No.
DRAWN	ROWAN DIXON	30/04/2018	A3 SCALE 5:1	1
APPROVED				

RK

5. References

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6 - http://www.xtek.com/pdf/wp-gear-terminology.pdf

7 - http://www.helipal.com/product_info.php?