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Designing, manufacturing and testing a robot actuator

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Abstract

The goal of this project is to learn how to design and manufacture actuators for robots, especially quadruped robots. This poses several design requirements: low weight, low gear ratio, sufficient torque, and high efficiency. The result is an actuator weighing 914g with a gear ratio equal 6:1 and an estimated efficiency of 95%, that is theoretically capable of producing 27.55 Nm of torque.

1 Introduction

In the process of designing and manufacturing efficient, low-cost, and small utility robots using proper actuators is crucial. The actuator should have enough torque to fulfill the needs of all tasks, as well as being lightweight and efficient. The last two requirements are especially important in mobile robots, where the amount of available energy is limited by the battery size. An example of a robot where having proper actuators is crucially is a quadruped robot. In order for such a robot to be able to move in all directions, 12 actuators (3 per leg) are needed. This adds a considerable amount of weight to the construction.

This project was devoted to learning how to design and manufacture actuators that potentially can be used in quadruped robots. This poses one more requirement – the ability to back-drive the motor. Back-drivability allows the motors to act as virtual springs that spread in time the forces acting on the leg on impact with the surface. This property can be achieved by using low reductions in the gearbox of the actuator.

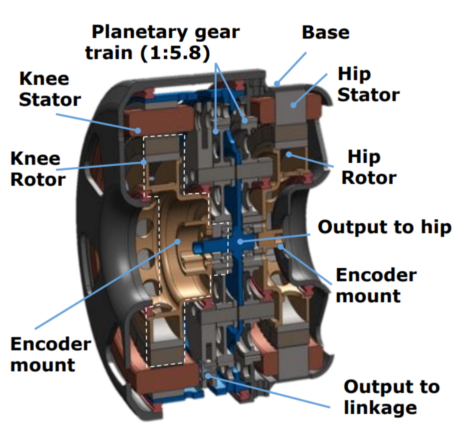
2 Related work

The issue of designing efficient, small, and lightweight actuators has been addressed in several publications. Wensing et al. [1], Yu et al. [2] and Zeng et al. [3] all propose to use planetary gearboxes in such actuators. In the case of quadruped robots, planetary gearboxes have several advantages over other designs. Namely:

- they are able to satisfy the required torque with a smaller size of the gearbox;
- it is possible to fit the gearbox inside the stator, further reducing the size;
- smaller size means smaller weight, thus the torque to weight ratio increases;
- due to fewer contact points the efficiency of such gearboxes is high;
- the motor is in-line with the gearbox and this allows to stack the gearboxes without using much space (as showed in Fig. 1a);
- straightforward construction.

Designing a planetary gearbox to satisfy the torque needs that fits inside the stator of the motor is challenging. An alternative approach was proposed by Singh et al. [4] where the planetary gearbox is comparable in size to the motor and is attached as an additional module. This approach is demonstrated in Fig. 1b.

Due to easier manufacturing and design, the method proposed in [4] was used in this project.



(a) Actuator used in MIT Cheetah [1]

(b) Modular actuator proposed in [4]

Figure 1: Different designs of planetary gearboxes

3 Design

This section will be devoted to the description of the design process of the actuator. As stated before, the modular approach was taken. That means the final actuator consists of two parts: the motor module and the planetary gearbox module. The motor module consists of:

- the motor,
- the housing,
- the input shaft and sun gear.

The planetary gearbox consists of:

- the carrier,
- the planet gears,
- the ring gear,
- the housing.

Autodesk Fusion360 is the CAD software used to design all parts in this project. At the time of writing, this report is available under a free-to-use personal license. However, some more advanced features are limited to the commercial version. There also exists a student license that unlocks some features from the commercial one.

The parts were design to be possible to manufacture both additively (3d printing) and subtractively (CNC machining).

3.1 Tolerances and fits

In mechanical assemblies multiple parts are connected with each other in different ways. In some cases it is required that the parts move freely, in other the parts should be rigidly connected. The question is how to consistently design parts that interact with each other in the desired way despite the finite accuracy of machining? The answers to this question are fits and tolerances charts (Fig.2). There are three main types of fits:

- Clearance fits – the shaft and the bore move freely and there is a considerable give between them.
- Transitional fits – the shaft and the bore move freely, but there is little give between them.
- Inference fits – the shaft and the bore are rigidly connected.

In case of gearboxes, to reduce the backlash, transition fits are preferred between the gears, bearings, and shafts and inference fits are preferred between shafts and gears.

When designing parts that are manufactured using home-grade 3D printers, using the fit and tolerance charts does not make sense due to the low accuracy of such machines (It is safe to assume that the accuracy usually is around $\pm 0.5mm$). Usually, the nominal size of the part is selected by trial and error.

3.2 Designing the planetary gearbox

A schematic view of a planetary gear system is shown in Fig. 3. In the simplest case it consists of a sun gear, a ring gear and three planet gears rigidly connected with the use of the carrier. The gear system can work in different modes, but here only one of them will be consider. Namely, the case when the ring gear is fixed. In that case the rotation of the sun gear causes the rotation of the planet gears that are connected to the carrier. This causes the carrier to rotate at a lower speed and in the same direction as the sun gear.

To design a planetary gearbox with a given gear ratio G_r one must use the following equations

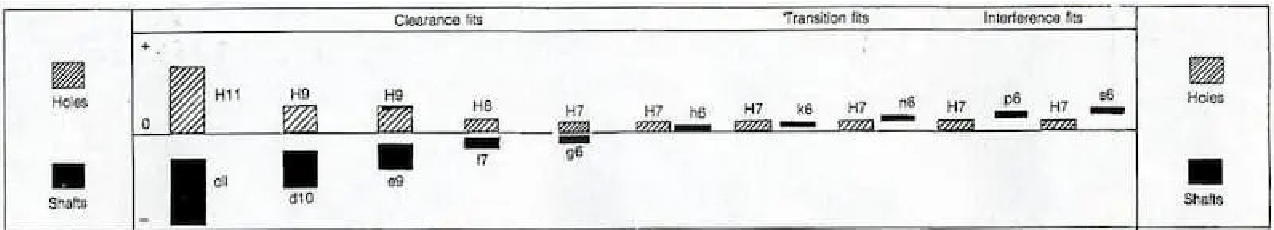
$$S = \frac{R}{\frac{1}{G_r} - 1},$$

$$P = \frac{R - S}{2},$$

where R is the number of teeth of the ring gear and is a design parameter and S is the resulting number of sun gear teeth. In order to check if the number of selected planet gears will mesh correctly, the following condition must be met:

$$\frac{R + S}{N_p} \in \mathbb{Z},$$

where N_p is the number of planet gears.



Upper and lower deviations for tolerance class (Values μm)

Basic size (mm) Above	Up to and incl.	H11 +	c11 −	H9 +	d10 −	H9 +	e9 −	H8 +	f7 −	H7 +	g6 −	H7 +	h6 +	H7 +	k6 +	H7 +	n6 +	H7 +	p6 +	H7 +	s6 +	Basic size (mm) Above	Up to and incl.
0	3	60 / 0	60 / 120	25 / 0	20 / 60	25 / 0	14 / 39	14 / 0	6 / 16	10 / 0	2 / 8	10 / 0	6 / 0	10 / 0	6 / 0	10 / 0	10 / 4	10 / 0	12 / 6	10 / 0	20 / 14	0	3
3	6	75 / 0	70 / 145	30 / 0	30 / 78	30 / 0	20 / 50	18 / 0	10 / 22	12 / 0	4 / 12	15 / 0	8 / 0	15 / 0	10 / 1	15 / 0	19 / 10	15 / 0	24 / 15	15 / 0	32 / 23	3	6
6	10	90 / 0	80 / 170	36 / 0	40 / 98	36 / 0	25 / 61	22 / 0	13 / 28	15 / 0	5 / 14	18 / 0	11 / 0	18 / 0	12 / 1	18 / 0	23 / 12	18 / 0	29 / 18	18 / 0	39 / 28	6	10
10	18	110 / 0	95 / 205	43 / 0	50 / 120	43 / 0	32 / 75	27 / 0	16 / 34	18 / 0	6 / 17	21 / 0	13 / 0	21 / 0	15 / 2	21 / 0	28 / 15	21 / 0	35 / 22	21 / 0	48 / 35	10	18
18	30	130 / 0	110 / 240																			18	30
30	40	160 / 0	120 / 280	62 / 0	80 / 180	62 / 0	50 / 112	39 / 0	25 / 50	25 / 0	9 / 25	25 / 0	16 / 0	25 / 0	18 / 2	25 / 0	33 / 17	25 / 0	42 / 26	25 / 0	59 / 43	30	40
40	50	160 / 0	130 / 290																			40	50
50	65	190 / 0	140 / 330	74 / 0	100 / 220	74 / 0	60 / 134	46 / 0	30 / 60	30 / 0	10 / 29	30 / 0	19 / 0	30 / 0	21 / 2	30 / 0	39 / 20	30 / 0	51 / 32	30 / 0	72 / 53	50	65
65	80	190 / 0	150 / 340																	30 / 0	78 / 59	65	80
80	100	220 / 0	170 / 390	87 / 0	120 / 260	87 / 0	72 / 159	54 / 0	36 / 71	35 / 0	12 / 34	35 / 0	22 / 0	35 / 0	25 / 3	35 / 0	45 / 23	35 / 0	59 / 37	35 / 0	93 / 71	80	100
100	120	220 / 0	180 / 400																	35 / 0	101 / 79	100	120
120	140	260 / 0	200 / 450																	40 / 0	117 / 92	120	140
140	160	280 / 0	210 / 460	100 / 0	145 / 305	100 / 0	84 / 185	63 / 0	43 / 83	40 / 0	14 / 39	40 / 0	25 / 0	40 / 0	28 / 3	40 / 0	52 / 27	40 / 0	68 / 43	40 / 0	125 / 100	140	160
160	180	280 / 0	230 / 480																	40 / 0	133 / 108	160	180
180	200	290 / 0	240 / 530																	46 / 0	151 / 122	180	200
200	225	290 / 0	260 / 550	115 / 0	170 / 355	115 / 0	100 / 215	72 / 0	50 / 96	46 / 0	15 / 44	46 / 0	29 / 0	46 / 0	33 / 4	46 / 0	60 / 31	46 / 0	79 / 50	46 / 0	159 / 130	200	225
225	250	290 / 0	280 / 570																	46 / 0	169 / 140	225	250
250	280	320 / 0	300 / 630	130 / 0	190 / 400	130 / 0	110 / 240	81 / 0	56 / 108	52 / 0	17 / 49	52 / 0	32 / 0	52 / 0	36 / 4	52 / 0	66 / 34	52 / 0	88 / 56	52 / 0	190 / 158	250	280
280	315	320 / 0	330 / 650																	52 / 0	202 / 170	280	315
315	355	360 / 0	360 / 720	140 / 0	210 / 440	140 / 0	125 / 265	89 / 0	62 / 119	57 / 0	18 / 54	57 / 0	36 / 0	57 / 0	40 / 4	57 / 0	73 / 37	57 / 0	98 / 62	57 / 0	226 / 190	315	355
355	400	360 / 0	400 / 760																	57 / 0	244 / 208	355	400
400	450	400 / 0	440 / 840	155 / 0	230 / 480	155 / 0	135 / 290	97 / 0	68 / 131	63 / 0	20 / 60	63 / 0	40 / 0	63 / 0	45 / 5	63 / 0	80 / 40	63 / 0	108 / 68	63 / 0	272 / 232	400	450
450	500	400 / 0	480 / 880																	63 / 0	292 / 252	450	500

Figure 2: Example of a fits and tolerances chart taken from [5]

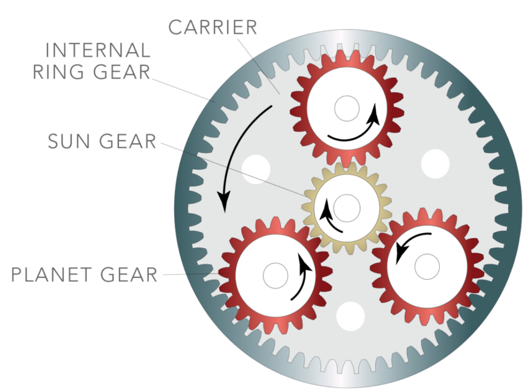


Figure 3: Schematic of a planetary gearbox [6]

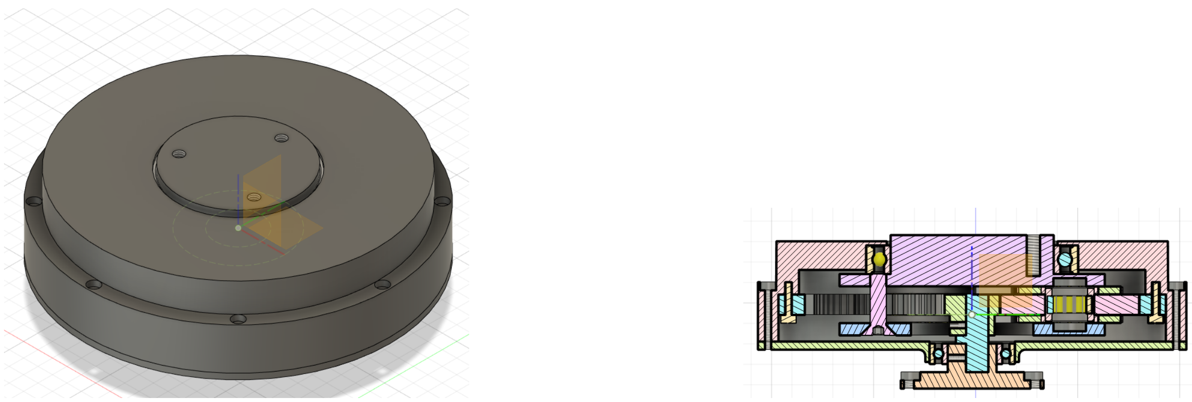
Ring gear teeth	80
Sun gear teeth	16
Plane gear teeth	32
N_p	3
Module	2

Table 1: Gearbox parameters

The number of ring teeth needs to be selected based on the manufacturing capabilities and the final size of the gearbox. The main parameter describing the teeth of the gear is the module. The final diameter of the gear will be equal to the module times the number of teeth. The smaller the module, the smaller the gear and the lower the torque it can carry. Smaller gears are also harder to manufacture on a 3D printer.

The diameter of the motor is equal to 92 mm, thus the outer diameter of the ring gear was set to 95mm. In order to fix the gear to the housing some space is needed, thus the module was set to 1 and the number of teeth to 80 giving a diameter of 80 mm. The gear ratio was set to $G_r = \frac{1}{6}$. These values result in the gearbox parameters summarized in Tab. 1

The carrier was designed in a way to clamp the planet gears between two parts, which increases rigidity. The carrier is also directly connected to the output shaft. The housing was designed in a way to enclose the gearbox. The final design of the gearbox is shown in Fig. 4



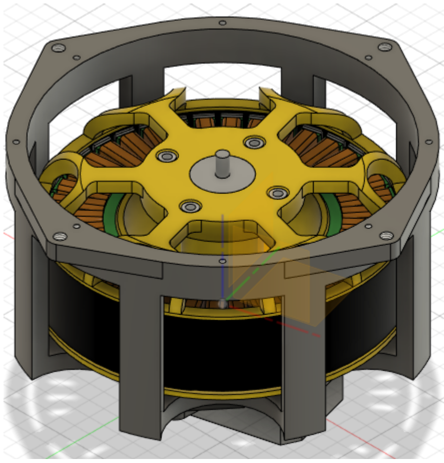
(a) Overview picture

(b) Cross section

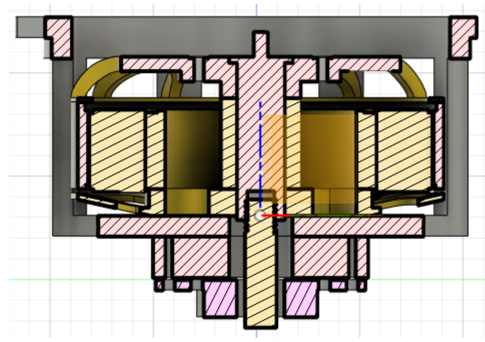
Figure 4: Final gearbox design

3.3 Designing the motor module

The motor is mounted inside a housing with holes to allow air circulation and cooling. Outside of the housing an encoder is attached via an adapter. The encoder is used by the controller to rotate the motor. Fig. 5 shows the final motor module design.



(a) Overview picture



(b) Cross section

Figure 5: Final motor module design

3.4 Electrical parameters

The motor was selected based on three criteria: price, maximal torque, and size. The maximal torque of the engine increases as the voltage constant decreases. It can be estimated as

$$\tau \simeq \frac{8.3 I_a}{Kv},$$

where I_a is the current supplied to the motor, and Kv the voltage constant. A PMSM with a voltage constant equal to 100 and continuous current capability of 58A was selected. With the gearbox this gives a theoretical maximum torque equal to about 29 Nm, which is enough.

ODrive v3.6 was selected as the controller. It is able to supply the motor with 58A. The controller requires an encoder to work in position control mode, the selected encoder was the one recommended by the manufacturer.

4 Manufacturing

We distinguish two different manufacturing techniques:

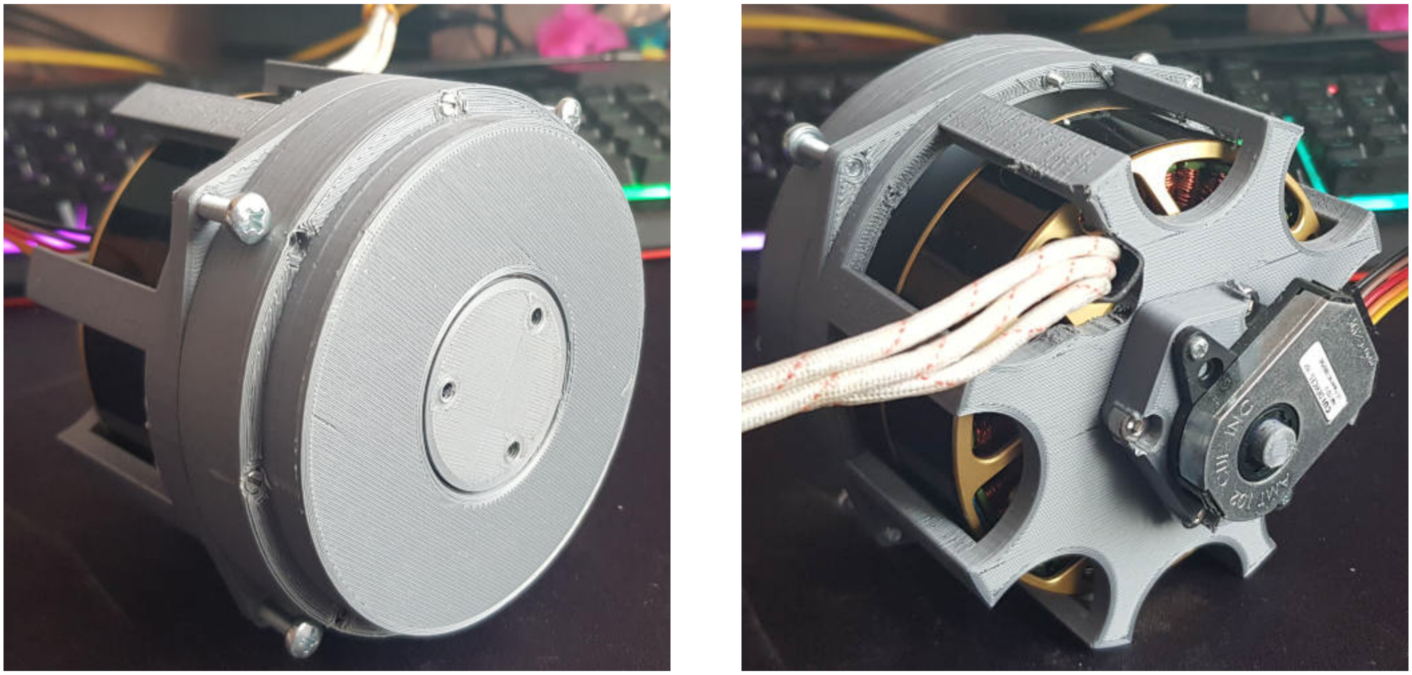
1. additive – material is added to produce the part,
2. subtractive – material is removed to produce the part.

In the case of this project, additive manufacturing was used, namely 3D printing.

The Prusa i3 MK3S+ printer was used to produce the parts. In order to use a 3D printer the model of the object needs to be separated into layers, which the printer will then stack on each other. Special software is needed to prepare the instructions for the printer. In case of this project the `PrusaSlicer 2.3.0` was used. `PrusaSlicer 2.3.0` has an Open-Source license.

All parts, except the shafts, where printed with PLA filament. PLA is a polymer which has a relatively low melting point, is easy to print and has moderate strength and durability. It is well suited for fast prototyping. The shafts where made from an aluminum rod.

The assembly of the gearbox is shown in Fig. 7. Fig. 6 shows the entire actuator.



(a) Front view

(b) Rear view

Figure 6: The entire actuator

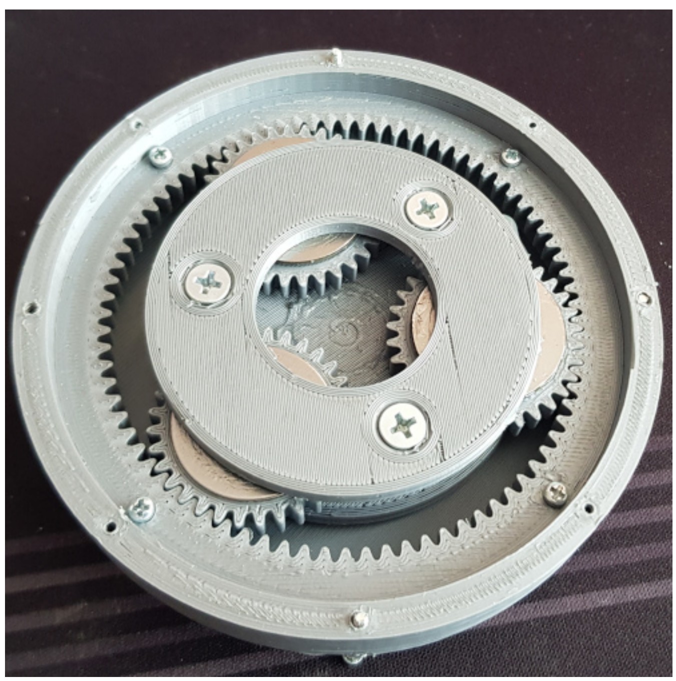


Figure 7: The gearbox

5 Control

The motor is controlled by the ODrive v3.6 BLDC motor controller. The device allows to control both low and high power motors. If the cooling is sufficient it is able to provide 120A to the motor. Additionally, the board is able to control two motors simultaneously. However, in this project only one motor was controlled. Due to this flexibility, the controller needs to be manually configured. This report will not go over the configuration details, as they can be found in the documentation of the device [7].

5.1 Tuning

In some cases where the default parameters do not suffice, tuning of the PID controller is required. It is important to tune the parameters with the load attached to the output shaft. However, the preliminary tests showed that the default tuning parameters perform well. The tuning process is described in the documentation [8].

5.2 Control modes

It is possible to control the motor in three modes:

1. Torque control – the current supplied to the motor is stabilized as the set point, this mode is useful when moving constant loads. Otherwise the motor accelerates to the maximum allowed speed.
2. Velocity control – the angular speed of the motor is stabilized at the set point, this mode can be used for example in a electrical bike.
3. Position control – the angle of the motors output shaft is stabilized at a set point, this mode can be used for example when building a robotic arm.

6 Preliminary tests

To test the actuator, a testing rig was prepared. It is shown in Fig. 8. Three tests where conducted:

- general movement and control test,
- backlash measurement test,
- efficiency measurement test.

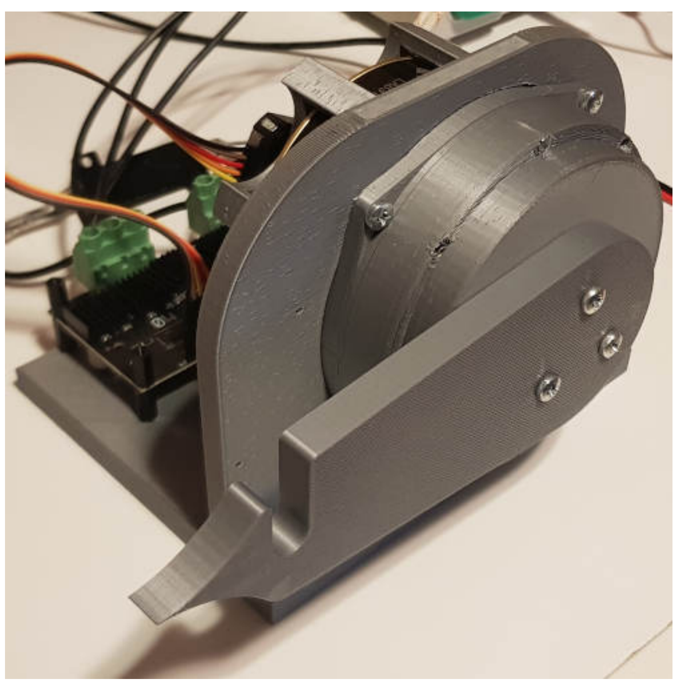


Figure 8: Constructed testing rig

6.1 General movement and control

The main goal of this experiment was to check whether the default tuning parameters are sufficient for velocity and position control.

Firstly, the velocity control was evaluated. The controller was set to velocity control mode and the set point was changed several times. The controller was able to realize these changes without any problem. One such change is shown in Fig. 9.

Secondly, the position controller was tested. The controller was set to position control mode and the set point was changed several times. The controller was able to realize these changes without any problem. Additionally, external disturbances where applied and the controller was able to return to the proper position. The results are shown in Fig. 10.

Based on the results, it can be concluded that the default tuning is sufficient.

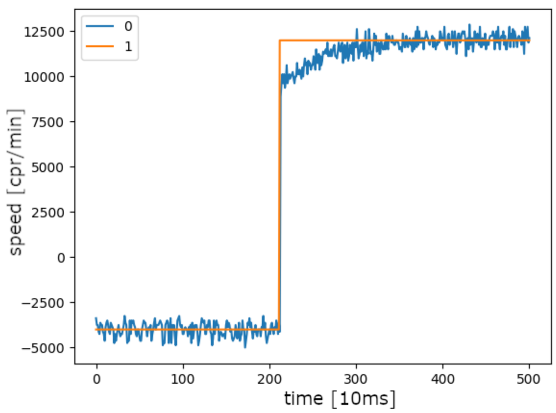
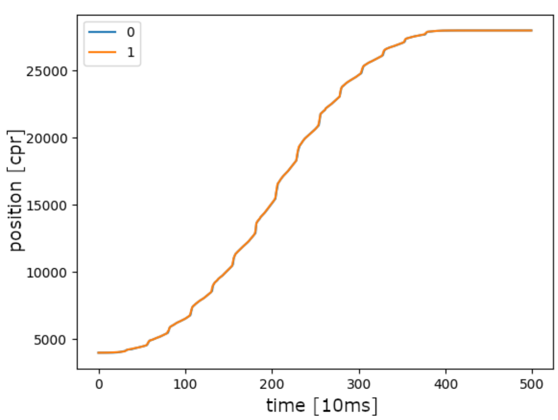
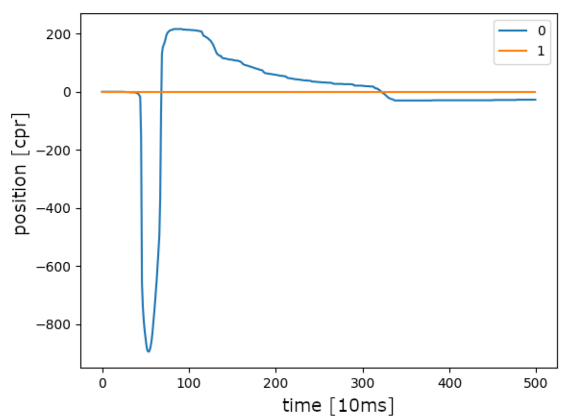


Figure 9: Changing the velocity set point



(a) Changing the position set point with the use of `move_incremental(*)`



(b) External disturbance test

Figure 10: The entire actuator

6.2 Backlash

The backlash was measured as the angle of free movement at a constant set point. A ruler was placed near the point of the arm, then the arm was moved up and the first measurement was taken, next the arm was moved down and the second measurement was taken. Based on them and the distance from the center of the actuator, the angle was calculated

$$\theta = \frac{M_1 - M_2}{d} = \frac{70 - 69}{135} \simeq 0.007rad = 0.4°$$

6.3 Efficiency

The efficiency is measured as the ratio between the output torque and the input torque times the gear ration. However, without sophisticated measuring tools, the torques can only be estimated.

A mass of 4kg was attached at a known distance, equal to 10 cm, from the center of the actuator. Then the maximum input current was measured. The output torque was equal to 4 Nm and the input torque was equal to:

$$\tau_{in} \simeq \frac{8.3 \cdot 8.43}{100} \simeq 0.7Nm,$$

then the efficiency is equal to:

$$\eta = \frac{\tau_{out}}{\tau_{in} \cdot 6} \cdot 100\% = \frac{4}{0.7 \cdot 6} \cdot 100\% \simeq 95\%.$$

As for a 3D printed gearbox, this is high.

7 Summary

The project resulted in producing a working actuator that can be used in a quadruped robot. Tab. 2 contains the parameters of the actuator.

Parameter	Value
Diameter	120 mm
Height	100 mm
Mass	914g
Gear ratio	6:1
Efficiency	95%
Theoretical maximum torque	27.55 Nm
Theoretical maximum speed	400 RPM

Table 2: Actuator parameters

References

[1] Wensing, Patrick Wang, Albert Seok, Sangok Otten, David Lang, Jeffrey Kim, Sangbae. (2017). ”Proprioceptive Actuator Design in the MIT Cheetah: Impact Mitigation and High-Bandwidth Physical Interaction for Dynamic Legged Robots.” IEEE Transactions on Robotics. PP. 1-14. 10.1109/TRO.2016.2640183.

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