Master Degree in

Automation Engineering and Control of Complex Systems

Complex adaptive systems (mod. Biorobotics)

Design of new leg for Quadbot’s

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1. The reason for the new version

The primary version of Quadbot was built as a model with two degrees of freedom on each leg. This creates a relatively simple model, but without any major expansion possibilities. The use of elastic elements allows you to save energy and cushioning during e.g a gallop. The leg model with the elastic elements used was also the basis for the diploma theses realized on DIEEI UNICT. In order to develop the project, among others implementation of a new control algorithm based on CNN-based CPG, it was decided to design a new leg, with 3 DOF and elastic / spring elements.

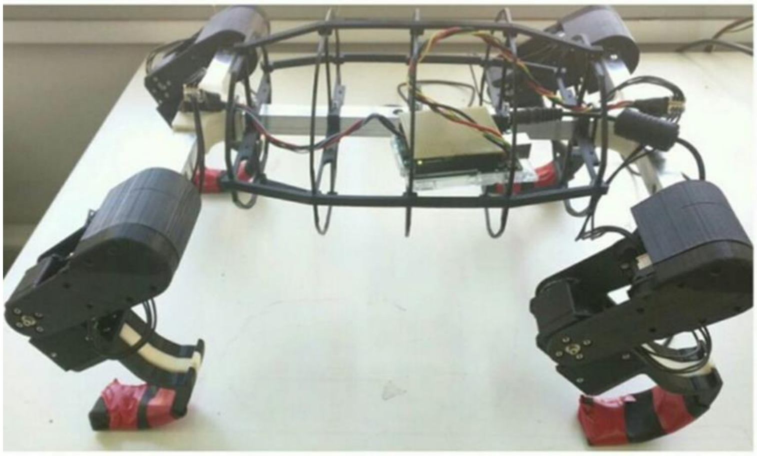


Figure 1 Primary version of Quadbot

2. Nature and technics inspirations

The design of the new leg was based on Boston Dynamics robot designs, mainly SpotMini, and analysis of the construction of the horse's hind leg.

Figure 2 SpotMini by Boston Dynamics

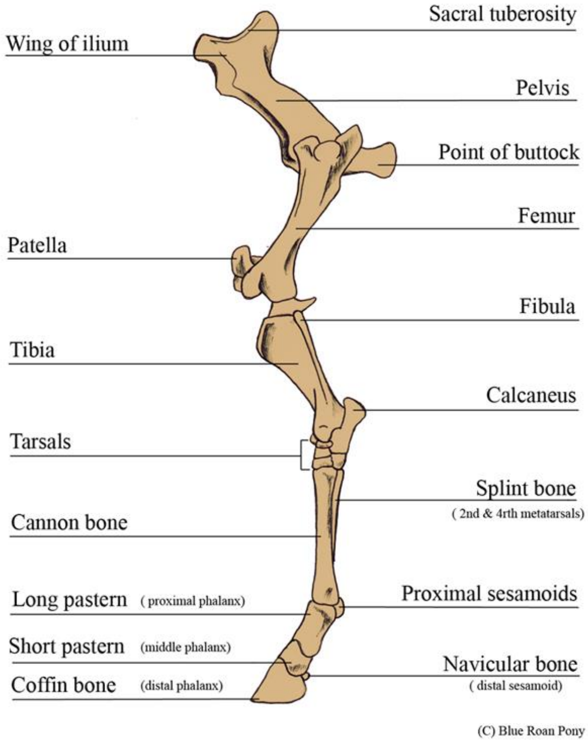


Figure 3 Anatomy of horse hind leg

3. Kinematics of leg

   Kinematics of leg has been described by using Denavit-Hartenberg notation and it's:

Joint nr.	α	d	A	θ
1	-90°	0	L1	β1
2	0	0	L2	β2
3	0	0	L3	β3

   Where:

   β1, β2, β3 – angles between each joint during work

   L1,L2,L3 – distances between each joint

4. Project realization

   The project was carried out in the SolidWorks program, and ready-made models were prepared for 3D printing on the MakerBot Replicator 2X printer.

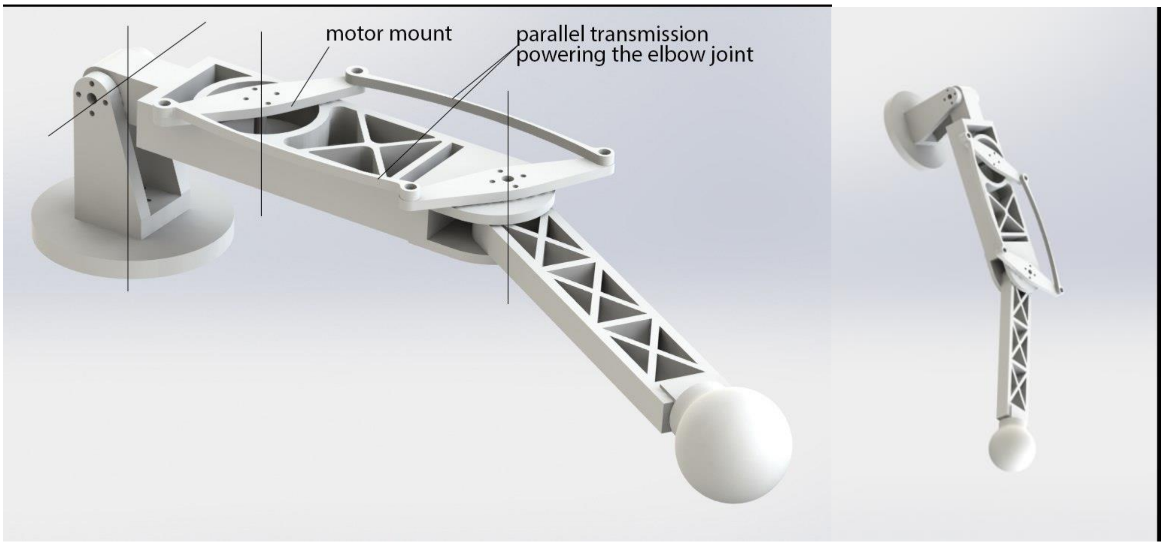


Figure 4 1st version of leg

The project originally planned to use BLDC motors used in camera stabilizers, which, in contrast to standard 3-phase BLDC (used, among others, in drones) are characterized by a smaller range of rotational speeds, but with higher torque and easier control.
To maintain the stiffness of the structure, proper weight distribution and the possibility of using elastic elements, it was decided to simulate the biceps and triceps by moving the tibia-part motor and using a special transmission system.
After designing the first version, it turned out that the engines selected at the time had too little lifting capacity in relation to the predicted mass of the robot and the leg itself. It was decided to reconstruct the femur part to fit the most powerful engines available on the market with a lifting capacity of 1900g ,which is Turnigy HD 5208.
Also the new design of tibia part has been designed for the purpose of stiffness and easier printing.

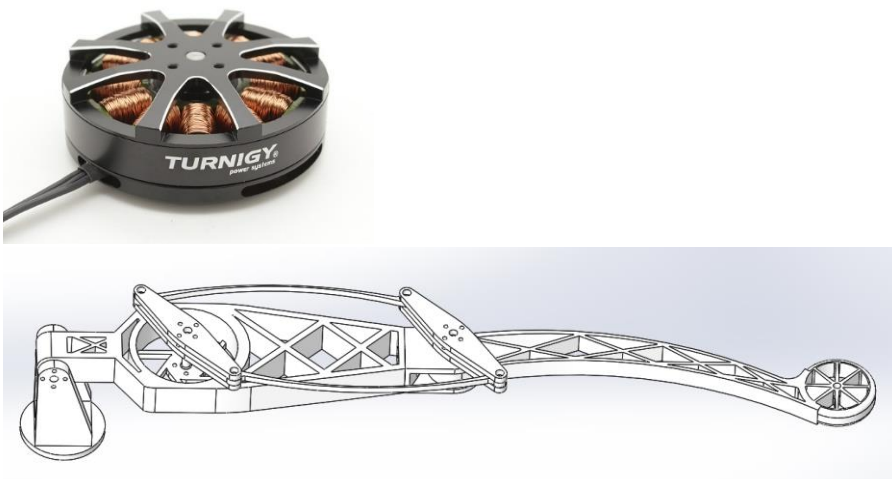
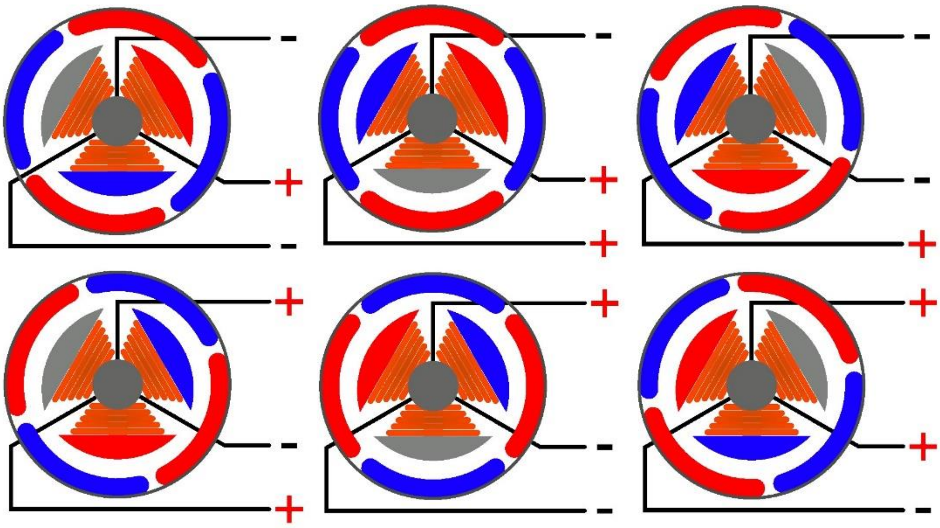


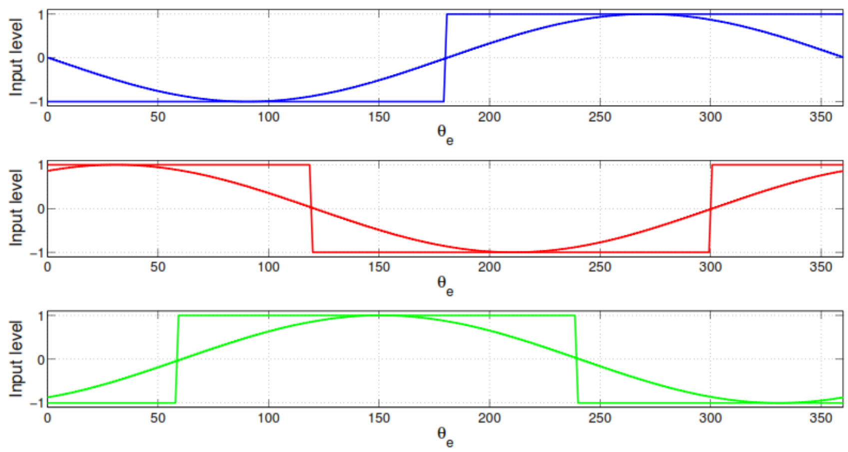
Figure 5 Turnigy HD 5208 and 2nd version of leg

4.1 BLDC Control

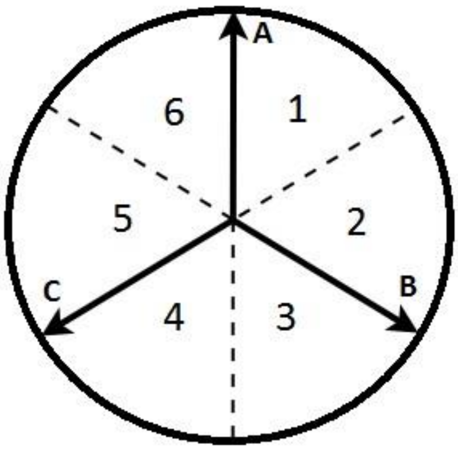
A brushless DC motor consists of a rotor and stator, where the outer circle is the rotor and the inner part is the stator. The rotor consists of permanent magnets, where the blue and red colour represent the north and south pole respectively. The stator has in this case three electromagnets which differ in polarity by alternating the current, a so called three-phase motor. Typically the three electromagnets differ a 120 degrees in phase. Figure below shows the rotor turning counter clockwise while the electromagnets are changing polarity. By changing the polarities at a constant frequency, the rotor will turn with a constant speed.



The motor which is chosen has fourteen poles, which means that one electrical rotation is one seventh of a full mechanical rotation. Figure below shows only high and low signals, which would mean that each electrical rotation consists of six steps. The amount of steps can be extended when using PWM signals. A PWM signal can take a value between zero and 255, which means sending a voltage at zero per cent or 100 per cent respectively.



In Figure 3.3 one electrical rotation is divided in six parts, where A, B and C are the voltage vectors. If voltage A is set to a PWM value of 255 and both B and C are kept zero the resulting vector is pointing in the A direction. To operate in area one, voltage A is set to the maximum PWM value while B can be varied and C is turned off. Looking at table below shows which phases are used to operate in a certain area.



	PWM_A (PWM value)	PWM_B (PWM value)	PWM_C (PWM value)
Area 1	255	X	0
Area 2	X	255	0
Area 3	0	255	X
Area 4	0	X	255
Area 5	X	0	255
Area 6	255	0	X

Using this method means that every electrical rotation can be divided into six parts and subsequently these parts can be divided into 255 steps. Eventually every electrical rotation thus consist of 1524 steps (eliminate double scenarios) which make up one seventh of a mechanical rotation which thus consist approximately of 10.660 steps. Each step making up approximately 0.03 mechanical degrees. The exact PWM value to create a certain resulting vector can be determined by using geometric functions if the operating area is known.

$$\begin{aligned}
&\text{Area 1:} \quad \mathrm{PWM_B} = \mathrm{round}\left(\frac{\tan(\theta_e)\mathrm{PWM_A}}{\sin(\frac{2}{3}\pi) - \cos(\frac{2}{3}\pi)\tan(\theta_e)}\right) && 0 \leq \theta_e \leq 60, \\
&\text{Area 2:} \quad \mathrm{PWM_A} = \mathrm{round}\left(-\frac{\tan(\theta_e)\cos(\frac{2}{3}\pi)\mathrm{PWM_B} - \sin(\frac{2}{3}\pi)\mathrm{PWM_B}}{\tan(\theta_e)}\right) && 60 \leq \theta_e \leq 120, \\
&\text{Area 3:} \quad \mathrm{PWM_C} = \mathrm{round}\left(\frac{\tan(\theta_e)\cos(\frac{2}{3}\pi)\mathrm{PWM_B} - \sin(\frac{2}{3}\pi)\mathrm{PWM_B}}{\sin(\frac{4}{3}\pi) - \cos(\frac{4}{3}\pi)\tan(\theta_e)}\right) && 120 \leq \theta_e \leq 180, \\
&\text{Area 4:} \quad \mathrm{PWM_B} = \mathrm{round}\left(\frac{\tan(\theta_e)\cos(\frac{4}{3}\pi)\mathrm{PWM_C} - \sin(\frac{4}{3}\pi)\mathrm{PWM_C}}{\sin(\frac{2}{3}\pi) - \cos(\frac{2}{3}\pi)\tan(\theta_e)}\right) && 180 \leq \theta_e \leq 240, \\
&\text{Area 5:} \quad \mathrm{PWM_A} = \mathrm{round}\left(\frac{\sin(\frac{4}{3}\pi)\mathrm{PWM_C} - \tan(\theta_e)\cos(\frac{4}{3}\pi)\mathrm{PWM_C}}{\tan(\theta_e)}\right) && 240 \leq \theta_e \leq 300, \\
&\text{Area 6:} \quad \mathrm{PWM_C} = \mathrm{round}\left(\frac{\tan(\theta_e)\mathrm{PWM_A}}{\sin(\frac{4}{3}\pi) - \cos(\frac{4}{3}\pi)\tan(\theta_e)}\right) && 300 \leq \theta_e \leq 360(0).
\end{aligned}$$

Note that the PWM value in the second part of the equations is at its maximum value of 255 but this is left out to make the equations more universal.

It was found out that unfortunately none of the manufacturers of BLDC motors used in gimbals does not provide engine characteristics (eg maximum torque), which makes the use of such engines in the project useless. What's more, the following problems have appeared:

- the design is too large for the existing frame and for the 3D printer
- the original version of the shoulder design has limitations when it comes to movement

All the above issues were resolved in the last version of the project, in which the following changes were made:

- BLDC motors were replaced with Dynamixel MX-28 servomotors, originally used in the first Quadbot version
- The whole project was adapted to the printing possibility of MakerBot printer
- the shoulder was rebuilt to avoid problems with limited mobility

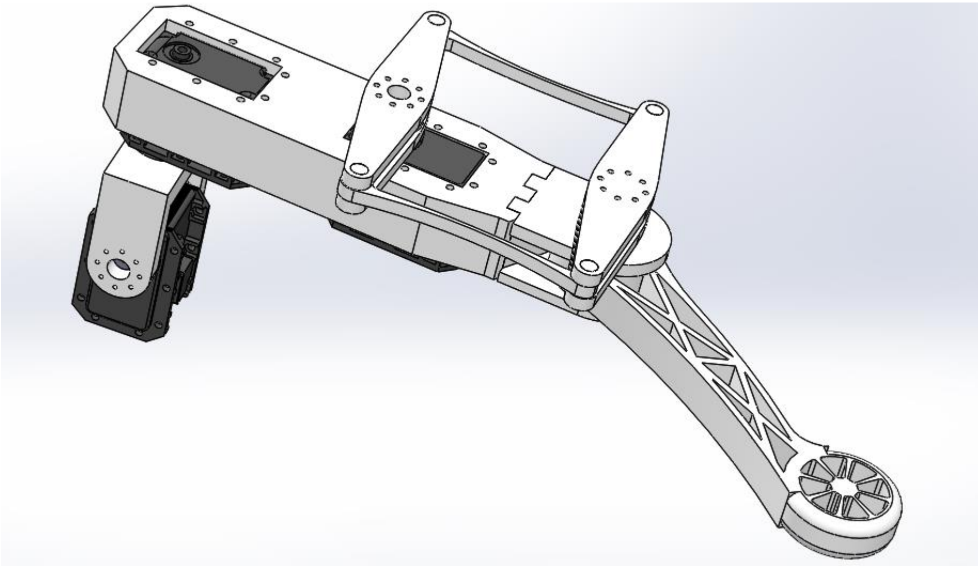


Figure 6 Final version of leg

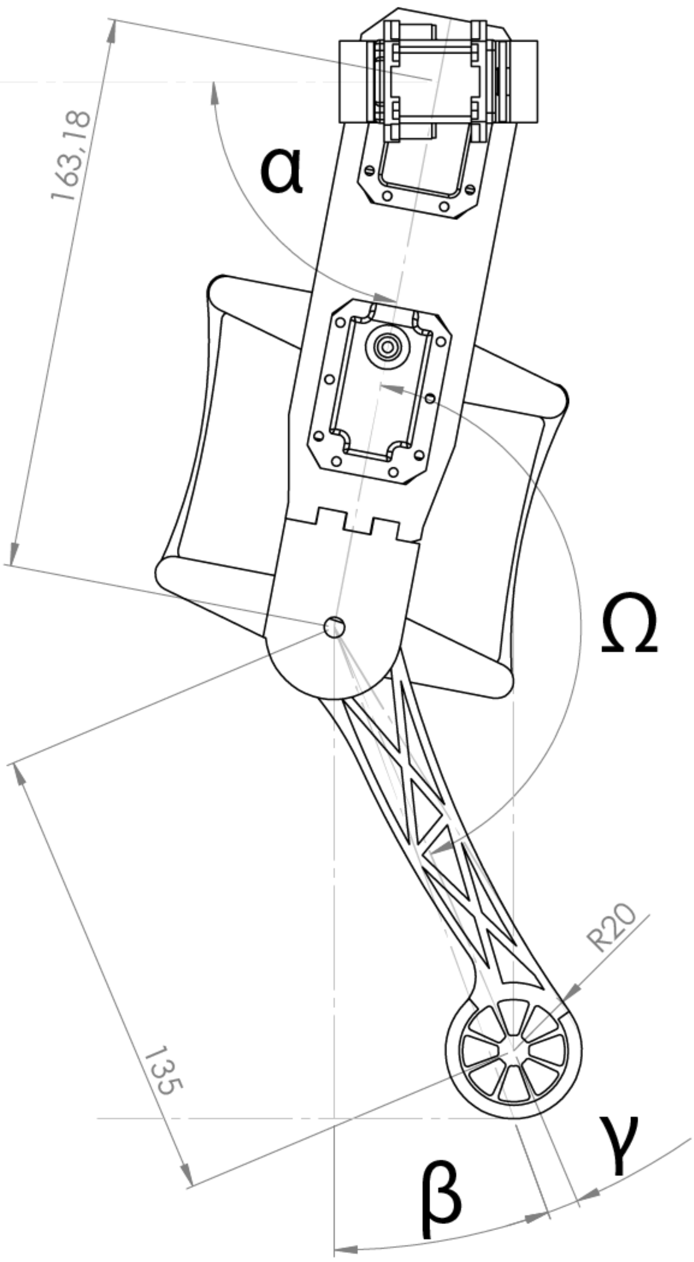
5. Payload calculation

The maximum load (or the maximum force that one leg can generate) is calculated based on the maximum torque generated by the MX-28 engine, the size of the individual leg components (length) and the achievable range of motion. The calculations are divided into two parts:

- force generated in movement in a straight line (eg. Waking up, gallop)
- force generated during tilting of the robot in its axis of symmetry (along the spine)

The force generated in the first case was calculated as the component perpendicular to the earth of the sum of forces generated by the engines per individual element (joint).
Maximum torque (described as M) generated by MX-28 is 31.6 kg/cm.

For this purpose, a layout of forces should be drawn, as shown in the graphic below:



Individual angles that can be achieved by each joint leg are included in the values:

$\alpha = 0 - 90°$
$\beta = 0 - 73°$
$\gamma = 0 - 8°$
$\Omega = 56 - 180°$

The relationship between the beta and gamma angle, which results from the change of the contact point between the leg and the ground, should be taken into account, which in turn results in a change in the actual length of the arm affected by the moment. This is described by function:

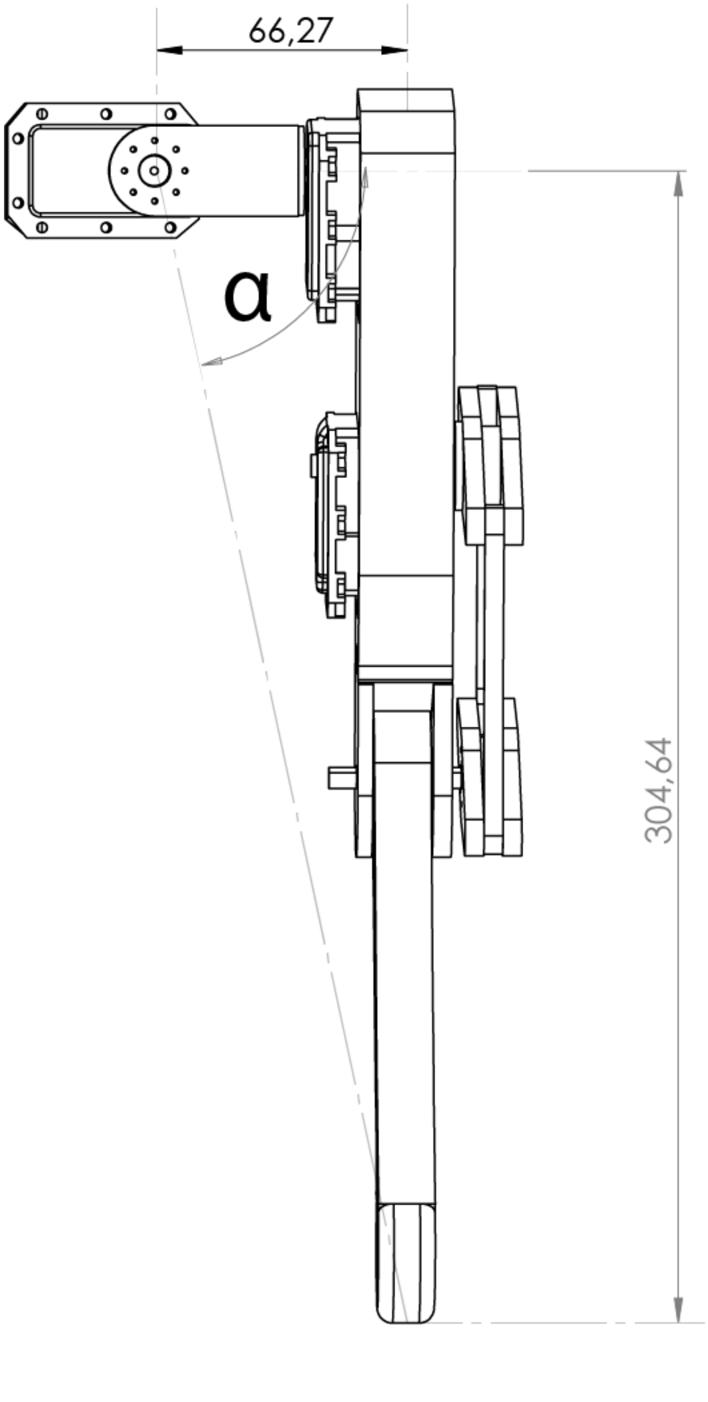
$$\gamma = f(\beta) = 0{,}11214 * \beta$$

Based on the information gathered, the formula for the generated force:

$$F = \frac{M}{16{,}31} * sin\alpha + \frac{M * 0{,}5\sin(2\beta)}{13{,}5 * \sin(1{,}11214 * \beta)}$$

Which for base configuration is around 3.5 kg

In the case of a tilting movement, the layout is as follows:



Where alfa is equal:

$$\alpha = \pm 45°$$

The length of the force arm depends on the deflection of the individual leg members. For calculations, a range of + 45 degrees from the axis perpendicular to the ground was assumed.

The range of arm length is:

$$L = 180 - 304\, mm$$

The radius that the moment is calculated from the Pythagorean theorem I is:

$$R = 192 - 311\, mm$$

On this basis, the range of forces that can be generated by the leg is equal:

$$F(R, \alpha = 45°) = \frac{\sqrt{2}}{2} * \frac{M}{R} = 0{,}71 - 1{,}16\, kg$$

As you can see, the force in the tilting movement is smaller than when moving in a straight line And this should be taken into account when selecting elements fastened on the robot (eg batteries or control), the sole leg with the assumption of printing with 100% filling weighs 233g.

6. Spring elements
   For the project, 3 different versions of elastic elements were designed for use as a transmission between the motor and the tibia part. Unfortunately, SolidWorks was not able to perform the analysis allowing to determine the elasticity coefficient and only the experimental method with the use of an actuator and a deflection meter remains.

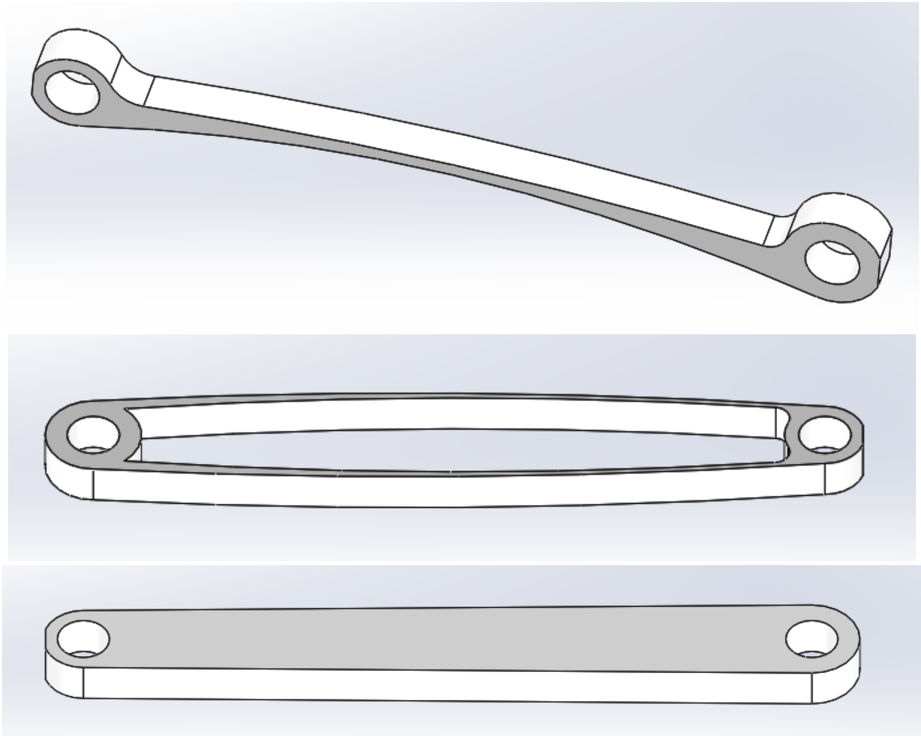


Figure 7 Different version of spring (single, double, rigid)