



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

DESIGN OF A COMPLIANT SPINE FOR THE LOCOMORPH QUADRUPED ROBOT

Semester Project

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Abstract

Since a long time, animals are studied to base robot mechanisms on real animal design. Since the beginnings of the field, many studies have been performed on animal legs, in our case for quadruped robot legs. Among many studies, only a few discuss the design of an improved spine. In this project we want to study a possible improvement on quadruped robot locomotion in terms of displacement speed and energy usage, by using an actuated and compliant spine. The main tasks of this project have been the design of a spine based on existing studies on animals, in particular the cheetah, and also on existing mechanisms for actuation and compliance. After having chosen the ideas, we have dimensioned the system and physically built it. Some analysis have been performed on the resulting structure, like the deformation (in our case of a maximal value of 1mm).

Finally, as a future work, we will have to test this new design of the spine and compare the performance results mentioned above with the ones of a quadruped robot with a rigid spine.

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1 Introduction

Many studies have been performed up to now on quadruped robot locomotion and in particular on how to optimize their energy usage and increase speed. This work is essentially based on the leg mechanism to optimize the movement, but only few studies exist on spine morphology and actuation aimed at increasing the performance. During this project we will discuss first how we could theoretically improve the performance and then we will find a mechanism solution, dimension it and build it so that the predictions of increased performance are confirmed.

2 Project definition

2.1 Analysis of nature

The first step in this project was to look at the spine movement of animals during motion. We focused in particular on the spine movements of a cheetah since it is the fastest running animal in the world. We have found, thanks to the studies of M. Hildebrand on "Motions of the running cheetah and horse" [1], that the spine bends and unbends during motion as we can see in figure 1.

The two main characteristics of this spine are:

- Spine bending increases the maximal length between front and rear legs.
- Spine compliance permits to have a flexible system, able to absorb energy during shocks and to have a better energy usage during motion.



Figure 1: Cheetah spine bending during running [2].

2.2 Project goal

During this project we want to implement a spine based on the main characteristics of a cheetah spine into the Locomorph robot by replacing its rigid actual system, as we can see in figure 2. The main goal of this project is to:

- Conceive a compliant and actuated spine for a quadruped robot.
- Build the mechanism and implement it into the Locomorph robot.

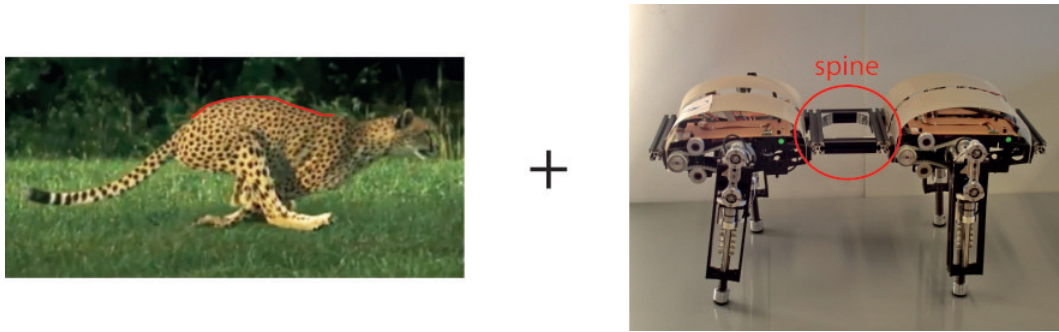


Figure 2: Left: Cheetah's bendable and compliant spine [2]. Right: Locomorph robot with actual rigid spine by the EPFL Biorob Laboratory.)

- Compare the results between the actuated and the rigid spine during motion for speed variation and energy consumption.
- Optimize the final mechanism to have better speed and reduce energy losses.

2.3 Boundary conditions

In this section we are going to define the main characteristics that our mechanism needs to fulfill.

Robot movement

- Operation environment : indoor/outdoor, irregular terrain/flat terrain
- Movement : straight line (no spine steering) because we just want to analyze movement performance for the spine degree of freedom seen previously in the cheetah spine movement analysis (section 2.1)
- Movement type : bound, trot
- Speed level goal : 2 Hz
- Max spine bending amplitude: 30° which is the typical spine bending angle of a cheetah [3].

Desired spine properties

- Actuated spine
- Design a spine that can be torque-controlled.
- Springs (compliance) and actuation (bending mechanism) in the spine must be in series.
- Configurable: spine compliance can be varied ("Morphosis")

Global characteristics

- Lightweight and optimum weight distribution
- Minimize energy consumption by storing the energy in the mechanism and releasing it at an optimal time.
- Security: protect mechanism from environment to avoid damage to the system (e.g: during a collision), by protecting the main fragile parts.

2.4 Motivations

Previous studies of M. Hildebrand have denoted some advantages of having a bendable and compliant spine for locomotion, which have influenced our project direction. M. Hildebrand says himself that: ‘The flexibility of the spine can be likened to a spring which has energy storage capabilities. In this mode, the articulated spine can decrease energy and power requirements’[5] p 11.

In his publications he enumerates a list of major contributions to flexion and extension of the back [5] p 12. :

- As the swing of the limbs increases, the distance covered during the aerial phase is increased.
- With the combination of spine muscles and limb muscles working concurrently, the limbs move faster than a single group of muscles working alone.
- The spine adds to the maximum forward extension of the legs, increasing the maximum backward acceleration of the limbs before they strike the ground.
- The spine aids in moving the body forward in an inch-worm fashion.
- The spine reduces the relative forward velocity of the girdles when their respective limbs are moving the body.

Additional studies by Hildebrand [3] showed an increase in speed of 10% due to the flexion/extension of the spine in the cheetah (see sketches in figure 3).

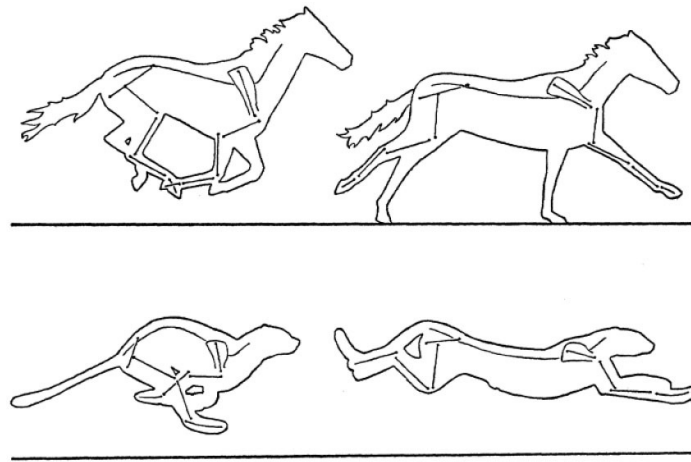


Figure 3: Hildebrand’s sketches of flexion / extension in spine of horse and cheetah[3].

2.5 Series vs parallel actuations

As discussed earlier, one of our main goals is to store the actuator energy in the flexible part so that it can be released at the right moment to minimize the energy consumption and maximize the movement efficiency. Thus it is really important that the actuation used to bend the spine acts in series (figure 4a) with the elastic part of the spine. This is essential because if these two elements are placed in parallel (figure 4b), the elastic part will work against the actuation, causing a big loss of energy.

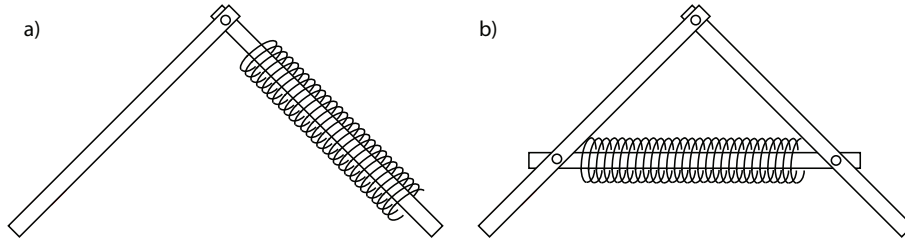


Figure 4: a) Systems in serie. b) Systems in parallel

2.6 Existing work

Even if the research on actuated spine has not been extensively developed yet, we can consider some designs to start from.

MIT's Planar quadruped robot with articulated spine: [4] p.20-22

Pictures 5 and 6 show the MIT Planar quadruped robot with its articulated spine. The goal of their spine was to increase the effective leg length, storing/transferring energy, and providing auxiliary power to legs.

In figure 6 b) we can see the kinematic configuration of the robot. The circles represent revolute joints and each leg contains a single actuated prismatic joint in series with a pneumatic airspring. The mechanism is actuated by electronic servo-motors and hydraulic actuation.

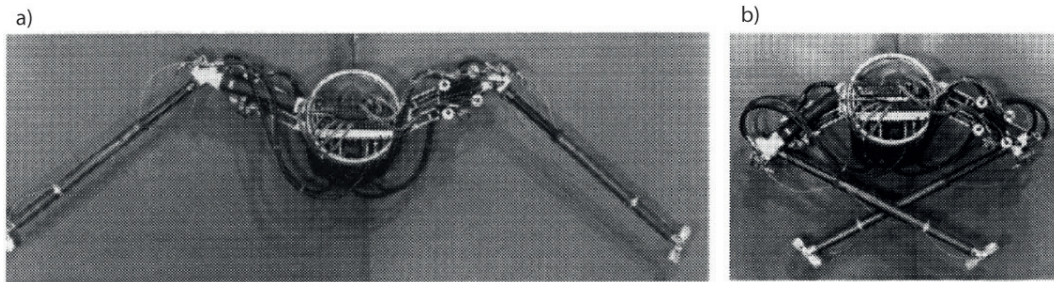


Figure 5: MIT's Planar quadruped robot with articulated spine pictures.

BISAM robot: [5] p.18-19

Picture 7 show the BISAM robot. "The articulation in the spine was investigated using a biologically inspired adaptive control concept. Subsequent research with this robot focused on learning gaits using advanced reinforcement learning techniques for posture control during movement."

SQ43 robot: [5] p.19-20

Picture 8 show the SQ43 robot. This robot has a multi-segment spine. The spine was implemented on the quadruped robot by using a genetic algorithm as the motion generator. The motivation for this articulated spine is to be able to perform a tasks in many different environments. Another great advantage of this solution is to be able to accept harsh forces by applying the load along its length rather than at a localized point.

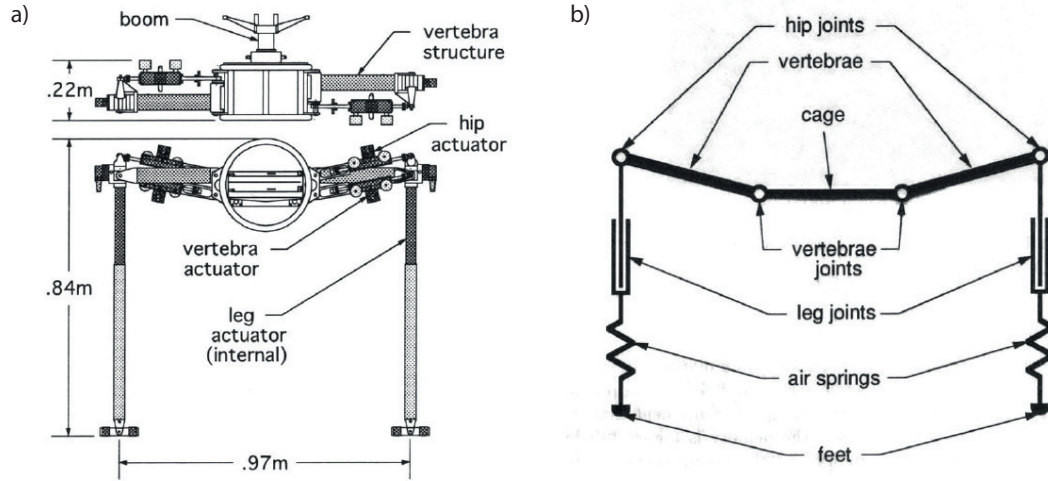


Figure 6: MIT's Planar quadruped robot with articulated spine schemes.

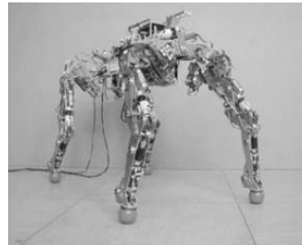


Figure 7: BISAM robot.

3 Brainstorming on mechanical solutions

3.1 Bending mechanism

In the following, different possible solutions for the actuation of the bending mechanism are sketched and discussed. This different actuation techniques are based from the EPFL course "Bases de la robotique" [6]

DC motor with gears:

In this solution, illustrated in figure 9, one gear is attached to the motor axis and the other one is fixed on the rotation axis of the bending structure. The main problem of this mechanism is that, since the gear fixed on the motor axis is directly in contact with the gear which is attached



Figure 8: SQ43 robot.

to the structure, shocks on the structure could easily damage the motor axis. That is why it is probably more interesting to have an interface between them.

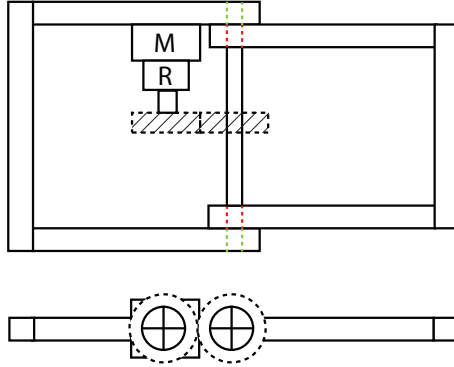


Figure 9: DC motor with gears, with motor (M) and gearbox (R).

DC motor with gears and timing-belt:

In this solution (figure 10), a timing belt is attached to the motor axis and to the structure bending axis. The rotation of the timing belt is foreseen to make the mechanism bend. Advantages of this solution is that shocks can be absorbed by the timing belt, and that the reduction factor of the motor speed can be adjusted using a gear ration between the two gears. The drawback of this solution is that it is essential to have a system that keeps the timing belt constantly under tension. An advantage of this solution is that the amplitude of movement can easily be changed the by making the motor to rotate up to the desired position.

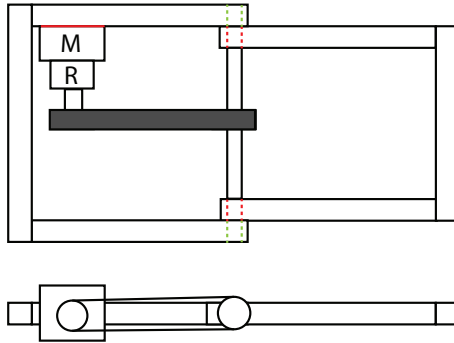


Figure 10: DC motor with gears and belt with motor (M) and gear (R).

DC motor direct axis on spine:

In this solution, that can be appreciated in figure 11, two motors are directly fixed on the spine bending axis. The drawbacks of this solution are that shocks on the spine will directly affect the motor axis, that it is not possible to manage the speed reduction factor other than through the gearbox and that two motors are present, so that the speed will be increased even if they are smaller mainly because of the electronics, the gearbox and the fixing mechanism.

DC motor with crank-slider:

In this solution (see figure 12), the motor acts on the structure bending axis using a crank-slider. Disadvantages of this solution are that the torque on the motor changes depending on the position of the crank-slider during rotation and that attention has to be paid to avoid collisions with

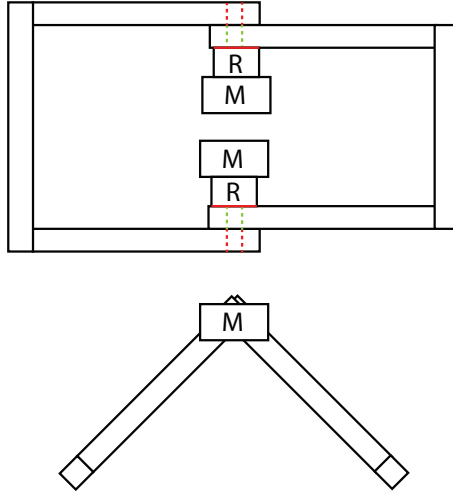


Figure 11: DC motor direct axis on spine, with motor (M) and gearbox (R).

another part of the structure. We will also have to pay attention to build a structure that is sufficiently resistant to avoid breaking because of the lever effect. The advantage of this solution is that the motor always rotates in the same direction. The advantage of this solution is that the motor doesn't have to pass by the commutation phase where it has to decelerate, change direction and accelerate again, which would be a loss of time. Another advantage is that since the motor rotates at constant speed, torque is smaller than if it had to accelerate.

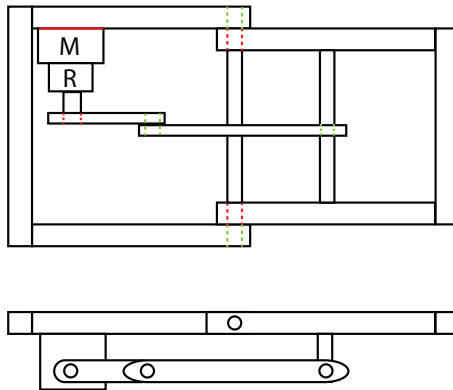


Figure 12: DC motor with crank, with motor (M) and gearbox (R).

DC motor with worm-gear:

This solution (figure 13) uses a motor with a worm gear to bend the structure. The disadvantages of this mechanism are that the worm-gear is a slow mechanism which is normally used for precision displacements and that the worm-gear mechanism cannot be brought back using a spring. This kind of actuation will rather be used, for example, to regulate mechanism stiffness or amplitude.

DC motor with parallelogram system:

This solutions (figure 14) works according to the parallelogram principle. The second arm has a slider sliding on a point attached to the first arm. When the slider is moved by the motor, the second arm will start to bend. The disadvantage of this solution is mainly that the torque needed to bend the structure will be really larger than in other bending mechanisms.

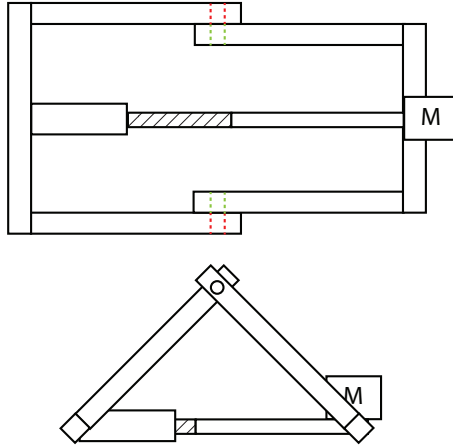


Figure 13: DC motor with worm-slider.

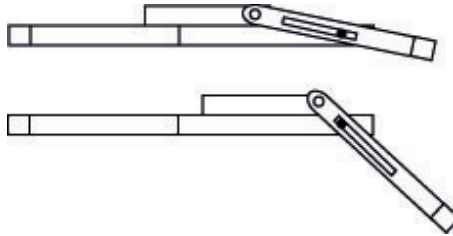


Figure 14: DC motor parallelogram system.

3.2 Compliance mechanism

In the following some sketches are presented, of different possible solutions for mechanism stiffness.

Two springs, one on each segment:

This solution (figure 15) has linear springs on the segments of the spine. To change the stiffness of the mechanism we will have to vary the length of the springs by moving the two sliders. The disadvantage of this solution is that the spring will not be compressed but also bend which is not something optimal to do with linear springs..

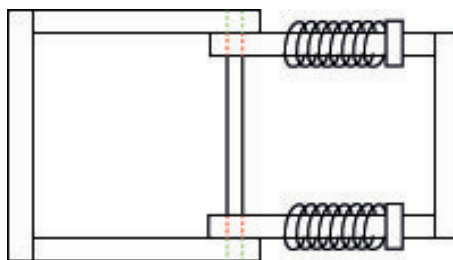


Figure 15: Two springs, one on each segment.

Arc spring: [7] p.89

In this solution the structure touches a leaf-springs (on the left of figure 16). Cables are attached to the extremities of the leaf-spring and are also attached to a motor. When rotating the motor, the leaf-spring get preconstraint and the structure becomes more rigid.

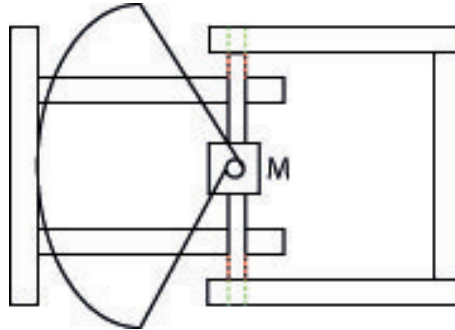


Figure 16: Arc spring.

Central leaf spring: [7] p.89

In this mechanism (figure 17) a leaf-spring is used for the flexibility of the system and moving the 2 sliders results in preconstrainting the spring so that the structure becomes more rigid. The problem of this solution is that the bending mechanism works in parallel to it. The leaf-spring could be used however in other ways that could be interesting to explore.

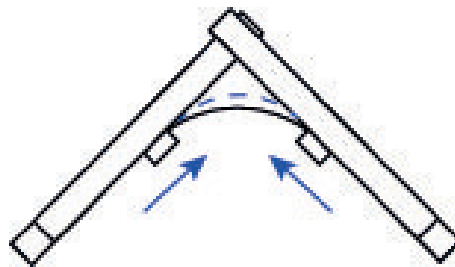


Figure 17: Central leaf spring.

Oval spring:

In this solution (figure 18) a linear spring with an oval section is used. By rotating the spring along the axis, the spring flexibility to bending can be changed. The problem of this solution, as for the one of the linear spring, is that it is not optimal to bend a linear spring.

Central spring:

The principle, illustrated in figure 19, is the same as for the oval spring. The disadvantage is as we said that the linear spring is not meant to be bent.

Springs in triangle: [7] p.86

In this solution (figure 20) the structure is attached to a gear that is kept in position by a belt. At the other two extremities of the belt two motors are rotating in opposite directions. By rotating they pull on the belt, whose effect is to compress the two left springs, the third one becoming elongated to keep the belt under tension. The disadvantage of this mechanism comes from its complexity and its number of actuators.

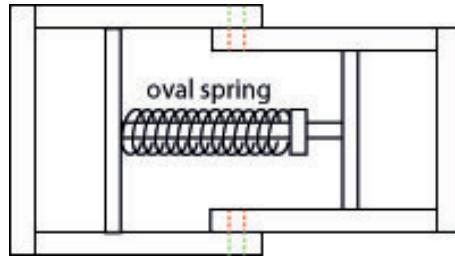


Figure 18: Rotating oval spring.

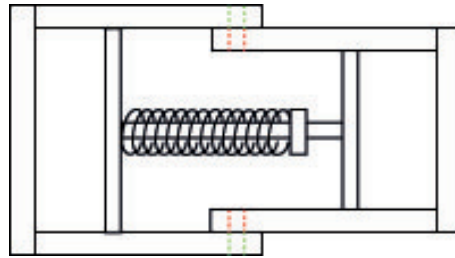


Figure 19: Central spring.

4 Main possible solutions

By reanalyzing the brainstorming previously developed, we decided to compare two main mechanisms:

1. The use of a DC motor with a timing belt for the bending mechanism and a leaf-spring for the flexibility of the structure.
2. The use of a DC motor with a crank-slider for the bending mechanism and a linear spring for the flexibility of the structure.

These two solutions are discussed below, and as a conclusion, one of the two mechanisms is chosen.

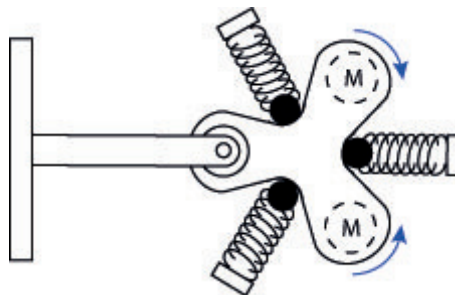


Figure 20: Springs in triangle.

4.1 Mechanism 1: DC motor, timing-belt and leaf-spring

4.1.1 Bending mechanism

In figure 21 we can see a scheme of the mechanism. Basically the mechanism is divided in two parts: the front part and the back part of the spine. These two parts are connected by a pivot liaison (in the center of figure 21 a) where the main rotation of the spine takes place. A DC motor and a gearbox are fixed to one of the two parts of the spine and they actuate the spine bending by rotating a timing-belt attached to the axis of the pivot liaison. An additional feature of our mechanism is the leaf-spring (in the center, dividing the two parts of the mechanism), that is used to store the energy of the motor and to release it at the right moment during the movement to optimize the energy usage.

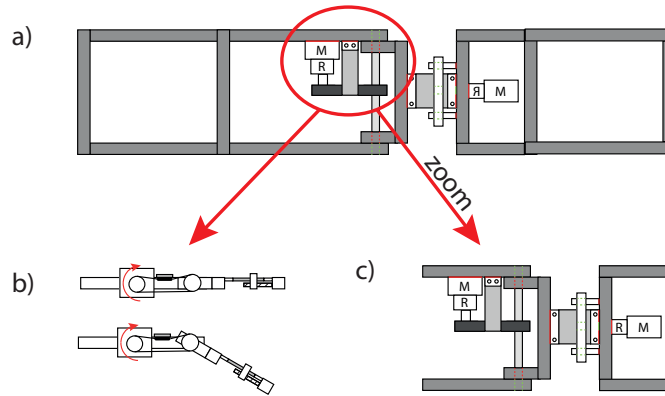


Figure 21: Principle of the bending mechanism

In figure 22 we can observe the different phase of this mechanism's movement :

- a) Stable position
- b) c) d) Energy storage phase: Leaf-spring stores energy (bending)
- e) Energy release phase: Leaf-spring releases energy (unbending)

4.1.2 Changing mechanism stiffness

Since we want to have a modular robot, we added a system that permits to change the mechanism stiffness. This is done by varying the pre-constraint of the leaf-spring. To do that we are going to vary the length of the leaf-spring by moving a slider on it as illustrated in figure 23.

There are two main ways to move this slider:

- Manually: for example by rotating a screw on an axis to make the slider to move.
- Automatically: using a motor and a worm slider

4.2 Mechanism 2: DC motor, crank-slider and linear spring

4.2.1 Bending mechanism

In figure 24 we can see a scheme of the second possible mechanism using a crank-slider for the bending motion and a linear-spring for the rigidity.

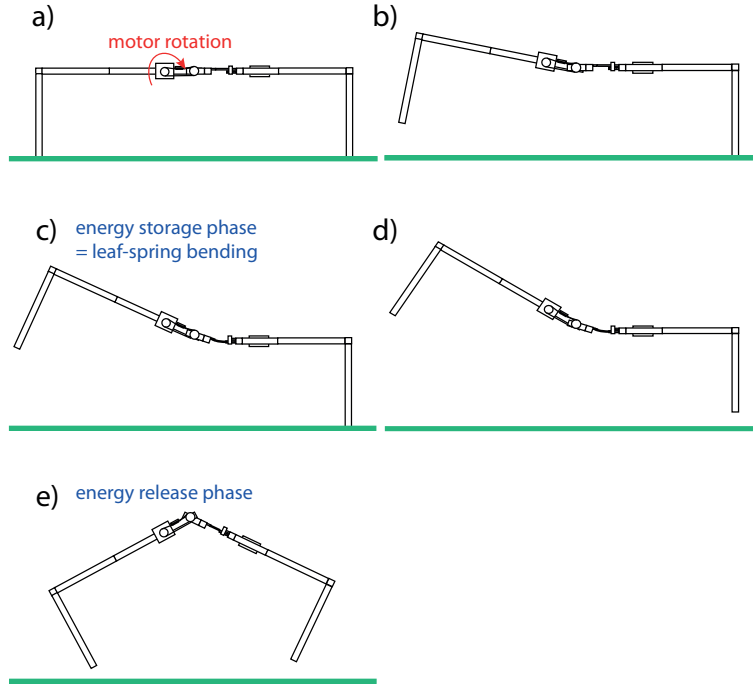


Figure 22: Phases of mechanism movement.

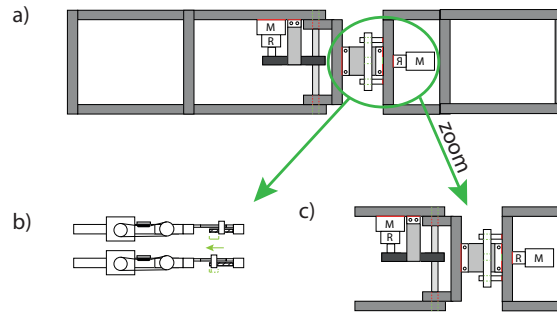


Figure 23: Principle of the mechanism stiffness variation

Basically the mechanism is divided in two parts: the front and the back part of the spine. These two parts are linked together by a pivot liaison (in the center of figure 24) where the main rotation of the spine occurs.

A crank-slider actuated by a DC motor and a gearbox are attached to one of the two parts of the spine and pushes/draws the second part of the spine, making the whole structure bend.

An additional feature of this mechanism is that the point where the crank-slider pushes the segment of the spine is a slider, and at the two sides of the slider we have placed two springs. The purpose of this is to store the energy of the motor and to release it at the right moment during the movement to optimize the energy usage. The two sliders will be used to modify the rigidity of the structure by preloading the springs.

In figure 25 we can find the different movement phases of this mechanism:

- a) Stable position
- b) Energy storage phase: Spring 1 stores energy (shortened), spring 2 (elongated)

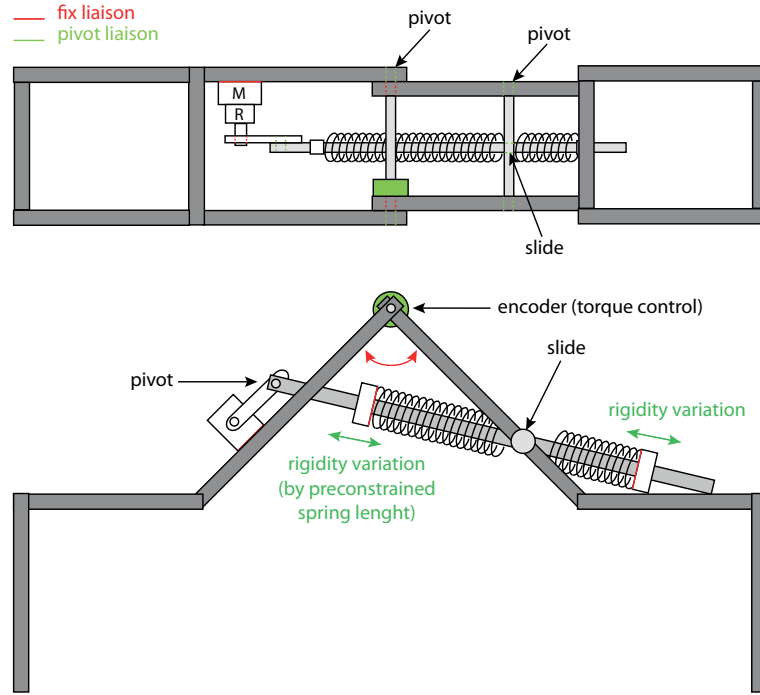


Figure 24: Complete scheme of the mechanism. (M: motor, R: gearbox)

- c) Energy release phase: Spring 1 releases energy (elongated)
- d) Energy storage phase: Spring 1 (elongated), spring 2 stores energy (shortened)
- e) Energy release phase: Spring 2 releases energy (elongated)
- f) Back to start of cycle b)

4.2.2 Changing mechanism stiffness

To change the rigidity of a spring, the main principle is to vary the spring pre-constraint.

This task can be performed in two ways:

- Changing the spring pre-constraint manually (ex: placing clamping rings)
- Changing the spring pre-constraint by actuating of a motor (ex: DC motor and worm-slider)

Finally we decided to choose the manual method because:

- It is more lightweight.
- It is a less complex mechanism.
- Cables passing in the main spine pivot.

In figure 26 a) we can observe the mechanism that is going to be used to change the spine stiffness. We can see two clamping rings attached one on each side of the spring system. We can observe in figure 26 c) that moving the clamping ring to increase the spring pre-constraint will cause the spine structure to stiffen.

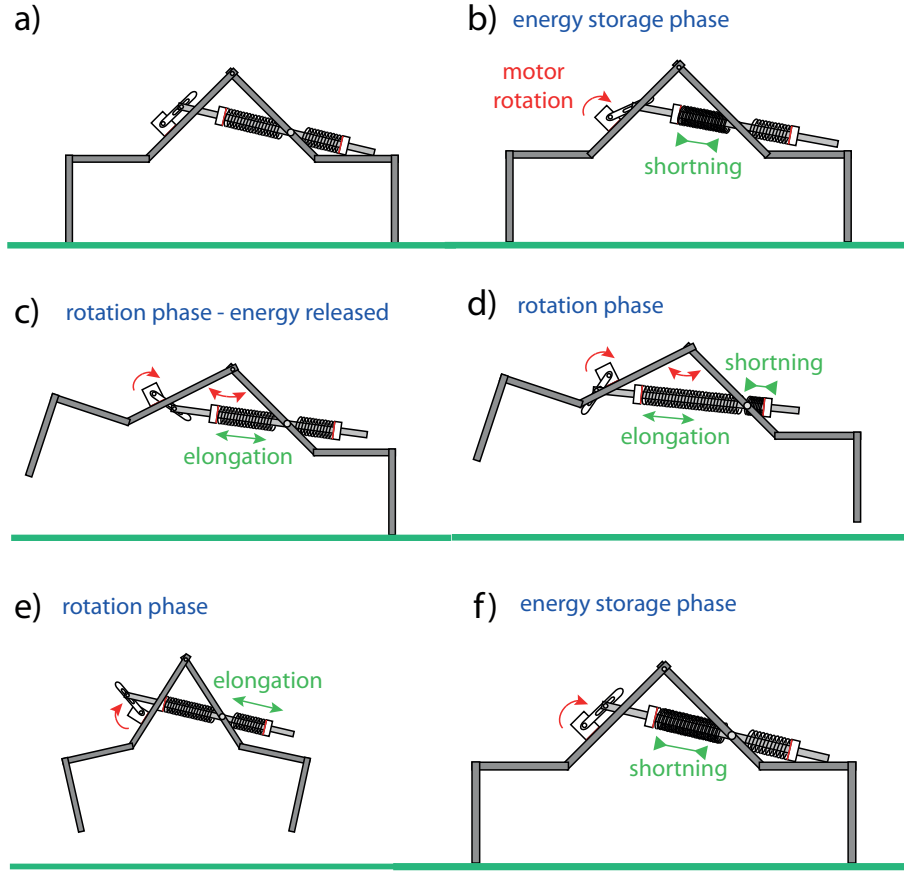


Figure 25: Principle of mechanism movement

4.2.3 Changing movement amplitude

To keep the mechanism as modular as possible we also implemented a system that allows to change the spine movement amplitude.

As it can be seen in figure 27, on the first segment of the crank-slider we added a second slider. This slider enables us to change the length of the first segment and so to change the amplitude.

4.3 Comparison

To choose the final mechanism a comparison between the two main mechanisms was performed (table 1).

As we have seen before, the advantage of having this crank-slider system is that the motor will be continuously rotating in the same direction unlike mechanism 1 where the motor has to stop and invert rotation direction which leads to a loss of time and an increased torque during acceleration.

Mechanism 2 has also the advantage to be a closed-loop system. That means that with two encoders, one on the motor axis and one on the main bending axis, we will be able to know the actual position of the mechanism, to torque-control the motor.

Mechanism 1 offers an advantage, which is the possibility to adapt precisely the gear-ratio to the use of the timing-belt. The inconvenient of the timing-belt, however, is that it needs a loading mechanism to always keep it under tension, a mechanism that adds complexity the structure.

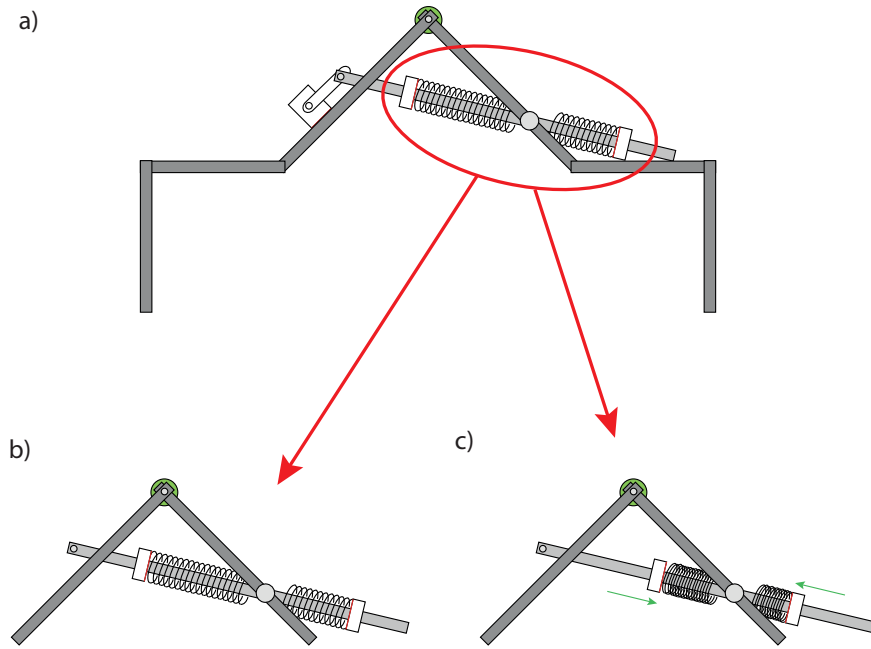


Figure 26: Varying the mechanism stiffness. a) Global view of the robot. b) Spine zoom with pre-constraint. c) Spine zoom with bigger spring pre-constraint

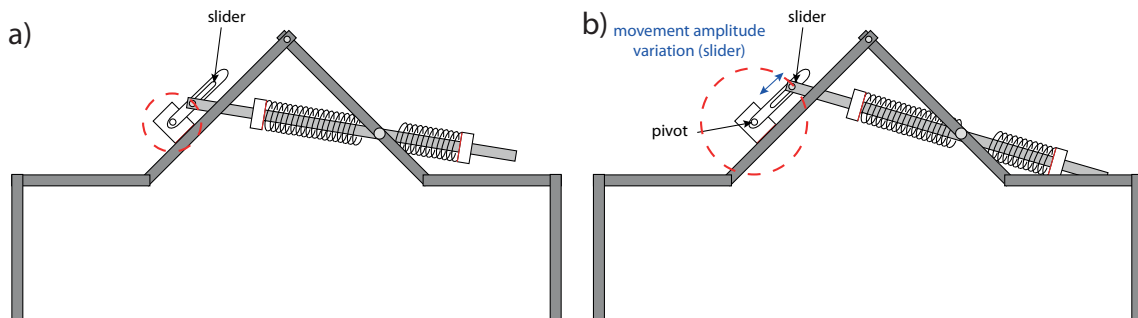


Figure 27: Varying the mechanism amplitude. a) Global view of the robot. b) Spine zoom with pre-constraint. c) Spine zoom with bigger spring pre-constraint

An advantage of mechanism 1 with the timing-belt is that we can easily control the amplitude of movement just by controlling the motor rotation. Instead, with the crank-slider we will have to implement a mechanical system permitting to change its geometry.

Finally, a disadvantage of the crank-slider is that depending on its position, the torque varies. From the comparison it is apparent that the crank-slider mechanism offers two main advantages: the first is that the motor never changes his rotational direction and the second point is that it is

Material	Young Modulus [gPa]
Aluminim	69
Bronze	96-120
Titanium	110.3
Titanium alloys	105-120
Copper	117
Carbon fiber reinforced plastic (50/50 fibre/matrix)	30-50
Carbon fiber reinforced plastic (70/30 fibre/matrix)	181
Wrought iron	190-210
Steel (ASTM-A36)	200

Table 2: Yong modulus table of principal structure elements for the leaf spring

Sum of torque:

$$M(x) = -P(l - x) \quad (1)$$

Differential equation for the beam bending:

$$y''(x) = -\frac{M(x)}{EI} \quad (2)$$

Putting (1) in (2):

$$EIy''(x) = P(l - x) \quad (3)$$

Integration of equation (3):

$$EIy' = Plx - P\frac{x^2}{2} + C_1 \quad (4)$$

$$EIy = Pl\frac{x^2}{2} - P\frac{x^3}{6} + C_1x + C_2 \quad (5)$$

Boundary conditions:

$$y'(x = 0) = 0 = C_1 \quad (6)$$

$$y(x = 0) = 0 = C_2 \quad (7)$$

Replacing (6) in (4), (7) in (5):

$$y = \frac{P}{6EI}x^2(3l - x) \quad (8)$$

$$y' = \frac{P}{2EI}x(2l - x) \quad (9)$$

The maximal bending length f and rotation angle β appear at $x = l$:

$$f = \frac{Pl^3}{3EI} \quad (10)$$

$$\beta \simeq tg\beta = \frac{Pl^2}{2EI} \quad (11)$$

Young modulus

E is the Young modulus of the material. It will vary depending on the material that we will use. It can be determined by using table 2

Moment of inertia

The moment of inertia depends of the section of the leaf spring (figure 29)

$$I_x = \frac{BH^3}{12} \quad (12)$$



Figure 29: Leafspring section for the calculus of the moment of inertia

Rapport H/B	1	1.5	2	3	4	6	10	inf
Factor α	0.208	0.231	0.246	0.267	0.282	0.299	0.313	0.333
Factor β	0.141	0.196	0.229	0.263	0.281	0.299	0.313	0.3333

Table 3: Coefficients for the torsion of a square beam

5.1.2 Torsion

In figure 30 we can observe the beam torsion principle.

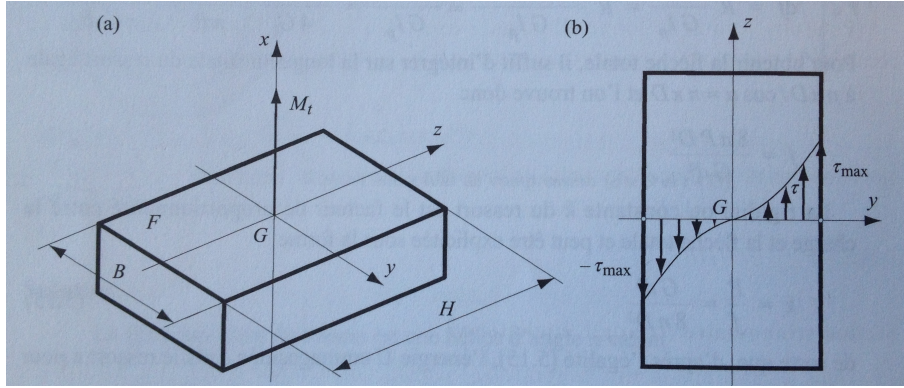


Figure 30: Leafspring torsion principle [8]

The St-Venant's theory yields for the maximum constraint :

$$\tau_{max} = \frac{M_t}{\alpha(HB^2)}$$

where

M_t : torsion torque applied to the leaf-spring

The torsion angle is given by :

$$\Theta = \frac{d\phi}{dx} = \frac{M_t}{\beta G(HB^3)}$$

where

G : shear modulus

α and β : coefficients

The coefficients can be determined using the table 3.

Shear modulus

Shear modulus can be determined by using table 4

Material	Shear Modulus [GPa]
Aluminium	41.4
Steel	79.3
Copper	44.7
Titanium	41.4
Polyethylene	0.117

Table 4: Shear modulus values for the main principal structure elements of the leaf spring

5.2 Motor for the spine bending mechanism

In figure 31 we can see the scheme of the belt system for the spine bending.

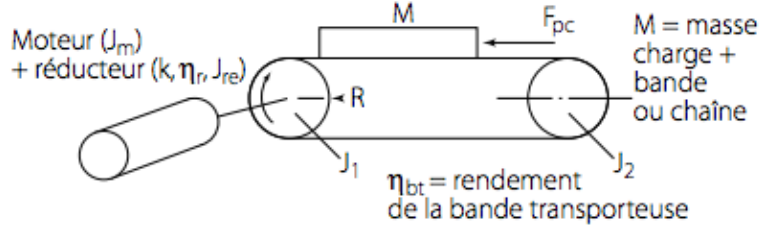


Figure 31: Scheme of the belt system for the spine bending.

5.2.1 Motor preselection

We have to determine the maximum power needed in permanent regime Pr_{max}

For selecting the appropriate motor, we have to consider first those motors where $P_{nom} = Pr_{max}$ and determine the nominal speed (N_{nom}) for each motor.

Procedure :

Torque of the charge : M_2 proportional to weight (P)

Torque of the charge seen by the gearbox ($\frac{R_2}{R_1}$ is the reduction ratio):

$$M'_{2r} = \frac{M_2}{\frac{R_2}{R_1}}$$

Then we add a gearbox of reduction factor n_r :

$$M'_2 = \frac{M_2}{\frac{R_2}{R_1} n_r}$$

Taking into account the efficiency of the gearbox, η_r and of the mechanic belt, η_{bt} , yields :

$$M'_2 = \frac{M_2}{\frac{R_2}{R_1} n_r \eta_r \eta_{bt}}$$

Power of the motor :

$$Pr_{max} = M'_2 \Omega_{mot}$$

$$\Omega_{mot} = \left(\frac{R_2}{R_1} n_r \right) \Omega_{charge}$$

where Ω_{mot} is the rotational speed of the motor and Ω_{mot} the rotational spine of the charge.

5.2.2 Gearbox selection

In a second step we have to fix the maximum speed of the bending rotation so that a gearbox with the correct reduction factor n_r can be chosen.

The reduction factor is :

$$n_r = \frac{\Omega_{mot}}{\Omega_{charge}}$$

Having this factor we can choose a gearbox for the reduction :

- n_r : reduction factor
- η_r : gearbox efficiency

5.2.3 Optimisation of the motor-gearbox complex

We have to find the dynamic torque of the motor C_m .

The torque M_2 proportional to the total weight (P), the acceleration (ma) and the angular acceleration ($I\omega'$).

$$C_m = M_2' + J_{me}a_m + I\omega'$$

where, J_{me} the equivalent inertia brought to the motor is given by:

$$J_{me} = J_m + J_{re} + \frac{J_1 + J_2 + MR^2}{n_r^2}$$

5.2.4 Motor selection

The motor has to be chosen such that:

- $(C_m)_{nom}$ is conform to the permanent regime
- Every point (C_m, N_m) is in the correct zone of the transitory regime

5.3 Belt for spine bending motion

5.3.1 Belt tension

The belt dimensions depend on:

- Stress (load) on the belt and bearings
- Ideal belt : lowest tension that does not slip in high loads
- Belt tension adjusted to : belt type, size, speed, pulley diameter

The power transmission is a function of the belt tension. The belt tension is determined by measuring the force needed to deflect the belt at a given distance per inch of pulley. Timing-belts need only an adequate tension to keep the belt in contact with the pulley.

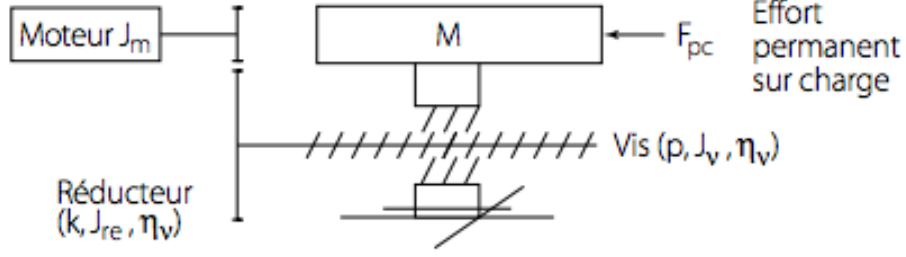


Figure 32: Scheme of the motor-screw mechanism

5.4 Motor for varying the leaf spring rigidity

In figure 32 we can see the mechanism principle that will be used to change the leaf-spring rigidity.

In this case the force F_{pc} is the force due to the friction of the table moved by the screw when the leaf-spring stiffness is changed. This is due to the fact that we change leaf-spring rigidity only when the leaf-spring is fully horizontal, to avoid too much strength. And then when the slider has been replaced it cannot move anyway due to the screw, so there will be no need of an additional force of the motor to keep the table in place.

Power needed by the motor :

$$P_{nom} = F_{pc}v$$

where

$$v = d/t$$

v : speed of slider displacement

d : displacement length

t : duration of displacement

The permanent torque due to the mass (slider) C_{pm} , in the motor referential is given by :

$$C_{pm} = \frac{1}{\eta_r \eta_v} \frac{1}{k} \frac{F_{pc} p}{2\pi} [Nm]$$

The equivalent inertia brought to the motor J_{me} :

$$J_{me} = J_m + J_{re} + \frac{J_v + M(\frac{p}{2\pi})^2}{k^2} [kgm^2]$$

5.5 Leaf-spring of belt tension

The principle of this part of the mechanism is the same as the one of the leaf spring for the spine compliance. We can reuse the equations (10) and (11) :

$$f = \frac{Pl^3}{3EI}$$

$$\beta = tg\beta = \frac{Pl^2}{2EI}$$

6 Chosen mechanism: DC motor, crank-slider and linear spring

In this section we will explain in details the finally chosen mechanism.

6.1 Geometry

6.1.1 Boundary conditions

Spine length:

To choose the length of our spine we used the same proportions as for the body of a cheetah. A typical cheetah spine [11] is 110-150 cm and the leg length is 66-94cm, which is a ratio of about 2/3 for legs length/spine length. By knowing the actual length of the robot leg we determined the length of the spine that will be of $\sim 250\text{mm}$.

Unavailable space next to the floor :

Since the robot will bend its legs, the body of the robot will approach the floor. We presume that the legs of the robot will bend at a maximum of 45° , but we want to always keep a distance of at least 120mm from the floor. Thus the height from the floor in a stable position (figure 33) is:

$$height = \frac{120}{\cos(45^\circ)} = 170\text{mm}$$

We then add a safety margin of 30 mm. This gives us a safety distance to the ground of:

$$height = 170 + 30 = 200\text{mm}$$

This safety distance leaves a space under the top of the legs of 100mm for the spine mechanism.

Unavailable space over the legs:

Space is unavailable above the legs (150mm $\times$ 230mm) due to the material present on top of the legs (structure and actuation mechanism of the legs).

6.1.2 Placing the main actuator

Placing the main actuator is a tradeoff between position for motor minimal torque and occupation of available space.

The optimal case would be:

- The attachment point of the crank-slider extremity is as close as possible to the leg structure.
- The force of the crank-slider should be applied perpendicularly to the structure.

By knowing the available space for the mechanism and knowing that we need a certain movement amplitude, we determined the attachment point of the actuator and the length of the crank-slider segments to approach as possible the optimal case.

- The motor was placed in the center of the spine to have a good weight distribution.

- The vertical distance from the motor to the floor is set using the maximum distance available under the spine.
- The dimensions of the two crank-slider segments were determined by knowing the desired amplitude of the movement.

6.1.3 Dimensionning

Figure 33 shows the structure dimensioning. In green and red we can see respectively the first and second arm of the crank-slider.

Figure 34 b) and c) shows what would look like the mechanism with respectively -15° and $+15^\circ$ angles. This two positions have been used to determine the exact size of the first arm (green) and second arm (red) of the crank-slider to have the right amplitude of movement.

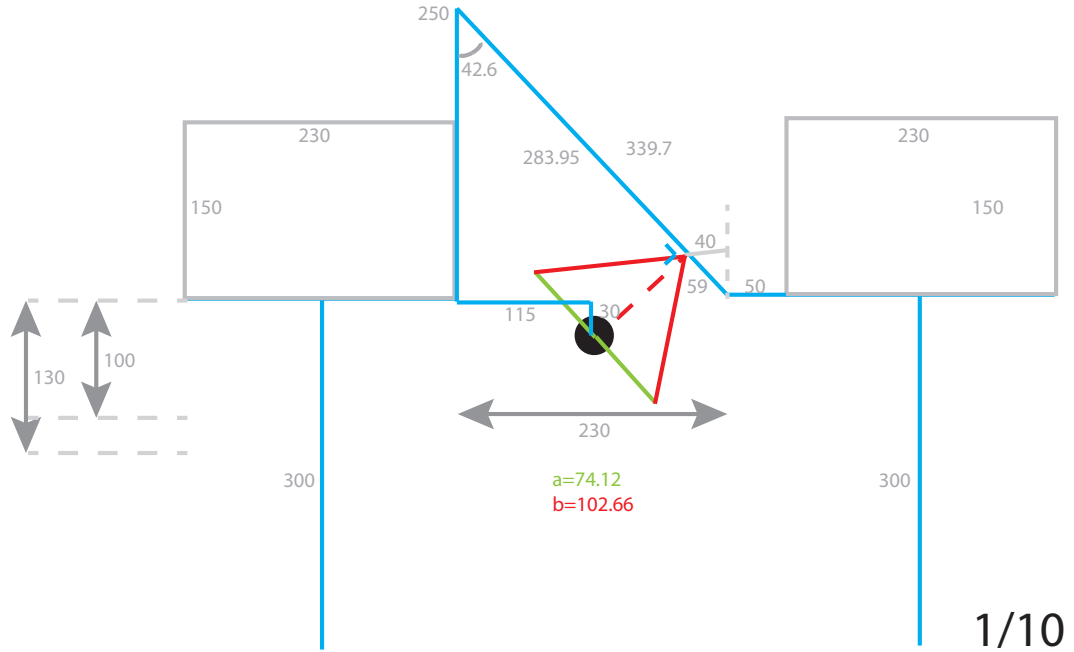


Figure 33: Robot geometry in stable position

6.1.4 Torque on the crank-slider

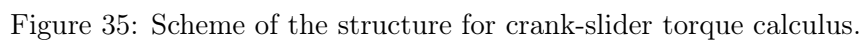
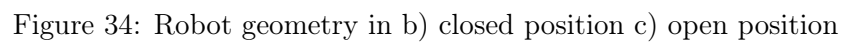
Now that we have the final structure geometry, we will have to determine the maximum torque that needs to apply the motor on the crank-slide to be able to pull up the 4kg legs. The torque the motor has to deliver depends on the position of the spine elements. To chose the appropriate motor, its maximum value has to be determined. For this purpose, the geometrical constraints can be expressed as equations, and mathematica can be used to maximize the value.

According to Fig. 35, the torque exerted by the mass $m_g = 40 \text{ N}$ at the point G has a magnitude

$$M_m = m_g(0.05 \text{ m} + 0.115 \text{ m}) \cos \alpha \quad (13)$$

Since the angle α always remains very small, we can approximate $\cos \alpha \simeq 1$, and thus

$$M_m \simeq 40 \text{ N}(0.05 \text{ m} + 0.115 \text{ m}) = 6.6 \text{ N} \quad (14)$$



24

The torque developed by the motor has to be

$$M = \overrightarrow{HC} \times \overrightarrow{F} = 0.7412 \text{ m} \cdot F \sin \delta \quad (17)$$

where δ is defined as the angle between the segment $\overrightarrow{HC}$ and the segment $\overrightarrow{CD}$:

$$\cos \delta = \frac{\overrightarrow{HC} \cdot \overrightarrow{CD}}{|\overrightarrow{HC}| \cdot |\overrightarrow{CD}|} \quad (18)$$

Equation 15 can be solved for F, yielding

$$F = \frac{M_m}{0.59 \text{ m} \cdot \cos \gamma} \quad (19)$$

and this can be inserted into Eq.17 to obtain an expression for the torque the motor has to develop

$$M = 0.7412 \text{ m} \cdot F \sin \delta \frac{M_m}{0.59 \text{ m} \cdot \cos \gamma} \quad (20)$$

To maximize the value of M, the dimensional constraints have to be taken into account, namely: The Point D with coordinates (x_D, y_D) is on a cercle centered in $E = (x_E, y_E) = (0, 0.25 \text{ m})$ with radius 0.28395 m . Its coordinates thus has to satisfy the equation

$$(x_D - 0)^2 = (y_D - 0.25 \text{ m})^2 = (0.28395 \text{ m})^2 \quad (21)$$

The Point C with coordinates (x_C, y_C) is on a cercle centered in $H = (x_E, y_E) = (0.115 \text{ m}, -0.03 \text{ m})$ with radius 0.07412 m . Its coordinates thus has to satisfy the equation

$$(x_C - 0.115 \text{ m})^2 = (y_C + 0.03 \text{ m})^2 = (0.07412 \text{ m})^2 \quad (22)$$

The segment $\overrightarrow{CD}$ defined as $(x_D - x_C, y_D - y_C)$ is on a cercle centered in C with radius 0.10266 m . Its coordinates thus have to satisfy the equation

$$(x_D - x_C)^2 = (y_D - y_C)^2 = (0.10266 \text{ m})^2 \quad (23)$$

All these constraints have been entered into Mathematica, and used to maximize the value of M. A result was obtained

$$M_{max} = \text{Max}(M) = 12.1232 \text{ Nm} \quad (24)$$

6.2 Mechanism details

6.2.1 Global view

Figure 36 represents the final mechanism of our spine.

The different main element of this system are (distinguished by colors):

- Blue: ball bearings
- Grey: crank-slider mechanism
- Orange: ball-spline
- White: ball-spline axis
- Pink: Ball-spline fixation to structure 2
- Green: structure 1
- Red: structure 2

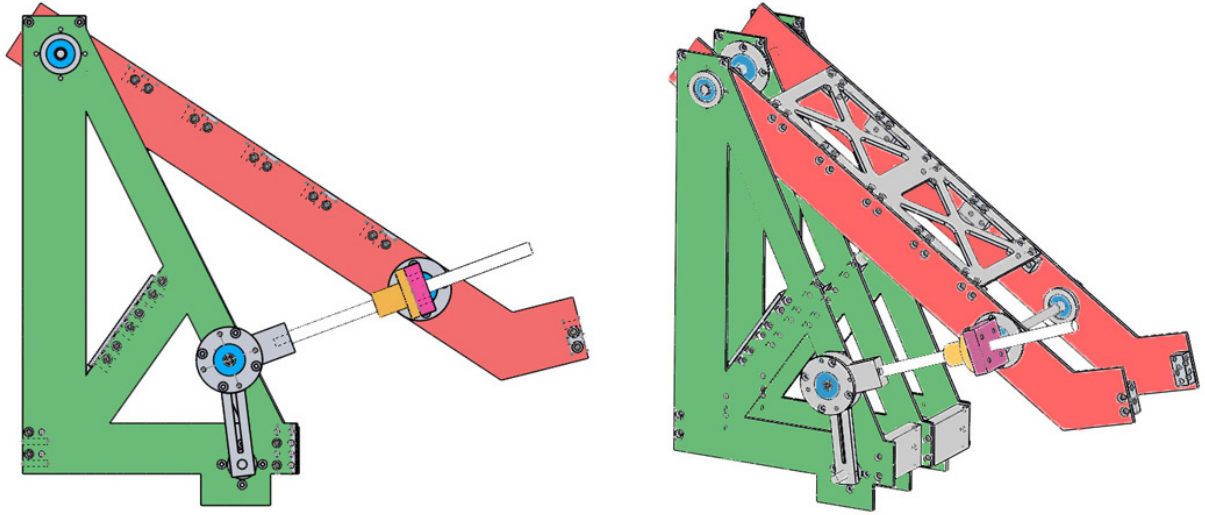


Figure 36: Global side view of the mechanism

6.2.2 Ball-bearings

Ball-bearing system

Figure 37 a) shows the global structure that allows to keep the ball-bearing in place. The outside ring of the ball-bearing is blocked by the inside part of the ring in figure 37 c) and the inside ring of the ball-bearing is blocked by two small rings on the two sides of it, as we can see in figure 37 b).

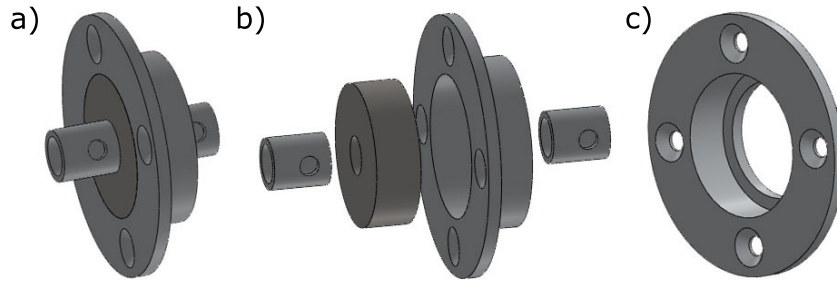


Figure 37: Ball-bearing complex. a) Ball-bearing complex. b) Exploded ball-bearing c) Ball-bearing cage

Fixation of the linear axis

Figure 38 shows how the ball-bearing mechanism is fixed on the axis. The structure is screwed onto the axis at the two locations marked in red. The screws used do not go through the whole axis diameter to avoid weakening the steel rod which is responsible to some extent for the structure rigidity.

Fixation on carbon-fiber plate

Figure 39 shows how the ball-bearing mechanism is fixed on a carbon-fiber plate. The mechanism is inserted in a hole in the carbon fiber plate that helps centering it. Some screws are then used to fix it to the carbon-fiber plate to avoid any movement.

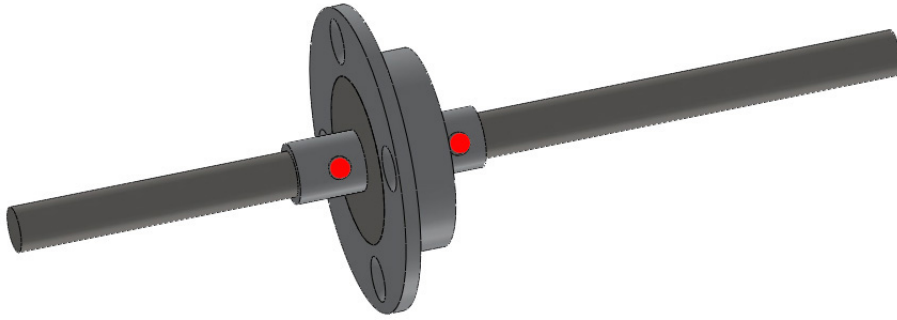


Figure 38: Ball-bearing fixation on the axis.



Figure 39: Fixation of the ball-bearing on a carbon-fiber-plate (back and front view)

6.2.3 Crank-slider mechanism

Global mechanism

Figure 40 represents the different elements of the crank-slider mechanism, distinguished by colors:

- Green: first segment
- Red: second segment and ball-bearing cage
- White: ball-spline steel axis
- Orange: ball-spline
- Pink: ball-spline fixation to structure 2
- Blue: ball-bearing
- Yellow: motor axis

The first segment (green) is inserted around the motor axis (yellow) and a screw goes through both pieces to keep them coupled together. The green and red parts are linked by a pivot liaison using a ball-bearing (blue). The ball-spline axis (white) is screwed in the red part and slides in the ball-spline (orange). The ball-spline is screwed onto a plate (pink) which is fixed to the grey structure of the spine (see all elements in figure 40).

When the motor axis start to rotate, it will bend the spine structure.

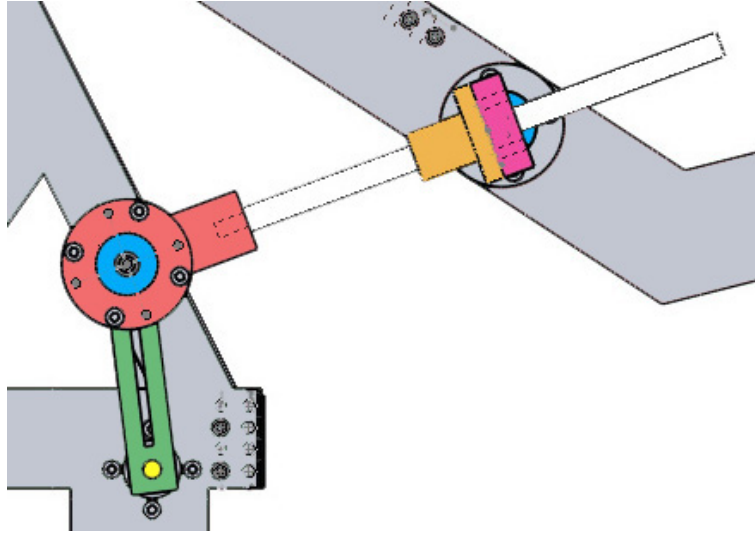


Figure 40: Crank-slider mechanism

Changing spline angle amplitude

To change the angle amplitude of the spine bending, the length of the first crank-slider segment needs to be changed. Figure 41 shows how to change this length. In blue we can see a slider that can move along the segment. To enable this movement we just need to loosen a screw that is placed on the other side of the ball-bearing of the crank-slider, then move the slider and tighten it again to fix it in the new position. In 41 b) we can see that the amplitude is increased from 41 a) by moving the slider to the left.

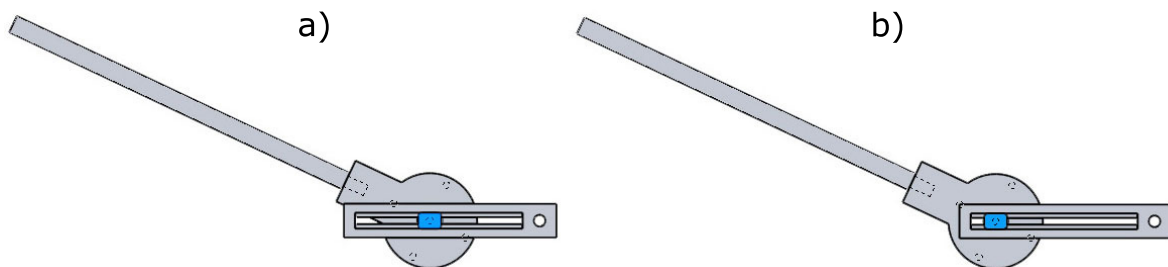


Figure 41: Changing the spine bending angle amplitude. a) Normal amplitude. b) Bigger amplitude.

6.2.4 Ball-spline

Fixing the ball-spline

Figure 42 shows how the ball-spline is attached to the rest of the spine structure. Basically the ball-spline (orange) is screwed to a plate (pink) through four holes (red), the two pieces being now solidary. Then the axis coming from the spine structure (grey) is inserted perpendicularly through a hole in the pink plate, and a screw comes from the back of the link plate to block the axis in place.

Attaching the axis to the crank-slider

The axis has a thread and is screwed directly on the second part of the crank-slider as we saw

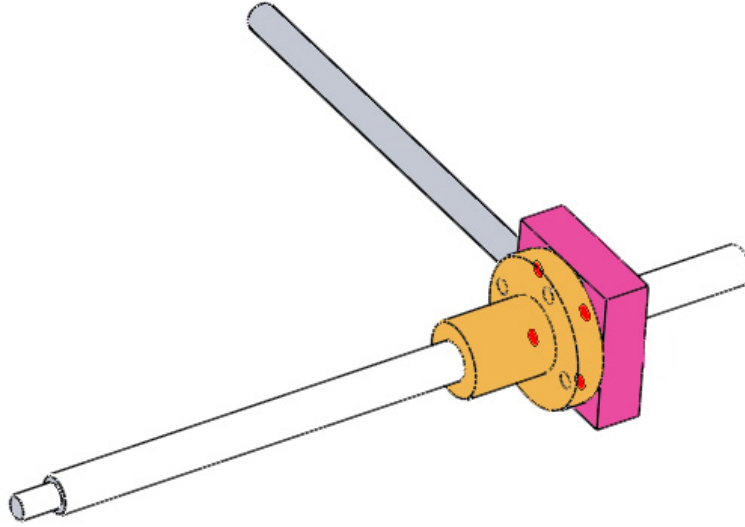


Figure 42: Fixing the ball spline to the rest of the structure. Ball-spline axis (white), ball-spline (orange), fixing plate (pink), structure 2 axis (grey)

previously in figure 6.2.3.

Analysis of deformation

To calculate the deformation of the ball-spline steel axis we will consider the worst case which is when the axis is horizontal to the ground and tries to push up the legs.

We can reuse the formula developed in section 5.1.1 which is:

$$f = \frac{Pl^3}{3EI} = 1.6 \text{ mm}$$

where,

$$P = 20 \text{ N}$$

$$l = 0.1 \text{ m}$$

$$E = 200 \text{ Gpa}$$

$$I_x = \frac{\pi d^4}{64}$$

This result gives really the worst case, where the deformation on the beam is calculated when a strength is applied perpendicularly to the axis. The deformation will be certainly smaller ,because in our case, a fraction of the force is pushed perpendicularly to the axis section surface.

6.2.5 Structure rigidification

Structure 1

Figure 43 shows how we rigidified the structure. A carbon fiber plate (green) is attached to the three main plates of structure 1. To fix these plates together we built a small POM square with holes were are screwed the plates perpendicularly. POM is used because it is more lightweight and because it absorbes a part of the shock during collision, to make the structure remains more resistant in these situations.

The plate has a grid structure with many big holes to make it lighter, the important point being to create a volume between these plates.

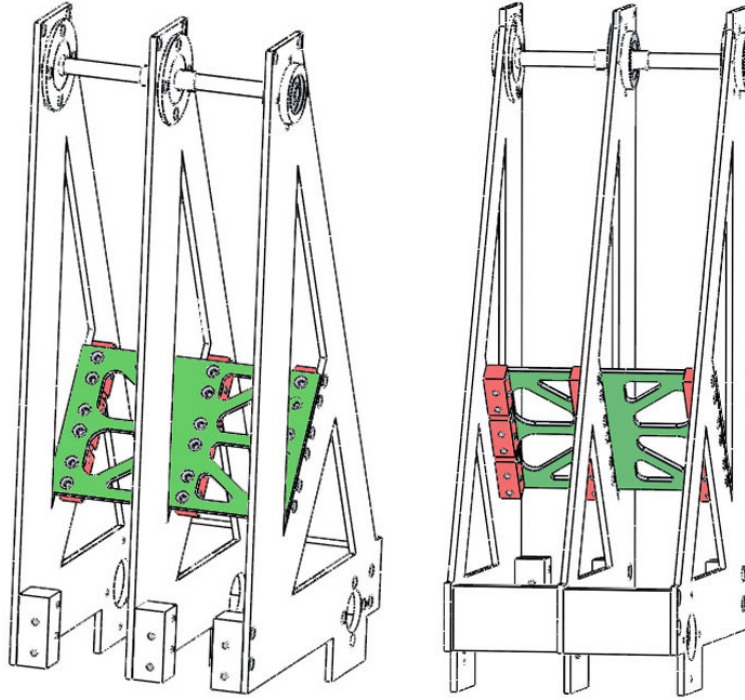


Figure 43: Rigidification of the structure 1.

Structure 2

Figure 44 shows that the same principle as for structure 1 has been used to rigidify structure 2.

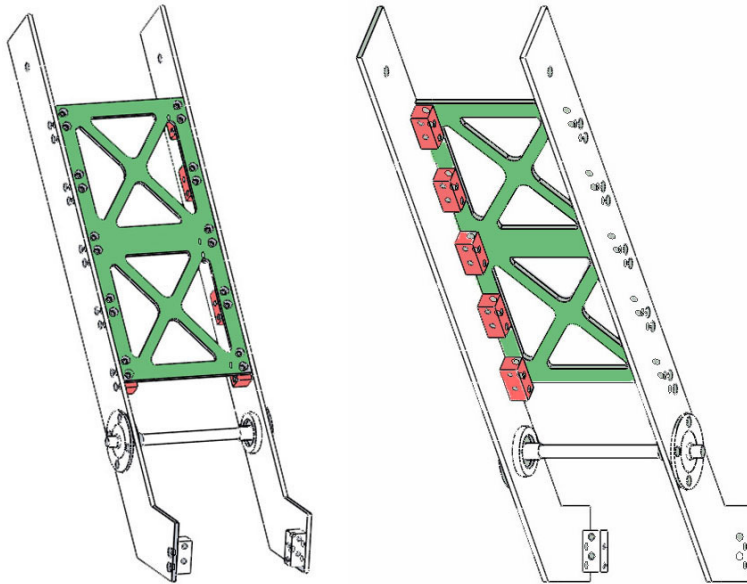


Figure 44: Rigidification of the structure 2.

6.2.6 Motor, gearbox, encoder

The three main elements that actuate our spine are a motor, a gearbox and an encoder as we can see in figure 45) where the gearbox is on the front with the axis, followed by the motor and

then by the encoder.

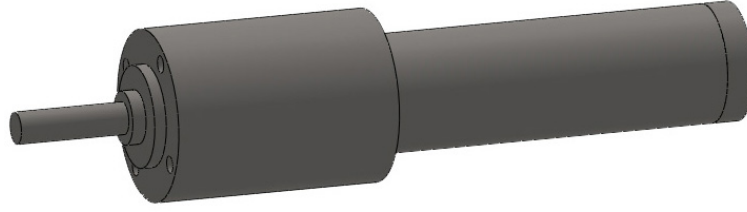


Figure 45: Motors system: gearbox, motor and encoder.

Motor

The chosen motor is a Maxon motor : EC 22, diam 22 mm, brushless, 100 Watt ([9] p.176).

It's characteristics are:

- Nominal torque: 49 mNm
- Nominal speed: 30'000 rpm

Gearbox

The choosen gearbox is a Maxon gearbox : Planetary Gearhead GP 22 C ([9] p.251).

Knowing the nominal speed of the motor (30'000 rpm) and using the defined speed of the spine bending system (2 Hz) we were able to determine the desired reduction factor of the gearbox of 250.

$$2Hz = 120 \text{ rpm}$$
$$I_{reduction} = \frac{30000}{120} = 250$$

Knowing the reduction factor and the torque on the crank-slider calculated in section 6.1.4 we can now calculate the torque seen by the motor:

$$M_{motor} = \frac{M_{crank-slider}}{I_{reduction}} = \frac{12.1232}{250} = 0.048Nm = 48 \text{ mNm}$$

The motor that we choosed can support up to 49mNm so it will be adapted for the actuation, since we also added a security margin of 10%.

The gearbox chosen is also correct. We will just have to choose the reference "143992" ([9] p.251) that has a reduction factor of 270.

Encoder

The chosen encoder is a Maxon encoder : Encoder HEDS 5540, 500 Counts per turn, 3 Channels ([9] p.305).

This encoder will be used to know the position of the motor during rotation.

Top encoder

A second encoder will be placed on top of the spine where the main pivot liaison is located that permits the spine to bend. This encoder will measure the angle of the spine.

Actually, by knowing the information from the two encoders, we will be able to torque control

the motor.

Fixing the motor

The system gearbox, motor and encoder are fixed together at the time of purchase. To fasten this complex to the structure, the gearbox is screwed onto the carbon-fiber plate of the structure, as visible in figure 46. This is possible, because the gearbox is already delivered with holes for screws.

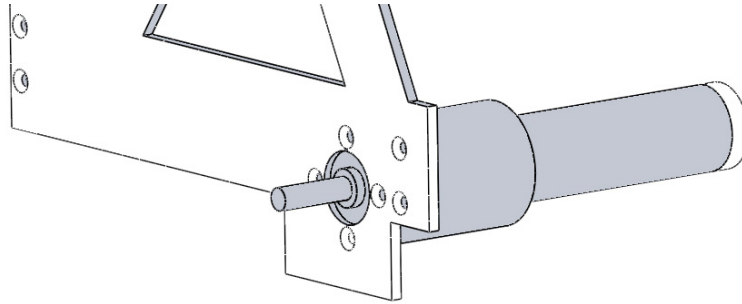


Figure 46: Fixing the motor.

6.3 Built mechanism

Figure 47 and 48 shows the actually build structure.

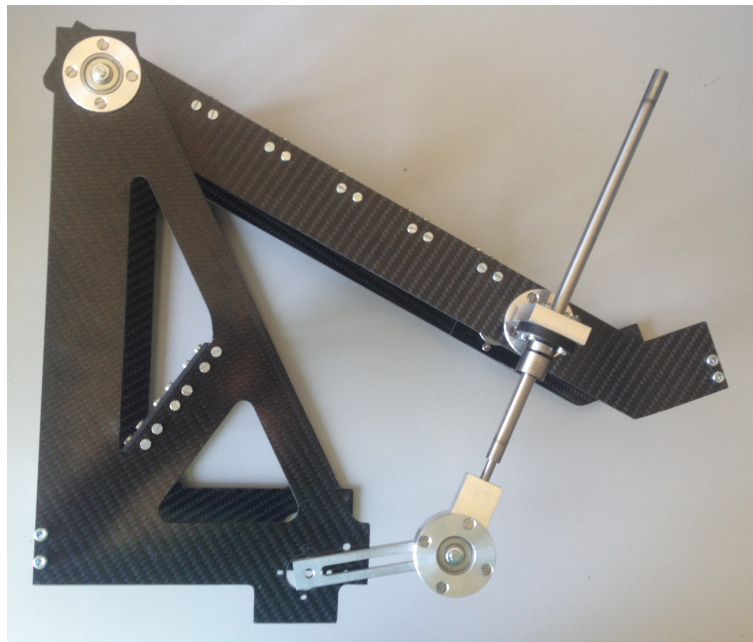


Figure 47: Built mechanism seen from the side.

6.4 Mechanism analysis

6.4.1 Weight

The weight for each piece of the spine has been measured. Every piece is listed in appendix A.

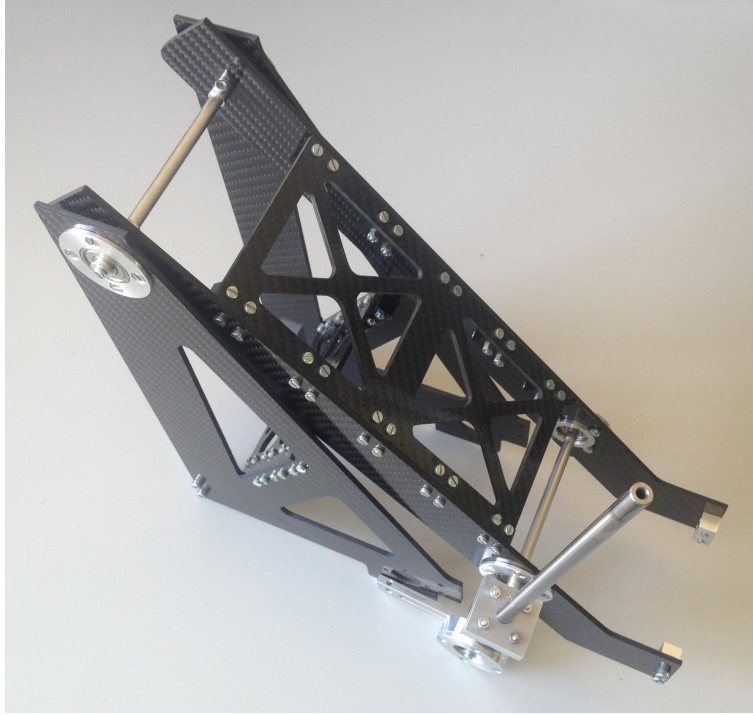


Figure 48: Built mechanism viewed with an angle.

The total weight of the spine is of **1239.55 g** (appendix A). This weight can be separated in three main categories:

- Small parts (various material): 352.05 g
- Structural parts (carbon-fiber): 554 g
- Purchased parts (motor, bearings, etc...): 333.5; g

Improving the weight

Weight can only be improved in the category “Small parts”, were some items have been choosen made of a heavier material because of their easyness of machining or they are slightly overdimensionned. In table 5, the parts are listed, that can be replaced.

Name	Actual Material	Actual weight [g]	Modification	New weight [g]
arm2_ballfix	ALU 7022	39 (1piece)	Make it smaller	20
ballfix_out	ALU	4 (1 piece)	Make it smaller	2
fixing_plate	ALU	23 (1 piece)	Make it thinner	15
fixbloc_1	ALU	17 (3 pieces)	Make it smaller	36
fix_ext_ring	ALU	8 (5 pieces)	Make it in POM	20
Weight gain				60

Table 5: Parts were the weight can be improved.

In conclusion, the weight cannot be greatly improved by changing the “small parts” (around 60 g). Possibly, by redesigning the carbon-fiber structure, the weight could be slightly reduced, but doing that, attention has to be given to avoid jeopardizing the structure rigidity.

6.4.2 Center of gravity

The center of gravity of the spine is 2.4 cm from the central vertical (triangular) plate going in the direction of the crank-slider (figure 49). This non-centrality is caused mainly by the crank-slider mechanism.

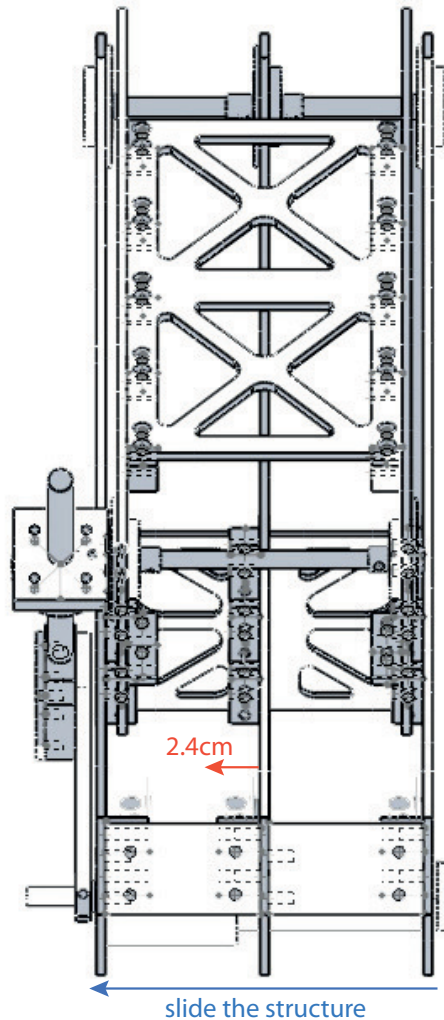


Figure 49: Center of gravity of the mechanism displaced of 2.4 cm from the center.

Balancing the structure

A solution to counteract the problem of an unbalanced structure is simply to fix the spine off-center with respect to the mid-point between the legs. This can be done because the legs structure is larger than the spine structure and because the legs have a slider that allows to easily regulate the position of the spine.

6.4.3 Deformation analysis

Figure 51 shows the deformation analysis of the structure. The purpose of this analysis is to determine the deformation of the spine when pulling up the front legs. To perform this analysis, we applied a force vertically to the floor that is equal to the weight of the front legs (40N) as we can see in purple in the figure.

Analysis results

The results in figure 51 show that the maximal deformation is of 1 mm. This deformation point is in the right part of the mechanism, a point distant from the crank-slider. This result was expected, because the crank-slider is not centered and it applies the force on the structure only from one side.

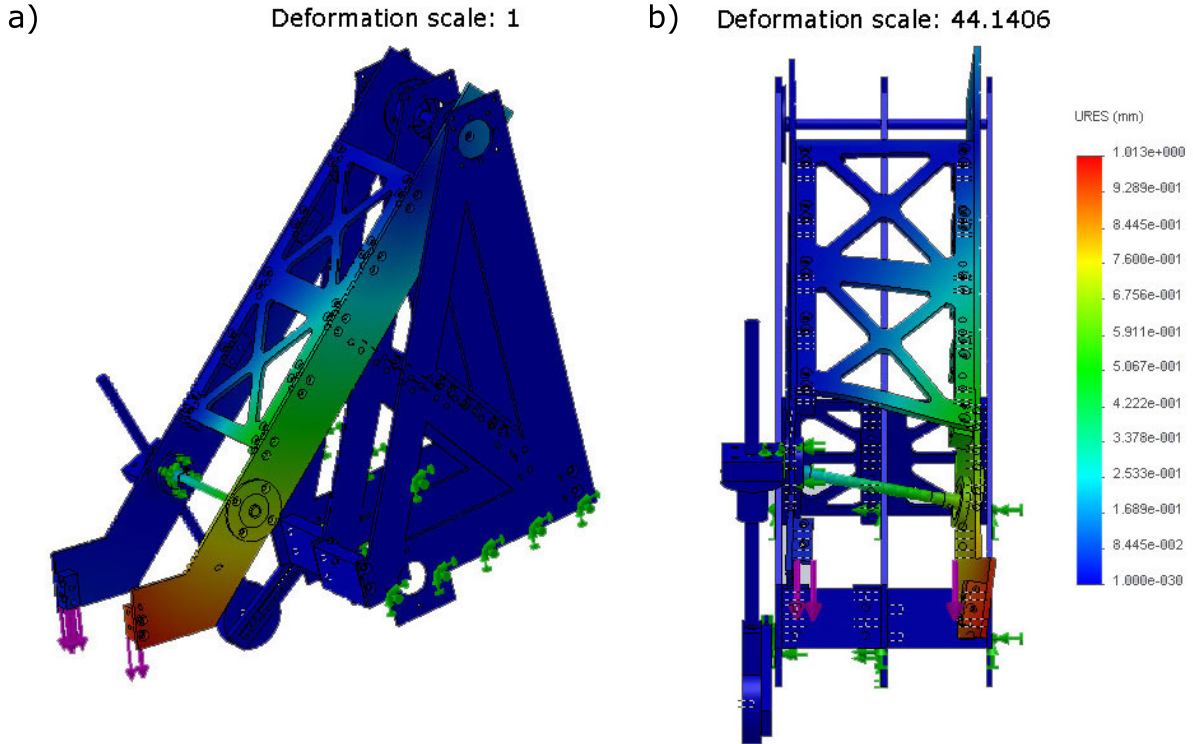


Figure 50: Deformation analysis of the structure with applied forces of 40N (purple). a) Deformation scale: 44.1406. b) Deformation scale: 1.

6.4.4 Stress analysis

Figure 51 shows the stress in all points of the structure. The purpose of this analysis is to understand how stresses are distributed over the structure when pulling up the front legs. To perform this analysis, we applied a force vertically to the floor that is equal to the weight of the front legs.

Analysis results

The result in figure 51 shows that the main points that are subject to stresses are the rigidification plate on the top of the structure and the attachment point of the crank-slider with the structure it is pushing. This result was expected, since the crank-slider pushes only from one side, thus a large fraction of the force will be applied on the attachment point. Since this all was expected, this plate was placed on top to rigidify the structure, so that it would manage a large part of the structural stresses.

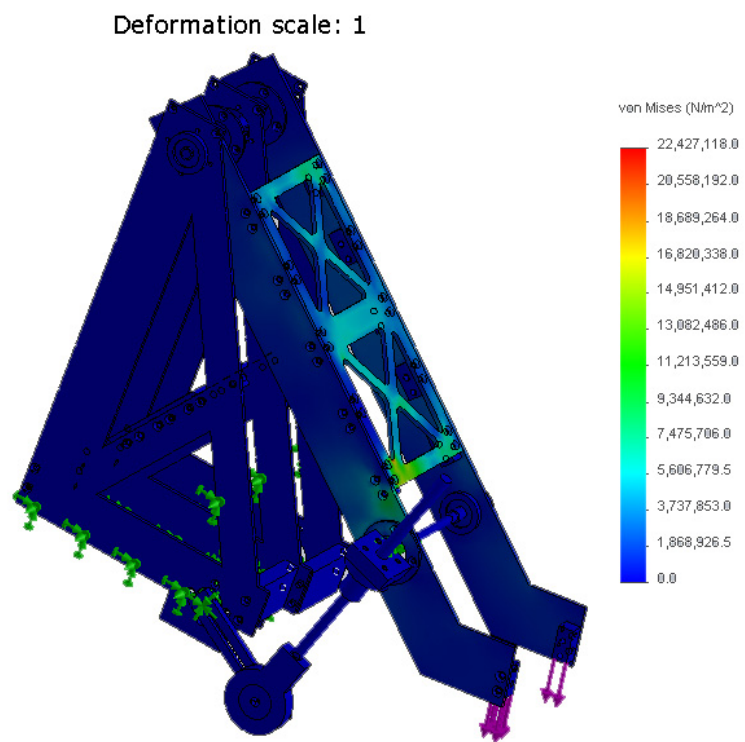


Figure 51: Stress analysis of the structure with applied forces of 40N (purple).

7 Conclusions

This project period can be divided in three main task: gathering ideas and choosing the solution, dimensioning the system, building the prototype and comparing the displacement results to those of a quadruped robot with a rigid spine. At the end of this project we managed to dimension, design and construct a first prototype version of our actuated spine that respects the defined boundary conditions which are the design of an actuated spine that can be torque controlled, the usage of linear springs in serie with the actuation to store energy and release it at the right moment and the "Morphosis system" which allows us to change the system rigidity and the movement amplitude so that we could regulate the system optimally.

The structure analysis show that the system structure has been correctly reinforced so that it will deform only in a negligible way (maximum of 1 mm) and that the global weight of the structure can be probably decreased by 10-15% at most of the weight.

8 Future work

With the first prototype now in hand we should continue first by testing it through fixing the spine on the the rear and front legs of the quadruped robot, testing its performance and comparing it with the same quadruped system but with the rigid spine.

Further improvements can also be found by rethinking the morphology of some pieces of the system to make the system easier to assemble or to reduce a percentage of its weight. The elements that could be modified in the next version of the spine mechanism are (see Appendix B):

- arm2 ballfix: Global size of the piece can be reduced and the M5 hole for the ball spline axis has to be deeper.
- fixing plate: The 3 mm hole used to fix the plate to the axis needs to have a thread so that is can be easily fixed, the plate can be made thinner to decrease its weight and the angles of the piece can be rounded.
- arm1: In this first segment of the crank slider we should make a thread in the hole used for the screw that fixes the part on the motor axis.

A Spine items list

Table 6 shows the items list to build the structure.

Name	Material	Quantity	Unit weight [g]	Total weight [g]
arm2_ballfix	ALU 7022	1	39	39
rondelle	ALU	6	0.15	0.9
rondelle2	ALU	1	0.15	0.15
fixing_plate	ALU	1	23	23
fixbloc_1	ALU	3	17	51
squares	Stainless Steel	2	5	10
fix_ext_ring	ALU	5	8	40
rondelle_fixe	ALU	4	0.5	2
axe	Stainless Steel	1	26	26
squares_struct	POM	19	3	57
axe2	Steel	1	25	25
fixbloc_final	POM	2	24	48
arm1	ALU 7070	1	25	25
ballfix_out	ALU	1	4	4
slider	ALU	1	1	1
structure_2	Carbon Fiber	1	113	113
structure2-1	Carbon Fiber	2	73	146
structure_2.5	Carbon Fiber	1	114	114
structure_3	Carbon Fiber	1	114	114
grid_plate	Carbon Fiber	1	44	44
diag_plate	Carbon Fiber	1	23	23
motor	-	1	128	128
gearbox	-	1	68	68
encoder	-	1	15	15
ball_spline	Steel	1	50	50
bearing	Steel	5	14.5	72.5
Total				1239.55g

Table 6: Spine items list. (See al the pieces drawings in appendix XX)

B Mechanism parts drawings

In the following, the individual parts drawings of the mechanism can be found.

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