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Effect of Leg Design on Locomotion Stability for Quadruped Robot

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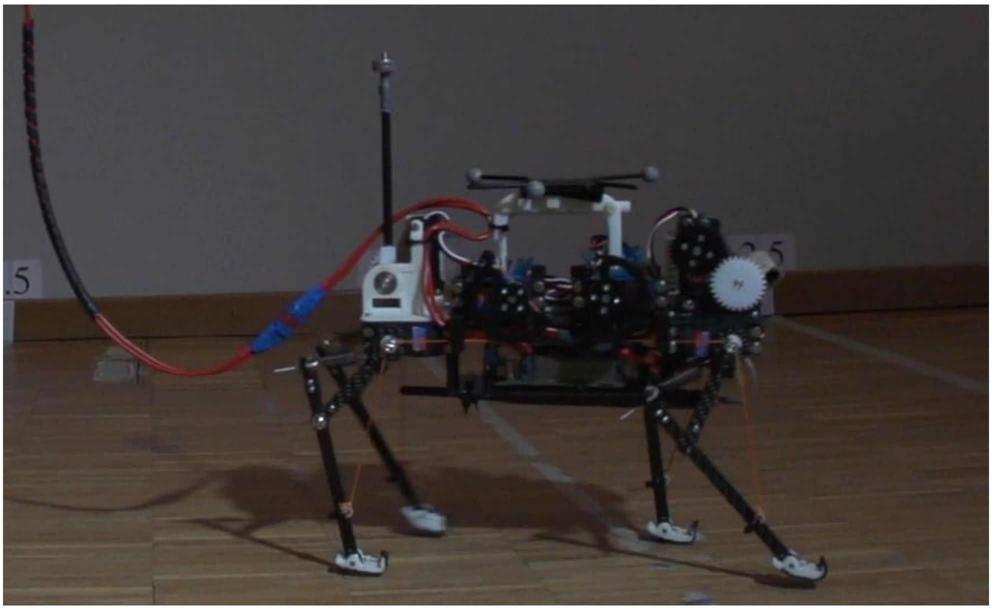

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1. Introduction

When animals came on the ground, they evolved and acquired legs to enable locomotion. This natural solution presents great possibilities, such as the displacement on rough terrains, the passage on obstacles, etc. The robotic labs around the world are trying to take this solution from nature and to apply it to their robots in order to better understand the biological motion and to bring new capabilities to actual robots.

The biorobotics laboratory (BIOROB) at EPFL developed a compliant quadruped robot called Cheetah-cub [1] that can run very fast considering its size. It is actually moving using three segment bio-inspired pantographic legs, which are actuated by two motors placed on the body. In this way, the mobile parts can be very light.

In the other hand, other quadruped robots are showing good performances using two segment legs with serial actuation. This solution doesn't use energy storage and restitution, involves heavy mechanics on the leg but makes the leg stiffer.

The goal of this project is to explore this possibility by designing, producing and testing two segment legs in the idea of Cheetah-cub (actuators on the body, energy storage by elastic parts, light legs, etc.). The results will be compared to the actual pantographic legs with the hope to make simpler and lighter legs and see the consequences of this.

Two legs are designed: the first is similar to the pantographic leg but with one segment less and the second is made in one single flexible part. The actuation remains the same in the two cases. The energy storage is done in the first case by a spring and in the second case by the whole leg.

This report begins with a brief description of Cheetah-cub and the actual pantographic legs. After that, the two leg designs are motivated and explained. The final part presents the experiments and their results.

2. State of the Art

2.1. Actual Robot

2.1.1. Cheetah-Cub

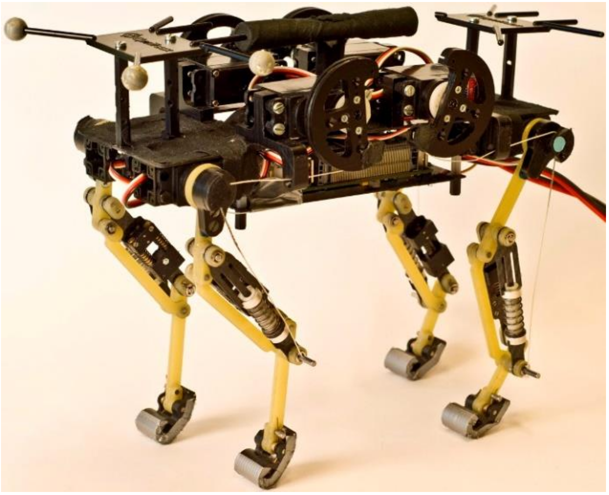


Figure 1: Cheetah-cub, a compliant quadruped robot

Cheetah-cub is a robot inspired by cat morphology. It is composed by a horizontal platform that supports the electronic as well as the 10 servo motors. This version of Cheetah-cub has a head and a tail with one rotational degree of freedom each. The eight other motors actuate the legs (this part will be more described in the next section). The power supply come from a cable that bind it to a power station. It makes it not fully autonomous, but allows to make long experiment sessions without having to change batteries. Furthermore, it provides a kind of leash to the robot and help guiding it when it turns or avoiding damages when it falls. It usually runs under 8-12 Volts.

A Linux operating system runs on the robot and controls it. The user can communicate with the robot and access to its files by connecting an external laptop through Wi-Fi. The configuration files need to be changed according to the wanted gait and the offset on the positions of the motors should be updated before experimentations. After that, a program allows to send commands like start or stop to the robot. For more information about Cheetah-cub hardware, see [1]

The movement is controlled by a central pattern generator (CPG) that runs without feedback, in open-loop control. Complete explanation about the CPG and the controller of the robot can be found at [2]. Videos and details about the Cheetah-cub robot can be found at [3].

2.1.2. Pantographic Leg

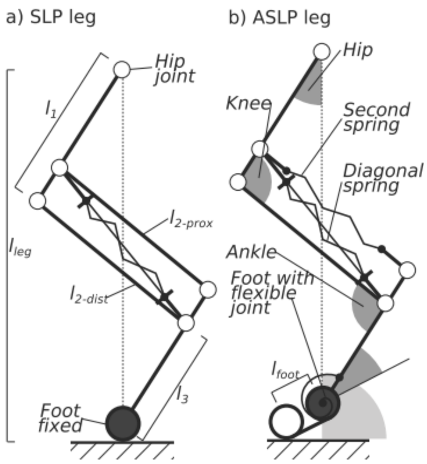


Figure 2: Spring-Loaded Pantograph (on the left) and the advanced version (on the right)

The four legs of Cheetah-cub are currently Advanced Spring-Loaded Pantograph (ASLP). “Pantograph” means that the first and the third segments are kept parallel by a parallelogram construction. In this case, it is not absolutely true, because the “second spring” enables a little displacement. The diagonal spring is responsible for the leg extension and passively supports the body weight. The leg contraction is done through the cable attached to the third segment that goes to one servo motor through a fixation at the hip.

The pantographic leg is followed by a foot that is connected through an elastic joint. It adds some elasticity to the whole leg and allows to store more energy. In this project, the term “leg” considered the structure from the hip to the ankle and only this part will be changed, conserving the same foot.

Each leg is actuated by two motors: one that contracts the leg through the cable as described before (called knee motor) and one that makes the hip rotate (called hip motor). It means that no motor or heavy mechanical part are fixed on the legs. It allows faster movements and spares some energy. The hip motors are directly connected to the hips and cams are placed between the knee motors and the cables to enable large movement of the leg without making several motor rotations.

The length of the segments are not equal for the fore and hinder limbs: behind, the first segment is longer and the third is smaller than in front. This difference makes the morphology of the robot more nature-like, as the limbs of a cat are not equal: the fore limb represents the scapula, the humerus and the radius/cubitus segments and the hinder limb represents the femur, the tibia and the foot, as illustrated by the figure 3. In this way, the two kind of legs have the same shape, with different lengths.

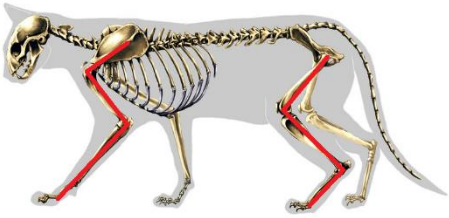


Figure 3: Cat's skeleton. Red parts are the one that are represented by the ASLP leg

Experiments done on Cheetah-cub with those legs are presented in [2]. It shows a very good compliance, natural stability and robustness. It has able to pass a step down without falling. The optimization on the speed went to seven times its length per second, what is fast for a 1 kg robot.

2.2. Two Segment Robots

Seeing at the other quadruped robots, the two segment leg model seems very competitive too. For example, the figure 4 presents StarlETH from ETHZ and Spot from Boston Dynamics, The first can walk for more than 1 hour and run faster than 2 km/h and the second is able to climb stairs and slopes.

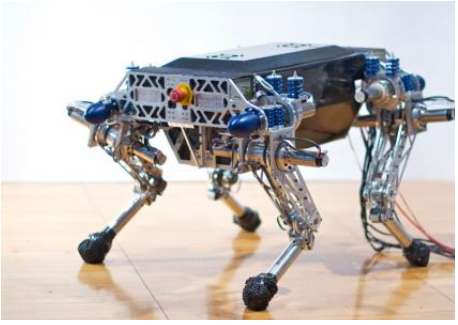


Figure 4: StarlETH (on the left) and Spot (on the right), two quadruped robots with two segment legs

But there are two main differences between these robots and Cheetah-cub: the weight and the actuation type. StarlETH weights 23 kg and Spot weights 72 kg versus 1 kg for Cheetah-cub. Furthermore, these two robots move their forelimbs with direct actuation from motors on the limbs. These two differences make the comparisons with Cheetah-cub difficult, but it shows a possibility of design for new legs. The main advantage would be to create legs with simpler and/or less parts. More information about StarlETH can be found at [4].

2.3. Flexible Legs

The idea of storing energy leads to consider a fully flexible leg that can uniformly accept the load and release it at the push-off. It would be composed of one or few parts, which makes easier to replace or adapt them.

In this field, an inspiration source was the cheetah blade used in prosthetic domain, which can be seen in the figure 5. It is used to replace the foot and a part of the leg and allows the user to run and even sprint as fast as human feet. There are made of carbon fibre and it is difficult to gather precise information about the exact design, but it shows a possibility to create leg from a single part.

Figure 5: Cheetah blade (Xtreme model) from Össur America

Another idea can be to use flexible mechanic parts such as flexible blades or necks, which are used in mechanic to create no friction joints. The travel angle of such mechanisms are short, but using many of those one after another can lead to great deformations with a uniform distribution of energy storage.

Figure 6: flexible blade (on the left) and flexible neck (on the right)

3. Two Segment Leg Design

The first goal of this project is to design a two segment leg following the Cheetah-cub concept. It means that the actuation is made by two motors that are supported by the main platform. One of those motors directly actuate the hip as the second allow the leg to contract through the action of a cable. The extension of the leg should be done passively, using for example a spring. The idea is to keep compliance and passive robustness, to reduce the number of parts and ideally to design simple parts to produce.

3.1. Specifications

The leg should:

1) Store the energy at the touch-down and free it at the push-off ;
2) Support passively the weight and the inertia of the robot;
3) Contract itself actively through the cable;
4) Be fixed to the robot's hip;
5) Be comparable to the ASLP leg;
6) Low inertia and weight.

Important values (mainly taken of actual performances of the ASLP leg):

- Length (hip axis to ankle axis)	90 - 150 mm
- Angular travel at the knee	72°
- Supported weight	~500 g
- Maximal weight (whole robot)	~1 kg

3.2. Solutions

Table 1: Specifications and solutions

Constraint	Value	Solution
Energy storage	-	Spring (1)
Contraction through cable	-	Cable fixation (3)
Support the weight	500 g	Spring design (1)
Fixation to the hip	-	Standard part to the motor (4)
Length of the leg	90 – 150 mm	Segments dimensions (2)
Angular Travel	72°	Spring design (1)
Low inertia and weight	~ 1 kg (whole robot)	Specific material (5) Low number of parts

3.2.1. Spring

Three main types of spring are available: compression springs, torsion springs and tension springs. The table 2 shows the comparison between those possibilities.

Table 2: Springs comparison

Functions	Contraction through cable	supporting the robot	Rigidity variation	Spring replacement	Space needed	Need of guidance	Total
Tension	ok	+	ok	+	-	+	++
Torsion	+	-	-	-	+	+	ok
Compression	ok	+	ok	ok	ok	-	ok

The torsion spring allows to bend easier the leg due to the great available lever, but it makes it less good at supporting the weight. The main disadvantage of the compression spring is the need of a guidance, which involves more parts than other springs. Finally, the tension spring seems to be more accurate to this leg, because of the simplicity that it brings: it is easy to change it, involves less parts and doesn't generate less force than the compression spring.

It becomes clear that the second segment should have a part that goes further than the knee to enable to attach the spring. The spring will be fixed on a screw so the initial tension can be changed as shown in the figure 7. In this way, the user can tune the generated force and modify the rigidity of the leg.

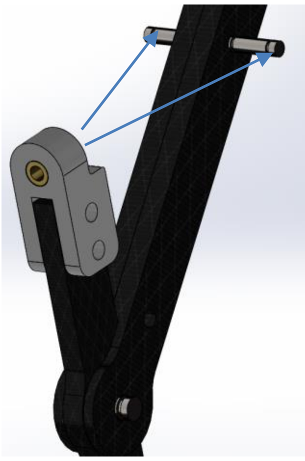


Figure 7: Spring fixation. A screw come in the gold part, the spring is fixed to the pin and the screw

The difficult part is to choose a particular spring. Calculation on the leg is possible, but define the good stiffness that will support the weight of the robot and its inertia once it is running while allowing to easily bend the leg when needed is fast impossible without simulating it. To avoid this, several springs will be tested on the robot to define the best stiffness to apply.

3.2.2. Dimensions

The dimensions were easily founded by transforming the ASLP geometry. The figure 8 presents this transformation: the new first segment has the same length as the old second segment and the new second segment has the combine length of the old first and third segments. The angle between the two segments is taken from the angle between the old first and second segments. In this way, the length from hip axes to ankle axes is conserved.

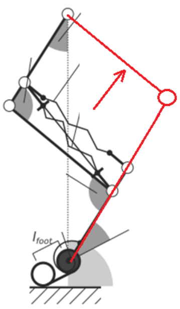


Figure 8: Transformation from ASLP to two segment leg

The extrusion made in the first segment to build the pivot is so design that it stops the second segment at the position where the leg measures 150 mm. in this way, when the spring will tense the leg, it will have the good dimension. The final dimensions are 67.6mm for the first segment and 93.6mm for the second.

The M2 size was chosen for any mechanical elements because the smallest available tool as a diameter of 2mm. The only exception is the main pivot that is a 3mm diameter pin.

The width was set to 8mm, so it is as small as possible, but big enough to support the robot. The thickness of the second segment was fixed to 3 mm to have enough lateral rigidity and the first segment was so design to 6 mm as the second should go through it.

3.2.3. Cable Fixation

The cable fixation consists of two parts. First, an element should allow the cable to go near the hip axis in order to avoid that the rotation of the leg modify the length of the cable. This was already done on the previous leg and the parts can simply be adapted to the new leg.

Secondly, the cable should be fixed to the second segment near to the ankle. To do this, a pin goes through the leg so the cable can be attached to the both sides of the segment. In this way, the force given by the cable remains in the axis of the leg avoiding parasite torque.

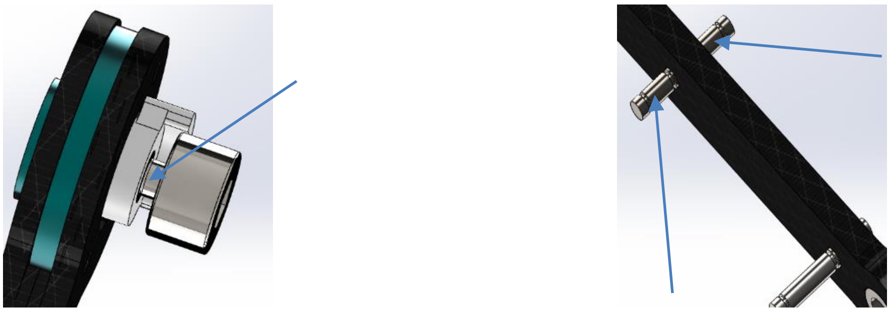


Figure 9: Cable path (on the left) and fixation (on the right)

3.2.4. Attachment to the hip

To attach the leg to the hip, the standard part is used and a screw bind the whole system to the hip motor. In order to do this, the standard part is added in the middle of the first segment, because 6 mm width would be too big.

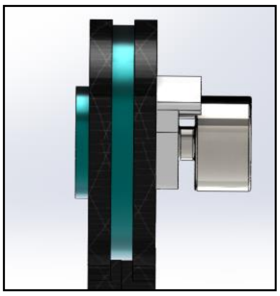


Figure 10: Attachment to the hip

3.2.5. Materials and Production Techniques

The available production methods were milling, turning and 3D printing. As the milling machine allows to work only from one face, it is sometimes needed to produce two different parts and to assemble them. It is the case for the second segment, because it needs some hole from the side to insert pins and a hole from the top for the spring fixation. The table 3 resume the parts, the materials and production techniques used.

Table 3: Materials and production techniques

Part	**Material**	**Method**
Segments	Carbon fibre	Milling
Additional part to segment 2	POM	Milling
Pins	Steel	Turning

3.3. Result

The Figure 11 presents the designed leg as well as the final result. Drawings are provided in the appendix B. As time became a pressure, the final fixation of springs and cables were done with cable straps instead of turning the pin to place snap rings and the axes were just secured by tape. This realization wasn't really proper, but it enabled to begin sooner the experimentation part of the project.

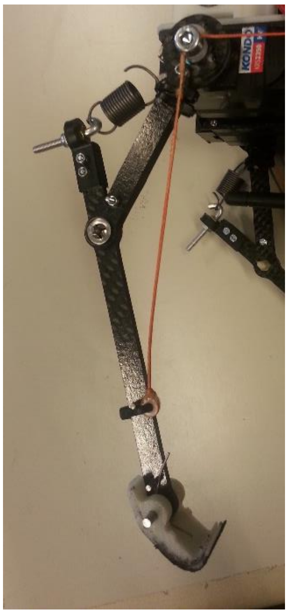


Figure 11: Leg design (on the left) and final product (on the right)

4. Flexible Leg Design

The idea here is to take benefit of a whole flexible leg done from one single part. The cable mechanism and the hip actuation are kept but the leg will bend rather than comport a pivot. As the time lacked, the first design remained the focus of the project and this leg wasn't produced and no final solution was chosen. The encountered problems, emerging ideas and possible variants are presented here.

4.1. Specifications

The specifications are the same as for the previous design. The main problems are the shape of the leg and the used material, so other solutions were let apart. The table 4 presents the solutions to the constraints.

Table 4: Specifications and solutions

Constraint	Value	Solution
Energy storage	-	Shape design
Contraction through cable	-	Cable fixation
Supporting the weight	500 g	Shape design
Fixation to the hip	-	Standard part to the motor
Length of the leg	90 – 150 mm	Shape design
Angular Travel	72°	Shape design
Low inertia and weight	~ 1 kg (whole robot)	Specific material Shape design

4.2. Solutions

4.2.1. Material

The first idea was to use carbon fibre to replicate the effect obtained in the prosthetic field. After research on those blades, it appeared that the shape as well as the exact composition of the material (matrix, fibre's density…) were certainly experimentally founded by companies and it seems so very difficult to obtain them.

A second idea was to use the steel that is used to make springs, because it has a good resistance to the fatigue and a good elasticity. It is made from stainless steel 1.4310 (X10CrNi18-8). A possible problem with this material is the production of the parts, because it would need very thin beams to be flexible under the 1 kg weight of the robot.

A third explored possibility was the plastic. For example, polymer used in SLS technique (Selective Laser Sintering) showed a good behaviour in this type of applications. Other projects of the lab, like [6], used it successfully for foot design. Simulations were made with POM as parts made of it are easily realisable by the laboratory.

Material	E [Gpa]	accept σ [Mpa]
Steel 1.4310	200	195
POM	2.9	110

Figure 12: Characteristics of simulated materials

4.2.2. Leg's Shape

To obtain the flexibility, two main options were explored: the blade shape and the flexible neck. In the first variant, the leg is designed with a thickness that allows flexion. The leg would be entirely made of thin blade directly connected one to another or even from one single blade. In the second variant, weaknesses are added to the leg by milling two half-circles, one on each edge. A succession of several flexible necks would be placed on the leg to enable a longer travel. The equations that rules those structures can be found in [5] and are presented in the figure 13.

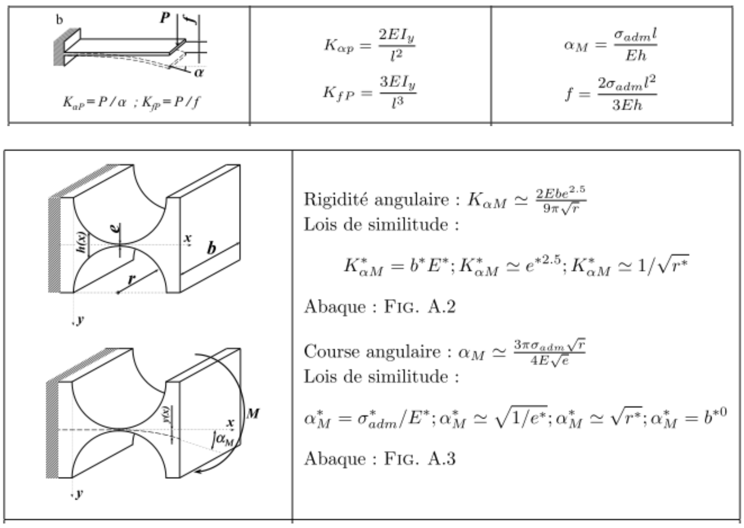


Figure 13: acceptable travel and rigidity of flexible blades (top) and necks (bottom)

For example, a flexible neck made of stainless steel with dimensions $b = 8mm, e = 0.1mm, r = 2mm$ can flex from 0.58°. The same geometry on a part made of POM allows a travel of 22.9°. The problem of those approximations is that it doesn't prove that the parts are feasible or that it would resist to a 1 kg stress. That's why those equations were used only to make quick checks and that repeated simulations were made instead of calculate all the dimensions.

The first tested design is presented in the figure 14. It was simulated as it was made of steel.

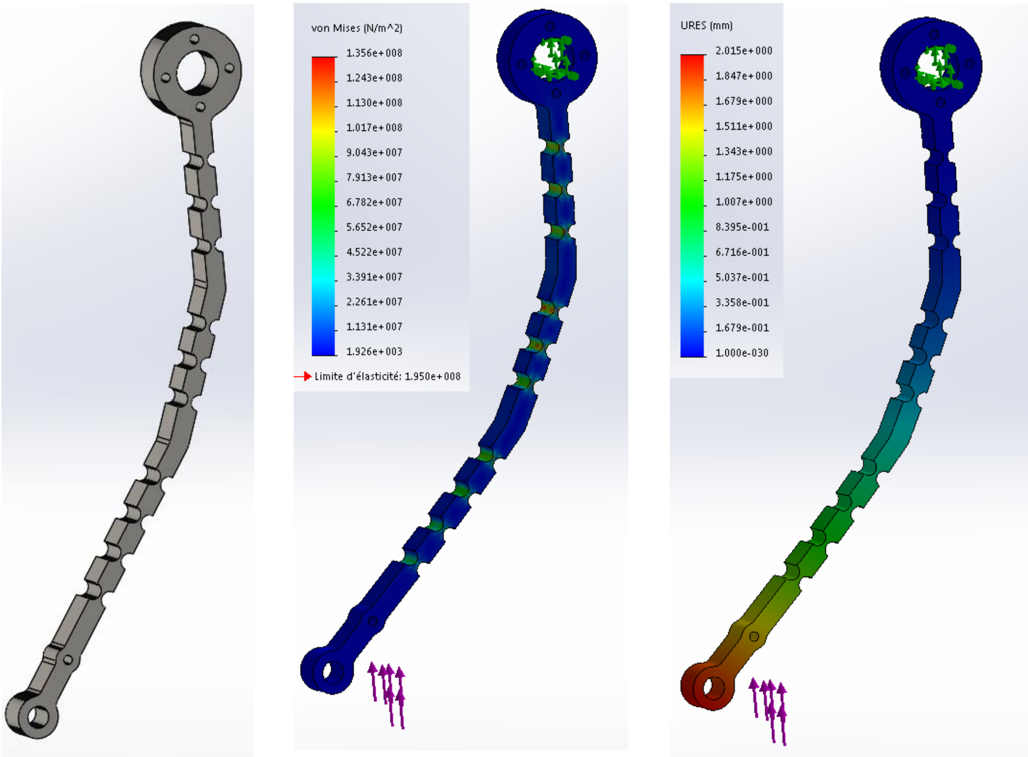


Figure 14: Flexible leg based on flexible necks (on the left) and simulation of a vertical 5N stress (displacement in the middle and stress on the right)

With this design, the displacement is too short. If it is increased, the stress on the necks become too high. That is why more round shapes were explored, in order to increase the total length of the leg, what could distribute the stress even more.

4.3. Result

An example of a possible leg is shown on the figure 15. The ankle move 6.6mm under a force of 15N (approximatively the robot's weight) and can support 23N, what would make the ankle move 3.65mm further. The obtained displacement remain a lot under what is needed to make Cheetah-cub walk and more simulations and/or experiments would be necessary to obtain good results.

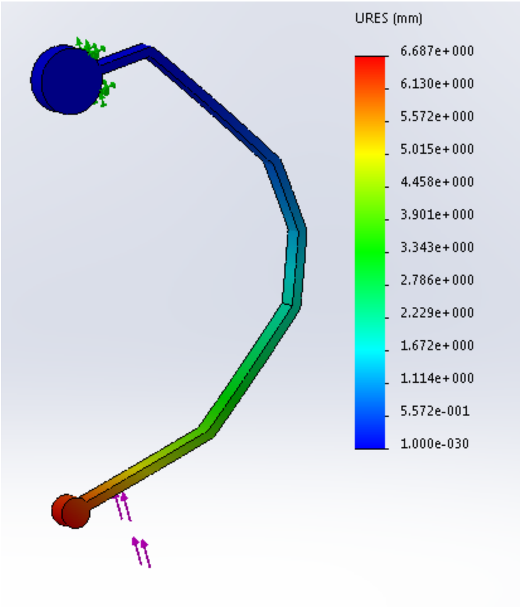


Figure 15: Possible flexible design under a force of 15N

Finally, it seems difficult to realize such a leg. The proper balance should be found for the stiffness and experimentation on real prototypes would be mandatory in order to approach a feasible shape. As it would take far more time than what was available for this project, the research in the flexible leg domain didn't go further.

5. Experiments

At the end of the project, several experiments were leaded to test and characterize the two segment leg. The first experiment was a grid-search to find the best parameters to apply to the CPG in order to obtain a valid gait. The goal of the second experiment was to isolate the influence of each variable. Then a third experiment tested the robot walking under different voltage and with different springs. Finally, the step-down experiment was performed in order to give another mean of comparison with the pantographic leg.

Generally, a lot of vibration were encountered during the experiments. It seems that it comes from the motors and was not constant during all runs. It added a lot of noise to the experiments and it happened that axes moved or that some screws get out of their place. Those facts compromised the repeatability and the uniformity of the experiments. Consistent tests and results were possible anyway, but it should be taken into account.

Furthermore, as several projects were running on the same robot, the legs were removed and replaced between two experiments, what can explain the differences in obtained results for the same configuration from one experiment to another.

As last consideration, the limited available time and issues like the need to recalibrate the robot or to fix the robot after it breaks made difficult to realize as many experiments as wanted. However, the experiments presented in this section can still lead to solid conclusions even if more experiments could be done.

5.1. Method

To achieve those experiments, Cheetah-cub is commanded from a laptop using a wireless connection. The operator access the robot files and can modify the configuration in order to tune the motor’s offsets or to launch the program that makes the robot walk. The CPG uses the parameters of another configuration file where the amplitudes of the movements, their offsets and the frequency can be changed. For each run, the robot walk between one and two meters. The displacement of the robot is tracked by an infrared based motion capture (MoCap) system using three markers attach to the top of the robot. 250 datapoints are taken from the MoCap each seconds, using 14 cameras all around the scene.

The data are stored in a c3d file and BTK (Biomechanic ToolBox) library is used to translate them into simple position data that can be easily read with Matlab. This toolbox was developed by the Laboratory of Movement Analysis and Measurement (LMAM) at EPFL and the Willy Taillard Laboratory of Kinesiology at Geneva University. It can be found in free access on the internet.

The main used metric is the speed, deduced from the markers displacement. The used algorithm take the distance travelled in one second and deduce immediately the speed on each axis. Then, the horizontal speed is calculated making the norm of the x and y components. Other more developed algorithms aren't useful in this case, because it is easy to isolate a sample of one second where the speed is linear, except when the robot falls quickly. In such a case, the speed of the robot isn't really important and the algorithm simply return 0 as speed. The used Matlab code is provided in the appendix A.

A second metric used is the roll and pitch variation of the robot during the experiment. The instant values of the angles are computed using the height of the three tracked markers. The angles can be deduced from the difference of heights and the horizontal distance between the markers. Then, the mean of the angle over the studied part of the run is removed to discard the offset. Finally, the root mean square is computed to give an idea of the amplitude of the oscillation. The used Matlab code is provided in the appendix A.

5.2. Results

5.2.1. Grid Search

In this first experiment, four parameters on the hip motors are tuned to find a good trot gait to use for further experiments. The parameters on the knee motors are not tuned, because they are considered less important for the gait in a first approach.

$fore\ legs'amplitude \in [20°, 25°, 30°]$ $hind\ legs'amplitude \in [20°, 25°, 30°]$

$fore\ legs'offset \in [-47°, -42°, -37°]$ $hind\ legs'offset \in [-47°, -42°, -37°]$

The offset is taken from the initial position, which was defined in this case 42° for the vertical position. All the 81 combinations were tested and the grids presented in the figure 16 and 17 give an overview of the results. The success grid shows if the robot fall (grad 0) or not (grad 1), the quality grid shows if it slips, turns a lot, walks backward… (grad 0) or not (grad 1) and the speed grid indicate the speed in meter per second using the already told algorithm.

Success

	Hind	Ampl	20	20	20	25	25	25	30	30	30
Fore		Off	-37	-42	-47	-37	-42	-47	-37	-42	-47
Ampl	Off										
20	-37		0	1	1	0	0	1	0	0	1
20	-42		1	1	1	1	1	1	0	1	1
20	-47		1	1	1	0	1	1	0	1	1
25	-37		1	1	1	0	0	1	0	0	1
25	-42		1	1	1	0	1	1	0	1	1
25	-47		1	1	1	1	1	1	1	1	1
30	-37		1	1	1	0	0	1	0	0	0
30	-42		1	**1**	1	0	1	1	0	1	1
30	-47		0	1	1	0	1	1	0	1	1

Quality

	Hind	Ampl	20	20	20	25	25	25	30	30	30
Fore		Off	-37	-42	-47	-37	-42	-47	-37	-42	-47
Ampl	Off										
20	-37		0	1	1	0	0	1	0	0	0
20	-42		1	1	1	0	1	1	0	0	1
20	-47		1	1	1	0	1	1	0	0	0
25	-37		1	1	1	0	0	0	0	0	0
25	-42		1	1	1	0	0	0	0	0	0
25	-47		0	1	1	0	0	0	0	1	0
30	-37		0	1	1	0	0	1	0	0	0
30	-42		1	**1**	1	0	1	1	0	0	0
30	-47		0	1	1	0	1	1	0	0	0

Figure 16: Results of all runs showing its quality (on the right) and if it avoids falling (on the left)

Speed

	Hind	Ampl	20	20	20	25	25	25	30	30	30
Fore		Off	-37	-42	-47	-37	-42	-47	-37	-42	-47
Ampl	Off										
20	-37		0.41	0.41	0.43		0.41	0.35	0.47	0.39	0.36
20	-42		0.45	0.43	0.40	0.48	0.41	0.34	0.49	0.46	0.32
20	-47		0.44	0.43	0.37	0.45	0.38	0.30	0.44	0.34	0.27
25	-37		0.51	0.48	0.45		0.46	0.34	0.52	0.47	0.35
25	-42		0.39	0.49	0.41	0.50	0.44	0.44	0.50	0.41	0.35
25	-47		0.38	0.48	0.37	0.45	0.39	0.29	0.44	0.35	0.35
30	-37		0.48	0.46	0.47	0.46	0.46	0.42	0.52	0.49	0.46
30	-42		0.48	0.51	0.47	0.47	0.43	0.39		0.45	0.33
30	-47		0.45	0.51	0.41	0.46	0.43	0.39	0.43	0.33	

Figure 17: Speed of each run

After those results, the amplitude of 20° for the hind legs seems the best regarding the quality of the walk. The -37° offset seems bad for both hind and fore legs. In such a configuration, the legs are initially for the vertical position and the robot fall backward. In the remaining solutions, the fastest was chosen as base configuration for all other experiments, i.e. [30,-42,20-42] respectively for fore legs' amplitude, fore leg's offset, hind legs' amplitude and hind legs' offset. The whole configuration of the chosen reference is presented in the table 5. The different experiments done with this configuration show a mean of $0.45ms^{-1}$ and a standard deviation of $0.0313ms^{-1}$.

This standard deviation can be used to know if a run is significantly better than another. For example, it wouldn't be appropriate to say that a run measured at $0.48ms^{-1}$ is absolutely worse than the reference run.

During this experiment, no trot gait was found. Trying to modify the phase lags didn't resolve the problem. An approaching gait was chosen to perform experiments.

Table 5: Parameters of the reference run

Parameter	Value	Parameter	Value
fore hip amplitude	30	fore knee stance deflection	0.2
fore hip offset	-42	hind knee stance deflection	0.2
fore knee amplitude	1	frequency	3
fore knee offset	0	duty_ratio	0.48
hind hip amplitude	20	fore hip knee phase lag	2.4
hind hip offset	-42	hind hip knee phase lag	2.9
hind knee amplitude	1	fore-hind phase lag	π
hind knee offset	0	left-right phas lag	π

Notice: the parameters are the number that are entered in the CPG and it doesn't mean that the leg really travel so far. The higher is the amplitude, for example, the higher the leg will go, but not necessary until the given amplitude. Moreover, limitations are set to the motors to avoid mechanical, what stops the movement at a given point, making the leg travel less far at one side.

5.2.2. Motors Parameters

The influence of individual parameters was studied under two methods: firstly an Analysis of the Variance (ANOVA) was done on the previous results, then new experiments were performed on each parameter to complete and validate the results.

Hip Motor

The ANOVA for separated parameters gives the following results:

Table 6: ANOVA results (individual parameters)

Parameter	F	Prob > F
hinder offset	3.84	0.026
hinder amplitude	6.3	0.003
fore offset	1.76	0.179
fore amplitude	1.53	0.223

It shows that the parameters of the hind legs are more influent and that the most influent is the amplitude. The figure 18 presents the resulting graphs for the hind legs' parameters, which confirm that the amplitude of 20° and the offset of -42° are the best settings for the hind legs. Note that an amplitude of 20° is not significantly better than an amplitude of 25°.

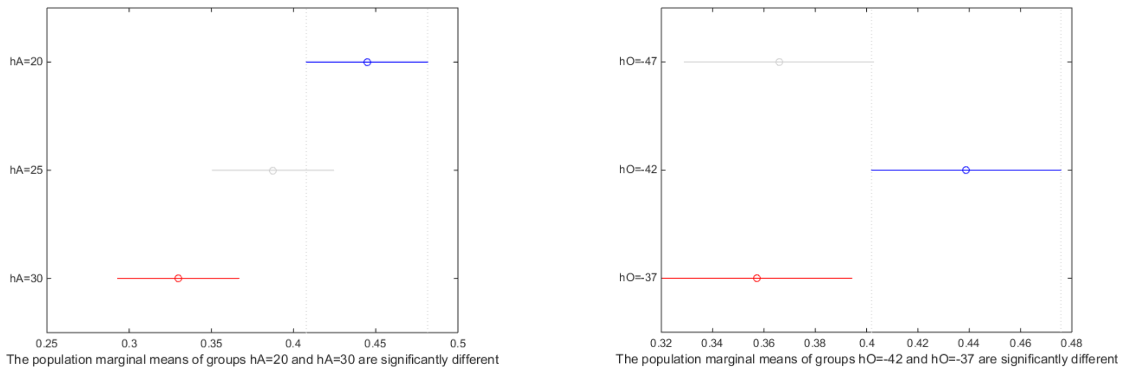


Figure 18: Result of the Analysis of the Variance (ANOVA) for hind legs' amplitude (on the left) and offset (on the right)

The interaction between parameters can be analyse in the same way, giving the results of the table 7.

Table 7: ANOVA results (interaction between parameters)

Parameter 1	Parameter 2	F	Prob > F
hind offset	hind offset	4.31	0.019
hind amplitude	hind amplitude	7.08	0.002
fore offset	fore offset	1.98	0.149
fore amplitude	fore amplitude	1.73	0.189
hind offset	hind amplitude	0.97	0.435
hind offset	fore offset	2.99	0.028
hind offset	fore amplitude	0.36	0.837
hind amplitude	fore offset	0.68	0.612
hind amplitude	fore amplitude	2.35	0.067
fore offset	fore amplitude	0.9	0.47

It only confirm that the main influence comes from the amplitude and the offset of the hind legs.

Further experiments on the parameters of the hip motors confirm those results. The figure 19 presents the experiments done changing only one parameter and it can be seen that the parameters of the hind legs bring more variance to the speed. Increasing the amplitude of the fore legs and reducing the offset of the hind legs seem to increase the speed, but they were not tested together. It would be interesting to test further those possibilities to optimize the speed of the robot.

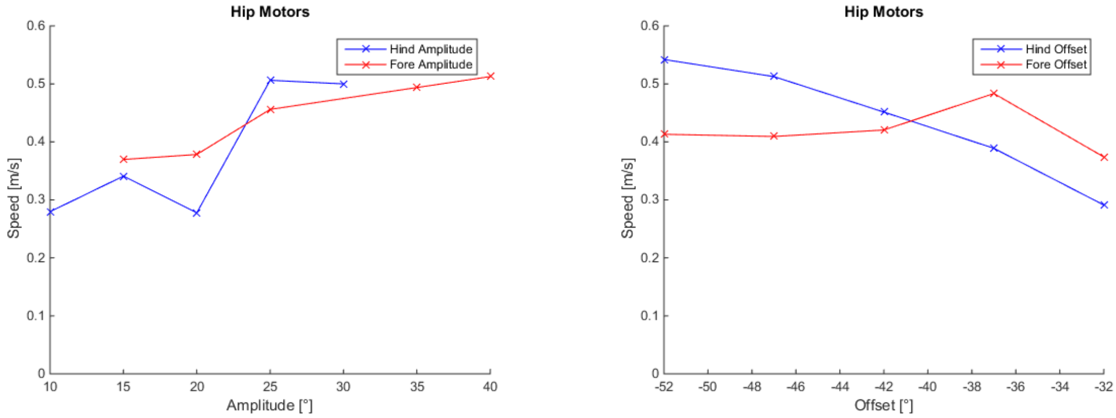


Figure 19: Effect of the fore legs' parameters on the speed

Knee Motor

Modification on the parameters of the knee motors don't show good results. Modifying the amplitude doesn't significantly affect the speed and changing the offset make the robot fall, as seen in the figure 20.

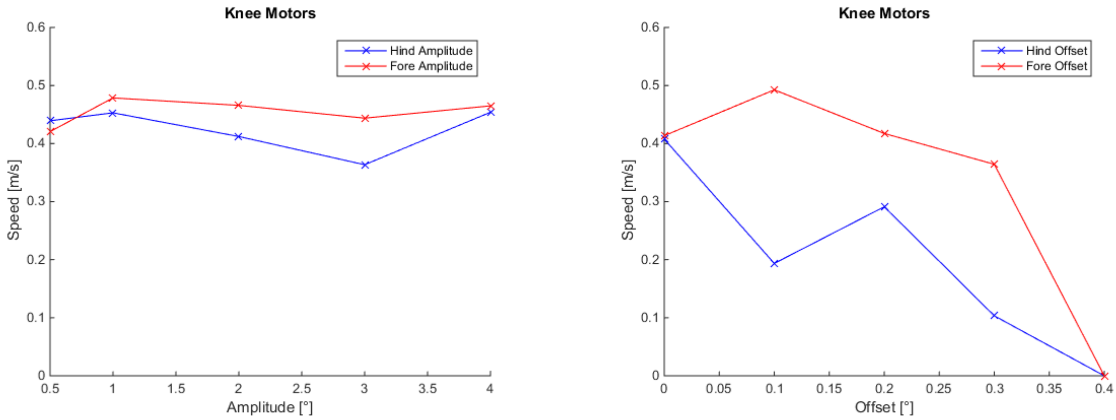


Figure 20: Effect of knee motors' parameters on the speed

5.2.3. Voltage and Spring Effect

Tests were made with less voltage input than the standard 10V. With the pantographic legs, the robot encountered difficulties to run under 9V. The figure 21 shows the results for the new leg and it appears that Cheetah-cub can now run with less power without decrease the performences. The experiments were done in two times, that's why a single representation was built on the figure to merge them. To make it, the two experiments are simply biased of half the difference seen on the common 9V run. It shows that the speed doesn't change with voltage.

Another set of experiment was done changing the springs to test the effect of different ridgidities. The characterisitcs of the three tested springs are presented in the table 8.

Table 8: Characteristics of the springs

Spring	F0	Rigidity
zf-1411	3.02	0.97
rzf-1390	3.41	1.51
rzf-11461	4.03	2.04

Three experiments were done with the RZF-1390 and the RZF-1461 and nine were done with the ZF-1411 as it is the reference spring. The results can be seen in the figure 21 and it shows little difference between different springs. It would have been interestning to test less rigid springs, but no one was available.

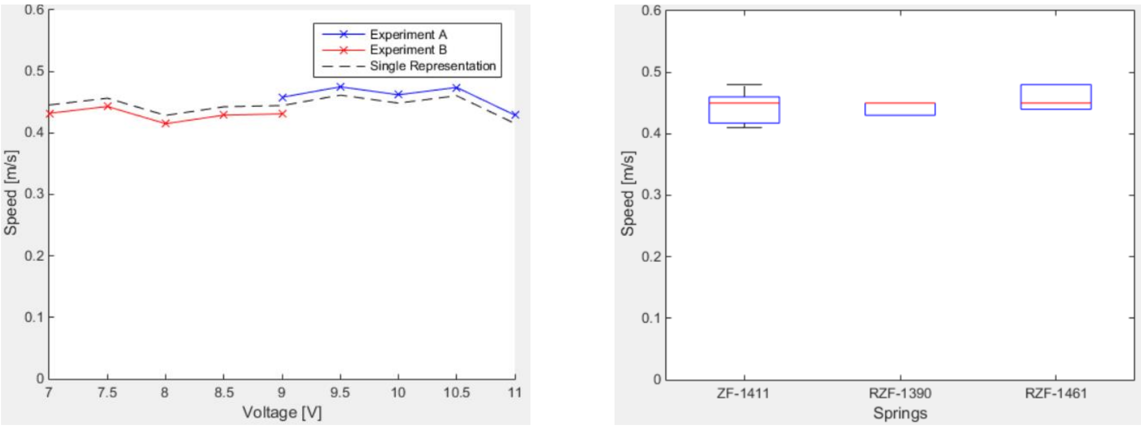


Figure 21: Effect of the Voltage (on the left) and the Rigidity (on the right) on the Speed of the robot

5.2.4. Comparison with the Pantographic Leg

Speed

The figure 22 presents the speed obtained for the 5 best runs with two different calibrations of pantographic legs and the two segment leg. The fore legs' amplitude, fore legs' offset, hind legs' amplitude and hind legs' offset are respectively for the pantographic configurations [35°,0°,40°,0°] and [40°,5°,35°,5°]. The reference configuration is used for the two segment leg.

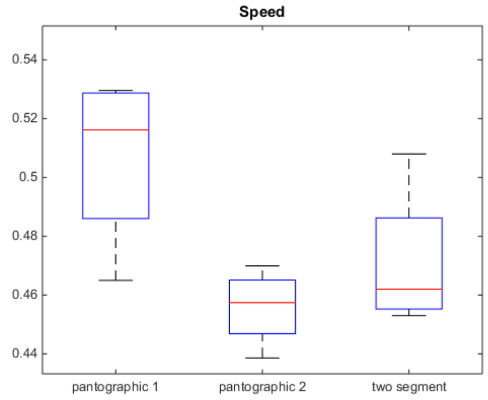


Figure 22: Comparison of the speed between pantographic and two segment legs

It shows that the new leg is in the same performance area that the pantographic leg, but can't achieve the same speed. It could maybe be different if more time was passed on the optimization of the parameters, but the experiments done during this project show that it would be difficult to really surpass the pantographic leg.

Stability

The figure 23 present the RMS pitch and roll for the same runs that in the previous section.

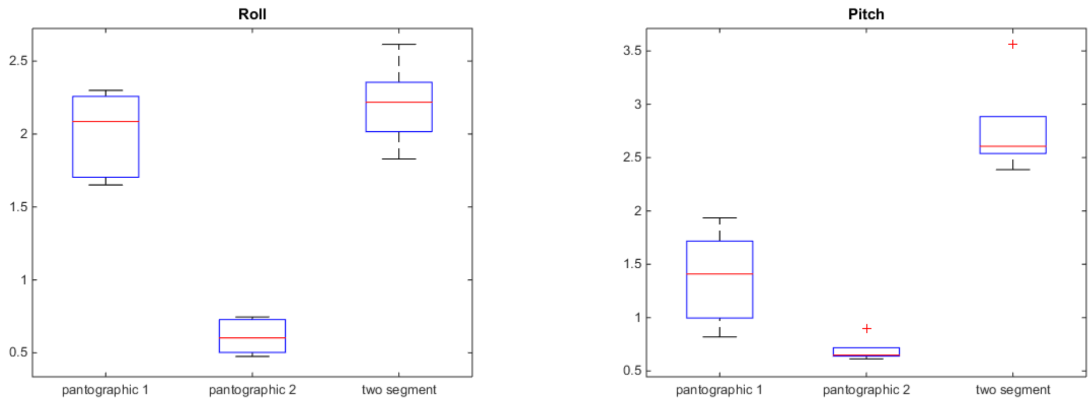


Figure 23: Comparison of the roll (on the left) and the pitch (on the right) between pantographic and two segment legs

For the pitch, it is clear that the two segment legs shakes more the robot. It is probably due to the higher rigidity between the foot and the hip that makes it bounce when the foot touch the ground. In such a situation, the pantographic leg flex under the inertia of the robot and the body feels less bumps.

For the roll, the results are closer to those found with pantographic leg, but there is still below.

The consequences of this greater roll and pitch variation are not obvious and it doesn't mean that the motion is better or worse. However, it is an indication of stability, because oscillating a lot around the equilibrium makes the system go near to unstable areas. For example, if at the moment when the "head" is the lowest, a perturbation makes it go still below, the robot can fall. This situation is avoided if the head stay permanently at the horizontal position. Thus, it doesn't give a rigorous indication of robustness, but it seems better if the body platform doesn't tilt.

Robustness

The robot equipped with pantographic legs was able to pass a step down of 4.5cm. It can do it with two segment legs too, being successful 4 times out of 5. One of those run is shown in the figure 24. The Y axis is parallel to the starting orientation of the robot, the X axis is the second horizontal axis and the Z axis is the vertical one.

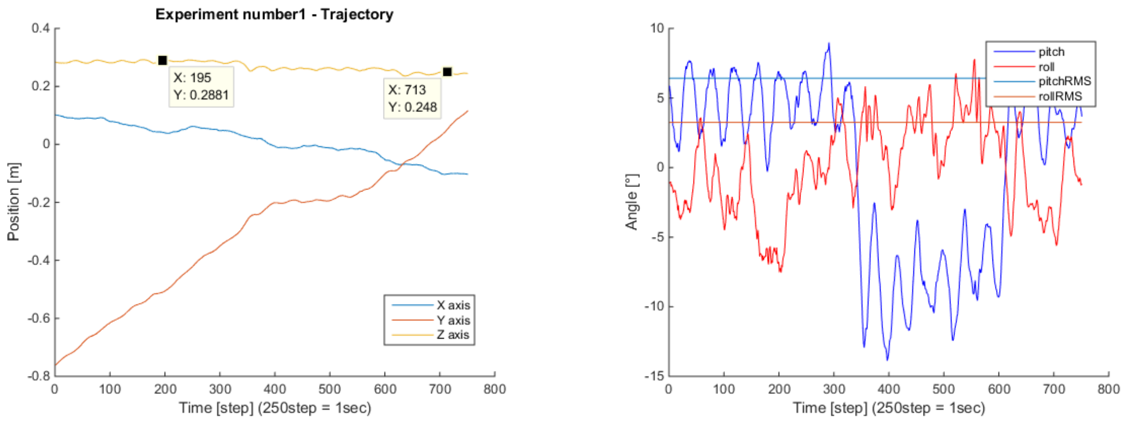


Figure 24: Trajectory (on the left) and pitch and roll evolution (on the right) of the robot achieving a step-down

Three phases can be observed: firstly the robot is on the step and walks, then the fore legs fall on the ground, what destabilize the robot and in the end it is walking on the ground. They can be identified by the height of the body, by the modification of speed on the Y axis or looking at the pitch.

Qualitatively, the passage is less fluid than with the pantographic legs, but those experiments show the robustness of the new legs. Here, the robot encounter a huge perturbation on the pitch, but it is able to recover its standard gait.

5.3. Discussion

5.3.1. Leg Design

The first observation made about the leg design is that the cluttering of the motor and the body wasn't taken into account and it was a mistake. Indeed, the back part of the leg, where the spring is attached, tend to collide with the body. To avoid this, the limit of the fore hip motors was set to a new position, stopping the leg before touching the body, as shown on the figure 25. It is bad, because greater amplitude couldn't be tested in this direction.

Figure 25: collision between leg and body

In the field of versatility, this leg is really an improvement compared to the pantographic design. The springs can easily be removed and replaced and it is composed of less parts. Moreover, the distances between axes can be quickly modified on the drawings and new legs with different proportions can be made without difficulties, in a short time. An improvement can still be made on the cable fixation, because nowadays, one need to cut the cable straps to remove cables. It stay easier than removing the cable on the pantographic leg, but this way of doing isn't really proper.

5.3.2. Performances

In term of performance now, the two segment leg seems slower than the pantographic one. On the other hand, the robot can run with less power using them. It was observed that the hip motors work less with this new design, revealing a different way to manage the movement of the feet. Those results could be greatly affected by the type of spring that is used and further experiment on less rigid springs can be interesting. However, the general impression led by this project is than the robot equipped with the two segment legs can't go faster.

On the contrary, the robustness of the design is interesting. The robot can perform step down, but it seems robust to high pitch disturbances. What lack to the robot is a mean to compensate the lateral disturbance, it means forces that affect the roll. Qualitatively, it seems that this design can reject lateral perturbations in a given proportion, but no experiment was done in this direction.

6. Conclusion

In this project, the goal was to design a flexible leg, a two segment leg and compare them with the pantographic leg previously developed. It was known from the start that realizing and testing to new design was ambitious and the production of the flexible leg was cancelled.

Concerning the design of the flexible leg, first ideas were sketch up and tested through simulation. It reveals that producing a flexible leg in one single part would be rewarding but extremely complex considering the given constraints.

In the topic of two segment leg, a design was prototyped and produced. The design can be improved and failure as the collision with the body can be may be corrected, but it was sufficient to test the concept and to compare it with the pantographic leg. The results obtained with this designed shouldn't be generalized to all the two segment leg, as many parameters like limbs length weren't explored, but it give a first view on the two segment concept. It reveal that it can't achieve the same performance as the previous design in term of speed. On the other hand, it can run with less power and seems robust.

In a more general way, it is the most bio-inspired design that shows the best performances here, indicating that the third segment of the leg is needed to perform a powerful and fast locomotion with a quadruped body. What can be still explored is to differentiate the fore legs and the hind legs, using for example two segment legs before and pantographic legs behind.

Returning to the inspiring models, the key fact to keep in mind is that Cheetah-cub set its own specific rules. At the difference of the bigger robot that inspired this project, Cheetah-cub is used with an open-loop control and so need a high passive compliance and robustness to work. It is very good to test the passive properties of leg and foot designs, so the final conclusion would be that the bio-inspired pantographic leg shows more powerful passive characteristics than the two segment leg.

7. References

7.1. Bibliography

[1] S. Ruthishauser, *Cheetah – compliant quadruped robot*, Biologically Inspired Robotics Group, EPFL, 2008

[2] A. Spröwitz, A. Tuleu, M. Vespagnani, and all, *Towards dynamic trot gait locomotion: Design, control, and esperiments with Cheetah-cub, a compliant quadruped robot*, Int. Journal of Robotics Research, 0 (0). pp. 1-19, 2013

[3] *Cheetah-Cub – a compliant quadruped robot*, http://biorob.epfl.ch/cheetah, 15.05.2015

[4] M. Hutter, C. Gehring, M. Bloesch, and all, *StarlETH: A compliant quadrupedal robot for fast, efficient, and versatile locomotion*, 15th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, 2012

[5] S. Henein, *Conception des Guidages Flexibles*, Collection META, PPUR, 2003

[6] S. Komi, P. Eckert, A. Ijspeert, *Improvement of Cheetah-cub by new Foot Design*, Semester Project, Biorobotics Laboratotry (BIOROB), EPFL, 2015

7.2. Figures

Figure 1	http://biorob.epfl.ch/cheetah
Figure 2	[2]
Figure 3	http://www.deviantart.com/art/Cat-Skeleton-72300139
Figure 4	[4] and http://www.digitaltrends.com/cool-tech/boston-dynamics-spot-robot/
Figure 5	http://www.ossur.com/prosthetic-solutions/products/feet/feet/cheetah-xtreme
Figure 6	[5]
Figure 8	[2]
Figure 13	[5]

Appendix A: Matlab Code

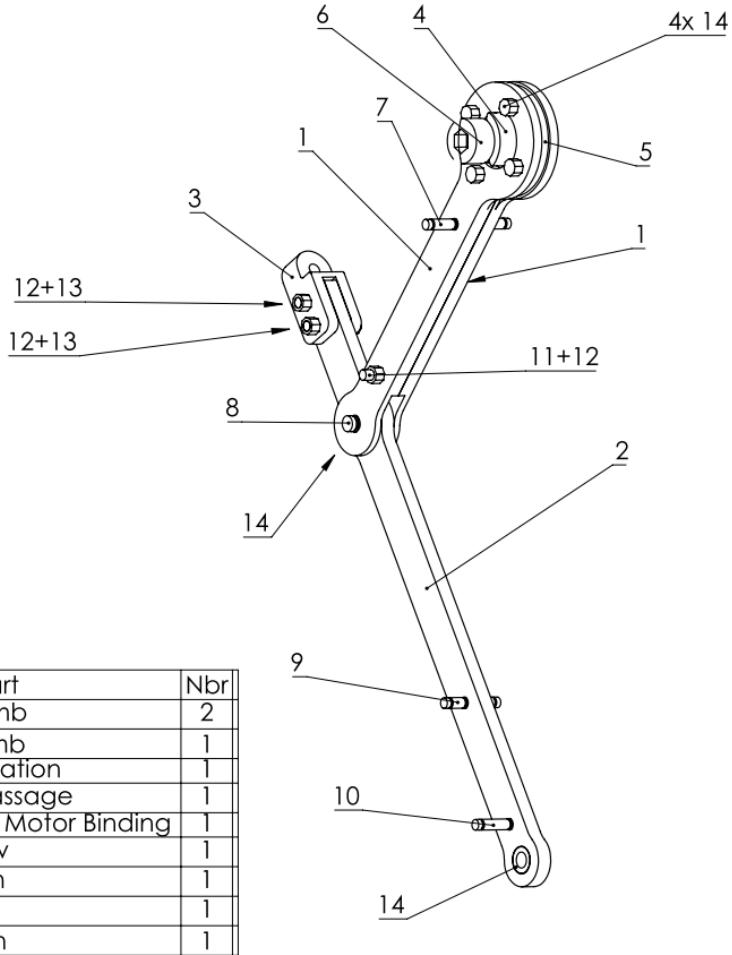
Speed Computation

```
freq = 250;
ExperimentNum = 5;

% Read C3D File
c3dfile = strcat('TakeNewleg_',num2str(ExperimentNum),'.c3d')
h = btkReadAcquisition(c3dfile);

% Extract Data
markers = btkGetMarkers(h);
mark1 = markers.Rigid_Body_1_Marker_1;
mark2 = markers.Rigid_Body_1_Marker_2;
mark3 = markers.Rigid_Body_1_Marker_3;
body = (mark1+mark2+mark3)/3;
% Note that mark(:,1) is X, mark(:,2) is Y and mark(:,3) is Z

% Take Area of Interest (when the speed on y axis is ~linear)
AOIbegin = 200;
AOIend = 700;
if(size(body,1)>700)
    body = body(AOIbegin:AOIend,:);
else
    body = body(AOIbegin:end,:);
end

% Computing Speed (from a 1 second sample)
if (size(body,1) >= 250)
    spdx= body(freq,1)-body(1,1);
    spdy = body(freq,2)-body(1,2);
    speed(ExperimentNum) = sqrt(spdx^2+spdy^2)
else
    speed(ExperimentNum) = 0;
end
```

Pitch and Roll Computation

```
%% stability
% fore marker : mark2
% hind marker : mark1
% side marker : mark3

d12 = 0.110;        % distance mark1 - mark2
d3  = 0.090;         % distance mark3 - droite12
d1p = 0.045;         % distance mark1 - pointP

roll = (mark2(:,3) - mark1(:,3));
roll = atan(roll/d12)/2/pi*360;
rollMean = mean(roll);
roll = roll-rollMean;
rollRMS(num) = rms(roll)

markp = mark1(:,3) + (mark2(:,3)-mark1(:,3))/10*3;

pitch = (markp(:) - mark3(:,3));
pitch = atan(pitch/d3)/2/pi*360;
pitchMean = mean(pitch);
pitch = pitch-pitchMean;
pitchRMS(num) = rms(pitch)
```

Appendix B: Drawings



N°	Part	Nbr
1	1001 - Upper Limb	2
2	1002 - Lower Limb	1
3	1003 - Spring Fixation	1
4	1004 - Cable Passage	1
5	Standard Servo Motor Binding	1
6	1005 - Hip Screw	1
7	1006 - Spring Pin	1
8	1007 - Knee pin	1
9	1008 - Cable Pin	1
10	1009 - Ankle Pin	1
11	Screw M2X10	3
12	Screw M2X6	4
13	Nut M2	3
14	Bearing	2

SAUF INDICATION CONTRAIRE:
LES COTES SONT EN MILLIMETRES
ETAT DE SURFACE:
TOLERANCES:
LINEAIRES:
ANGULAIRES:

FINITION:

CASSER LES ANGLES VIFS

1:10

REVISION

Cheetah - 2 seg leg

	NOM	SIGNATURE	DATE
AUTEUR			
VERIF.			
APPR.			
FAB.			
QUAL.			

TITRE:

Two Segment Leg

MATERIAU:

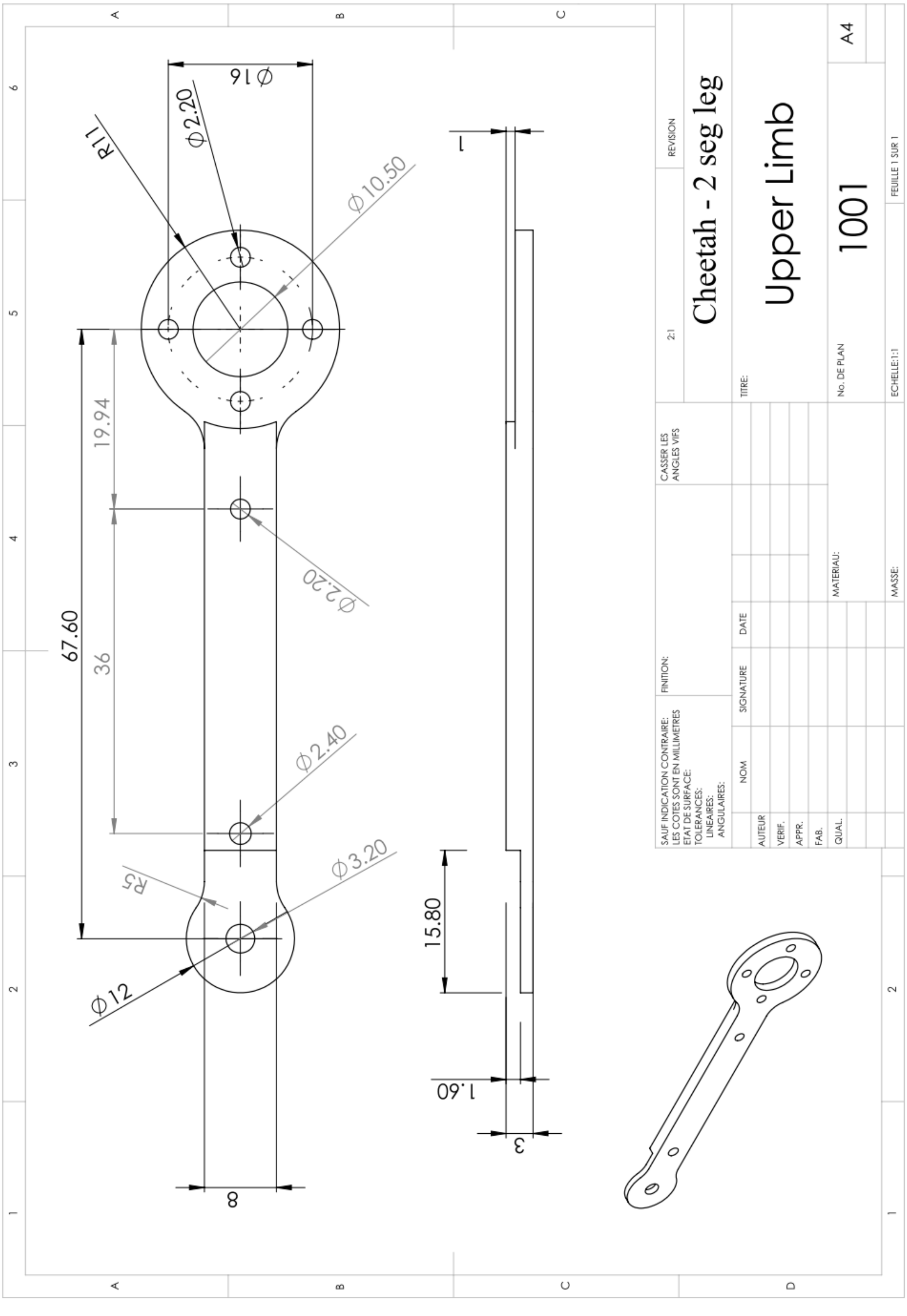
No. DE PLAN 1000

A4

MASSE:

ECHELLE:1:2

FEUILLE 1 SUR 1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Upper Limb
1001
A4
2:1
REVISION
TITRE:
No. DE PLAN
ECHELLE:1:1
FEUILLE 1 SUR 1
MATERIAU:
MASSE:
SAUF INDICATION CONTRAIRE:
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ETAT DE SURFACE:
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R5
Ø12
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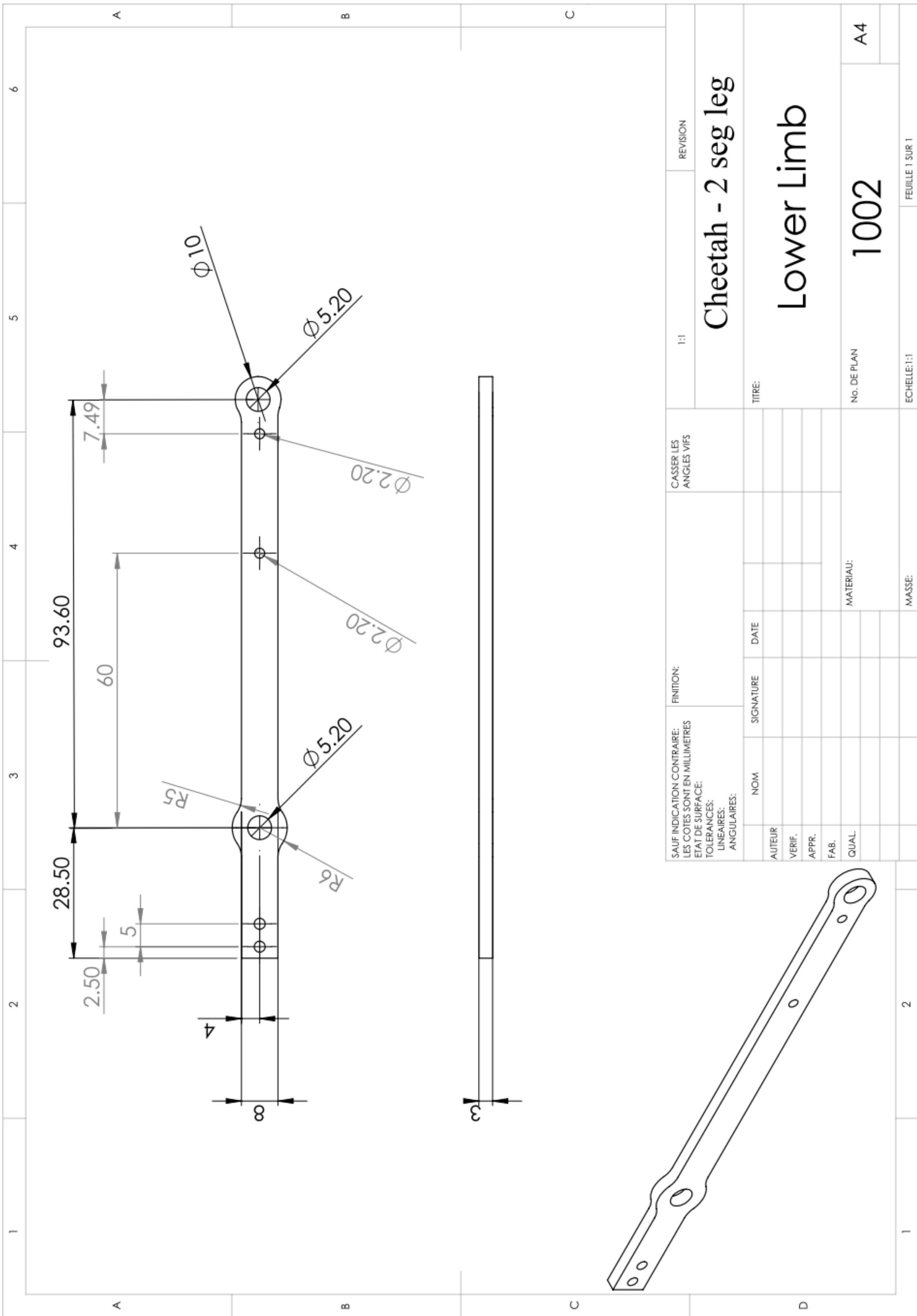
15.80
1.60
3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Lower Limb
1002
A4
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MASSE:
SAUF INDICATION CONTRAIRE:
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R6
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4
8
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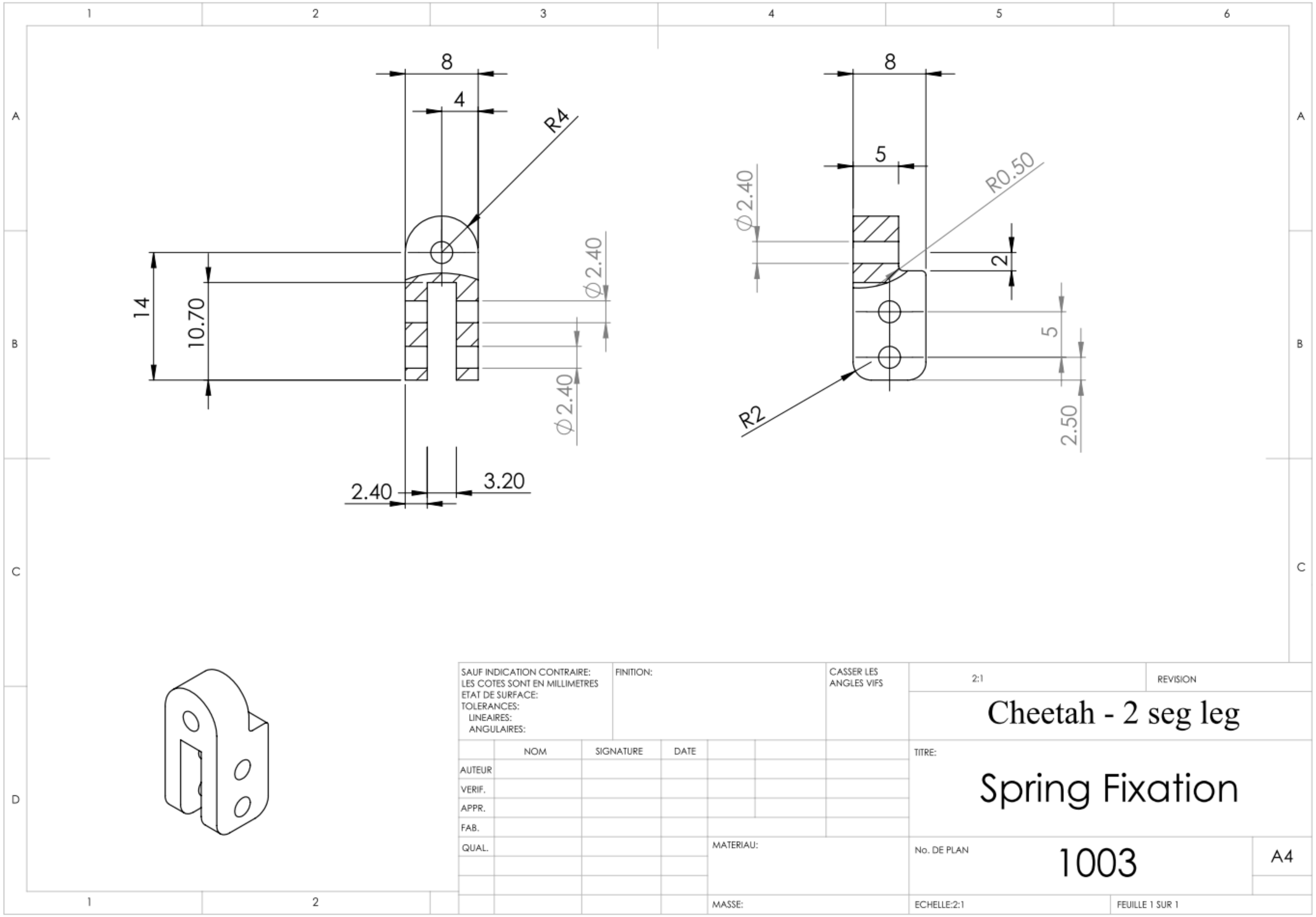
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Cheetah - 2 seg leg
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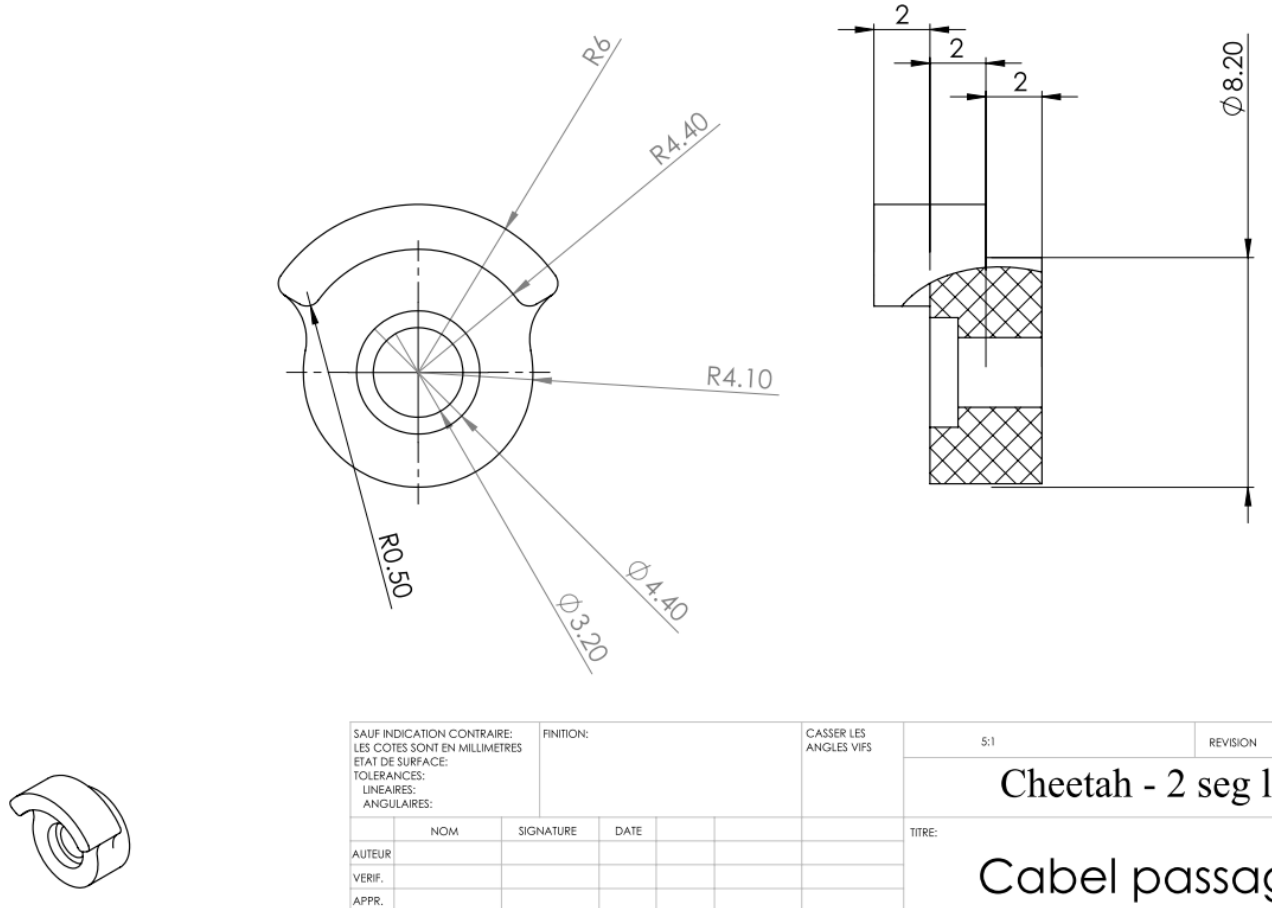

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CASSER LES ANGLES VIFS

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REVISION

Cheetah - 2 seg leg

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MATERIAU:

MASSE:

TITRE:

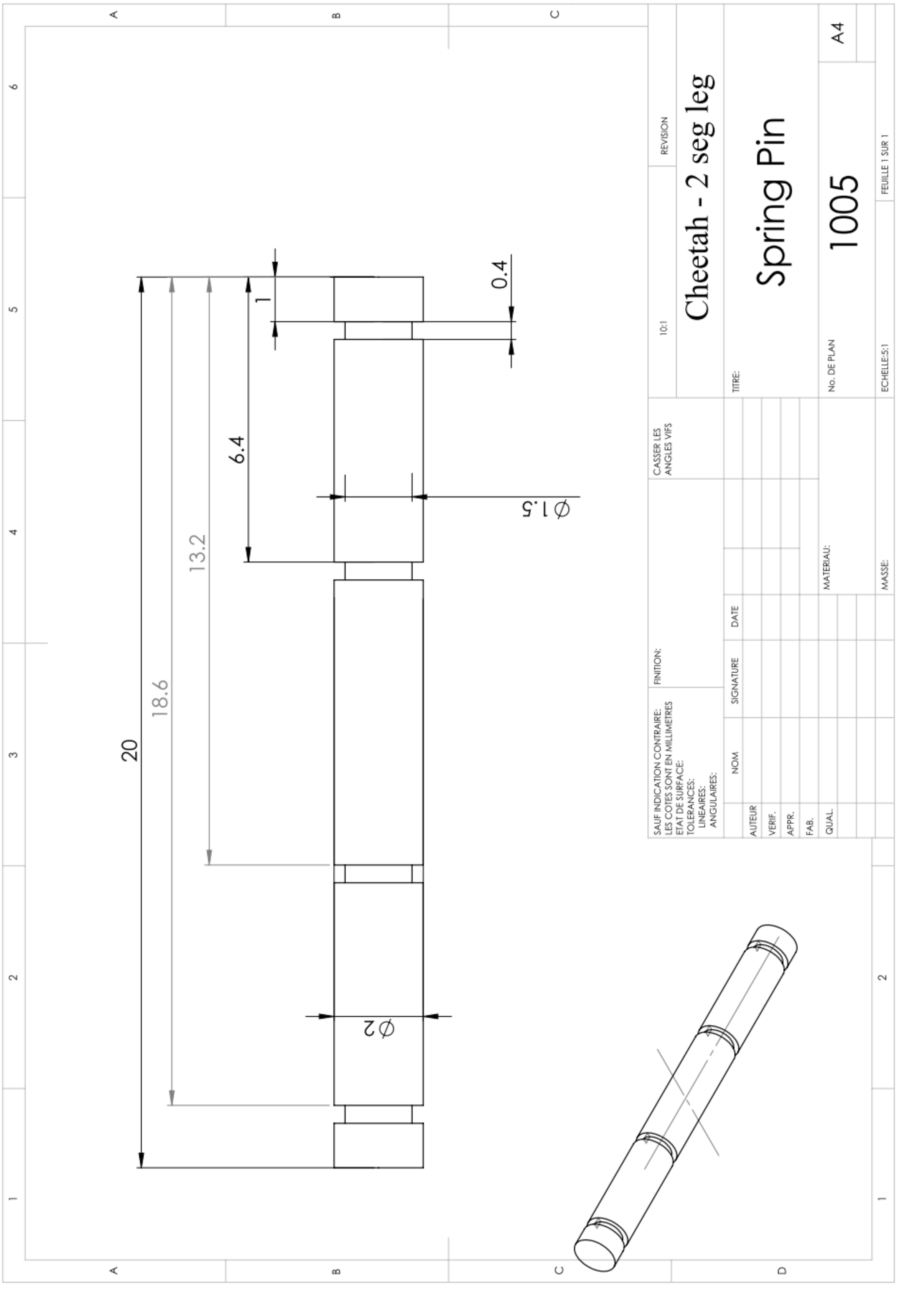
Cabel passage

No. DE PLAN 1004

A4

ECHELLE:1:1

FEUILLE 1 SUR 1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Spring Pin
1005
A4
10:1
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FEUILLE 1 SUR 1
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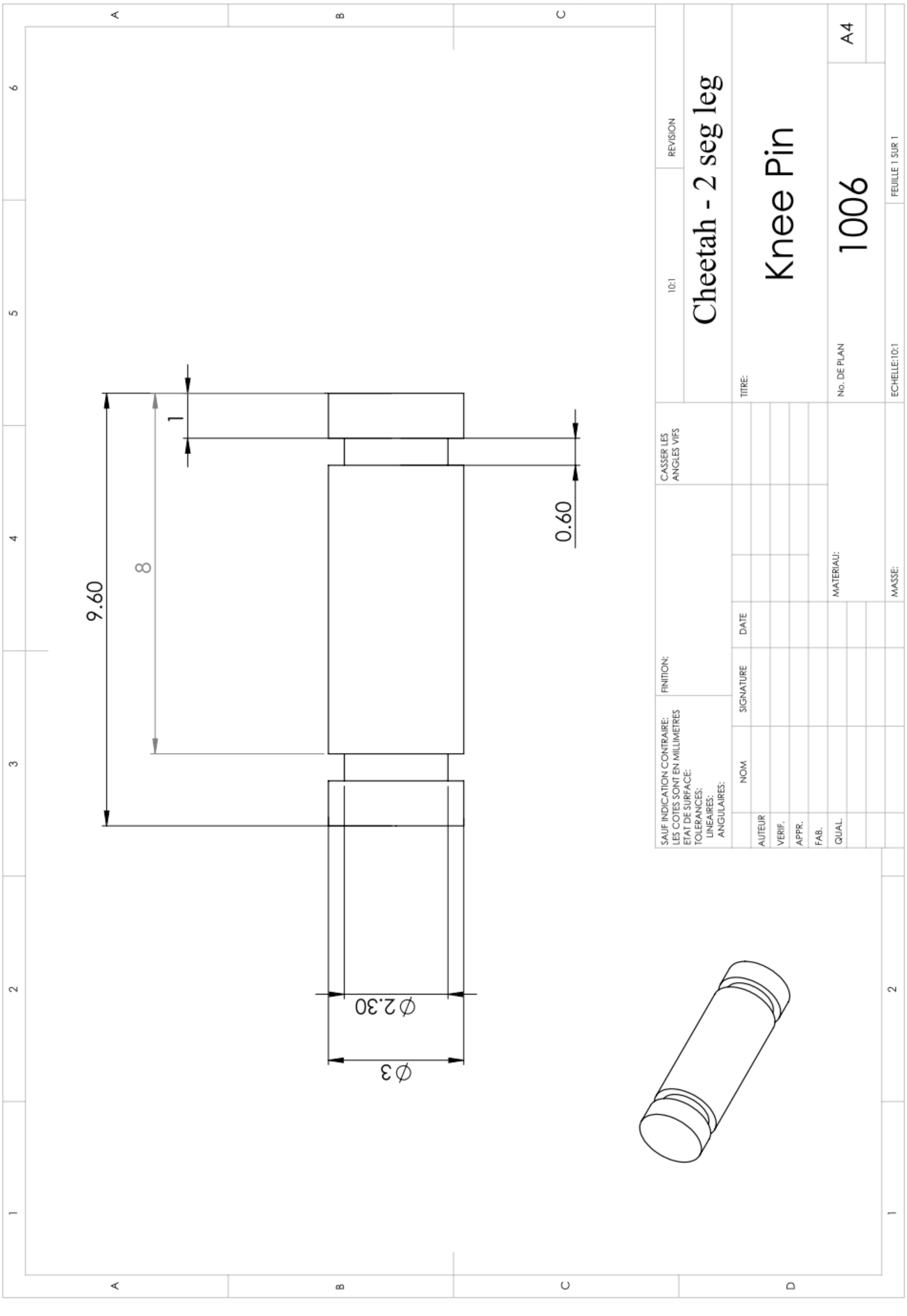
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1006
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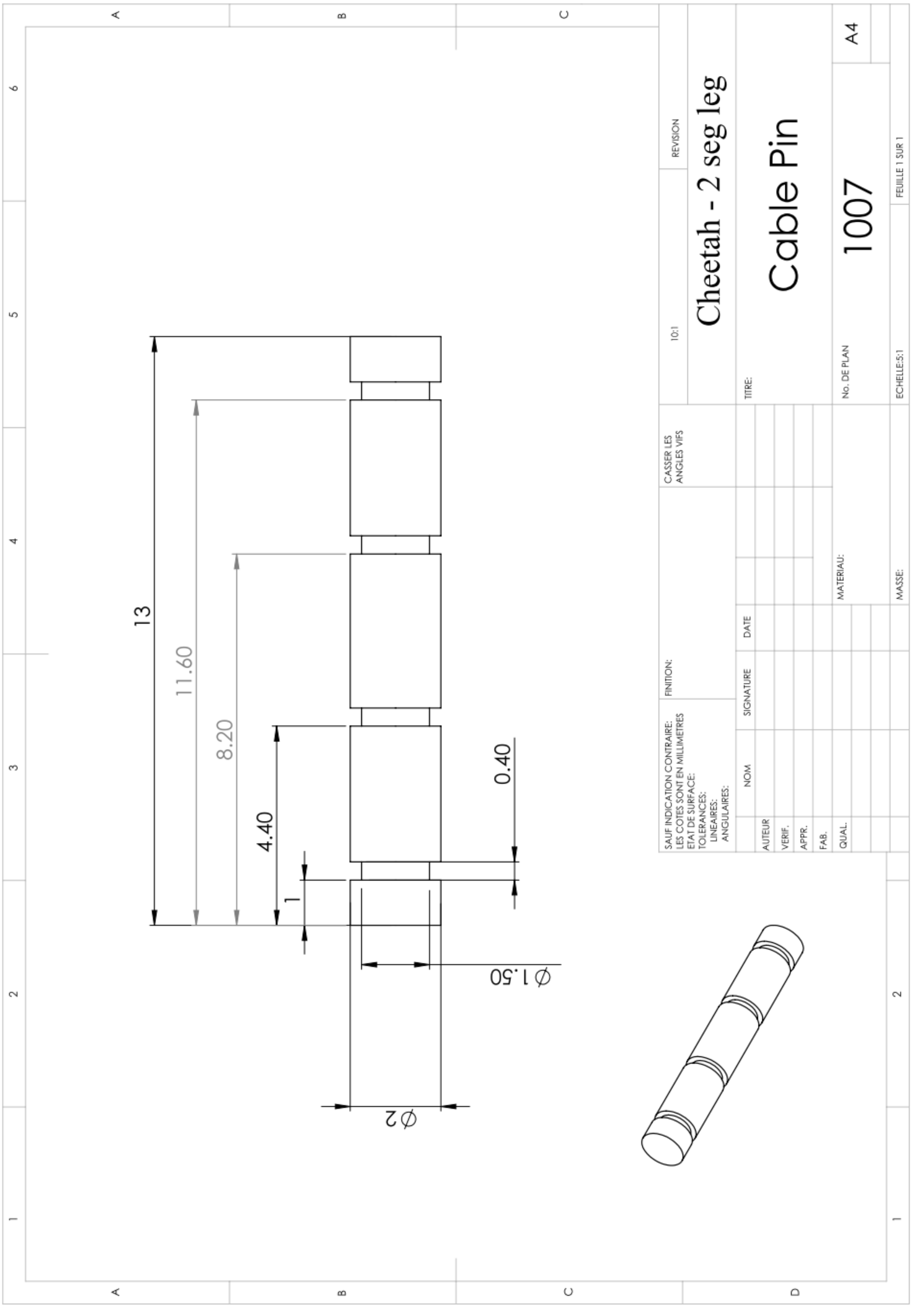
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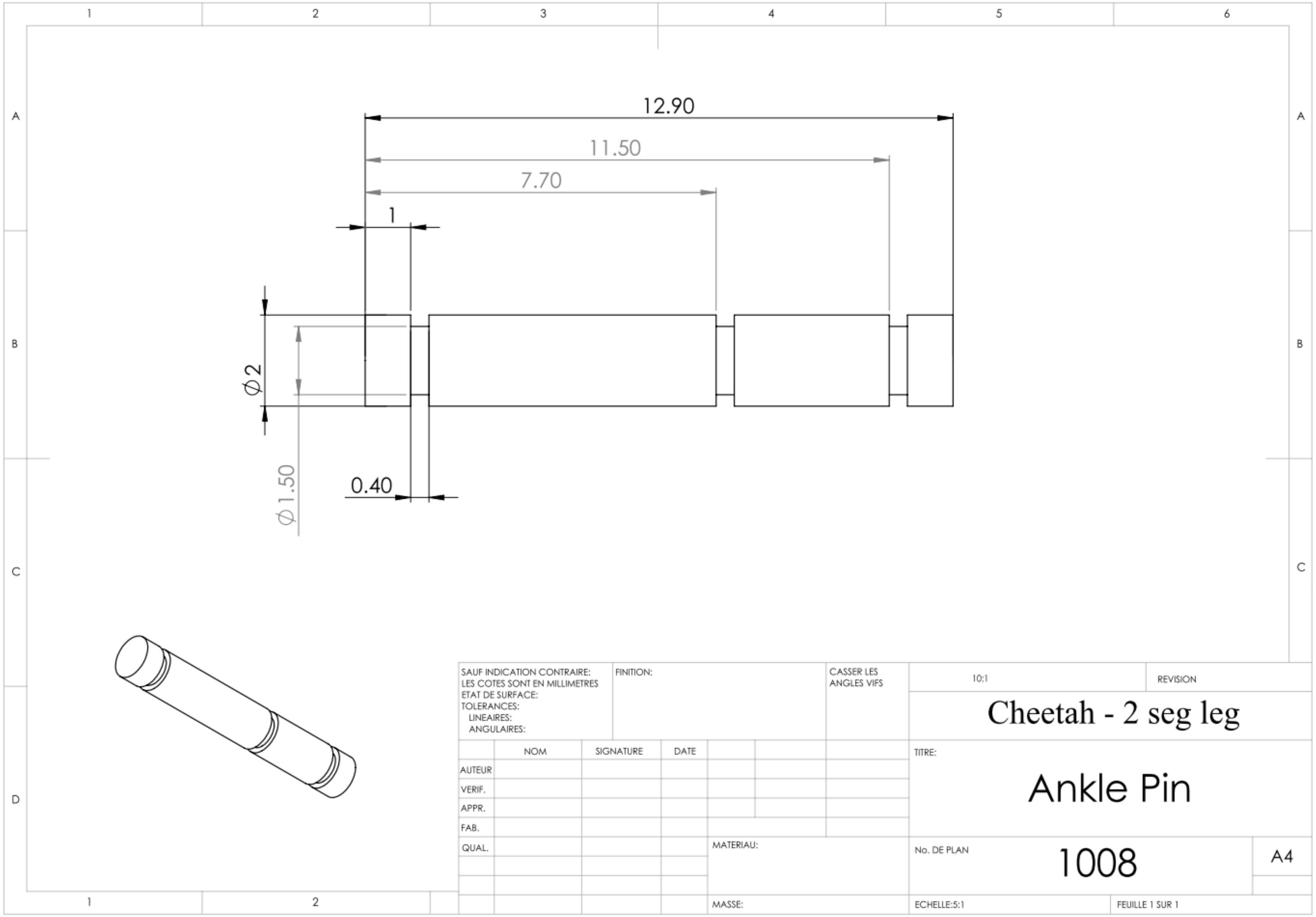
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