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DIEEI

“MIT Mini Cheetah redesigned in ABS”

Home Project A.Y. 2019/2020

MASTER’S DEGREE IN AUTOMATION ENGINEERING AND CONTROL OF COMPLEX SYSTEMS
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INDEX OF CONTENTS

INTRODUCTION

This project was developed as a final report for the *Complex Adaptive Systems and Biorobotics – Biorobotics Module* course, which the aim was to re-build and re-design the *Mini Cheetah* bioinspired robot from the *MIT (Massachusetts Institute of Technology)* to make it suitable for the 3D printing using **ABS (acrilonitrile-butadiene-stirene),** a particularly solid and cheap polymer that is considered very reliable for the construction of robotics' structures.

This report is focused on the improvement and the re-design of the robot's legs and the development of several different kinds of feet, since these parts are the most stressed during jumps and running phases, tasks for which this robot was originally designed and built.

The feet are quite different one to the other so the robot can walk in every kind of environment and they're fully interchangeable thanks to the universal link in the lower part of the leg.

Finally, a housing structure for a *Lidar* system was placed on the chassis, since the robot should be able to move in an undefined environment and orient itself in it.

1 - PRELIMINAR ANALYSIS

The robot's structure is natively predisposed to jump and run. Both activities stress its structure in a very huge way, so it's very important, when a new component is built, to perform a static analysis in order to see and quantify how much the entire structure is stressed during these particular operative conditions.

To quantify the impulsive force after a jump the "***Impulse and momentum theorem***" was used:

$F = \frac{mv}{\Delta t}$ with v as the velocity at the time of the impact with the ground.

$$v = t * g; \qquad h = \frac{1}{2} * g * t^2; \qquad t = \sqrt{\frac{2*h}{g}}; \qquad \text{with } g = 9{,}81\,\frac{m}{s^2}$$

From these formulas the velocity has been calculated:

$$v = \sqrt{2 * g * h}$$

So that:

$$F = \frac{m * \sqrt{2 * g * h}}{\Delta t}$$

By substituting numbers to letters in the previous equation, it's possible to determine that for a 50cm height jump and a 0.3s contact time with the ground, for each leg acts a force of 50 N.

We indicate as "*contact time* Δt" the time that the robot's structure takes to perform a compression-expansion operation once, after a jump, it touches the ground again.

1.1 - SAFETY FACTOR

During the development of the new robot's structure, a finite element analysis was performed for each component, and a parameter called **safety factor** was taken into a very big consideration.

The **Factor of Safety (FoS)** is how much could a system withstand beyond the expected loads or actual loads. It is also known as safety factor and it's often calculated by using ratio of the ultimate load to the allowable load for a model or structural design. [1]

This value is dimensionless and considers the yield's tension of a ductile material that depends on the physical and chemical characteristics of the material itself, and indicates the strain's values for which it's possible to see a plastic deformation of the structure, from a point when the material can return to the original condition to a situation when it irreparably breaks or is permanently deformed. In this report the safety factor was considered as a main parameter to study the response of the structure to a stress, since it's very good to have an idea on the maximum load that the structure can bare before being irreversibly compromised.

From literature is known that an acceptable security factor should be more or equal to 2 or 4, or between these two values [2].

Higher the factor, more robust is the structure to external stress, while a value less than 1 usually means that that part of the body is affected by permanent deformations.

Using *Autodesk Inventor Professional 2020* was easy to see the robot's most stressed areas since the software is able to find them automatically when the user builds a force vector on the considered part. It also indicates with different colors from blue (big safety factor) to red (small safety factor) all the yield's areas: obviously, the red areas are more apt to suffer for permanent deformations even if it's always important to take into account the numerical value given by the software, in order to better understand what happens to the structure and if it can be considered as "solid" or not.

2 - ORIGINAL STRUCTURE

The original *Mini Cheetah* is showed in *Fig 1*. The structure was originally built using mainly aluminum, a material that's far more ductile and resistant respect to the ABS plastic.

So, starting from these considerations, it was obvious that the original structure required some modifications in order to make it more robust and suitable for jumping and running activities, even because the finite element analysis performed on this structure using ABS instead of aluminum gave very bad results.

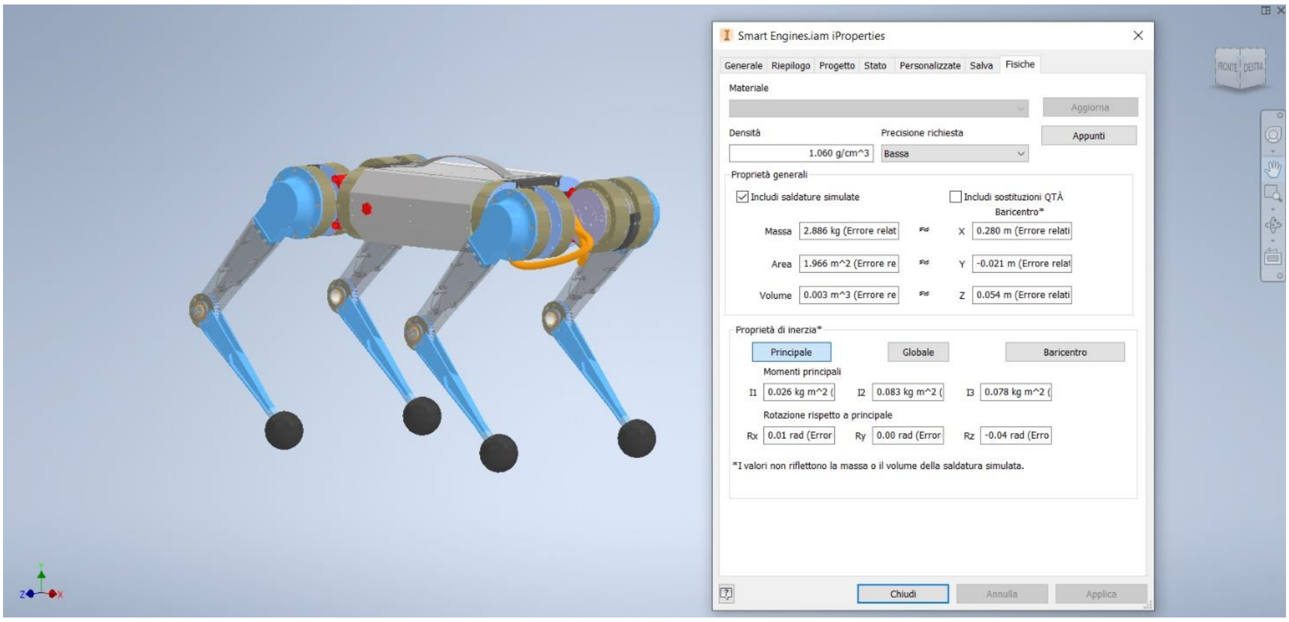

Figure 1 – Old Mini Cheetah's structure

3 - NEW STRUCTURE

The *Fig.2* shows the new *Mini Cheetah* robot's structure. In particular, legs, feet and femur were radically readapted to make the new structure, made of ABS plastic, more robust and suitable for jumping and running.

The new robot is heavier than it used to be, since now it weights 3,740 kg respect to the initial 2,886 kg. For the weight's computation, only the bare structure was considered, since for every haunch there are two motors which haven't been taken into account for now and that transmit the motion to the rest of the leg.

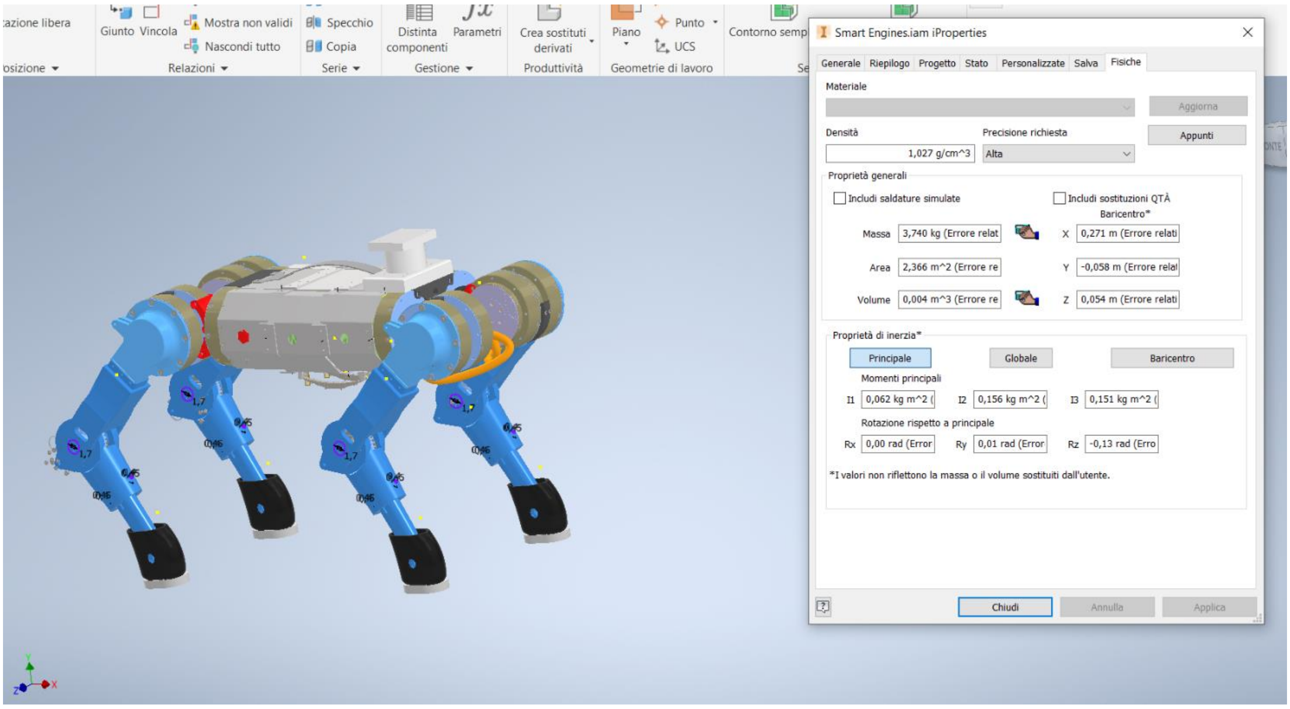

Figure 2 – New Mini Cheetah's structure

4 - FINITE ELEMENT ANALYSIS FOR THE NEW STRUCTURE

4.1 - FEMUR'S ANALISYS

The femur was modified less than the other parts of the leg, since it was compulsory to respect a link between the upper part of the femur and the lower part of the haunch which couldn't be modified due to the fixed positions of the motors. For this reason, the link between the femur and the haunch is the same as the original one, while the rest of the bone was enlarged and made more robust in order to house the new leg.

The femur's version that is reported and analyzed here is the final one and the best among all the versions that were made since the beginning of this work and its end.

This version responds very well to stress and was build making several experiments and trials, that helped to develop this "final version".

The sizes respect to the three geometrical axes are:

x: 4,5 cm

y: 14,34 cm

z: 5,4 cm

Differently from the original structure that was divided in two parts made as one with screws, now the femur is just one, big, compact piece with an empty space inside that performs two functions:

- Make the robot lighter: accordingly to the cats' biology, which have very thin and flexible bones that guarantee them high speed and agility [3], it was decided to imitate this structure as much as possible.
- Is the perfect space for a drive belt that, from the motors through a small wheel gear between the femur and the tibia, transmits the movement from the motor to the legs.

Given a force of 50 N applied in the direction in *Fig.3* and considering the base of the femur as fixed, the software gave a very good result since the safety factor was higher than 15 for the whole piece: it means that this part, thanks to the fact that's connected to two other components that are able to rotate, is not very stressed; moreover, as it's been said before, its structure is very robust by itself so even if the empty space inside is very big, the reliability is always guaranteed.

It should also be considered that the lower part of the femur is linked to the rest of the leg with screws and a wheel gear, that make the real structure even more robust since it allows it to rotate a little bit during the impact with the ground, reducing the power of the impact that the structure has to release.

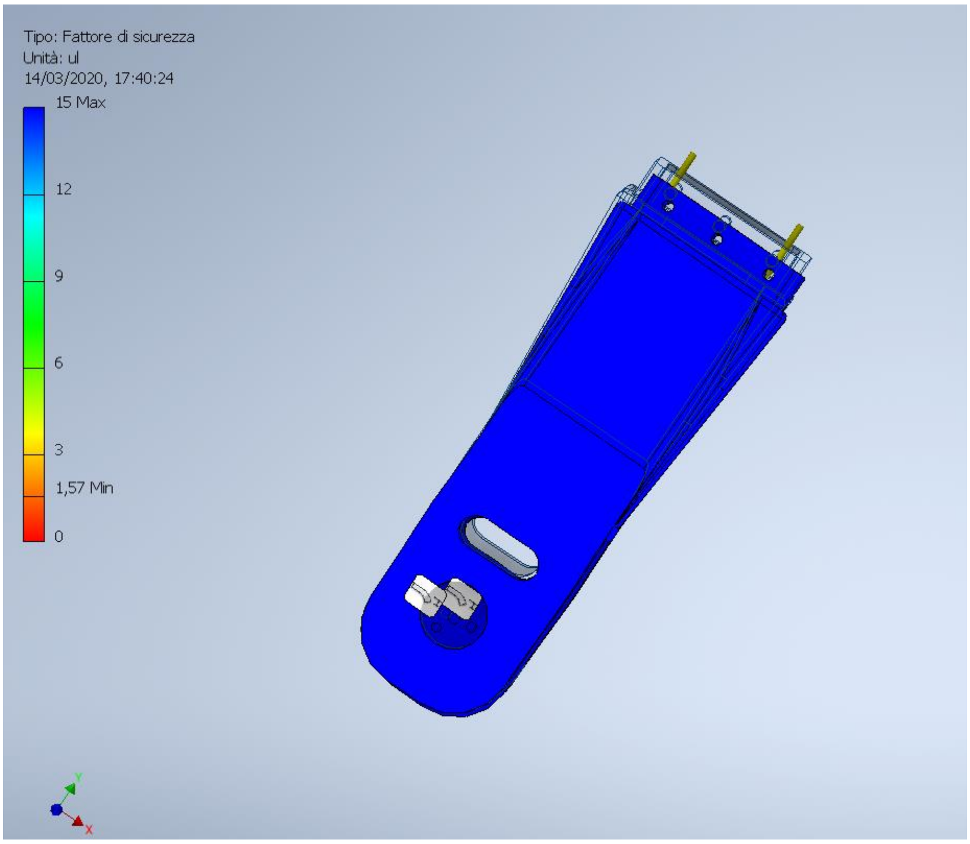

Figure 3 – FEA Analysis of the femur

4.2 - LEG'S ANALISYS

Due to some issues with the available 3D printer, all the parts must have a maximum length of 15cm: this is the reason why the leg was split in two different parts connected with a screw and two sliding guides, that have the double feature to make the structure more robust and to better link the upper and the lower part of the leg.

4.2.1 - UPPER LEG

In *Fig. 4* the upper part of the leg is showed. Since the dimensions of the gear were fixed, it was necessary to keep the original holes' dimension and places. As it's possible to see, this part is also characterized by a small hole to the right: it's the space that would allow the fixing of a tendon intensively studied in previous researches, that should reduce the impact force on the structure after a jump.

Two more small holes were made in order to link the upper and the lower part of the leg with a screw and the structure is empty so it's lighter and it's possible to put sensors and whatever is needed inside it.

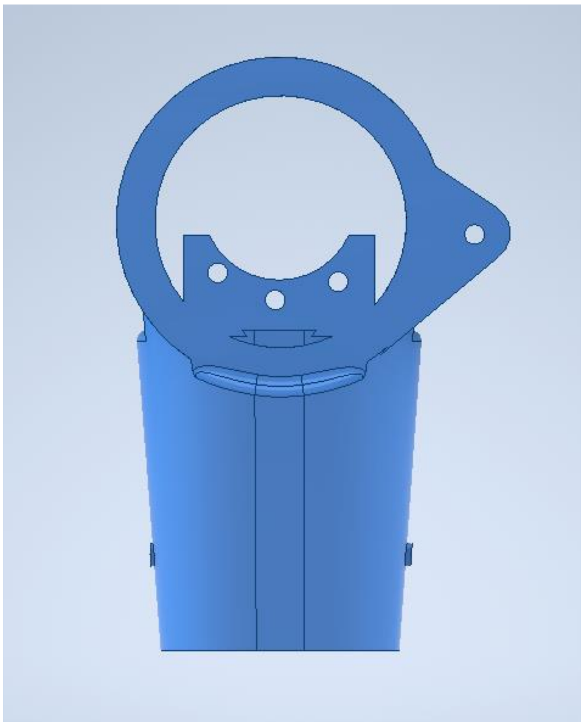

Figure 4 - Upper leg side picture

The *Fig. 5* shows a bottom sight of this component, so it's possible to see the "male" sliding guide symmetrically built in the internal part of the leg. These sliding guides make the structure more robust and help, along with the screw, the fixing of the two parts of the leg together.

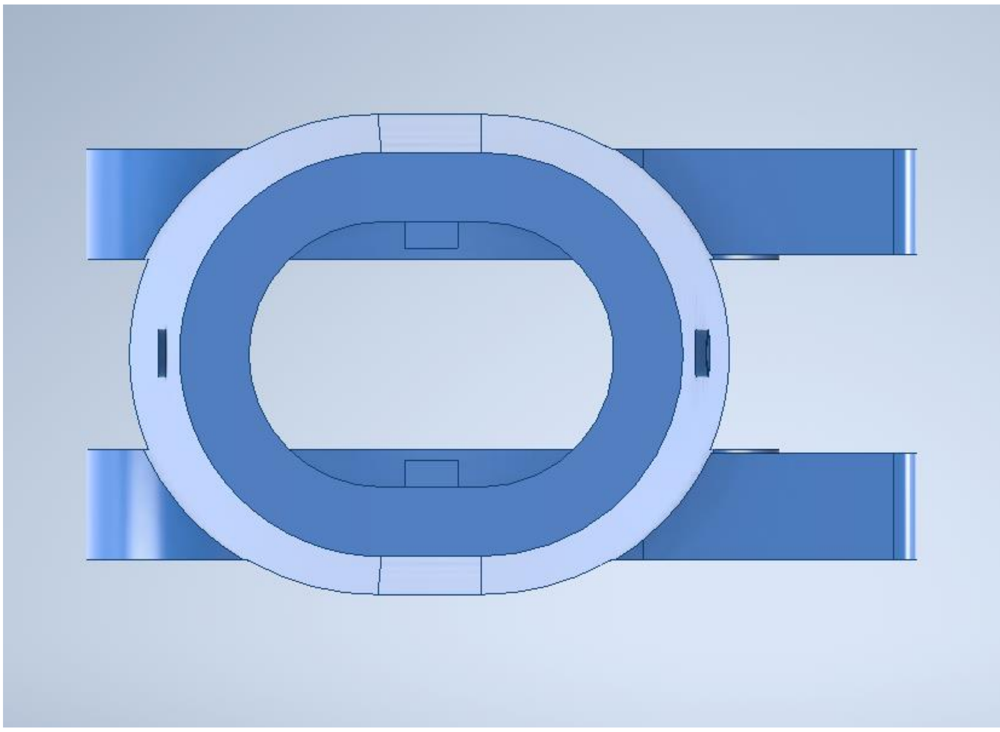

Figure 5- Upper leg, picture from the bottom

The dimensions of this part are, accordingly to the axes:

x: 7,5 cm

y: 11 cm

z: 4,5 cm

4.2.2 - DOWN LEG

The "*down leg*" component is complementary to the "*upper leg*". It is characterized by the "female" part of the sliding guide and two small cavities to fix the upper leg with a screw, a bigger hole at the bottom to allow the fixing of the different kinds of feet and a "*fork connection"* where, just in case, it would be possible to fix the original foot of the robot, the so called "*small tennis ball foot*".

Moreover, as it's possible to see in *Fig. 6*, this leg is empty for the same reasons of the upper part, but in this case there's also a buttonhole to better fix whatever is needed, since this component is very small so it could be very difficult to put something inside it without a "window".
Although this buttonhole seemed to make the structure more fragile, the FEA analysis showed that it is not true.

Figure 6- "Down leg" picture

The dimensions of this component, accordingly to the axes, are:

x: 3 cm;

y: 12,6 cm;

z: 2,2 cm.

4.2.3 - FEA ANALISYS

To successfully perform a reliable FEA analysis, the whole leg was considered and examined: four links were added between the upper and the lower part of the leg, to simulate the screw.

Six pins on the upper part of the leg were also considered to simulate the link with the gear that would allow the leg to rotate along with the motors.

A 50 N force was applied as it is possible to see in *Fig. 7* in the direction of the impact, so the software is able to calculate the impact's response in a more reliable way: it comes out that such a leg is very strong and robust, in fact the software gave for the whole structure a security factor always more or equal than 15, which means that the new leg is better than the original one that was intensively examined in a previous research.

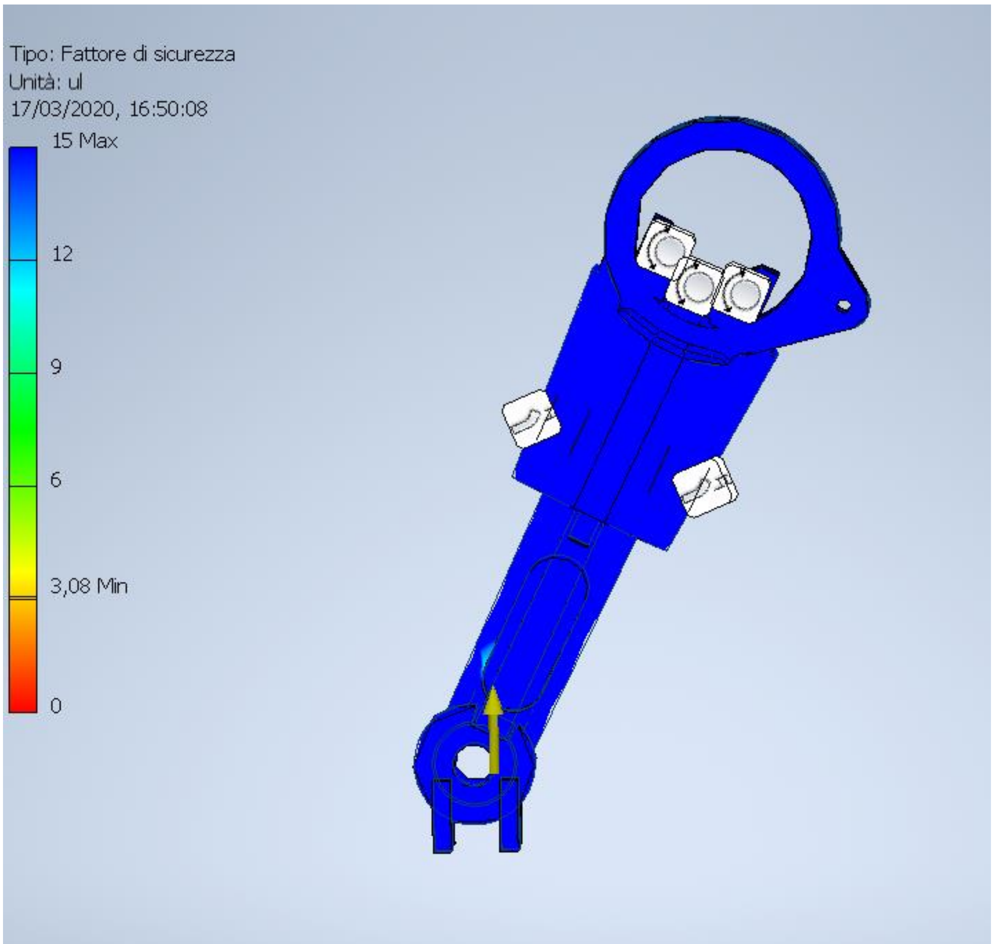

Figure 7 - FEA analysis to the leg

5 - NEW FEET FOR DIFFERENT KINDS OF ENVIROMENTS AND AIMS

5.1 - “SPHERICAL” FOOT ANALISYS

A spherical foot was developed to prevent the robot from falling while running and jumping in a controlled environment, where the ground is flat and without big obstacles. The spherical structure is very similar to the original foot because it has the same benefits but it’s bigger, so it gives a wider contact area that increases the equilibrium of the robot.

The foot is printed with an elastic material similar to ABS plastic and is fixed to the rest of the leg with a custom pin.

The *Fig. 8* shows the foot attached to the leg.

Since the foot is spherical, its dimensions are considered just by measuring the diameter of the sphere itself, that’s about 8 cm.

Figure 8- leg with the spherical foot

5.2 - ”HOOF” FOOT ANALISYS

This foot was mainly developed to allow the robot to walk in a steep environment. The dimensions in the three axes are, respectively:

x: 4 cm;

y: 6,6 cm;

z: 5 cm.

As it’s possible to see in *Fig. 9*, the foot is equipped with a sort of “*sole*” that will be filled with a gel glue with the help of a ring with the same dimensions of the foot.

After the holes are filled with glue, it’s possible to fix another sole made of elastic material to the base of the foot, which will give it more grip during the walk phase.

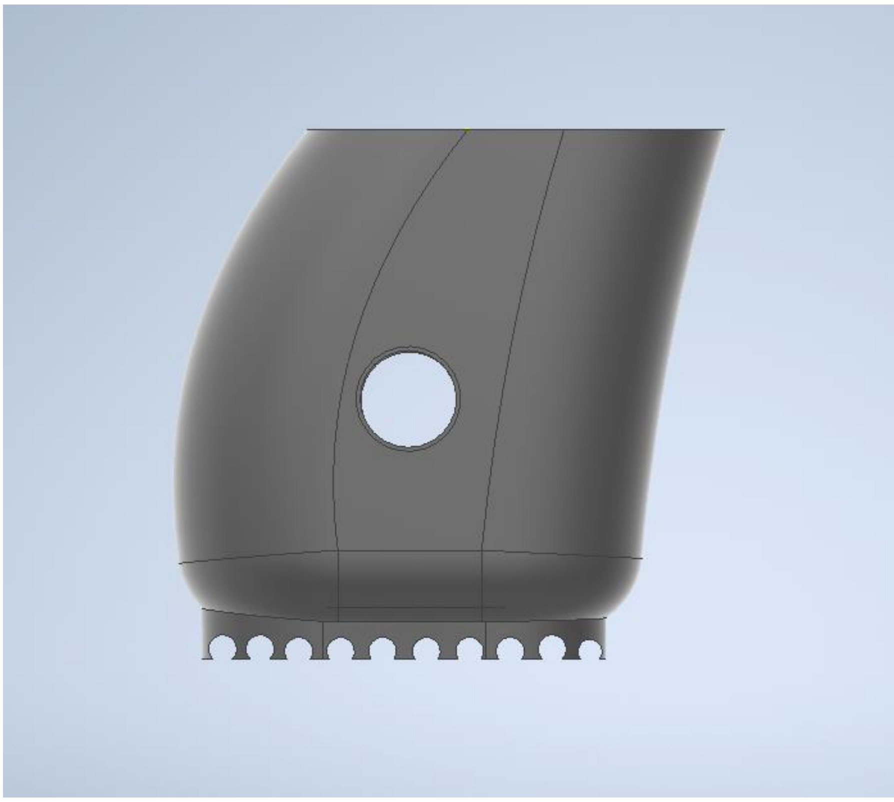

Figure 9 – “Hoof foot”

The base of the foot is also not perfectly square but quite rounded, so the robot can still maintain the equilibrium while it walks.

Moreover, while the structure is quite big on the base, when moving to the ankle it's possible to see that it becomes smaller: this is to prevent small stones, dust and other materials from the environment to get into the foot.

Finally, its internal part contains a custom housing for the leg, so the robot is more stable and the foot itself is linked in a much more robust way.

In *Fig.10* it's possible to see the internal part of the foot and the housing that perfectly contains the leg.

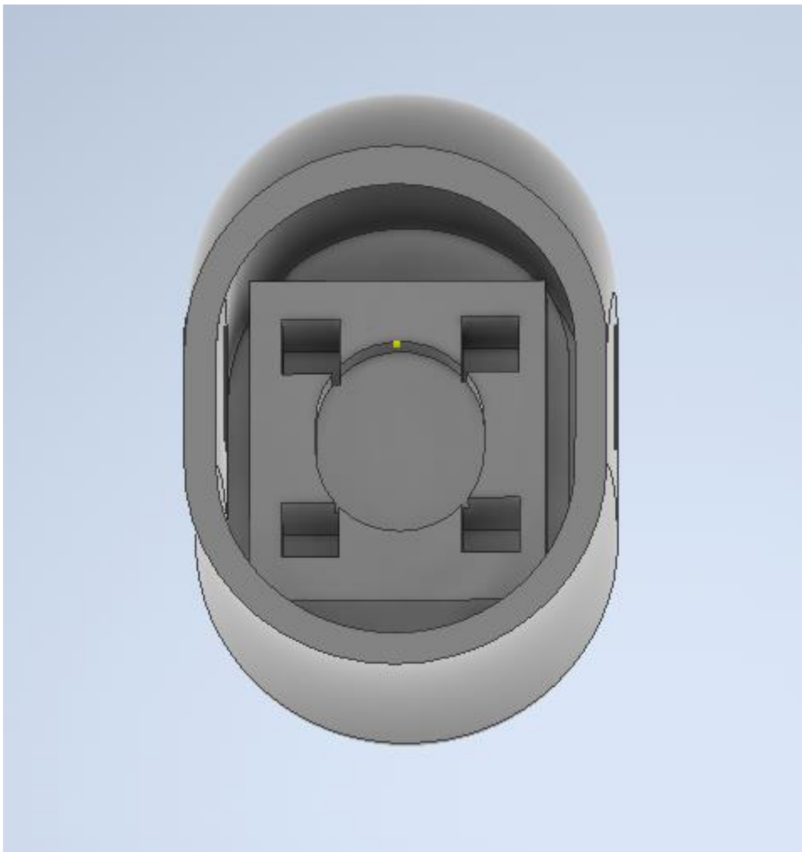

Figure 10 – "Hoot foot" internal part

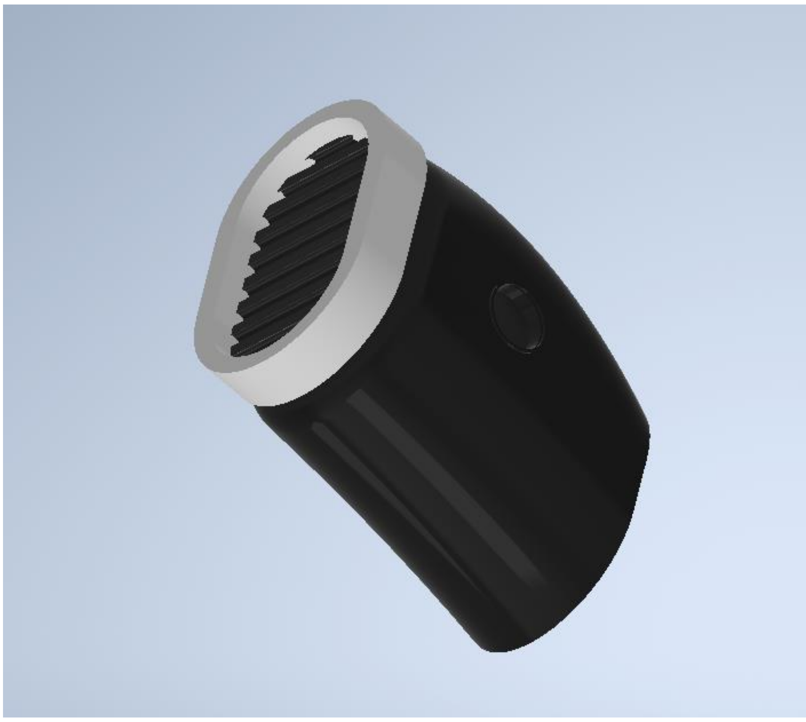

Figure 11 – The custom ring made for filling the sole with gel's glue

Figure 12 –The leg with the "hoof foot" equipped

5.3 - "PROSTHETIC LEG" MODIFICATIONS

The "prosthetic leg" foot [4] that was adapted to the purpose of making this robot walk, was already intensively studied in a previous report, so it won't be the focus of this research to study again its properties and to see how it responds to the FEA analysis, since this research has been already done. Though, a couple of changes were made to this foot in order to make it more suitable to the new leg. The original foot is showed in *Fig.13*: it was originally split in two parts that were then unified, so the foot could be successfully printed and mounted on the robot.

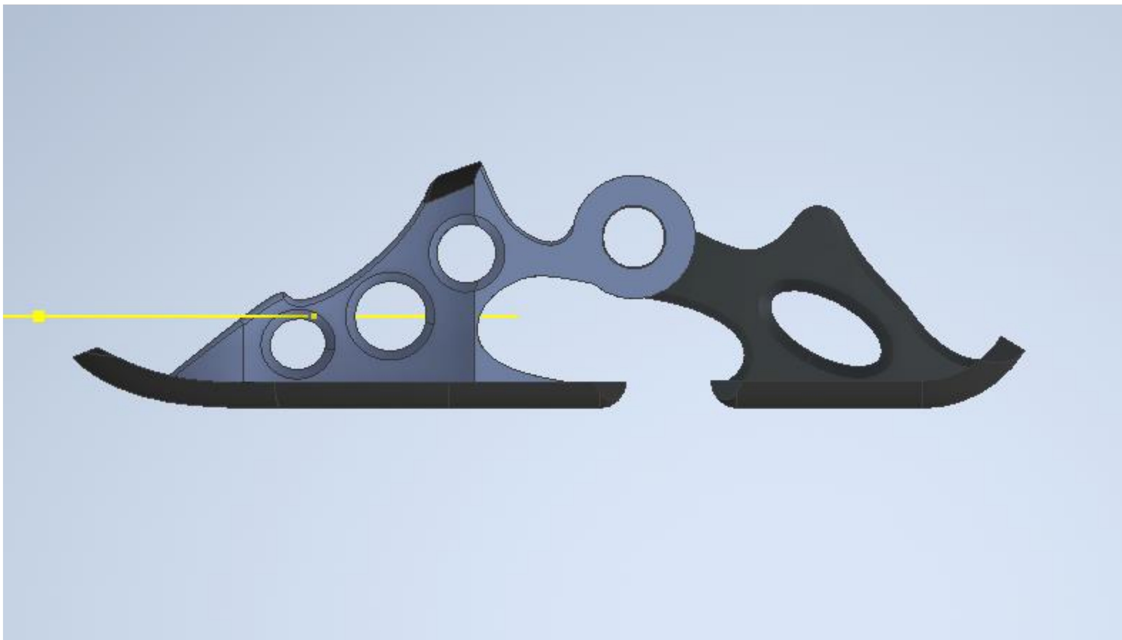

Figure 13 – The original "Prosthetic Leg"

The necessity of using such a foot came from the idea to fix a flexible "*tendon*" between the foot and the leg, to better release the impulsive force on the ground after a jump: so the foot was modified adding a small strap to meet this purpose. The entire structure was also made quite bigger than before to better house the leg, since the original foot was too small to do that.

In *Fig.14* the final “prosthetic leg” foot is showed.

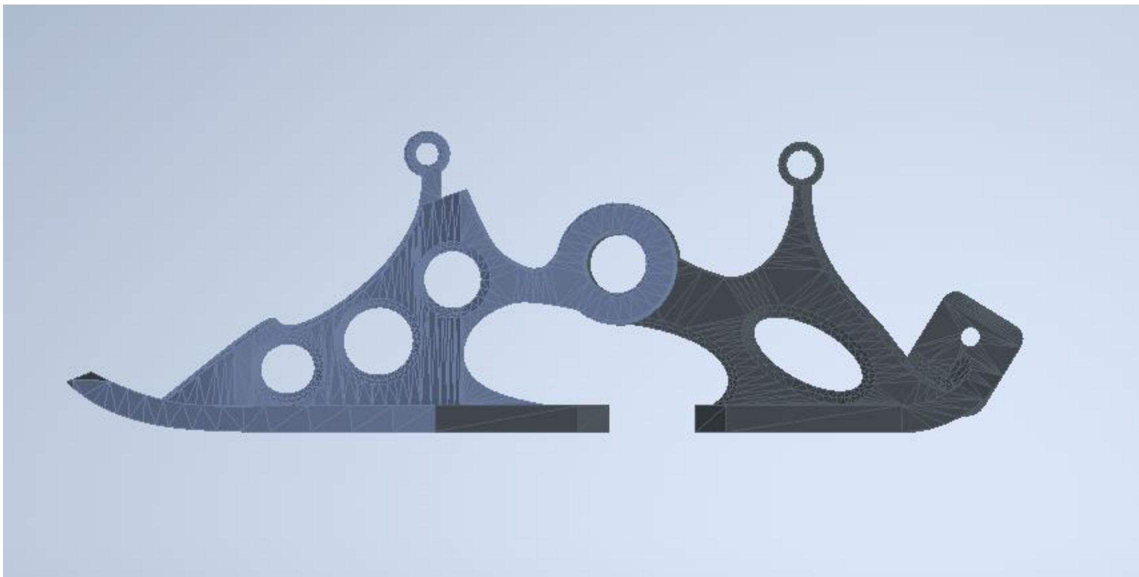

Figure 14 – The modified “Prosthetic Leg”

The dimensions of the new foot are, respectively:

x: 5,4 cm

y: 18,8 cm

z: 6,2 cm

6 - STRUCTURE FOR THE LIDAR'S HOUSING

Since the aim of this robot is to move and orientate into unknown places, it should be equipped with sensors and instrumentations that allow him to not get lost while walking into a new environment. While different kinds of sensors can be put everywhere on the robot, the main idea was to give it a *Lidar* orientation system.

A *Lidar* is a surveying method that measures distance to a target by illuminating the target with laser light and measuring the reflected light with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. [5]

Figure 15 – Lidar system

Since *Lidars* can be very light and small nowadays, a small structure was built in order to house it in a way that the robot can scan the whole environment around it. In fact, if it's able to build a 3D map of the surrounding environment, by programming an opportune control strategy the robot can perform all the tasks it was developed for.

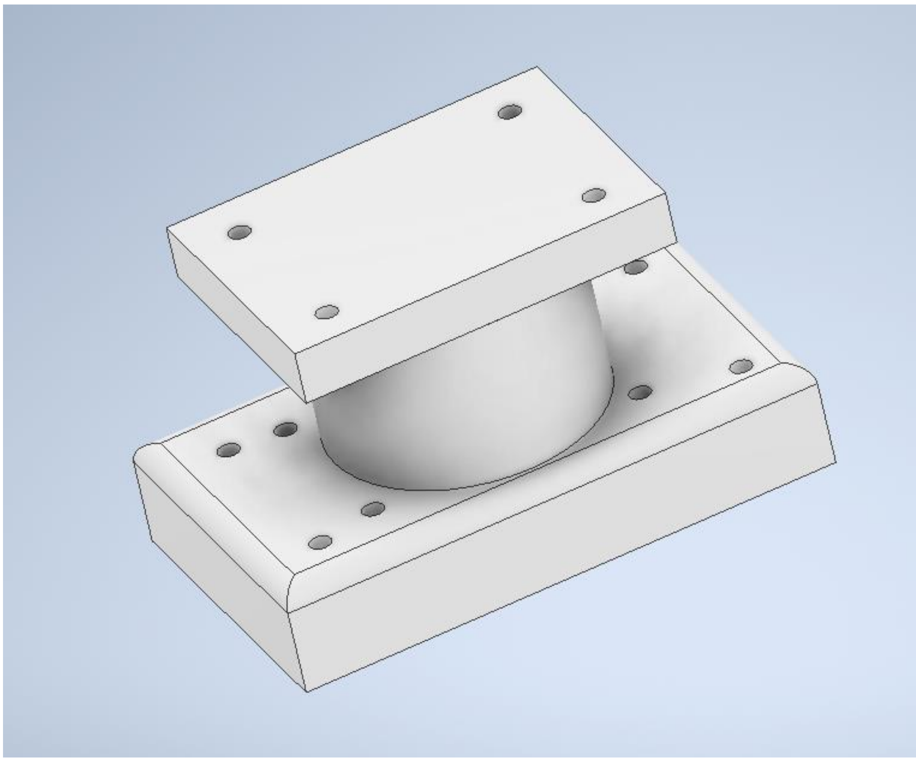

Figure 16 – Lidar's housing

As it's possible to see in *Fig. 16*, the structure is very simple since it contains just four holes to fix a lidar on the upper base, while the lower base is fixed to the robot's chassis.
Since the lidar's housing was just an idea to be well developed in the future, this is just a prototype that has to be better defined in future researches.

7 - CONCLUSIONS

The aim of this research was to develop a new structure for the Mini Cheetah bioinspired robot, and at the end the goal was achieved, since the new components are better than the old ones in terms of stability and robustness, considering that the new structure has to be realized in ABS plastic rather than aluminum.

Some of these pieces have already been physically realized using a 3D printer with very good results, even if some of them was then modified in *Inventor* after the printing in order to fix and improve some features.

Anyway, the last modified pieces are the ones that were intensively studied in this report and should be the most suitable for building a working bioinspired robot with a flexible structure, able to walk, run and jump as the original one and also able to move and orientate in every kind of environment, from planar grounds to steep woods.

The robot’s chassis wasn’t touched at all in this research due to time reasons and the fact that it was very difficult to work with 3D shapes, but the structure should be robust enough to contain the batteries and the electronics that would allow the robot to move.

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