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# DELIVERABLE 2.2
## First Prototypes of Passive and Active sole

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# 1 Introduction

This document reports the description of the first prototypes of the passive and active THING adaptive feet, developed by UNIPI in collaboration with QBROBOTICS. This activity has been carried out within Task 2.3, the description thereof is as follows.

**Task 2.3 - Adaptive Foot Design**

Based on the design already developed in UNIPI, a novel robotic foot will be developed in agreement with the specifications derived in T2.1.
Based on our experience in the development of dexterous robot hands and on the specifications (outcomes of T3.1), we will evaluate different mechanisms to robustly and reliably hold to the ground. Two foot solutions will be tested, and compared with the classic rigid foot: passive adaptive foot, and active adaptive foot. The actuation will be included in the foot design taking into account all the measurements to comply with the specifications (e.g. remotized actuation to have proper IP).
The workflow toward the foot realization will be composed of three phases. In the first phase prototypes of active and passive adaptive foot will be realized. Then a testing phase will follow which will provide feedback on how to improve the foot design and the choice on the robot configuration (e.g. two active and two passive feet). In the third phase the foot design will be finalized.

This document, intended to give an overview of the first two prototypes of the adaptive feet, has the following structure.

In Section 2 the first prototype of the passive adaptive foot is described mainly from a technical point of view; then its main features and limitations are presented.

Section 3 depicts the initial version of the actuated adaptive foot, discussing its main technical traits and features.

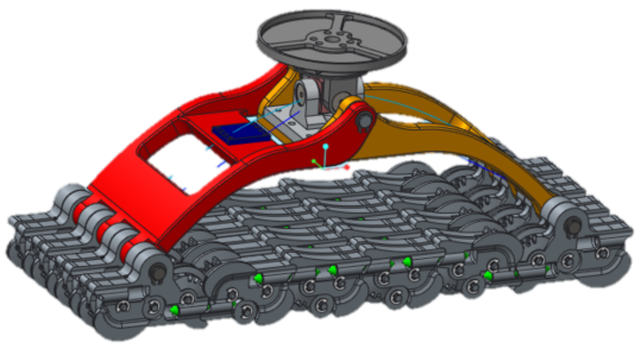
Finally, Section 4 quickly compares both the prototypes and draws some relevant conclusions.

# 2 Passive Adaptive Sole

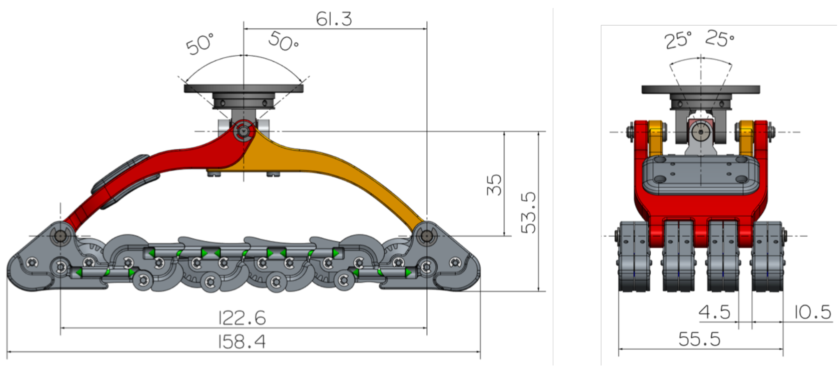
In this section a detailed description of the first prototype of the passive adaptive foot is given primarily from a mechanical point of view. Some details about the related sensing system and software are also briefly discussed.

## 2.1 Foot Design

Taking inspiration from the anatomy of the human foot and from previous works from UNIPI [1, 2, 5], particularly in the field of soft adaptive underactuated robotic hands and feet, a first prototype of passive adaptive foot was devised (Figure 1).



(a) A three dimensional CAD view of the passive adaptive foot.




(b) Front and side CAD views and the relevant dimensions of the passive foot.

Figure 1: CAD view of the mechanical design of the passive foot.

The proposed design, shown in Figures 1a and 1b, consists essentially of six main components:

- an ankle base,
- two arch links and
- four chains of phalanges.

The leg of the robot is meant to be connected to the ankle base, to which two arch links are attached by means of a double revolute joint. Finally, the extremities of the arch links, which are opposite to the ankle base, are connected to each other by means of the aforesaid chains.

With a height of around 60 mm and a footprint area of almost 86 $cm^2$, the whole prototype weighs approximately 0.21 kg. The double revolute joint makes it possible to perform both a pitching and a rolling motions in the range of $\pm 50°$ and $\pm 25°$ respectively.

(a) Side and front photos of the passive THING adaptive foot.

(b) The passive foot mounted on ANYmal.

Figure 2: Photos of the passive adaptive foot.

The four chains of phalanges are heavily inspired by the Pisa/IIT SoftHand: a tendon of nominal length 155 mm is routed through each of them, enabling the group of chains to be a sole which is flexible, yet rigid in extension. This enables the adaptiveness of the foot because, as it approaches an uneven terrain, the chains will move to reach a "settling" position until the flexible sole becomes fully tense. Thus, the foot would envelop around the convex hull of a subset of the points on the ground. The relevant dimensions of the mechanical parts of the foot are reported in Figure 1b and some essential details are provided in Table 1.

The passive foot was tested both indoor and outdoor on the ANYmal robot and was found to perform decently for specific gait and robot posture parameters. From a mechanical perspective some limitations were found for this design:

- The contact area was found to be limited on flat surfaces (see Figure 2b) as the chains tend to remain curved upwards.
- This caused a consequent drop in the friction of the sole with the contact surface.

- The double joint was sometimes seen to cause roll instability.

These issues can be solved effectively by introducing rubber pads under the chain and by decoupling and lowering the position of the roll joint.

One of the aims of THING project is to combine soft adaptive components, underactuation and inertial sensing into an adaptive foot, to be inherently robust and able to sense the environment to retrieve information on the contact locations. To this end, two inertial measurement unit (IMU) modules are placed on the feet in appropriate locations: one below the double roll joint and another on the upper part of the front arch link. These are made water resistant by coating them with an appropriate resin and by positioning them inside protective cases. An illustration of the sensor positions on the foot is depicted in Figure 4.

The IMUs provide the measurements of the acceleration and angular velocity of the foot, which in turn can be used to estimate other quantities like the force applied by the foot during locomotion [3] or to detect slippages.

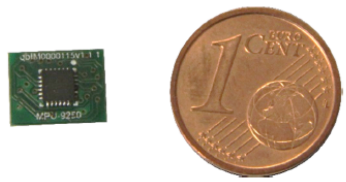


Figure 3: IMU sensor module with coin for scale.

Each IMU module (Figure 3) contains a MPU9250 as IMU sensor, three capacitors and two JST connectors, where the first one (IN) is employed to connect to the IMU Board while the second one allows a connection with another IMU module. It is possible to connect in the same chain up to three IMU modules. In the case of the passive THING foot, a chain of two IMU modules are used. The aforementioned IMU Board is is a 41x16 mm electronic board, with a PSoC5-based microcontroller. This board is usually used in conjunction with a power board in order to control motors of devices such as the PISA/IIT SoftHand, but it is also used to read the measurements from magnetic encoders, EMG sensors, analog sensors and IMUs.

Hence, the communication with the chain of sensors are established through the IMU board, which can be positioned in the ankle and to which all IMUs are connected. Each board, so each foot, is provided with a connection port for a USB cable, which in turn can be attached to a HUB in order to get measurement data from all feet.

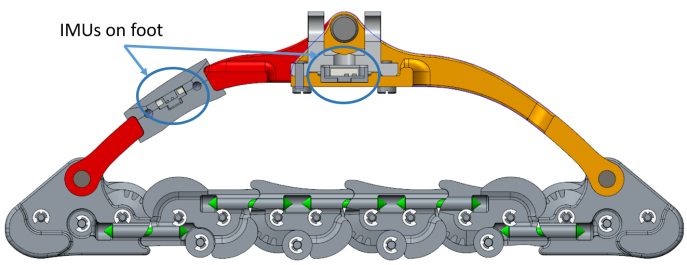



Figure 4: Schematics of the locations of the IMU sensors.

## 2.2 Software

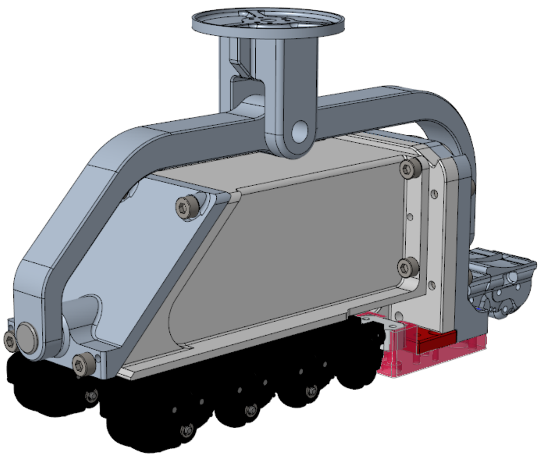
The software packages required to obtain the measurements, namely `ROS-NMMI` and `ROS-Base`, run on ROS and are opensource [4]. The driver ROS node is capable of reading 4 feet (16 IMUs) at a rate greater than 200 Hz. More details are available from the README.md files of the individual repositories.

# 3 Active Adaptive Sole

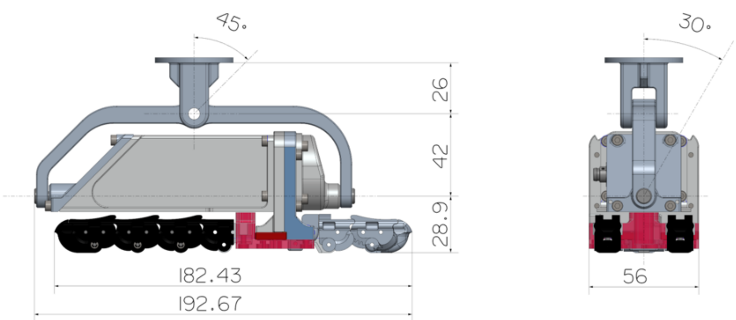
In this section the main details about the first prototype of the active version of the adaptive foot are outlined.

## 3.1 Foot Design

Once again, taking inspiration from previous work on soft adaptive feet [5] and from the Pisa/IIT SoftHand [2], an actuated version of the adaptive foot was devised by UNIPI.



(a) A 3D CAD view of the active adaptive foot.




(b) Side and front views of the active adaptive foot.

Figure 5: CAD view of the mechanical design of the active foot.

As seen in Figures 5 and 6, the foot consists of the following components:

- an ankle base,
- a single arch link,
- a case that contains all the required elements for the actuation,
- two front fingers with four phalanges (three hilberry joints) each and

- one rear finger with two palanges with a revolute joint and a hilberry joint.

Figure 6: The actuated adaptive foot prototype.

The active adaptive foot weighs approximately 0.42 kg, it is about 96.9 mm tall and has a footprint area greater than the passive version (102 $cm^2$).

Decoupled pitching and rolling movements are provided by the revolute joint between the ankle base and the arch link and by two joints of the same kind between the two ends of the case and the arch link. The ranges of motion of both the pitch and roll joints are somewhat different than the passive version of the adaptive foot: $\pm 45°$ and $\pm 30°$ respectively for the pitch and roll angles.

The electronic board and the sensing system have been re-designed to match the size requirements of the new platform. The electronic board has been divided in two functional layers: power board and logic board. This new layout allows a better arrangement of the electronic boards inside the case. Figure 7 shows the two boards (in the middle) in comparison with the classic one (on the left).

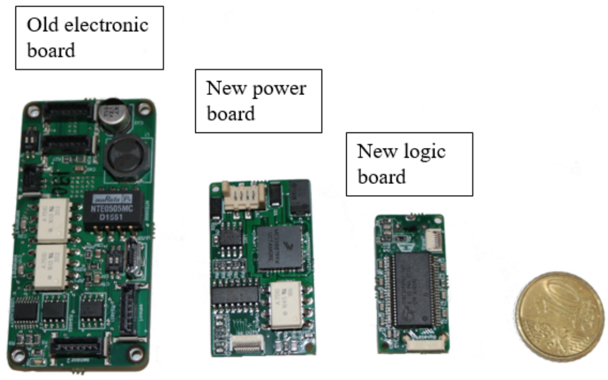



Figure 7: Comparison between new boards and the old one.

The actuator - a single motor, located inside the case - powering the active foot is a 24W Maxon motor DCX22S with a reduction ratio of 231:1 equipped with a 12 bit magnetic rotary position sensor (Austrian Microsystems AS5045) with a resolution of

4096 position per revolution. The embedded electronic unit hosts sensor processing, motor control and communication. The opening and closing of the foot is controlled via a single set point reference, communicated via an RS-485 bus. This scheme is totally new and was developed *ad hoc* for the project.

The synergistic actuation of the fingers of the feet, by means of a tendon, enables the prototype to grasp objects and features of the environment. A sequence of the THING actuated foot grasping an object is shown in Figure 8.

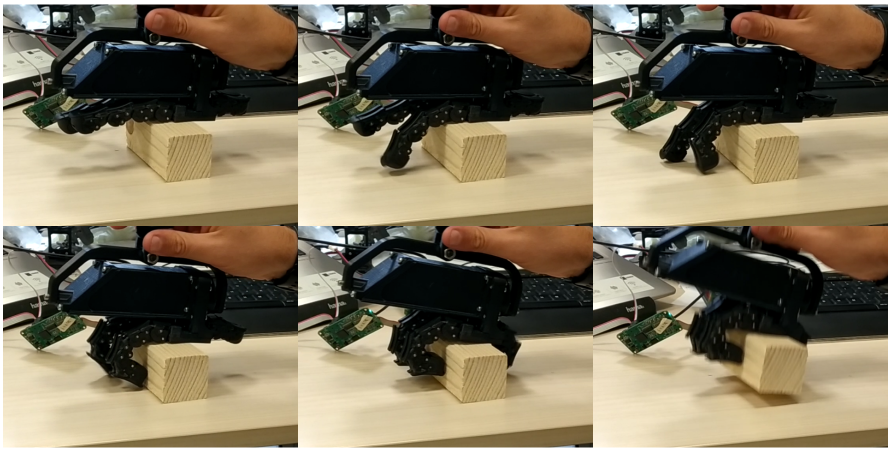


Figure 8: Photo sequence of the active adaptive foot grasping an object.

# 4 Comparision and Conclusions

In this section the two versions of the adaptive foot are quickly compared and the conclusions drawn.

## 4.1 Comparison

Figure 9: Comparison photo of the two adaptive foot prototypes.

From a purely dimensional point of view, both the versions of the adaptive foot are comparable, though the active version is slightly bigger. A simpe comparative analysis of the two versions of the THING adaptive feet can be found in Table 1.

The adaptiveness of the passive version is opposed to the prehensile capabilities of the active sole. Both feet can passively perform pitching and rolling motions, however, the active foot has a lower roll joint which effectively decouples the pitching and rolling motions.

Moreover, the actuated foot does not have chains; instead, three underactuated fingers equip it with grasping capabilities.

Table 1: Some technical details about the passive foot.

| | **Passive** | **Active** |
|---|---|---|
| Weight | 0.21 kg | 0.42 kg |
| Footprint | $55.5 \times 155.0$ mm | $56.0 \times 182.4$ mm |
| Roll RoM | $\pm 25°$ | $\pm 30°$ |
| Pitch RoM | $\pm 50°$ | $\pm 45°$ |
| Yaw RoM | - | - |

The passive prototype has been extensively tested on ANYmal and its main features and limitations are known (see Section 2.1); on the other hand, the active prototype is yet to be evaluated and its adaptiveness and robustness are yet to be tested.

## 4.2 Conclusions

In conclusion, a prototype of passive foot (Figure 1a) with a flexible sole to increase adaptiveness to the terrain was designed and evaluated. The design was found to be robust and mostly effective on different terrains. From tests, the prototype was indeed shown to adapt adequately to the shape of uneven grounds thus maximizing the contact surface and friction.

An active prototype of the adaptive foot (Figure 5a), able to exert interaction forces with objects and the environment by grasping it, was also devised. The actuation design, strongly inspired by the Pisa/IIT SoftHand design, leverages upon the expertise of UNIPI in the design of robust under-actuated robotic hands and explores a synergistic actuation, relying on a single motor. This confers to the foot the ability of grasping, while only minimally increasing its complexity, ensuring robustness and reliability.

# References

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