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THING

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DELIVERABLE 2.4

Evaluation of the first prototypes of soles and selection of the final configuration.

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1 Introduction

This document reports the evaluation of the performance of the prototypes of feet that have been developed. This activity has been carried out within Task 2.3 and T2.4, the description thereof is reported in the following.

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.

Task 2.4 - Sensorization

Based on the specifications derived in task T2.1, the foot design will be provided with a sensing system. Different solutions for the foot sensorization will be investigated. A customized 6-DOF F/T sensor able to measure the interaction forces with the environment will be added to the foot design. The highly integrated strain-gauge-based solution is currently under final development at ETH. Further sensing solutions (e.g. IMU, angle encoders, optical devices) will be considered to estimate the foot pose and contact informations (e.g. contact area estimation, force distribution under the foot). Moreover, with specific focus on sewer inspection (see also T6.6), the foot will be equipped with a number of inspection sensors that allow measuring temperatures, pH values, or other parameters of interest (see also T6.3)in order to get a large number of samples at any place the robot was and correlated with the actual location.

This document is organized as follows. In Sec. 2 the prototypes of adaptive feet that has been realized are briefly reported. In Sec. 3 the sensing systems that have been developed are briefly described. In Sec. 4 the testing activities that have been conducted are reported. In Sec. 5 the specifications of the different prototypes are summarized.

Due to the number of involved partners and the rapid evolution of the considered equipment and related technologies, this deliverable could also be viewed as a "working document" that could be reviewed and updated as our understanding of the end-user requirements changes throughout the project lifetime.

2 Prototypes of Adaptive Feet

In this section a brief description of the prototypes of adaptive feet that have been developed is reported.

2.1 Passive Adaptive Foot Preliminary Prototype

A first prototype of passive adaptive foot has been realized (Figure 1).

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 ± 50 and ± 25 degrees respectively.

Figure 1: Side and front photos of the passive THING adaptive foot.

Further details were given in D2.2.

2.2 Passive Adaptive Foot Finalized Prototype

Some important modifications have been carried out on the foot, i.e. ankle range of motion, dimensions and materials which led to a second release.

The Soft Foot V2, shown in Figures 2, and 3, is composed of four main components, the first three made in aluminium and the last one in stainless steel:

- an *ankle link* acts as the base component of the foot;
- two *arch links* provide the foot with pitching movements;
- two *roll links* makes it possible to perform rotations around the forward axes;
- three *chains* are the core components of the Soft Foot V2 as they deform when coming into contact with an uneven terrain.

The lower extremity of the leg of the quadruped is meant to be connected to the ankle base, to which two arch links are attached by means of a revolute pitching joint and, finally, two roll links are added at the extremities of the arch links opposite to the ankle base to provide the foot with rolling rotations. The two arch links are connected to each other using also a spring - positioned near to the pitching joint - for ensuring relative stiffness of the arch closure. Three paddled chains, attached to the front and back roll links, provide a flexible, yet rigid in extension, sole. This enables the adaptiveness of the foot because, as it approaches an uneven terrain, the chains will move and adapt the terrain 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.

Figure 2: A photo of the passive version ot the THING adaptive foot.

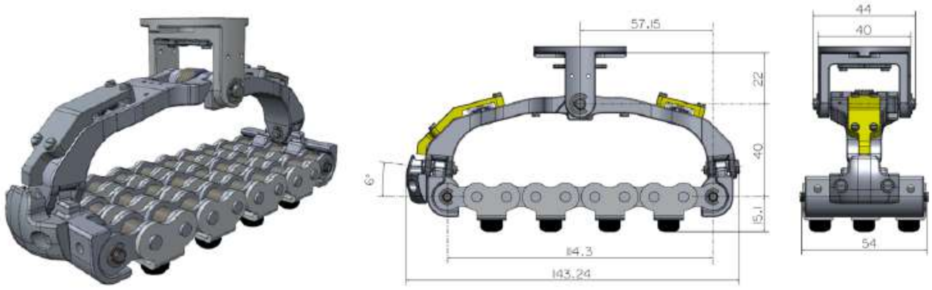

Figure 3: CAD view of the mechanical design of the passive foot.

It is noteworthy that, when the foot is at rest, the two roll axes of the foot are inclined approximately 6 degrees with respect to the horizontal plane (see Figure 3). This choice is of extreme importance as it permits the roll movement within a good range of foot poses. Another significant remark to be made is about the different positioning of the roll joint relative to the pitching one: we noticed throughout the testing of the preliminary prototype that a high position of the roll joint seriously affects the stability of the Soft Foot V2. This is caused by the fact that the sole is not very wide and this a high positioning of the roll joint might cause the force exerted by the foot to lie outside the friction cone of the contact.

The relevant dimensions of the mechanical parts of the foot are reported in Figure 3 and some essential details are provided in Table 1. Figure 4 shows some examples of feet deformations and interactions with obstacles of different shape.

Table 1: Some technical details about the passive foot.

Quantity	**Value**	**Units**
Foot weight	0.420	kg
No. links per chain	9	-
Chain weight	0.085	kg
Sole weight	0.255	kg
Footprint	54×143	mm^2
Roll Range of Motion	± 30	deg
Pitch Range of Motion	± 45	deg
Yaw Range of Motion	-	-

Figure 4: Examples of feet deformations and interactions with different obstacles and terrains.

To properly test the robot control algorithms with the soft feet on, it is essential to have a reliable simulation package to be employed before using the real robot. All of the software of ANYmal runs on ROS and Gazebo is its simulator. Devising a Gazebo simulation package for the passive adaptive foot was found to be challenging as it is well known that URDF does not support closed kinematic chains. However, when a robot model is spawned into Gazebo, it takes the URDF model and converts it into SDF, which in turn supports closed chains.

Hence, to keep the model of the foot consistent, the best solution was found to be the one of creating a Gazebo ModelPlugin that, once the URDF is converted into SDF in Gazebo, creates the needed joints to close the kinematic chains. A picture of the passive version of the soft feet mounted on ANYmal and spawned into Gazebo simulation can be found in Figure 5.

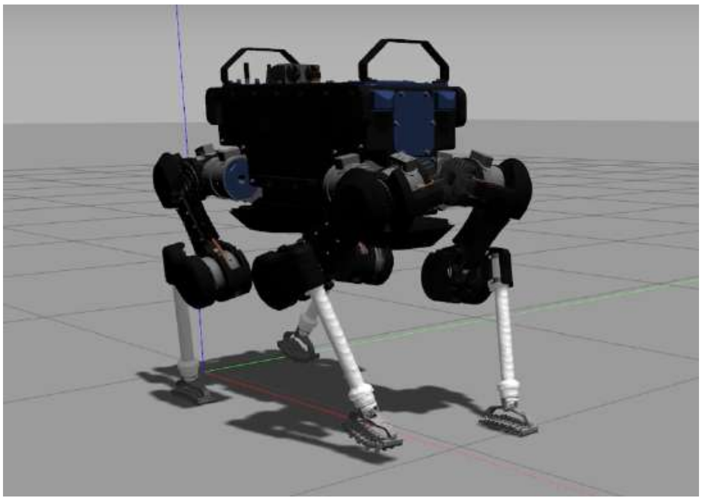

Figure 5: Pose reconstruction and simulation of the Soft Foot on ANYmal.

2.3 Active Adaptive Foot Finalized Prototype

In this section the first prototype of the active version of the adaptive foot is briefly described (see Fig. 6).

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: ± 45 and ± 30 degree respectively for the pitch and roll angles.

Further details were given in D2.2.

3 Sensing Systems

This section briefly presents the sensing systems for adaptive feet that have been developed.

3.1 Plantar Arch Sensing System

Four inertial measurement units (IMUs) are placed on the feet in appropriate locations to sense the pose of the plantar arch of the feet. The location of the sensors on the feet is shown in Figure 7. The first one is embedded in an electronic board inside the ankle base, two on the upper part of the arch links and one in front of the forward roll link. Moreover, these are water proof via a coating applied to them with an appropriate resin and by positioning them inside protective cases, a part from the one inside the base. It is to be remarked that the positions of the IMUs on the foot are in such a way that there are always two sensors on the adjacent links of each joint of the foot (see Fig. 8).

The communication with the sensors are established through the board in the ankle to which all IMUs are connected. The foot provides a USB cable which can be attached to a HUB to get measurement data from all feet. A simplified illustration of the sensor positions and the communication is depicted in .

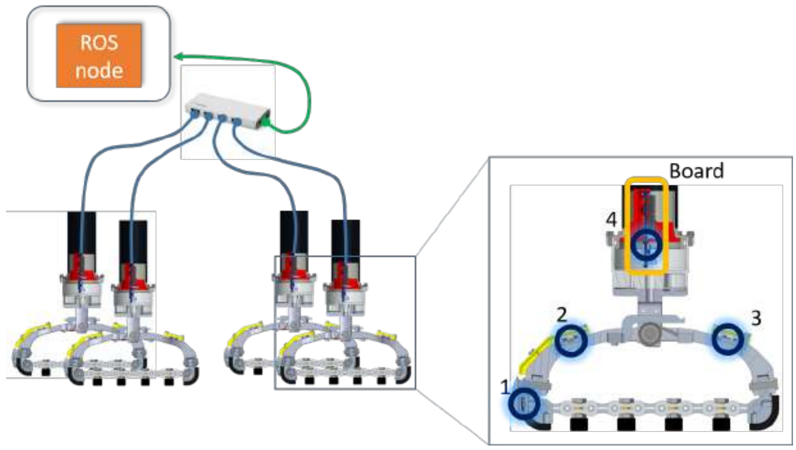

Figure 7: Schematics of the locations of the IMUs and of the communication structure.

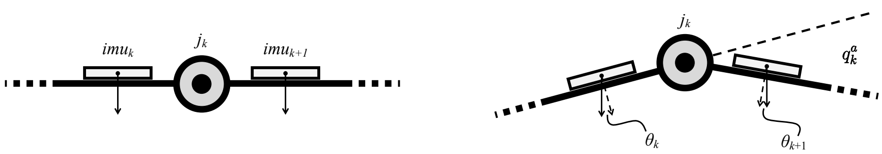

Figure 8: Simple illustration of revolute joint with two IMUs on the adjacent links.

The reconstruction of the foot pose makes use of a Complementary Filter that fuses two estimates of the joint angles: one obtained through integration of angular velocities, measured by the gyroscopes, and the other from geometric considerations on the local gravity vector, acquired by the accelerometers. The first might suffer from integration drift but is generally a smoother estimate, the second is more reliable in spite of being more noises.

The pose reconstruction algorithm that we use, which is explained below, is quite simple and common: it is based on the following assumptions:

- The IMUs on each link are placed on the same locations and with the same orientation on all four feet.
- The movements of the IMUs w.r.t the related link bodies (changes in relative pose) are negligible.
- The foot will not be constantly subject to accelerations that are much greater than the acceleration of gravity.

The pose estimation algorithm has been implemented in ROS Melodic: a screenshot of the estimated pose and the relative real pose of the foot on ANYmal is shown in Figure 9.

Figure 9: Pose reconstruction and simulation of the Soft Foot on ANYmal.

3.2 Adaptive Sole Sensing System

We developed a system with the purpose of estimating contact forces in soft feet from purely postural measurements, by exploiting the intrinsic capability of these systems to conform to the environment. More specifically, we propose a perception system that relies on Inertial Measurements Units (IMUs) placed on top of the adaptive foot links, as the only source of direct measurements. We show that this perception system enables the accurate reconstruction of the foot posture and, via a novel algorithm, to estimate the contact points of the foot sole and the force distribution under the contact surface.

The algorithm is specifically tailored on the SoftFoot but its working principles are generally applicable to a vast kind of soft feet.

The proposed framework is shown in Fig. 11, and it is composed by two main components. The first extracts the full posture of the foot from the IMU measurements. This information is merged by the second layer with the a priori knowledge of the

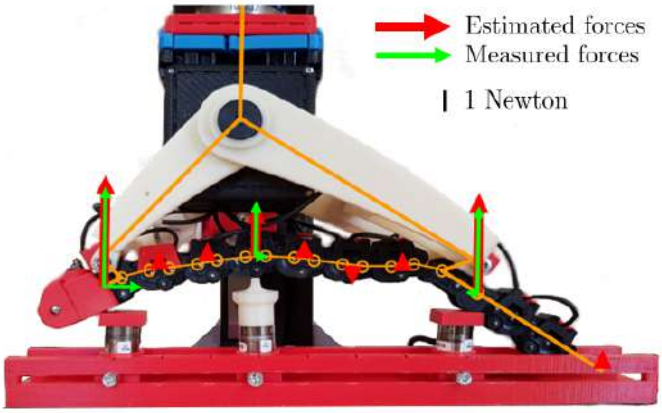

Figure 10: The reconstruction of the contact forces on a soft robotic foot sole allowed by the proposed method. Three 6 axis F/T sensors are placed in contact with the robotic foot metacarpus, heel and plantar fascia, and their measured force is visualized in green. The estimated forces on the foot sole, shown in red, is estimated by the foot pose reconstruction filtering process, allowed by IMU sensorization.

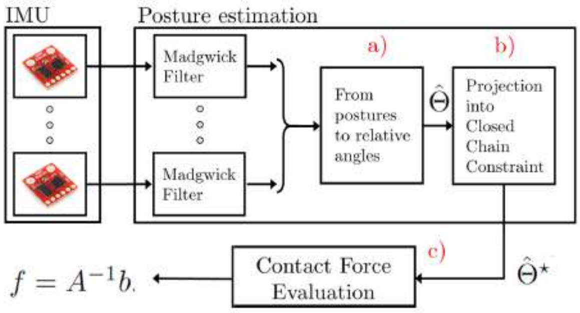

Figure 11: Complete architecture of the proposed method. Its main components are showed (red letters): a) extraction of the full posture of the foot from the IMU measurements and the Madgwick filter, b) merging of the posture reconstruction with the *a priori* knowledge of the model. In c) the refined relative angle estimate is used to reconstruct a set of contact forces by means of the kinematic regression allowed by the model structure.

model, to estimate a set of contact forces by means of the kinematic regression allowed by the model structure. Madgwick Filters are used to extract posture information from each IMU. An estimation of the angles $\hat{\Theta}$ is then obtained by simple projection of the 3D rigid body rotation to the plane on which the joints move. We carried put experimental validation to test the accuracy of the force vector reconstruction. The complete experimental setup is shown in Fig. 12. The experimental validation goals are i) to observe how close the forces measured by a given number of six-axis F/T sensors placed under the foot sole are to the forces given by the model, and ii) to assess the precision of the proposed method in correctly identifying the application point of a contact force on the foot fascia. Figs. 10 and 13 show the concept of the experiment results, visualizing the forces estimated by the model in red and the forces measured by the sensors in green, for different positions and heights of the plantar obstacle support. The contact horizontal forces are plotted only in green, as we have modelled them as purely vertical in the foot model.

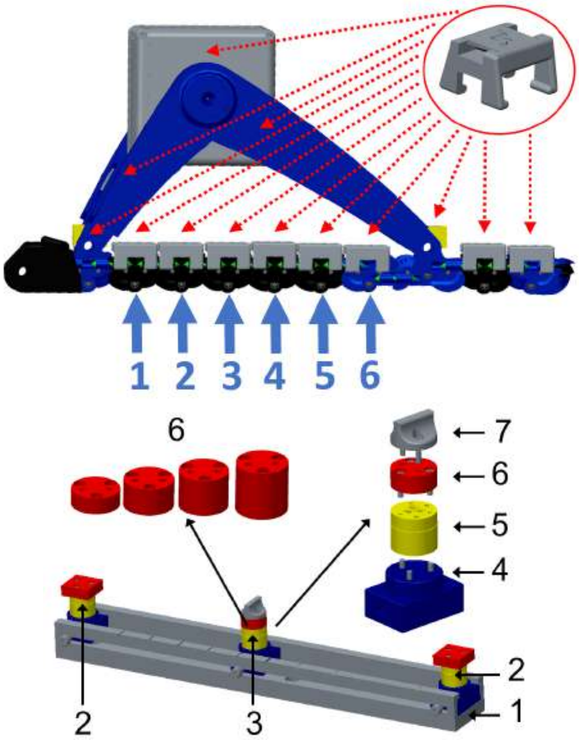

Figure 12: The figure on top shows the chain of modules that constitute the fascia and the finger of the SoftFoot. The locations of the IMUs (mounted on a support represented in grey) are highlighted. The figure on the bottom shows the linear guide (1) used to place both the fixed obstacles (2) and the sliding obstacle (3). The obstacles are composed of the following parts: i) a F/T sensor (5), placed in a custom-made support (4); ii) a support (6) where the contact with the foot occurs in the fixed obstacles, and that is of different heights in the sliding obstacle; and iii) an apical rubber part (7) for the sliding obstacle.

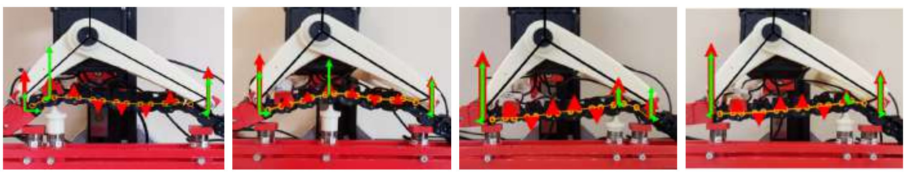

Figure 13: Figure shows the reconstructed posture of the foot sole in orange, the measured forces in green, and the estimated forces in red. Different positions/heights of the sliding obstacle are shown: a) pos. 2, height 19 mm; b) pos. 3, height 19 mm; c) pos. 6, height 7 mm; d) pos. 6, height 11 mm.

Figure 14: Soft Foot V1 on the testing machine

4 Testing Activities

In this section a brief description of the testing activities is reported. In the first half of the project we performed four testing activities in Zurich in collaboration with ETH. In these tasks the performance of the two versions of the passive adaptive feet were assessed via the test machines described in D2.1 and robot trials indoor and outdoor.

4.1 Testing Session 1 28-08-2018

In the first testing session the Soft Foot V1 has been tested. It has been tested via the testing machine for interaction described in D2.1 as reported in Fig 14. In the indoor testing activities the foot has been mounted on the robot and tested on flat terrain and on different obstacles including: bars, bricks, and slopes. In the outdoor activities the robot has been tested on sand, gravel, stones, and mud. Examples of the experimental tests are reported in Figs. 15 and 16.

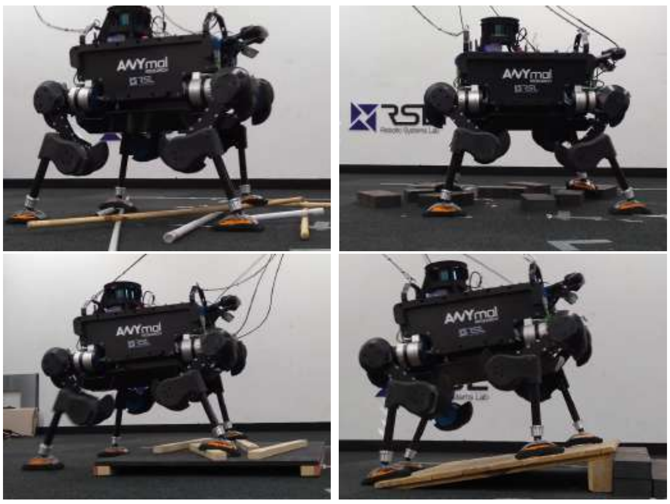

Figure 15: Indoor tests on bars, bricks, and slope

Figure 16: Outdoor tests

4.2 Testing Session 2 15/16-10-2018

In the second testing session an improved version of the the Soft Foot V1 has been tested together with the sensing system for the plantar arch. The tests were mainly devoted to assess the capability of the sensing system to correctly retrieve signals even in the water (see Fig. 17). To this aim the activities were conducted in the sewerage system of Zurich.

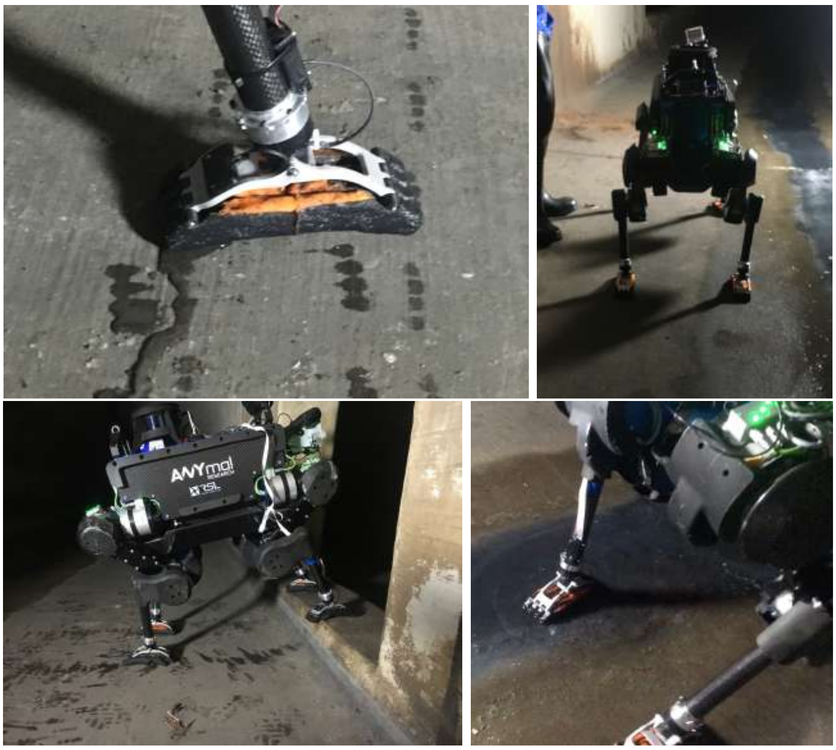

Figure 17: Sewerage system tests

4.3 Testing Session 3 16/17-04-2019

In the third testing session the Soft Foot V2 has been tested. In the indoor testing activities the foot has been mounted on the robot and tested on flat terrain and on different obstacles including: bars, bricks, and slopes. In the outdoor activities the robot has been tested on sand, gravel, stones, and mud. Examples of the experimental tests are reported in Figs. 18 and 19.

Figure 18: Indoor tests

Figure 19: Outdoor tests

4.4 Testing Session 4 03-07-2019

In the fourth and last testing session the Soft Foot V2 has been tested in a lightweight version with a software module able to reconstruct online the plantar arch pose of the four feet. It has been tested in indoor and outdoor activities. Examples of the experimental tests are reported in Figs. 20.

Figure 20: Military Tests

Table 2: Summary of General Specifications for ANYmal feet

ID	Function	Description	Difficulty	Importance	Value	Unit
G01	Mobility	Maximum size of the footprint of the feet (width x length)	l	D	160 x 80	mm
G02	Mobility	Maximum mass of the feet	m	D	0.4	kg
G03	Mobility	Maximum pitch inertia	m	D	0.02	kg m^2
G04	Reliability	No cables stick out	l	D	-	-
G05	Mobility	No singularities within the range of motion	m	D	-	-
G06	Cost	Maximum Cost of one foot considering a series of 100 pieces per year	h	W	2.5	kEuro

5 Evaluation of Performance and Specifications

The main specifications of the adaptive feet versions that have been developed are summarized in Table ??. The table includes some symbols that are defined in the following:

- - in the columns of the feet (SFv1, SFv2, and SFa) means that the corresponding value has not been evaluated yet
- Y means that the requirement is satisfied
- N means that the requirement is not satisfied
- NM means that the testing activities highlighted that the specification matching is not mandatory
- Alu (D,W) means that the friction coefficient has been evaluated on an Aluminum plate in dry and wet conditions (with water)
- NA is for not applicable
- TBU means that the specification is not matched because a component (hardware or software) has to be updated

Here will be used the same alphanumeric IDs presented in the Deliverable D2.1 for the general, functional and interface specifications. The tables with the description of each ID are reported also here for convenience.

5.1 Slippage Evaluation

The complexity of the executed tasks (e.g. walking on bricks or unstable terrain) together with their stochastic nature, makes difficult to properly highlight the impact of the different feet.

However we performed an evaluation of the feet performance by estimating how much each foot type slip. The slippage evaluation has been performed in two ways.

In the first we exploit the ANYmal capability to perform state estimation relying on fusion of data coming from its perception system composed of IMUs, joint position and torque sensors, and on the model of the robot. Outputs of the state estimator are the detection of the contact of the feet and the motion of the base of the robot. Relying on these estimates it is possible to assess the slippage of the feet to quantitatively compare the performances of the different sets of feet.

Table 3: Summary of the functional specifications for ANYmal feet

ID	Function	Description	Difficulty	Importance	Value	Unit
F01	Robustness	The foot should not report damages that prevent its functionality after a fall from given heights with given mass	l	D	N. of damaged components	#
F02	Robustness	The foot should not report damages that prevent its functionality after walking on rough terrains (gravel, stones, sand)	h	D	N. of damaged components	#
F03	Sensing	Detection of contact (load, accuracy)	m	D	30, 80; 50, 95	N, %; N, %
F04	Sensing	Detection of contact points under the foot sole (resolution)	h	W	±15	mm
F05	Sensing	Estimation of sole-environment interaction forces: range, accuracy	h	W	30-500, 5	N, %
F06	Sensing	Contact area estimation (resolution)	h	W	6	cm^2
F07	Sensing	Estimation of foot shape (angular resolution of the estimation of the relative angle between two segments of the foot sole)	m	W	±2	deg
F08	Mobility (adaptivity)	Minimum range of motion around pitch	m	D	±40	deg
F09	Mobility (adaptivity)	Minimum range of motion around pitch	h	W	±60	deg
F10	Mobility (adaptivity)	Range of motion around roll	m	D	±30	deg
F11	Mobility (adaptivity)	Range of motion around yaw	h	W	±20	deg
F12	Mobility	Allow continuous rotation of the shank	h	D	-	-
F13	Mobility	Minimum Friction Coefficient on the following materials and terrains: metal (aluminum and steel), gravel, sand	h	D	0.6	-
F14	Mobility	Hold for stair climbing at pitch	m	D	−90	deg
F15	Mobility	Traversing flat ground (Minimum average speed over a distance of 2 m)	m	D	0.7	m/s
F16	Mobility	Traversing flat slopes (max. 20 deg) (Minimum average speed over a distance of 2 m)	m	D	0.4	m/s
F17	Mobility	Traversing uneven terrains (gravel, sand) (Minimum average speed over a distance of 2 m)	h	D	0.4	m/s
F18	Mobility	Traversing wet terrains (Minimum average speed over a distance of 2 m)	h	D	0.3	m/s
F19	Reliability	Water and Dust protection	h	D	IP67	-
F20	Reliability (moderate thermal loads)	Minimum temperature range	m	D	0 to 30	$^\circ C$
F21	Reliability (severe thermal loads)	Minimum temperature range	h	W	-10 to 40	$^\circ C$
F22	Reliability (mechanical loads)	Minimum payload, min. acceleration, cycles	m	D	30, 3g, 10^6	kg, m/s^2, -

Table 4: Summary of Interface specifications for ANYmal feet

ID	Function	Description
I01	Electrical	Voltage and Power supply: 48V up to 300 W
I02	Electrical Interface	No analog signal routing to the body
I03	Electrical Interface	USB max power 500mA (fit-PC, max 1.5 A total), 2.4 A (Hub active port USB3)
I04	Communication Interface	check of signal integrity at interface to high-level control
I05	Mechanical Interface	Foot has to fit on interface of ANYmal (any-drive 1.2/2.1)
I06	Mechanical Interface	Easy removal of foot assembliy

ID	Unit	SFv1	SFv2	SFa	Notes
G01	mm	55.5×155	51×143	56×182.4	
G02	kg	0.21	0.31	0.42	
G03	kg cm^2	9.7	10.1	14.1	
G04	-	partial	partial	N	
G05	-	Y	Y	Y	
G06	Euro	-	-	-	
F01	m	0.2	-	-	NM
F02	-	Y	Y	-	
F03	N, %	-	-	-	
F04	mm	±15	±12.7	-	
F05	cm^2	4.35	3.75	4.35	
F06	deg	±2	±2	±2	
F08-09	deg	± 50	±45	±45	
F10	deg	± 25	±30	±30	
F11	deg	N	N	N	N M
F12	-	Y	Y	Y	
F13	-	0.52,0.37	0.57,0.53	0.52,0.37	Alu (D,W)
F14	deg	-	-	-	
F15	m/s	Y	Y	-	
F16	m/s	Y	Y	-	
F17	m/s	Y	Y	-	
F18	m/s	Y	Y	-	
F19	-	IP64	IP64	IP64	
F20-21	C	Y	Y	-	
F22	kg, m/s^2, -	-	-	-	
I01	-	NA	NA	N	TBU
I02	-	Y	Y	Y	
I03	-	Y	Y	N	
I04	-	N	N	N	TBU
I05	-	Y	Y	Y	
I06	-	Y	Y	Y	

Table 5: Summary of main specifications for adaptive feet

Let C be the trajectory of the base reference frame of the robot and C_i the trajectories of the feet (with $i = 1, 2, 3, 4$). C_i^j will be the j-th part of the trajectory C_i in contact with the ground. With the usual meaning of line integrals, the metric can be expressed as in (1).

$$m = \frac{\sum_i \sum_j \int_{C_i^j} ds}{\int_C ds} \tag{1}$$

Such a metric has the following properties: it is null in absence of slippage, larger when more slippage occurs, not affected by to the length of the path and by still phases and, finally, it is only slightly affected by punctual events. However, particular attention must be devoted in comparing similar runs since different gaits, speed, payload and other parameters might affect the metric final value. An example of the collected data is reported in Figure 21. Results of the evaluation are reported in Table 6.

The second way to evaluate the slippage has been performed by watching the

Table 6: Average Slippage in experiments.

	Stones	**Collapsible**	**Slope**	**Overall**
Ball	1.48	1.42	1.54	1.77
Flat	1.83	2.53	1.91	2.09
Soft v2	1.37	1.28	1.25	1.36
Improvement (B-Sv2) (%)	7.4	9.4	18.8	23.2
Improvement (F-Sv2) (%)	25.1	49.1	34.7	34.9

recording of the experiments and counting how many times a foot slippage occurs. Results of this slippage evaluation are reported in Table 7. The table includes some symbols that are defined in the following:

- Fw and Bw stand for forward and backward walking direction
- F-R stands for the front right foot
- F-L stands for the front left foot
- B-R stands for the back right foot
- B-L stands for the Back left foot

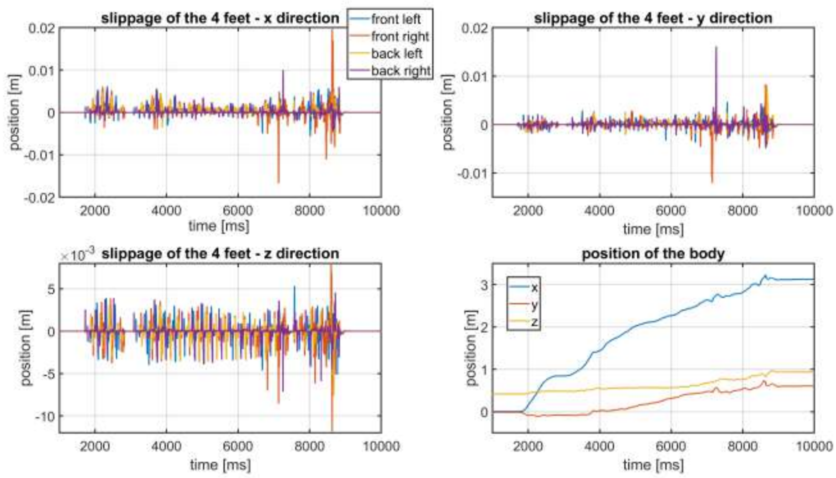

Figure 21: Slippage metric calculation example.

Table 7: Slippage Table for ball, flat and the two versions of adaptive feet.

Foot	**Dir.**	**F-R**	**F-L**	**B-R**	**B-L**	**Total**	**Steps**	**%**
Ball	Fw	1	1	0	0	2	56	3.6
	Bw	2	2	1	2	7	56	12.5
	Tot.	3	3	1	2	9	112	8.0
Flat	Fw	0	1	1	2	4	40	10.0
	Bw	3	2	2	2	9	40	22.5
	Tot.	3	3	3	4	13	80	16.2
Soft v1	Fw	0	0	1	2	3	56	5.3
	Bw	1	0	1	1	3	36	8.3
	Tot.	1	0	2	3	6	92	6.5
Soft v2	Fw	0	1	1	0	2	46	4.4
	Bw	0	1	1	0	2	54	3.7
	Tot.	0	2	2	0	4	100	4.0