Adaptive foot design for small quadruped robots

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I. INTRODUCTION

Biologically inspired robots that are used for research of the animal and the technological realm become more and more refined. Control schemes for sensor-less and sensorized robots were developed, are able to handle torque control and sometimes even adapt to a changing task set. Further mechanics and electronics have evolved and take part in more reliable and robust bio-inspired robots. Robots reproduce animal structures or use bio-mechanical principles to excel in a specific task. Never the less, during this evolution of robots the feet were often oversimplified compared to their animal counterparts. Our current work centers around the foot as a bio-mechanically complex but extremely important end-effector. The foot is often implemented as a simple ball-foot [1] out of various materials with different friction coefficients, or a simple compliant bending structure [2], [3]. This gives the freedom to the controller to use the approximation of the ground contact to be a discrete point or line contact. In consequence high performing control-schemes such as the spring loaded inverted pendulum (SLIP) model [4] were developed. Moving away from flat terrain often results in the need of sensory feedback which alters foot trajectories to ensure a precise ground contact. If we look at our biological inspirations, feet seem to be the opposite of their robotic counterparts: complex, highly actuated, adaptable and maybe most importantly made out of soft as well as hard tissue. The latter leads to the ability of changing ground contact points dynamically during stance phase. We speculate that this property plays an important role in the open loop adaptation of the foot to perturbations and uneven terrains. In this abstract, we propose a novel foot concept with flexible toes and an additional anisotropic friction to move on small cluttered terrain.

II. FEET IN NATURE AND ROBOTS

a) Feet in nature: Feet in animals are highly adapted to their living environment and the mode of usage. Structures range from highly articulated feet in cats with soft paw-pads and retractable claws, over horse feet that consist of the combined toes forming a single solid structure, to highly specialized feet like the Geckos. Our robot foot design takes inspiration and links to the flexible toes and claws, like the ones of dogs. These structures are used to increase traction, protect the fine bones and joints of the foot from impacts and among others sense the surface. Additionally flexible pads exist that consist of a layer of harder skin, enclosing multiple layers of soft tissue with nerves and blood vessels.

b) Feet in currently used robots: Already mentioned in the introduction, the design of feet in robots is often oversimplified. Table I illustrates that independent of gait, speed, weight, or size, many modern quadruped robots use very simple feet. Nevertheless most of these feet feature a slight elasticity, either through use of springs or the choice of elastic material.

TABLE I: Selected quadruped robots showing high independence of currently used feet to robot size, weight or speed: table data extended on the basis of [2], [3] and [5] ; mass, robot height at hip-level, robot length, speed in body lengths/second, and foot geometry.

Robot	m_{rob} kg	h_{hip} m	l_{rob} m	BL/s $m\,s^{-1}$	Gait s^{-1}	Foot
Scout II [6]	20.8	0.323	0.552	2.4	bound	ball/cylinder
BigDog [7]	109	1	1.1	2.8	bound	ball
ANYmal [1]	not yet published					ball
HyQ [8]	91	0.789	1.0	≈ 2	trot	ball
StarlETH [9]	23	≈ 0.5	0.5	1.5	trot	ball
Puppy I [10]	1.5	0.2	0.17	2.9	bound	half cylinder
Puppy II [11]	0.27	0.075	0.142	3.5	bound	half cylinder
Cheetah-cub [2]	1.1	0.158	0.205	6.9	trot	half cylinder
Bobcat [13]	1.03	0.125	0.166	4.7	bound	half cylinder
Lynx-SV3 [5]	1.2	0.154	0.225	2.7	bound	half cylinder
Cheetah-Cub-S [3]	1.16	0.158	0.205	1.66	trot	half cylinder
Cheetah-Cub-AL[2]	1.2	0.16	0.206	4.8	trot	claw shaped

III. PROPOSED FOOT CONCEPT

The foot concept centers around an intelligent combination of flexible elements between the base of the foot and the toes as well as the implementation of claws or anisotropic friction. The feet aim at robots with small size (under 400mm hip height) and moderate weight characteristics (under 4kg). Never the less scaling of the proposed concept might be an option although different production methods should then be taken into consideration.

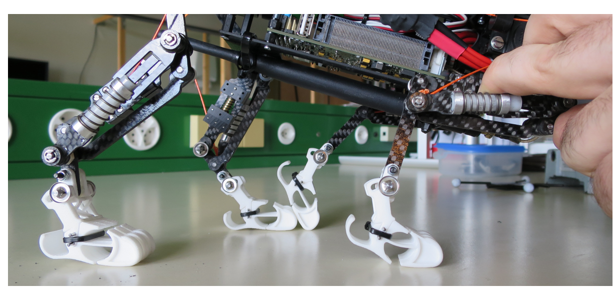

Fig. 1: Cheetah-Cub with foot prototype.

From previous design iterations done with students, flexible toes seem to have promising properties as they made the

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robot slightly more stable with no loss in locomotion speed. We implemented a 3 toe foot made out of 3D-printed parts (SLS laser sintered) on the robot Cheetah-Cub ($m = 1.1$kg) as seen in Fig. 1. It also featured a flexible heal with high stiffness. The design of these feet is quite elegant as only one production step is needed and the used material can be used also as the elastic element, see Fig. 2. An additional flexible ankle joint was first implemented as well, but discarded after the first test due to bad performance. For a robot with higher weight, this method of production is probably not feasable anymore. Forces that should be produced by the toe springs to achieve better or equivalent performance are most probably too high to just rely on elasticity properties of the SLS-printed Polyamid.

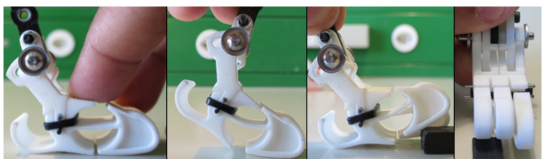

Fig. 2: Flexible foot prototype performing adaptation to different surfaces due to manually applied force.

If one takes into account a robot of up to triple the weight of Cheetah-Cub, a combination of milled POM or aluminum and elastic NiTiNol wires seems to be a promising material combination. Additionally we increase from 3 to 4 toes to reach finer adaptability. This increases production and design complexity drastically but gives also advantages in shock absorption, wear and tear adaptability to different toe lengths.

Another key factor that should increase performance is the addition of anisotropic friction to the tip of the toe. This can be done by carefully placed and curved rigid claws, that allow more grip at the end of the stance phase or using other mechanisms like spines. Spines are small, flexible and spiky tips, that are pre bend in one direction, enabling them to slip over a surface when moved in one direction and stick when moved in the other one [14]. They act much like scales of a snake. Placing them on the round edge of a toe might have the same effect as a claw, with two possible advantages: First, the stick effect takes place not only in the end of the stance, but throughout the whole stance phase; and Second, it is not possible to get stuck into the ground if stance occurs while protraction of the leg is still in course, as spines slip very good in one direction. Claws might get stuck due to their rigid material behavior (see Fig. 3)

IV. Questions to the Dynamic walking community

1) When are spines useful for locomotion?
2) Does compliance in the feet hinder control more than it benefits it (keyword: closed loop control)?
3) When does compliance in the feet become unfeasable (keyword: scaling)?
4) Are there control models that include compliant feet?
5) Can, e.g. the SLIP model be extended with compliance in the ground contact? Already done?

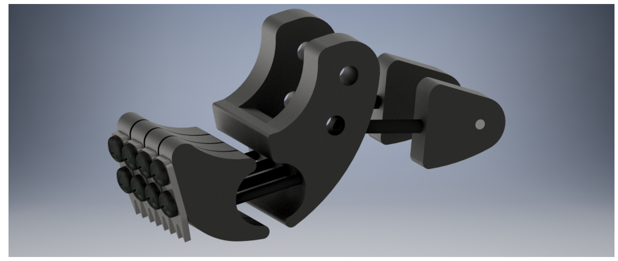

Fig. 3: CAD rendering of the flexible foot concept with spines and NiTiNol wires as compliant elements

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