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Citation	The 11th International Symposium on Adaptive Motion of Animals and Machines (AMAM2023). 2023, p. 47-48
Version Type	VoR
URL	https://doi.org/10.18910/92260
rights	
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Adaptable and Changeable Feet for a Bio-inspired Robot to Facilitate Versatile Climbing on Various Surfaces

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1 Introduction

Enabling climbing robots to climb on a variety of surfaces remains a challenging problem. One of the keys to success in climbing is foot design. Most recent bio-inspired climbing robots can climb only on a smooth or rough surface [1-2]. In addition, their feet have limited life cycles. The traditional way of replacing old feet with new ones is difficult and time-consuming. Therefore, we developed adaptable and changeable feet for a bio-inspired climbing robot. The novel foot design consists of two main parts: a passively adjustable ankle and a changeable foot sole. With the developed feet, we can design the stiffness of the ankles for proper terrain adaptation and easily implement foot soles that are suitable for climbing on a surface to achieve the best performance. Real robot climbing experiments on different slopes with various angles and surfaces were used to demonstrate the effectiveness of the proposed foot design. The findings indicate that silicone and asymmetrically structured foot soles are appropriate for climbing on smooth and rough sloping surfaces, respectively.

2 Materials and Methods

2.1 Bio-inspired Climbing Robot

A bio-inspired climbing robot (Black Panther) used for the experiments here consists of four legs (each with four DOFs), a flexible tail, and proposed feet (Fig. 1). Black Panther has 17 active joints in total, four at each leg and one at the tail base. Each active joint is driven by a Dynamixel servomotor. The robot has a total weight of 2.5 kg. Neural central pattern generator (CPG)-based control is applied to generate robot climbing behavior with a trot gait. Here, the neural control is not the main focus of concern, for more details see [3].

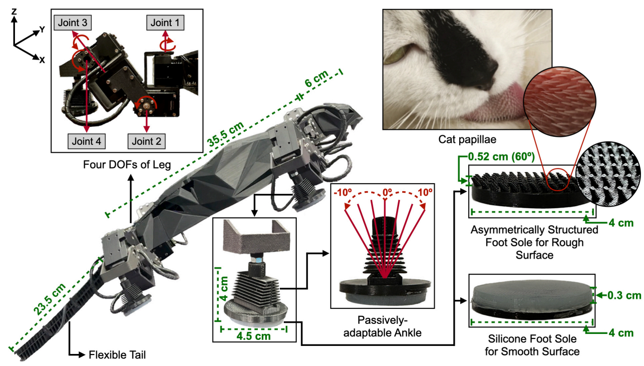

Figure 1: A bio-inspired climbing robot (Black Panther) with adaptable and changeable feet. The asymmetrically structured foot sole is inspired by the anisotropic papillae of a cat tongue [4]. The tongue image is reproduced from [4] with permission (Copyright (2018) National Academy of Sciences).

2.2 Adaptable and Changeable Foot Design

The new foot design consists of passively-adaptable ankles and changeable foot soles (Fig. 1). Based on a rib structure, the adaptable ankle enables the foot to comply with the terrain and maintain ground contact during the stance phase. Using the rib structure and its triangular stacking pattern, we can design the ankle's stiffness by adjusting the thickness and width of the ribs and spire (middle axis). Here the thickness and width were empirically tuned to obtain an ankle flexion ranging from -10 deg to 10 deg, which provides stable climbing. The changeable foot sole allows for easily removal or insertion into a slot at the ankle base. In this way, we can apply the proper foot sole to each ankle for specific surface climbing. For instance, if the robot climbs on a rough surface, we will use rigid asymmetrically structured foot soles (i.e., a foot sole with PLA sawtooth profiles inspired by the papillae of a cat tongue [4]) which can catch or grip a rough surface [4]. If the robot climbs on a smooth surface, soft silicone foot soles will be used which can provide good adhesion-mediated friction to the surface. Furthermore, if a foot sole or ankle breaks, we can easily replace the part with a new one, allowing the robot to continue climbing. The new feet are manufactured by a 3D printer (Raise3D E2) using polylactic acid (PLA) material. This can significantly reduce the weight of the feet by over 60% compared to the original feet, made of aluminum and several stainless-steel screws [3].

3 Experiments and Results

We set up two different terrains: a rough sloping terrain (carpet slope) and a smooth sloping terrain (acrylic slope) for testing the adaptable and changeable feet (Figs. 2(a) and 2(b)). We varied slopes into four different angles on both terrains and tested the robot's climbing ability with two different foot sole types (rigid asymmetrically structured foot soles (RAS) and soft silicone foot soles (SSS)). On the rough surface, we tested at 40, 50, 60, and 65 degrees. On the smooth surface, we tested at 30, 35, 40, and 50 degrees. We found that on the rough terrain, the robot could climb up to 65 degrees with RAS, slid backward while climbing with SSS (Fig. 3(a)). RAS has cat tongue-inspired asymmetrically structured sharp tips that act like claws to interlock with the terrain's roughness. It could also enable the robot to climb on rough, wet surfaces. SSS, on the other hand, has a flat silicone surface that cannot provide sufficient attachment to a rough terrain. In contrast, on the smooth terrain, the robot could climb up to 50 degrees with SSS, while it slid backward with RAS (Fig. 3(b)). This is because the sharp tips of RAS cannot provide adhesion to the smooth terrain, while the silicone material of SSS can provide the adhesion-mediated friction important for climbing on a smooth terrain. In addition to the foot soles, the feet's flexible ankles could passively bend to allow for effective foot attachment and detachment to and from the terrain, respectively, during the stance phase (Fig. 2(c)).

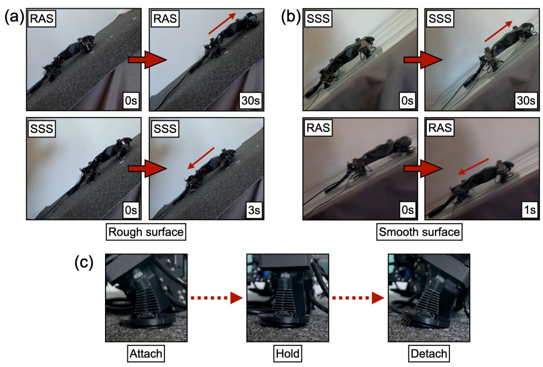

Figure 2: (a) Black Panther with RAS and SSS on the carpet-based rough terrain. (b) Black Panther with RAS and SSS on the acrylic-based smooth terrain. (c) Snapshots of foot attachment and detachment movements of the robot's right hind leg during the stance phase. A video of this experiment can be viewed at http://www.manoonpong.com/AMAM2023/Video.mp4

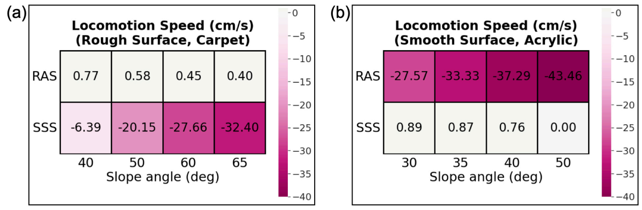

Figure 3: Heat maps of locomotion speed in two conditions on (a) the rough terrain and (b) the smooth terrain. The area colored white shows positive climbing speed (i.e., climbing forward) and the purple the negative climbing speed (i.e., sliding backward).

4 Discussion and Conclusion

In the experiment, we showed that the robot could climb on both smooth and rough sloping terrains by simply changing its foot soles. The RAS provided strong grip on the rough terrain through mechanical interlocking and enabled an effective climbing performance on rough steep slopes. The SSS, on the other hand, offered substantial adhesion-mediated friction to adhere to the smooth ground. Besides the foot soles, the adaptable ankles based on the rip structure could passively bend to achieve efficient foot-to-surface attachment and detachment. The combination of adaptable ankles and changeable foot soles make the feet unique and allow for stable and continuous climbing of the bio-inspired robot. The overall weight of all feet is significantly reduced compared to the original feet due to the use of a 3D printing technique with PLA, and the feet can be easily built. In future work, we will perform detailed mathematical modeling and finite element analysis to further optimize the foot structure, ankle stiffness, and sole structured surfaces, enabling the robot to achieve faster and steeper slope climbing various surfaces.

5 Acknowledgments

This work was supported by the Company of Biologists Limited (Travelling Fellowship) to PB, LSBU External Participatory and Collaborative (EPaC) Research Fund to HR, and the National Key R&D Program of China, Topic 4-NUAA (Grant No. 2020 YFB1313504) to PM. We are also grateful to David L. Hu for giving his permission to reuse the cat tongue picture in his previous work.

References

[1] P. Borijindakul, A. Ji, Z. Dai, S.N. Gorb, P. Manoonpong, "Mini Review: Comparison of Bio-inspired Adhesive Feet of Climbing Robots on Smooth Vertical Surfaces," *Front. Bioeng. Biotechnol.*, Vol.9, pp.909, 2021.

[2] Q. Jiang, F. Xu, "Grasping claws of bionic climbing robot for rough wall surface: Modeling and analysis," *Appl. Sci.*, Vol.8, No.14, 2018.

[3] W. Haomachai, D. Shao, W. Wang, A. Ji, Z. Dai, P. Manoonpong, "Lateral undulation of the bendable body of a gecko-inspired robot for energy-efficient inclined surface climbing," *IEEE Robot. Autom. Lett.*, Vol.6, No.4, pp.7917-7924, 2021.

[4] A. C. Noel, D. L. Hu, "Cats use hollow papillae to wick saliva into fur," Proceeding in *Proc. Natl. Acad. Sci. U.S.A.*, Vol.115, No.49, pp.12377-12382, 2018.