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研究課題名（和文） Multimode Frictional Anisotropic Skin for Supporting Locomotion of A Snake-like Soft-bodied Robot on Various Frictional Ground Surfaces

研究課題名（英文） Multimode Frictional Anisotropic Skin for Supporting Locomotion of A Snake-like Soft-bodied Robot on Various Frictional Ground Surfaces

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研究成果の概要（和文）：本研究では、環境に応じ動的に構成を変えることができる柔らかいロボット用のロボットスキンを開発することを目的としている。蛇型軟体ロボットに着目し、異なる摩擦環境下でのロボットの運動について検討した。蛇型ロボットの運動特性を予測するシミュレータを開発し、プログラマブルなロボットスキンを設計するために、可変な摩擦パターンに双安定構造を用いた研究を行なった。数値解析と実機の実験により、これらの双安定構造の機械的特性と制御性を研究しました。
また、双安定構造に関する研究に基づき、超軽量ジャンパーの研究にも取り組みました。折り畳み可能でプログラマブルなソフトロボットスキンの設計にも適用できると考えられます。

研究成果の学術的意義や社会的意義
This research elucidated the important factors in designing a programmable soft robotic skin. The design, simulation, and fabrication of illustrated in the research laid a foundation to design highly adaptive soft robots that will be used in environment exploration and safe human robot interaction.

研究成果の概要（英文）：We aimed to develop a programmable robotic skin for soft-bodied robots that could dynamically change its configuration to adapt to changing environments. Specifically, we focused on the case of snake-like soft-bodied robots and their locomotion in different frictional environments. We developed a simulator to predict the locomotion of a wriggling snake-like robot in different frictional configurations. Additionally, we investigated bistable structures that could be used to design self-configurable frictional patterns for the programmable robotic skin. We studied the mechanical properties and controllability of these bistable structures through numerical analysis and physical robot experiments. Our results are currently under review.
Based on our research on bistable structures and their controllability, we also worked on a bistable origami structure for lightweight jumpers. This research could serve as a precursor for further investigation into foldable, programmable soft robotic skins.

研究分野： Robotics

キーワード： Soft Robotics　Robotic Skin　Printable Robots　Bistable Structure　Adaptive Robot　Programmable Friction　Snake-like Soft Robots　3D Print

１．研究開始当初の背景

Soft robotics is aiming at building a robot system that is comprised of soft and flexible materials. As being a continuum structure, the soft robots come closer to the printable robots. The softness of the body of the robot makes it safer to humans and more gentle to the surrounding environment. Besides, the elasticity of the body allows the robot to deform and adapt to unknown constrained spaces freely. Therefore, soft-bodied robots will be helpful in field missions such as exploring and rescuing.

Many robots, both rigid and soft ones, have been designed for the environment exploration and rescue missions. One of the most common types is the stringy robot, which is inspired by the worms and snakes. A rigid snake-like robot is multilink of rigid body segments with actuators to control the angle made by two consecutive segments. On the other hands, a soft-bodied snake-like robot is a continuum of soft body segment which undulates by continuously bending the body segments. In a real snake, the undulation can generate the moving forward locomotion thanks to the scales on the skin of the snake. These scales form an anisotropic frictional surface (different friction coefficients in different directions) when the snake contact to the ground. In general, both rigid and soft-bodied snake-like robots mimic the anisotropic frictional surface by attaching wheels along the body. The most significant disadvantage of the wheels is that they make the robot challenging to be printed.

In order to design a printable soft-bodied snake-like robot, our previous work [1] has proposed a static anisotropic frictional surface using the combination of high and low frictional material that can be patterned at the ventral side of the snake-like robot to support the undulation locomotion. However, because this anisotropic frictional surface (as shown in Figure 1) is static after printed, it limits the ability of the robot to navigate different surfaces with different texture and friction coefficient.

A real snake does not have any limbs, but it can navigate in various different environment. We think that the scale structure as well as the way the snake controls each scale is important. However, how do the switching in scale structure and scale friction contribute to the locomotion of both a real snake and a snake-like soft-bodied robot? Can we learn from it and create a better snake-like soft-bodied robot? In order to help the soft-bodied snake-like robot deal with the changing in friction of the navigating surfaces, we need to address the problem of how to make the anisotropic frictional surface dynamic (i.e., design a mechanism to dynamically switch between anisotropic frictional surface modes). This task can be realized by using bistable structures to joint different anisotropic frictional elements to the ventral side of the robot. This approach will be illustrated in the next parts. The ability to alternate between ventral skin patterns does not only make the robot more responsive to the change of the environment but also enables it to travel with new locomotion gaits. For understanding the behaviors of the soft-bodied snake-like robot while alternating the anisotropic frictional surface, we will have to build a theoretical model to simulate the crawling patterns of the robot.

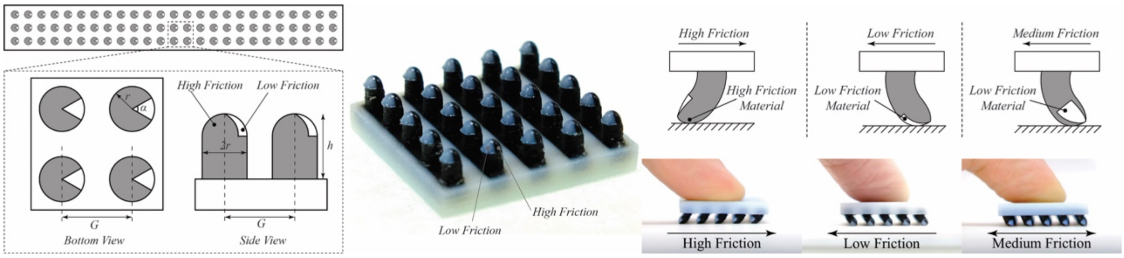

Figure 1: Design of a single-mode anisotropic frictional surface

２．研究の目的

The goal of this project is to build a printable wriggling soft-bodied robot which navigates through multiple environments with different frictional properties. When the environment frictional property changes, the wriggling robot needs to change its frictional patterns to support the locomotion efficiently. The target of this research is to design a mechanism that helps to switch between anisotropic frictional surface patterns responsively and dynamically.

３．研究の方法

In this research project, we sequentially conducted three main studies including (a) simulation of wriggling snake-like soft robots with different frictional patterns, (b) evaluation of bistable structures that would help designing frictional patterns switching mechanism, and (c) numerical analysis and experiment with 3D printed frictional bistable structures .

a. Locomotion simulation

This sub-project focused on building a simulator for analyzing the locomotion of a snake-like soft robot with different frictional patterns at the contacting surface between the robot and the ground.

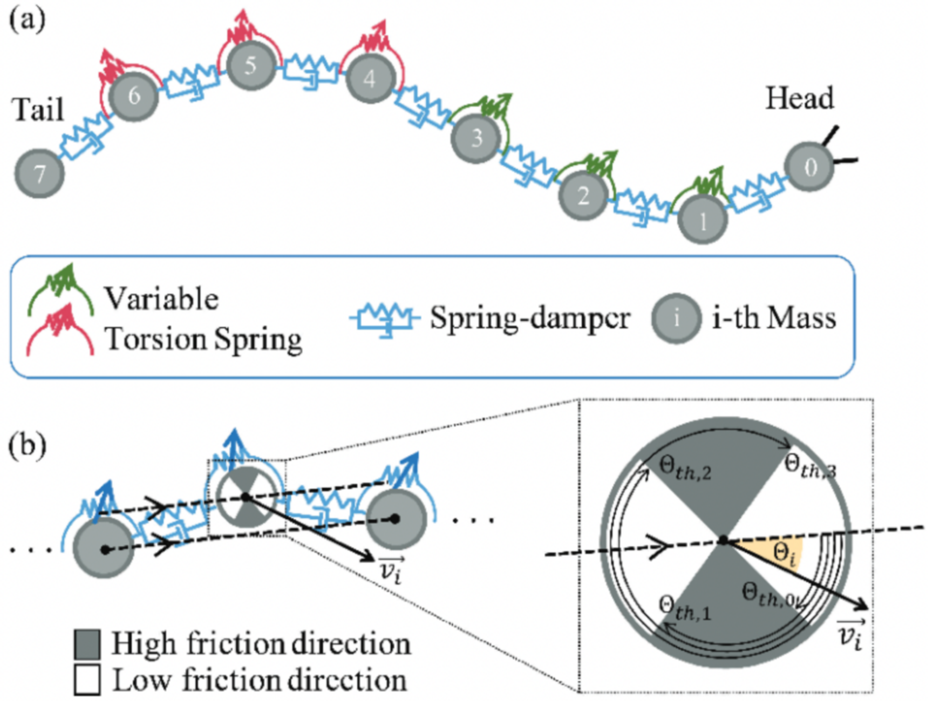

Figure 2: (a) The mathematical model to simulate the locomotion of the robot, which is constructed with springs, masses, dampers, and torsion springs. (b) How the friction coefficient changes depending on the moving direction of particle *i*. The illustration exemplifies one of the 5 frictional patterns.

We model the mechanical system of the wriggling robot (i.e., the deformable beam) as a mass-spring-damper system, in which eight mass points are linearly connected by a spring-damper and a torsion spring (as shown in Figure 2).

After running simulation with different patterns of anisotropic friction (5 patterns), we compared the simulating result with the result of the real snake-like soft-bodied robots to check whether our simulator matches with the real robots.

b. Bistable structures

Following the implementation of a simulator for different anisotropic frictional patterns. However, these anisotropic frictional patterns are fixed on the robot after printing. In this sub-project, we were looking for ways to switch between frictional patterns without re-printing. We investigated several bistable structures that develop swift transition between two stable states. By dynamically controlling these transition, we could change the behavior of the robot skin responsively. We studied two approach of making bistable structures: origami-based and 3D printing-based.

- Origami-based: in this approach, we designed, fabricated, and evaluated the performance of waterbomb-based bistable structure (as shown in Figure 3).
- 3D printing-based: in this approach, we parameterized the design of a flexible cone-shaped bistable structure to evaluate the performance of bistable transition (as shown in Figure 4).

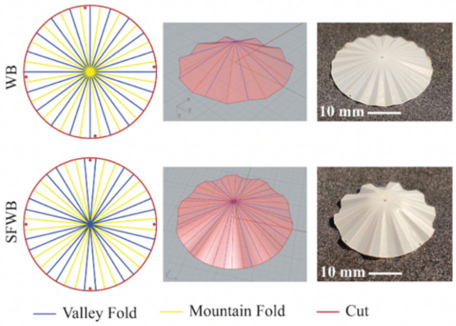

Figure 3: Bistable origami waterbomb-based structures

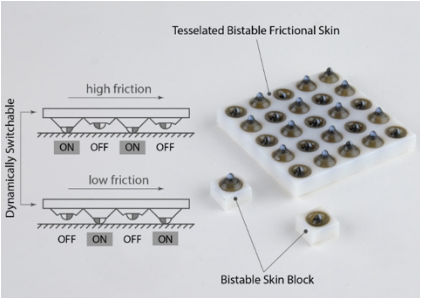

Figure 4: A 3D-printed programmable frictional skin of soft-

c. Bistable structure numerical analysis and experiment

Though the study in origami-based bistable structures display the ability to swiftly switch between bistable states, we found that they are more difficult to integrate smoothly into our existing snake-like soft-bodied robots. On the other hand, the 3D printed-based structures are inherently compatible to the softness of the 3D printed snake-like soft-bodied robots.

In this sub-project, we modeled the 3D printed cone-based bistable structures and used finite-element method to calculate the behavior of the structure under deformation (as shown in Figure 5). Then we combined the 3D printed bistable structures with anisotropic frictional patterns to make a bistable frictional robotic skin (as shown in Figure 6).

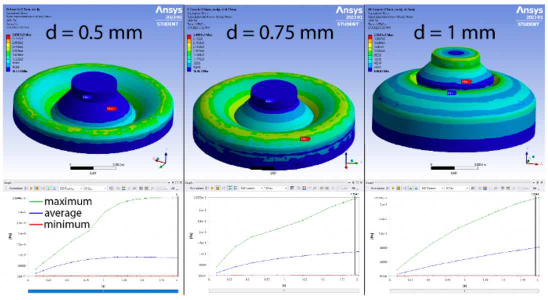

Figure 6: FEM analysis of parameterized 3D printed cone-shaped bistable structures.

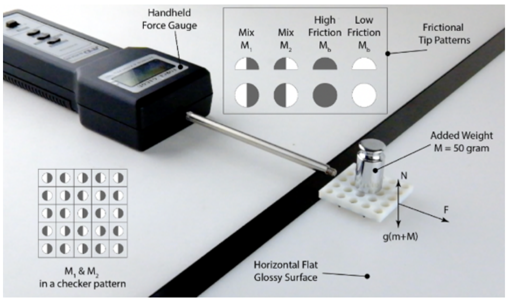

Figure 5: Experiment with switchable anisotropic frictional patterns

４．研究成果

The achievements of the research project are including the research result of the three sub-projects.

a. Locomotion simulation

The output of this sub-project include:

- A simulator that helps predict the behaviors of a snake-like soft-bodied robot with different anisotropic frictional patterns
- A comparison between the simulator and the real soft robots.

The result of this research was published in the Journal of Information Processing under the title of **"A Printable Soft-bodied Wriggle Robot with Frictional 2D-anisotropy Surface"** [2].

b. Bistable structures

The output of this sub-project include:

- Evaluation of origami bistable structures that are easy to design, fabricate, and perform swift transition between two bistable states. The result of this origami bistable structures are described in our publication in IEEE International Conference on Robotics and Automations 2022 with the title **"Printable origami bistable structures for foldable jumpers"** [3].
- 3D printed parameterized cone-shape bistable structures that can be integrated directly to 3D printable snake-like soft-bodied robots.

c. Bistable structure numerical analysis and experiment

This sub-project focused on analyzing the behaviors of the 3D printed cone-shape bistable structures that were designed in the previous project. We elucidated the parameters that are important for the state switching performance of the bistable structures. The output of this project is a foundation for design bistable robotic skin blocks that can be tessellated into a bistable robotic skin. This robotic skin will help extend the adaptability of snake-like soft-bodied robots and can be generalized to other soft robots that are beneficial from the switching of robotic skin patterns. The result of this research were submitted to IEEE International Conference on Intelligent Robots and Systems 2023 with the title **"Printable Bistable Structures for Programmable Frictional Skins of Soft-bodied Robots"**. The manuscript is under-reviewing.

[1] T. D. Ta, T. Umedachi, and Y. Kawahara, "Design of Frictional 2D-Anisotropy Surface for Wriggle Locomotion of Printable Soft-Bodied Robots," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, Brisbane, Australia, 2018, pp. 6779–6785.

[2] T. D. Ta, T. Umedachi, M. Suzuki, and Y. Kawahara, "A Printable Soft-bodied Wriggle Robot with Frictional 2D-anisotropy Surface," *Journal of Information Processing*, vol. 30, no. 0. pp. 201–208, 2022.

[3] T. D. Ta, Z. Chang, K. Narumi, T. Umedachi, and Y. Kawahara, "Printable origami bistable structures for foldable jumpers," in *2022 International Conference on Robotics and Automation (ICRA)*, Philadelphia, PA, USA, 2022.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　0件／うちオープンアクセス　1件）

１．著者名 Ta Tung D.、Umedachi Takuya、Suzuki Michiyo、Kawahara Yoshihiro	４．巻 30
２．論文標題 A Printable Soft-bodied Wriggle Robot with Frictional 2D-anisotropy Surface	５．発行年 2022年
３．雑誌名 Journal of Information Processing	６．最初と最後の頁 201～208
掲載論文のDOI（デジタルオブジェクト識別子） 10.2197/ipsjjip.30.201	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Caremel Cedric、Ishige Matthew、Ta Tung D.、Kawahara Yoshihiro	４．巻 34
２．論文標題 Echo State Network for Soft Actuator Control	５．発行年 2022年
３．雑誌名 Journal of Robotics and Mechatronics	６．最初と最後の頁 413～421
掲載論文のDOI（デジタルオブジェクト識別子） 10.20965/jrm.2022.p0413	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Tung D. Ta, Zekun Chang, Koya Narumi, Takuya Umedachi, Yoshihiro Kawahara
２．発表標題 Printable Origami Bistable Structures for Foldable Jumpers
３．学会等名 International Conference of Robotics and Automation 2022（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関