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研究課題名（和文）Mechanics of Variable Afferent Network Morphology, with Design of Soft Sensing Devices

研究課題名（英文）Mechanics of Variable Afferent Network Morphology, with Design of Soft Sensing Devices

研究代表者

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研究成果の概要（和文）：本研究では、変更可能な神経ネットワークの形態（VANmorph）の提案に基づいて、柔軟なボディにおける能動的な変形によりロボットの体の感覚や触覚など様々なセンシングへの実現ができることを検証した。具体的には、しわ形態などの概念を通じて、解析モデルや数値的なシミュレーションにより、ソフトなセンサに適切な駆動メカニズムを統合した上でVANmorphの実現を確認することもできた。また、そういったシステムは能動的な形態の変形で、単なセンシング素子（歪みゲージなど）でも、ボディの変形への検知やインタラクションにおける触覚などを備えることができる。最後に変形可能なロボットハンドやプロペラの提案も成功した。

研究成果の学術的意義や社会的意義
本研究は、現在人気が集まっているソフトロボティクスの一つの科学的な課題のある形態の計算方法を取り組んで、ソフトロボットの能動的な変形により埋め込んだセンサの動的な変動に基づいた様々なセンシング機能を実現する提案であり、その研究分野に貢献した。また、本研究によって得られた結果はスマートなソフトロボットの取り組みへの貢献につながるとともに、今後人間に近いところでも自ら体の変形や周辺とのインタラクションなどの状態を十分検知できる安全性をロボットに与え、ロボットへの安心感を高めることができる。

研究成果の概要（英文）：In this project, we succeeded in clarifying how dynamic change of the morphology may benefit the sensing abilities of a soft sensorized body, thanks to the idea of Variable Afferent Network morphology (VANmorph). By introducing novel designs of shape-changing sensing systems, such as wrinkled morphology, in companion with thorough analytical modeling and numerical simulation, we showcased that VANmorph can be efficiently implemented by integration of an actuating mechanism inside a sensorized soft body. In addition, we clarified that sensors designed based on VANmorph idea can possess different sensing abilities by changing their morphology, such as sensing of self-deformation and interaction. Our platform also indicated that morphological change of the sensor would lead to implementation of active sensing, where the sensor can select its suitable morphology for different sensing task. Finally, the ideology of VANmorph helped us propose other soft mechanisms in grasping, propellers.

研究分野：ソフトロボティクス

キーワード：ソフトロボット　形態の計算　しわの形態　触覚センサ　Beam Bundle Model　ロボットハンド　プロペラ　Vision-based sensor

１．研究開始当初の背景

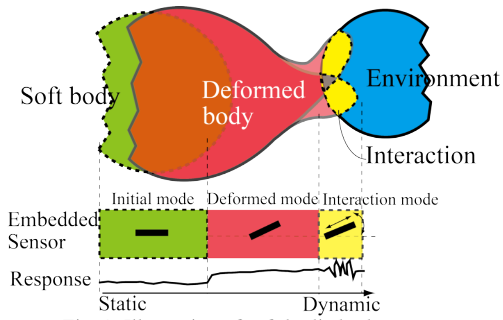

Fig. 1: Illustration of soft-bodied robot

Soft robots utilize soft materials, exploiting the compliance of an environment by deforming to it, enabling soft and safe interactions (see Fig.1). Since soft bodies have infinite degrees of freedom, common mapping model of sensor to movement in rigid-body kinematics is not sufficient. Also, embedded sensors are no longer fixed inside the body, they actually can displace and change posture during self-deformation and interaction with the outside environment. Currently, there is no theoretical platform that can describe this phenomenon, thus remains a challenge in development of soft sensing system which can detect the body's deformation, and respond actively to interaction with environment. Therefore, it comes to a key scientific question that: how to understand the dynamics of the embedded sensors inside soft bodies under self-deformation and interaction? Then, by clarification of sensors' mechanical properties from dynamics point of view, this leads to another question: how to utilize this study in creation of soft structures that can satisfy both deformation and interaction perception, for state feedback in control of soft robots. The quest for answering these scientific issues are also our motivation for proposal of this research project.

２．研究の目的

The purpose of this research is to clarify the mechanism of Variable Afferent Network morphology (or **VANmorph**) for assessment of sensorized soft bodies' dynamics under the self-deformation and interaction with surrounding environment. Based on thorough theoretical investigation, we aim to propose a platform for development of soft sensing systems with multiple sensing abilities for utilization in soft robotics.

３．研究の方法

(1) Build both analytical and numerical models related to **VANmorph** for mechanical study of the dynamic change of embedded sensors' location and orientation inside soft-bodied networks, as well as sensors' corresponding mechanical responses under self-deformation and interaction.

(2) Proposal of a design platform based on **VANmorph** framework for designing soft sensorized bodies that can sense both self-deformation (elongation, contraction, bending, twisting) and interaction with environment (touch, vibration, rubbing, squeezing.) This platform considers mechanical responses of embedded sensors based on dynamic investigation in **VANmorph**, subjected to specific morphology of the soft body and sensing tasks, for proposal of optimal design of the sensorized soft bodies with multiple sensing abilities that can be utilized in soft robotics. By studying dynamic response of sensors, methods for discrimination of different states are also proposed

(3) Utilization of integration of sensing elements and actuator inside a soft body. Based on calculation from VANmorph, the soft bodies can deform themselves (under actuation) to actively change the locations and postures of embedded sensing elements so that these sensing elements can well perceive external tactile stimuli. Thus, with one type of sensing principle, different modalities can be done.

４．研究成果

(1) ***Variable Afferent Network morphology for the case of wrinkled sensor***:

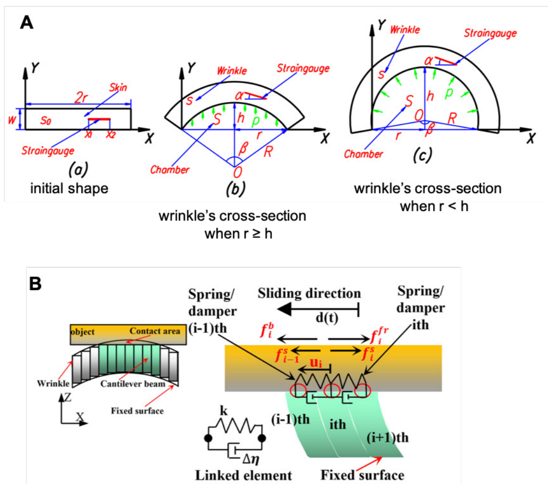

Fig. 2: Analytical model

This is a main research content of this project that covers modeling, simulation, fabrication, and perception of self-deformation and interaction. This work has been done with contribution of Ho group, Shibuya group, and Hirai group. Summary of the obtained results can be found below:

① Analytical modeling of the variable morphology of the wrinkle mechanism activated by air-pressurization: We present a theoretical model for the design of a soft-fingered robotic hand/gripper with a friction-tunable function based on the idea of active wrinkles on its surface. Inspired by the formation of wrinkles on the human finger in a wet environment, our robotic finger is integrated with a pneumatic actuator inside a multilayer soft substrate. Under pressurization, wrinkles are formed on the finger's surface, changing the contact tribology between the finger and the grasped object (Fig. 2 A). The morphology of wrinkles (both geometrical and mechanical characteristics) is predicted by the radius basic function network with data collected from an analytical model and experiments. We also investigated the change of the friction coefficient under different wrinkle morphologies using our predicted model. Furthermore, based on our previously proposed Beam Bundle Model, we present a dynamic contact model between a wrinkle and an object to investigate the effect of wrinkle morphological changes on friction's behavior during sliding motions (Fig. 2 B). The theoretical model was validated by experiments. The model can also predict the response of the embedded strain gauge in different scenario of sensing (self-deformation and interaction).

② Numerical modeling of the variable morphology of the wrinkle mechanism activated by pre-stretched mechanism: Different to the above pressurization, we also proposed a method for changing the morphology of the wrinkle mechanism based on pre-stretch mechanism. A Finite Element Analysis (FEA)-based simulations were conducted for both cases of actuation: stretching (Fig. 3 A) and bending (Fig. 3 B). We demonstrated in this research a wrinkled soft tactile sensor with variable morphology, leading to tunable sensing and perception property.

③ Implementation of wrinkled soft sensor with variable afferent morphology: There is an increasing interest in morphological computation due to its advantages in exploring underlying mechanism of soft robotics, especially in tactile sensing. We proposed the idea of variable afferent network morphology (VANmorph) for describing the phenomenon that morphology change of soft sensor

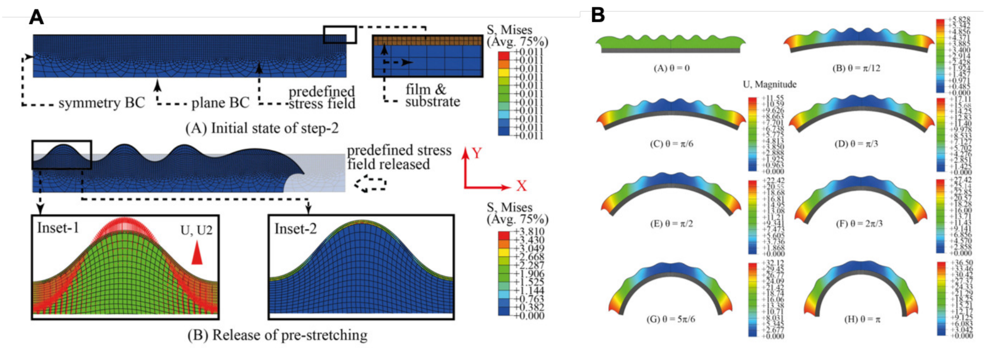

Fig. 3: FEM-based modeling of morphological change of the wrinkle sensor

varies the sensing capability. The characteristics of VANmorph are verified and evaluated based on a novel prototype of sensorized soft body inspired by water-induced wrinkle morphology of human fingers. Preliminary results reveal the advantages of such design in introducing multiple sensitivities to both normal indention and tangential sliding stimuli, and demonstrate potentials in future development of active tactile sensing system. For example: (a) By stretching and releasing, embedded strain gauge's posture, as well as electrical response change, resulting in self-deformation response (Fig. 4 A); while (b) The sensor in various morphology (wrinkle magnitude and wavelength) responds differently to even same sliding stimuli (Fig. 4 B-C). Furthermore, these morphological variations were found to closely affect the performance of sensor in three tasks including force sensing, shape discrimination and texture detection (Fig. 4 D). Interestingly, for each task, there was always an optimal morphological state that maximized the sensor performance, namely force sensitivity and perception accuracy.

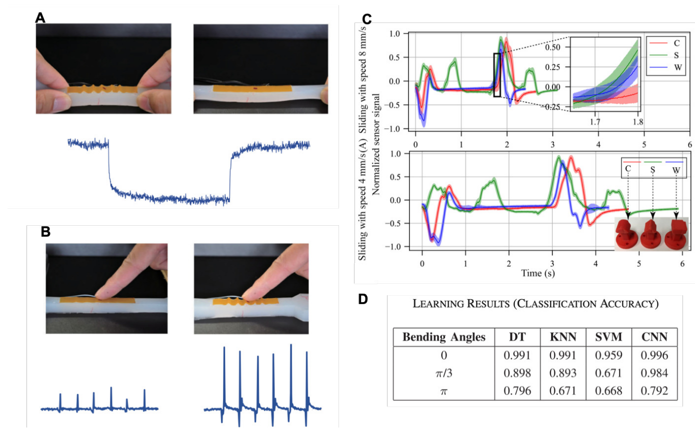

Fig. 4: Wrinkle sensor for multimodal sensing functions

The obtained result in this content sheds light to novel active tactile sensing system design, thus realizing "active" by adapting morphology instead of sensorimotor control algorithm to optimize perception gain. This work also inspired other results in this project.

(2) ***Soft tactile sensor with large-scale and changeable morphology:***

Based on the idea of **VANmorph**, we proposed a design of a vision-based tactile sensor with large skin and variable stiffness for enhancement of human-robot interaction. This work has been conducted in Ho group. We developed a large-scale tactile sensing system for a robotic link, called TacLINK, which can be assembled to form a whole-body tactile sensing robot arm. The proposed system is an elongated structure comprising a rigid transparent bone covered by continuous artificial soft skin. The soft skin of TacLINK not only provides tactile force feedback but can change its form and stiffness by inflation at low pressure. Upon contact with the surrounding environment, TacLINK perceives tactile information through the three-dimensional (3-D) deformation of its skin, resulting from the tracking of an array of markers on its inner wall by a stereo camera located at both ends of the transparent bone. A finite element model (FEM) was formulated to describe the relationship between applied forces and the displacements of markers, allowing detailed tactile information, including contact geometry and distribution of applied forces, to be derived simultaneously, regardless of the number of contacts. This sensing system is equipped with a micro-pump, thus it can vary the stiffness and shape of the soft skin by alternating inner pressure. We will investigate how the active change of the skin's morphology may benefit in human-robot interaction.

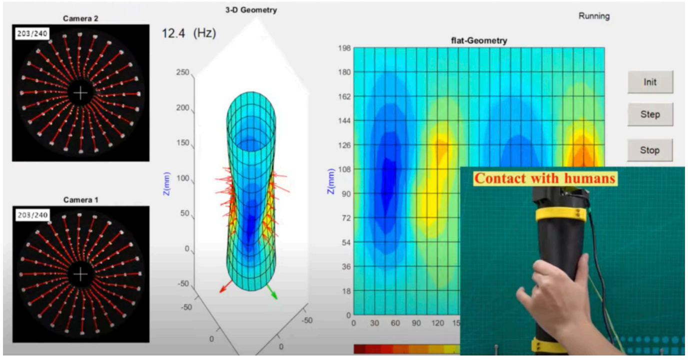

Fig. 5: Stiffness-variable vision-based tactile sensing interface

(3) ***Other results related to VANmorph***

During the project, we attempted to introduce other sensing mechanisms using different sensing principle (acceleration) or actuation (phase change of material). This content was mostly conducted by Shibuya group. With more designs to come, we aim for a design platform based on VANmorph idea, for implementation of soft sensing system integrated seamless actuation for various sensing purpose. First, we addressed the design, fabrication and preliminary experimental results of a morphologically changeable soft tactile sensing system aiming at detecting the location of a sliding movement. The proposed system consists of a silicon rubber base with a chamber and a thin silicone rubber skin covering the chamber. A three-axis accelerometer is embedded in the skin (see Fig. 6). By pressurizing the chamber, the skin inflates, changing its sensitivity to sliding movements on the surface of the skin. From the obtained data, we concluded that we can judge the location of the sliding movement of the indenter and that the sensing system potentially has the ability to detect the direction of the movements.

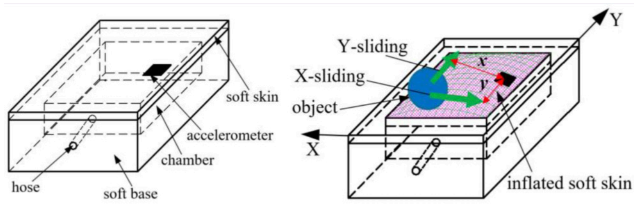

Fig. 6: Active sensor with embedded accelerator

We also presented a fabrication and preliminary experiments conducted on two prototypes of sensitivity-changeable soft tactile sensors, which utilize the phase change of gallium between the solid and liquid states (see Fig. 7). Ordinal materials change their stiffness by the process of melting or coagulation, which leads to stiffness and sensitivity changes in the entire tactile sensor. We fabricated two types of prototypes, namely flat and dome-shaped sensors, created from silicone rubber, gallium, and strain gauges. The sensitivity of the former in the liquid phase is higher than in the solid phase. Conversely, the sensitivity of the latter is higher in the solid state than in the liquid phase.

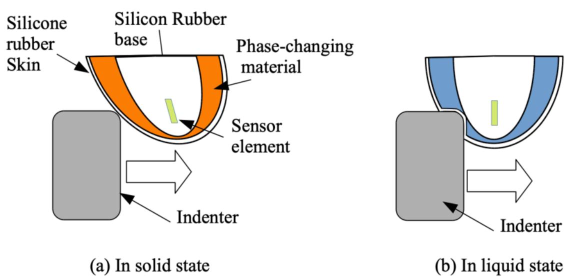

Fig. 7: Sensitivity-changeable soft tactile sensors

(4) ***Wet adhesion on soft contact interfaces***:

We extended the morphology of soft robotic fingerpad with deposition of micro patterned for evaluation of the *wet adhesion* in grasping and manipulation of soft fragile objects in wet environment, done by Ho and Takamura

First, we presented a mechanical approach to understanding the role of morphological design in achieving wet adhesion for secure grasping by a soft pad. The pad was designed and analyzed based on the wet attachment. We proposed a method to estimate the contact force in both normal and tangential directions between a soft pad with a micropattern surface and a rigid flat surface substrate. A square mold containing 3600 (85 µm×85µm) cells interspaced by grooves 15µm wide and 15µm deep was fabricated for molding micropattern pad (Fig. 8). Experimental results showed good agreement with theoretical results. The micropattern enhanced the contact force of the pad by approximately two-fold for the normal and 1.2 to 1.4-fold for the tangential force.

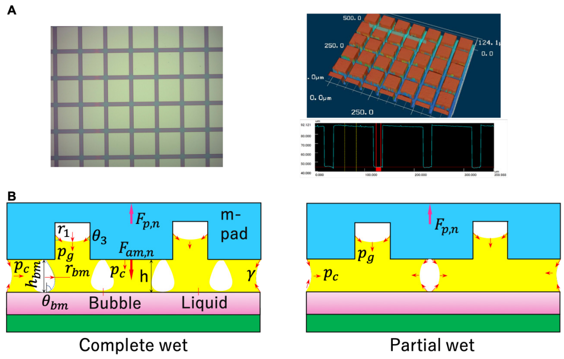

Fig. 8: Micro-patterned soft pad and contact

Then, we utilized the obtained analytical results in application to soft robotic hand that can grasp thin object (contact lens) (see Fig. 9 B) or food products (see Fig. 9 C). We found that the wet adhesion phenomenon caused by micro patterns on the soft pads were helpful in increasing the adhesion while reducing the applied gripping forces. This means that the soft robotic hand with micro patterns can be utilized in grasping fragile objects in wet environment. The obtained result is not only scientific, but also applicable to actual scenarios.

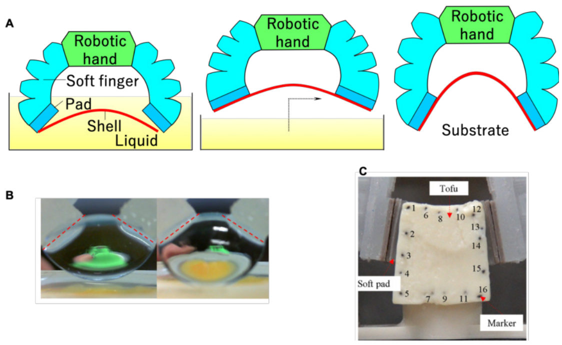

Fig. 9: Applications to handling soft, fragile objects

(5) ***Deformable propellers for drones***:

As partially supported by this project, we were successful to create deformable propellers that can withstand contacts with the surrounding environment, reducing the risk of falling of drones upon collisions. The design of the propeller was inspired by the *nodus* (bendable mechanism) of a dragonfly (see Fig. 10). This flexible segment can bend, twist and even fold upon collision, absorbing force upon impact and protecting the propeller from damage. Part of the leading edge of the propeller consists of a pliable silicone rubber surface able to absorb impact forces and reducing blade sharpness. The propeller, which is approximately 10inches long, can generate a thrust force of nearly 1.3 N at maximum velocity of about 3200rpm. Results of blade sharpness tests showed that the deformable propeller was safer than a rigid propeller. After deformation upon collision, the propeller can return to its original form and work normally within 0.4 seconds. We then put the deformable propellers onto a drone (total weight of 1 kg), and tested the flight ability with these propellers in two cases: by manual control, and autonomous control with motion tracking systems. The obtained results showed the drone with deformable propellers still keep the flight ability such as altitude-keep, hovering in both manual and autonomous modes.

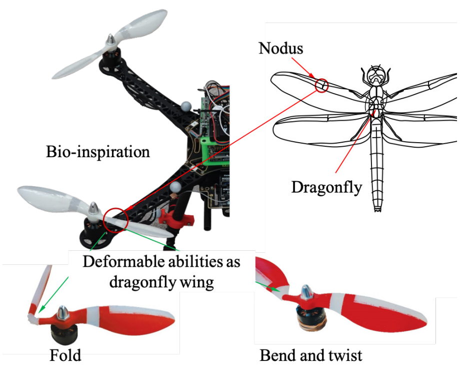

Fig. 10: Deformable propeller

(6) ***Conclusion and future plan:***

Above is the summary of the obtained results of this project. Overall, the project is not only fulfilled with initial plan on implementation of the **VANmorph** ideology, it also paves a new trend of research in soft mechanism with embedded sensing elements for multi-modal sensing of self-deformation and interaction. In addition, the utilization of VANmorph can be extended to proposal of novel soft mechanism, in which softness may benefit gentle interaction with the surrounding environment.

In the future, we plan to extensively develop the proposed ideas/designs to other aspects of robotic applications, such as grasping, locomotion, flying, as well as human-robot interaction. We also aim to address new challenge in science of soft robotics, such as morphological compensation, embodied intelligence, and so on.

５．主な発表論文等

〔雑誌論文〕　計12件（うち査読付論文　10件／うち国際共著　0件／うちオープンアクセス　2件）

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３．雑誌名 Sensors	６．最初と最後の頁 2036～2036
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１．著者名 Nguyen Pho Van、Ho Van Anh	４．巻 14
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１．著者名 Van Duong Lac、Ho Van Anh	４．巻 37
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TRO.2020.3031251	査読の有無 有
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１．著者名 Nguyen Van Pho、Ho Van Anh	４．巻 6
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〔図書〕　計0件

〔出願〕　計2件

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特許、特願2019-198143	2019年	国内

産業財産権の名称	発明者	権利者
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〔取得〕　計0件

〔その他〕

研究室のホームページにおける研究内容の紹介
http://www.jaist.ac.jp/ms/labs/vanho/research-e.html
研究内容を紹介するビデオチャネル
https://www.youtube.com/channel/UCMY5Pqokpamovx2pGF4N5eA

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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