様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　 ５ 月 ３１ 日現在

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研究種目：基盤研究(B)（一般）
研究期間：2021～2023
課題番号：２１Ｈ０１２８７
研究課題名（和文）Mechanics of Morphological Compensation, and its Application to Sensing and Control of Soft Robots

研究課題名（英文）Mechanics of Morphological Compensation, and its Application to Sensing and Control of Soft Robots

研究代表者
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研究者番号：６０７５７５０８

交付決定額（研究期間全体）：（直接経費）　　13,300,000円

研究成果の概要（和文）：本研究では、形態による補正の基礎物理を明らかにすることに成功し、埋め込みセンサーの出力とソフトボディの形態変化（切断やトリミングなど）の間の関係を明らかにした。特にSOFAに基づいたシミュレーションフレームワークを構築し、ソフトボディロボットのトポロジカルな変化を可能にし、埋め込みアクチュエータの下でのソフトボディの形態変化をシミュレーション環境上再現できた。このフレームワークにより、重要な変化の間にソフトロボットの性能（センシング、アクチュエーション、インタラクション）を維持することが可能となるソフトボディの形態変化に基づく補正戦略（MorphCom）を調べられる。

研究成果の学術的意義や社会的意義
The scientific characteristics of this research is to elucidate mechanics of the embedded sensors’ output at critical change of soft body’s morphology from the dynamics’ point of view, and how morphological compensation may benefit in offloading computation burden from the brain to the body.

研究成果の概要（英文）：In this research we succeeded in clarification of the underlying physics of morphological compensation, which reveals the correlation between the output of embedded sensors and critical changes in the morphology of the soft body (such as damage or trimming). We built a simulation framework based on SOFA, which allows topological change of the soft bodied robots, and simulating morphological change of the soft body under embedded actuator. From this framework, it is possible to investigate compensation strategies based on the morphological changes of the soft body, or MorphCom, to maintain the performance of the soft robot (sensing, actuation, interaction) during critical changes.

研究分野：ソフトロボット

キーワード：形態変形　ソフトセンシング　Whiskered sensor　FEMシミュレーション

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

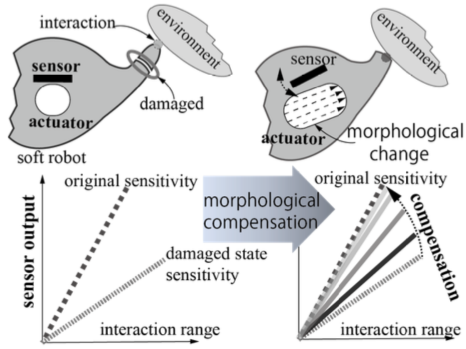


Fig. 1: Illustration of proposed morphological compensation

Biological systems can handle environmental uncertainty and adapt to morphological changes, such as growth or disability. For instance, rodents reconfigure their brain barrel cortexes to compensate for sensitivity to a trimmed whisker [1], and spiders are believed to adjust their sensing and actuation mechanisms in broken legs to maintain performance [2]. This natural adaptability has not been applied to conventional robots due to their fixed and rigid structures. Soft robots, however, can integrate both sensing and actuation within their flexible bodies (Fig. 1), offering novel mechanisms not typically seen in traditional designs [3]. Despite this potential, soft robots are susceptible to partial damage during extended operation or environmental interaction. There was no established morphological strategy for maintaining the performance of soft mechanisms when they are partially damaged, primarily due to the lack of a methodological framework for compensation.

In Japan, the 新学術領域研究「ソフトロボット学」project had addressed a wide range of disciplines to clarify the science of soft robotics. Recent trends emphasize morphological computation and the use of softness to enable complex operations in soft robots, with Dr. Helmut Hauser being a pioneer in this area [4]. While several proposals focused on actuation functions, there has been relatively little effort dedicated to using morphological computation for sensing. Apart from Dr. Nakajima's work on reservoir computing [5], there had been no significant attempts in Japan to exploit morphological computation for soft sensors. This raises a key scientific question: how can we understand the correlation between dynamic changes in embedded sensors and alterations in the soft robot's shape when partially damaged? Furthermore, by clarifying the mechanical properties of sensors from a dynamics perspective, we face another question: how can we implement morphological compensation in sensing to maintain the overall performance of the soft body with minimal computational effort from the controller (see Fig. 1)? Addressing these scientific issues forms the motivation for proposing this research project.

２．研究の目的

The purpose of this research is to clarify the underlying physics of morphological compensation, which reveals the correlation between the output of embedded sensors and critical changes in the morphology of the soft body (such as damage or trimming). From this framework, we aim to propose a compensation strategy methodology based on the morphological changes of the soft body, or **MorphCom**, to maintain the performance of the soft robot (sensing, actuation, interaction) during critical changes (see Fig. 1). We plan to apply this strategy to actual robotic mechanisms to demonstrate how compensation can be shifted from the brain (controller) to the body, which is crucial in soft robotics.

３．研究の方法

In this research, to investigate the MorphCom phenomenon, we applied the following methods:

1) **Build a SOFA-based environment for dynamic investigation of the soft-bodied object**. SOFA stands for Simulation Open Framework Architecture, which allows Finite Element Method (FEM) dynamic simulation with fewer computer resources. This plugin enables the construction of a soft body model embedded with specific sensing elements, simulating the dynamic response of the sensors and critical topology changes. To represent topological changes (tear, wear, broken) in the simulated models, remeshing the model at the location of the damage will be utilized through two possible approaches:
   - *Offline* method: Used for trimmed or broken states in the topological change. The model will be re-meshed before conducting separate simulations with conditions

similar to the original model.

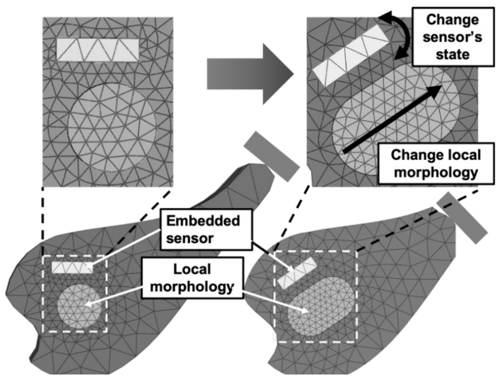
- *Online* method: Used for tearing or fracture states in the topological change (less critical cases). Remeshing will be conducted during the solving of dynamic equations of the simulated model.

By combining these approaches, it is possible to assess the dynamics of embedded sensing elements under critical changes in the soft body's topology. This study is valuable for proposing compensation strategies for sensing and controlling soft robots under partial damage.

2) **Morphological compensation strategy framework:**

When a soft robot undergoes a critical change, embedded sensing elements generate different feedbacks, potentially causing malfunction. We propose a method that: if the morphology of the soft body can be adjusted so that the embedded sensing elements produce outputs similar to those of the original state, modifying the controller would become unnecessary. This approach, related to body morphology, is termed the Morphological Compensation strategy (**MorphCom**). Based on our previous research, we found that utilizing existing actuation elements can actively vary the sensitivity of embedded sensors, benefiting the MorphCom approach. In detailed (see the illustration below, too):

- The FEM model can be used for an intensive study of the embedded sensors' response to critical changes in morphology. In this investigation, the local morphology (shape/stiffness) around the sensor's location can be varied so that, with active changes to this local morphology, the sensor generates outputs similar to those of the robot's original state (before the critical change).



- Design a mechanism that allows changing the local morphology of the soft body around the embedded sensor. Following actuators could be considered using pneumatic actuators, DEAs (dielectric elastomer actuators), SMPs (shape memory polymers), and so on. Depending on the specific sensing needs, various types of sensors can be used, such as strain gauges, accelerometers, optical sensors, and magnetic/coil sensors.

Based on this method, integration of such sensing and local actuating mechanisms on specific soft robots can be implemented, paves a way to a new class of sensorized soft bodies for soft robotic system.

４．研究成果

1) **SOFA-based environment for simulating topological change of the soft bodies**

Based on the proposed methods, we built two programs for updating the topological changes of the soft bodies offline and online, depending on the evaluation's requirements. Details can be seen below:

a. Offline mode:

For a straightforward evaluation of topological changes, the process illustrated in the figure can be followed. The diagram depicts the offline mode process for topology reconstruction of a soft body using the SOFA platform.

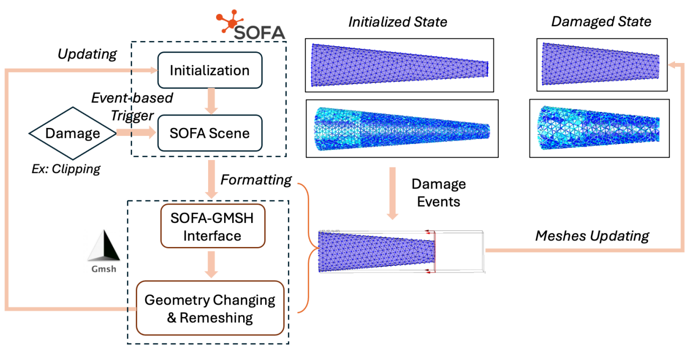


Fig. 2: Topological reconstruction (Offline mode)

Initially, SOFA creates the mesh for the soft body in its initial state. If damage occurs, the detected damage triggers updates to the SOFA scene, transitioning the soft body from its initial state to a damaged state. The damage information is then formatted and passed through the SOFA-GMSH interface. The SOFA-GMSH interface facilitates geometry changes and remeshing to accommodate the damage events. Finally, the updated meshes reflect the new topology, showing the soft body in its damaged state. This updated state is fed back into the system for further updates as needed. This process ensures that the topology of the soft body is accurately reconstructed and updated in response to damage events.

a. Online mode:

We also succeeded in building a process for online updating the mesh of the 3-D soft body upon topological change. The diagram (Fig. 3) illustrates the online mode process for topology updates of a soft body using the SOFA platform.

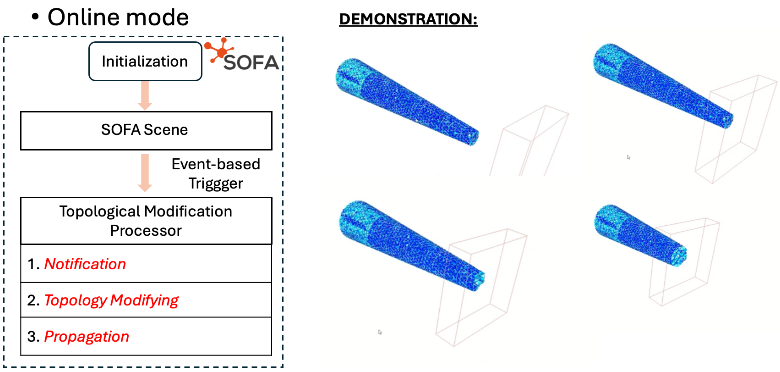


Fig. 3: Topological reconstruction (Online mode)

The process can be summarized as follows: First, the SOFA platform initializes the scene and the mesh for the soft object. If topological changes are triggered by specific events detected in the SOFA scene, it will create a notification for adding the topological change event to the action queue, then execute the topological change action. Note that, currently, only the addition and removal of elements are supported. Next, SOFA will send the topological change event to all components within the simulation (e.g., FE solver, mechanical models). This process ensures that the topology of the soft body is dynamically modified and updated in real-time in response to specific events within the simulation. In the demonstration shown in Fig. 3, the notification of topological changes occurs when any element falls within a specified box space. The initial mechanical model is then updated based on the topological changes, then, other tasks such as interaction, load bearing, can be conducted based on the updated topology.

2) SOFA-based toolbox for complicated soft structure:

To implement the morphological change at local locations inside the soft bodies, we constructed a SOFA-based model of the soft body embedded with fiber-reinforced chamber.

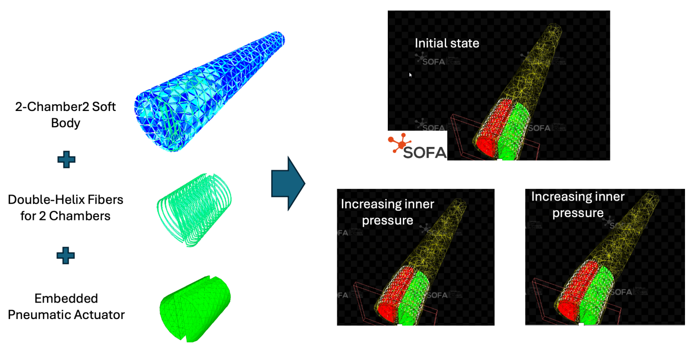


Fig. 4: Integrating actuation into soft body (simulation)

This structure allows the simulation of the morphological change of the soft bodies under embedded actuation. Here, the soft body has two chambers, where the inner pressure variation would lead to inflations. Two chambers, therefore, are reinforced by two double helix fibers wounded around the chambers' wall. We succeeded in incorporating all components in one simulation, generating different morphology for the soft body under variational inner pressures of chambers (Fig. 4). This toolbox can be extended to other configuration with different setup, types of actuators. It is expected to be an efficient tool for investigating the behavior of the soft body with morphological change under embedded actuating systems.

3) **Case study**: Morphological compensation of sensing ability for sensory whiskers with critical topological change:

Recent studies have drawn inspiration from natural whiskers to propose a tactile sensing system aimed at enhancing the sensory capabilities of autonomous robots. In this study, we introduce a novel artificial soft whisker sensor (Fig. 5) that is both flexible and capable of adapting and compensating for damage, such as trimming or breaking, during operation. Our sensor employs a morphological compensation mechanism designed from an analytical model of the whisker, allowing the device to actively adjust its structure to regain sensitivity nearly equivalent to its original, undamaged state.

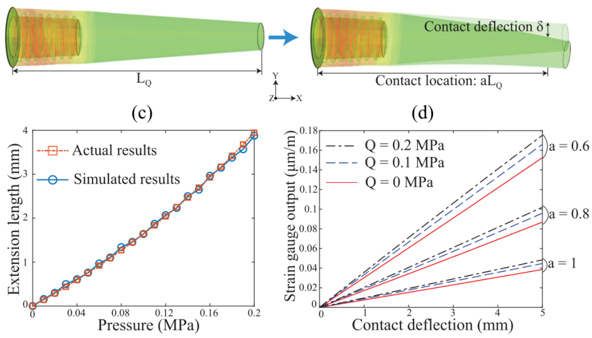


Fig. 5: Trimmed whiskers and compensation validation

The whisker's body consists of a silicon-rubber truncated cone with an internal air chamber serving as the medulla layer, which can be inflated to adjust rigidity. A small strain gauge attached to the outer wall of the chamber records strain variations upon contact. The chamber wall is reinforced with two inextensible nylon fibers wound around it, ensuring that morphological changes occur only in the strain gauge's measuring direction by compressing or releasing pressurized air within the chamber [6]. We developed an analytical model to regulate whisker sensitivity by altering the chamber's morphology. Experimental results aligned well with numerical simulations, demonstrating the sensor's performance in both intact and compensation modes. Adaptive functionality was tested in two scenarios: (1) A short whisker (65mm) compensating for a longer one (70mm), including a self-compensation case, and (2) the reverse scenario. Preliminary results indicated the feasibility of the concept and the analytical model's efficiency in the compensation process, with the compensator achieving an average compensation error of 20.385% in typical scenarios. Extended works are also reported in [7]-[8].

The implementation of this concept in the current study advances the idea of morphological computation in soft robotics, paving the way for an active sensing system capable of overcoming critical events like a broken whisker through optimized morphological compensation.

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５．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　6件／うち国際共著　1件／うちオープンアクセス　3件）

１．著者名 Nguyen Nhan Huu、Hauser Helmut、Maiolino Perla、Ho Van Anh	４．巻 10
２．論文標題 Tactile Resilience of Sensory Whisker by Adaptive Morphology	５．発行年 2022年
３．雑誌名 IEEE Access	６．最初と最後の頁 101814～101824
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2022.3208883	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 該当する

１．著者名 Nguyen Duy Dang、Nguyen Nhan Huu、Ho Van Anh	４．巻 8
２．論文標題 Morphology-Changeable Soft Pads Facilitate Locomotion in Wet Conditions	５．発行年 2023年
３．雑誌名 IEEE Robotics and Automation Letters	６．最初と最後の頁 1～8
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LRA.2023.3264731	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 －

１．著者名 Charernchai Sumamal、Chikae Miyuki、Phan Tue Trong、Wonsawat Wanida、Hirose Daisuke、Takamura Yuzuru	４．巻 94
２．論文標題 Automated Paper-Based Femtogram Sensing Device for Competitive Enzyme-Linked Immunosorbent Assay of Aflatoxin B Using Submicroliter Samples	５．発行年 2022年
３．雑誌名 Analytical Chemistry	６．最初と最後の頁 5099～5105
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.analchem.1c05401	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 Huang Yueh-Han、Hirose Daisuke、Minami Jun、Wang Meng-Jiy、Takamura Yuzuru	４．巻 94
２．論文標題 Fabrication and Characterizations of Axial View Liquid Electrode Plasma Atomic Emission Spectrometry for the Sensitive Determination of Trace Zinc, Cadmium, and Lead	５．発行年 2022年
３．雑誌名 Analytical Chemistry	６．最初と最後の頁 8209～8216
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.analchem.2c00122	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 Luu Quan Khanh、Nguyen Nhan Huu、Ho Van Anh	4．巻 39
2．論文標題 Simulation, Learning, and Application of Vision-Based Tactile Sensing at Large Scale	5．発行年 2023年
3．雑誌名 IEEE Transactions on Robotics	6．最初と最後の頁 1～17
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TRO.2023.3245983	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 -

1．著者名 Nguyen Nhan Huu、Ho Van Anh	4．巻 9
2．論文標題 Mechanics and Morphological Compensation Strategy for Trimmed Soft Whisker Sensor	5．発行年 2022年
3．雑誌名 Soft Robotics	6．最初と最後の頁 135～153
掲載論文のDOI（デジタルオブジェクト識別子） 10.1089/soro.2020.0056	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 -

〔学会発表〕　計13件（うち招待講演　2件／うち国際学会　6件）

1．発表者名 Tuan Tai Nguyen and Van Anh Ho
2．発表標題 Miniaturized Soft Continuum Robot with Integrated Vision: Statics Analysis
3．学会等名 2023 IEEE/SICE International Symposium on System Integration（国際学会）
4．発表年 2023年

1．発表者名 Van Anh Ho
2．発表標題 Soft Robotic Hand for Sushi Grasping and Handling
3．学会等名 2023 IEEE/SICE International Symposium on System Integration（国際学会）
4．発表年 2023年

1．発表者名 Jianglong Guo
2．発表標題 Self-morphing Soft Parallel-and-coplanar Electroadhesive Grippers Based on Laser-scribed Graphene Oxide Electrodes.
3．学会等名 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems（国際学会）
4．発表年 2022年

1．発表者名 高村禅
2．発表標題 ltra-compact metal-analysis by liquid electrode plasma and its application to biosensing
3．学会等名 Japan-Africa Hybrid Workshop on Promotion of Science, Engineering, and Technology in Innovative Solutions to Environmental Problems in Metal Mining Area（招待講演）
4．発表年 2022年

1．発表者名 Van Anh Ho
2．発表標題 Adaptive Morphology Facilitates Embodied Inteligence
3．学会等名 2023 IEEE International Conference on Soft Robotics, Workshop on Adaptive Sensing（招待講演）
4．発表年 2023年

1．発表者名 渋谷恒司
2．発表標題 感度変更可能な柔軟触覚センサの開発 -内部チャンバー構造がセンサ出力に与える影響-
3．学会等名 日本機械学会ロボティクス・メカトロニクス講演会2022
4．発表年 2022年

１．発表者名 渋谷恒司
２．発表標題 ガリウムの相変化を利用した柔軟触覚センサの開発
３．学会等名 日本機械学会ロボティクス・メカトロニクス講演会202
４．発表年 2022年

１．発表者名 森一登
２．発表標題 大変形可能な変位センサを用いた柔軟触覚センサの開発
３．学会等名 日本機械学会ロボティクス・メカトロニクス講演会2021(Robomech2021)
４．発表年 2021年

１．発表者名 森一登
２．発表標題 感度変更可能な柔軟触覚センサの開発　―内部チャン バー構造がセンサ出力に与える影響―
３．学会等名 日本機械学会ロボティクス・メカトロ ニクス講演会2022(Robomech2022)
４．発表年 2022年

１．発表者名 中山悠之介
２．発表標題 ガリウムの相変化を利用した柔軟触覚センサの開発
３．学会等名 日本機械学会ロボティクス・メカトロニクス講演会2022(Robomech2022)
４．発表年 2022年

1．発表者名 Nhan Huu Nguyen
2．発表標題 Morphological Approach for Enabling Intelligent Damage-recovery Function and Beyond: Case of Soft Whisker Sensor
3．学会等名 Workshop on Soft Sensing: Environment, Morphology, Brain in Biology and Robotics, IEEE International Conference on Soft Robotics（国際学会）
4．発表年 2022年

1．発表者名 Yunosuke Nakayama
2．発表標題 Development of Soft Tactile Sensor Utilizing Phase Change of Gallium
3．学会等名 Workshop on Soft Sensing: Environment, Morphology, Brain in Biology and Robotics, IEEE International Conference on Soft Robotics（国際学会）
4．発表年 2022年

1．発表者名 Kazuto Mori
2．発表標題 Effect of Soft Tactile Sensor's Inner Structure on Output
3．学会等名 Workshop on Soft Sensing: Environment, Morphology, Brain in Biology and Robotics, IEEE International Conference on Soft Robotics（国際学会）
4．発表年 2022年

〔図書〕　計0件

〔出願〕　計1件

産業財産権の名称	発明者	権利者
ロボットハンド、制御装置及び収容容器	ホ アンヴァン、河野晋也、ソン ティエン ブイ	国立大学法人北陸先端科学技術大学院大学
産業財産権の種類、番号	**出願年**	**国内・外国の別**
特許、特願2023-016702	2023年	国内

〔取得〕　計0件

〔その他〕

Workshop at IROS 2022
https://sites.google.com/view/iros2022ws-lsrobskin/
Workshop on Soft Sensing at RoboSoft 2022
https://sites.google.com/view/robosoft2022ws-ss-bio-rob

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
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研究分担者	都　英次郎 (Miyako Eijiro) (70443231)	北陸先端科学技術大学院大学・先端科学技術研究科・准教授 (13302)	

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2件

国際研究集会	開催年
Large-scale robotic skin: Perception, Interaction, and Control	2022年～2022年
Workshop on Soft Sensing: Environment, Morphology, Brain in Biology and Robotics, 2022 IEEE International Conference on Soft Robotics	2022年～2022年

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