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研究課題名（和文）Learning in-hand manipulation for a compliant underactuated gripper with interactive human supervision

研究課題名（英文）Learning in-hand manipulation for a compliant underactuated gripper with interactive human supervision

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研究成果の概要（和文）：私たちのプロジェクトは、操作タスクを学習するためのロボットグリッパーやハンドの開発に焦点を当てています。デカップリングジョイントを備えたケーブル駆動グリッパーや、リンク機構を使用した人間型ロボットフィンガー、3本指のアンダーアクチュエイトロボットハンドを開発しました。シミュレーション環境で小さな物体の操作を訓練し、強化学習アルゴリズムを実装して検証しました。また、シミュレーションから実際の適用への移行を促進するために、CUTを実装しました。

研究成果の学術的意義や社会的意義
Our research achievements enable safe and precise manipulation with robotic grippers and hands, promoting human-robot collaboration in several fields that require delicate manipulation such as assembly operations, wearable and field robotics, assistive devices, and prosthesis.

研究成果の概要（英文）：Our project has focused on developing robotic grippers and hands for learning manipulation tasks. We proposed several innovative designs, including a cable-driven gripper with decoupled joints for effective grasping force estimation and a variation of anthropomorphic robotic fingers using linkage mechanisms to increase rigidity and pinch force. Additionally, we developed a three-finger underactuated robotic hand with compliant joints and cable-driven actuation, where each finger is actuated by a single motor managing both flexion and abduction movements. Significant progress has been made in enhancing the control mechanisms and interaction capabilities of this new hand gripper. We created a simulation environment to train in-hand manipulation of small objects, implementing and validating several reinforcement learning algorithms. Furthermore, we implemented Image-to-Image Contrastive Unpaired Translation (CUT) for realistic policy training inputs to facilitate sim-to-real transfer.

研究分野：ロボティクス、知能機械システム

キーワード：compliant robotic hand　in-hand manipulation　reinforcement learning　sim-to-real

１．研究開始当初の背景

Recently, robotic manipulation has gained widespread attention with recent research showing unprecedented dexterity in manipulating small objects such as Rubik's cube with multi-fingered robotic hands. This is traditionally a challenging problem because of the need for high-dimensional control, a large number of potential contacts, partial observability, and real-world deployment. A reinforcement learning approach is commonly used to solve the object reorientation task in randomized simulation environments without any human input and deploy the same policy on a real platform. However, the computational power needed to explore all possible states is still considerable, and only rigid objects were considered.

Additional works have tried to extend this approach by using human demonstrations in addition to model-free deep reinforcement learning methods to reduce the complexity and accelerate search execution for manipulation tasks in simulation. The main drawback of model-free learning approaches is the requirement for a large number of samples. Model-based trajectory optimization methods, on the other hand, can provide high performance and sample efficiency for high dexterous tasks. They, however, suffer from the lack of generalization.

End-effectors are also critical for dexterous in-hand manipulation. Fully actuated anthropomorphic hands can provide task flexibility and adaptability and are considered the best option for high dexterous manipulation. They, however, increase hardware and control complexity and are often expensive and fragile. Other gripper mechanisms have also been proposed based on soft materials. They are low-cost, reduce the number of actuators, and provide intrinsic compliance, but lack sensing and precise actuation.

２．研究の目的

This research project aimed to provide more adaptive and versatile end-effectors with enhanced capabilities for grasping and object manipulation. The core components of this project are:

a. An underactuated compliant gripper suitable for safe interaction and dexterous manipulation,
b. A novel framework for learning complex in-hand manipulation skills by combining the use of deep reinforcement learning, expert demonstrations, and realistic simulation environments, and
c. Real-world deployment in the physical robot.

３．研究の方法

- <u>Developing underactuated compliant grippers for safe and dexterous object manipulation</u>

  We explored the intrinsic compliance of cable-driven mechanisms to provide safe human-robot interaction. We further integrated rigid linkage configurations to increase grasping forces in anthropomorphic fingers. We finally developed an underactuated three-finger robotic hand with cable-driven actuation for safe interaction. The goal was to provide fast and precise control of the fingers' positioning while ensuring the desired compliance by controlling the tendon tension. The mechanical modeling of the gripper elements was performed with CAD software and FEM analysis.

- Learn in-hand manipulation skills by model-free Deep Reinforcement Learning (DRL) and human demonstrations in randomized simulation environments

  A simulation environment for deploying manipulation tasks of various objects was developed using Nvidia's GPU-based Isaac Sim. This platform includes a particle dynamics library capable of simulating both rigid and deformable objects, such as clothing and ropes. Isaac Sim provides a high-performance learning platform to train policies directly on the GPU and supports dynamic randomization to facilitate adaptation to unknown real-world dynamics. Initial demonstrations were collected by controlling the gripper within this simulation environment using a hand tracker to map kinematic motion, which helped reduce state space exploration. Subsequently, a model-free policy was trained using several deep reinforcement learning (DRL) algorithms. Learning was accelerated by running up to 64 simultaneous simulation environments. Integration between the simulator, gripper, interface, sensors, and controllers was implemented using the Robot Operating System (ROS).

- Transfer to physical robot

  To facilitate transferring to the real world, we added domain randomization during the training in simulation. Furthermore, to enhance the transition of these methodologies to real-world applications, we utilized Image-to-Image Contrastive Unpaired Translation (CUT) to provide realistic inputs for policy training. The transfer to the real world is still ongoing work and constitutes the focus of our future work.

4. 研究成果

- We developed a cable-driven compliant gripper with decoupled joints for grasping force estimation, shown in Fig.1. The gripper was primarily designed for safe human-robot interaction, focusing on reducing the risk of damage during manipulation tasks. This design was experimentally evaluated in surgical scenarios where safe gripper-tissue force interactions are critical. The evaluation included testing the gripper's ability to handle delicate tissues without causing damage, ensuring the precise and gentle manipulation necessary for surgical applications. Additionally, the gripper's design allows for adaptive grasping, making it versatile for various tasks beyond surgery. Its decoupled joints enable accurate force estimation, enhancing its functionality in scenarios requiring precise control.

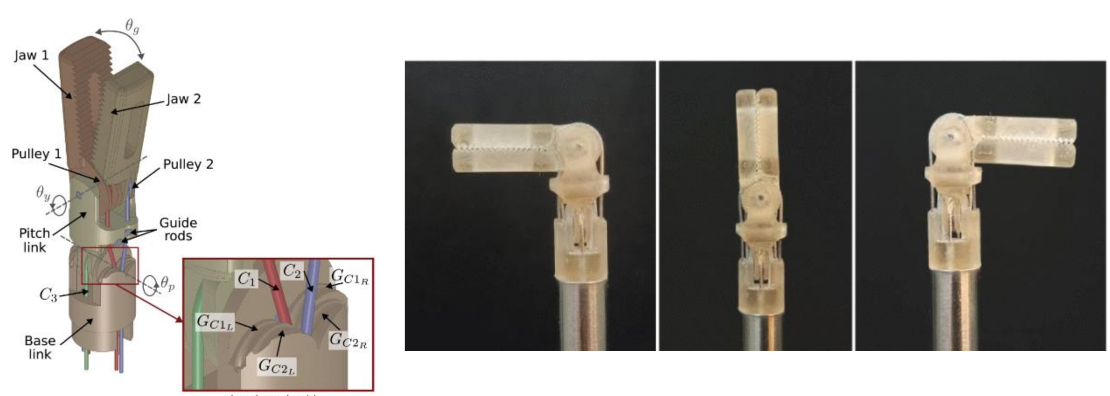

Fig.1. Cable-driven mechanism for a compliant robotic gripper.

- A variation for cable-driven anthropomorphic robotic fingers was proposed based on linkage mechanisms that increased rigidity and pinch force during grasping, shown in Fig.2. This innovative design enhances the functionality of the robotic fingers by combining the flexibility of cable-driven mechanisms with the strength provided by linkage systems. The cable-driven mechanism ensures compliance, making it safe for human-robot interactions. At the same time, the incorporation of linkages significantly increases the rigidity and pinch force, improving the overall performance and effectiveness of the gripper. This enhancement allows for a more robust and secure grasp, with increments in grasping forces of up to 80%.

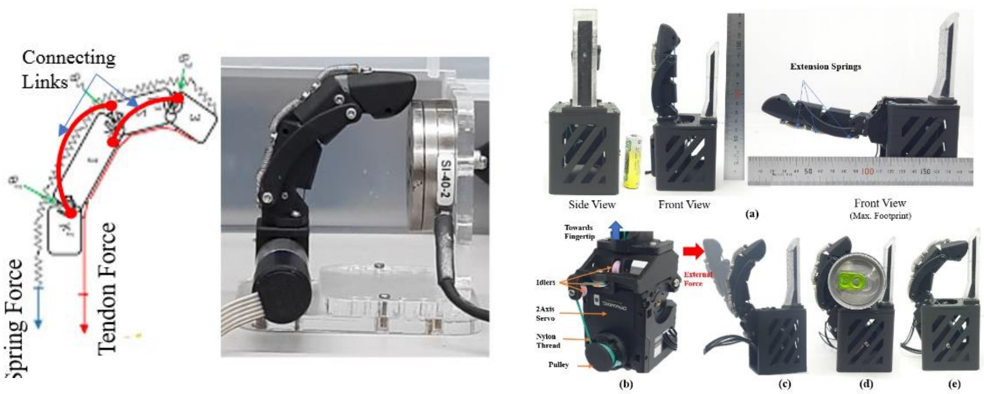

Fig.2. Prototype of an enhanced anthropomorphic cable-driven finger with linkage mechanism.

- A three-finger underactuated cable-driven robotic hand was developed to provide higher dexterity while ensuring safe physical human-robot interaction, as shown in Fig.3. This robotic hand combines the use of rigid links with soft joints and cable-driven actuation. The rigid links offer structural integrity and precise movement, while the soft joints and cable-driven mechanism ensure compliance and adaptability, making it safe for interactions with humans. To test and refine the robotic hand, a simulation environment mimicking real-world conditions was developed within the Isaac Sim framework.

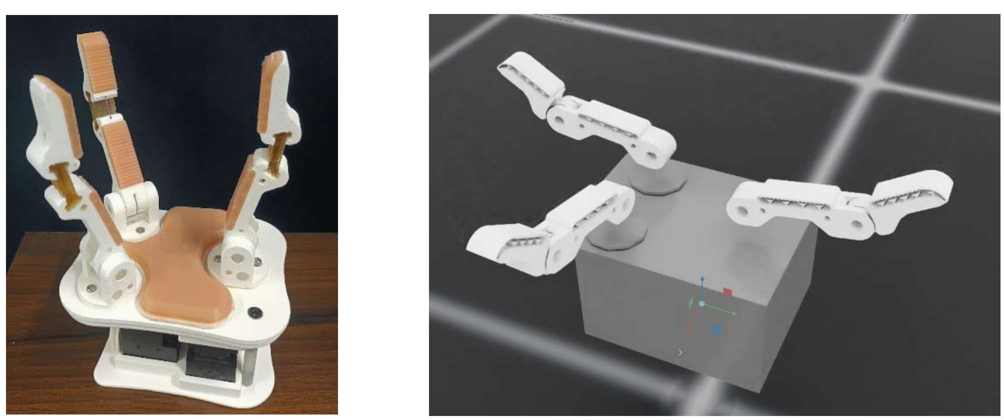

Fig.3. **Right**. Underactuated cable-driven three-finger hand. **Left**. Simulation version of the proposed hand

- The simulation environment was expanded to include interactions with both rigid and soft objects. The first in-hand manipulation task was defined as the reorientation of a rigid cube to a desired target orientation. To accelerate the learning process, multiple simultaneous environments were deployed for learning in the simulation, as shown in Fig. 4, leveraging the computational power of advanced GPUs. This approach significantly enhanced the efficiency and speed of training, allowing for more rapid development and refinement of manipulation skills within the simulated environment.

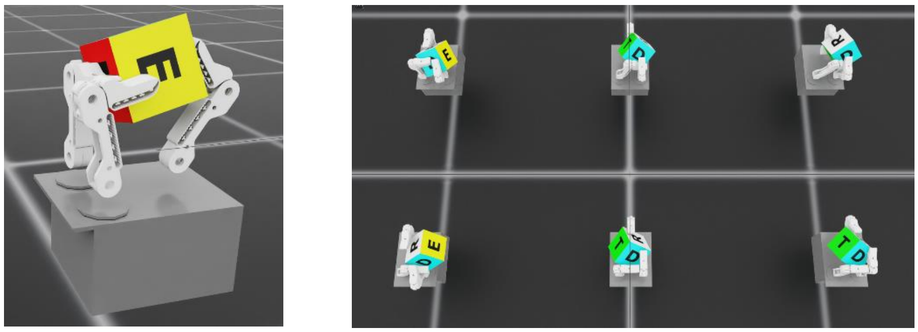

Fig.4. Simulation environment for in-hand cube manipulation learning

- An Image-to-Image Contrastive Unpaired Translation (CUT) was implemented to provide realistic inputs for policy training, enhancing the quality and relevance of the simulated data. We evaluated the performance of the proposed algorithm using deformable 2D objects, as shown in Fig.5, demonstrating its effectiveness in generating realistic and useful inputs for training purposes. The transfer of these methodologies and trained policies to real-world applications is still an ongoing effort and will be a primary focus of our future work.

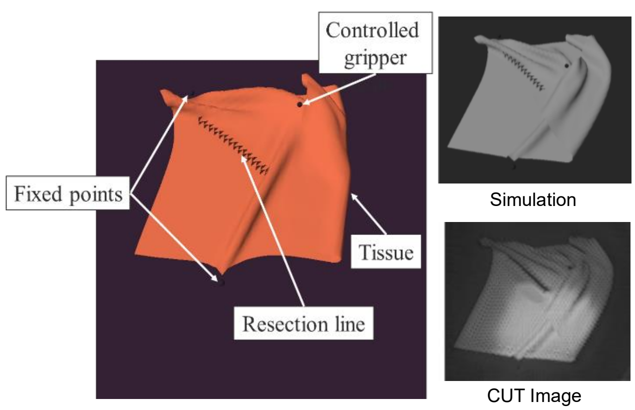

Fig.5. PBD Simulator and I2I output

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　4件／うちオープンアクセス　3件）

１．著者名 Davila Ana、Colan Jacinto、Hasegawa Yasuhisa	４．巻 11
２．論文標題 Real-time inverse kinematics for robotic manipulation under remote center-of-motion constraint using memetic evolution	５．発行年 2024年
３．雑誌名 Journal of Computational Design and Engineering	６．最初と最後の頁 248～264
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/jcde/qwae047	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 Davila Ana、Colan Jacinto、Hasegawa Yasuhisa	４．巻 146
２．論文標題 Comparison of fine-tuning strategies for transfer learning in medical image classification	５．発行年 2024年
３．雑誌名 Image and Vision Computing	６．最初と最後の頁 105012～105012
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.imavis.2024.105012	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 該当する

１．著者名 Colan Jacinto、Davila Ana、Zhu Yaonan、Aoyama Tadayoshi、Hasegawa Yasuhisa	４．巻 11
２．論文標題 OpenRST: An Open Platform for Customizable 3D Printed Cable-Driven Robotic Surgical Tools	５．発行年 2023年
３．雑誌名 IEEE Access	６．最初と最後の頁 6092～6105
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2023.3236821	査読の有無 有
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１．著者名 Colan Jacinto、Davila Ana、Fozilov Khusniddin、Hasegawa Yasuhisa	４．巻 23
２．論文標題 A Concurrent Framework for Constrained Inverse Kinematics of Minimally Invasive Surgical Robots	５．発行年 2023年
３．雑誌名 Sensors	６．最初と最後の頁 3328～3328
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s23063328	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

〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　5件）

1．発表者名
Ana Davila, Jacinto Colan, Yasuhisa Hasegawa

2．発表標題
Gradient-Based Fine-Tuning Strategy for Improved Transfer Learning on Surgical Images

3．学会等名
2023 International Symposium on Micro-NanoMechatronics and Human Science（国際学会）

4．発表年
2023年

1．発表者名
Jacinto Colan, Ana Davila, Yasuhisa Hasegawa

2．発表標題
Enhancing Gradient-Based Inverse Kinematics with Dynamic Step Sizes

3．学会等名
2023 International Symposium on Micro-NanoMechatronics and Human Science（国際学会）

4．発表年
2023年

1．発表者名
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2．発表標題
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1．発表者名
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2．発表標題
Sensorless grip force estimation of a cable-driven robotic surgical tool based on Gaussian Process Regression

3．学会等名
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4．発表年
2022年

１．発表者名 Jacinto Colan, Ana Davila, Yasuhisa Hasegawa
２．発表標題 Constrained motion planning for a robotic endoscope holder based on Hierarchical Quadratic Programming
３．学会等名 8th International Conference on Control and Robotics Engineering（国際学会）
４．発表年 2023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