Visual Learning Towards Soft Robot Force Control using a 3D Metamaterial with Differential Stiffness

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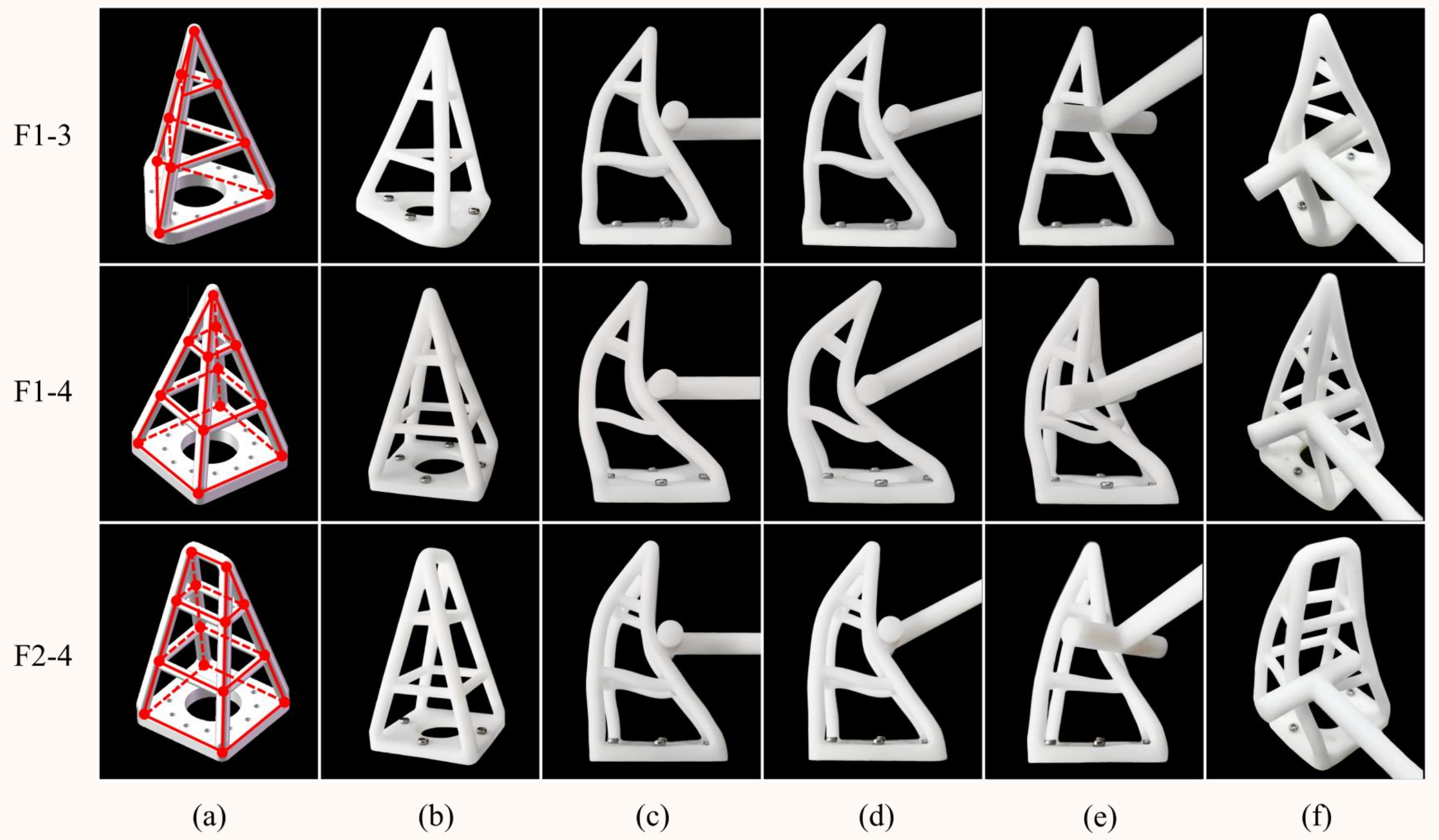
CoRL 2021

Introduction

- Force feedback and force control become mandatory to achieve a robust and versatile interaction between a robotic system and the physical environment, as well as safe and dependable operations in the presence of human.- Traditional sensing methods for force and torque rely heavily on rigid-body theories to measure and directly react to the contact dynamics.
- Soft robots made from compliant materials usually show life-like, adaptive motions at a relatively low cost. However, they are challenging to model due to their non-linear mechanics, making it difficult to integrate advanced sensory. Instead, field sensing solutions are usually adopted for soft robots for proprioceptive sensing, which promotes the application of learning-based solutions to overcome the modeling challenge.
- Periodic properties, such as electromagnetic, optical, acoustic, and mechanical ones, provide 3D metamaterials with the engineering potential towards distributed sensing for advanced robot control, where learning-based methods become an effective tool for end-to-end integration.

3D Metamaterial Design

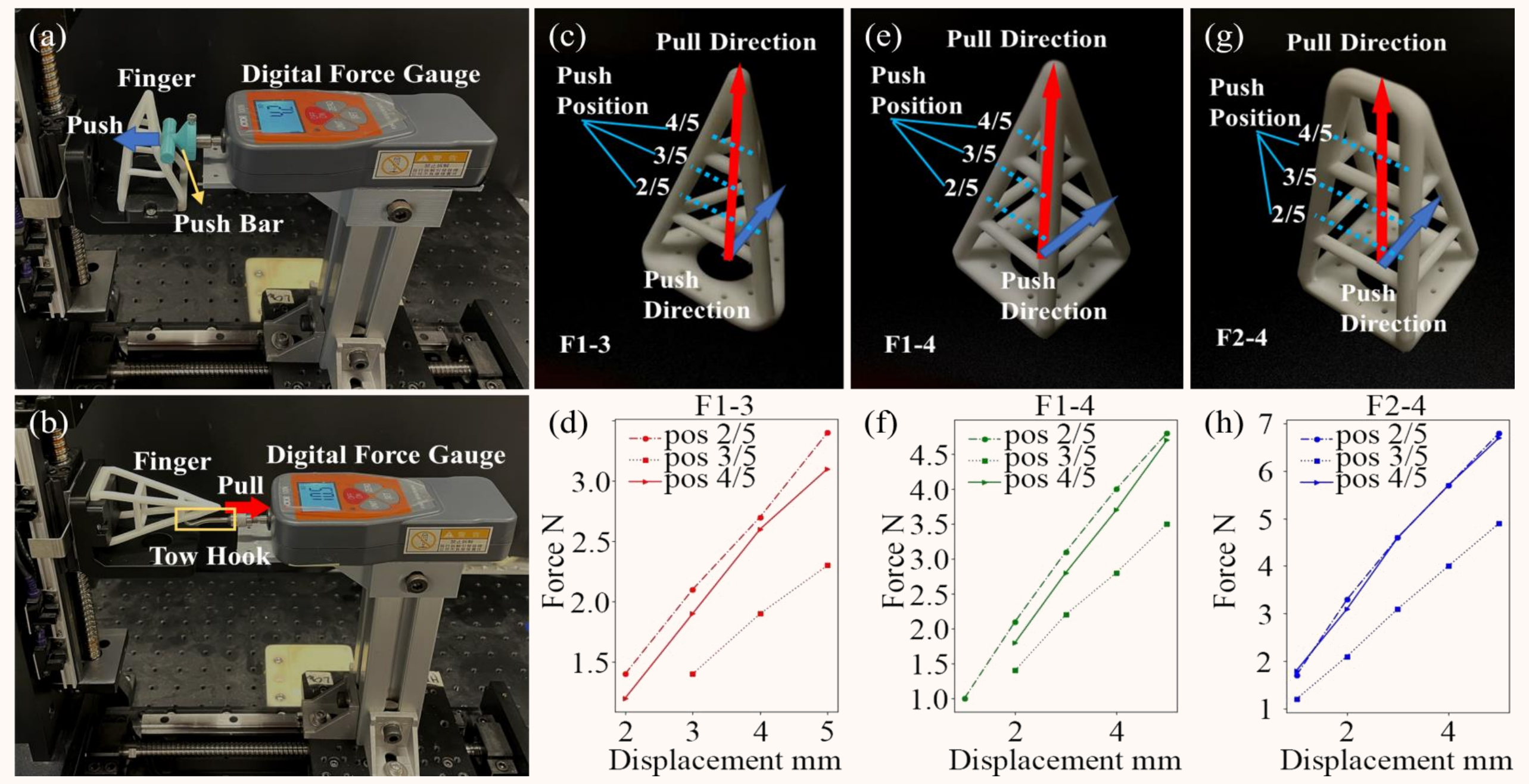
The proposed 3D metamaterial features a gradually shrinking cross-section from the base to the tip, which can be designed with various geometric layouts based on the desired adaptation and form factor.



The proposed 3D metamaterial is capable of three major adaptive modes, including surface adaptation, twisted adaptation, and edge adaptation in all directions in the radial plane.

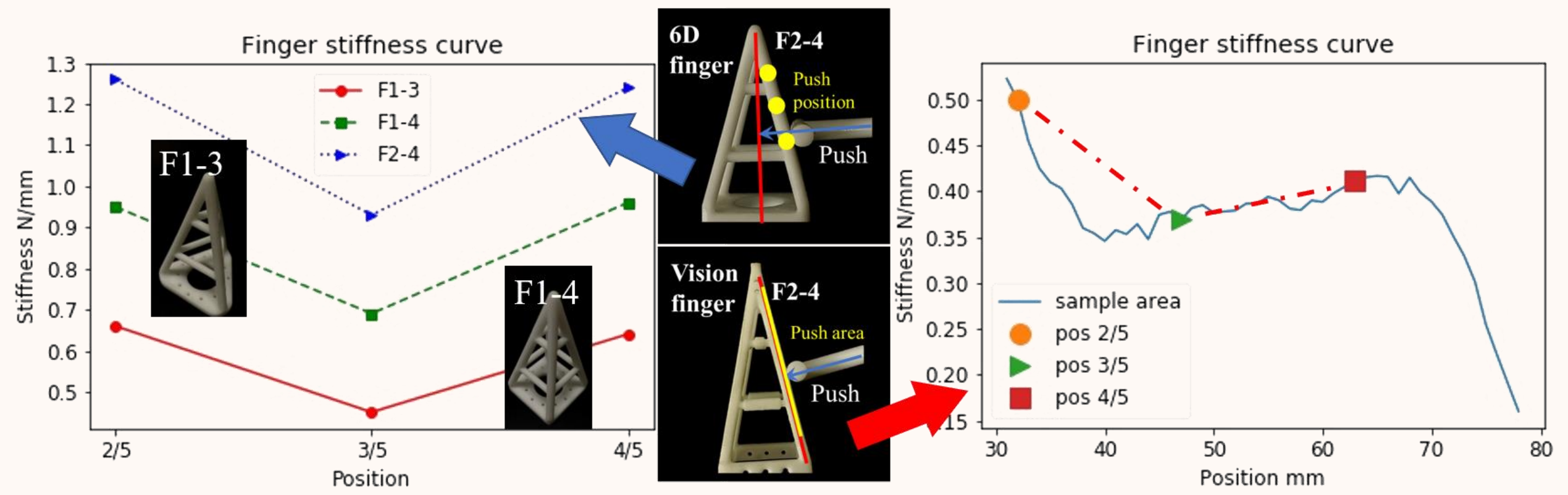
Radial Stiffness Distribution

We developed a simple test rig to measure the finger's radial stiffness, and reorient the finger to measure its axial stiffness.



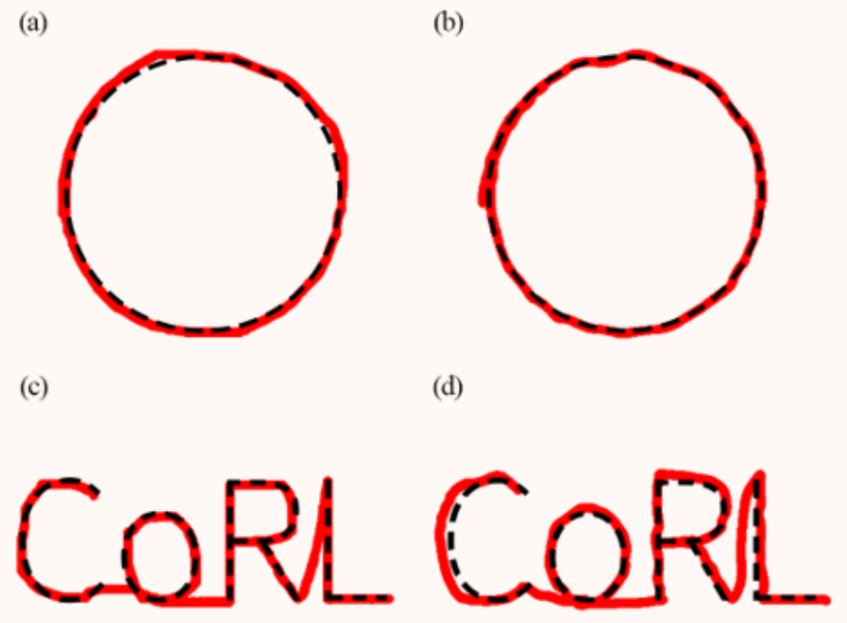
Omni-directional Adaptation

The figure below explains our soft finger's omni-directional form adaptation in the radial direction during the interaction under external force.



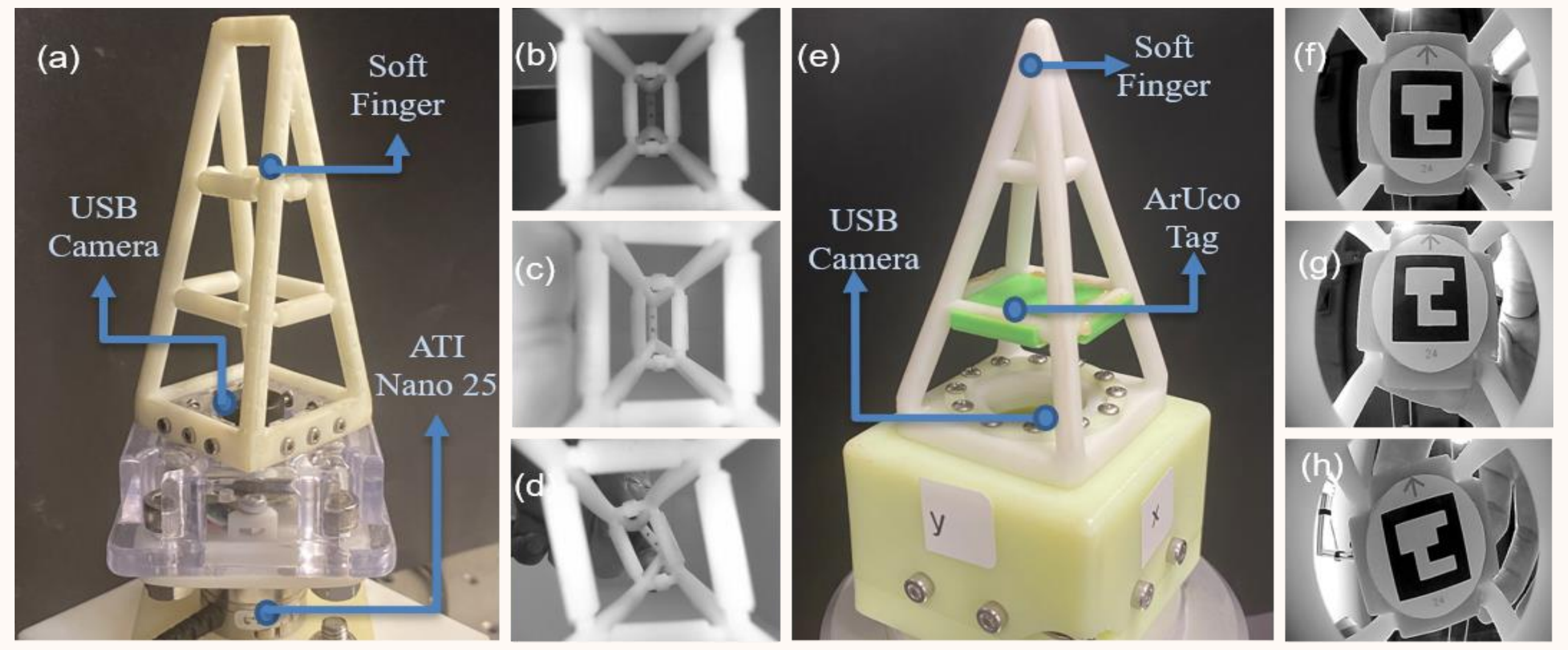
Tracking Interaction using 6D Pose

We conducted control experiments using a UR10e robot arm. The task is to drag the TCP so that it follows a particular path on a horizontal. We record the positions of the TCP while we taught the robot and plotted the paths using the soft finger (Figs. (a)&(c)) and a force-torque sensor (Figs. (b)&(d)). The finger has demonstrated a smooth experience in human-robot interaction while executing the task.

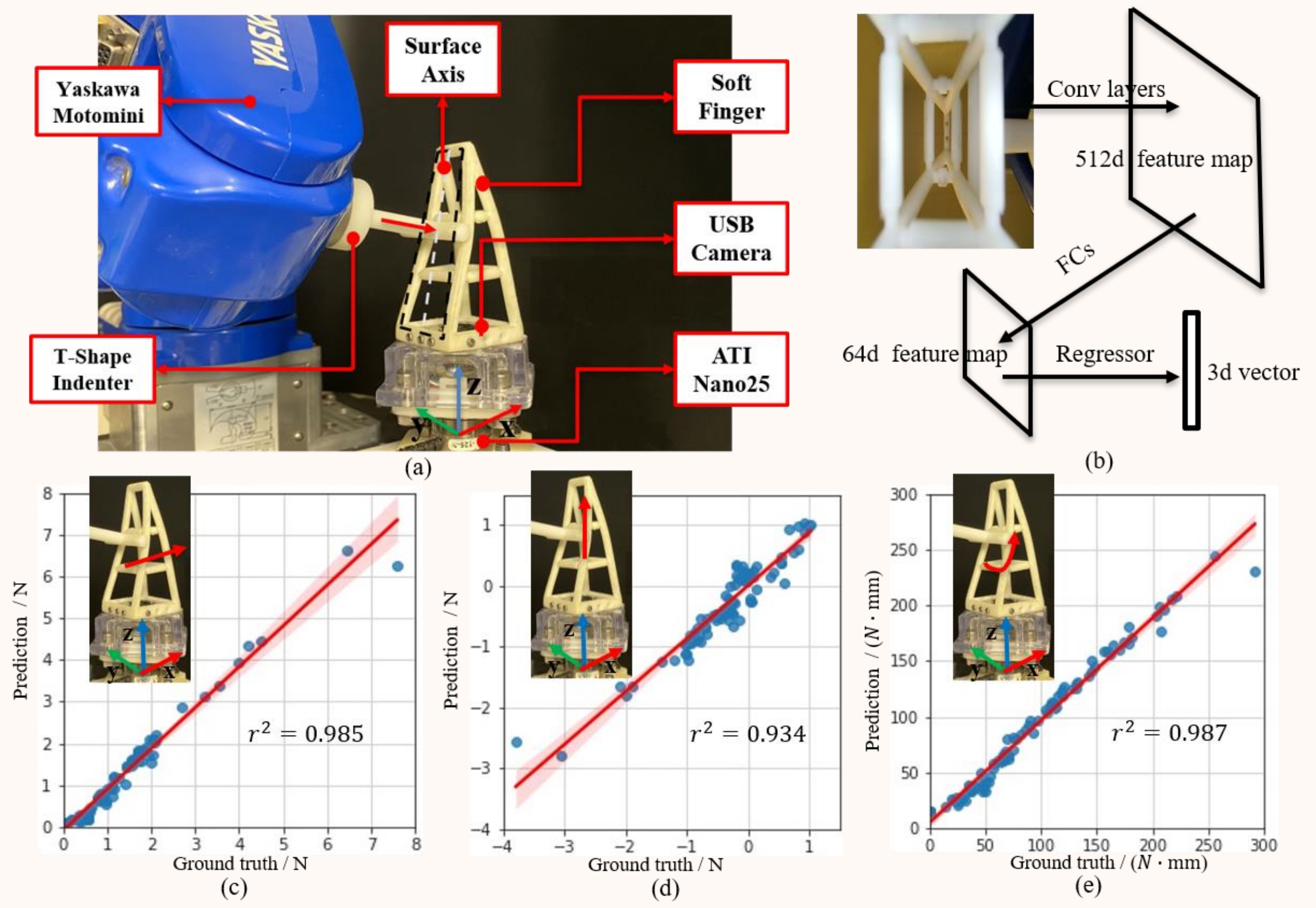


Learning Rigid-Soft Interaction

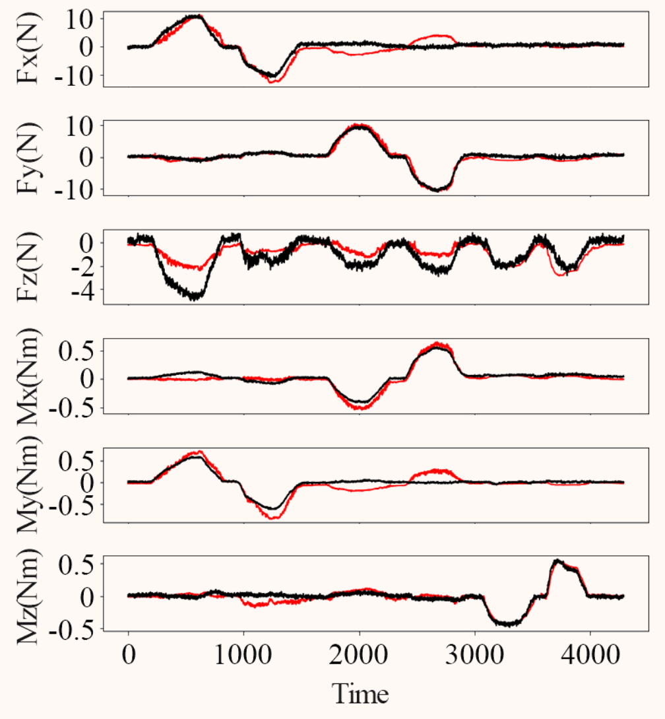
We explored the possibility of learning the rigid-soft interaction of the soft finger by both deep learning and tracking the ArUco tag.



To automatically collect the contact of the finger on the left, an automated data collection platform was built. CNN was to directly predict the force along the x-axis and z-axis and torque along y-axis due to the contact condition. The result shows that our visual force CNN is capable of making precise predictions, with $R^2 > 0.9$ in each dimension.



The 6D displacement of the tag could well represent the deformation of the finger under external force. The figure shows the real-time force and torque predicted by the learned model in red, and the values obtained from the robot controller in black. The model can give a fairly good prediction even with discrepancies.



Final Remarks

- We systematically investigated the metamaterial's design characteristics, which feature a radial stiffness ratio with differential distribution along its axial direction, resulting in an omni-directional adaptation that is challenging to model, yet attractive to interact with.
- The tactile sensor employing camera suffers from the relatively low frame rate and higher computational cost compared with other conventional sensor. However, it made the proposed soft sensor to be more accessible and easily assembled with much lower cost.
- One of the major difference of our proposed soft sensor is that the physical contact to light conversion is based on large deformation of the soft metamaterial. In order to investigate the soft metamaterial alone, we kept it bare and did the experiment in daily lighting condition in the lab without any extra lighting devices.
- Our results show that it could become a promising direction to use data-driven learning method to leverage the modeling challenge of soft robots for advanced robot control and interaction, where a potential future for soft robot force control may be of interest to researchers seeking more adaptive, versatile, and low-cost sensing and interaction of their robotic system.

Acknowledgements

The authors would like to acknowledge the constructive comments provided by the reviewers and editors. This work was jointly supported by National Science Foundation of China (No. 51905252), Shenzhen Institute of Artificial Intelligence and Robotics for Society Open Project (No. AC01202005003), Shenzhen Long-term Support for Higher Education, and AncoraSpring, Inc.

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