Graduate Research Plan: Sensor-Based Control for Soft Robot Systems – Jessica Yin

Intellectual Merit: Inspired by the adaptability of biological organisms, soft robots have emerged to address some of the technical limitations of conventional rigid robots. Although rigid robots are remarkably capable at high-precision and load-bearing tasks, their stiff material properties, with a Young's modulus in the range of $10^9 – 10^{12}$ Pa, inherently limit their ability to physically interact with their environment. In contrast, soft robots are composed from gels, fluids, and elastomers with a Young's modulus of $10^6 – 10^9$ Pa. These soft materials mimic the mechanical properties of biological tissues and can bend, stretch, and compress.

This ability to conform is key for applications in human-robot interaction, biomedical devices, and space-restricted environments. For example, a rigid wearable accessory has limited placement locations that are both comfortable for the user and informative for the device. In comparison, a soft wearable device, that can compress and stretch, greatly increases compatible locations and therefore potential applications, such as biometric monitoring or activity tracking. These advantages have also been shown to enable successful applications in medicine, such as organ-assist sleeves, drug delivery, prostheses, and surgical tools [1].

However, soft robot applications still face prevalent barriers to improved functionality over rigid robot solutions. The same material properties that give soft robots their versatility also create challenges in actuation, control, sensing, and modelling. In contrast to rigid systems with a small number of joints, soft robots possess many more degrees of freedom due to their continuous elastic bodies. In order to fully understand their environment, soft robots require effective sensing tools in a stretchable format. However, soft and stretchable sensing solutions have only been recently developed for strain and pressure sensing. The lack of sensory information has resulted in the absence of sensor-based control and higher-level decision making that would be customary for a rigid robot [2].

The Soft Machines Lab at Carnegie Mellon University led by Professor Carmel Majidi made a breakthrough in soft robotic sensing capabilities by demonstrating a hybrid soft sensor skin with orientation, pressure, temperature, and proximity sensing processed on-board [3]. Finally armed with multimodal sensing to determine the soft robot's environmental and internal state, a unique opportunity has arisen for the development of sensor-based control for soft robots.

Proposal: As part of the team that developed the soft sensor skin in [3], I will build on our previous work and implement sensor-based control of a robotic arm and gripper using the sensor skin. This will serve as the first demonstration of the feasibility of sensor-based feedback control on this soft robot system. The approach can then be extended to a wider range of soft robotic systems, which I will further explore in my graduate research.

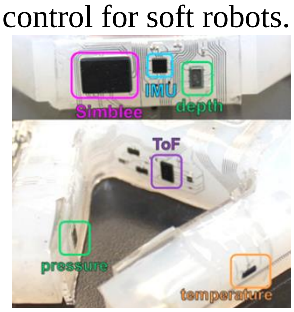

Fig. 1: Hybrid soft sensor skin described in [3].

I. Physical System: The sensor-based control system will be implemented on a robotic arm and elastic sensor skin adhered to a two-finger soft gripper. The sensor skin will have two soft strain sensors made of liquid metal traces, a time-of-flight (TOF) sensor to measure distance, an IMU, and an on-board microprocessor to process sensor data. The strain sensors will be located on each of the inner fingertips to detect the presence of the object. The TOF sensor will be placed on the palm of the gripper, parallel to the scanning surface. The IMU will be placed next to the on-board processor, which will be located at the top of the gripper, to sense the gripper's orientation. The sensor skin will be connected to a computer hosting a finite state machine to sequence behaviors. The computer will be connected to the robotic arm, so that the finite state machine can generate its movement.

II. Control System: The sensor-based control system will consist of two main components.
i. TOF data processing: The gripper will scan the table in uniform rows, collecting TOF data to create a 2D array of distance measurements. This 2D array can then be analyzed as an image using OpenCV to identify the size, orientation, and location of each object on the table. The development of this TOF algorithm is crucial to the development of soft robot feedback control by allowing for rudimentary image processing when camera sensors are inaccessible.
ii. Finite state machine: The robot arm and gripper will be controlled by a finite state machine (FSM) that uses sensor input to govern the state. The size, orientation, and location of the object will be determined by the TOF algorithm in the first state. After the object has been identified, the strain, IMU, and TOF sensor data will be used to sense the presence of the object in the grasp of the gripper. The presence or absence of the object would inform the system of a successful grasp, lift, transport, or release of the object. This information will be used to traverse the states of the system. The FSM will demonstrate basic autonomy with feedback control of a soft system.
III. Testing: The performance of the sensor-based control of the robotic arm and gripper will be tested against an open-loop robotic arm and gripper in a grasping and placement task. Objects of varying size will be placed on a flat surface in front of the gripper. The gripper and robot arm will be programmed to have four potential actions: grasp, lift, move, and release. The open-loop system will use provided object locations and complete each of the actions strictly in sequence. The sensor-based control system will not have prior information about object locations; instead, it will use sensor data to determine the object locations after scanning the workspace. The sensor-based control system will also have the opportunity to decide whether to move onto the next action or repeat previous actions based on sensor data. The success rate of grasping, lifting, placing, and overall task completion for each system will be compared over multiple trials.

One potential challenge with this system is noise from ambient light conditions affecting the accuracy of the TOF data. Because the system relies on the TOF data to locate and interact with the object, the accuracy of this data is crucial. A potential solution would be calibrating the TOF sensor to the specific environment that it will be operating in.

Broader Impacts: This proposal addresses a key challenge in the control of soft robot systems by demonstrating a novel implementation of sensor-based control using a multimodal sensing skin. A successful demonstration will further push the boundaries of control and autonomy in the field of soft robotics, as well as provide a platform for more complex control architectures in the future. These advancements are necessary for ubiquitous soft robots in everyday life; for example, soft robot applications in the care and improved quality-of-life for the elderly.

One practical application for this specific soft robot system consisting of a sensing skin, soft gripper, and robot arm would be to sort and grasp food objects in a food processing facility. The soft gripper would be better-suited to handling delicate food objects than a rigid gripper, which would reduce the amount of damaged food from handling errors. The sensor-based control system would allow for unsupervised operation, as expected in a modern facility.

In addition, this project could be demonstrated in STEM outreach to inspire interest in STEM from K-12 students. Because the differences in performance of this system could be easily seen and understood with little technical background, and the task of grasping and placing is familiar, this demonstration would be particularly well-suited to a young audience.

[1] M. Cianchetti, et al.,"Biomedical Applications of Soft Robotics." Nature Reviews. Materials 3.6 (2018): 143-53.
[2] T. Thuruthel, et al.,“Control Strategies for Soft Robotic Manipulators: A Survey,” Soft Robotics, Vol. 5, No. 2 (2018).
[3] T. Hellebrekers, K. B. Ozutemiz, **J. Yin** and C. Majidi, "Liquid Metal-Microelectronics Integration for a Sensorized Soft Robot Skin," 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).