EECS C106B / 206B Robotic Manipulation and Interaction **Spring 2020**

Lecture 20: (Soft Robotics Part 1)

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20.1 Overview

Soft robotics is the design, fabrication, and control of robots composed compliant materials, not rigid links. It is important to note that while rigid links can exhibit joint compliance (i.e. via feedback control), this is distinct from the material compliance of soft robots. Generally materials may include flexible materials like plastic, films, or foils; stretchable materials like rubber; or fluidic materials like gases or liquids. In contrast to rigid robots, soft robots generally have: inherent material compliance, are good in low force regimes, are lighter, have infinite degrees of freedom (DOFs), high behavioral diversity, and are currently difficult to control accurately. Rigid robots have contact smoothed through feedback control instead of material compliance, are good for high force regimes, have low behavioral diversity, and are easier to control with high accuracy. Now we will present some common approaches to soft robot actuation, followed by control methods that have been employed for soft robots, then introduce several other interesting mechanisms that do not fall into the introduced categories of actuation or control.

20.2 Common Approaches to Soft Robot Actuation

20.2.1 Longitudinal Tensile Actuators

One of the most basic ways to actuate a soft robot is with a longitudinal tensile actuator. These are usually composed of a tensile element such as a cable or shape memory alloy stretched longitudinally on the robot appendage. The tensile element is not attached to the center of the appendage, but rather to one side, so as to force the appendage to turn to one side when the tensile element is tightened. Fig. 20.1.A shows an example of a longitudinal tensile actuator in action. The tensile element causes the appendage to actuate in one direction when the element is tightened.

Two common tensile elements are cables and shape-memory alloys. Cables are usually driven by a motor or other actuation device that is not in the appendage. Shape-memory alloys are materials that contract when heated and expand when cooled. A common way to deliver heat to activate shape memory alloys is Joule heating, wherein electricity is sent through a resistor to generate heat.

20.2.2 Transverse Tensile Actuators

As the name suggests, the transverse tensile actuators can cause the robot body to extend when the actuators contract. Similar mechanism can be seen in the octopus. It works in a similar way was the longitudinal tensile actuator describe above

20.1.B shows an example of a transverse tensile actuator in action.

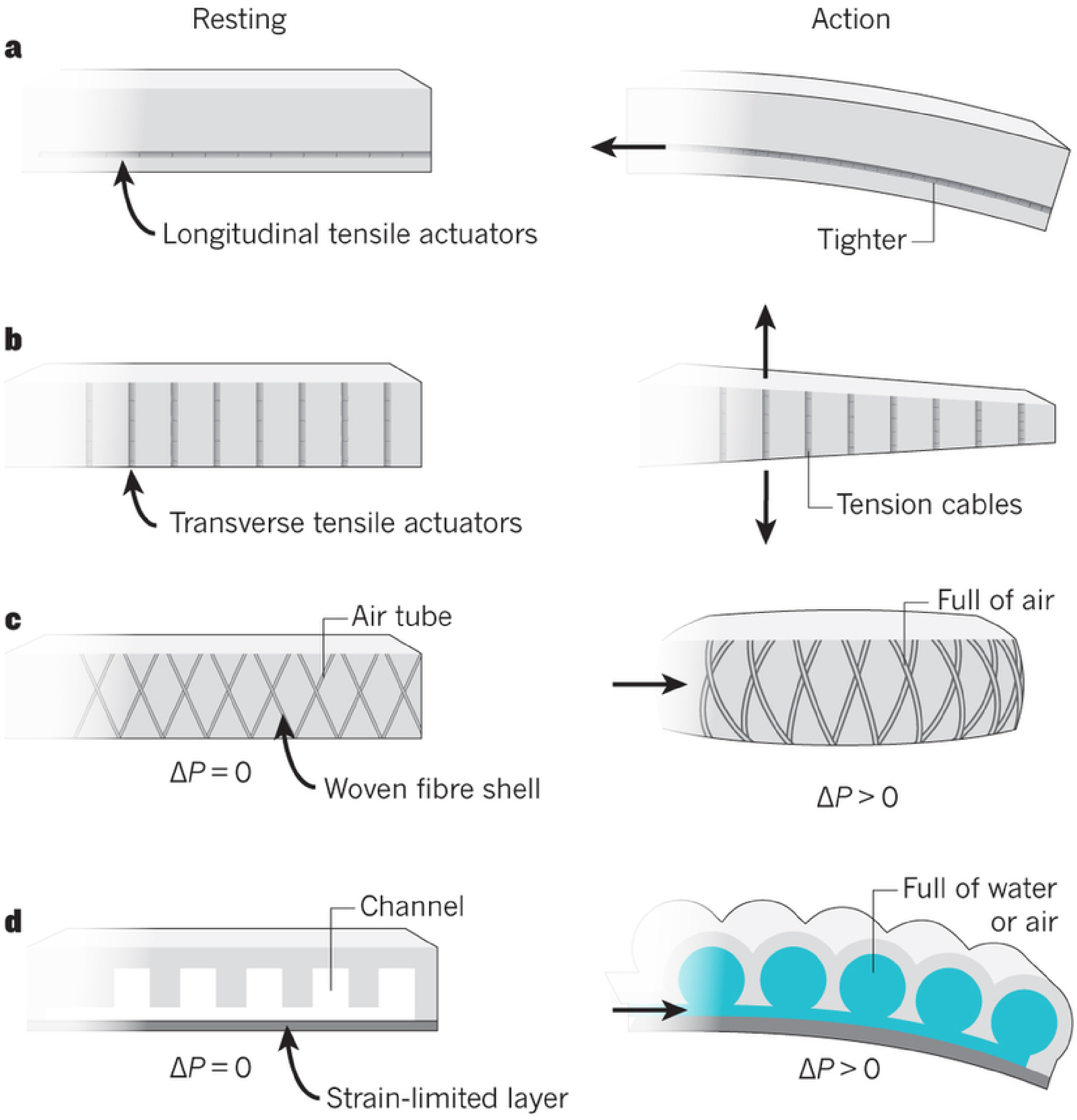

Figure 20.1: **Several common approaches to soft robot actuation. A.** An example of a longitudinal tensile actuator. **B.** An example of a transverse tensile actuator. **C.** An example of a Pneumatic Artificial Muscle. **D.** An example of a Pneumatic Network.

20.2.3 Pneumatic Artificial Muscle (PAM)

Pneumatic artificial muscles (PAMs) are contractile or extensional devices operated by pressurized air filling a pneumatic bladder. In an approximation of human muscles, PAMs are usually grouped in pairs: one agonist and one antagonist. It is composed of an elastomeric tube in a woven fiber shell. A pressure applied internally causes the tube and shell to expand radially, causing longitudinal contraction, as Fig.20.1.C shows.

20.2.4 Pneumatic Networks (PneuNets)

One increasingly popular method of soft actuation is the use of Pneumatic Networks (PneuNets). These are composed of a sequence of channels that can hold air, water, or some other fluid, as well as a strain-limited layer. When these channels are filled with fluid, the side of the appendage without the strain limited layer expands and stretches while the side with the strain limited layer stays the same length and is forced to bend inward. Fig. 20.1.D shows an example of a PneuNet in action. The soft robot appendage is thus actuated by modulating the fluid pressure of each channel to force the appendage to bend in a certain direction.

20.3 Control Techniques

20.3.1 Model-based

20.3.1.1 Analytical Models

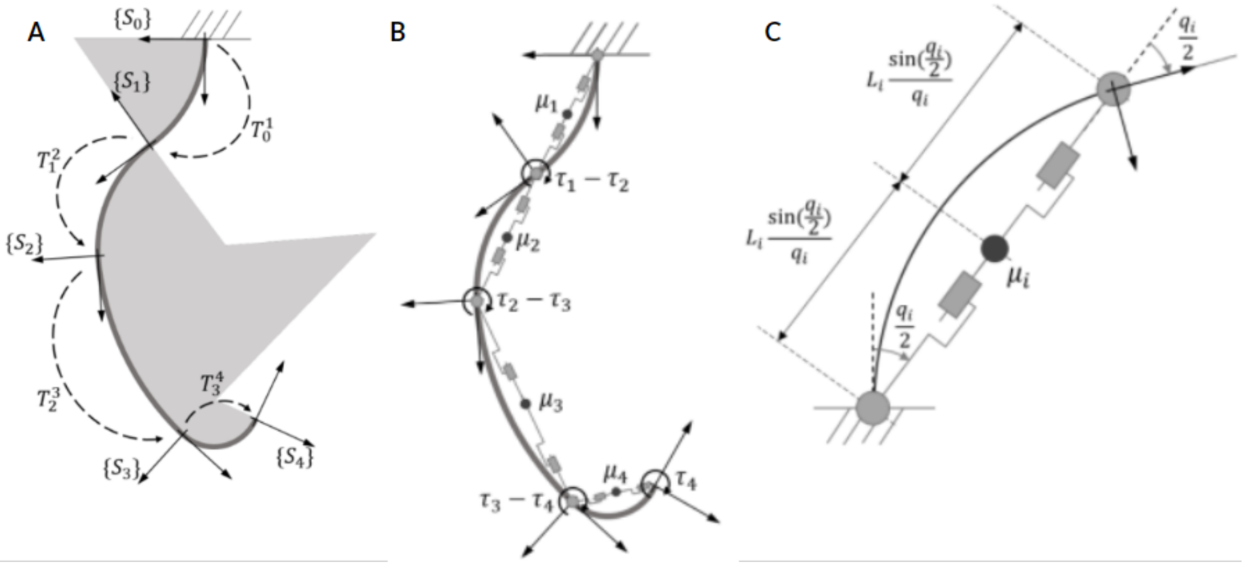

Figure 20.2: **Example of analytical soft robot control.** **A.** An illustration of the Piecewise Constant Curvature assumption. **B.** A full 4 segement robot modeled with PCC and the augmented state representation. **C.** A segment of constant curvature can be simplified to a RPPR rigid robot for the purposes of control.

For some soft robots, it is possible to impose assumptions that reduce their complexity and allow us to bring classical control techniques to bear on them. [1] provide one such example; they first make the assumption of Piecewise Constant Curvature (PCC), which models the robot as n segments of constant curvature. The robot can now be described with generalized state variables $q \in R^n$ that describe the curvature of each segment. An illustration of this can be found in Fig. 20.4.A. Given the PCC assumption, [1] then model each individual segment as a two revolute joints and two prismatic joints, as shown in Fig. 20.4.C. Fig. 20.4.B shows a full 4 segment robot simplified in this way. By simplifying the soft robot as an equivalent rigid robot, we can express the dynamics of the robot as

$$M\ddot{q} + (C + D)\dot{q} + G + Kq = \tau + J^T f_{ext} \tag{20.1}$$

for some inertia matrix M, Coriolis matrix C, damping D, gravity G, stiffness K, control inputs τ, and external forces f_{ext}. For most soft robots, additional system identification would be needed to identify some of these terms. The paper then goes on to introduce two feedback controllers using these dynamics for curvature control and impedance control.

20.3.1.2 Numerical Methods (i.e. FEM)

Numerical method typically using the finite element method (FEM) to solve PDEs in order to model soft robots. It essentially separates the robots by a finite amount of sections. It handles and generic shapes and constitutive materials, also models the contact between the soft robot and other objects in the environment, soft or rigid. This method is widely used in industry. The major draw back is that this method is computationally intensive

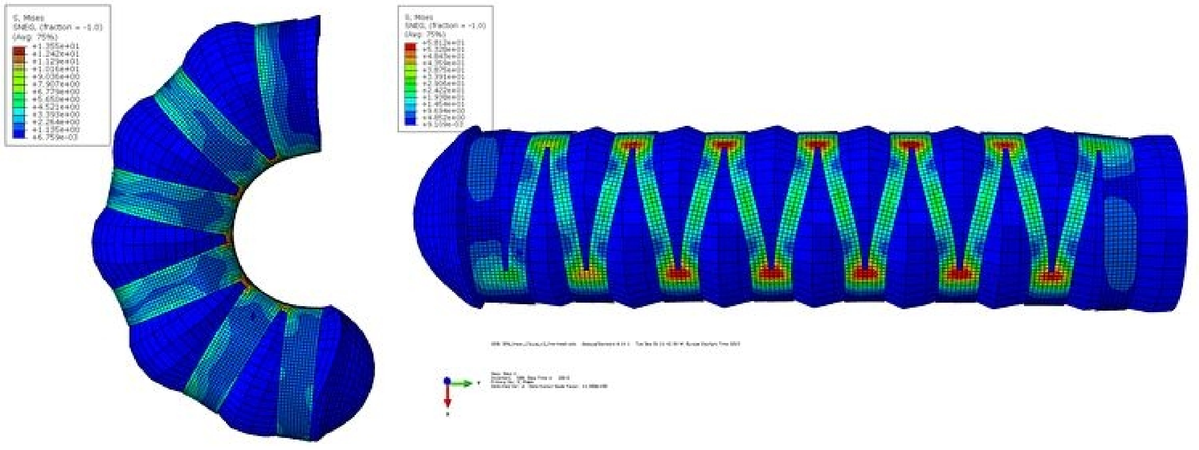

Figure 20.3: **Example of FEM simulation of soft robots.**

20.3.1.3 Data-Driven Methods

Data-driven methods often utilize machine learning to derived the model of the soft robots from experimental data. A Machine Learning algorithm is then trained to learn the Inverse Kinematics of the robot, meaning the mapping between the actuator variables and the robot pose. The main advantage of these methods is that they are very fast to provide a solution to the IK problem, and thus enable real time control.

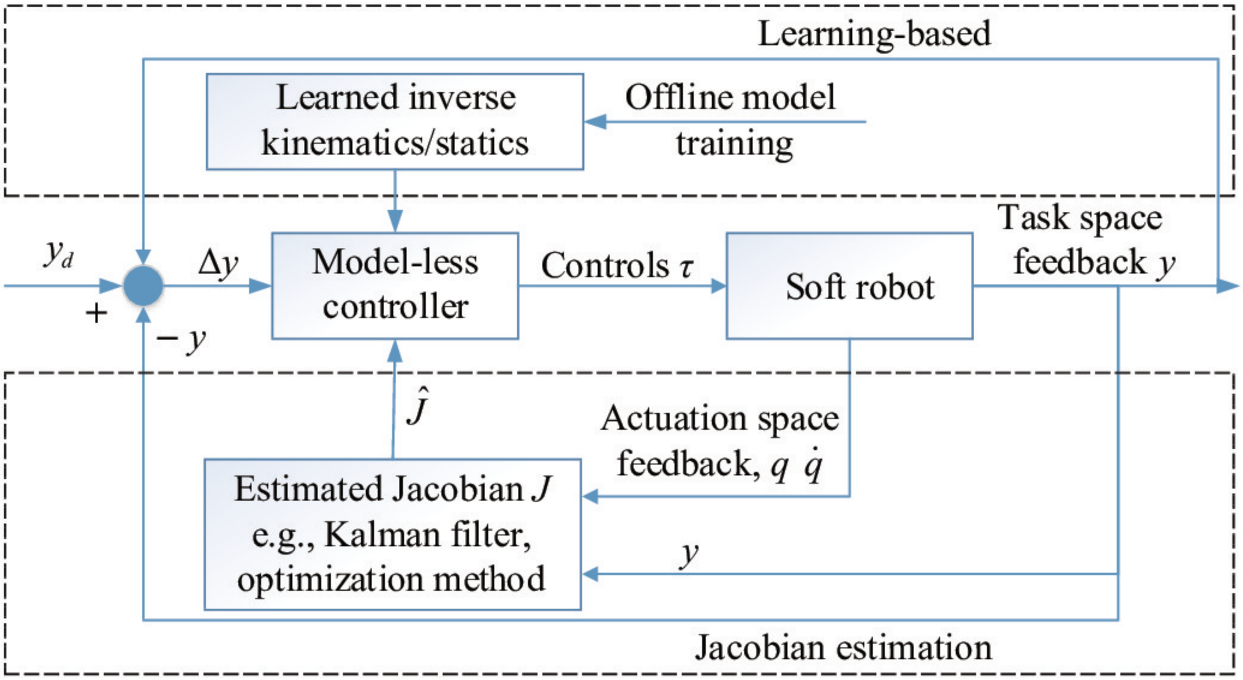

Figure 20.4: **Example of data-driven method**

20.3.2 Model-Free

Because models are difficult to build for soft robots due to their infinite degrees of freedom and non-standardization, model-free control methods are particularly popular in this field. These algorithms seek to directly learn a policy $\Pi(s)$ that maps states or observations s to actions a that the robot takes to try to actuate itself. For example, [2] used deep reinforcement learning to control a soft robot appendage (shown in Fig. 20.6). In particular, they used Q-learning, a deep reinforcement learning algorithm that learns a policy $\Pi(s) = argmax\tilde{Q}(s,a)$, where the Q function (usually learned with a deep neural network) predicts the expected reward of taking action a at state s. They collected data to train the Q network by collecting states and actions offline using a simulation.

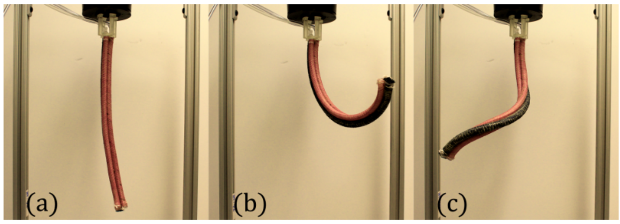

Figure 20.5: Soft robot controlled by deep Q learning from [2].

20.4 Other Interesting Mechanisms

20.4.1 Soft Robotics and Bionics

Researchers try to combine soft robotics with bionics. The goal is to analyze the design and dynamics of biological systems and transform them into robotic/mechatronic systems for human life. We are interested in bio-inspired design of soft robots and development of novel manufacturing methods for multi-material smart structures.

Soft systems are a promising direction for future biomedical systems in which human-machine interactions are highly critical. The use of soft sensing and actuation materials and flexible electronics are imperative to build systems that both interact with and assist humans, as our bodies are covered with soft tissues. The target example systems include soft wearable rehabilitation/assistive devices, motion-sensing suits for whole body biomechanics, active soft prosthetics and orthotics, soft surgical/interventional tools, and haptic interface devices.

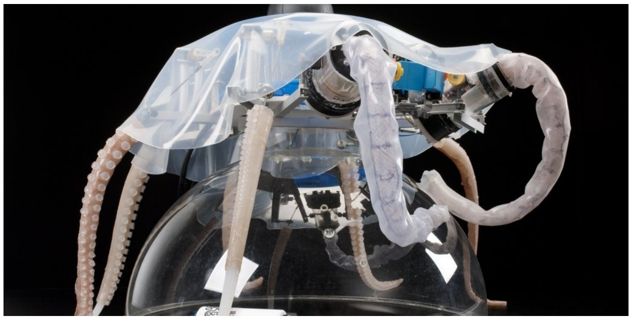

Figure 20.6: **Octopus-inspired soft robots**

References

[1] Della Santina, C., Katzschmann, R. K., Biechi, A., and Rus, D. Dynamic control of soft robots interacting with the environment. In *2018 IEEE International Conference on Soft Robotics (RoboSoft)* (2018), IEEE, pp. 46–53.

[2] Satheeshbabu, S., Uppalapati, N. K., Chowdhary, G., and Krishnan, G. Open loop position control of soft continuum arm using deep reinforcement learning. In *2019 International Conference on Robotics and Automation (ICRA)* (2019), IEEE, pp. 5133–5139.