Discrete Simulation of Soft Robotic Grippers for Underwater Applications

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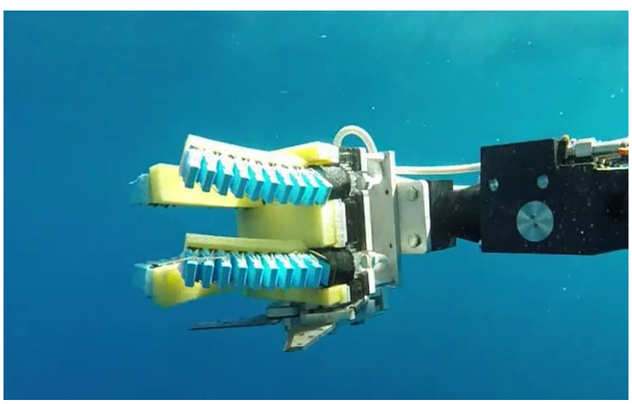
***Abstract*— Soft robotics has emerged as a field with tremendous upside in creating end effectors for applications that need a compliant or delicate grasp. This proposal aims to increase appropriate discrete modeling techniques for soft grippers for better simulation.**

I. Introduction

One of the largest applications of soft robotic mechanisms is found in robot end-effectors [1]. The advantages of soft grippers are found in applications that require gentle or flexible grasps, like picking up fruit or cacti. Soft grippers are often the best option in especially harsh environments, namely underwater, due to their ability to passively adapt to external stimuli. Most of the grippers seen in literature are made of multiple single degree of freedom elastic fingers that wrap around the given object [2][3]. This project aims to model one of those grippers [2]. Specifically, introducing the concept of a gripper with programmable variable stiffness in an underwater environment [4].

Figure 1. Soft robotics finds applications in underwater environments, picking up delicate artifacts or species [5].



II. Background

Traditional robotic grippers consist of rigid links and joints that can be actuated by motors or tendons [6]. While this class of grippers excel in known environments, like industrial settings, they lack much of the adaptability needed to interact with all objects, namely odd shaped or fragile objects [6]. In these cases, contact between a hard gripper, at high forces, can damage an object or move it in unpredictable ways. Soft robotics has emerged as the leading candidate to solve these problems, by creating a class of robotic grippers that provides delicate grasps and can easily conform to a given object.

The actuation method for soft robotic grippers contrasts typical robotic end effectors. Pneumatics are commonly used to provide a pressure differential inside of a hollow gripper finger, with the localized bending or stretching being dependent on the geometry and material properties of the finger [6]. For this reason, many soft robotic fingers are made from soft plastic or elastomer that contain intrinsic elastic properties, i.e. if they are bent, they apply some sort of restoring force. Many researchers focus on deriving the equations of motion from the geometry and pressure differential for each node in the finger and follow up by simulating their designs in finite element analysis [7].

These grippers, due to their restoring elastic properties, are considered underactuated, as motion is due to deliberate actuation, or passive elastic forces. It is important to model the motion of the grippers since their kinematics is not as simple as rigid-link end effectors.

The project aims at a different approach to modeling soft robotic grippers: discrete analysis. This approach boils down the material properties to a single node and edge-based beam but provides advantages in modeling external forces.

III. Objectives

A. Individual Motivations

Benjamin Forbes: I am a PhD student in the Biomechatronics lab at UCLA, under the advisement of Dr. Veronica Santos. Currently I am working on a project that creates a novel controller for underwater end effectors that considers tactile data. This project runs tangential to the work being done currently and explores modeling viscous forces and contact underwater. While the type of end effector is drastically different to the work I am currently doing, it provides insights into how I can simulate gripping and actuation in an underwater environment.

Premkumar Sivakumar: As a graduate student specializing in Robotics, I am intrigued to learn new methods to model and simulate the motion of robotic structures. While finite element-based modeling of rigid structures is familiar to me, discrete differential geometry-based simulation of the motion of soft robots is new to me and interests me. The discrete simulation of the soft robotic gripper would provide me great exposure to the same.

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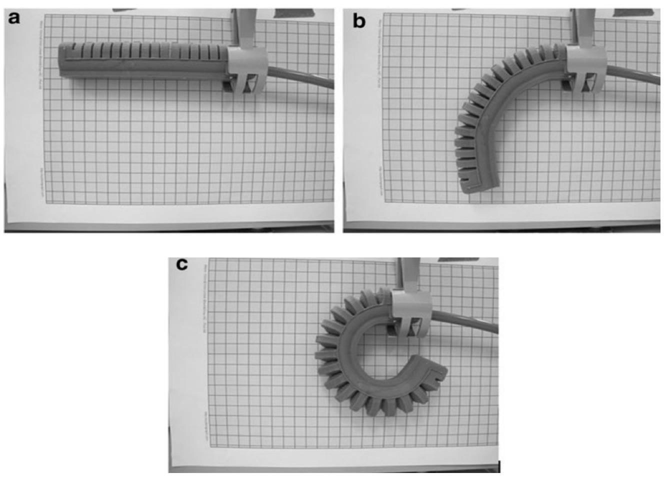
B. Overall Objectives

We are borrowing the experimental setup of a soft robotic gripper from Alici et al. in the aims at using a discrete approach to model it in an underwater environment (i.e. subject to viscous forces or external flows) [2]. Additional complexity can be added to model the soft gripper when the elastomer has been intentionally programmed to have variable stiffness, as seen in Haibin et al [4]. It has been noted that the traditional ways of simulating grippers in finite elements or in dynamics is a challenging process [8]. Thus, we hope the discretization simplifies the process and allows for more flexibility in applications.

Figure 2. The soft gripper used in the work by Alici et al. in which this discrete simulation will be based off of at various pressures and actuation states [2]. a) is unactuated, b) is partially actuated, and c) is fully actuated.

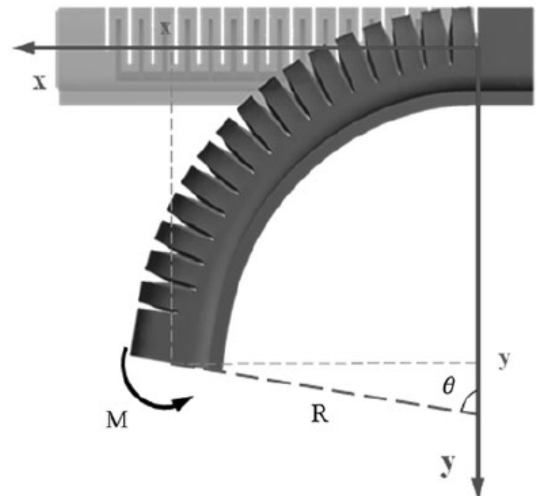


IV. Problem Setup

A. Gripper Schematic

The physical soft robotic gripper has three fingers, where each finger is a chamber-based pneumatic actuator made up of elastomeric silicones embedded with a bistable layer, like a thin flexible metal. The elastomeric part is designed with ridges which allows the finger to bend. However, since the elastomeric part can bend under its own weight without any actuation, the embedded bistable layer offers rigidity making the actuator behave stiff under zero input conditions. But at a reasonably small input pressure would shift to its second state of mechanical stability, allowing bending. This bistable layer would also be inextensible, preventing any lateral extension, turning any extension force into bending moment. Figure 2 depicts the configuration of the soft pneumatic actuator under various pressures.

Figure 3. A soft gripper "finger" and the varables associated with describing its movement [2].



V. Methods

A. Formulation

The goal of the formulation is to build a numerical simulation tool for a soft robotic gripper that draws inspiration from discrete differential geometry-based simulation of slender structures (found in the course notes). Simulation of the actuation of the underwater soft robotic gripper described above is essentially that of a discrete elastic cantilever beam in viscous medium, which can be modelled as N nodes connected by $N-1$ edges. However, as the actuators are made up of composite structure and elastomeric materials with non-linear properties, the effective modulus of elasticity of the actuators are calculated from the experimental bending angle and block force versus pressure. This relationship is shown in Equation 1.

$$EI = L^2 \frac{F_B}{\theta} \tag{1}$$

Where F_b is the blocking force, θ is the bending angle and L is the length of the actuator. Since the motion of the gripper finger is confined to a plane there will not be any twisting and due to the inextensible bistable layer, the stretching energy is not considered as well. The mechanical deformation of the gripper finger is associated with local elastic bending energy at each discrete node. We compute the inertial force, external forces due to viscous properties and formulate the discrete elastic energies and, subsequently, the discrete equations of motion representing the balance of forces using principles from classical elastic rod theories (Euler-Bernoulli Beam Theory). For the inertial force calculation, the mass of the fingers of the gripper is distributed as point masses at different nodes. The external force acting on the gripper will be the viscous force from water.

B. Simulation

The simulation incorporates an implicit treatment of the elasticity of the gripper fingers. A small enough time step size Δt and a large enough number of nodes N will be chosen based on sensitivity analysis for the simulation. The motion of the gripper is driven by pneumatic actuation which is given as an input by varying curvature κ and hence the bending stiffness with time.

The turning angle φ_i, at node x_i between two consecutive edges can change - similar to a torsional spring. Associated with each turning angle φ_i, is the discrete bending energy:

$$E_{i,B} = \frac{1/_2 EI(\kappa_i - \overline{\kappa_i})^2}{\Delta L} \tag{2}$$

Where *EI* is the bending stiffness, and the curvature is:

$$\kappa_i = \frac{2\tan\left(\frac{\varphi_i}{2}\right)}{\Delta L} \tag{3}$$

and $\overline{\kappa_i}$ is the natural curvature (i.e., curvature evaluated in undeformed configuration). The total bending energy is:

$$E_B = \sum i E_{i,B} \tag{4}$$

C. Assumptions

Here the first node is fixed and the remaining nodes are free to move in a plane from the initial configuration. The initial configuration of the fingers of the gripper will be straight and in horizontal or oblique position with respect to the gripper housing.

Acknowledgment

This work was done for MAE 263F, a class taught by M. Khalid Jawed. The authors are in the class and use code referenced in the class course notes.

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