Midterm Progress Report: Discrete Simulation of Soft Robotic Grippers for Underwater Applications

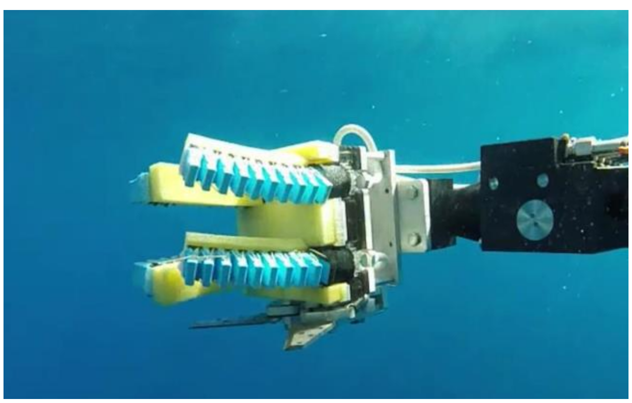
Premkumar Sivakumar, Benjamin Forbes, *Mechanical Engineering, University of California, Los Angeles*

***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 project aims to increase appropriate discrete modeling techniques for soft grippers for better simulation in an underwater environment.**

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]. The goal of the midterm progress report is to reintroduce the project description and the steps we have made in simulation to: 1) simulate a soft gripper with elastic properties, 2) add hydrodynamic effects to simulate underwater environments, and 3) add contact forces at the fingertip to simulate gripping an object.

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

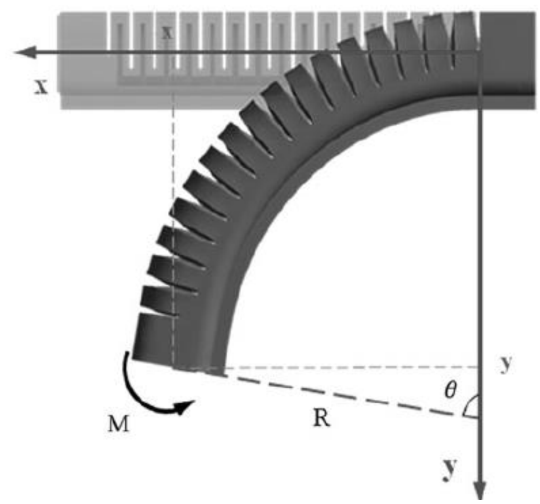


II. Problem Setup

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 a reasonably small input pressure would shift to its second state of mechanical stability, allowing bending. This bistable layer is also 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 2. A soft gripper "finger" and the varables associated with describing its movement [2].



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 their soft gripper in an underwater environment (i.e. subject to viscous forces) [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.

III. Simulation

A. General Formulation

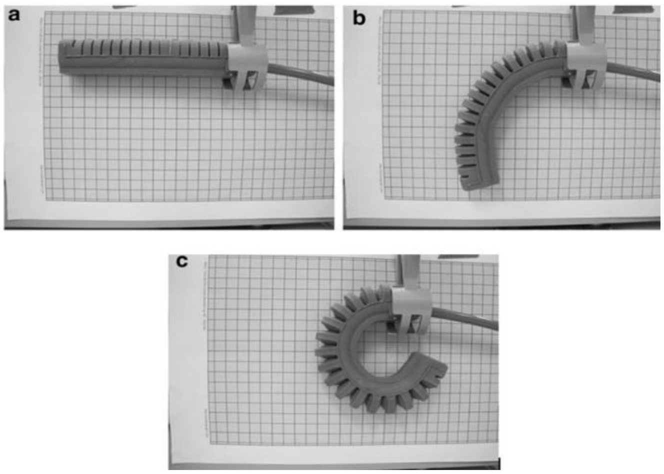
The goal of the formulation is to build a numerical simulation tool for a soft robotic gripper that draws inspiration from discrete differential geometry-based simulation of

Premkumar Sivakumar, is a master's student at the University of California, Los Angeles (e-mail: premkumar22@g.ucla.edu).

Benjamin Forbes is a PhD student at the University of California, Los Angeles (e-mail: benforbes@ucla.edu).

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.

Figure 3. 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.



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 physically there will not be any twisting and due to the inextensible bistable layer, there will be no stretching as well. The mechanical deformation of the gripper finger is associated with local elastic bending energy at each discrete node but for the simulation stretching and twisting energies are also modelled. 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 and edges. The external force acting on the gripper will be the viscous force from water and gravitational force

B. *Bending Stiffness Simulation*

The simulation incorporates an implicit treatment of the elasticity of the gripper fingers. We have used a step size $\Delta t = 0.01\, sec$, and a large enough number of nodes $N = 20$, which has been chosen based on sensitivity analysis for the simulation.

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:

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

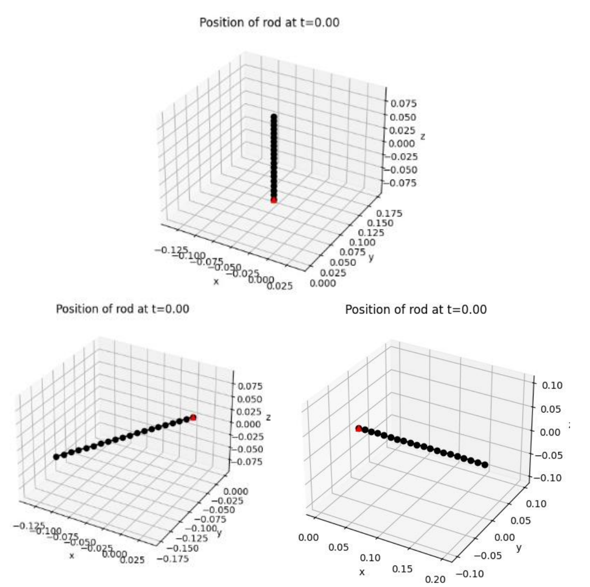
The motion of the gripper is driven by pneumatic actuation which is given as an input by varying curvature κ and hence the bending stiffness with time. Thus, $\overline{\kappa_i} = f(t)$, the natural curvature is a function of time. For smooth actuation, we have defined this function to be:

$$\overline{\kappa_i} = -0.15 * ctime \tag{5}$$

Where $ctime$ is the current time in the simulation. The definition for this natural curvature allows for the gripper to reach an actuated position as seen in Figure 3b during the given simulation time.

A single finger was simulated by defining the initial q_0 vector to be in the x-y plane and then actuate in the z direction. After the simulation for a single finger was dialed in, the initial q_0 vector was rotated by $\pi/3$ and $2\pi/3$ to define the two other finger grippers respectively. A major assumption made here is that the first node is fixed, and the remaining nodes are free to move in a plane defined by the initial configuration and the z-axis. The initial configuration of the fingers is depicted in Figure 4.

Figure 4. Starting positions of the gripper fingers.



C. *Viscous Forces Simulation*

The viscous damping coefficient matrix is given by a diagonal matrix with the size of $ndof$. That coefficient is given by Stokes' Law for a spherical node in a viscous fluid with a low Reynold's number:

$$C = 6 * \pi * r * \eta \tag{6}$$

While this formulation is not exactly for the geometry involved in [2], we are making the simplification to model the gripper where each node is a sphere moving through the fluid. We have chosen not to model the links between the nodes for simplicity in defining *C*.

IV. Preliminary Results

A. *Single gripper simulation*

Initially, the viscous forces and change in natural curvature were added to the simulation for a single soft robotic gripper finger. Figure 5 depicts how the last node of the gripper finger moves under the changing natural curvature with time and the elastic forces that resist the change to that motion.

Figure 5. Z-coordinate positions of the gripper finger with respect to time.

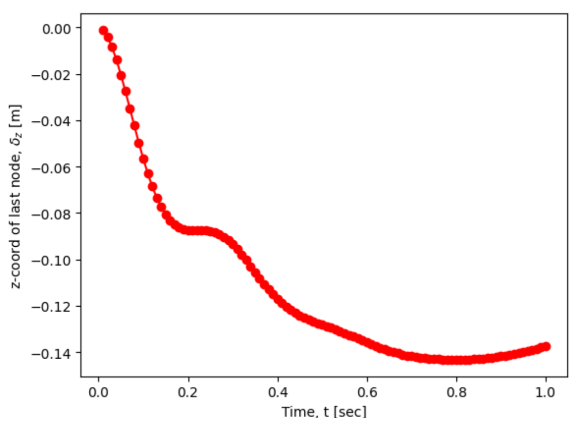
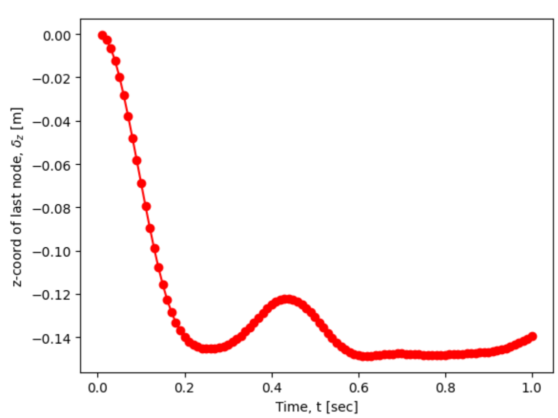


Figure 5 is particularly interesting when considering that the graph is not linear. This makes sense as the relationship between the elastic bending force and the natural curvature is not a linear term. For example, at $t = 0.2\ sec$, the gripper finger stalls, as the natural curvature is unable to overcome the bending stiffness of the elastomer. After that point, we simulate that the pneumatic actuator can overcome the natural resistance to bending that due to the elastic bending force.

Figure 6. Z-coordinate positions of the gripper finger with respect to time for a different value of Y, the modulus of elasticity $Y = 100\ kPa$.

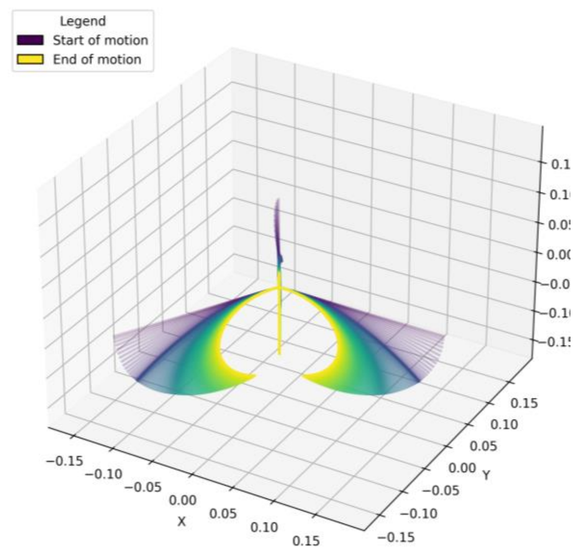


When we change the modulus of elasticity, the motion of the gripper changes. As depicted in Figure 6, which tracks the the Z-coordinate of the gripper over time, the actuation is able to overcome the elastic forces involved, but at $t = 0.4\ sec$, the gripper rebounds.

B. *Full gripper simulation*

The next step is to repeat the simulation for the entire gripper. The simulation was repeated assuming that the gripper fingers are identical, except for their starting position with respect to the origin. Figure 7 depicts a timelapse of the motion of all 3 grippers in 3D.

Figure 7. Timelapse plot of the entire gripper over the simulation period including viscous forces.



This method of actuation seems able to assume the physical positions in order to pick up objects in an underwater environment. Figure 8 shows the same plot without viscous forces, the other parameter we are analyzing in this report.

Figure 8. Timelapse plot of the entire gripper over the simulation period not including viscous forces.

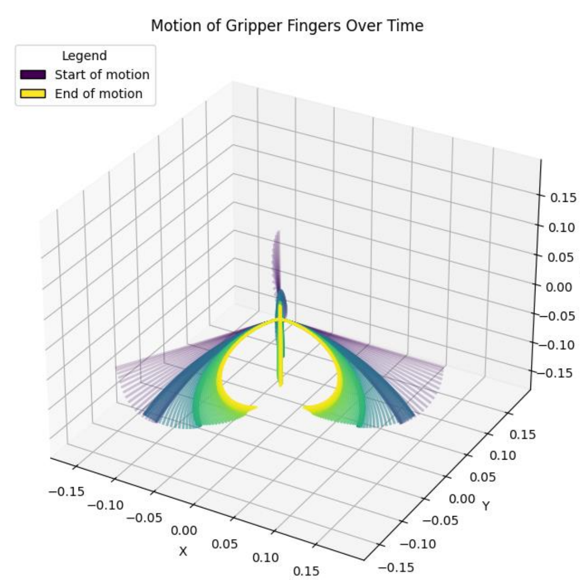


Figure 8 shows more oscillation in the movement of the gripper, confirming that the viscous forces indeed play a role in damping the actuation of the finger.

V. Additional Work

The goal of this simulation is to test out simulating theory from another paper, [4], in which the robotic gripper is able to be programmed with a variable stiffness based on the application. We intend to implement this into our project in the coming weeks.

More work is needed to include the contact forces at the fingertips for simulation of the gripper picking up an object underwater. If time permits, we plan to incorporate the predictor-corrector method for modeling of the contact forces. The cross-sectional area of the actuator fingers will be changed to represent the actual finger geometry.

Acknowledgment

This project 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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