Discrete Simulation of Soft Robotic Grippers for Underwater Applications

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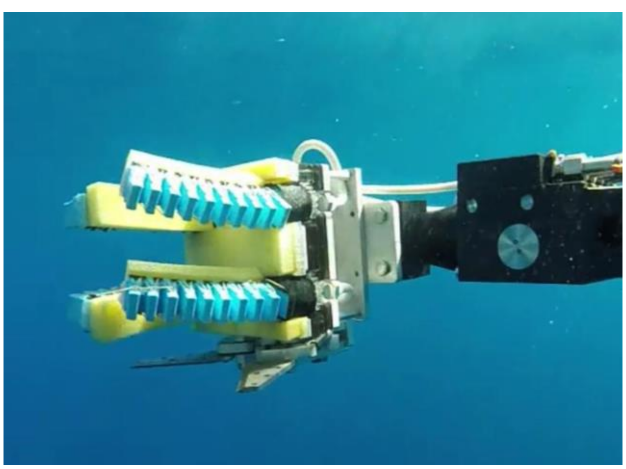
***Abstract*— Soft robotics has emerged as a field with tremendous upside in creating end effectors for applications that need a compliant or delicate grasp. This project aims to increase appropriate discrete modeling techniques for soft grippers for better simulation in an underwater environment with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

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 discrete analysis to the soft gripper space for quick analysis. We will be utilizing a known soft gripper from literature and adding simulation features like programmable variable stiffness and an underwater environment[2][4]. The goal of this project is to: 1) numerically simulate a soft gripper with elastic properties using the discrete differential geometry method[5] with hydrodynamic effects to simulate underwater environments, 2) add and analyze the effect of variable stiffness in the gripper simulation, and 3) add contact forces at the gripper simulation to animate grasping an object.

Figure 1. Soft robotics finds applications in underwater environments, picking up delicate artifacts or species [6].



II. Background

Traditional robotic grippers consist of rigid links and joints that can be actuated by motors or tendons[7]. 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[7]. 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[8]. For this reason, many soft robotic fingers are made from soft plastic or elastomer that contain intrinsic elastic properties, i.e. when they are bent, they apply some sort of restoring force[9]. 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[10]. 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[8]. 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. Methods

A. Problem Setup

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 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 [5]. Thus, we hope the

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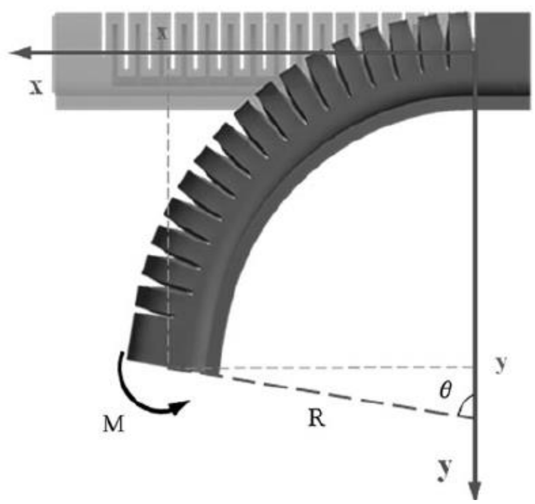
discretization simplifies the process and allows for more flexibility in applications.

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].



IV. SIMULATION

A. General Formulation

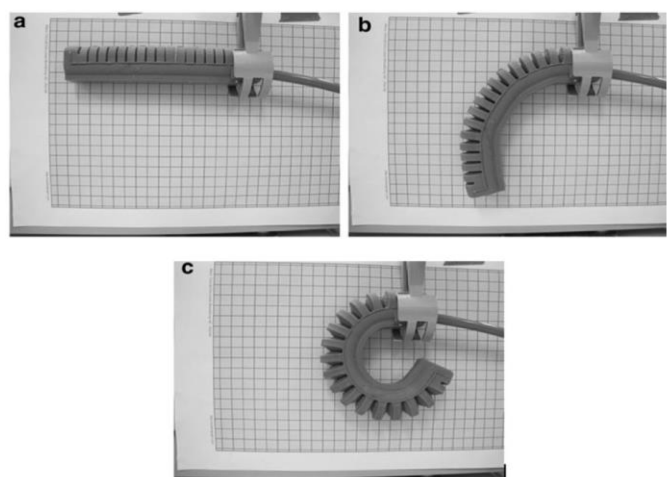
The goal of the formulation is to build a numerical simulation tool for a soft robotic gripper that draws inspiration from discrete differential geometry-based simulation of slender structures. Simulation of the actuation of the underwater soft robotic gripper described above is essentially that of a 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 blocking 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. Due to the bistable metal layer in the actuator fingers, the effective elastic modulus will vary with pressure. But for the purpose of the simulation a constant modulus of elasticity is considered ignoring the bistable nature of the actuator while accounting for the stiffness of the composite structure. The physical actuator finger has a non-circular cross-section such that the neutral axis is offset from the pressure center which enables bending while actuated with pressure. However, for the simulation a circular cross-section is used for simplicity. 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, nevertheless, for the simulation stretching and twisting energies are also modelled. We compute the inertial force, external forces due to gravity and viscous properties, 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.

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.



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:

$$E_B = \sum iE_{i,B} \quad (4)$$

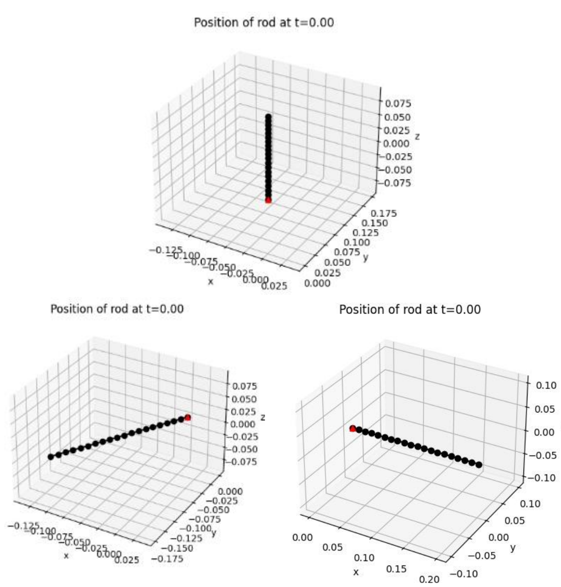
The motion of the gripper is driven by pneumatic actuation which is given as an input by varying curvature κ and hence the bending stiffness with time. Thus, the natural curvature is a function of time, $\bar{\kappa_\iota} = f(t)$. For smooth actuation, we have defined this function to be:

$$\bar{\kappa_\iota} = -0.15 * ctime \quad (5)$$

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 gripper fingers respectively. A major assumption made here is that the first two nodes are 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. Initial 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:

$$C = 6 * \pi * r * \eta \quad (6)$$

While this formulation is not exactly for the geometry involved in Alici et al., 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*.

D. Variable Stiffness Simulation

Once the gripper was fully simulated with viscous forces the code was modified to include an option for variable stiffness. Variable stiffness was defined by changing the geometry of the elastic rod, varying the radius over the length of the rod, r_0. This allowed the same bending stiffness parameters calculated in Equation 1 to still hold for the given gripper in [2]. The scheme for defining the variable stiffness is given by Equation 7.

$$r_0 = 0.001 * (nv - index) \quad (6)$$

Where the scaling factor, 0.001 was chosen to keep the first node radius equal to that of the initial simulation and the gripper we are simulating which has a cross-sectional radius of $r_0 = 0.02\ m$. This way of calculating the variable radius results in a linear decrease in the cross-sectional radius from the initial r_0. The gripper simulated in the results section has an initial cross-sectional radius of $r_0 = 0.02m$ and decreasing to $r_0 = 0.001\ m$ at the tip. The result of this change meant that the nodal elastic bending stiffness varied from $485\ GPa$ at the base of the finger to $304\ Pa$ at the fingertip.

E. Contact Forces Simulation

Contact forces were added to the simulation using the predictor-corrector approach. This approach checks if each node of the finger crosses the surface boundary of the object to be grasped at each time step. When a node crosses the object boundary, the node is fixed to a point projected on the surface of the object in the direction of the normal at the point of intersection with the object. For the simulation a spherical object is considered. From the equation of motion, the difference between the inertial force and the elastic and external forces will be equal to the reaction force which will be non-zero only for the nodes that come in contact with the object.

V. Results

As part of the simulation, the motion of the gripper was observed and the results corresponding to the motion, grasping of an object, reaction forces at the contact zone, sensitivity of modulus of elasticity, effect of constant and variable stiffness, sensitivity of material, the effect of viscous forces and the timeline of the actuation were captured.

A. Single Actuator Results

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 influence of 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.

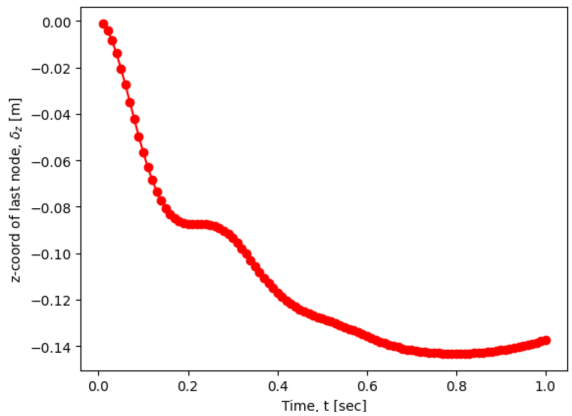
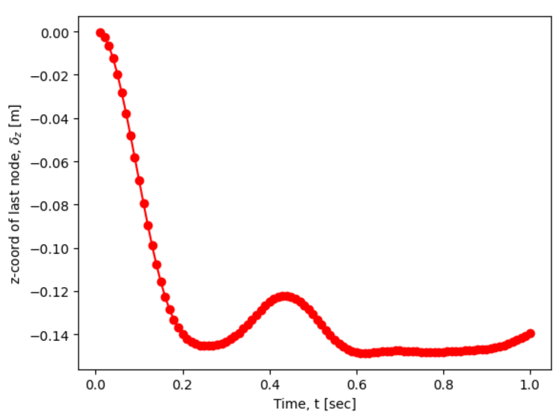


Figure 5 is particularly interesting when considering that the graph is not linear. This makes sense as the relationship between the elastic bending force and the natural curvature is not a linear term. For example, at $t = 0.2\, sec$, the gripper finger stalls, as the natural curvature is unable to 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 $Y = 100\, kPa$.

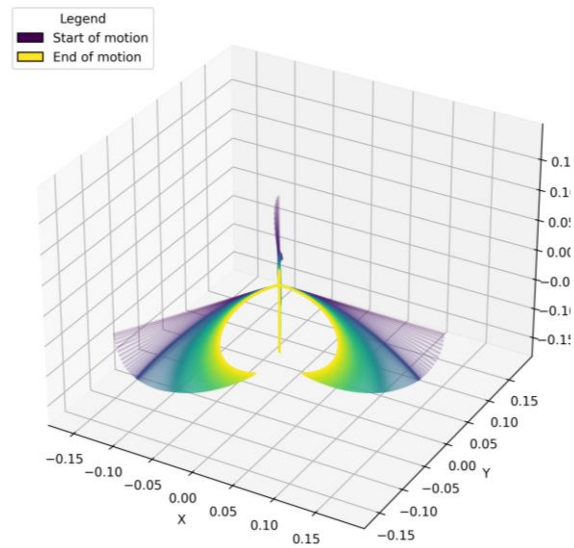


When we change the modulus of elasticity, the motion of the gripper changes. As depicted in Figure 6, which tracks the Z-coordinate of the gripper over time, the actuation is able to overcome the elastic forces involved, but at $t = 0.4\, sec$, the gripper rebounds.

B. Full Gripper Results

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 assumes the physical positions to pick up objects in an underwater environment. Figure 8 shows the same plot without viscous forces, one of the parameters we are analyzing in this report.

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

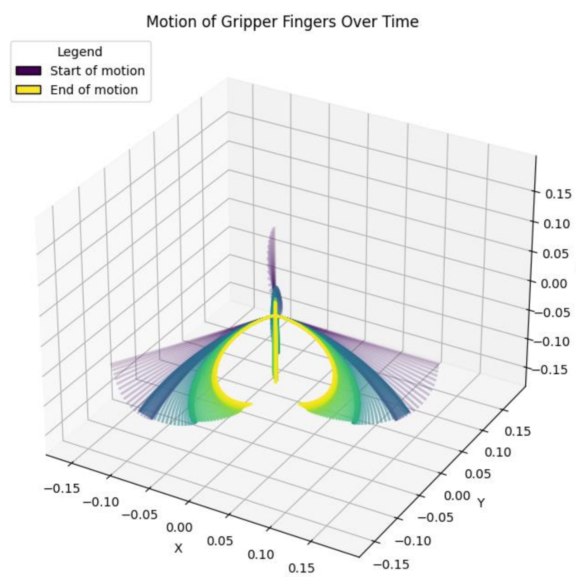
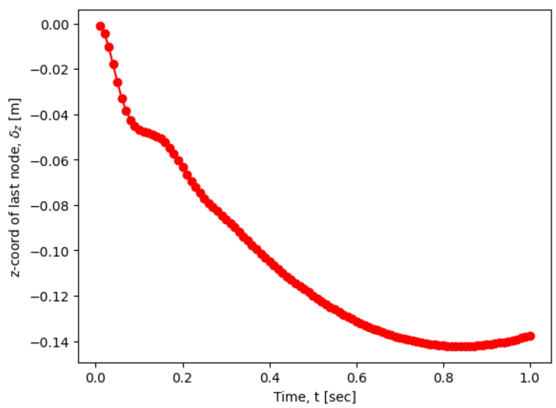


Figure 8 shows more oscillation in the movement of the gripper, confirming that the viscous forces indeed play a role in damping the actuation of the finger and increased control in an underwater environment.

C. Variable Stiffness Results

The 3-finger gripper was simulated using the variable stiffness as set by a decreasing radius. This resulted in changes in the motion of the gripper. Figure 9 depicts that the motion of the fingertip seems to be much more controlled, with no clear instances of the elastic forces overcoming the actuation method. This displays the effectiveness of changing the bending stiffness by varying the actuator radius to get smoother actuation profile.

Figure 9. Z-coordinate positions of the gripper finger with respect to time for a finger with variable stiffness.



Specifically, compared to Figure 5, which is under the same parameters (except the variable stiffness), the difference in the actuation profile is clear.

D. Contact Forces Results

The simulation was also simulated grasping a spherical ball of radius 0.065 meters. Figure 10 shows a single finger grasping the ball and the normal vectors at the points of contact. Figure 11 shows the full gripper grasping the ball along with the timeline of actuation.

Figure 10. Single gripper finger grasping the ball (top) and the normal vectors at the points of contact (bottom).

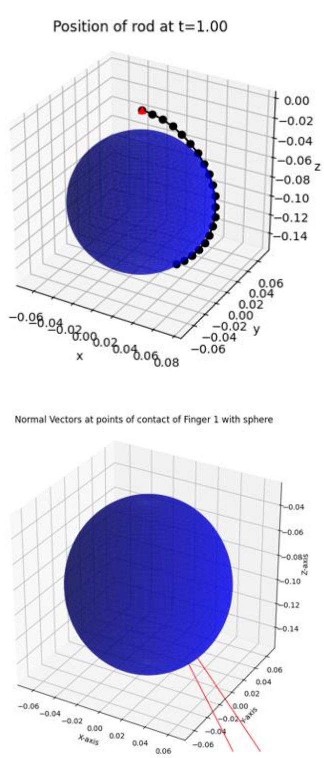
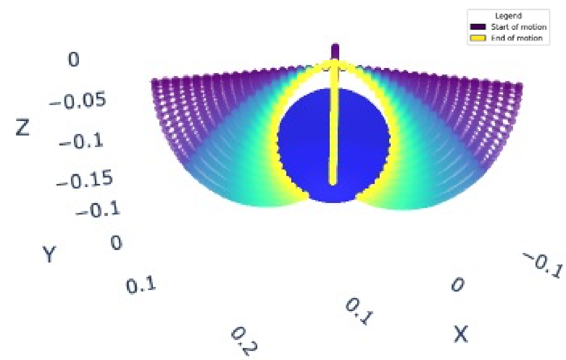


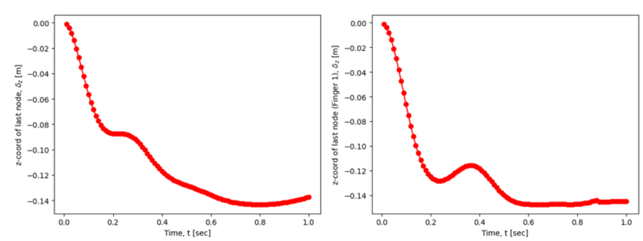
Figure 11. Full gripper actuation timeline with contact forces.



E. Material Sensitivity

The sensitivity of two different elastomeric materials were studied through the simulation. Elastosil MA 4601 and Soft Translucent silicone with an effective modulus of elasticity of 386.66 kPa and 169.56 kPa respectively. Figure 12 shows the difference in the motion of the tip of the finger between the two materials.

Figure 12. Material sensitivity analysis for Elastosil MA 4601 (left) and Soft Translucent solicone (right).



The total reaction force in the two cases are 33.86 N and 21.23 N per finger in the contact zone for Elastosil MA 4601 and Soft Translucent silicone respectively. From the tip deflection and reaction forces it could be inferred that Elastosil performs better for the purpose of grasping due to smoother actuation, higher stiffness and hence a higher grasping force.

VI. Additional Work

The goal of this simulation is to implement Discrete Elastic Rod theory in the context of soft grippers. We have demonstrated proper implementation but have not compared it to other methods of modelling. With more time we want to do a proper analysis of this gripper system using other methods like finite element analysis and compare this numerical method of solving the equations of motion[11]. Additionally, we could implement other topics learned in this class like feedforward neural networks with gradient descent to calculate or predict the bending stiffness for a given gripper based on its geometry.

VII. Conclusion

All code for this project can be found in the github repo for this submission.

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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