16741: MECHANICS OF MANIPULATION

FINAL PROJECT REPORT

Exploring the Dynamics of Octopod Manipulation

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CONTENTS

1 INTRODUCTION

The Octopus arm is one of the most sophisticated and fascinating appendages found in nature, lacking a rigid skeleton, and having virtually infinite degrees of freedom [Engel et al., 2005]. The material properties of the arm impart a high degree of redundancy, and make the arm capable of stretching, contracting, folding, and following the contours of arbitrarily shaped objects. The muscles present in the arm generate forces to maintain structural rigidity, which is made possible through a constant volume constraint.

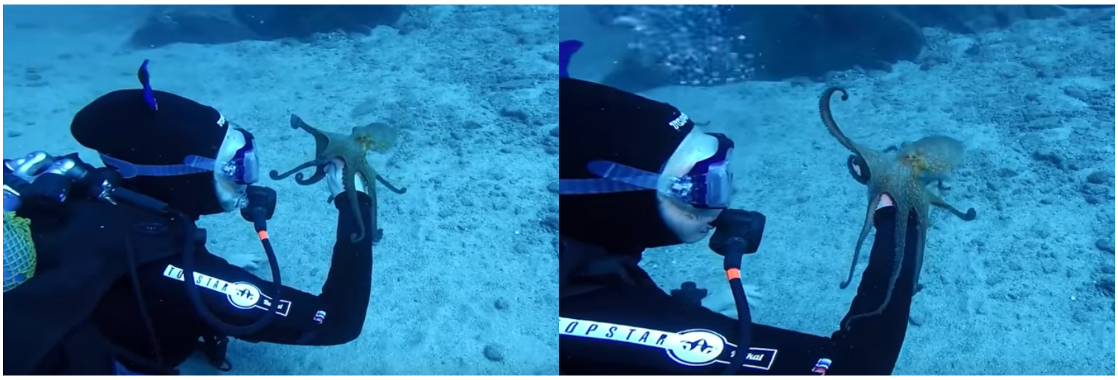

Figure 1.1: Snapshot of a video showing an octopus latching onto a diver's arm. Notice how the appendage is able to curl into extraordinarily flexible poses. Credit: National Geographic. Original video may be found here.

This project was an exploration to analyze the dynamics of the different types of forces acting on the arm (internal forces, vertical forces, drag forces, pressure-induced forces). This was done by understanding and probing the behavior of existing models found in the literature, which we[1] categorize as the following:

- Planar Model
- 3D Dynamic Model
- Cosserat Rod Model

and explain in further sections.

These insights were then used to simulate rudimentary behavior. We end with comments on ideas for future work.

[1] The use of we is purely stylistic. This project had a single contributor, aided by discussions and feedback from course instructors

2 Models

2.1 Planar Model

Yekutieli et al. [2005a] propose a 2D model to analyze the dynamics of octopod manipulation where the arm is decomposed into quadrilateral components. The constant volume constraint is translated into a constant area constraint on each of these components. The model was subsequently used in a follow up work to used to investigate the neural strategies used for controlling the reaching movements of the octopus arm [Yekutieli et al., 2005b].

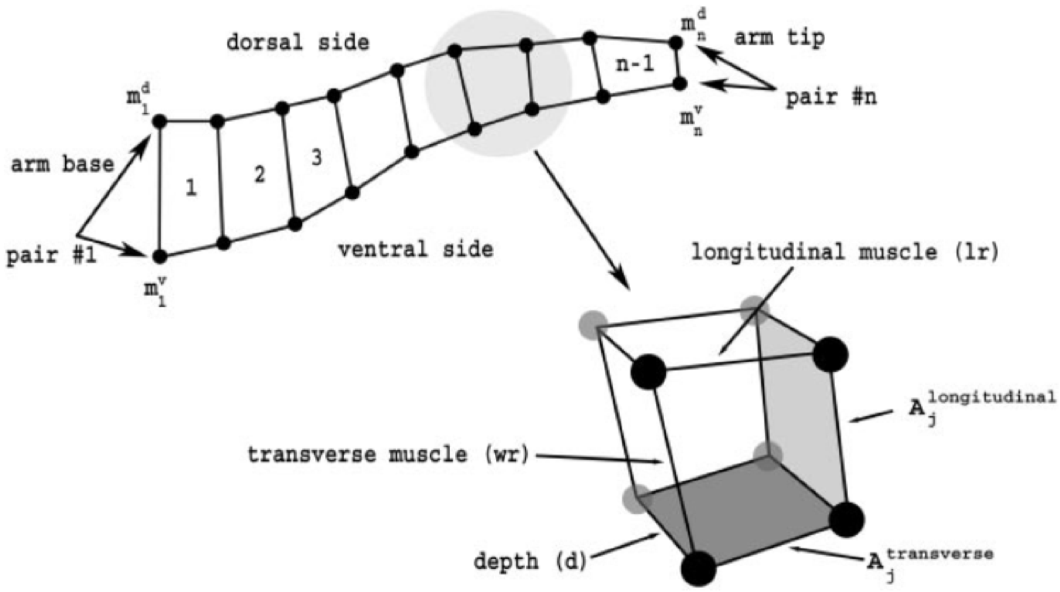

Figure 2.1: Figure illustrating the planar model of an octopod arm as described in [Yekutieli et al., 2005a].

The model assumes the following:

1. Simulated movements are free movements (e.g. appendage does not interact with other objects).
2. Discrete model (for simplicity). The discretization was done with 20 segments, but using more segments (40) yielded marginal experimental advantage.
3. All forces were confined to a single plane.

The forces thus acting on the arm included the following:

- Internal forces from arm muscles f^m
- Vertical forces from gravity & arm buoyancy f^g
- Drag forces (from water) f^w

- Internal forces (from constant volume constraints) f^c

This leads to the following dynamics equation:

$$M\ddot{q} = f^m + f^g + f^w + f^c \tag{2.1}$$

where M is the mass matrix and q is the position vector.
The vertical forces from gravity & arm buoyancy are modeled using Archimedes' law

$$f^g = (\rho_{arm} - \rho_{water})V_{arm}\vec{g} \tag{2.2}$$

where ρ is the density, V is a matrix encoding the segment volumes, and g is the gravitational acceleration.
The equations for modeling drag forces from water are arrived at using dimensional analysis

$$||\vec{d}_{per}|| = \frac{1}{2}\rho_{water}p_a c_{per}||\vec{v}_{per}||^2 \tag{2.3}$$

$$||\vec{d}_{tan}|| = \frac{1}{2}\rho_{water}s_a c_{tan}||\vec{v}_{tan}||^2 \tag{2.4}$$

where p is the projected area of the arm segment, s is the surface area of the segment, and v_{per}, v_{tan} are the perpendicular and tangential directions of velocity.
The constraint forces are encoded as

$$f^c = Cp \tag{2.5}$$

where the matrix C encodes the constant volume constraint, and p encodes the compartmental pressures. f^c cannot be solved for directly, and hence the equation for p is first derived

$$p = (GM^{-1}C)^{-1}[\gamma - GM^{-1}(f^m + f^g + f^w)] \tag{2.6}$$

We refer the reader to the appendix of [Yekutieli et al., 2005a] for the complete derivation of p, the definition of the matrix G and more intuition about the process of solving equation 2.5 We can now invert the original dynamics equations to obtain the acceleration vector, which can be integrated to retrieve the position vector

$$\ddot{q} = M^{-1}(f^m + f^g + f^w + f^c) \tag{2.7}$$

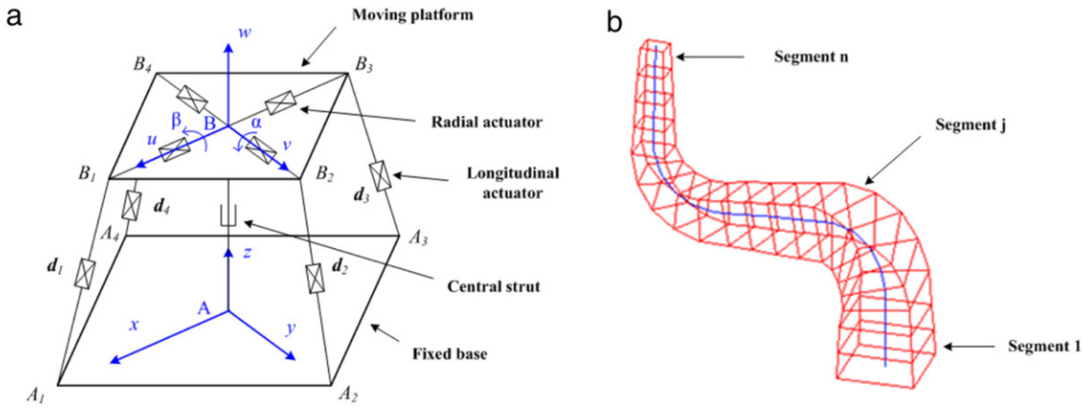

Figure 2.2: 3D dynamic continuum model of an octopus arm as described in [Kang et al., 2012].

For the complete derivation of the dynamics equations, we refer the reader to the original paper [Kang et al., 2012]. Here, we aim to provide a gist of the main ideas.

Figure 2.2 shows the geometry of a single segment of the octopus arm. It is composed of a fixed based, a moving platform, a central strut, and 4 longitudinal and radial rods. The muscles are modeled as a linear piston system, and are attached to a moving platform with spherical joints, and to the base with universal joints, which can be used to adjust the height and orientation of the moving platform. The central strut provides kinematic constraints to prevent shear motion between the base and moving platform, which is modeled using a single prismatic joint fixed to the center of the base, and connected to the center of the moving platform using a universal joint.

The free body diagrams for the longitudinal muscles, central strut, radial muscles, and the moving platform can be found in the paper and are also attached to the appendix for reference.

Individual dynamics equations for a single segment are then derived which include:

1. Longitudinal muscle dynamics
2. Central strut dynamics
3. Radial muscle dynamics
4. Moving platform dynamics
5. Isovolumetric constraints

The authors then describe the implementation of this model using MATLAB/Simulink to chain together multiple single segments into an entire multi-segment octopus appendage. External forces are modeled including: buoyancy and gravity, hydrodynamic forces, and interaction forces (between a sucker and object). The completed model is used to simulate different arm motions including: reaching, fetching, picking, throwing, crawling, and swimming.

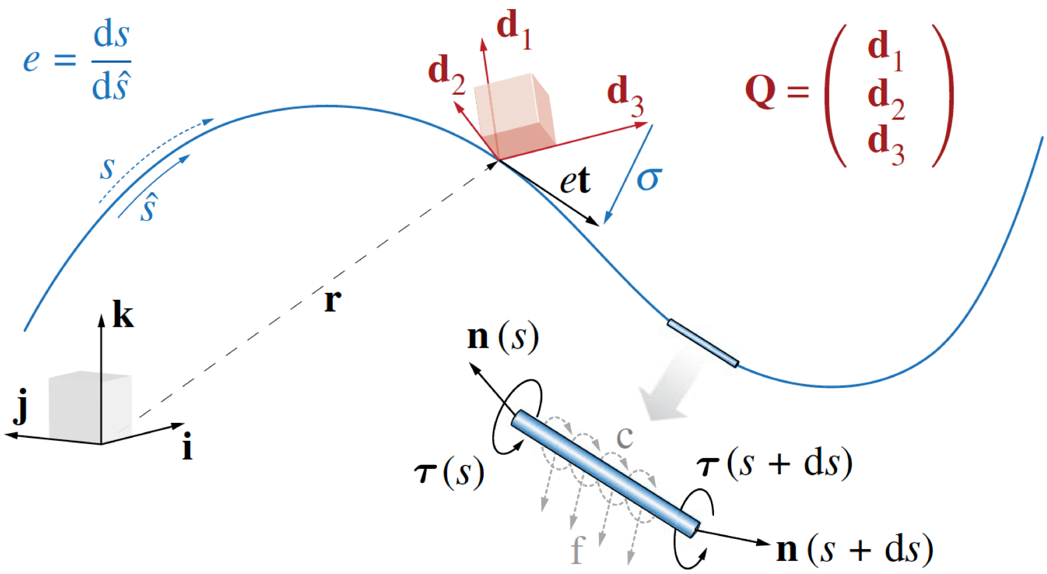

Figure 2.3: Cosserat rod model as described in [Gazzola et al., 2018].

Kirchoff rods are used to model 1D slender rods incorporating bend and twist. Cosserat rods are a generalization of Kirchoff rods, that also allow stretching and shearing, thus modeling all possible system deformation modes. The key assumption is that $L >> r$ where L is the length of the rod and r is the radius, which allows the rod behavior to be approximated by averaging balance laws at every cross section.

We refer the reader to Gazzola et al. [2018] for a more in depth description. This model provides momentum (linear + angular) balance equations which are then numerically solved with appropriate boundary conditions. The model is released as open source software[2], with both C++[3] and Python bindings[4]. We use this library to create a basic model of an octopus twirling its arms, which we describe in Section 3 (Simulation).

For a higher level overview of what the Cosserat rod model formulation allows, we refer the reader to the following talk aimed at a broad audience explaining the geometric simulation of rods and beams.

[2] Elastica: cosseratrods.org/
[3] Elastica++: `https://github.com/mattialab/elastica`
[4] PyElastica: `https://github.com/GazzolaLab/PyElastica`

3 SIMULATION

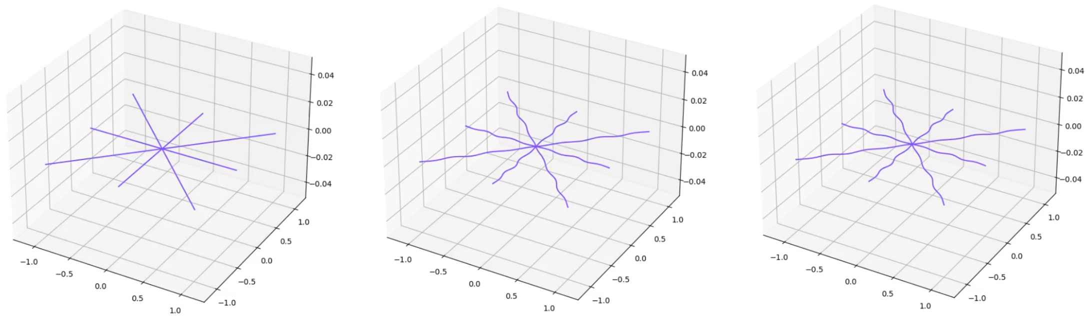

Figure 3.1: Simulation of octopus arm movement (twirling) using PyElastica.

We use the software library implementing the Cosserat model described in Section 2.3 to construct a toy model of an octopus arm. The model is constructed using 8 rods linked together by a hinge joint. We've provided the physical parameters used for the simulation in the appendix.

The code can be found at: `https://github.com/bhaprayan/octopie`. A short clip of the simulation can be found at: `https://youtu.be/ghesGOXUUlo`.

4 FUTURE WORK / IDEAS

The original aim of this project, as described in a preliminary proposal was:

- Analyze the dynamics of the different types of forces acting on the arm (internal forces, vertical forces, drag forces, pressure-induced forces)

- Generate sample movements of the octopod appendage in different configurations.

Towards this end, the first goal was satisfied as described by the review of existing models (Section 2.1, 2.2, 2.3). The second goal was also satisfied, as the movements of the appendage were simulated. Future work could include

- Simulating the movement of this appendage in more configurations such as picking, placing, swimming, and translational movement.

- Design a controller to manipulate the movements of this appendage using reinforcement learning[5][6]

- Explore the dynamics involved with the interaction of the appendage with arbitrarily shaped objects in the scene.

[5] Relevant to the research of the primary author of this report

[6] Originally formulated as a stretch goal in the project proposal

5 Conclusion

In the course of this project we have analyzed the dynamics of the different types of forces acting on an octopod arm, through existing models found in the research literature. Further we used one such model to generate a toy simulation of an octopod arm, and identified avenues for further extensions of this project.

References

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6 APPENDIX

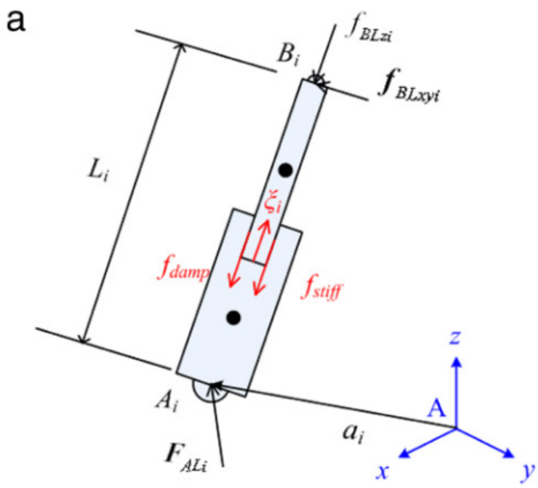

Figure 6.1: Free body diagram of **(a)** longitudinal strut **(b)** central strut as found in Kang et al. [2012].

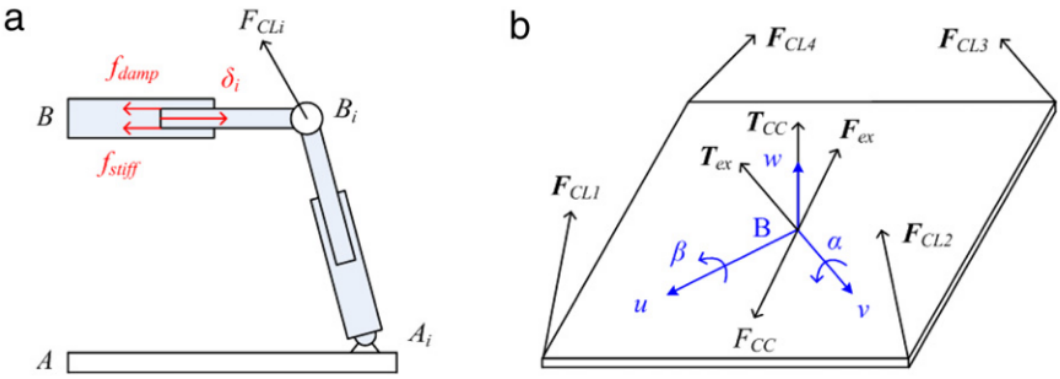

Figure 6.2: Free body diagram of **(a)** radial strut **(b)** moving platform as found in Kang et al. [2012].

Physical Parameter	Value
Base Length	1.0
Base Radius	0.025
Density	1e3
nu	5.0
Poisson Ratio	0.5
Period	1.0
Fluid Density	1.0
Reynolds Number	1e-4

Table 6.1: Physical parameters used to simulate model of an octopus arm as described in Section 3