MAE 263F Proposal: Snake Motion in Viscous Fluids

Sarah Enayati and Jonathan Gray

I. INTRODUCTION

In the field of robotics, drawing inspiration from nature has opened new avenues for technological innovation. This proposal sets out to design a robotic snake that mirrors the movements of biological snakes to navigate through and operate within challenging environments such as honey and water, which are inaccessible to traditional UAVs. Our robotic snake aims not just to match but to exceed the capabilities of these conventional models by improving efficiency and reducing control effort through optimized motion.

Our project centers on constructing an analytical framework that accurately represents the snake-like undulation and its interactions with viscous fluids. This framework will allow the robotic snake to optimize movement and control in ways that traditional UAVs cannot, thus achieving longer mission durations and requiring less energy.

II. SNAKE MOTION – BIOLOGICAL INTRODUCTION

Snakes are very adaptable in their movement, using at least five distinct modes of locomotion to navigate various terrains and environments that we wish to exploit/mimic in our snake robot. Assuming the x-axis is backwards-forwards, y is lateral, and z is vertical movement, the snake is able to move in the following manners:

1) **Lateral Undulation:** The snake propagates itself forward through lateral bending, pushing against the ground/surfaces. Our robot would have 2 degrees of freedom (x and y axes) in this mode of movement.
2) **Sidewinding:** The snake uses both lateral bending and lifting of the body off the ground to move, allowing movement on smooth or slippery surfaces by minimizing sliding friction and maximizing static contact. This would utilize 3 degrees of freedom, in the x, y, and z axes.
3) **Concertina Locomotion:** Alternating segments of the snake's body pull into bends and then extend to push forward, using static friction against tunnel sides or vertical surfaces to prevent backsliding. This would utilize 2 degrees of freedom, in the y- and z-axes.
4) **Rectilinear Locomotion:** The snake's body moves in a straight line using very small movements by lifting and pulling. This primarily uses only one degree of freedom, in the x-direction, with subtle/negligent movement in the y/z-direction.
5) **Slide-Pushing:** This is when intense, irregular waves pass through snakes' bodies that produce a pattern of slipping forward, making the snake move widely across the surface. This has two degrees of freedom primarily, in the y- and z-axes.

III. PREVIOUS WORK

The use of unmanned vehicles in recent years for the purposes such as exploration and search and rescue missions has increased. However, while traditional UAVs can be effective for simple mediums such as air and even water, they fail for more complex, viscous fluids.

Yamano et al. acknowledge the necessity of developing a robotic snake due to the uniqueness of its ability to move through viscous fluids. They primarily explore and develop methods for accurately characterizing the forces acting on snake-like robots as they maneuver through various viscous fluids. They make use of the biological advantages of snakes and eels who can traverse both on land and within viscous fluids by changing the way they move their links. They tested their robot in mediums such as water and industrial lubricating oils in hopes of replicating the viscosities of mud and clay[1].

In [2], following similar motivations, they follow up their own work by attempting to solve for the optimal swimming motion via numerical analysis using equations of motion for a snake swimming in a viscous fluid that they constructed. Their goal was to balance energy consumption with swimming speed.

Cicconofri and DeSimone investigate snake-like movement by modeling a snake as a flexible, inextensible rod, using a Cosserat rod model to analyze the mechanics of motion. They explore how different constraints on the rod's movement, such as predefined paths versus free movement on flat surfaces, influence the dynamics and control of locomotion [4].

In [5], the authors provide an estimation of fluid forces acting on a snake-like robot swimming in various viscous fluids, considering the effect of boundary layer thinning. The authors took experimental measurements of a robot with eight links swimming in fluids of different viscosities, coupled with numerical modeling using an unscented Kalman filter to identify unknown added mass and drag coefficients.

IV. OBJECTIVES

This research project proposes three main objectives:

1) We wish to construct equations of motion that accurately and satisfactorily model the motion of a N linkage robotic snake.
   a) The number of links/nodes will be obtained through sensitivity analysis.
2) Using numerical methods and graphing software, we will simulate and plot the optimal motion and velocity of the snake robot in each viscous fluid.

[width=1]image.png

Fig. 1. Idealization of fluid-structure interaction[6]

a) We will repeat this process for the following fluids: mud, water, clay, and honey.

3) We will compare our methods and results to existing solutions, as described in [1-3].

V. Kinematics of Snake Motion in Water

In this effort, we explore the design of a snake-like robot represented by a series of discrete elastic rods (DER). The DER system will be used to explore the primary mode of snake motion in water via lateral undulation. Other means of motion may be explored in future efforts that consider land motion (and therefore contact/friction) but are not applicable for aqueous environments considered herein. A 1952 study by Sir Geoffrey Taylor explored the mechanics of such motion with an in-depth analysis based on Resistive Force Theory. The study covers the idealized model, force equilibrium, wave propagation and speed, energy efficiency, surface characteristics, and dimensional parameters (e.g. Reynold's number, wave amplitude, and body shape) [6]. This study can serve as the blueprint for design considerations of the idealized snake robot.

The primary mode of motion is driven by the wave equation of lateral motion for the snakes body which can be idealized as a sinusoid that varies with location along the body, x, the longitudinal speed of the body wave (relative to the snake), U, and the longitudinal speed of the snake CG (relative to the fluid), V, as well as the wave amplitude and wavelength, B and λ, respectively (Equation 1).

$y(x,t) = Bsin(2\pi/\lambda)$*($x + (UV)t$) (Equation 1)

The motion of a snake through fluid is driven by the thrust produced from normal coefficients of drag along the snake's body while the motion is resisted by drag along the tangent of the body path. Figure 1 shows the break down of local drag components of force along the body while undulating for forward (x direction) body motion.

In this idealized model, the thrust is characterized by empirical relationships between the discrete segmental forces imparted by anisotropic drag give by:

$f_t = C_t\rho\ U^2$ and $f_n = C_n\rho\ U^2$ (Equation 2)

Where f_t is the tangential segmental force and f_n is the normal segmental force applied as part of a force equilibrium with the internal body motion (undulation) causing the system to propel forward in viscous and low Reynold's number conditions [6].

Resistive force theory has its limitations. It works well for systems where the hydrodynamic environment is unperturbed from local motion of the swimming bodies thus neglecting boundary effects and long-range effects of flow around the body. For a more general approach to slender structure motion slender body theory (SBT) will be visited. SBT is useful when the body is long and thin compared to its cross-sectional diameter and navigating complex flow fields. SBT is generally more appropriate for intermediate to high Reynold's number applications (such as the swimming of eels or snakes in water). However SBT's mathematical formulation is more rigorous and not as easily applicable to discrete elastic models since it involves the Laplace equation for fluid velocity potential, Φ [7]:

$\vec{\nabla}^2\Phi$ = 0 (Equation 3)

Force is computed by integrating the pressure over the surface using Bernoulli's thus accounting for both local and global hydrodynamic forces. The The gradient of fluid flow near the surface and along the body axis is usually determined through a series of singularities along the body to represent the effect of the body around the surrounding flow field. A key approach to SBT is to express the fluid flow as a superposition between the axisymmetric flow and cross-flow [7]. Finally,

Degrees of freedom (types of snake motion)

References

[1] A. Yamano, K. Shimizu, M. Chiba, H. Ijima, Fluid force identification acting on snake-like robots swimming in viscous fluids, Journal of Fluids and Structures, Volume 106, 2021, 103351, ISSN 0889-9746, https://doi.org/10.1016/j.jfluidstructs.2021.103351

[2] A. Yamano, T. Kimoto, Y. Inoue, M. Chiba, Optimal swimming locomotion of snake-like robot in viscous fluids, Journal of Fluids and Structures, Volume 123, 2023, 104007, ISSN 0889-9746, https://doi.org/10.1016/j.jfluidstructs.2023.104007.

[3] Moore, B. R. (n.d.). Snake locomotion. University of Louisiana at Lafayette. Retrieved October 30, 2024, from https://userweb.ucs.louisiana.edu/b̃rm2286/locomotn.htm

[4] Cicconofri, G., & DeSimone, A. (2015). A study of snake-like locomotion through the analysis of a flexible robot model. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 471*(2182), 20150054. https://doi.org/10.1098/rspa.2015.0054

[5] Kimoto, T., Yamano, A., & Chiba, M. (2023). Estimation of fluid forces on a snake-like robot swimming in viscous fluids considering boundary layer thinning. In *2023 IEEE/SICE International Symposium on System Integration (SII)* (pp. 1-6). IEEE. https://doi.org/10.1109/SII55687.2023.10039336

[6] G. Taylor, "Analysis of the Swimming of Long and Narrow Animals," *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, vol. 214, no. 1117, pp. 158-183, Feb. 1952.