Advancing Robot Design through Morphology and Fluid Environment Interactions

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I. Introduction

Advances in new fabrication techniques, actuator technologies and novel materials are enabling the development of increasingly capable soft robots that locomote in fluids [20, 16]. Unlike typical rigid robots, these soft bio-inspired robots have the potential to allow for more energy efficient locomotion, while also offering a compliance and adaptability that is advantageous for navigating complex or uncertain environments [2]. However, due to the complexity of interactions between the soft body and the fluid environment, designing and optimizing these robots is challenging [14], and the design space is combinatorially large. To fully utilize advances in robotic hardware, new design and optimization tools are needed which optimize the morphology (body shape and structure) and also understand the rich interactions between the fluid and the soft bodies. Such tools will enable the automatic and rapid design and fabrication of robots that exploit the fluid environment in addition to exploring designs and solutions that might not be otherwise found.

Bioinspired swimming robots have been optimized for thrust generation [4], including octopus-inspired [6] and starfish robots [7], while others leverage central pattern generators for locomotion [18]. However, few underwater robots exploit their morphology for control, despite its potential for stability and behavioral shaping [11, 26]. Advances in modeling approaches, from beam theory [8] to CFD [17], highlight the challenge of accurately simulating soft body-fluid interactions, leading to increasing reliance on data-driven methods [19]. Biological systems inherently exploit nonlinear dynamics for complex emergent behaviors [10, 5], inspiring evolutionary approaches in robot design [12]. Large-scale robotic experimentation is emerging as a powerful tool for optimization and discovery, such as automated laboratory research in other scientific domains like chemistry and food science [3, 13].

II. Current Research

I am passionate about advancing the robustness and efficiency of bio-inspired robots that interact with the environment and exploit fluid interactions. These robots have the potential to achieve tasks including underwater monitoring, manipulation, or removal of debris, contributing to sustainable management and improvements of underwater environments. I approach this by developing novel soft robotic platforms and leveraging methods such as large-scale experimentation, data-driven design, and fluids analysis. My work, stemming from the study of embodied intelligence for soft robots that exploit fluid interactions, is summarized below and shown as Fig. 1.

A. Online Robot Design and Optimization

I study emergent behaviors—patterns that naturally arise from the interaction between a robot and its environment—to inform design principles. To address the challenge of designing an optimal paper plane with non-linear mapping between the geometry and behavior, I developed an experimental setup that automates the design and manufacturing of paper planes and uses computer vision to analyze their flight trajectories [22]. This setup captured large-scale data to create a probabilistic understanding of their flight behaviors for various paper plane geometries. Additionally, I built a large-scale robotic automation setup for fabricating and testing different flag shapes in a wind tunnel, where dynamic modes of flapping were captured using event-based cameras to aid in the discovery of new flapping. I applied similar techniques to underwater robots to enhance their swimming performance or finding an optimal controller. A key publication [23] involved the optimization of controllers for an underwater soft, asymmetric fin in a water tank, where Bayesian optimization was used to iteratively converge on a solution. Through these automated systems, we can gather large datasets, enabling real-time online optimization and revealing critical insights into the relationship between robot shape and performance.

B. Soft Robotic Manufacturing, Sensing, and Modeling for Underwater Applications

Designing and deploying soft robots for underwater environments presents several unique challenges, from the materials used to waterproofing electronics and modeling fluid-structure interactions. In some of my key publications [21], to develop soft bio-inspired swimmers which have high efficiency and controllability, I utilized a hybrid method combining multibody physics simulation with steady-state computational fluid dynamics (CFD). Although the CFD captured the macro-level trends of the robot, there was a significant discrepancy between the simulated and real-world thrust values. To address this, I developed a transformation matrix that uses minimal experimental data to map and scale the simulated results, improving their quantitative accuracy. This iterative approach enabled the design of underwater robots optimized for efficient propulsion and maneuverability. In terms of materials, I often utilize silicone, multi-material (rigid and soft) 3D-printed components, and thin plastic films or waterproof fabrics. For sensing, I have integrated pressure sensors by embedding them into voids within soft materials [27], as well as utilizing hydrogel-based piezoresistive strain sensors and conductive rubber to create robust sensing mechanisms within

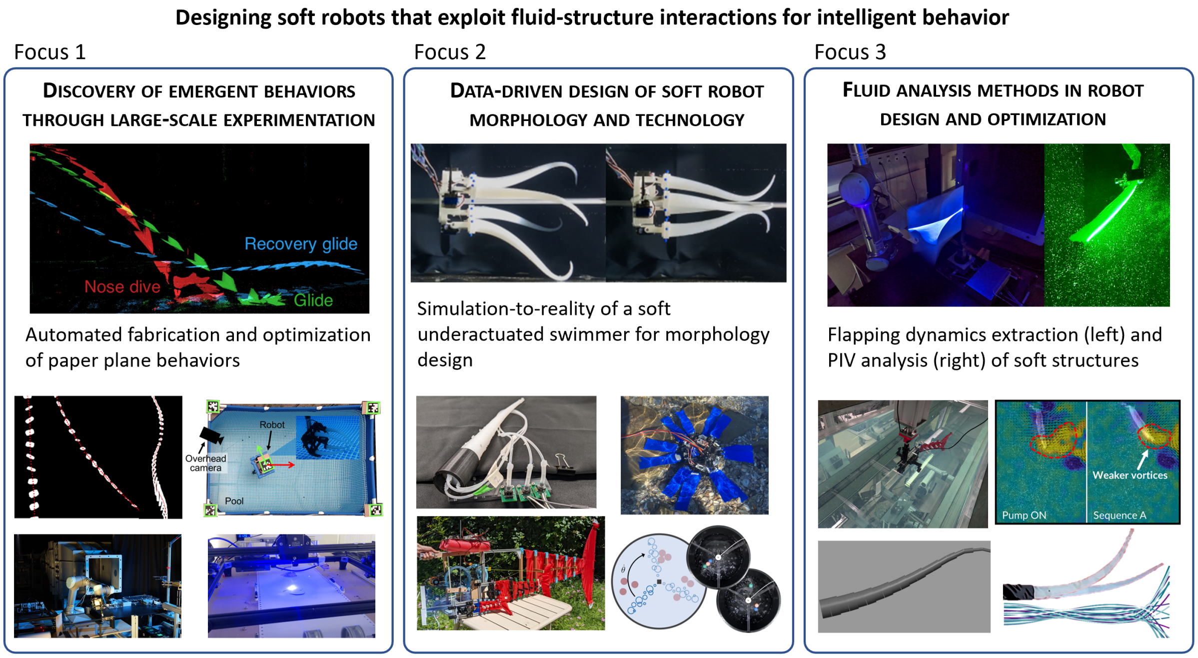

Fig. 1. Key areas of my work and a selection of robotic hardware and platforms for design and optimization of morphology in diverse fluid environments.

underwater soft structures [1]. This enables soft robots to possess proprioceptive (or self) sensing capabilities, allowing the reconstruction of their deformations from sensor data. By constraining these deformations to an affine curvature model, we can predict swimming performance.

C. Novel Mechanisms and Robotic Platforms for Adaptive Performance in Fluids

My work in fluid-adaptive robotics spans multiple projects designed to exploit various biological principles and ecological niches. I developed a scalable robotic fish using glass fiber rods in three sizes, ranging from 40 cm to 300 cm, to explore biological scaling and its benefits. This work aims to create large soft robots which currently don't exist in state-of-the-art, addressing gaps in ecological exploration across different fluid regimes. In another project, I designed a feather star-inspired robot with detachable limbs for improved maneuverability [15]. The feathers generate asymmetric thrust based on movement direction, mimicking biological creatures that optimize thrust for directional efficiency. Additionally, I created a pneumatically actuated soft fish tail capable of varying its stiffness during the tail beat cycle, validated using Particle Image Velocimetry (PIV), which resulted in improved thrust and energy efficiency [25]. In analyzing my robots, I have frequently integrated fluid dynamics setups such as wind tunnels, PIV, and water channels into the experimental workflow, allowing for robust testing and validation of these robotic systems.

III. Future Research Directions: Adaptive Robots & Data-Driven Design in Multi-Density Fluids

One of the core challenges in robotic design is creating systems that can adapt to and function effectively across diverse fluid environments, where fluid characteristics shift dramatically at different scales. To address this, my research will focus on leveraging multi-material design, including state-of-the-art 3D printing of soft materials, to fabricate robots that can physically "grow" or adapt their bodies to different fluid regimes. Using tendon-driven soft robots for example, printed in a single process with continuously varying morphological parameters, we can optimize robotic performance through material selection and dynamic behavior. These techniques also enable the creation of novel soft sensors, where fluidic voids allow pressure measurements to inform both strain and tactile data for closed-loop control. Applications span underwater exploration, such as inspecting fragile ecosystems like coral reefs or industrial oil rigs, to atmospheric research and climate monitoring. This work will help develop versatile, multi-scale robots for ecological inspection, pollution tracking, and environmental monitoring.

Additionally, automated large-scale experimentation will play a crucial role in robotic embodiment and morphology optimization in fluid environments. Data-driven robotic platforms will conduct real-world iterative testing, bridging theoretical fluid dynamics with practical applications. While initiatives like the MIT's Intelligent Towing Tank [9] have laid important groundwork, there remains a critical need for benchmarking and standardization across different designs and research groups and real-world conditions. My research will address this by developing evaluation frameworks that integrate theoretical fluid dynamics with large-scale experimentation, ensuring reproducibility and comparability across robotic platforms. This will provide a foundation for standardized testing methodologies, enabling continued growth in soft robotics [24].

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