ECE 445 / ME 470

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Softbot: Jellyfish-Inspired Bionic Soft Robot with Visual Perception

Team #14

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1 Introduction

In recent years, soft robotics has gained significant attention due to its potential to mimic the flexibility and adaptability found in biological systems. Unlike traditional rigid robots, soft robots are made from flexible materials such as dielectric elastomers (DE), hydrogels, and fluids, which enable them to adapt to complex, dynamic environments [1]. These robots leverage advanced actuators like pneumatic, hydraulic, and electrohydraulic systems, including the innovative HASEL (Hydraulically Amplified Self-healing Electrostatic) actuators, which allow for biomimetic, muscle-like motion [2]. Soft robots have promising applications in various fields such as healthcare, prosthetics, industrial automation, and exploration of extreme environments, where their high adaptability and safety are highly valued [3].

While existing soft actuators, including pneumatic and shape memory alloy-based systems, offer considerable flexibility, they face limitations in terms of efficiency, speed, and portability. Dielectric elastomer actuators (DEAs) have shown great promise in providing muscle-like actuation but often require rigid frames and pre-stretching, limiting their potential [4]. On the other hand, HASEL actuators, which combine electrostatic and hydraulic forces, offer significant advantages, including linear contraction without the need for rigid frames. These actuators are cost-effective, can achieve up to 10% contraction, and possess self-sensing capabilities, making them ideal for applications requiring high performance, such as prosthetics and robotics [2]. Despite their advantages, a key challenge for existing soft actuators remains their ability to achieve optimal force feedback while maintaining flexibility and portability.

To address these challenges, this project proposes the development of a new soft robotic actuator system inspired by the unique efficiency and structure of jellyfish. Jellyfish exhibit remarkable control over their movement, achieved through the coordinated use of fluidic and muscle-like actuation. Our project aims to create a novel actuator by combining dielectric elastomers with dielectric liquids, resulting in a robust and efficient system that can mimic muscle-like movements while overcoming the limitations of traditional soft actuators.

The new actuator system will not only improve force feedback but will also ensure stability, flexibility, and portability. Furthermore, to enhance the functionality of the soft robot, the system will integrate visual perception using a neural network-based vision module. This module, coupled with reinforcement learning or PID (Proportional-Integral-Derivative) control, will optimize movement and trajectory tracking, enabling the robot to adapt to its environment and interact seamlessly with humans or objects. The ultimate goal of this project is to push the boundaries of soft robotics, making it more efficient, adaptable, and suitable for real-world applications [5], [6].

1.1 Objective and Background

1.1.1 Goals

Current soft actuators such as Soft Pneumatic Actuators, Dielectric Elastomer Actuators (DEAs), and Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators face several challenges, including low efficiency, bulkiness, and poor robustness. DEAs and HASEL actuators offer advantages such as flexibility and high energy density but also suffer from issues such as complex structures and low durability. Our goal is to combine the benefits of both HASEL and DE actuators to create a more efficient, robust, and flexible soft actuator that can be effectively used in portable and adaptable robotic systems.

Meanwhile, we will also apply this structure to practical applications. By combining control algorithm with visual neural networks for recognition, A soft robot that can travel along our predetermined route will be brought to existence.

1.1.2 Functions

The proposed actuator combines dielectric elastomers with a dielectric liquid, forming a bell-shaped structure inspired by jellyfish movement. This actuator provides a strong force feedback while maintaining a stable structure, which is crucial for soft robotic applications. Additionally, the softbot system integrates a visual perception network to process environmental data and a reinforcement learning or PID control mechanism to optimize robot movement in response to real-world feedback. With the collaborative function of software and hardware, the product is supposed to be capable of moving smoothly according to the predetermined trajectory of operator.

1.1.3 Benefits

This solution improves the efficiency and adaptability of soft robots, enabling them to perform tasks in a wider range of environments. By combining the flexibility of HASEL actuators and the high energy density of DE actuators, the system offers an efficient and reliable solution for soft robotics. It also enhances the robot's ability to interact with its surroundings intelligently, making it suitable for dynamic and interactive applications, such as in human-robot collaborative environments.

1.1.4 Features

Unlike existing soft actuators, the proposed design integrates the benefits of both DEAs and HASEL actuators, combining flexibility, high energy density, and enhanced robustness. The jellyfish-inspired actuator design allows for strong force feedback while maintaining a stable structure. Additionally, the integration of a visual perception network and reinforcement learning control provides the robot with the ability to interact intelligently with its environment, which is a unique feature compared to current actuator designs that lack such capabilities.

1.2 High-Level Requirements List

Here are three measurable characteristics to evaluate the solution:

- The actuator must provide strong force feedback while maintaining a stable structure, demonstrating higher efficiency and adaptability compared to existing soft actuators.
- The robot's control system should be capable of recognizing and responding intelligently to environmental input, facilitated by the integration of a visual perception network.
- With the utilization of PID control or reinforcement learning control algorithm, the system must allow the robot to accurately move along a predefined path, using voltage signals to actuate the movement, ensuring precise and repeatable motion.

2 Design & Requirements

2.1 Diagram

2.1.1 Physical Diagram

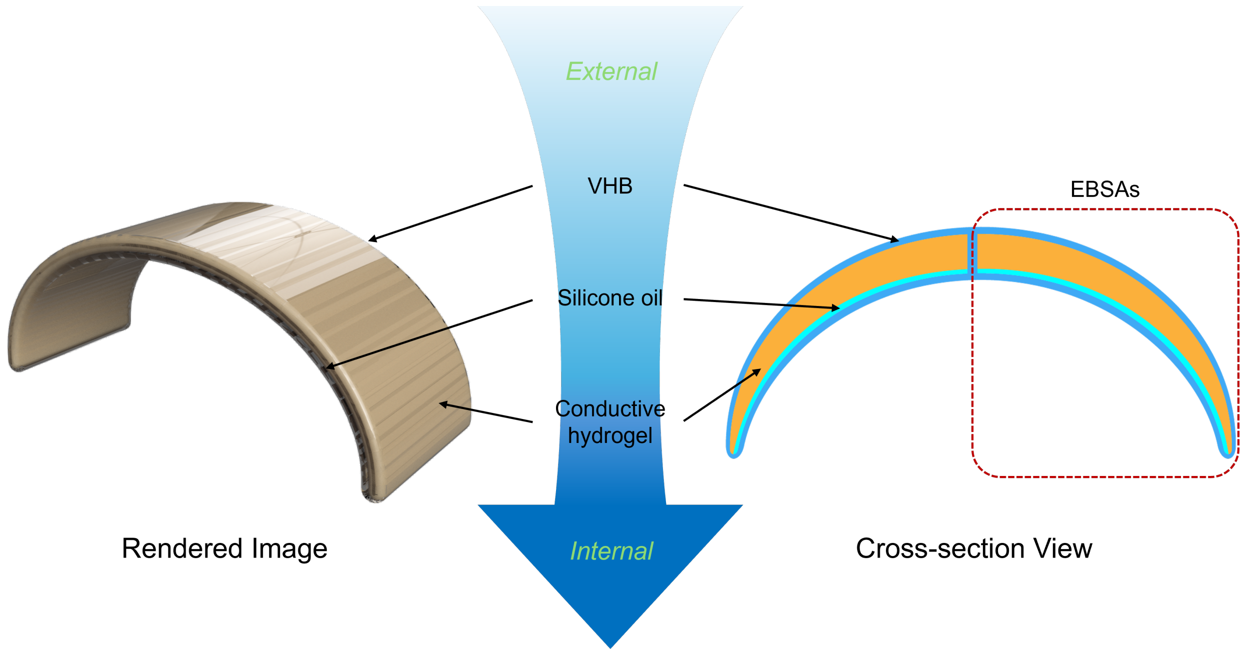

Figure 1: Rendered image and cross-sectional view of two-dimensional bionic jellyfish robot. The robot has two Electrohydraulic Bent-to-Straight Actuators (EBSA), which consist of Very High Bond (VHB), silicone oil and conductive hydrogel.

2.1.2 Block Diagram

2.2 Block Descriptions

2.2.1 Robot Motion Trajectory Planning Program

The robot motion trajectory planning program provides an intuitive interface for users to specify and visualize robot movement trajectories. It generates trajectory data for use by the computing node.

- **Requirement 1**: Must accurately export defined trajectories in a compatible data format (e.g., JSON or CSV).
- **Requirement 2**: Real-time trajectory editing and visualization at refresh rates greater than 30 FPS.

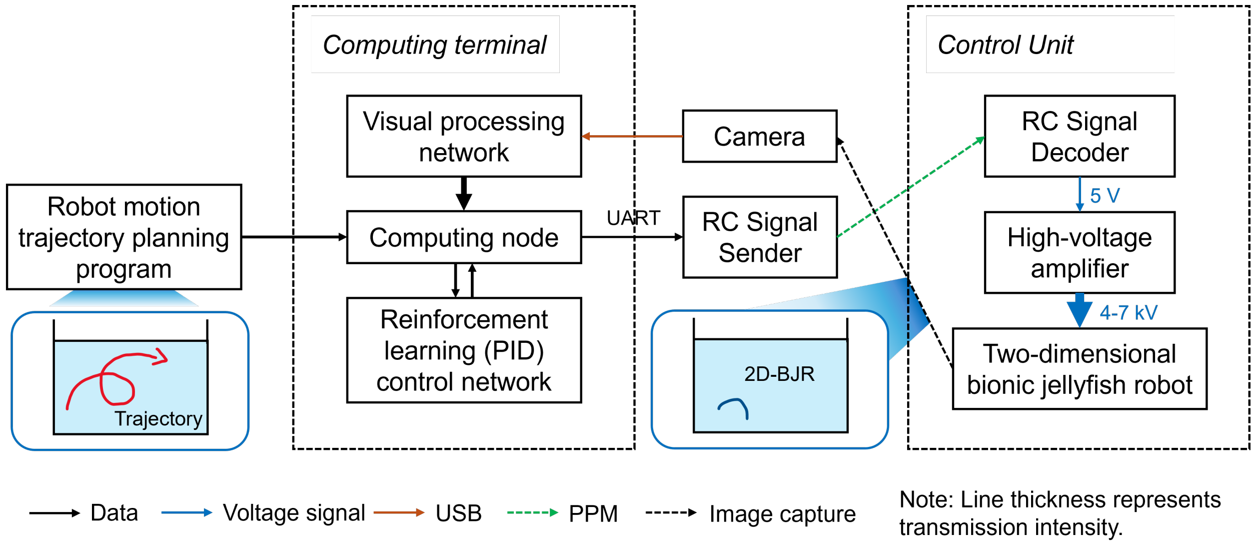

Figure 2: Block diagram of our senior design.

2.2.2 Computing Terminal

The computing terminal integrates data from trajectory planning, visual feedback, and control algorithms to generate remote control signals.

Visual Processing Network

- The visual processing network captures real-time visual information via a camera and performs trajectory recognition and tracking.It communicates with the computing node via internal data buses.
- **Requirement 1**: Must support USB communication protocol for visual data acquisition using Jetson Nano Raspberry Pi 5 camera module.
- **Requirement 2**: Must process video streams at minimum 30 frames per second with less than 100 ms latency.

Reinforcement Learning (PID) Control Network

- The control module will use the feature extracted data of the visual perception network and test both Reinforcement Learning (PPO) and PID control algorithms to figure out the best configuration for optimizing movement. The PPO algorithm will be trained on real-time feedback from the environment, allowing the robot to adapt its behavior based on its experiences [7]. The reinforcement learning model will be responsible for high-level decision-making, enabling the robot to navigate and adjust to dynamic environments autonomously. The PID controller might be useful in fine-tuning of actuator responses, ensuring stable and accurate movements, especially in the face of disturbances or unexpected changes in the environment. We will find out which model is better for the project (or use both).

- **Requirement1**: The PPO algorithm should be capable of running and optimizing robot actions at least once every 1000 ms, based on real-time sensor data.
- **Requirement2**: If we use PID controller, it must ensure that the robot maintains precise control over its movements with minimal overshoot and steady-state error, providing stability even in noisy environments.

Computing Node

- The computing node is the central data processing and decision-making unit, combining visual data and reinforcement learning results to produce precise remote control signals.
- Communicates signals externally to the RC signal sender through Universal Asynchronous Receiver/Transmitter (UART) protocol.
- **Requirement**: Must process combined signals and output UART control signals at baud rates of at least 115,200 bps.

2.2.3 RC Signal Sender

- This PCB board transmits processed control signals to the robot wirelessly through Pulse Position Modulation (PPM) protocol.
- Communicates via standard RF modulation at 2.4 GHz frequency.
- **Requirement**: Signal transmission latency less than 10 ms with reliable range exceeding 30 meters.

2.2.4 Control Unit

The control unit receives, decodes, amplifies, and delivers high-voltage signals for actuator control, enabling physical robot movements.

RC Signal Decoder

- Receives and interprets wireless signals from the RC Signal Sender.
- Outputs low-voltage analog control signals to the high-voltage amplifier.
- **Requirement**: Decode accuracy greater than 99%, latency under 5 ms.

High-voltage Amplifier

- Amplifies low-voltage signals (0–5 V) from the RC signal decoder to high-voltage signals up to 7 kV required by the actuators.
- Utilizes Wisman AMR10R20 high-voltage amplifier.

- **Requirement**: Voltage amplification accuracy ±1%, output ripple voltage less than 0.5%, and maximum output current safely limited.

Two-dimensional Bionic Jellyfish Robot (2D-BJR)

- Actuates movements based on high-voltage signals, mimicking natural jellyfish motion via electrohydraulic bent-to-straight actuators.
- **Requirement**: Actuator response time under 100 ms, capable of repetitive cyclic motion with stable and predictable trajectories.

2.3 Risk Analysis

Waterproofing failure prevention in the hydrogel jellyfish robot is necessary to prevent system failure by water entry. This section presents potential waterproofing threats and their impact analysis and mitigation.

2.3.1 Potential Risks

The primary risks in the waterproofing design of the hydrogel jellyfish robot include:

- **Seal Failure:** The electronic devices inside the robot must be sealed under tight protection. If the sealing structure (e.g., the hydrogel layer or thin-film encapsulation) fails due to mechanical fatigue or material aging, water can penetrate the system.
- **Encapsulation Defects:** During the course of fabrication, variations in thickness of hydrogel or microcracks can form, which would be sites of water entry and compromise the long-term stability of the robot.
- **Pressure-Induced Leakage:** As the robot operates at depths, increased hydrostatic pressure could challenge the integrity of the hydrogel encapsulation. If such pressures cannot be supported by the material, deformation or leakage would occur in the structure.
- **Material Degradation:** Prolonged exposure to water may lead to swelling, degradation, or mechanical damage to the hydrogel, which compromises its waterproofing capabilities and may ultimately lead to failure.

2.3.2 Risk Assessment

The identified risks are assessed based on their likelihood and potential impact, as shown in Table 1.

2.3.3 Mitigation Strategies

To minimize the impact of these risks, the following mitigation strategies are implemented:

Table 1: Risk Assessment for Waterproofing in Hydrogel Jellyfish Robot

Risk	**Likelihood**	**Impact**	**Overall Risk Level**
Seal Failure	Medium	High	High
Encapsulation Defects	Low	Medium	Medium
Pressure-Induced Leakage	Medium	High	High
Material Degradation	High	Medium	High

- **Encapsulation Optimization:** A multi-layer hydrogel architecture or composite coating is employed for maximizing encapsulation uniformity and reducing the probability of microscopic flaws.
- **Precision Thickness Control:** Advanced 3D printing or molding technique is employed in order to build uniform hydrogel layer thicknesses, removing hotspots and achieving better overall water resistance.
- **Pressure Adaptation Testing:** Laboratory experiments simulate various water depths to examine the pressure resistance of the hydrogel structure without leakage or failure.
- **Mechanical Durability Enhancement:** Tougher and more resilient hydrogel formulations are selected in order to withstand long-term degradation under underwater conditions.

By applying these mitigation strategies, the hydrogel jellyfish robot's waterproofing reliability is significantly improved, ensuring stable operation in aquatic environments.

3 Safety & Ethic

3.1 Ethical Considerations

3.1.1 Adherence to IEEE Code of Ethics

This project aligns with the IEEE Code of Ethics by:

- **Ensuring public safety and ethical research practices:** The soft underwater robot is designed to operate autonomously in underwater environments without harming underwater life or damaging the ecosystem.
- **Protecting data privacy and security:** The vision-based sensing system collects underwater images for navigation and target detection purposes only. All data processing follows ethical data collection and storage guidelines and we will prevent unauthorized access or misuse.
- **Maintaining integrity and accuracy:** The robot must operate reliably to avoid navigation errors that could lead to environmental disturbances or unintended consequences.

3.1.2 Ethical Concerns Related to This Project

Environmental Impact

- The project ensures that the soft robot fabricated from hydrogel is biodegradable or developed from eco-friendly materials for lesser pollution in aquatic bodies.
- The robot's operation will be closely monitored to prevent interference with marine life.

Privacy and Data Protection

- Underwater vision system takes real-time images for control and navigation. Ethical concerns include:
  - Prevention of unauthorized storage and dissemination of underwater images.
  - Refraining from using gathered data for purposes other than intended.
- Procedures such as data encryption and anonymization of gathered data will be implemented to safeguard privacy.

Testing and Safety in Natural Environments

- In case real-world marine testing is to be performed, relevant approvals from environmental regulatory authorities shall be sought.
- The robot will be extensively tested in lab environments prior to use in actual bodies of water to avoid the spread of alien substances and contaminants.

3.2 Safety Considerations

Our project follows **ECE 445 Safety Guidelines** to ensure a safe working environment for both developers and the ecosystem where the robot operates. Below, we address potential safety concerns related to **electrical, mechanical, and environmental safety**.

3.2.1 Electrical Safety

- The system is primarily comprised of **low-voltage electronics** for image processing and actuator control to minimize electrical hazards.
- The system is designed to be totally sealed to prevent water intrusion into electrical components.

3.2.2 Mechanical Safety

- The compliant robotic structure is **built from soft hydrogel material**, reducing the risk of damage from mechanical components.
- Moving parts, including actuators, will be subjected to controlled tests to give **safe force output** and prevent mechanical breakdown.

3.2.3 Environmental Safety

- The hydrogel-based materials used in the robot will be biodegradable or environmentally friendly, with no potential for long-term pollution in marine environments.
- The robot's locomotion system will be designed to **minimize disturbance to aquatic ecosystems**, avoiding unnecessary turbulence in the water or disturbance of marine life.

3.2.4 Safety Plan

- **Prevention:** Extensive software and hardware testing will be performed to determine potential failure points prior to actual-world deployment.
- **Fail-Safe Mechanisms:** Emergency stop facilities shall be incorporated into the robots to stop the robot movement in case of failure.
- **Protective Measures:** There will be built-in **power controls and automatic shutdown systems** to prevent damage from sudden errors.
- **Training & Documentation:** All members will receive safety processings and emergency protocol training before using the robot.

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