Modeling a Soft Modular Adaptive Robotic Technology (SMART) Arm

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Abstract — **This project proposal highlights the theory and simulated modeling behind an innovative solution to maximizing the adaptability and workspace of modern robotic arms. This proposal considers a modular approach to soft robotic arms to support a cost vs. benefit analysis of modularizing them.**

I. Introduction

Soft robotic arms present a promising avenue for enhancing the versatility of robotic systems, particularly in terms of increasing the reachable workspace. Unlike conventional robotic arms, which are limited by fixed joint lengths and a rigid structure, soft robotic arms can modify their joint locations and lengths dynamically. This adaptability allows for significantly expanded movement capabilities and a broader range of functions.

II. Current Landscape Analysis

Existing solutions for robotic arms pose many issues. The two leading branches for solutions in this landscape include rigid and soft robotic arms. Both offer benefits and drawbacks in various conditions, with soft robotic arms often being more adaptive than their rigid counterparts, but still not an optimal choice for many applications.

1. Rigid Robotic Arms

Rigid robotic systems, while effective in many industrial applications, face a range of inherent complications that limit their versatility. One significant issue is the constraint imposed by fixed link lengths and rigid components, which inherently restrict the workspace and adaptability of these robotic systems. Fixed joints and link lengths inhibit rigid robotic arms from reaching a desired end-effector position through various configurations, making it challenging to navigate complex or confined spaces.

Rigid robotic arms also struggle in unpredictable or dynamic environments. Since most rigid robotic arms are often designed for repetitive, pre-programmed tasks in controlled settings, sudden changes in task requirements or environmental conditions can lead to failures, collisions, or the inability to complete a task. The lack of flexibility also requires these robotic arms to be precisely calibrated and extensively programmed to perform even relatively simple tasks in a dynamic environment.

Additionally, rigid robotic systems often face issues related to safety when operating near humans. Their rigid structure and significant force potential pose a risk to human operators, necessitating additional safety measures such as barriers or complex control systems to prevent accidents. These safety concerns can limit the potential for direct human-robot collaboration, reducing their utility in environments where flexibility and safe human interaction are important.

2. Soft Robotic Arms

Most soft robotic arms offer advantages over their rigid counterparts in areas of workspace, versatility, adaptability, and safety. However, such systems still have drawbacks. Currently, many soft robotic arms have a limited number of modules as additional modules would increase the complexity of the system due to an increased number of actuation points.

Soft robotic joints often also yield a reduced range of motion and degrees of freedom (DOFs) in relation to their rigid counterparts. Coupled with the limited number of modules, soft robotic arms often have a limited workspace with reduced mobility and dexterity. This inhibits their ability to perform complex movements and fully capitalize on their flexibility.

Existing soft robotic arms' limited dexterity makes it difficult for them to handle intricate or precise operations. This directly impacts the complexity of tasks that these robots can perform, confining their functionality to simpler tasks rather than more sophisticated, multi-step operations. Addressing these limitations will require advancements not only in actuator technology but also in the fundamental design of soft robotic system architectures to enhance their range, dexterity, and task complexity.

III. Objective

The objective of this project is to develop a multi-modular soft-robotic arm model to establish a foundational framework that supports the development of various applications, including intravascular travel, extraterrestrial environment exploration, and highly dexterous arm functionality. This model aims to overcome the limitations of current soft robotic systems by allowing for modularity and variability at the joints, ultimately enabling advanced capabilities in challenging and diverse environments. By leveraging flexible materials and adaptive configurations, this study will demonstrate how soft robotics can overcome traditional limitations, ultimately paving the way for more efficient and versatile robotic applications.

IV. Potential Applications

By modularizing soft robotic bodies and arms, the system earns the potential to become versatile in its scope of functionality. While an arm with fewer modules reduces cost and complexity, one with more modules capitalizes on the complexity through additional potential for control, robustness and redundancy, resilience to physical damage, and an increased workspace. An increased number of modules would enhance flexibility, dexterity, and range of motion, making these systems suitable for a diverse set of applications.

One potential application is using the soft robotic arm as a manipulator, like a human arm, for tasks that require precision and flexibility. Soft robotic bodies could also be used in climbing applications, where their ability to adapt to complex surfaces would enable them to traverse challenging vertical environments. Additionally, soft robotic bodies could be utilized to explore complex or confined environments, such as caves, where traditional rigid robots would struggle to navigate.

The inherent ability of a soft robotic body to leverage an arm-like structure to traverse complex environments with obstacle handling opens the doors to a variety of applications where a dangerous environment poses threats to humans and thus favors a robot to investigate and explore the region first. Examples of applications include reconnaissance missions in the military sector, rescue operations where tight spaces are inaccessible to humans, and medical assistance through intravascular travel if the model were to be scaled down significantly.

Soft robotic bodies' potential ability to move through confined areas in an inchworm or snake-like manner makes them particularly valuable for scenarios where human intervention is not possible or favorable.

V. Simulation Framework Architecture

To model a modular soft robotic arm capable of the aforementioned applications, the team plans to develop a simulation framework for an arm to support dynamic link lengths, variable joint count, and variable joint stiffness.

From a first principles perspective, such an arm can be approached through beam-bending analysis. The proposed simulated framework design fixes the first node, which serves as the base of the arm while incorporating N number of nodes along the length of the arm, where each node represents a joint associated with a physical module, as seen in *Figure V.1*.

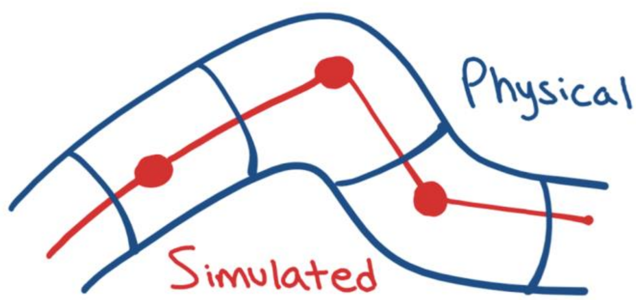

Figure V.1: Physical modules being simulated through nodes

At each module, or node, forces can be applied to induce bending about the joint associated with and within the module. A constant gravitational force will also be applied to each module.

A joint is introduced at a module if its stiffness is low enough to support reasonable bending. To achieve this, a stiffness vector that corresponds to each node will control the bending capabilities of each node individually. A chain of nodes with a large enough stiffness will act as a rigid link while a node with a low enough stiffness will promote bending, simulating the appearance of a joint.

Variable nodal stiffness affects the joint stiffness and effective link lengths and count. The number of joints can be reduced by stiffening other nodes to produce rigid links. Doing so allows for dynamic link lengths, variable joint count, and variable joint stiffness.

This adaptability allows the arm to navigate complex environments and reach areas that are otherwise difficult to access. By selectively stiffening certain nodes, the team can induce targeted bending to achieve desired positions. Once the required nodes are stiffened, the beam gains flexibility and the team can apply a force to actuate the arm towards a specific direction.

This framework allows for precise control over the arm's movement and the ability to adapt its configuration to suit various tasks. The combination of variable stiffness and targeted actuation provides a versatile approach to addressing the limitations of traditional robotic systems.

VI. Hypothetical Physical Model

The proposed simulation framework has the potential to materialize into a tangible and physical robotic arm in many ways. The simulated model was designed with physical feasibility in mind so that the model can come to fruition and offer a good fundamental understanding and representation of its physical counterpart.

The leading methods of stiffness variation and actuation can be incorporated with the proposed simulation model such the three key characteristics can be honored in the physical representation: dynamic link length, variable joint count, and variable joint stiffness.

1. *Methods of Stiffness Variation*

The variable stiffness that the proposed simulation aims to imitate can model a variety of leading methods currently implemented in industry, including thermally induced density variation, pneumatic pressure systems, granular jamming, fiber jamming, and layer jamming.

Stiffness can be achieved in a variety of formats to change if a module is to resemble a rigid link or a joint. By reducing the stiffness, the module becomes "softer" and promotes bending about itself, thus mimicking a joint. The fundamental difference behind stiffness variation methods is the medium and scale of observation for density control.

- *Thermally Induced Density Variation*: Materials whose density properties can be controlled through thermal variation effectively mimic granular jamming at a microscopic level, where the molecules get closer or farther apart.
- *Pneumatic Pressure Systems*: Air sacs or pouches can simulate rigidity when fully filled with air to produce structure in a module. When not pumped, the sac is nothing but the skin of the shell and is free to deform.
- *Granular Jamming*: In a way, many stiffness variation methods are forms of granular jamming. Macroscopic granular jamming is the packaging of some granular material, where finer materials offer higher dexterity, such as beads, sand, or other particulates. When a vacuum is created, the effective density of the module increases, and rigidity is simulated. When the vacuum is released, the grains are free to move in a fluid-like state.
- *Fiber Jamming*: Free fibers that slide against each other can produce rigidity when "jammed" within a vacuum pouch.
- *Layer Jamming*: An accordion-like architecture leverages planar layers to offer rigidity when "jammed" together in a vacuum pouch. When free, they slide against each other and allow for controlled fluid-like motion where fluidity is more present in some axes than others.

2. Methods of Actuation

Understanding realistic and implementable methods of actuation drives the design of the simulation model to better represent how forces are applied physically.

The team investigated various leading methods for actuation including pneumatic, hydraulic, dielectric elastomer, shape memory alloy/polymer, and cable actuation. These methods rely on the deformation of soft materials to generate motion and force.

- *Pneumatic Actuation*: Bioinspired models of muscles often leverage pneumatic systems to vary the pressure in air sacs or pouches in each module. The skeleton of the module is tied to the sacs such that when a sac shrinks or expands, it acts as a “muscle” and induces a moment in a direction corresponding to the location of the sac.
- *Hydraulic Actuation*: A more controlled form of pneumatic actuation where the fluid at play has some additional intrinsic density, unlike the gases used in pneumatic actuation. This allows for additional control and stiffness.
- *Dielectric Elastomer Actuation*: A voltage potential applied across electrodes induces an attractive force, thus compressing the elastomer sandwiched in between the electrodes. The Poisson’s ratio of the elastomer governs its expansion in the other axes, resulting in a net force being produced on objects tied to the elastomer.
- *Shape Memory Alloys and Polymers*: SMA and SMP actuators are programmable structures that respond to chemical, electrical, and thermal stimuli to deform into a preconfigured shape, thus inducing forces.
- *Cable Actuation*: A less complex method of applying forces at a module and offering actuation is by leveraging the tensile properties of cables connected directly to a module. Varying the tension induces a moment on the module in the direction of that cable.

VII. Framework Capabilities

By implementing variable nodal stiffness, variable nodal distances, and variable nodal count, the framework successfully represents a SMART Arm that is fully modularized, allowing researchers to model any arm based on the inputs they provide.

The force actuation method has been designed to resemble, as closely as possible, current 1-DOF actuation force methods such as those described in *Section VI.2*, and others resembling muscular contraction. In addition, the framework also allows forces to be applied in a 2-DOF manner to extend the modeling capabilities and potential for a researcher.

By allowing forces to be applied at each node, the SMART Arm simulation can depict the structure’s response to those forces. With the end-effector position being fixed at a desired location the researcher intends the physical arm to reach, the simulation outputs a configuration that would allow the Arm to reach that location. Due to the intrinsic nature of the Arm being soft and modular, there are infinite solutions to reach any given point in a workspace. A researcher can thus apply forces at nodes to further constrain the solution set. These forces can simulate an arm avoiding collisions with obstacles and the output solution by the framework will depict a configuration to reach a desired endpoint given the nodal force constraint. As seen in *Figure VII.1*, the arm can successfully reach an endpoint whilst using the least energy.

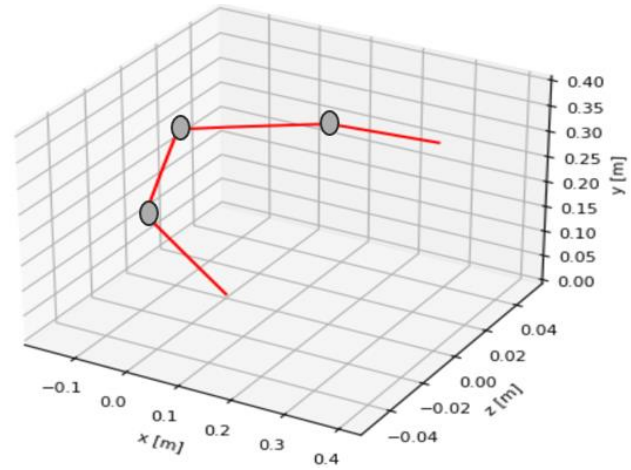

Figure VII.1: SMART Arm’s “induced” joints represented by gray ovals

By applying forces, the arm contorts its shape to avoid obstacles and still reach the same goal, as seen in *Figure VII.2*.

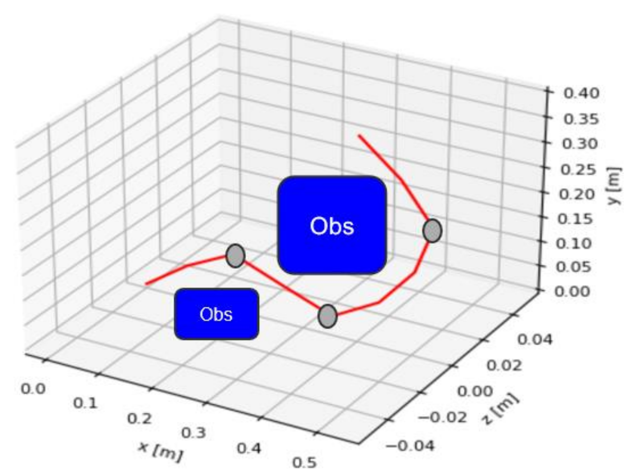

Figure VII.2: Arm can reach the endpoint while dodging obstacles in blue

Due to the Arm’s soft nature, it enjoys an enhanced workspace, beating the capabilities of a standard rigid robotic arm. As seen in *Figure VII.3*, the SMART Arm can reach points close to its base, points that most rigid arms cannot find in their workspace.

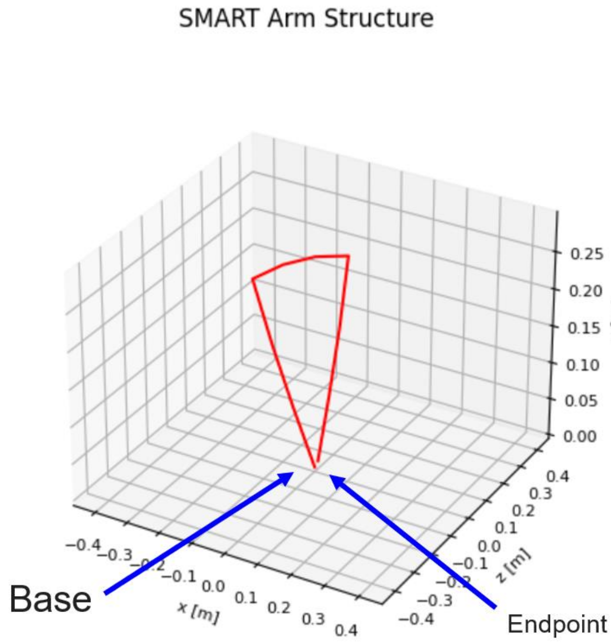

Figure VII.3: Reaching points typically outside of a rigid arm's workspace

The Arm's soft capabilities allow for it to take on the shape of a robot with any number of degrees of freedom as joints can be "induced" at will. This allows the Arm to reach desired positions in a more fluid and continuous manner, free of discrete bends as a rigid arm may require. As seen in *Figure VII.4*, the SMART Arm and a traditional rigid arm are compared in their capabilities to reach an endpoint. The nodal stiffnesses at the two "induced" joints are also seen next to the respective nodes on the SMART Arm.

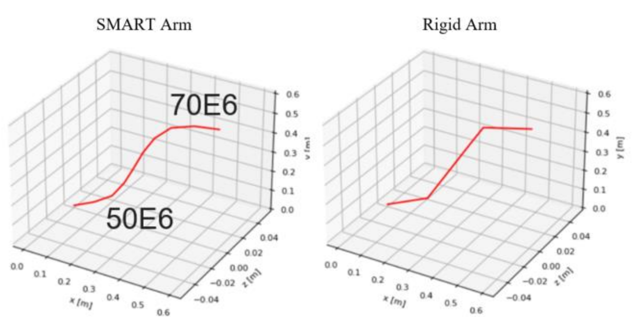

Figure VII.4: SMART Arm (left) and rigid arm (right) reaching an endpoint

While both are successful in reaching the endpoint, the SMART Arm is more fluid and can also reach a point that may require 3 DOF, while the 2 DOF rigid arm cannot undergo significant physical modification.

The robust framework is successful in its versatility. The software allows for varying mechanical properties of the robot arm including material density, cross-sectional area, link length, and number of modules (nodes). Varying these properties and setting a new goal position allowed for the creation of another SMART Arm configuration as seen below in *Figure VII.5*.

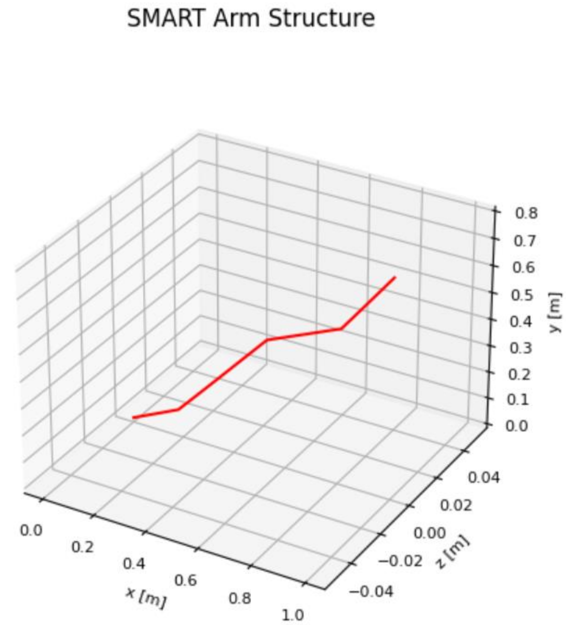

Figure VII.5: SMART Arm under various mechanical properties

VIII. Inverse Kinematics Solver

The SMART Arm has been developed as a versatile Inverse Kinematics (IK) solver, capable of dynamically adjusting its configuration to achieve a specific end-effector position. By optimizing the framework to act as a form of numerical-methods-based IK solver, the arm can compute the necessary joint angles to reach a desired endpoint, considering the robot's current configuration and the task constraints. This functionality is crucial for applications that require precise control and adaptability, such as robotic manipulation in unstructured environments.

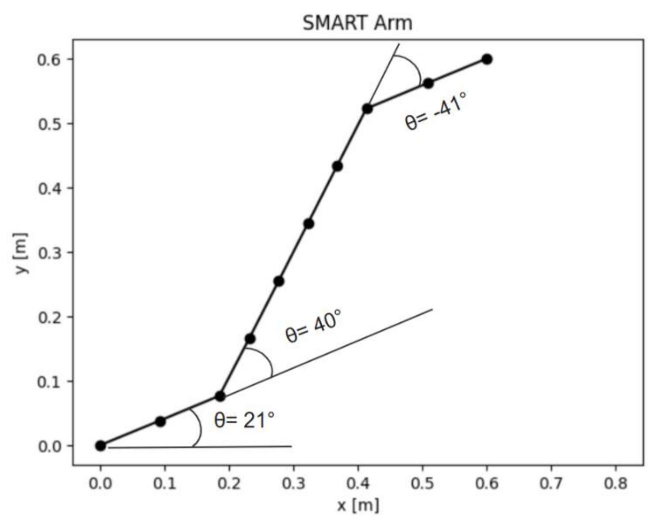

Figure VIII.1: Joint angles calculated for a specific configuration

The SMART Arm integrates manual force inputs, enabling the robot to dynamically adjust its motion and avoid obstacles. These inputs are used to calculate the arm's final configuration, from which the required joint angles are determined. This feature allows researchers to accurately discover the joint angles necessary to reach a certain goal position or endpoint given certain task constraint. The output joint angles can then be translated into corresponding actuator forces, capable of producing those angles, for a physical configuration developed by a researcher.

By tuning the stiffness of individual segments, the arm can exhibit both fluidity and rigidity, depending on the task at hand. The framework thus allows for quick and real-time adjustments to study how various inputs affect the kinematic characteristics of a soft-robotic system. Through sensitivity analysis, a characterization can be developed to relate the joint angles to the physical forces required to create those angles.

IX. Conclusion

This project proposes the development of a simulation framework capable of modeling a modular soft robotic arm with dynamic link lengths, variable joint counts, and variable joint stiffnesses. By leveraging stiffness variation and soft actuation, the framework offers a high-level representation of soft robotics with flexible, adaptable capabilities that far exceed the limitations of rigid robotic systems. This flexibility enables the arm to modify its structure in real-time, expanding its reach and versatility in a variety of complex environments.

The successful implementation of this framework creates numerous opportunities for future research and applications. The framework serves as a solid foundation for future research and development in robotic control, specifically soft robotic kinematics. Researchers can use this framework to conduct feasibility studies, selecting optimal configurations for soft robotic arms based on specific tasks. The framework's ability to model variable stiffness and joint dynamics enables efficient optimization to determine the best joint locations, counts, and stiffnesses for precise movement while minimizing energy loss, or any other cost, and ensuring obstacle avoidance when necessary. This adaptability makes the system particularly valuable in applications where precision and workspace maximization are critical.

The system's versatility and robust support for customization allow it to support and model a wide array of applications. Physical implementations of this model can revolutionize industries requiring high adaptability, such as space exploration, medical robotics, and hazardous environment navigation. The soft robotic arm's ability to dynamically adjust its structure enhances its safety, versatility, and workspace, offering superior performance in tight, confined spaces. With these capabilities, the framework opens new possibilities for soft robotics in a wide range of fields, ensuring more efficient robotic systems in the future.

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