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 conduct a feasibility vs. benefit analysis of modularizing soft robotic arms to study their ability.**

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. The proposed research aims to model the behavior of a soft robotic arm to understand and optimize its workspace and functional advantages. 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

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. The current actuators used in these systems are vacuum-induced pneumatic networks, which rely on large vacuum pumps and segmented vacuum chambers to achieve movement. However, the existing hardware presents significant drawbacks—if more nodes are to be added, more advanced hardware is needed that can provide the required actuation while minimizing space and mass. The current bulky and complex setup limits scalability, making it challenging to expand the capabilities of soft robotic arms without substantial improvements in actuator technology.

In addition to hardware limitations, current soft robotic arms face several other drawbacks. They have limited degrees of freedom (DOFs), which restricts their range of motion and reduces their ability to perform complex movements. The workspace of these robots is also limited, meaning they cannot reach as far or as flexibly as desired for a wide range of tasks. Furthermore, the dexterity of soft robotic arms is limited, making it difficult for them to handle intricate or precise operations. This limitation in dexterity 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 arhitectures 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.

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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 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, similar to 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 as a beam-bending problem. 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.

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 not only affects the joint stiffness but also the effective link lengths and joint 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, to some extent, 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 in reality.

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*: Bionispired 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 gasses 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. Conclusion

The team plans to study existing leading methods of stiffness variation and soft actuation to produce a simulation framework that can offer a high-level representation of a modular robotic arm with dynamic link lengths, variable joint count, and variable joint stiffnesses.

The successful development of this framework offers various implementation opportunities to researchers. One could leverage this framework to conduct a feasibility study to choose a soft robotic arm structure and the number of modules it needs to best complete the tasks at hand. Additionally, given an existing modular soft robotic arm, one could use an inverse kinematics algorithm in addition to the proposed framework to determine the optimal joint locations, count, and stiffnesses required to reach a position while minimizing cost factors. Cost factors may include power loss, speed, configuration strength, obstacle avoidance, and other considerations a researcher may have.

Applications of physical implementations of this model can offer numerous benefits including increased adaptability, safety, versatility in functionality, and workspace.

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