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Embodied Stability in a Minimally-Actuated Soft Robot for Autonomous Exploration

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Abstract—**Soft robots offer an opportunity to embed intelligence directly into morphology, potentially reducing the need for continuous feedback regulation. We present an autonomous, minimally actuated multi-stable soft robot for exploration in confined and cluttered environments. The robot is composed of a serial chain of multi-stable elastic elements whose energy landscape encodes discrete, passively stable configurations, enabling reversible shape transformation and shape retention without sustained actuation. A single mobile pneumatic actuator triggers transitions between these stable states, producing complex three-dimensional configurations with minimal hardware complexity.**

Autonomy is achieved through the integration of nonlinear hybrid modeling, visual pose estimation, and sampling-based motion planning within a ROS2 framework. Rather than regulating continuous deformation, computation in our system selects and sequences mechanically admissible state transitions, while structural multi-stability provides inherent stabilization and memory. Experimental results demonstrate closed-loop navigation in cluttered environments using this distributed balance between mechanics and control.

These results highlight an alternative organization of autonomy in soft robotics, where feedback and planning operate over discrete embodied states while low-level stability is handled by the material and structural design.

Index Terms—**Mechanical Intelligence, Metamaterial Robotics, Soft Robotics, Hyper-redundant Robots, Exploration Robots, Pose Estimation, Motion Planning**

I. INTRODUCTION

Wheeled and legged robots perform well on open surfaces, but search-and-rescue and confined-space robots must be slender to access voids and reconfigurable to navigate unpredictable obstacles in partially unknown terrain. Such demands require more than locomotion; they call for bodies capable of selectively changing and retaining shape.

Conventional robots for these tasks typically use multiple serial links, joints, and motors, which increase control complexity, hardware burden, weight, and cost. Their rigid structures also limit navigation in narrow passages or highly irregular terrain.

Soft and elastic robots alleviate some of these constraints, offering continuous motion, compliance, and lightweight, inexpensive fabrication. Yet they introduce kinematic and dynamic complexity. Elastic bodies deform asymmetrically under actuation but typically return to a single stable shape when actuation stops, restricting shape retention.

Vine robots achieve movement through growth, mimicking natural vines, using tip-localized strain, distributed actuation pouches, or concentrated tendon actuation.

Multistable structures, inspired by plants and animals, achieve shape fixation via mechanical means, implemented through origami or linked conical frusta. Models have been developed to predict their axisymmetric and antisymmetric behaviors. Recent work extends multistability to load-bearing robotic arms, integrating multistable units into inflatable architectures for shape retention in tension and bending, and sequentially actuated growing structures for pre-defined paths. Together, these advances provide a foundation for reconfigurable, multistable robots suitable for exploration and search-and-rescue.

Our hyper-redundant robot combines a multistable, reconfigurable structure with a single mobile actuator, enabling growth and reversible 3D steering. Actuation along any point of the body creates complex, reversible shapes with small radii of curvature, enhancing navigation through cluttered environments. Its plastic shell is puncture-resistant and insensitive to pressure loss. Integrated with motion planning and state estimation, this design enables autonomous navigation in complex, unstructured spaces with improved accuracy, robustness, and versatility compared to existing growing robots.

This architecture opens a path to a new class of long-range, reconfigurable, low-power growing robots, combining continuum adaptability with energy-efficient mechanical latching. By scaling the structural units and mobile actuator, the concept can span centimeter-scale medical devices to multi-meter field robots for search-and-rescue, inspection, or planetary exploration. The conduit-forming capability also suggests applications in lifeline delivery, transporting air, water, power, or communication to remote or hazardous sites.

II. MODELING, ESTIMATION, AND PLANNING

In order to capture the robot's behavior and support advanced control and planning, we developed dynamic models with progressively richer physical fidelity and computational complexity. A comprehensive nonlinear hybrid-dynamics framework incorporates elasticity, multi-stability, body and actuation forces, and contact effects. Finally, a

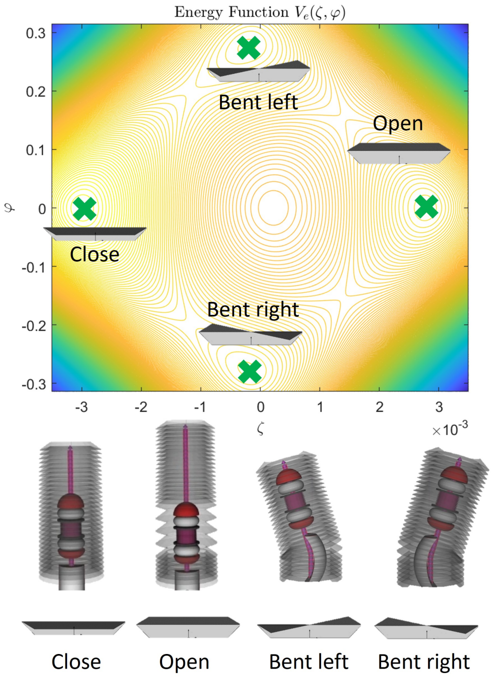

Fig. 1: The stable equilibrium states of each element according to the strain energy function (Top). Basic actions applied to multi-stable elements transforming between states (Bottom)

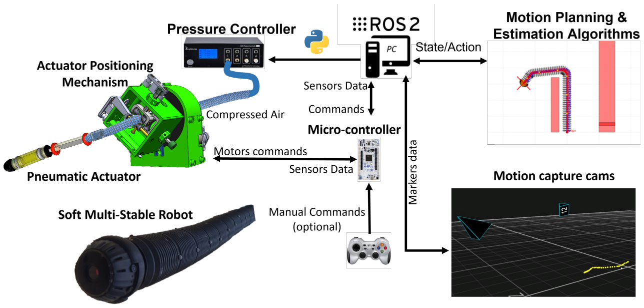

Fig. 2: Soft Multi-Stable Robotic platform's main blocks

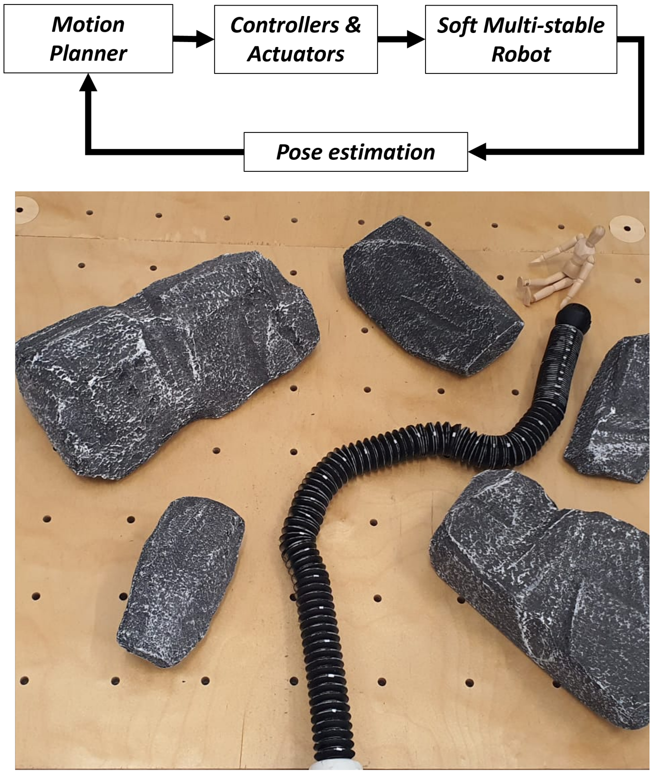

Fig. 3: Overview of the closed-loop scheme and robot demonstration.

custom Gazebo (physics engine) plug-in integrates these dynamics into ROS2 for hardware-compatible simulations.

Building on this foundation, we first estimated the robot's pose using an external motion capture system combined with filtering techniques to obtain a reliable configuration estimate. While effective, this approach required external infrastructure and limited operational flexibility in confined spaces and real-world environments. Nevertheless, it enabled controlled laboratory experiments and provided ground-truth pose information, laying the groundwork for the development and evaluation of on-board visual pose estimation methods. We therefore developed a novel visual shape estimation system to provide accurate online knowledge of the robot's configuration, which is critical for effective control and motion planning.

We then developed sampling-based motion planning frameworks tailored to the robot's kinematics and actuation model. The planner accounts for system-specific constraints and feasible motion primitives, enabling efficient exploration of the robot's high-dimensional configuration space while balancing computational cost and planning accuracy.

Finally, we built a complete experimental robotic platform, encompassing the mechanical structure, custom actuators capable of transforming the robot's states, and the corresponding driving and positioning mechanisms. Physical calibration experiments were conducted on the multi-stable elements to estimate stiffness, damping, and friction parameters, showing strong correspondence between model predictions and observed deformations. A ROS2-based control architecture integrates sensing, actuation, and motion-planning modules, enabling autonomous navigation experiments that validate the system's performance and demonstrate the seamless integration of modeling, perception, planning, and control.