Model-Based Method for Estimating the Workspace of Soft Manipulators

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***Abstract*— Soft manipulators have potential capabilities beyond those of their rigid counterparts. However, the performance of commonly used soft fluid-driven actuators is both pressure and state dependent, making it non-trivial to characterize the workspace of soft manipulators actuated by them. In this paper, we propose a model-based approach to estimate the workspace of a manipulator composed of combinations of soft fluid-driven actuators, and experimentally demonstrate its accuracy on a 2 DOF system.**

I. INTRODUCTION

Soft robotic manipulators have the potential to offer capabilities that go far beyond those of traditional rigid-bodied robots. Their compliant structure allows them to adapt their overall shape to navigate unstructured environments, to safely work alongside humans, to manipulate delicate goods, and to absorb impacts without damage [1].

Many soft robotic systems are actuated by fluid-driven soft actuators [2], [3], [4], [5] due to their ability to produce forces without imposing a rigid structure. This property makes them well suited to be combined in parallel to actuate soft manipulators, where the forces of the individual actuators are superimposed to generate a multidimensional spacial force at the end effector.

In a fluid-driven soft actuator, forces are created by a pressurized fluid pushing against the walls of a deformable chamber. As the geometry of this chamber changes, the relationship between fluid pressure and force also changes. This means that force is both pressure and state dependent, unlike a rigid fluid-driven actuator such as a piston.

The workspace of a soft manipulator, i.e. the set of points that can be reached by its end effector under admissable control inputs, is an important design consideration for many tasks, but it is non-trivial to compute due to the state dependent performance of soft actuators. In this work we propose and evaluate a model-based approach to estimating the workspace of soft manipulators founded on the notion of a *fluid Jacobian*, which linearly maps the geometrical deformation of a soft actuator, or of a system of actuators, to a change in their volume. Due to its linear structure, this model enables the efficient numerical calculation of the set of feasible end effector states. We demonstrate this approach by estimating the workspace of a 2DOF manipulator actuated by a parallel configuration of cylindrical soft actuators, known as Fiber-Reinforced Elastomeric Enclosures (FREEs), which are capable of exerting forces and moments about their central axis based on the angle at which their fiber reinforcements are wound [6], [7], [8], [9].

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II. THEORY

In a manipulator actuated by a combination of several fluid-driven actuators, the position of the end effector can be controlled by varying the internal pressures inside of the actuators. For a specific end effector position, we use a force balance model to solve for a corresponding set of actuator pressures. If such a set of pressures exists, that end effector position is included in the estimation of the workspace, otherwise it is excluded.

With the internal pressures of the actuators described by the vector $\vec{p}$ and the position and orientation of the end effector described by a state vector $\vec{x}$, the force $\vec{f}$ exerted at the end effector can be expressed in terms of $\vec{x}$ and $\vec{p}$ as

$$\vec{f}(\vec{x},\vec{p}) = J_x^T(\vec{x})\vec{p} + \vec{f}_{\text{elast}}(\vec{x}), \tag{1}$$

where $J_x = \frac{\partial \vec{V}}{\partial \vec{x}}$ is the *fluid Jacobian* which relates the change in volume of the actuators $(\vec{V})$ to the change in the state of the end effector $(\vec{x})$, and $\vec{f}_{\text{elast}}$ is the force due to the deformation of the elastomeric components of the actuators [10]. J_x is constructed from known geometric parameters, while $\vec{f}_{\text{elast}}$ is characterized via system identification

This expression enables us to determine the pressure required to actuate the system toward a desired equilibrium state, $\vec{x}_{\text{des}}$, by solving the following force balance equation for $\vec{p}$,

$$0 = J_x^T(\vec{x}_{\text{des}})\vec{p} + \vec{f}_{\text{elast}}(\vec{x}_{\text{des}}) + \vec{f}_{\text{load}}, \tag{2}$$

where $\vec{f}_{\text{load}}$ is the force imposed by external loads. Since (2) is a linear equation of $\vec{p}$, it is amenable to efficient numerical solving methods. In principle, (2) may have multiple solutions, so we restructure it as a quadratic program that minimizes the magnitude of the pressure input and has inequality constraints that ensure that the minimizer solves

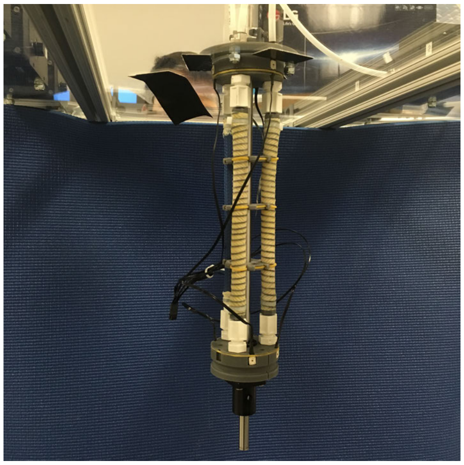

Fig. 1. System comprised of a parallel combination of three FREE actuators as described in section III. The end effector is constrained to 2DOF motion by a central rod and linear/rotary bearing.

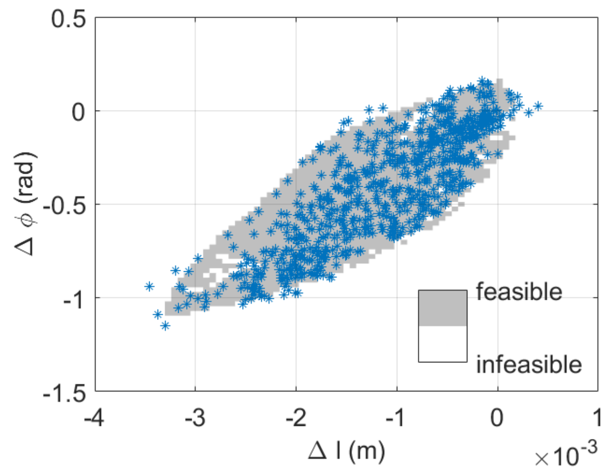

Fig. 2. The workspace calculated by the method described in section II in grey, overlayed with the set of achievable points found by sweeping over the entire range of admissible pressures and measuring end effector positions.

(2) to within a desired tolerance, tol,

$$\begin{aligned} \underset{\vec{p}}{\text{minimize}} \quad & \vec{p}^T Q \vec{p} \\ \text{subject to} \quad & \begin{bmatrix} J_x^T \\ -J_x^T \\ -\mathrm{I} \\ \mathrm{I} \end{bmatrix} \vec{p} \leq \begin{bmatrix} -\left(\vec{f}_{\text{elast}} + \vec{f}_{\text{load}}\right) + \text{tol} \\ \vec{f}_{\text{elast}} + \vec{f}_{\text{load}} + \text{tol} \\ -\vec{p}^{\text{min}} \\ \vec{p}^{\text{max}} \end{bmatrix} \end{aligned} \tag{3}$$

where Q is positive semi-definite (e.g. the identity matrix), and $\vec{p}^{\text{min/max}}$ are the vectors containing the minimum and maximum allowable pressure for each actuator.

If a desired end effector state $\vec{x}_{\text{des}}$ lies within a system's workspace, (3) will converge to the control pressure needed to achieve it, but if $\vec{x}_{\text{des}}$ lies outside the workspace (3) will fail to converge. Therefore, we can approximate the workspace by sampling over its state space and taking the set of all values of $\vec{x}$ such that (3) converges.

III. Experiment

Using our model-based control approach we constructed an estimate of the workspace of a linear/rotary 2 DOF system, which contained over 95% of measured states (see Fig. 2). The system, shown in Fig. 1 was comprised of a parallel configuration of three FREE actuators constrained to only linear and rotary displacements $(\Delta l, \Delta \phi)$. All three actuators had a nominal radius and length of 5 mm and 100 mm, respectively. In order to ensure that both clockwise and counterclockwise rotations would be attainable, a counterclockwise twisting FREE with reinforcing fibers wrapped at a 15° angle with respect to its central axis, and a clockwise twisting FREE with the fibers wrapped at a -15° angle were both used, as well as another counterclockwise twisting FREE with fibers wrapped at a 52.77° angle. Each of these FREEs is also of the contracting type, which is why the work-space lies almost entirely to the left of the origin in Fig. 2.

IV. Conclusion

This work demonstrates that the workspace of a manipulator actuated by soft FREE actuators can be numerically calculated via a model-based iterative approach. Such an approach could be used to inform the design and control of similarly actuated manipulators. Future work will investigate the efficacy of this method for other types of soft actuators and systems with more degrees of freedom.

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