Synchronization of Soft Pneumatic Actuators for Reliable Grasping

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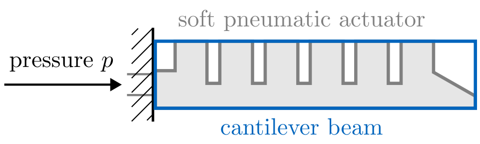
Abstract
Soft pneumatic actuators (SPAs) are often used in soft robotics due to their low cost and lightweight. However, their compliance and flexibility often lead to nonlinear dynamics, which complicates the design and control of soft robots. This paper deals with the synchronization of multiple SPAs in a soft gripper to ensure the grasping success rate. The synchronization is transformed into an optimization problem with constraints, where the optimal time-dependent input pressures of multiple actuators are determined. The optimized input leads to a synchronized movement of the SPAs and increases the reliability of gripping an object. An example of the synchronization of three different stiff SPAs is used to demonstrate the proposed approach.

1 Mechanical Model
The geometric shape of SPAs is characterized by a pattern of parallel ridges and grooves and contains multiple discrete chambers. The formulation of an analytical model for such a structure results in a complex mechanical model. In this paper, the shape of soft actuators is approximated by a cantilever beam to simplify the mechanical analysis; see Fig. 1(a). Soft robots are subject to large deformation and rotation, and the material exhibits a nonlinear behavior. The nonlinear stress-strain curve can be formulated by applying Ludwick's Law [2]. The governing equations are given by a nonlinear first-order differential system

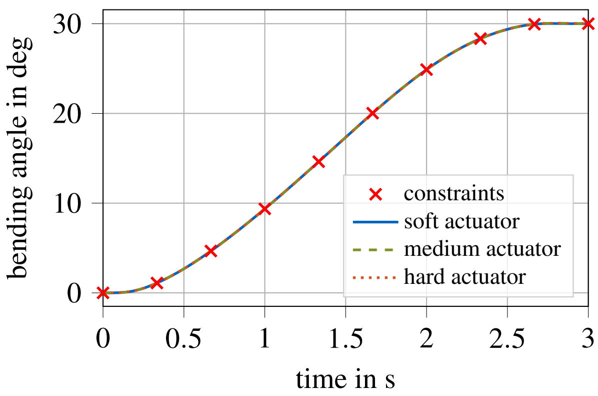
$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, p) = \begin{pmatrix} v \\ \frac{1}{m}(cp - dv - k\theta^n) \end{pmatrix}, \tag{1}$$

wherein the state variables are expressed by $\mathbf{x} = (\theta, v)^\mathsf{T}$ with the bending angle θ and its velocity v. The mechanical model consists of a mass m, a linear damping parameter d, and a linear spring parameter k. The nonlinear force term $k\theta^n$ results from Ludwick's Law, with the fractional power n. The system is driven by a time-dependent pressure p, including a constant factor c to map the pressure into the corresponding force.

2 Optimization Problem
Using N soft actuators to grasp an object requires a synchronization of all actuators to ensure a reliable process, especially if the actuators have different material parameters. This paper focuses on realizing synchronization by solving an optimization problem to determine the optimal input pressure for N actuators. The input pressure of a single actuator is formulated by a discrete spline parameterization as proposed in [1] with $p = \mathbf{C}\bar{\mathbf{p}}$, where $\mathbf{C}$ is an interpolation matrix and $\bar{\mathbf{p}}$ is a set of discretized grid nodes. The set of optimization variables consists of the discretized grid nodes regarding N soft actuators, i.e.,



(a)



(b)

Figure 1: (a) Soft pneumatic actuator approximated by a cantilever beam and (b) synchronized bending angles obtained by optimization including uniformly distributed constraints

$\mathbf{z}^\mathsf{T} = (\bar{\mathbf{p}}_1^\mathsf{T}, \dots, \bar{\mathbf{p}}_N^\mathsf{T})$. The nonlinear programming (NLP) problem can be formulated by

$$\min_{\mathbf{z}} J \tag{2}$$

s.t.

$$\mathbf{z}_{\min} \leq \mathbf{z} \leq \mathbf{z}_{\max} \tag{3}$$

$$\hat{\boldsymbol{\theta}}_1 - \hat{\boldsymbol{\theta}}_2 = \mathbf{0},\ \hat{\boldsymbol{\theta}}_2 - \hat{\boldsymbol{\theta}}_3 = \mathbf{0},\ \dots,\ \hat{\boldsymbol{\theta}}_{N-1} - \hat{\boldsymbol{\theta}}_N = \mathbf{0} \tag{4}$$

$$\theta_{1,\mathrm{f}} = \theta_{2,\mathrm{f}} = \dots = \theta_{N,\mathrm{f}} = \theta_\mathrm{d} \tag{5}$$

$$\dot{\mathbf{x}}_{1,\mathrm{f}} = \dot{\mathbf{x}}_{2,\mathrm{f}} = \dots = \dot{\mathbf{x}}_{N,\mathrm{f}} = \mathbf{0} \tag{6}$$

$$\dot{\mathbf{x}}_1 = \mathbf{f}(\mathbf{x}_1, p_1),\ \dot{\mathbf{x}}_2 = \mathbf{f}(\mathbf{x}_2, p_2),\ \dots,\ \dot{\mathbf{x}}_N = \mathbf{f}(\mathbf{x}_N, p_N) \tag{7}$$

with special attention to the constraint formulation. The equations in (4) imply the synchronization of the constraints on position level evaluated on a uniformly distributed time grid in the interval $t \in [0, t_\mathrm{f}]$. Equation (5) ensures a desired final value of the bending angles, and Eq. (6) forces the velocities and accelerations to zero at the final time. In this approach, the cost function in (2) optionally provides to minimize a certain performance measure of the system, e.g., the final time t_f. However, in this paper, we set the cost function to a constant value, and the optimization problem is dedicated to fulfilling the defined constraints. The NLP can be solved with classical direct optimization methods.

3 Example

In this paper, the synchronization is carried out with $N = 3$ soft actuators with different material parameters (soft, medium, hard). As an initial guess regarding the NLP, the assumption for all pressure grid nodes is set to $\bar{\mathbf{p}} = \mathbf{0}$. The optimization computes optimal pressures for the actuators, leading to synchronized bending angles despite different bending stiffnesses, and fulfills the final boundary conditions for the angles for perfect gripping conditions. Figure 1(b) shows the resulting perfectly synchronized bending angles and the desired boundary value at the final time.

4 Conclusions

This paper discusses the synchronization of bending angles of multiple SPAs in a soft gripper. The synchronization is crucial to grasp an object reliably with soft actuators. An NLP problem is formulated to obtain the synchronization. This approach can be easily adapted to a higher number of soft actuators.

Acknowledgments

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References

[1] Lichtenecker, D.; Rixen, D.; Eichmeir, P.; Nachbagauer, K.: On the use of adjoint gradients for time-optimal control problems regarding a discrete control parameterization. Multibody System Dynamics, Vol. 59, No. 3, pp. 313–334, 2023.

[2] Yang, W.T.; Stuart, H.; Kürkçü, B.; Tomizuka, M.: Nonlinear Parameter-Varying Modeling for Soft Pneumatic Actuators and Data-Driven Parameter Estimation. ArXiv preprint, 2023.