Piston-Driven Pneumatically-Actuated Soft Robots: modeling and backstepping control

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I. INTRODUCTION

Continuum soft robots are systems entirely made of deformable materials, so to resemble the trunk of an elephant [1]. Controlling these systems is challenging because of the infinite amount of Degrees of Freedom (DoFs), the multi-body dynamics, nonlinear potentials, underactuation, and the high degree of uncertainties [2]. Combining feedback controllers and simplified dynamical models can help taming this complexity and achieve good experimental performance [3], [4].

Accurate low-dimensional models of the continuum dynamics have been thoroughly investigated in recent years [5], [6], serving as the base for model-based controllers [7]. In comparison, researchers have devoted little or no attention to modeling the actuator dynamics, despite this being far from a negligible effect in practice, in particular for pneumatic actuation. The lack of models pairs with the scarcity of model-based dynamic controllers. Existing strategies only rarely reason on the actuators' dynamics, if not through simple heuristics. For example, [3], [8] use a combination of PID control and inversion of quasi-static linear approximations to compensate for the actuators' dynamics. This strategy may present clear limitations in terms of performance and stability assessment.

As model-based control of soft robots becomes a mature discipline, the need for general ways of dealing with actuators' dynamics becomes more pressing. In this work we deal with this challenge by follow a backstepping approach - which is an established strategy to deal with dynamical systems with triangular structure. A pneumatic model based on the ideal gas law is derived and the pneumatic actuation system is compensated in a quasi-static fashion in Falkenhahn et al. [9]. Recent work by Wang et al. [10] uses backstepping for control of a continuum soft bending arm. Although interesting, the work is limited because it targets a linear model of a single DoF. Similarily, Franco et al. [11] derive an energy-based control scheme for pneumatic manipulators while using a backstepping-based controller for comparison purposes. Both pieces of work focus on pneumatic actuation with valves and thus cannot be immediately applied to systems actuated with fluidic drive cylinders.

To conclude, this work targets the dynamic control of piston-driven pneumatic-actuated soft robots (see for example Fig. 2, 3). We provide general strategies for (i) augmenting existing dynamic models of soft robots through a description

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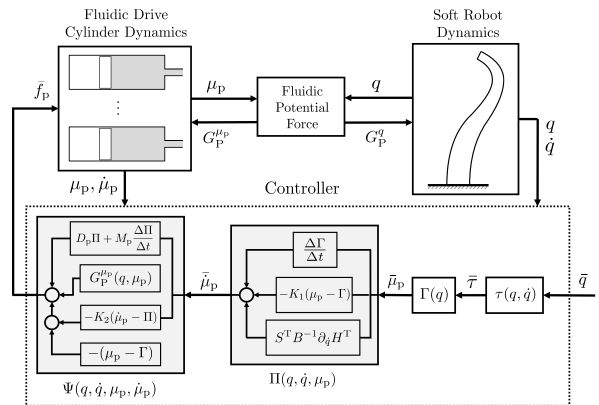

Fig. 1: Schematic block diagram of the proposed nonlinear backstepping controller for a pneumatically-actuated soft robot. The approach considers both the fluidic drive cylinder and the soft system dynamics. It is agnostic to the chosen soft system controller in configuration-space $\tau(q, \dot{q})$.

of pneumatic actuation, (ii) controlling these systems via model-based feedback. As an example, we specialize the model to planar soft robots satisfying the Piecewise Constant Curvature (PCC) assumption [3] including the proposal of a kinematic model for the air volume in the chambers, and the controller to the set-point regulation of configuration. In this context, we also propose a simplified, potential coupling-aware PID-like controller. We provide simulations showing the effectiveness of both strategies.

II. DYNAMIC MODEL

We consider the robot made by a sequence of n_S segments. Each segment is described with n_D configuration variables by using one of the many modeling techniques are being developed in the state of the art [5], [6]. We denote with $n_\mathrm{q} = n_\mathrm{S} n_\mathrm{D}$ the total number of configuration variables, which also represents the approximated DoFs of the soft arm. Although we show planar kinematic relations for the PCC-case in Figure 3 as an example, the dynamic model derived in this section is agnostic to the chosen kinematic approximation.

All of kinematic modelling techniques produce multi-body dynamics of the soft robot as follows [7]

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + K(q) + D(q,\dot{q}) + G_\mathrm{P}^\mathrm{q}(q,\mu_\mathrm{p}) = 0, \tag{1}$$

where $q \in \mathbb{R}^{n_\mathrm{q}}$ describes the configuration of the robot in generalized coordinates, $B(q) \in \mathbb{R}^{n_\mathrm{q} \times n_\mathrm{q}}$ the inertial matrix, $C(q,\dot{q}) \in \mathbb{R}^{n_\mathrm{q} \times n_\mathrm{q}}$ contains the Coriolis and Centrifugal forces and $G(q) \in \mathbb{R}^{n_\mathrm{q}}$ compensates for the gravitational effects. The elastic forces are captured in the matrix $K \in \mathbb{R}^{n_\mathrm{q}}$ and the natural damping is represented by $D(q,\dot{q}) \in \mathbb{R}^{n_\mathrm{q}}$.

Each segment is actuated through a set of n_{C} dedicated chambers. The dynamics of the piston when not interacting with the fluid can be easily written as being

$$M_{\mathrm{p}}\ddot{\mu}_{\mathrm{p}} + D_{\mathrm{p}}\dot{\mu}_{\mathrm{p}} + G_{\mathrm{P}}^{\mu_p} = f_{\mathrm{p}}, \quad (2)$$

where $\mu_{\mathrm{p}} \in \mathbb{R}^{n_{\mu_{\mathrm{p}}}}$ denoting the displacement of every piston from the zero-volume configuration, $M_{\mathrm{p}} \in \mathbb{R}^{n_{\mu_{\mathrm{p}}} \times n_{\mu_{\mathrm{p}}}}$ the mass matrix of the piston system, $G_{\mathrm{P}}^{\mu_p} \in \mathbb{R}^{n_{\mu_{\mathrm{p}}}}$ describing the conservative force caused by the compressed fluid acting on the pistons, and $D_{\mathrm{p}} \in \mathbb{R}^{n_{\mu_{\mathrm{p}}} \times n_{\mu_{\mathrm{p}}}}$ the damping matrix of the piston system.

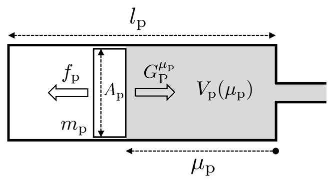

Fig. 2: Fluidic drive cylinder parameters for a piston of mass m_{p}, length l_{p} and cross-sectional area A_{p}: f_{p} describes the actuation force while $G_{\mathrm{P}}^{\mu_{\mathrm{p}}}$ is the conservative force applied by the compressed fluid on the cylinder. μ_{p} represents the actuators' state variable.

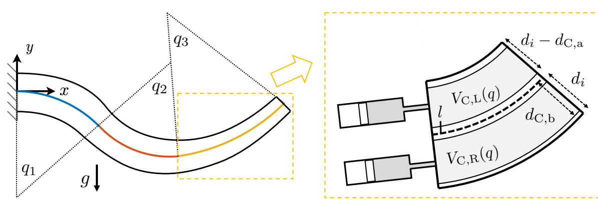

Fig. 3: Shape regulation under PCC approximation - **Left:** A planar soft robot consisting of three segments each modelled to have constant curvature **Right:** Model parameters for fluidic volume in soft segment chambers. Each chamber is actuated independently by a fluidic drive cylinder connected through tubing.

In first approximation, we model the compressible fluid (typically air) as an ideal gas. Furthermore, we consider the process to be isothermal and that no exchange of fluid with the external world is happening. The overall volume of the fluid can be evaluated as

$$V(q, \mu_{\mathrm{p}}) = V_{\mathrm{C}}(q) + V_{\mathrm{p}}(\mu_{\mathrm{p}}) = V_{\mathrm{C}}(q) + A_{\mathrm{p}}\mu_{\mathrm{p}}, \quad (3)$$

where $V(q, \mu_{\mathrm{p}}) \in \mathbb{R}^{n_{\mu_{\mathrm{p}}}}$ describes the total volume of fluid stored in the system, $V_{\mathrm{C}}(q) \in \mathbb{R}^{n_{\mu_{\mathrm{p}}}}$ the volume of fluid in each chamber and $V_{\mathrm{p}}(q) \in \mathbb{R}^{n_{\mathrm{S}} n_{\mathrm{p}}}$ the volume in the piston with $A_{\mathrm{p}} \in \mathbb{R}^{n_{\mu_{\mathrm{p}}}}$ the cross-sectional area of every piston. While will present an example of analytical derivation of $V_{\mathrm{C}}(q)$ in this work, for now we consider it known.

The total energy stored in the system due to fluid compression is

$$\mathcal{U}_{\mathrm{fluid}}(q, \mu_{\mathrm{p}}) = \sum_{j=1}^{n_{\mu_{\mathrm{p}}}} \int_{V_{j,0}}^{V_j(q_i, \mu_{\mathrm{p},j})} -(p_j(\nu) - p_{\mathrm{atm}})\,\mathrm{d}\nu \quad (4)$$

The force exerted on the ith segment of the robot by the fluid is

$$G_{\mathrm{P},i}^{\mathrm{q}}(q_i, \mu_{\mathrm{p},j}) = -\partial_{q_i} V_{C,j}\left(p_j(q_i, \mu_{\mathrm{p},j}) - p_{\mathrm{atm}}\right). \quad (5)$$

Similarly, the force applied on jth piston by the fluid is

$$G_{\mathrm{P},j}^{\mu_{\mathrm{p}}}(q_i, \mu_{\mathrm{p},j}) = -A_{\mathrm{p},j}\left(p_j(q_i, \mu_{\mathrm{p},j}) - p_{\mathrm{atm}}\right). \quad (6)$$

III. Backstepping Control of Piston-Driven Pneumatically-Actuated Soft Robots

This section discusses the main contribution of this paper, a backstepping-based approach to generalize controllers $\Gamma(q, \dot{q})$ designed in the directly actuated case, to systems that can be modeled through (1) and (2). We suppose that we have access to $\Gamma(q, \dot{q})$ controlling the piston position μ_{p}. Next, we perform backstepping twice to the controllers of the piston velocity $\dot{\mu}_{\mathrm{p}}$ and the piston actuation force f_{p} and prove the stability of each controller with Lyapunov arguments. The derived model-based control approach assumes that all model parameters are known, and all states are measurable (namely the configuration q, its time derivative $\dot{q}$, the piston position μ_{p} and the piston velocity $\dot{\mu}_{\mathrm{p}}$), and that there are no disturbances or model uncertainties.

We introduce the closed-loop feedback controllers

$$\begin{aligned} f_{\mathrm{p}} &= \Psi = G_{\mathrm{P}}^{\mu_{\mathrm{p}}} + D_{\mathrm{p}}\Pi + M_{\mathrm{p}}\dot{\Pi} - K_2(\dot{\mu}_{\mathrm{p}} - \Pi) - (\mu_{\mathrm{p}} - \Gamma), \\ \Pi &= \dot{\Gamma} - K_1(\mu_{\mathrm{p}} - \Gamma) + S^{\mathrm{T}}(q, \mu_{\mathrm{p}}, \Gamma)B^{-1}(q)\partial_{\dot{q}} H^{\mathrm{T}}, \end{aligned} \quad (7)$$

and prove their convergence to a desired trajectory $\bar{q}(t)$, $\forall(q(0), \dot{q}(0)) \in \mathbb{R}^{2n_{\mathrm{q}}}$ in this paper with Lyapunov arguments, where we assume that the convergence of $\Gamma(q, \dot{q})$ for the soft system is already proven through the Lyapunov function $H(q, \dot{q})$

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