Towards Safer Collaboration - Closing the Loop on Position and Stiffness of Soft Articulated Robots

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***Abstract*—With the expansion of collaborative robots, the necessity to ensure safe interaction between humans and robots has also arisen. Herein, a paradigm is proposed that considers closed loop control of both position and stiffness in soft articulated robots. More precisely, we propose and discuss a methodology entailing results on decoupled adaptive control, where the information about the current stiffness is obtained via input-state estimators.**

I. INTRODUCTION

The safety of a human-robot collaboration can be evaluated by leaning on the danger index defined in [1]. It is suggested that the index should be a product of several factors, such as distance between robot and human, then their relative velocity, and finally the inertia and stiffness of a robot. In this work, the spotlight is on the enhancement of safety by estimating and regulating stiffness in robot joints, motivated by the development of articulated robots with intrinsic compliance and variable stiffness actuation (VSA).

The first challenge arises from the fact that stiffness is not a measurable quantity. Hence, to obtain an accurate model of stiffness, one can either perform extensive identification of the system or rely on the manufacturer's data. In both cases, however, the model is only initially reliable due to the temperature drifts and impact forces that affect the elastic elements in robot joints. This has motivated the development of online stiffness estimators [2], [3]. Nonetheless, there have not been results with the estimators being used in the closed loop stiffness control yet.

This comes as a result of stiffness being usually set in an open loop, even though closed-loop control has several benefits, as it provides feedback on both the position and stiffness, as well as information about the dynamical relation between the actuation system and joints. Furthermore, if decoupling position and stiffness control is obtained, soft robots are able to achieve high position accuracy, while simultaneously realizing a range of possible joint stiffness. The foundation for the decoupled position and stiffness control was set within the framework of the feedback linearization approach [4], and recently equipped with practical implementability through the adaptive control method [5].

Within this setting, the aim is to briefly present a paradigm of closing the loop on position and stiffness as shown in Fig. 1, such that the following is achieved:

- the information on stiffness is obtained via estimator;
- decoupled closed loop control of position and stiffness;
- robust asymptotic tracking with a complete lack of knowledge of inertial and geometric parameters;
- robust asymptotic tracking with a complete lack of knowledge of the construction-dependent parameters of the actuation model;
- practical implementability via the use of lower-order derivatives of joint position and stiffness estimates.

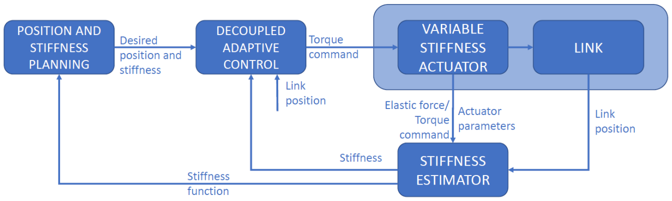

Fig. 1. Depiction of the proposed paradigm.

II. STIFFNESS ESTIMATION

Since stiffness is not a measurable quantity, we must rely either on a link-side non-invasive stiffness estimator, such as the one proposed by [6], or an actuator-side invasive approach based on input-state observers [3]. The first type of solution requires the knowledge of robot dynamic parameters, such as mass, inertia, and length of links, while the second one leans on the actuator parameters (in the case of electrical VSAs, information on motor inertia and damping is necessary). Furthermore, these two approaches have different sensor requirements. In the former case, the elastic force has to be measured, while the latter case requires the knowledge of the commanded torques to the motors.

Thus, the decision on choosing the convenient approach depends on two factors: accessibility of information from sensor data and the accuracy of parameters knowledge. To this respect, since the knowledge of actuator parameters is often more accurate compared to one of robot dynamics, the conclusion is that the invasive stiffness estimator can be used in the loop with the adaptive controller, which is described in the following section.

III. DECOUPLED ADAPTIVE CONTROL

The key idea enabling the development of decoupled position and stiffness control for soft articulated robots is to

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consider the full robot's dynamics [4], which has the form:

$$\begin{aligned} & B(q)\,\ddot q + C(q,\dot q)\,\dot q + G(q) = \tau - \tau_{\text{ext}}\,, \\ & \chi(\tau, q, \dot q, \theta, \dot\theta, u, \dot u) = 0\,, \\ & \dot S = -\frac{d}{dt}\frac{\partial \tau}{\partial q}\,, \end{aligned} \tag{1}$$

where q is the robot configuration vector, S robot joint stiffness, and τ_{ext} is an external torque. Function χ in the above expression describes the actuation dynamics and consists of an implicit possibly differential equation, describing the generation of the elastic torque τ as a function of the actuator's internal input u and variables θ.

In the case of pneumatically-driven robots with so-called McKibben artificial muscles in antagonistic configuration, where every joint is actuated by a pair of muscles, the elastic torque vector τ is generated via a static map. In this case, the second and third equation of the model become

$$\begin{aligned} \tau &= K\,\Phi(q)\,u\,, \\ \dot S &= -K\,\dot\Phi_q(q)\,u - K\,\Phi_q(q)\,\dot u\,. \end{aligned} \tag{2}$$

where u is the commanded pressure in the McKibben muscles. For electrically-driven robots, the elastic torque τ is the output of the of the actuator subsystem, which is described, along with the stiffness dynamics, as follows:

$$\begin{aligned} & \tau = f_\tau(q,\theta)\,, \\ & B_\theta\,\ddot\theta + C_\theta\,\dot\theta = u\,, \\ & \dot S = f_S(q,\dot q,\theta,\dot\theta)\,, \end{aligned} \tag{3}$$

where u is the motor torque vector, f_τ is a function depending on the joint deflection, and f_S is also depending on the derivative of joint deflection.

Under the hypothesis that all system parameters are known, in the case of flexible robots with electrically-driven actuators, decoupled and simultaneous control of joint position and stiffness can be obtained via the approach presented in [4]. When the system parameters are uncertain or even completely unknown, but the objective is to control only the robot's joint position, the solution in [7] is handy. If, as in the present case, both position and stiffness need to be independently and accurately tracked, the system's adaptability skill must be extended to both sets of variables. To this purpose, as it is known, the system parameters appearing in the first equation of the robot's full dynamics in (1) are *linearly separable*. Such equation can be written as the product of a regressor function matrix Y and the vector of unknown parameters π, i.e. $Y(q,\dot q,\ddot q)\,\pi = \tau - \tau_{\text{ext}}$.

Leveraging on this property, the following results can be proven for pneumatically-driven robots [5]:

Theorem 1: A soft robot with dynamics as in (1), such that matrix $K^{-1}B(q)$ is positive definite for all q, can be controlled so as to simultaneously track desired position and stiffness signals, q_d and S_d, by an adaptive controller of the form:

$$\begin{aligned} \dot\nu &= f_\nu(q,\dot q,\dot q_d,\ddot q_d,S,S_d)\,, \\ \dot{\hat\Pi} &= K_\pi\,Y_*^T(q,\dot q,q_d,\dot q_d,\ddot q_d)\,\sigma\,, \\ u &= \Phi(q)^\dagger\left(Y_*(q,\dot q,\dot q_d,\ddot q_d)\,\hat\Pi + K_d\,\sigma\right) + \Phi(q)^\perp\nu\,, \end{aligned}$$

where $\nu \in \mathbb{R}^n$ is an internal controller state, $\hat\Pi \in \mathbb{R}^\kappa$ is the estimated parameter vector, K_d, K_S, and K_π are suitable positive definite matrices, Y_* is a regressor matrix for the robot's position dynamics, $\Phi(q)^\dagger$ and $\Phi(q)^\perp$ are the pseudo-inverse and a basis of null column-space of $\Phi(q)$, respectively. Fig. 2 shows the results obtained by applying this method to the GioSte robot. It highlights the benefits of the simultaneous position-stiffness closed-loop approach, compared to solutions where only the joint position is fed back.

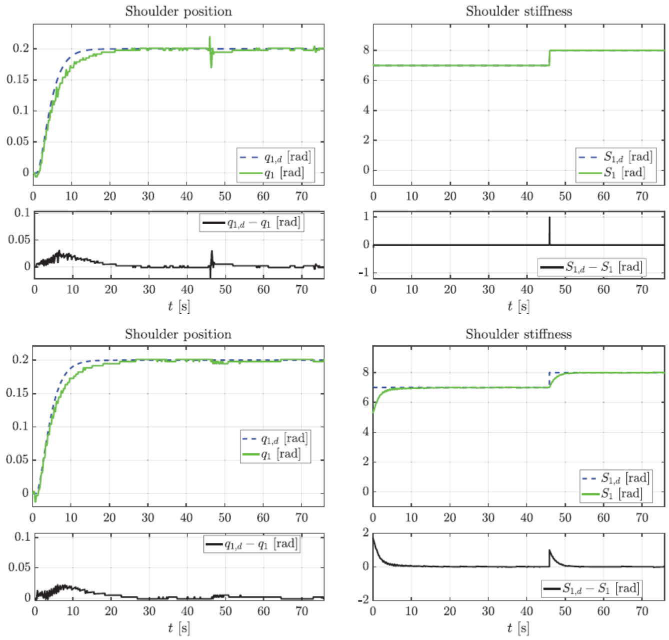

Fig. 2. Experimental result on a pneumatic soft articulated robot. Top row shows the performance when stiffness is controlled in open loop, while bottom row depicts system behavior when both position and stiffness are controlled in closed loop.

IV. CONCLUSION

In this paper, a procedure for controlling soft articulated robots has been proposed. Considering that stiffness plays an important role in securing the safe human-robot interaction, a decoupled adaptive control is used to provide simultaneous tracking of position and stiffness in the closed loop.

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