Kernel-based Nonlinear Adaptive Control of Stiffness and Position for Soft Robots Actuators

Maja Trumic, Kosta Jovanovic, Adriano Fagiolini

Abstract—**Soft robots have been extensively studied for their ability to provide both good performance and safe human-robot interaction. This paper describes a novel approach for soft robot joint position and stiffness control. The work is focused on robot arms actuated by the pneumatic antagonistic pair of actuators, so-called McKibben artificial muscles. The dynamic parameters of the system are considered imprecise. Nonlinear adaptive control is used for the control of the joint position and stiffness, while the decoupling of the control is achieved by using kernel. Simulation results are provided to verify the performance of the algorithm prior to its application on available laboratory setups.**

Index Terms—**Adaptive control, soft robots, variable stiffness actuator, pneumatic actuator, kernel, McKibben muscles, antagonistic drive.**

I. Introduction

To have a highly efficient assembly process of complex products, advantages of both human and robot need to be used. The worker's dexterity and robot's strength enable the optimized production, which is achieved if they collaborate in the shared environment [1], [2], [3]. Concerning the safety of humans in the vicinity of typical heavy industrial robot, soft robots with intrinsic compliance have been developed as an alternative to stiff ones. Soft robots also found their application in the gait rehabilitation processes and surgical procedures thanks to the natural behavior. The compliancy of robot may be achieved either by reducing the robot's inertia or by introducing compliant joints. In [4] and [5] was addressed that robots with variable stiffness actuators (VSA) may have multiple advantages over rigid robots, as improved robustness to the external disturbance and increased load-to-weight ratio. However, it is a challenging task to accurately track the trajectory with the compliant robot due to its highly nonlinear behavior. Therefore, compromise between safe interaction and good performance needs to be accomplished by controlling the stiffness in a way that robot is stiffer when accuracy is important and more compliant when interacting within the anthropic environment.

McKibben pneumatically driven artificial muscles, developed back in 1950s [6], are characterized by flexibility, lightweight and high force-to-weight ratio. The design of muscles is inspired by human arm biceps and triceps mechanism. The simplified nonlinear model of McKibben muscles, obtained in the work of Chou-Hannaford [7], assumes that the pneumatic artificial muscle is represented by an elastic spring with nonlinear quadratic characteristic. The nonlinear relation between tension force and elongation permits McKibben muscles to obtain variable stiffness.

There are several techniques used for the control of robots with elastic joints. Accurate modeling of robot dynamics has been mostly a precondition in order to obtain good performance. In [8], [9] the feedback linearization technique is applied to the control of VSA assuming perfect knowledge of dynamic parameters, which is de facto unfeasible. The backstepping technique is experimentaly validated on electrically driven VSA [10], however it is still not immune to the parametric uncertainity.

The pioneer work in the adaptive control of single flexible joint position [11] has been followed by the [12] where besides position joint stiffness is controlled in open loop. As concluded in [13], the feedforward action combined with low-gain feedback control gives better soft robot performance compared to the ordinary feedback control.

In this paper a nonlinear adaptive control [14] that has both feedforward and feedback term is used for independent and simultaneous joint position and stiffness control is presented. Compared to [12], in this paper stiffness is controlled in closed loop. Taking into account that stiffness is not measurable, scheme for estimation, as e.g. the one proposed in [15], has to be applied. Soft robot arm actuated by antagonistically coupled McKibben artificial muscles is used for algorithm proof of concept. Its practical implementation is expected on both pneumatic and electrical compliant antagonistic actuators. The dynamic model of the multi degree-of-freedom (DoF) soft robot arm actuated by McKibben muscles is given in the section II. The control law is described in section III. In section IV simulation results of adaptive control applied to a two-DoF soft arm actuated by antagonistic pair of McKibben muscles, are presented.

II. Dynamic model

Each joint in soft robot arm is antagonistically actuated by two McKibben pneumatic artifical muscles. The dynamic model of *n* DoF soft robot arm, where the indirectly actuated joints position is denoted with $q \in \mathbb{R}^n$, can be written as

$$B_{nxn}(q)\ddot{q} + C_{nxn}(q,\dot{q})\dot{q} + G_{nx1} - \tau_{nx1} = \tau_{ext} \qquad (1)$$

where *B(q)* is the inertial matrix, *C* contains Coriolis and centrifugal, assumed to depend only on the joint position and

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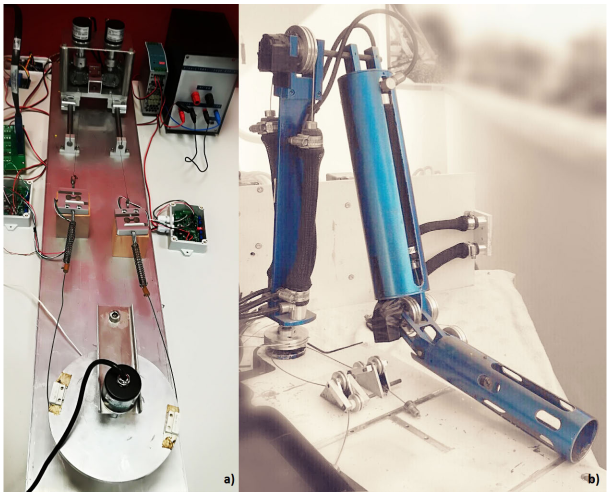

Fig. 1: Laboratory setups for antagonistic compliant actuators: (a) Actuator driven by electrical drives and nonlinear extension springs at University of Belgrade (b) Actuator driven by pneumatic McKibben drives at University of Palermo at courtesy of University of Pisa;

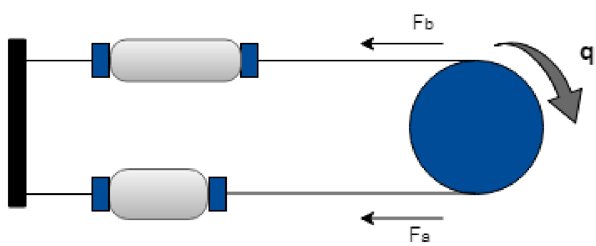

Fig. 2: The McKibben artifical muscle scheme

velocity, G presents gravitational forces and τ is the elastic torque acting on the joint. The external influence on robot arm denoted as τ_{ext} is considered to be zero. The McKibben muscles dynamics is neglected. Antagonistic pair of McKibben muscles scheme is presented in Fig. 2. If Chou-Hannaford model is used, elastic (tension) forces for each i-th joint are

$$\begin{aligned} F_i^a &= K_i^a(l_{ia}^2 - l_{iamin}^2)P_i^a \\ F_i^b &= K_i^b(l_{ib}^2 - l_{ibmin}^2)P_i^b \end{aligned} \tag{2}$$

where a and b denote the actuator in the antagonistic configuration, K_i is the construction parameter assumed to be the same for both antagonistic muscles, l is the muscle extension, P_i is the inflated pressure in the muscle, l_{max} and l_{min} are the maximum and minimum length of the muscle, respectively. Elongation of antagonistic muscles is expressed as

$$\begin{aligned} l_{ia} &= l_{max} - qR \\ l_{ib} &= l_{min} + qR \end{aligned} \tag{3}$$

Each joint torque can be defined as in the following

$$\tau_i = (F_i^a - F_i^b)R_i \tag{4}$$

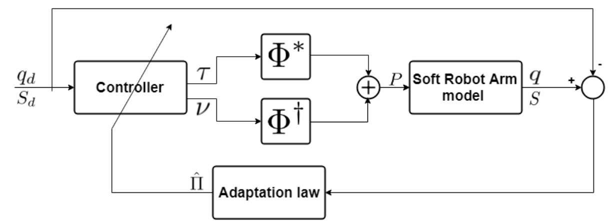

Fig. 3: The diagram of adaptive control

where R is the radius of the pulley. Substituting equations for tension forces 2 in 4, leads to the torque of the form

$$\tau_i = K_i R_i(\phi_i^a P_i^a - \phi_i^b P_i^b) \tag{5}$$

with $\phi_i^a = l_{ia}^2 - l_{iamin}^2$, $\phi_i^b = l_{ib}^2 - l_{ibmin}^2$, and $P_i = \begin{bmatrix} P_i^a & P_i^b \end{bmatrix}$. The matrix $\Phi_i = \begin{bmatrix} \phi_i^a & \phi_i^b \end{bmatrix}$, that maps torque to pressures inflated in muscles, is called actuator matrix.

Recall from [12], that the stiffness for the i-th joint can be approximated as

$$S_i = -\frac{\mathrm{d}\tau_i}{\mathrm{d}q} = -K_i R_i \left[\frac{\mathrm{d}\phi_i^a}{\mathrm{d}q}P_i^a - \frac{\mathrm{d}\phi_i^b}{\mathrm{d}q}P_i^b\right] \tag{6}$$

assuming that $\frac{\mathrm{d}P_i}{\mathrm{d}q}$ is equal to zero. Therefore, the elastic torque and stiffness are connected to pressures in a way that the independent control of joint position and stiffness is possible

$$\begin{bmatrix} \tau_i \\ S_i \end{bmatrix} = K_i R_i \begin{bmatrix} \phi_i^a & -\phi_i^b \\ -\frac{\mathrm{d}\phi_i^a}{\mathrm{d}q} & \frac{\mathrm{d}\phi_i^b}{\mathrm{d}q} \end{bmatrix} \begin{bmatrix} P_i^a \\ P_i^b \end{bmatrix}. \tag{7}$$

To achieve the dynamic regulation of stiffness, its first derivative is calculated as

$$\dot{S} = -\frac{\mathrm{d}\dot{\Phi}}{\mathrm{d}q}P - \frac{\mathrm{d}\Phi}{\mathrm{d}q}\dot{P} \tag{8}$$

The generalized form for multi DoF robot arm is given by:

$$\begin{bmatrix} \tau \\ S \end{bmatrix} = K \begin{bmatrix} \Phi \\ -\frac{\mathrm{d}\Phi}{\mathrm{d}q} \end{bmatrix} P \tag{9}$$

with vectors $P = \begin{bmatrix} P_1^a & P_1^b & \dots & P_n^a & P_n^b \end{bmatrix}^T$, $\tau = \begin{bmatrix} \tau_1 & \tau_2 & \dots & \tau_n \end{bmatrix}^T$, $S = \begin{bmatrix} S_1 & S_2 & \dots & S_n \end{bmatrix}^T$, $K = \begin{bmatrix} K_1 R_1 & K_2 R_2 & \dots & K_n R_n \end{bmatrix}^T$ and

$$\begin{bmatrix} \Phi \\ \frac{\mathrm{d}\Phi}{\mathrm{d}q} \end{bmatrix} = \begin{bmatrix} \phi_{11} & -\phi_{12} & \dots & 0 & 0 \\ 0 & 0 & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \phi_{n1} & -\phi_{n2} \\ -\frac{\mathrm{d}\phi_{11}}{\mathrm{d}q} & \frac{\mathrm{d}\phi_{12}}{\mathrm{d}q} & \dots & 0 & 0 \\ 0 & 0 & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & -\frac{\mathrm{d}\phi_{n1}}{\mathrm{d}q} & \frac{\mathrm{d}\phi_{n2}}{\mathrm{d}q} \end{bmatrix}. \tag{10}$$

III. Adaptive control and kernel-based decoupling

A nonlinear adaptive control law based on the Model Reference Adaptive Control scheme is used as in Fig. 3. The structure of the dynamic model as well as its linearity with respect to all dynamic parameters are assumed, i.e

$$B_{nxn}(q)\ddot{q} + C_{nxn}(q,\dot{q})\dot{q} + G(q) = Y(q,\dot{q},\ddot{q})\Pi = \tau \tag{11}$$

where Y is a regressor matrix and Π is a column vector of uncertain parameters. The uncertain actuator parameters in column vector K can be appended to the uncertain dynamic model parameters Π

$$\begin{aligned} \tau &= K\Phi P = Y(q,\dot{q},\ddot{q})\Pi \\ \tau_{new} &= \Phi P = K^{-1}Y(q,\dot{q},\ddot{q})\Pi = Y(q,\dot{q},\ddot{q})\Pi_{new} \end{aligned} \tag{12}$$

When the nonlinear adaptive control from [14] is adopted, control and parameter adaptation law are

$$\begin{aligned} \tau_{new} &= K^{-1}Y(q,\dot{q},\dot{q_r},\ddot{q_r})\hat{\Pi} + K_d\sigma \\ &= \hat{B}(q)\ddot{q_r} + \hat{h}(q,\dot{q},\dot{q_r}) + K_d\sigma \\ \dot{\hat{\Pi}} &= K_\pi^{-1}Y(q,\dot{q},\dot{q_r},\ddot{q_r})^T\sigma \\ \dot{q_r} &= \dot{q_d} + \Lambda\tilde{q} \\ \sigma &= \dot{\tilde{q}} + \Lambda\tilde{q} \\ \tilde{q} &= q_d - q \end{aligned} \tag{13}$$

where K_π denotes the convergence speed of estimated parameters to their real values, Λ and K_d determine the gains of the proportional-derivative controller, and q_d is the desired trajectory for the soft robot joints. The first part of control law is based on inverse dynamics that cancels nonlinearities and decouples joints, while the second part implements the proportional-derivative control. Parameter adaptation law depends on the tracking error and its first derivative.

Compared to [12] where the change of the open-loop stiffness has small impact on the joint position, the main goal in this paper is to apply decoupling of the joint position and stiffness control. Kernel (null space) of the actuator matrix is used to achieve so. The control law of pressures, applied to McKibben muscles in order to attain desired behavior, is

$$P = \Phi^*\tau + \Phi^\dagger\nu \tag{14}$$

where Φ^* is the pseudo-inverse of actuator matrix, $\Phi^\dagger$ is an orthonormal basis for the null space of Φ obtained from the singular value decomposition and the part which controls stiffness is denoted with ν.

After substituting expression for the comanded pressure 14 in 8, the following is obtained

$$\begin{aligned} \dot{S} &= -\frac{\mathrm{d}\dot{\Phi}}{\mathrm{d}q}P - \frac{\mathrm{d}\Phi}{\mathrm{d}q}\frac{\mathrm{d}}{\mathrm{d}t}(\Phi^*\tau + \Phi^\dagger\nu) \\ &= -\frac{\mathrm{d}\dot{\Phi}}{\mathrm{d}q}P - \frac{\mathrm{d}\Phi}{\mathrm{d}q}(\dot{\Phi}^*\tau + \Phi^*\dot{\tau} + \dot{\Phi}^\dagger\nu + \Phi^\dagger\alpha) \end{aligned} \tag{15}$$

where α denotes the first derivative of the control ν. The desired behavior of stiffness is adopted as

$$\dot{S} = K_s(S - S_d) \tag{16}$$

where S_d is the desired stiffness reference. The control α is obtained equating 15 and 16, so that stiffness tracks the reference, which leads to

$$\begin{aligned} \alpha = &\left(\Phi^\dagger\right)^* \left(\frac{\mathrm{d}\Phi}{\mathrm{d}q}\right)^* \left(K_s\left(S - S_d\right) - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\mathrm{d}\Phi}{\mathrm{d}q}P\right) + \\ &+ \left(\Phi^\dagger\right)^* \left(-\frac{\mathrm{d}}{\mathrm{d}t}\left(\Phi^*\tau\right) - \frac{\mathrm{d}}{\mathrm{d}t}\Phi^\dagger\nu\right) \end{aligned} \tag{17}$$

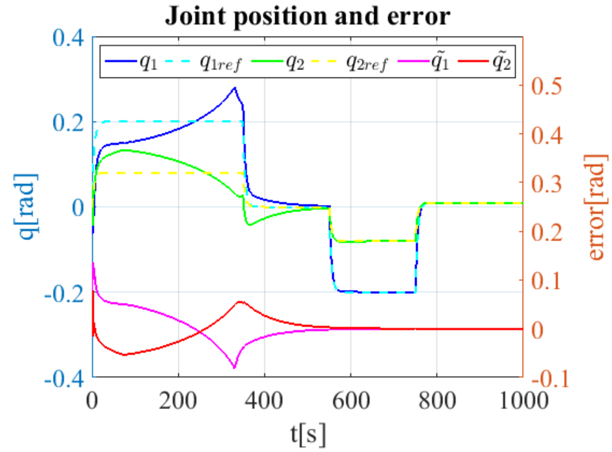

Fig. 4: Trajectory tracking simulation of soft robot arm joint position

IV. Simulation

The proposed control approach for soft-robots has been validated in simulation. The test is conducted for a two DoF soft robot arm actuated by antagonistic McKibben artificial muscles. Recalling the well-known dynamic model from [16], the inertial matrix of the robot arm dynamic model is given by

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \tag{18}$$

where $B_{11} = I_1 + m_1(\frac{1}{2}l_1)^2 + I_2 + m_2l_1^2 + m_2(\frac{1}{2}l_2)^2 + m_2l_1l_2c_2$, $B_{12} = I_2 + m_2(\frac{1}{2}l_2)^2 + \frac{1}{2}m_2l_1l_2c_2$, $B_{21} = B_{12}$ and $B_{22} = \frac{1}{2}m_2l_2^2 + I_2$ with the abbreviations $c_1 = cos(q_1)$, $c_2 = cos(q_2)$, and $c_{12} = cos(q_1 + q_2)$, respectively. The matrix containing terms related to Coriolis and centrifugal forces is

$$C(q,\dot{q}) = \begin{bmatrix} h\dot{q_2} & h(\dot{q_1} + \dot{q_2}) \\ -h\dot{q_1} & 0 \end{bmatrix} \begin{bmatrix} \dot{q_1} \\ \dot{q_2} \end{bmatrix} \tag{19}$$

where $h = -\frac{1}{2}m_2l_1s_2$, where $s_2 = sin(q_2)$, and the vector containing gravitation components is

$$G = \begin{bmatrix} (\frac{1}{2}m_1l_1g + m_2l_1g)cos_1 + \frac{1}{2}m_2l_2gc_{12} \\ \frac{1}{2}m_2l_2gcos_{12} \end{bmatrix}. \tag{20}$$

It is assumed that uncertain parameters are 15% less than their real values. In Fig.4 positions of two joints are presented together with their desired trajectory and the tracking error. It is noticed that the tracking error becomes smaller during the time, as the adaptive control *learns* parameters. From Fig. 5 where stiffness of both joints is given, one concludes that the stiffness reference is tracked successfully. The influence of the joint position change is negligible. The corresponding commanded muscle pressures are depicted in Fig. 6 and estimated parameters are in Fig. 7. It is important to notice that the change of stiffness does not affect position of the joints.

V. Conclusion

This work presented a nonlinear adaptive control approach, combined with kernel-based decoupling, for independent control of stiffness and position in flexible joint systems, which

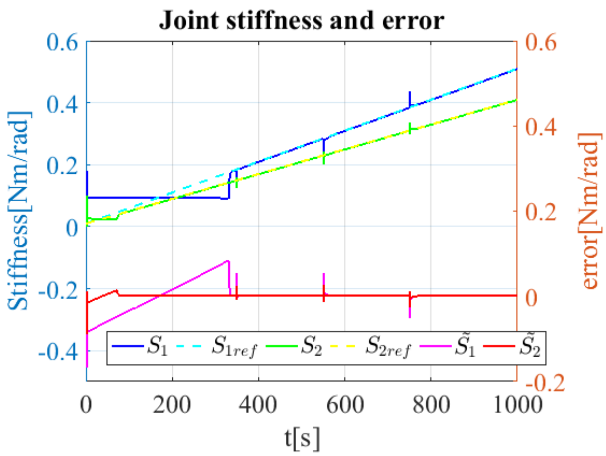

Fig. 5: Trajectory tracking simulation of soft robot arm stiffness

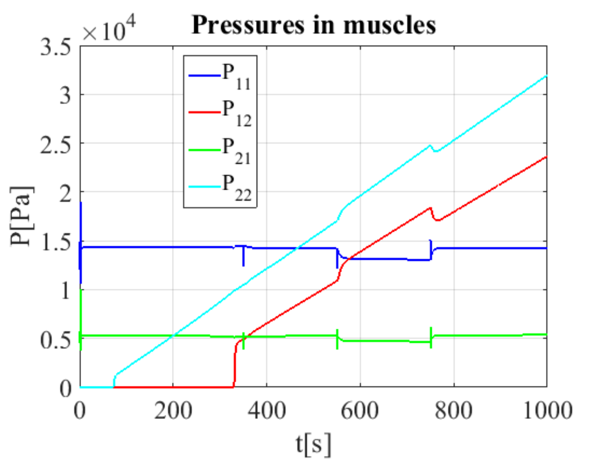

Fig. 6: Inflated pressures in soft robot arm antagonistic pairs of actuators

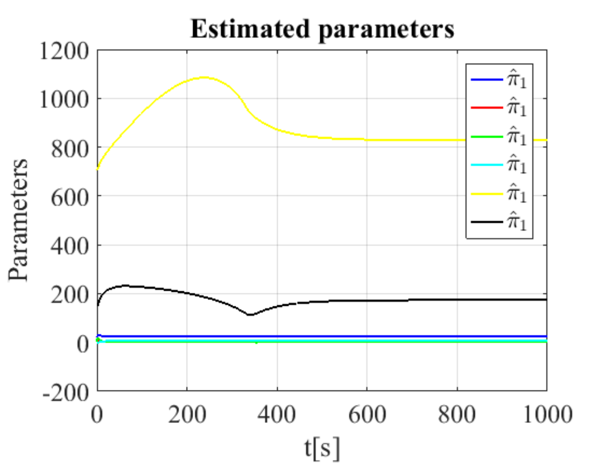

Fig. 7: Estimated dynamic parameters of a two-link soft robot arm.

showed promising results. The method was evaluated on a two DoF robot arm actuated by the antagonistic pair of McKibben muscles. Robustness to parameter uncertainty and improvement of trajectory tracking accuracy in time is shown. Experimental validation on both antagonistic compliant actuators driven by pneumatic McKibben drives at University of Palermo and by electrical drives and nonlinear extension springs at University of Belgrade, will be considered in future work.

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