Comparison of Model-Based Simultaneous Position and Stiffness Control Techniques for Pneumatic Soft Robots

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Abstract. Soft robots have been extensively studied for their ability to provide both good performance and safe human-robot interaction. In this paper, we present and compare the performance of two model-based control techniques with the common aim to independently and simultaneously control position and stiffness of a pneumatic soft robot's joint. The dynamic system of a robot arm with flexible joints actuated by a pneumatic antagonistic pair of actuators, so-called McKibben artificial muscles, will be regarded, while its dynamic parameters will be considered imprecise. Simulation results are provided to verify the performance of the algorithms.

Keywords: Soft robots · Variable stiffness actuator · Pneumatic actuator · Antagonistic drive · Adaptive control · Model based control

1 Introduction and Related Work

To have a highly efficient assembly process of complex products, the advantages of both humans and robots 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]. Concerning the safety of humans in the vicinity of a typical heavy industrial robot, soft robots 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 natural behavior. The compliance of a robot may be achieved either by reducing the robot's inertia or by introducing flexible joints. The works [3] and [4] discuss that robots with variable stiffness actuators (VSA) may have multiple advantages over rigid robots, as improved robustness to the external disturbance and increased one-to-one load-to-weight ratio. However, it is a challenging task to accurately track the

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trajectory with the compliant robot due to its highly nonlinear behavior. Therefore, the compromise between safe interaction and good performance needs to be accomplished by controlling the stiffness in a way that the robot is stiffer when accuracy is important and more compliant when interacting within the anthropic environment.

Variable stiffness actuation can be achieved with the antagonistic setup of McKibben pneumatically-driven artificial muscles developed back in 1950s [5], that 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 [6], 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 [7,8] 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 experimentally validated on electrically driven VSA [9], however, it is still not immune to the parametric uncertainty. The pioneering work in the adaptive control of a single flexible joint position [10] has been followed by the [11] where, besides position, joint stiffness is controlled in an open loop.

In this paper we compare a recent result of a decoupled nonlinear adaptive control [12] with the feedback linearization, since both of them control flexible robot joint's position and stiffness simultaneously and in the closed-loop. Taking into account that stiffness is not measurable, the scheme for estimation, as e.g. the ones proposed in [13] and [14], has to be applied. Soft robot arm actuated by antagonistically coupled McKibben artificial muscles is used as an example.

The dynamic model of the multi-degree-of-freedom soft robot arm actuated by McKibben muscles is given in Sect. 2. The control laws are described in Sect. 3, while in Sect. 4 simulation results of feedback linearization and decoupling adaptive control applied to a two-degree-of-freedom (DoF) soft arm actuated by antagonistic pair of McKibben muscles, are presented and compared.

2 Dynamic Model of a Pneumatic Soft Robot

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

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

where $B(q)$ is the inertial matrix, $C(q,\dot{q})$ contains Coriolis and centrifugal, assumed to depend only on the joint position and velocity, $G(q)$ 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.

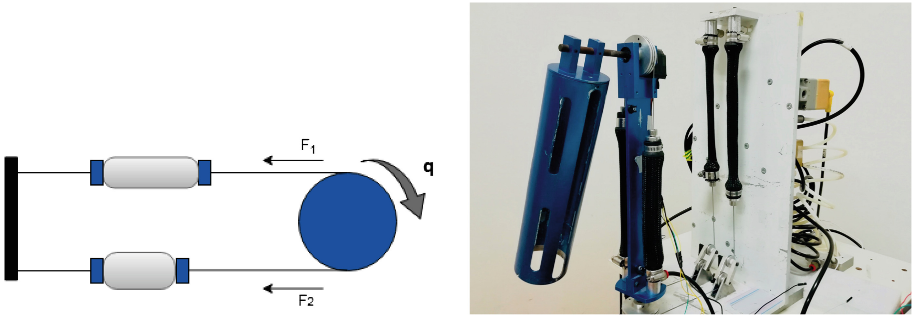

Fig. 1. One DoF McKibben artificial muscle scheme (left) and the experimental setup that will be used for experiments (right)

Using Chou-Hannaford model of McKibben muscles, elastic (tension) forces acting on i-th joint are calculated as

$$\begin{aligned} F_{i,a} &= K^g_{i,a}\phi_{i,a}p_{i,a}, \\ F_{i,b} &= K^g_{i,b}\phi_{i,b}p_{i,b}, \end{aligned} \tag{2}$$

where a and b denote the agonist and antagonist muscle, respectively, K_i^g is the construction parameter assumed to be the same for both antagonistic muscles, $\phi_{i,a} = (l_{i,a,n} - q_iR)^2 - l^2_{i,a,min}$, $\phi_{i,b} = (l_{i,b,n} + q_iR)^2 - l^2_{i,b,min}$, $l_{i,a,n}$ and $l_{i,b,n}$ are the nominal, while $l_{i,a,min}$ and $l_{i,b,min}$ are the minimal muscle extension. Inflated pressure in the muscle is denoted with P_i and R is the radius of the pulley. Scheme of antagonistic pair of McKibben muscles is presented in Fig. 1.

Considering previous assumptions on muscles' equality, elastic torque acting on i-th joint can be defined as in the following

$$\tau_i = (F_{i,a} - F_{i,b})R, \tag{3}$$

or as a generalized vector $\tau_{n\times1} = K\Phi p$, where $K = \text{diag}(K_i^g R)$ is a construction-dependent matrix, actuator matrix $\Phi_{n\times2n}$ is equal to

$$\Phi_{n\times2n} = \begin{pmatrix} \phi_{1,a} & -\phi_{1,b} & \dots & 0 & 0 \\ 0 & 0 & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \phi_{n,a} & -\phi_{n,b} \end{pmatrix}, \tag{4}$$

and pressures commanded to muscles are $p = (p_{1,a}, p_{1,b}, \dots, p_{n,a}, p_{n,b})^T$. The muscle pressure dynamics is assumed to be linear:

$$\dot{p}_i = -ap_i + bp_{c,i}, \tag{5}$$

with p_c being the commanded pressure, and constants a and b are to be identified or obtained from datasheet.

Recalling from [11], stiffness in the i-th joint can be approximated as

$$S_i = -\frac{\partial \tau_i}{\partial q_i} = -K_i \left(\frac{\partial \phi_{i,a}}{\partial q_i} p_{i,a}, -\frac{\partial \phi_{i,b}}{\partial q_i} p_{i,b} \right), \tag{6}$$

assuming that $\frac{\partial P_i}{\partial q_i}$ is equal to zero. The vector of stiffness in joints is given with $S = -K\Phi_q(q)p$, where $\Phi_q(q)$ collects partial derivatives of $\phi_i(q)$ with respect to q, leading to the stiffness dynamic model

$$\dot{S} = -K\dot{\Phi}_q(q)p - K\Phi_q(q)\dot{p}. \tag{7}$$

Finally, full dynamic model of the soft robot considered in this paper is as follows

$$\begin{aligned} B_{nxn}(q)\ddot{q} + C_{nxn}(q,\dot{q})\dot{q} + G_{nx1}(q) - \tau_{nx1} = \tau_{ext}, \\ \dot{S} = -K\dot{\Phi}_q(q)p - K\Phi_q(q)\dot{p}, \\ \dot{p}_i = -ap_i + bp_{c,i}. \end{aligned} \tag{8}$$

3 Model-Based Control Techniques

In this section, feedback linearization and decoupled adaptive control techniques are described, since both of them are formal approaches that enable simultaneous and decoupled position and stiffness control.

3.1 Feedback Linearization

The groundwork for the feedback linearization method, applied to the soft robots with variable stiffness actuators in the antagonistic setup has been laid by the authors of [7,8]. In this subsection very same approach is used for pneumatic soft robot - the nonlinear system dynamics is transformed by the appropriate control law into the chain of integrators, so that system becomes linear.

Consider two degree-of-freedom soft robot with the position and pressure dynamics presented in the state-space form:

$$\begin{aligned} \dot{x} = f(x) + g(x)\,u \\ y = h(x) \end{aligned} \tag{9}$$

where outputs are $y = (q_1, q_2, S_1, S_2)^T$, inputs are $u = (p_{c,1,a}, p_{c,1,b}, p_{c,2,a}, p_{c,2,b})^T$, and states are $x = (q_1, q_2, \dot{q_1}, \dot{q_2}, p_{1,a}, p_{1,b}, p_{2,a}, p_{2,b})^T$. The first step implies differentiating each output until the input variable appears. If the sum of both outputs orders is equal to the number of states, then full linearization can be achieved. It is straightforward to calculate that the direct relation between outputs (position and stiffness) and commanded pressure is obtained when position is derived three times and stiffness once:

$$\begin{aligned} q_1^{(3)} &= L_f^3 h_{q,1}(x) + E_{1,1}p_{c,1,a} + E_{1,2}p_{c,1,b} + E_{1,3}p_{c,2,a} + E_{1,4}p_{c,2,b}, \\ q_2^{(3)} &= L_f^3 h_{q,2}(x) + E_{2,1}p_{c,1,a} + E_{2,2}p_{c,1,b} + E_{2,3}p_{c,2,a} + E_{2,4}p_{c,2,b}, \\ \dot{S}_1 &= L_f h_{S,1}(x) + E_{3,1}p_{c,1,a} + E_{3,2}p_{c,1,b} + E_{3,3}p_{c,2,a} + E_{3,4}p_{c,2,b}, \\ \dot{S}_2 &= L_f h_{S,2}(x) + E_{4,1}p_{c,1,a} + E_{4,2}p_{c,1,b} + E_{4,3}p_{c,2,a} + E_{4,4}p_{c,2,b}, \end{aligned} \tag{10}$$

where $E_{i,j}$ for $i = 1, \cdots, 4$, $j = 1, \cdots, 4$ is element of matrix E. As the sum of orders for both positions and stiffness is equal to the number of states, one can conclude that all states are fully observable as a result of having no zero dynamics. It can be concisely written as:

$$\begin{pmatrix} q^{(3)} \\ \dot{S} \end{pmatrix} = \begin{pmatrix} L_f^3 h_q(x) \\ L_f h_S(x) \end{pmatrix} + E \begin{pmatrix} p_{c,1,a} \\ p_{c,1,b} \\ p_{c,2,a} \\ p_{c,2,b} \end{pmatrix}, \tag{11}$$

with the control input:

$$\begin{pmatrix} p_{c,1,a} \\ p_{c,1,b} \\ p_{c,2,a} \\ p_{c,2,b} \end{pmatrix} = E^{-1} \left(- \begin{pmatrix} L_f^{(3)} h_q(x) \\ L_f h_S(x) \end{pmatrix} + \begin{pmatrix} v_{q,1} \\ v_{q,2} \\ v_{S,1} \\ v_{S,2} \end{pmatrix} \right), \tag{12}$$

where $v_{q,1}$, $v_{q,2}$, $v_{S,1}$ and $v_{S,2}$ are newly-introduced inputs, chosen such that for given desired trajectory of position $q_{d,i}$ and stiffness $S_{d,i}$ following polynomials are Hurwitz:

$$\begin{gathered} v_{q,i} = q_{d,i}^{(3)} + K_{q,2}(\ddot{q}_{d,i} - \ddot{q}_i) + K_{q,1}(\dot{q}_{d,i} - \dot{q}_i) + K_{q,0}(q_{d,i} - q_i), \\ v_{S,i} = \dot{S}_{d,i} + K_{S,0}(S_{d,i} - S_i). \end{gathered} \tag{13}$$

3.2 Decoupled Nonlinear Adaptive Control

In this section control technique proposed in [12] will be briefly presented. For the purpose of designing adaptive control law, it is convenient to express the robot's dynamic model (Eq. 1) as a linear combination of parameters, i.e

$$B_{nxn}(q)\ddot{q} + C_{nxn}(q, \dot{q})\dot{q} + G(q) = Y(q, \dot{q}, \ddot{q})\pi, \tag{14}$$

where Y is a regressor matrix and π is a column vector of uncertain parameters.

The nonlinear adaptive control law from [11] can be adopted in order to asymptotically track the desired position trajectory q_d:

$$\begin{gathered} \dot{\hat{\pi}} = K_\pi^{-1} Y^T(q, \dot{q}, \dot{q_r}, \ddot{q_r})^T \sigma, \\ p = \Phi(q)^\dagger \tau_* = \Phi(q)^\dagger (Y^T(q, \dot{q}, \dot{q_r}, \ddot{q_r})^T \pi + K_d \sigma), \end{gathered} \tag{15}$$

where K_π denotes the convergence speed of estimated parameters, $\dot{q_r} = \dot{q_d} + \Lambda \tilde{q}$, Λ and K_d determine the gains of the proportional-derivative controller, $\sigma = \dot{\tilde{q}} + \Lambda \tilde{q}$, and $\tilde{q} = q_d - q$, and $\Phi(q)^\dagger$ denotes the pseudo-inverse of the actuator matrix.

Then, in order to achieve closed-loop control of stiffness in the decoupled manner, additional control degree of freedom ν is introduced, laying in the null-space of the actuator matrix:

$$p = \Phi^\dagger \tau_* + \Phi^\perp \nu, \tag{16}$$

with $\Phi^{\perp}$ being an orthonormal basis for the null space of Φ obtained via singular value decomposition. The dynamics of the controller, that ensures asymptotical tracking of position and stiffness references q_d and S_d, is given by following

$$\dot{\nu} = \left(\Phi_q(q)\Phi(q)^{\perp}\right)^{\dagger} \Big(K_S(S - S_d) - K^{-1}\dot{S}_d - \Phi_q(q)\tfrac{d}{dt}\left(\Phi(q)^{\dagger}\tau_*\right) - \Phi_q(q)\Phi(q)^{\dagger}\tau_* - \left(\Phi_q(q)\Phi(q)^{\perp} + \dot{\Phi}(q)^{\perp}\right)\nu\Big), \tag{17}$$

$$\dot{\hat{\pi}} = K_{\pi}^{-1} Y^T(q, \dot{q}, \dot{q}_r, \ddot{q}_r)^T \sigma, \tag{18}$$

where K_s has terms on its main diagonal that determine the convergence speed of tracking stiffness error.

4 Simulation Results and Discussion

The proposed control approach for soft-robots has been validated in Matlab/Simulink environment on a two DoF soft robot arm actuated by antagonistic McKibben artificial muscles. Recalling the well-known dynamic model of robot, the inertial matrix of the robot arm dynamic model is given by

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}, \tag{19}$$

where $B_{11} = I_1 + m_1(\frac{1}{2}l_1)^2 + I_2 + m_2 l_1^2 + m_2(\frac{1}{2}l_2)^2 + m_2 l_1 l_2 c_2$, $B_{12} = I_2 + m_2(\frac{1}{2}l_2)^2 + \frac{1}{2}m_2 l_1 l_2 c_2$, $B_{21} = B_{12}$, $B_{22} = \frac{1}{2}m_2 l_2^2 + I_2$ with the usual abbreviations $c_1 = cos(q_1)$, $c_2 = cos(q_2)$, and $c_{12} = cos(q_1 + q_2)$, respectively, and I_n being the identity matrix of dimension n. The Coriolis and centrifugal force matrix $C(q, \dot{q})$ and the gravity vector G are

$$C(q, \dot{q}) = \begin{bmatrix} h\dot{q}_2 & h(\dot{q}_1 + \dot{q}_2) \\ -h\dot{q}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}, \; G = \begin{bmatrix} (\frac{1}{2}m_1 l_1 g + m_2 l_1 g)c_1 + \frac{1}{2}m_2 l_2 g c_{12} \\ \frac{1}{2}m_2 l_2 g c_{12} \end{bmatrix}, \tag{20}$$

respectively, where $h = -\frac{1}{2}m_2 l_1 s_2$, $s_2 = sin(q_2)$. The dynamic model parameters of the robot are the following: $m_1 = 0.44$[kg] and $m_2 = 0.35$[kg] are masses, $l_1 = 0.33$[m] and $l_2 = 0.225$[m] are link lengths, $I_1 = 0.004$[kgm^2] and $I_2 = 0.0015$[kgm^2] are link inertias, for both degrees of freedom.

Regarding the feedback linearization approach, all roots of the Hurwitz polynomials $v_{q,1}$, $v_{q,2}$, $v_{S,1}$, and $v_{S,2}$ have been chosen equal to -1, while the gains of the decoupling adaptive controller are set to $\Lambda = 1$, $K_d = 1$, and $K_{\pi} = 20$. As already discussed in [7], position and stiffness reference trajectories need to be differentiable up to the third and first order, respectively, so that their asymptotic tracking can be achieved. The simulations have been designed in a way that robustness of methods is verified with respect to dynamic parameter uncertainty, when both position and stiffness of the soft robot's joints are varying. The uncertainty of parameters is set to 1% since the apparent difference between those two approaches can already be noticed.

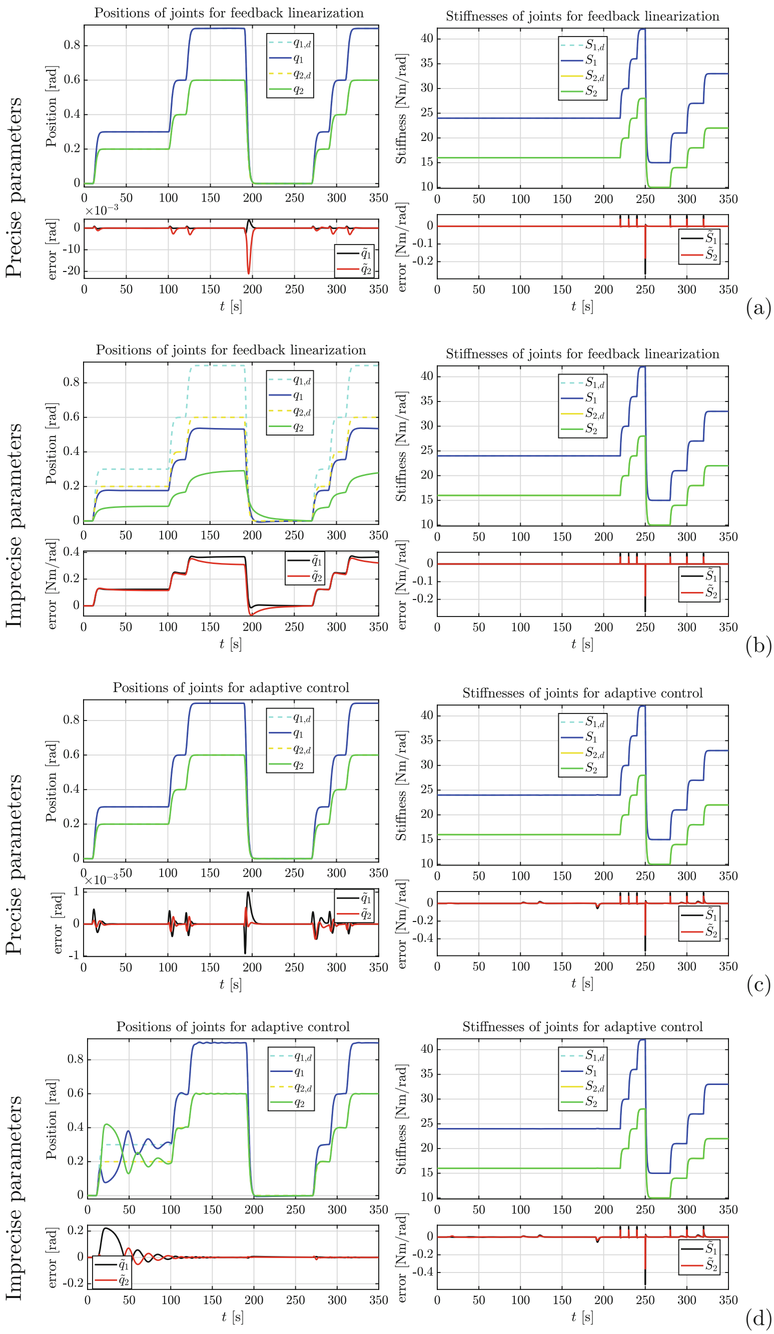

Fig. 2. Positions and stiffnesses of joints for feedback linearization approach with precise (a) and 1% imprecise (b) dynamic parameters, and adaptive approach with precise (c) and 1% imprecise (d) parameters

As shown in Fig. 2 (a) and (c), feedback linearization and decoupling adaptive control have a similar performance when parameters are precisely known, achieving satisfactory tracking of both position and stiffness. It can also be observed that when the feedback linearization approach is used, stiffness does not get affected at all by the variations of position, while small transient effects occur for the case of the adaptive approach. The source for these transients may lay in the calculation of actuator matrix pseudoinverse.

However, when the values of dynamic model parameters are reduced by 1% compared to their real value, the difference in performance achieved by the two methods becomes quite noticeable. In accordance with the previous results in the literature, the position is tracked with a constant error when the feedback linearization approach is used Fig. 2 (b). On the other hand, the adaptive control scheme manages to cope with the uncertainty of parameters, once those dynamic parameters are learned, and achieves good performance in tracking desired position and stiffness references, Fig. 2 (d). The tracking of stiffness is not affected by the uncertainty of dynamic parameters, as there is no mutual dependency. Indeed, the robustness of the feedback linearization approach can be improved by raising the gain values as shown in [15], but high gains affect the natural compliance of a soft robot and make practical implementation challenging. Finally, it is also worth remarking that the detailed comparison between the open-loop and the closed-loop nonlinear adaptive control of flexible robot joint's stiffness and position can be found in [12].

5 Conclusion

Feedback linearization and decoupled nonlinear adaptive control are control techniques that allow simultaneous, decoupled, and closed-loop control of both flexible robot joint's position and stiffness. The paper shows that the main difference between those two approaches lays in the fact that feedback linearization requires accurate knowledge of dynamic model's parameters, while the nonlinear adaptive control achieves good performance even with the imprecise information about the parameters' values. Consequently, while both the practical implementation and good tracking performance of the decoupled nonlinear adaptive control can be easily achieved [12], the same is hardly possible for the feedback linearization techniques, due to the very high gains necessary for satisfying the performance requirements [15]. On the other side, decoupled nonlinear adaptive control can so far only be used with pneumatically driven variable stiffness actuators.

References

1. Zanchettin, A.M., Ceriani, N.M., Rocco, P., Ding, H., Matthias, B.: Safety in human-robot collaborative manufacturing environments: metrics and control. IEEE Trans. Autom. Sci. Eng. **13**(2), 882–893 (2016)
2. Ajoudani, A., Zanchettin, A.M., Ivaldi, S., Albu-Schäffer, A., Kosuge, K., Khatib, O.: Progress and prospects of the human-robot collaboration. Auton. Robots **42**(5), 957–975 (2018)

3. Bicchi, A., Tonietti, G.: Design, realization and control of soft robot arms for intrinsically safe interaction with humans, pp. 79–87 (2002)
4. Albu-Schäffer, A., Haddadin, S., Ott, C., Stemmer, A., Wimböck, T., Hirzinger, G.: The DLR lightweight robot: design and control concepts for robots in human environments. Industr. Robot Int. J. **34**(5), 376–385 (2007)
5. Gavrilović, M., Marić, M.: Positional servo-mechanism activated by artificial muscles. Med. Biol. Eng. **7**(1), 77–82 (1969)
6. Chou, C.-P., Hannaford, B.: Measurement and modeling of McKibben pneumatic artificial muscles. IEEE Trans. Robot. Autom. **12**(1), 90–102 (1996)
7. Palli, G., Melchiorri, C., De Luca, A.: On the feedback linearization of robots with variable joint stiffness. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 1753–1759 (2008)
8. Jovanović, K., Lukić, B., Potkonjak, V.: Feedback linearization for decoupled position/stiffness control of bidirectional antagonistic drives. Facta Universitatis Ser. Electron. Energ. **31**(1), 51–61 (2017)
9. Petit, F., Daasch, A., Albu-Schäffer, A.: Backstepping control of variable stiffness robots. IEEE Trans. Control Syst. Technol. **23**(6), 2195–2202 (2015)
10. Ghorbel, F., Hung, J.Y., Spong, M.W.: Adaptive control of flexible-joint manipulators. IEEE Control Syst. Mag. **9**(7), 9–13 (1989)
11. Tonietti, G., Bicchi, A.: Adaptive simultaneous position and stiffness control for a soft robot arm. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 2, pp. 1992–1997 (2002)
12. Trumić, M., Jovanović, K., Fagiolini, A.: Decoupled nonlinear adaptive control of position and stiffness for pneumatic soft robots. Int. J. Robot. Res. (2020). https://doi.org/10.1177/0278364920903787
13. Fagiolini, A., Trumić, M., Jovanović, K.: An input observer-based stiffness estimation approach for flexible robot joints. IEEE Robot. Autom. Lett. **5**(2), 1843–1850 (2020)
14. Ménard, T., Grioli, G., Bicchi, A.: A stiffness estimator for agonistic-antagonistic variable-stiffness-actuator devices. IEEE Trans. Robot. **30**(5), 1269–1278 (2014)
15. Potkonjak, V., Svetozarevic, B., Jovanovic, K., Holland, O.: The puller-follower control of compliant and noncompliant antagonistic tendon drives in robotic systems. Int. J. Adv. Robot. Syst. **8**(5), 69 (2011)