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Adaptive Simultaneous Position and Stiffness Control for a Soft Robot Arm

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Abstract

In this paper, an independent joint position and stiffness adaptive control for a robot arm actuated by McKibben artificial muscles is reported. In particular, muscular *and* dynamic *parameters of the system are supposed unknown. Adaptive control performance is tested in a one degree of freedom experimental setup and compared with PID control performance. The adaptive control scheme is then applied to a robot arm that is conceived to perform tasks in anthropic environments. The adaptive control developed is such that performance of the robot arm is very similar to human arm performance. Experimental results are reported.*

1 Introduction

To design a robot arm that performs tasks in anthropic environments like a human arm, is the goal of many ongoing research projects (see e.g. [1, 2, 3, 4]). In designing such robot arm, several problems should be solved, i.e. lightness and robustness of robot arm, controllers and light actuators with high power to weight ratio design. Conventional actuators, such as electric motors, are not convenient to be used in *human like* robotics applications. Over the last decade, the development of artificial muscles is resulted in new actuators, such as pneumatic muscle actuators (PMA) [5], piezo-electric actuators [6] and electroactive polymers [7]. The force output and bandwidth of modern actuators have been evaluated with respect to those of human muscles [8]. Neverthless, if artificial muscles have to be compared with respect to human muscles, comparable control methods must also be considered. The design of efficient control requirements for artificial muscles could be inspired by the central nervous system organization and performance.

A well known theory, known as the *internal model theory* (IMT) [9], seems to fit the purpose. This theory, as opposed to *equilibrium point theory* [10], admits the existence of a (learned) dynamic model of the human arm used for its feedback control. This model, with unknown constant parameters, is continuously adapted by a feedback adaptive control, that generates the model parameters estimation [11].

The tracking of independent joint positions and stiffness, using a computed torque control scheme, for an n degrees of freedom robot arm actuated by McKibben artificial muscles, has already been studied in [12]. The main problem of this approach is that, in general, the control performance degrades if the system to be controlled is not completely known. In particular the parameters of PMA are subordinate to a slow variation when the number of working cycles increase [13]. In the present paper, following the IMT approach, the adaptive control scheme, described in [14], is applied to control the joint stiffness and positions of the robot arm in case of uncertain dynamics and muscular parameters. The nonlinear Chou-Hannaford artificial muscular model [15] is considered. This interesting model represents the PMA as a nonlinear quadratic spring, with, in this case, unknown elastic spring constant.

This paper is organized as follows: in section 2 the adaptive joint position and stiffness control is discussed for an n degrees of freedom robot arm actuated by PMA in antagonistic configuration. In section 3 the control is applied to a 1 degree of freedom experimental setup and the adaptive control results are compared with PID control results.

In section 4 experimental results of the adaptive control applied to a three degrees of freedom (DOF) Soft Arm developed in our laboratory, are reported. The robot performs a tracking trajectory task, with time varying stiffness at the joints.

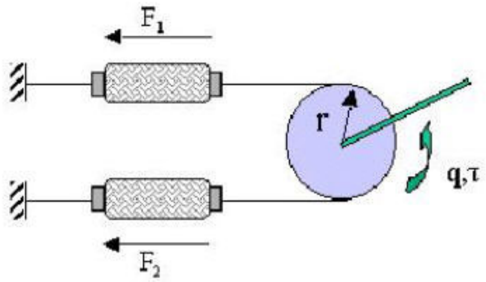

Figure 1: *A joint actuated by a pair of McKibben artificial muscles in antagonist configuration.*

2 Adaptive joint position and stiffness control of a n DOF robot arm actuated by McKibben artificial muscles

In [12], the realization of an independent joint position and stiffness control, for a n DOF manipulator actuated by McKibben artificial muscles, is shown using a computed torque control method. The main problem of this approach is that the control performance decreases if the manipulator and muscles parameters are not exactly known. In this section, an adaptive control scheme is applied in order to cope with model uncertainties. Another possible solution of the uncertainties problem is to introduce, in the control law, an integral term of the position error, so as to dominate unmodelled dynamics. In the following section, performance of those two different solutions will be compared.

The model of a n DOF robot arm is well known

$$B(q)\ddot{q} + h(q, \dot{q}) = \tau, \qquad (1)$$

where $B(q)$ represents the inertia matrix, $h(q, \dot{q})$ summarizes Coriolis and gravitational forces and τ is the actuators torque vector. If the joint actuator torque is generated by an antagonistic pair of McKibben artificial muscles (see fig.1), the i-th joint torque becomes

$$\tau_i = (F_{i1} - F_{i2})R_i, \qquad (2)$$

where R_i is the radius of the i-th pulley. The Chou-Hannaford model of pneumatic artificial muscles [15] is

$$F_{ij} = K_{ij}(l_{ij}^2 - l_{ijm}^2)P_{ij}, \qquad (3)$$

where F_{ij} is the ij-th muscle tension, K_{ij} is a parameter depending on constructive details, P_{ij} is the pressure inflated in the ij-th muscle and l_{ijm} is the minimum muscle length. Considering equation (3), the equation (2) becomes

$$\tau_i = (K_{i1}(l_{i1}^2 - l_{i1m}^2)P_{i1} - K_{i2}(l_{i2}^2 - l_{i2m}^2)P_{i2})R_i. \quad (4)$$

Supposing that the constants parameters K_{ij}, l_{ijm} are the same for muscles in antagonistic configurations, equation (4) can be rewritten as

$$\begin{aligned} \tau_i = K_i((l_{i1}^2 - l_{im}^2)P_{i1} - (l_{i2}^2 - l_{im}^2)P_{i2})R_i = \\ K_i(\phi_{i1}P_{i1} - \phi_{i2}P_{i2})R_i, \end{aligned} \qquad (5)$$

where $\phi_{ij} = ({l_{ij}}^2 - {l_{im}}^2)$. The latter equation implies that the torque vector can be expressed in the following form:

$$\tau = diag(K_i) \begin{bmatrix} \phi_{11} & -\phi_{12} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \phi_{21} & -\phi_{22} & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & \phi_{n1} & -\phi_{n2} \end{bmatrix} \begin{bmatrix} P_{11} \\ P_{12} \\ P_{21} \\ P_{22} \\ \vdots \\ P_{n1} \\ P_{n2} \end{bmatrix}$$

or, in more compact form as

$$\tau = K\Phi P. \qquad (6)$$

By the the well known property of linearity in parameters of robot dynamics can be written as

$$B(q)\ddot{q} + h(q, \dot{q}) = Y(q, \dot{q}, \ddot{q})\pi,$$

with

$$Y(q, \dot{q}, \ddot{q})\pi = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1m_1} \\ 0 & Y_{21} & \dots & Y_{2m_2} \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \dots & Y_{nm_n} \end{bmatrix} \begin{bmatrix} \pi_1 \\ \pi_2 \\ \vdots \\ \pi_{m1} \end{bmatrix} = \tau, \qquad (7)$$

where π is the dynamics parameters vector and $Y(q, \dot{q}, \ddot{q})$ is the so-called "regressor" matrix. By (6) and (7), equation (1) becomes

$$Y(q, \dot{q}, \ddot{q})\pi = K\Phi P. \qquad (8)$$

Furthermore, the non singularity of matrix K implies

$$K^{-1}Y(q, \dot{q}, \ddot{q})\pi = \Phi P. \qquad (9)$$

Our goal is then to find, starting from equation (9), a relationship similar to equation (7). But, in this relationship, we want the coefficients of the vector π to be combinations of robot dynamics parameters and coefficients K_i of matrix K.

Consider the equality

$$\begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1m_1} \\ 0 & Y_{21} & \dots & Y_{2m_2} \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \dots & Y_{nm_n} \end{bmatrix} \begin{bmatrix} \pi_1 \\ \pi_2 \\ \vdots \\ \pi_{m1} \end{bmatrix} = \begin{bmatrix} Y_1 & 0 & \dots & 0 \\ 0 & Y_2 & \dots & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \dots & Y_n \end{bmatrix} \begin{bmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_n \end{bmatrix} \qquad (10)$$

where $Y_i \overset{def}{=} [Y_{i1}, \ldots, Y_{im_i}]$ and $\Pi_i \overset{def}{=} [\pi_i, \ldots, \pi_{m_1}]$. Substituting this equality in equation (9), we have

$$K^{-1}Y(q,\dot{q},\ddot{q})\pi = diag(K_i)^{-1}\begin{bmatrix} Y_1 & 0 & \ldots & 0 \\ 0 & Y_2 & \ldots & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \ldots & Y_n \end{bmatrix}\begin{bmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_n \end{bmatrix},$$

and, using the definition of terms Y_i, Π_i, it is easy to find

$$\Phi P = \begin{bmatrix} Y_1 & 0 & \ldots & 0 \\ 0 & Y_2 & \ldots & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \ldots & Y_n \end{bmatrix}\begin{bmatrix} K_1^{-1}\Pi_1 \\ K_2^{-1}\Pi_2 \\ \vdots \\ K_n^{-1}\Pi_n \end{bmatrix},$$

that can be written in a more compact form:

$$\Phi P = \bar{Y}\bar{\Pi}. \qquad (11)$$

The latter expression allows us to apply the adaptive position tracking control scheme presented in [14] to the n DOF robot. This model reference adaptive control scheme (MRAC) imposes the following joint torque vector and parameters estimation dynamics

$$\begin{cases} \bar{\tau} = [K^{-1}\hat{B}(q)]\ddot{q}_r + [K^{-1}\hat{h}(q,\dot{q},\dot{q}_r)] + K_D\sigma, \\ \dot{\hat{\bar{\Pi}}} = K_\pi^{-1}\bar{Y}^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)\sigma, \\ \dot{q}_r = \dot{q}_d + \Lambda\tilde{q} \\ \sigma = \dot{q}_r - \dot{q}, \\ \tilde{q} = q_d - q, \end{cases} \qquad (12)$$

where K_D, K_π, Λ are positive definite matrices and q_d is the trajectory reference to be followed by the robot joints positions.

Imposing the equalities

$$\begin{cases} \bar{\tau} = \Phi P, \\ S = -\frac{d\bar{\tau}}{dq} = -\frac{d\Phi}{dq}P, \end{cases} \qquad (13)$$

with $\frac{dP}{dq} \approx 0$ and S is the vector of desired (open loop) joints stiffness (note that the relation, in this case, is independent of pneumatic muscles constants), relations in (13) can be expressed in the following matrix form

$$\begin{bmatrix} \bar{\tau} \\ S \end{bmatrix} = \begin{bmatrix} \Phi \\ -\frac{d\Phi}{dq} \end{bmatrix} P \qquad (14)$$

with

$$\begin{bmatrix} \Phi \\ \frac{d\Phi}{dq} \end{bmatrix} = \begin{bmatrix} \phi_{11} & -\phi_{12} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \phi_{21} & -\phi_{22} & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & \phi_{n1} & -\phi_{n2} \\ -\frac{d\phi_{11}}{dq} & \frac{d\phi_{12}}{dq} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & -\frac{d\phi_{21}}{dq} & \frac{d\phi_{22}}{dq} & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & -\frac{d\phi_{n1}}{dq} & \frac{d\phi_{n2}}{dq}. \end{bmatrix}. \qquad (15)$$

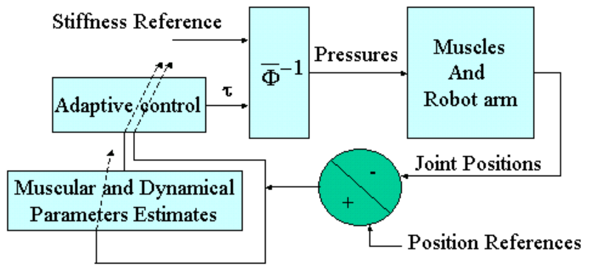

Figure 2: *A schematic representation of joint position and open-loop stiffness control method with muscular and dynamical parameters uncertainties discussed in section 2.*

Considering the i-th and the $(n+i)$-th matrix rows, we find

$$\begin{bmatrix} \bar{\tau}_i \\ S_i \end{bmatrix} = \begin{bmatrix} \phi_{i1} & -\phi_{i2} \\ -\frac{d\phi_{i1}}{dq} & \frac{d\phi_{i2}}{dq} \end{bmatrix}\begin{bmatrix} P_{i1} \\ P_{i2} \end{bmatrix} \overset{def}{=} \bar{\Phi}_i\begin{bmatrix} P_{i1} \\ P_{i2} \end{bmatrix}, \qquad (16)$$

hence

$$\bar{\Phi}_i^{-1}\begin{bmatrix} \bar{\tau}_i \\ S_i \end{bmatrix} = \begin{bmatrix} P_{i1} \\ P_{i2} \end{bmatrix}. \qquad (17)$$

This allows the possibility of independently tracking joints positions and stiffness for an n DOF robot arm (see fig.2).

In next section, we show experimental results of adaptive control method as applied to a simple 1 DOF setup, compared with those of PID control method.

3 A comparative experimental test: Adaptive control versus PID control

To test the adaptive control scheme examined above we have built a simple experimental setup, that consists in a planar 1 DOF link actuated by a pair of McKibben artificial muscles in antagonist configuration (see fig.3). Furthermore, a linear potentiometer provides data necessary for position feedback control.

The mathematical model of the experimental setup is

$$I\ddot{q} = (F_1 - F_2)R, \qquad (18)$$

where I is the link inertia momentum, $\ddot{q}$ is the joint angular acceleration, R is the radius of the pulley and F_i represents the Chou-Hannaford artificial muscles model reported in equation (3).

Substituting (3) in (18), we have

$$I\ddot{q} = K_1(l_1^2 - l_{1m}^2)p_1R - K_2(l_2^2 - l_{2m}^2)p_2R. \qquad (19)$$

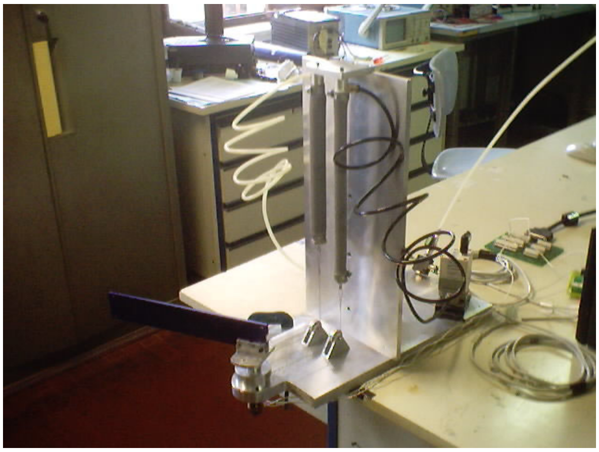

Figure 3: *Planar* 1 *DOF link actuated by a pair of McKibben artificial muscles in antagonist configuration.*

As discussed in the previous section, in the particular case in which the agonist and the antagonist muscles have the same length, we have $K_1 \approx K_2 = K, l_{1m} \approx l_{2m} = l_m$. This approximation implies

$$I\ddot{q} = K((l_1^2 - l_m^2)p_1 - (l_2^2 - l_m^2)p_2)R,$$

hence

$$\frac{I}{K}\ddot{q} = (l_1^2 - l_m^2)p_1R - (l_2^2 - l_m^2)p_2R,$$

and then

$$\frac{I}{K}\ddot{q} = (\phi_1 p_1 - \phi_2 p_2)R. \qquad (20)$$

Given equation (17), the pressures inflated in muscles are

$$\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \frac{1}{2R^3(l_1\phi_2 + l_2\phi_1)} \begin{pmatrix} 2l_2R^2\tau + \phi_2RS \\ -2l_1R^2\tau + \phi_1RS \end{pmatrix}, \qquad (21)$$

where $\phi_i = (l_i^2 - l_m^2)$, $l_1 = l_{max} - qR$, $l_2 = l_{min} + qR$, l_{max} and l_{min} are maximum and minimum muscle lengths, equal for the two muscles, respectively and S is the desired joint stiffness. Note that $S > 0$ implies $\phi_i RS > 0$.

$\bar{\tau}$, for the PID controller, is given by

$$\bar{\tau} = K_p\epsilon + K_d\dot{\epsilon} + K_I\int_0^t \epsilon\partial t,$$

while, for the adaptive controller is given by

$$\bar{\tau} = \left(\frac{\hat{I}}{K}\right)\ddot{q}_r + K_c\sigma,$$

where $(\dot{\widehat{\frac{I}{K}}}) = \gamma^{-1}\ddot{q}_r\sigma$, $\dot{q}_r = \dot{q}_d + \Lambda\tilde{q}$, $\sigma = \dot{\epsilon} + \lambda\epsilon$ and $\epsilon = q_d - q$.

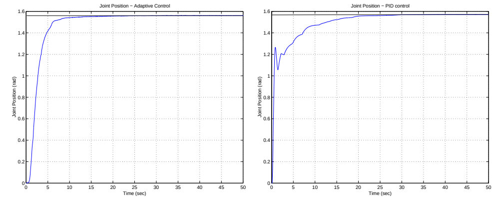

Figure 4: *Step Response comparative test. Adaptive (left) and PID (right) responses to a* $\frac{\pi}{2}$*rad step reference.*

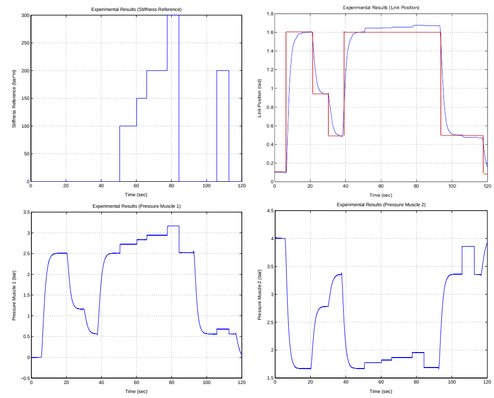

Figure 5: *Desired open loop joint stiffness (up-left), effective and desired joint position (up-right, blue and red respectively) and pressures inflated in agonist and antagonist muscles (bottom, left and right respectively) in the experiment of independent tracking of joint position and stiffness with the* 1*DOF setup.*

In fig.4, the step response of both adaptive and PID controller is reported. A comparison between the control approaches shows that the use of adaptive control implies better trajectory performance than the PID control, in particular when the trajectory excursions are high. A noterworthy feature of the adaptive controller is the relative ease by which good performance could be achieved, compared to the much more complex procedure needed for tuning the PID controller due to the nonlinearity of actuators.

A second, more complex experiment was devised to test the controller ability to track set-point references with the joint positions, and to monitor effects producted by a change in the desired joint stiffness S (see fig.5). During the initial $50sec$ of this experiment, the reference to the passive stiffness controller is set to its minimal value, while the position reference is varied stepwise (from 0.1 to 1.5 *rads*) and the active stiffness (the closed position loop gain, us-

Figure 6: *Appearance of the Soft Arm. The presence of McKibben muscles as actuators, and the possibility to independently tracking the position and the stiffness of the joints, allows the robot arm to interact with human operators safely.*

ing pressure feedback) is set to a constant, very high value. The minimal open-loop stiffness value is dictated by the necessity to maintain some tension in the tendons to avoid them going slack, and is set conventionally to zero in fig.5.

Successively, the open-loop stiffness is varied by five stepwise level changes (at times 50, 60, 65, 70, 75, and 85 *sec.*). The joint torque is slightly affected by the corresponding changes in actuator pressures, in agreement with results reported in section (2); this behavior can also be regarded as similar to co-contraction observed in animal sensorimotor control [16]. The experiment finally shows that the effect of a change of open-loop stiffness (at time 105 *sec.*) on a different position of the link (0.5 *rads*), is also negligible.

4 The adaptive control scheme applied to the robot arm: experimental results

In this section the adaptive control method, reported in section 2, is applied at the elbow joint and a shoulder joint of a 3 DOF Soft Robot Arm developed in our laboratory (see fig.6). The robot arm is conceived to operate in an anthropic unknown environment (see fig.7, for an example of a simple task) with high level of safety [12]. The hardware of the robot control loop consists of a 300MHz Workstation, two data acquisition board: the ADC ADAC 5803HR (*potentiometers feedback*) and DAC Advantech PCL 726 (*signals to the pneumatic servovalves*). The pressures inflated in the six McKibben muscles are controlled by a set of six pneumatic servovalves ITV2050 - SMC Corporation.

Figure 7: *Robot picking a screwdriver (up) with the prototype of light gripper developed in our laboratory (bottom).*

Dynamics, Coriolis and gravitational matrices of the two DOF model of the robot arm (see fig.8) are given by

$$B = \begin{bmatrix} (\pi_1 + \pi_2 cos(q_2) + \pi_3 cos(2q_2)) & (\pi_4 + \pi_5 cos(q_2) + \pi_6 cos(2q_2)) \\ \pi_{15} + \pi_{16} cos(q_2) + \pi_{20} cos(2q_2) & \pi_{14} + \pi_{18} cos(q_2) \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} \pi_7 sin(q_2)\dot{q}_2 + \pi_{10} sin(2\mathbf{q}_2)\dot{q}_2 & \pi_8 sin(q_2)\dot{q}_2 + \pi_9 sin(2q_2)\dot{q}_2 \\ \pi_{17} sin(q_2)\dot{q}_2 + \pi_{21} sin(2q_2)\dot{q}_2 & \pi_{19} sin(q_2)\dot{q}_2 \end{bmatrix}$$

$$G = \begin{bmatrix} \pi_{11} sin(q_1) + \pi_{12} sin(q_1 + q_2) + \pi_{13} sin(q_1 + 2q_2) \\ \pi_{22} sin(q_1 + q_2) + \pi_{23} sin(2q_2 + q_1) \end{bmatrix}$$

where, in particular, the parameters π_{ij} are combination of dynamic and geometric parameters (i.e., link lengths and masses). In order to control the mechanical structure with the adaptive scheme, it is sufficient to apply, to the robot model, results obtained in section (2).

To show the controller ability to allow a large range of stiffness at the joints, the results of step response

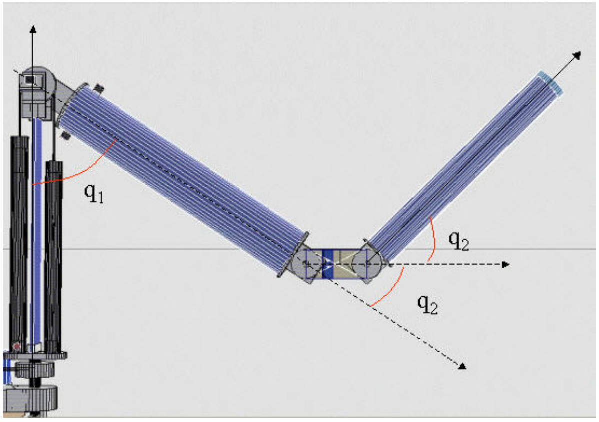

Figure 8: *CAD design of the robot arm.*

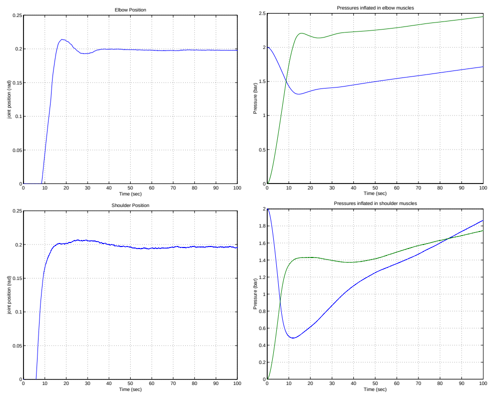

Figure 9: *Elbow (top) and Shoulder (bottom) joint positions and pressures inflated in the respectives agonist and antagonist muscles pairs with time varying stiffness. For both joints, the step reference is set to* $0.2rad$*, while* $S = 5t$*, with* $t \in [0, 100]sec$ *is the increasing time interval of the experiment.*

at the elbow and shoulder joints with time-varying stiffness are reported in fig.9. Notice that the joints positions are almost unvaried with respect to the steady-state value ($0.2rad$), while the pressures inflated in the muscles pairs are varied accordingly to the changes in joint stiffness references.

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