Compliant design for intrinsic safety: General issues and preliminary design.

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Abstract

In this paper, we describe some initial results of a project aiming at development of a programmable-compliance, inherently safe robot arm for applications in anthropic environmnets. In order to obtain safety in spite of worst-case situations (such as unexpected delays in teleoperation, or even controller failure), we will consider achieving compliance by mechanical rather than by control design. We first describe some of the control problems that the presence of large, possibly unknown mechanical compliance typically introduces, and present a result that shows the possibility to cope with these uncertainties in an adaptive way. In the second part of the paper we describe the initial development of a new prototype arm under construction in our laboratory. The arm is designed to achieve arbitrary position tracking in 3D with controlled effective compliance at the joints.

1 Introduction

Robots for use in environments shared with humans, such as e.g. in domestic or entertainment applications or in cooperative material-handling tasks ([1, 13]), must fulfill different specifications from those typically met in industry. It is often the case, for instance, that accuracy requirements are much less demanding. On the other hand, a primary concern is obviously safety and dependability [8] of the robot system.

Accordingly to this difference in specifications, the usage of conventional industrial arms for anthropic environments is severely limited. Although the inherent danger to humans of conventional arms can be mitigated by drastically increasing their sensorization (using e.g. proximity–sensitive skins such as those proposed by [6]) and changing their controllers, it is well accepted in the robotics literature that there are intrinsic limitations to what the controller can do to modify the behaviour of the arm if the mechanical bandwith (dominated by mechanism inertia and friction) is not matched to the task (see e.g. [18]). In other words, making a rigid, heavy robot to behave gently and safely is an almost hopeless task, if realistic conditions are taken into account.

One alternative approach at increasing the safety level of robot arms interacting with humans is to introduce compliance right away at the mechanical design level. Several projects are being pursued in research labs towards this goal, with particular reference to development of suitable actuators (see e.g. [11, 12, 14, 2, 16]).

In this paper, we describe the preliminary phases of development of a new prototype arm under construction in our laboratory. The main characteristics of the arm is that it is conceived for obtaining intrinsic safety by introducing relatively high, controllable compliance. The arm is designed to achieve arbitrary position tracking in 3D with variable effective compliance at the joints. Rather than achieving compliance by methods based on controller synthesis, in our design we have compliant nonlinear actuators that offer intrinsic compliance (hence safety), even in cases where the controller may fail.

This paper is mostly concerned with establishing some basic results concerning feasibility of such a design. In section 2 we consider the problem of controlling a compliant robot arm so as to achieve accurate positioning. We discuss a solution to this problem that is available in the literature, which is strictly dependent on the availability of a good model, and discuss the possibility of applying the scheme without such precise knowledge. In section 3 we consider the specification that not only positional trajectories are to be tracked by the robot arm, but also that compliance of its link should be controlled to vary in space and time according to desired profiles, and discuss what are the implications on the arm design. Finally, in section 4 we report on the design of a new intrinsically compliant robot under development at out laboratory.

2 Methods for compliance control and identification.

Methods for compliance control in robot manipulators have been studied since very early in the robotics literature. Most early results concentrated on task–space specifications of compliance of the end-effector motions with respect to a desired posture, or reference trajectory ([17, 10]). The basic idea of such controllers is that the rigid nature of robotic arms is compensated by control by suitably setting the gains of joint position servos so as to achieve a desired effective compliance at the end–effector. However, these approaches may not prove robust with respect to such model nonidealities as e.g. friction and backslash in transmission ([18]), by the simple reason that the insufficient mechanical bandwidth of the actuators/transmission subsystem does not allow the controller to take suitable countermeasures to unexpected collisions of the arm. As a consequence, severe harm to persons dealing with the robot arm can ensue if the robot is used in anthropic environments. In such applications, it seems to be preferrable that the arm is designed to be passively compliant, i.e., including compliant transmission that can prevent building up of excessive forces in the transients. Passive compliance, along with low inertia, are the two basic elements of inherently safe mechanism design.

The role of controllers with passivley compliant arms is in some sense converse to that described above, and consists of compensating compliance of the mechanical structure of the arm, to achieve acceptable levels of accuracy in positioning. To study this problem, we start by considering a very simple model of a passively compliant robot arm, which is the flexible joint model (see e.g. [4]). In this model, a rigid robot arm is considered whose n joints are actuated through a set of n springs. Let q denote the n-vector of joint configurations, and θ the n-vector of actuator positions. The kinetic energy and potential energy of the system can be written in general as

$$T = \frac{1}{2}\left[\begin{array}{cc} \dot{q}^T & \dot{\theta}^T \end{array}\right] \left[\begin{array}{cc} B(q) & S(q) \\ S^T(q) & J \end{array}\right] \left[\begin{array}{c} \dot{q} \\ \dot{\theta} \end{array}\right];$$

$$U = U_g(q) + \frac{1}{2}(q-\theta)^T K (q-\theta),$$

where $B(q) \in \mathbb{R}^{n\times n}$ describes te inertial properties of the rigid links, $J = \mathsf{diag}\,(J_1, J_2, \ldots J_n) \in \mathbb{R}^{n\times n}$ is a diagonal matrix collecting the effective rotor inertias of the actuators, and $S(q) \in \mathbb{R}^{n\times n}$ accounts for inertial couplings between rigid links and actuators; $U_g(q)$ is the gravitational potential, and $K = \mathsf{diag}\,(k_1, k_2, \ldots, k_n)$ denotes the joint stiffness matrix. The dynamics of such systems can be easily derived by the Euler-Lagrange equations for the Lagrangian $T-U$ as

$$\begin{array}{rcl} B(q)\ddot{q} + S(q)\ddot{\theta} + C(q,\dot{q})\dot{q} + g(q) + K(q-\theta) & = & 0 \\ S^T\ddot{q} + J\ddot{\theta} + K(\theta - q) & = & \tau \end{array}$$

The problem of accurately controlling a robot arm with (possibly large) joint flexibility has been studied by several researchers (see e.g. [5] for a review). It is well known in the literature ([19]) that flexible joint arms without dynamic coupling (i.e., with $S(q) = 0$) are exactly feedback linearizable by static state feedback. An important recent result ([4]) has shown that feedback linearizability (by dynamic feedback) holds true in general also for dynamically coupled flexible joint arms. Such results imply that it is possible, in principle, to track an arbitrary position trajectory with asymptotically vanishing error even in the presence of large compliance at the joints.

These results however rely on the assumption that the compliance is exactly known, which is seldom the case in practice. If the mechanical compliance of joints is not known, it would be desirable to have a control method that could cope with the uncertainty. Such an adaptive control problem is highly nontrivial due to the nonlinear dependence of the dynamics on compliance. Conceptually, the adaptive controller could be built by connecting a dynamic estimator of compliance to the control scheme of e.g. [4]. Two major steps are necessary towards this goal: firstly, it has to be proven that such an estimator can be built using the only information realistically available, i.e. that the unknown actual joint compliance of a manipulator can be identified by measurement of the joint positions only, along with knowledge of input torques. The second step would be to prove that some sort of a "separation principle" applies to this case, whereby the stability of the controller is unaffected by the estimator dynamics, and viceversa.

Below we provide a positive answer to the first of these questions. The proof is based on nonlinear observability tools, and relies on considering the unknown compliance values in $k = [k_1\ k_2\ \cdots\ k_n]^T$ as state variables in the system's dynamic model. To this purpose, define a state vector $\xi = [\xi_1^T\ \xi_2^T\ \xi_3^T\ \xi_4^T\ \xi_5^T]^T$ with $\xi_i \in \mathbb{R}^n$, $i = 1, \ldots, 5$, and let $\xi_1 = q$, $\xi_2 = \theta$, $\xi_3 = k$, $\xi_4 = \dot{q}$, and $\xi_5 = \dot{\theta}$. In the dynamically decoupled case ($S = 0$), the dynamics of the system can be written as

$$\left[\begin{array}{c} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{\xi}_3 \\ \dot{\xi}_4 \\ \dot{\xi}_5 \end{array}\right] = \left[\begin{array}{c} \xi_4 \\ \xi_5 \\ 0 \\ -B^{-1}(\xi_1)\gamma(\xi) \\ J^{-1}\,\mathsf{diag}\,(\xi_3)(\xi_1 - \xi_3) \end{array}\right] + \left[\begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ J^{-1} \end{array}\right]\tau \qquad (1)$$

where $\gamma(\xi) \stackrel{def}{=} [C(\xi_1, \xi_4)\xi_4 + g(\xi_1) + \mathsf{diag}\,(\xi_3)(\xi_1 - \xi_2)]$. Measurable outputs are assumed to be the joint positions only, i.e.

$$y = h(\xi) = \xi_1 .$$

Identifiability of the unknown, but constant parameters k amounts then to an observability problem for system (1), which can be tested by tools available in the nonlinear systems literature ([9]). To this end, consider the observation space for the system, which is comprised of all functions appearing in the output and its derivatives evaluated along the system's trajecctories, i.e. (omitting arguments of functions for brevity)

$$\begin{array}{rcl} h(\xi) & = & \xi_1 \\ L_f h(\xi) & = & \xi_4 \\ L_g h(\xi) & = & 0_{n\times n} \\ L_f^2 h(\xi) & = & -B^{-1}\gamma \end{array}$$

$$L_f^3 h(\xi) = \\ -B^{-1}\left[\left(B\frac{\partial B^{-1}\gamma}{\partial \xi_1} + \operatorname{diag}(\xi_3) + \frac{\partial g}{\partial \xi_1}\right)\xi_4 - \operatorname{diag}(\xi_3)\xi_5 - CB^{-1}\gamma\right]$$

$$\begin{array}{rcl} L_g L_f^3 h(\xi) & = & B^{-1}\operatorname{diag}(\xi_3) J^{-1}, \\ \vdots & = & \vdots \end{array}$$

The few elements of the observation space above evaluated explicitly are sufficient to prove identifiability of k. Indeed, if $5n$ of these functions can be shown to be independent, system (1) is completely locally observable. This implies that, in particular, the unknown initial conditions of the state component $\xi_3 = k$ can be reconstructed from knowledge of inputs (actuator torques) and outputs (joint positions). The indepedence of $5n$ functions out of the above listed can be checked by looking at the rank of their Jacobian (or, in other worlds, looking at the corresponding observability codistribution minor). We have easily that

$$\begin{array}{rcl} \frac{\partial h}{\partial \xi} & = & \left[\begin{array}{ccccc} I_{n\times n} & 0_{n\times n} & 0_{n\times n} & 0_{n\times n} & 0_{n\times n} \end{array}\right] \\ \frac{\partial L_f h(\xi)}{\partial \xi} & = & \left[\begin{array}{ccccc} 0_{n\times n} & 0_{n\times n} & 0_{n\times n} & I_{n\times n} & 0_{n\times n} \end{array}\right]. \end{array}$$

Moeover, considering that, for all $x, y \in \mathbb{R}^n$, it holds $\frac{\partial \operatorname{diag}(x)}{\partial x} y = \operatorname{diag}(y)$, we have

$$\frac{\partial L_f^2 h(\xi)}{\partial \xi} = B^{-1} \cdot \\ \cdot \left[\begin{array}{ccccc} -B\frac{\partial B^{-1}}{\partial \xi_1}\gamma - \operatorname{diag}(\xi_3) - \frac{\partial g}{\partial \xi_1} & -\operatorname{diag}(\xi_3) & -\operatorname{diag}(\xi_1 - \xi_2) & -C & 0_{n\times n} \end{array}\right]$$

while

$$\frac{\partial L_f^3 h(\xi)}{\partial \xi} = \left[\begin{array}{ccccc} \star & \star & \star & \star & -B^{-1}\operatorname{diag}(\xi_3) \end{array}\right]$$

where $\star$ denotes terms whose explicit evaluation is ininfluent to our purposes, and is omitted for brevity. As for the term $L_g L_f^3 h(\xi)$, it should be noted that it represents n^2 scalar functions $L_{g_i} L_f^3 h_j(\xi)$, $i, j = 1, 2, \ldots, n$. Using the Matlab–like notation $A_{(i,j)}$ to denote the element in the i–th row and j–th column in a matrix A, and letting the column symbol ":" denote "all indices", one can rewrite explicitely $L_{g_i} L_f^3 h(\xi) = B^{-1}\operatorname{diag}(\xi_3) J^{-1}_{(:,i)}$. For the differential $\frac{\partial L_{g_i} L_f^3 h_i(\xi)}{\partial \xi_3}$, one can write

$$\begin{array}{l} \frac{\partial L_{g_i} L_f^3 h_i(\xi)}{\partial \xi_3} = \left[\frac{\partial L_{g_i} L_f^3 h(\xi)}{\partial \xi_3}\right]_{(i,:)} = \\ \left[B^{-1}\frac{\partial \operatorname{diag}(\xi_3)}{\partial \xi_3}\hat{J}_i\right]_{(i,:)} = \\ \left[B^{-1}\operatorname{diag}(\hat{J}_i)\right]_{(i,:)} = \\ \left[\begin{array}{ccccccc} 0 & \cdots & 0 & B^{-1}_{(i,i)} J_i^{-1} & 0 & \cdots & 0 \end{array}\right]. \end{array}$$

To show that the $5n$ functions of the observation space $h(\xi)$, $L_f h(\xi)$, $L_f^2 h(\xi)$, $L_f^3 h(\xi)$, and $L_{g_i} L_f h_i(\xi)$ $(i = 1, \ldots, n)$, are independent, we consider then the determinant of the corresponding Jacobian matrix

$$\mathcal{J} = \left[\begin{array}{ccccc} I_{n\times n} & 0_{n\times n} & 0_{n\times n} & 0_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & 0_{n\times n} & 0_{n\times n} & I_{n\times n} & 0_{n\times n} \\ \star & B^{-1}\operatorname{diag}(\xi_3) & \star & \star & 0 \\ \star & \star & \star & \star & -B^{-1}\operatorname{diag}\xi_3 \\ \star & 0 & \Delta & 0 & 0 \end{array}\right]$$

where $\Delta = \operatorname{diag}(B^{-1}_{(i,i)} J_i^{-1}) \in \mathbb{R}^{n\times n}$. One easily gets that

$$\det \mathcal{J} = -\det \Delta \det \left(B^{-1}\operatorname{diag}(\xi_3)\right)^2$$

and hence that the system is observable. This confirms the possibility to build a dynamic estimator whose states will converge to the unknown stiffness parameters k, at least for inputs that are "sufficiently rich".

The local observability result above is a fundamental step in building a controller for position tracking with robot arms that have large and not precisely known compliance, and only uses output measurements. Indeed, it was proven in [3] that, under some mild assumptions applicable to our case, for a nonlinear system

$$\dot{\xi} = f(\xi, u)$$

for which an exponentially stabilizing static state–feedback control law $u = \alpha(\xi, v)$ exists, and which is locally observable from a set of outputs $y = h(\xi)$ in the sense above, then an output feedback law can be constructed $u = \bar{\alpha}(y, y', y'', \cdots, v)$ that asymptotically stabilizes the system based on output measurements and filtered derivatives thereof only ($y'(s) = \frac{y(s)}{Ts+1}$, $y''(s) = \frac{y'(s)}{Ts+1}$, etc.).

Such rather general scheme for building an output feedback controller based on a preexisting static state feedback controller for observable systems can in principle be adapted to our problem (using for instance the feedback linearization schemes of [19] as $\alpha(\xi, v)$). However, practical implementation of the scheme has not been performed yet, which can be expected to highlight possible shortcomings of this general approach. Also, the case where dynamic coupling imposes dynamic feedback lineariation can not be addressed by

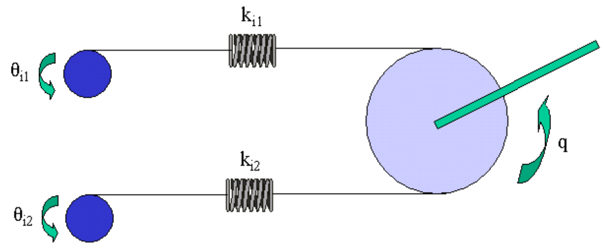

Figure 1: An antagonistic arrangement of two actuators per joint with nonlinear springs can control joint position and stiffness independently.

this technique as it presently stands. Future work will de devoted to implement the scheme on an experimental device, and to find particularizations for the specific system at hand.

3 Active control of compliance.

While the previous section reported on the possibility of accurately tracking a positional reference in spite of large, possibly unknown compliance at the joints, in this section we focus on the additional and more stringent requirement that the robot be able to also change its effective compliance at will while performing motions.

It might be noticed that tuning compliance while performing positional control has been considered already in the literature. For instance, the Salisbury hand [15] achieved this goal (albeit not for all joints independently) by actuating the three joints of its fingers by four independetly driven tendons. Compliance could be tuned by changing the positional gains of the tendon actuator servo loops. In our design, however, for the reasons already discussed we would like to implement compliance at the mechanical level directly.

Intuitively enough, independent tracking control of n positional degrees-of-freedom and n values of compliance at joints requires at least $2n$ actuators. The simplest configuration of an intrinsically compliant joint, illustrated in fig.1, utilizes two actuators connected to the same joint in an antagonistic arrangement through mechanically compliant elements (e.g., springs). It can be easily seen that, in order to be able to independently control the joint position and its stiffness, it is necessary that the stiffness characteristics of the springs are nonlinear. Indeed, the joint torque τ at joint angle q, corresponding to actuator angles θ_1 and θ_2, is simply given by

$$\tau = R\left[k_1(Rq - r\theta_1) + k_2(Rq + r\theta_2)\right]$$

with R the radius of the joint pulley in fig.1, r the radius of the actuator pulleys, and k_1, k_2 the stiffness of springs. Effective joint stiffness s is evaluated as

$$s = \frac{\partial \tau}{\partial q} = \\ R^2(k_1 + k_2) + R\left[\frac{\partial k_1}{\partial q}(Rq - r\theta_1) + \frac{\partial k_2}{\partial q}(Rq + r\theta_2)\right]$$

and is clearly indepedent of actuator angles if k_1, k_2 are constant. It follows that, for a passive compliance scheme such as that of fig.1 to allow tuning compliance, it is necessary to have nonlinear springs with deformation-dependent stiffness. For instance, assuming quadratic spring stiffness laws $k_1(q) = k(Rq - r\theta_1)$, $k_2(q) = k(Rq + r\theta_2)$ (we assume that springs are always stretched), one would get

$$\begin{array}{rcl} \tau & = & Rk\left[(Rq - r\theta_1)^2 - (Rq + r\theta_2)^2\right] \\ s & = & 2rR^2k(\theta_1 + \theta_2). \end{array} \qquad (2)$$

A desired torque and joint stiffness could then be set by solving this system of two nonlinear equations in θ_1, θ_2.

The nonlinearity of (2), along with the difficulty in building springs with desired elastic characteristic, made the usage of nonlinear springs not satisfactory in our application.

Another possibility to build controllable compliance is to use McKibben actuators. These are pneumatic actuators consisting of an inner inflatable tube, closed at the ends and surrounded by braided cords. Chou and Hannaford [7] provided a detailed analysis and an accurate yet simple model of McKibben actuators, which can be written as

$$f = (kL^2 - b)p$$

where p denotes the pressure in the inner tube, L the actuator length, f the force applied at its ends, k and b two constant parameters depending on constructive details. The model is valid under the condition that $\sqrt{b/k} < L_{min} \leq L \leq L_{max}$, which implies $f > 0$. We will henceforth assume actuators to work in such operating region. For the i–th robot joint actuated by two McKibben actuators in antagonistic arrangement as shown in fig.2, one can easily derive the relationship among control pressures $p_{i,1}$, $p_{i,2}$ and joint torque τ_i and stiffness s_i as

$$\begin{array}{rcl} \tau_i & = & \phi_{i,1}p_{i,1} - \phi_{i,2}p_{i,2} \\ s_i & = & \phi'_{i,1}p_{i,1} - \phi'_{i,2}p_{i,2} \end{array} \qquad (3)$$

where

$$\begin{array}{rcl} \phi_{i,1} & = & R_i\left[k_{i,1}(L_{i,1-max} - q_iR_i)^2 - b_{i,1}\right] \\ \phi_{i,2} & = & -R_i\left[k_{i,2}(L_{i,2-min} + q_iR_i)^2 - b_{i,2}\right] \\ \phi'_{i,1} & = & \frac{\partial \phi_{i,1}}{\partial q_i} = \\ & & -2R_i^2k_{i,1}(L_{i,1-max} - q_iR_i) \\ \phi'_{i,2} & = & \frac{\partial \phi_{i,2}}{\partial q_i} = \\ & & -2R_i^2k_{i,2}(L_{i,2-min} + q_iR_i) \end{array}$$

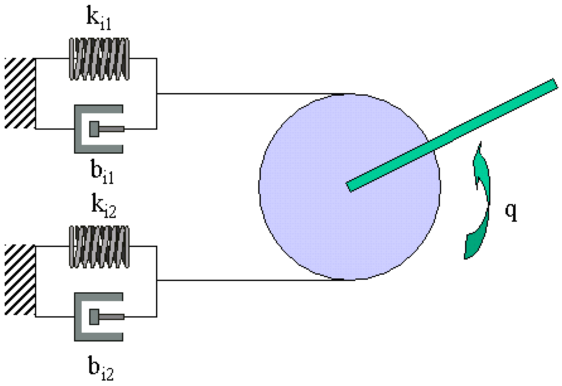

Figure 2: Model of a joint actuated by two antagonistic McKibben motors.

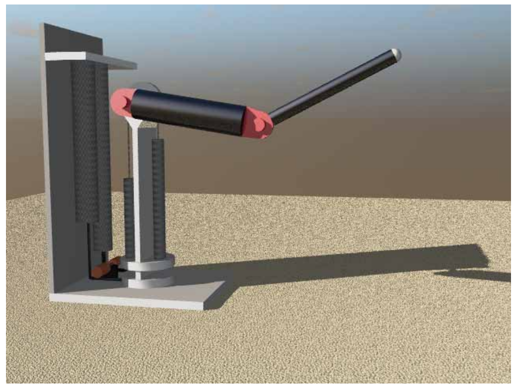

Figure 3: Appearance of the three d.o.f.'s intrinsically compliant robot arm.

In this case, the map (3) from control pressures to joint torque and stiffness is linear, and always invertible: indeed, it can be easily checked that

$$\det \begin{bmatrix} \phi_{i,1} & \phi_{i,2} \\ \phi'_{i,1} & \phi'_{i,2} \end{bmatrix} < 0 \tag{4}$$

in the operating region for the actuators.

4 Design and control of a compliant robot arm

Based on the previous analysis of Mckibben-actuated joints, the possibility of independently tracking position and compliance references for all joints of a robot arm can be easily established. Indeed, the dynamic model of the arm can be written in this case as

$$B(q)\ddot{q} + c(q,\dot{q}) = \tau = \Phi(q)p$$

where $q, \tau \in \mathbb{R}^n$ are the vectors of joint angles and torques, while $p \in \mathbb{R}^{2n}$ is the vector of actuator pressures; $c(q,\dot{q})$ summarizes gravitational, Coriolis and centrifugal forces, and $\Phi(q) \in \mathbb{R}^{n\times 2n}$ is given by $\Phi(q) = \mathsf{diag}\,([\phi_{i,1} \quad -\phi_{i,2}])$ (see (3)). An input-state-output model is obtained by setting $\xi = [\xi_1, \xi_2] \in \mathbb{R}^{2n}$, with $\xi_1 = q$, $\xi_2 = \dot{q}$, and is written as

$$\begin{array}{rcl} \dot{\xi}_1 & = & \xi_2 \\ \dot{\xi}_2 & = & -B^{-1}c(q,\dot{q}) + B^{-1}\Phi p \\ y_1 & = & \xi_1 \\ y_2 & = & s = \Phi' p, \end{array} \tag{5}$$

where the second group of outputs represent the vector of joint stiffnesses $s = [s_1, \cdots, s_n]$, and $\Phi' = \mathsf{diag}\,([\phi'_{i,1} \quad -\phi'_{i,2}])$ (see (3)). The system in (5) can be exactly linearized by static state feedback. Indeed, the decoupling equation for system (5) is

$$\begin{bmatrix} \ddot{y}_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} -B^{-1}c(q,\dot{q}) \\ 0 \end{bmatrix} + \begin{bmatrix} B^{-1}\Phi \\ \Phi' \end{bmatrix} p$$

The decoupling matrix $E(\xi) = \begin{bmatrix} B^{-1}\Phi \\ \Phi' \end{bmatrix}$ is invertible within the operating region of McKibben actuators (this follows directly from (4) and from the fact that $B(q)$ is invertible). Because outputs in the first group all have relative degree 2, while outputs in the second group have relative degree 0, the total relative degree is exactly $2n$, which proves feedback linearizability. A control law for tracking a positional reference $\hat{q}(t)$ and compliance $\hat{s}(t)$ can then be written as

$$p = E(\xi)^{-1}\cdot \cdot\left(\begin{bmatrix} B^{-1}c(q,\dot{q}) \\ 0 \end{bmatrix} + \begin{bmatrix} K_p(\hat{q}-\xi_1) + K_v(\dot{\hat{q}}-\xi_2) \\ 0 \end{bmatrix} \right)$$

which will guarantee asymptotic tracking of positions for suitable gains K_p, K_v. As for stiffnesses, being directly coupled to inputs by an algebraic relation (the relative degree is zero for these variables), no transient shaping is needed in this model (however, in implementations, it might be worthwile to introduce an integrator on the inputs so as to dominate unmodelled dynamics).

An undergoing project at our laboratory aims at building a three d.o.f. arm with mechanical, controllable compliance. The arm, pictorially described in fig.3, has anthropomorphic kinematics, and is actuated by a set of six McKibben acuators in the antagonistic arrangement discussed previously. Actuators are placed directly within the links, and are controlled by proportional pneumatic servovalves. At this stage, we have built all actuators and one link of the robot. Several experiments on the actuators showed that while Chou and Hannaford's model [7] is accurate and simple enough to be suited for analysis, a more detailed model of our actuators was necessary for the purposes of realistic simulation of the mechanism in contact with intruders in its workspace. The detailed model has been validated experimentally, and provided satisfactory results on a single joint setup, that will be reported elsewhere. By the time of presentation of this research, we hope to be able to show results concerning the whole arm.

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