Design, Realization and Control of Soft Robot Arms for Intrinsically Safe Interaction with Humans

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Robots designed to share an environment with humans, such as e.g. in domestic or entertainment applications or in cooperative material-handling tasks ([1, 18]), must fulfill different requirements from those typically met in industry. It is often the case, for instance, that accuracy requirements are less demanding. On the other hand, a concern of paramount importance is safety and dependability [11] of the robot system. According to such difference in requirements, it can be expected that usage of conventional industrial arms for anthropic environments will be far from optimal.

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 [7]) and changing their controllers. However, it is well known 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 bandwidth (basically dictated by mechanism inertia and friction) is not matched to the task (see e.g. [27]). 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. Accuracy in positioning and stiffness tuning would then be recovered by suitable control policies. This approach is clearly closer in inspiration to biological muscular apparatuses than to classical machine-tool design, which has inspired most robotics design thus far.

Several projects are being pursued in research labs towards the design of passively compliant, biologically inspired arms. Particular attention has been devoted to the development of suitable actuators (see e.g. [15, 16, 6, 25, 24, 2]). Studies on the organization of motor control in humans (see e.g. [17, 12, 10, 22, 3]) have been used to inspire control architectures of anthropomorphic robots (e.g., [23, 19]).

In this paper, we describe our approach to intrinsically safe robot arm design, and a prototype arm built in our laboratory. The main characteristic of the arm is that it introduces relatively high, controllable compliance at the mechanical level. The arm is designed to achieve 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. On the other hand, modern control techniques are adopted to recover accuracy in positioning and in tuning the arm compliance to accomplish tasks which require those features.

1 Compliance of Robot Arms

Methods for achieving compliance in robot manipulators have been studied since very early in the robotics literature.

Most of the work has been concerned with task–space specifications of compliance of the end–effector with respect to a desired posture, or reference trajectory ([26, 14]). The basic idea of 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 (see fig.1, top). However, these approaches may not prove robust with respect to such model nonidealities as e.g. friction and backlash in transmission ([27]), 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 or delays in feedback (fig.1, middle).

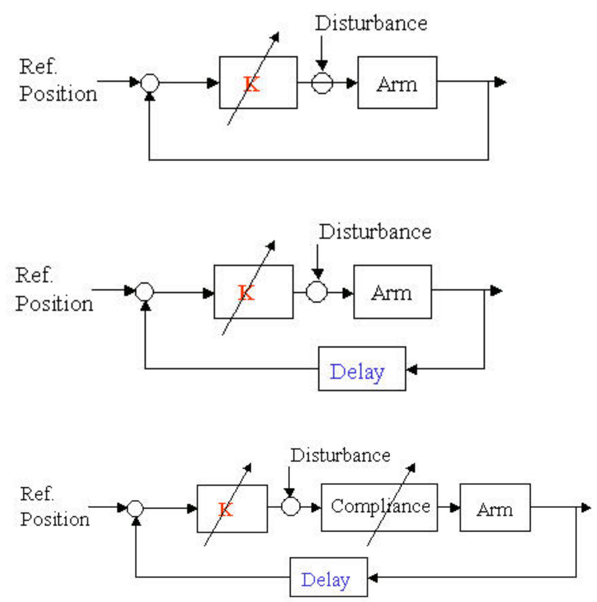

Figure 1: The classical approach to stiffness and impedance control amounts to independently tuning the set-point and the gains of a position controller (top). If applied to a rigid arm, the insufficient mechanical bandwidth of actuators and transmission may not allow the controller to take suitable contermeasures to unexpected collisions of the arm (middle). To guarantee higher priority to safety than to performance, a certain amount of passive (mechanical) compliance can be purposefully introduced in the system, while advanced control can be used to recover accuracy (bottom).

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, by e.g. including compliant transmission so as to 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 (fig.1, bottom.). The role of control design with passively 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.

A first possibility to realize robot arms with a low damaging potential to interacting humans is to have large mechanical compliance of the transmission between actuators and arm joints. By these means, indeed, the effective inertia at an impact of the arm is reduced with respect to rigid transmission, by decoupling the contribute of actuators' moving parts. This is particularly important for electrical motors using high reduction-rate gearboxes, also in view of their usually high static friction, which may prevent backdrivability. In many applications, however, the arm may have to perform different tasks, for which different compliance may be necessary. Hence, the need for a different type of robot arm design, with passive and tunable compliance. Robots arms of this type will be referred to as "soft", and will be considered in detail in the rest of this paper.

Perhaps, the simplest configuration of a soft joint actuation system is that illustrated in fig.2. Here, two actuators are connected to the same joint in an agonistic-antagonistic arrangement through mechanically compliant elements (depicted as springs). It is important to notice that actuators are conservatively assumed here to be "position sources", rather than "force sources": in other words, we assume that set-point positions θ_1, θ_2 are maintained by the actuators despite changes of the applied forces. In other words, the effective compliance of the manipulator arm will not rely on any closed-loop control on actuators (although the set-points can be changed by the controllers, we do not want to rely on this to ensure safety). The torque τ applied to the joint,

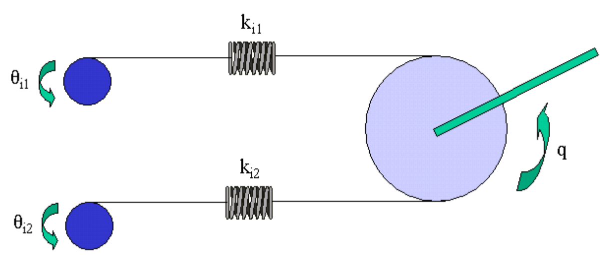

Figure 2: An agonistic-antagonistic arrangement of two actuators on a joint to control joint position and stiffness independently.

corresponding to a joint angle q, actuator angular positions θ_1 and θ_2, is given by

$$\tau = R\left[k_1(r\theta_1 - Rq) + k_2(r\theta_2 + Rq)\right] \qquad (1)$$

with R the radius of the joint pulley, r the radius of the actuator pulleys, and $k_1(q,\theta_1), k_2(q,\theta_2)$ denote the transmission stiffness functions. The effective joint compliance is defined as the infinitesimal variation of the joint angle corresponding to an infinitesimal change of external torque at the joint, while actuator inputs are held constant. The inverse of this quantity, i.e. the effective joint stiffness σ, is simply evaluated as

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

It can be easily observed that, if transmission stiffnesses k_i are constant, the joint stiffness is independent of the actuator inputs. In this case, indeed, only joint position regulation would be allowed, while the joint stiffness remains constant ($\sigma = R^2(k_1+k_2)$), independently from θ_1, θ_2 (and from q). On the other hand, a nonlinear transmission stiffness $k_i(q,\theta_i)$ may allow the simple passive compliance scheme above to allow tunable compliance.

More generally, we will refer to a whole class of possible agonistic-antagonistic actuator arrangements by defining the characteristic function of a joint,

$$\tau = \phi(q,\theta) \qquad (2)$$

which models the generation of the effective torque at the joint, τ, as a function of the joint position, q, and of the m joint actuators commands, collected in the joint reference vector $\theta \in \mathbb{R}^m$. For such a model, the open-loop joint stiffness is defined as the infinitesimal variation of joint torque coresponding to an infinitesimal variation of the joint position, while actuator inputs are kept constant, i.e.

$$\sigma = \frac{\partial\phi(q,\theta)}{\partial q} \qquad (3)$$

Let

$$\begin{bmatrix} \tau \\ \sigma \end{bmatrix} = \Psi_q(\theta)$$

denote the map $\mathbb{R}^m \to \mathbb{R}^2$ from actuator inputs to joint torque and stiffness. In general, it will be possible to control the torque and the stiffness independently in the vicinity of an equilibrium configuration $\bar{q}$ with inputs $\bar{\theta}$, if $\psi_q(\theta)$ is injective, hence the condition

$$\mathsf{rank}\ \frac{\partial\Psi_q(\theta)}{\partial\theta} = 2.$$

Assuming this condition is met, and that two actuators are connected to the joint ($m = 2$), the joint characteristic functions can be inverted (at least locally) to obtain

$$\theta = \widehat{\Psi}_q(\tau,\sigma)$$

Actuator commands can be distinguished between effective torque-generating commands θ_t, i.e. those which modify τ leaving unaffected σ; and co-contraction commands θ_c, which modify the joint stiffness without affecting joint balance. Explicitly, we let

$$\begin{aligned} \theta_t(\tau) &= \widehat{\Psi}_q(\tau, \sigma = const.) \\ \theta_c(\sigma) &= \widehat{\Psi}_q(\tau = const., \sigma) \end{aligned}$$

When building a "soft" robot arm with tunable, passive compliance, multiple actuators have to be connected to the arm's joints. Several arrangements are in general possible to map actuators to joint torques: for instance, the Salisbury hand [21] achieved a single-parameter tunable compliance for each of its fingers by actuating the three joints of the fingers by four independently driven tendons. In our design, however, we are interested in the capability of tuning the compliance of all joints independently, and will hence refer to the case that an arrangement of (at least) two actuators per joint is adopted.

2 Actuators for passive compliance control.

In this paragraph we consider the design of actuators systems that could be used to control independently joints position and stiffness of a robot arm, providing two examples that can be easily implemented in practical devices.

A first type of passive, tunable compliance joint can be obtained by the use of conical compression springs. The force-length relationship of conical springs, such as that depicted on the left in fig.3, is a function of several design and material parameters (such as upper and lower coil diameters, wire diameter, spring length, number of coils, elasticity and shearing moduli of the steel, etc.), which can be accurately evaluated by mechanical engineering CAD software packages. An example of the characteristic line (force path diagram) of a conical helical compression spring obtained by the Hexagon©Spring Software [13], is reported on the right of fig.3. Notice that the characteristic line becomes progressively steeper at the point where the larger coils begin to touch. By careful de-

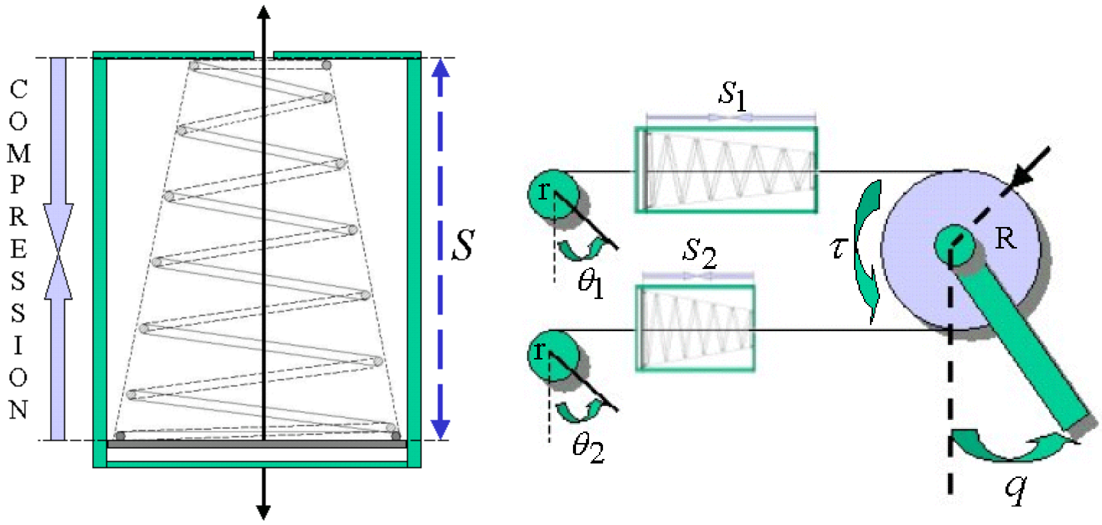

Figure 4: A possible arrangement of electrical actuators, tendons and conical springs to achieve tunable compliance at a robot joint.

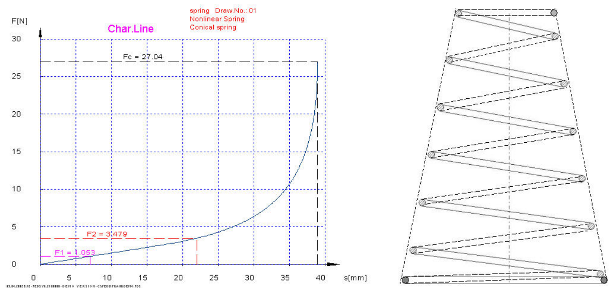

Figure 3: Conical compression spring: force-length characteristics and design.

sign and suitable preloading, conical springs can be made to work in the nonlinar region, where the force path is approximately parabolic. Notice that the nonlinear behaviour can only be obtained by compression of a conical spring. A possible scheme to apply conical springs to actuate robot joints using flexible tendons is reported in fig.4. To compute the joint characteristic function for the arrangement in fig.4, let us assume that in the working region the force path of each conical spring can be simply modeled by a parabolic law as

$$F_s = \gamma s^2,$$

where F_s represents the spring force, γ is a constant parameter that depends on constructive details, and s is the contraction of the spring.

The inputs to the joint are the angular positions of the two motors, i.e. $\theta = (\theta_1, \theta_2)^T$. Hence, the joint torque characteristic function is

$$\tau = \phi(q, \theta) = \gamma R(s_1^2 - s_2^2),$$

where $s_1 = (\theta_1 r - qR)$ and $s_2 = (\theta_2 r + qR)$ are the spring deformations (positive if compressive). The joint stiffness is easily evaluated as

$$\sigma = \frac{\partial \tau}{\partial q} = 2\gamma R^2 (s_1 + s_2).$$

That the compliance can be tuned independently from the applied torque can be checked by verifying that

$$\mathsf{det} \begin{bmatrix} 2\gamma R r s_1 & -2\gamma R r s_2 \\ -2\gamma R^2 r & -2\gamma R^2 r \end{bmatrix} = -4\gamma^2 R^3 r^2 (s_1 + s_2)$$

is not zero, provided that both springs are in compression (which has of course to be the case, in order for the tendons to be in tension in the arrangement of fig.4). Indeed, for this arrangement, the inverse map $\widehat{\Psi} : (\tau, \sigma) \mapsto \theta$ providing the motor angular positions corresponding to a desired torque and stiffness, can be explicitly evaluated as

$$\begin{cases} \theta_1 = \frac{R}{r} q + \frac{R^2 \tau}{\sigma} + \frac{\sigma}{4\gamma R^2} \\ \theta_2 = -\frac{R}{r} q - \frac{R^2 \tau}{\sigma} + \frac{\sigma}{4\gamma R^2} \end{cases} \quad (4)$$

Another possibility to build tunable compliance is to use McKibben actuators (fig.5). As it is well known, these are pneumatic actuators consisting of an inner inflatable tube, closed at the ends and surrounded by braided cords. Chou and Hannaford [8] provided a detailed analysis and an accurate, yet simple model of McKibben actuators, which can be summarized 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

Figure 5: A McKibben pneumatic artificial muscle built in our laboratory.

a robot joint actuated by two identical McKibben actuators in antagonistic arrangement as shown in fig.6, the joint characteristic functions for joint torque τ and stiffness σ, assuming commands to be control pressures, $\theta = (p_1 \, p_2)^T$, are obtained as

$$\begin{array}{rcl} \tau &=& \phi_1\theta_1 - \phi_2\theta_2 \\ \sigma &=& \phi_1'\theta_1 - \phi_2'\theta_2 \end{array} \tag{5}$$

where

$$\begin{array}{rcl} \phi_1 &=& Rk(L_1^2 - L_{min}^2) \\ \phi_2 &=& Rk(L_2^2 - L_{min}^2) \\ \phi_1' &=& -2R^2kL_1 \\ \phi_2' &=& -2R^2kL_2 \end{array}$$

In this case, it holds
$d = \mathsf{det}\,\frac{\partial\Psi_q(\theta)}{\partial\theta} = -2R^3k^2[L_2(L_1^2 - L_{min}^2) + L_1(L_2^2 - L_{min}^2)]$
which is strictly less than zero in the operating region for the actuators, where they are stretched

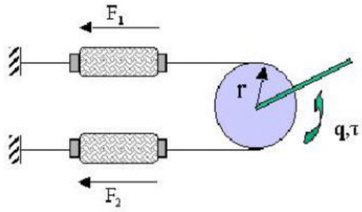

Figure 6: Model of a joint actuated by two antagonistic McKibben actuators.

to less than their minimum length. Hence, the map (5) from control pressures to joint torque and stiffness is invertible:

$$\theta = \left[\begin{array}{c} -\frac{1}{d}2R^2kL_2 \\ \frac{1}{d}2R^2kL_1 \end{array} \right] \tau + \left[\begin{array}{c} \frac{1}{d}Rk(L_2^2 - L_{min}^2) \\ \frac{1}{d}Rk(L_1^2 - L_{min}^2) \end{array} \right] \sigma. \tag{6}$$

The linearity of this inverse ensues that the space of actuator commands can be regarded as the cartesian product of the two subspaces of torque-generating commands and co-contraction commands.

3 Problems in controlling passively compliant arms

In this section, we will review some of the problems that are encountered when controlling passively compliant arms, providing pointers to papers where these problems have been solved, or pointing at important open problems.

The problem of controlling flexible arms has been studied extensively in the robotics literature since early times, in relation to both link flexibility ([29]) and joint compliance [30]. Techniques for accurately controlling positions in these cases exist, which are based on advanced nonlinear control techniques (see e.g. [9]). These typically assume knowledge of accurate models of compliance and inertial parameters.

If such knowledge is not available, adaptive control methods that could cope with such uncertainties should be used. The problem of adaptation to uncertain inertial parameters, in the presence of known elasticity, has been widely studied (see e.g. [5]). Adaptation to unknown stiffness parameters is a tougher problem, though, due to the fact that compliance parameters enter nonlinearly in the dynamic equations.

Some preliminary results in this directions have been recently obtained ([4]), showing that unknown but constant flexible joint models can be identified measuring only link positions. This capability can be used to build an adaptive controller for position tracking with robot arms that have large unknown joint compliance. Another possible approach, explored e.g. in [20], is to use learning control techniques.

Although accurate control of arms with large, constant (or mechanically adjustable) joint flexibility is to be considered an important direction for research, we already pointed out that in many applications robots may have to perform different tasks, for which different compliance may be necessary. Hence, the need for soft arms with a passive but tunable compliance.

The general model of an n degrees of freedom robot arm, actuated by a tunable compliance actuation system, can be given as

$$B\ddot{q} + h(q, \dot{q}) = \phi(q, \theta) \tag{7}$$

where q and θ will be regarded, from now on, as the vector of joint angles and of actuator command values, respectively. Actuator dynamics should in general be considered to be coupled with (7), which may have the form

$$\begin{array}{rcl} \dot{x} & = & f(x, q) \\ \Theta & = & h(x, q) \end{array} \tag{8}$$

For instance, in nonlinear spring actuator arrangements, one would have to consider for the latter

$$\begin{cases} J_1\ddot{\theta}_1 + \gamma S_1^2 R = \tau_1 \\ J_2\ddot{\theta}_2 + \gamma S_2^2 R = \tau_2 \end{cases}$$

with s_1, s_2, R, r as above specified, J_1, J_2 the moments of inertia of the electric motors and τ_1, τ_2 the actuator torque vectors. For the McKibben actuator arrangement, the dynamics of the electrovalve and air conduits should be considered. In some cases, for the sake of simplicity, it may be assumed that the response of actuators to commands is locally regulated by a quick and accurate inner control loop (as e.g. in fig.7), so that one can assume Θ to be directly available as a control input. An important control objective is to guarantee that arbitrary trajectories of the end–effector can be controlled while stiffness is controlled to desired values, without the two specifications intefering with each other (decoupled control). Some results in this direction have been presented in [4].

Naturally, the dynamic control of tunable compliant arms inherits many of the problems with the control of flexible arms, but only partially can they enjoy solutions provided in that field. A key difference is the presence of essential nonlinearities in the model of soft arms, which obviously make control much harder. This is particularly true when an exact model of the system parameters is not available, and adaptation is necessary.

A possibility to independently control the position and the stiffness of a soft robot arm is to adopt the Internal Model approach used in the biomechanical theory of human motion [17]. This theory admits the existence of a (learned) dynamic model of the human arm in its sensory-motor control. Such model, with unknown constant parameters, is continuously adapted by a feedback adaptive control, that generates the model parameters estimation [28].

4 Design, realization and preliminary experiments with a "Soft Arm"

As discussed in the previous sections, our approach at designing intrinsically safe robot arms is to use agonistic-antagonistic, compliant arrangements of actuators, in a rather anthropomorphic fashion.

The three degrees of freedom robot arm developed in our laboratory presents also has anthropomorphic kinematics (fig.8), lightweight structure. The current version employs McKibben artificial muscles, and is endowed with a simple light-weight gripper (see fig.9)

The control hardware of the Soft Arm is represented by a 333Mhz PC Workstation, three position feedback linear potentiometers, an ADC ADAC 5803HR and a DAC Advantech PCL726 boards. The pressures are controlled in the pneumatic muscles by six pneumatic servovalves SMC ITV2050. The arm has no sensors, except for joint position encoders: in particular, all interaction tasks are performed without measuring contact forces, which are kept within acceptable limits by virtue of the compliant structure of the arm.

Preliminary experiments in human–robot interaction, with disturbances at different frequencies induced by the operator in the structure (fig.10), have been focused on testing the mechanical robustness of the robot arm and the capability of the control system to varying the system bandwidth (in other words, the robot capability to interact with the environment with more or less sensibility with respect to external unpredictable distubances or controller delays or failures). One important result is that the use of intrinsic compliant actuators, instead of "rigid actuators", such as electric

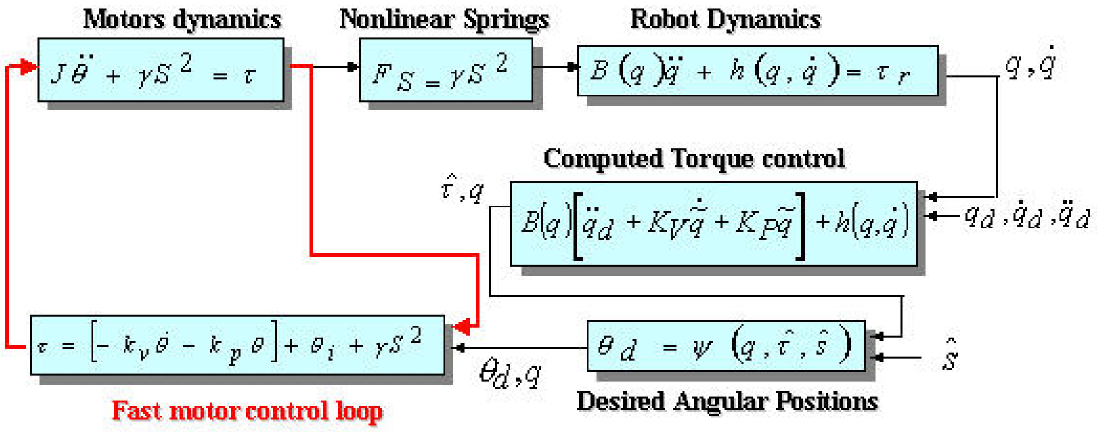

Figure 7: Nonlinear actuators control system where, in particular, q_d, θ_d are, respectively, vectors containing the desired joints and motors positions and Ψ represents the map between the joint torques and stiffness in equation (4). The fast inner control loop of the actuators is highlighted.

motors, and the possibility to varying the "open–loop" joints compliance (the variable σ in the previous sections), increase the robot arm robustness with respect to unmodelled disturbances.

Figure 8: The Soft Arm is a lightweight structure actuated by McKibben artificial muscles in antagonistic pairs with an antropomorphic kinematics.

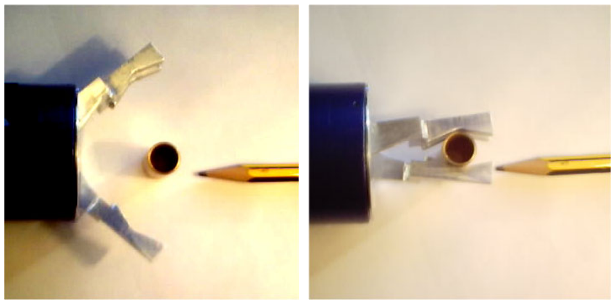

Figure 9: The light-weight gripper.

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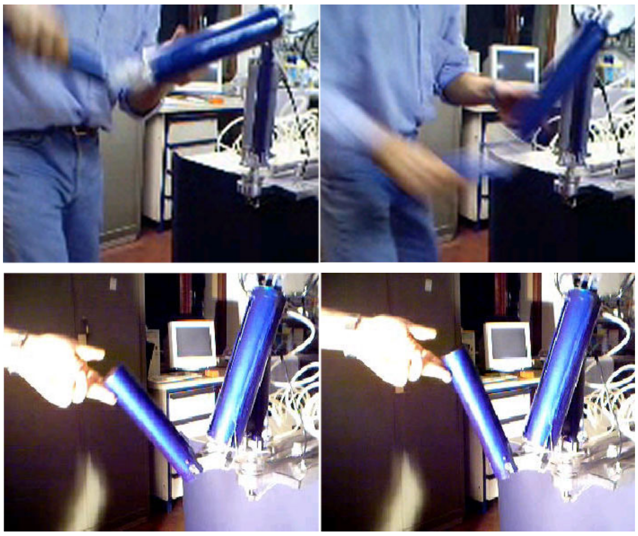

Figure 10: Experiments in Human–Robot interaction: high (left) and low frequency (right) interaction.

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