

# Compliant control for a cable-actuated anthropomorphic robot arm: an experimental validation of different solutions

Loredana Zollo\*, Bruno Siciliano<sup>o</sup>, Cecilia Laschi\*<sup>(1)</sup>, Giancarlo Teti\*, Paolo Dario\*

\*ARTS Lab (Advanced Robotics Technology and Systems Laboratory)  
Scuola Superiore Sant'Anna  
via Carducci 40 - 56127 Pisa, Italy  
Phone: +39-050-883400, Fax: +39-050-883402  
E-mail: {l.zollo, c.laschi, g.teti, p.dario}@mail-arts.sssup.it

<sup>o</sup>PRISMA LAB - Dipartimento di Informatica e Sistemistica  
Università degli Studi di Napoli Federico II  
Via Claudio 21 - 80125 Napoli, Italy  
Phone: +39-081-7683179, Fax: +39-062-33226128  
E-mail: siciliano@unina.it

## Abstract

*This paper presents a research work on compliant control of an anthropomorphic robot arm used as a 'personal robot', for assistance to humans in different aspects of their everyday life. In personal applications of robotics, human-robot interaction represents a critical factor for a robot design and introduces strict requirements on its behavior and control, which has to ensure safety and effectiveness. In this work, the problem of controlling the Dexter anthropomorphic robot arm with variable compliance has been investigated, not only to ensure safety in the interaction with humans, but especially to increase the robot functionality in tasks of physical interaction, performed in co-operation with humans.*

*Two different control schemes have been formulated and implemented on the peculiar structure of the robotic arm, so as to compare their performance through experimental trials. Both schemes aim at realising a self-controlled compliant behavior without using information from force/torque sensors.*

*The experimental comparison outlines how the performance of the two control systems are inverted with respect to the theoretical considerations, based on the classical control theory, on their accuracy and effectiveness.*

*The paper firstly describes the two implemented control systems; then, the performance of the two controllers in the experimental trials are shown and compared, and the functional compliance of the better one is graphically demonstrated.*

## 1 Introduction

In addition to the more and more sophisticated solutions required in industrial robotics, research on robot control has to face new scientific challenges, introduced by the application of robotics in services and personal assistance of human beings [1,2]. Control of robots designed and employed in the service of humans, in their everyday life activities and in their environment, has to face the problems related to human-robot interaction, at least at three levels:

- as robots and humans share the same environment, dynamic and mostly unstructured for the robot, safety must be guaranteed, so that robot movements are not dangerous for possible injuries to humans, nor to the environment or the robot itself;

- as personal robots are intended to provide support and assistance to humans, they should be able to get in touch with the user, move things in contact or around him/her, in most cases in accordance with his/her own movements [3,4];
- nevertheless, personal robots are also meant to accomplish service tasks for humans, e.g. at home, and are supposed to autonomously act in their partially known environment with a good accuracy [3].

For these reasons, research on robot control in this application context has to cope with the very delicate problem of finding a trade-off between personal safety in human-robot interaction and accurate execution of autonomous tasks. In the co-operation with humans, the human-robot interaction problem is faced with an adequate compliant control; instead, in the execution of well-assigned tasks in the autonomous mode accuracy and precision become the main target. But situations of unexpected transition from unconstrained motion (autonomous mode) to constrained motion (interaction) can occur.

Then, the property to pass from a stiff robot behavior in the free space to the compliant behavior in the constrained motion has been investigated in this work.

In the history of interaction control, compliant control, impedance control or hybrid position/force control can be traced. The pioneering force control work by Whitney and others [5,6] proposed a controller based on shaping of the end-effector impedance (*active accommodation matrix*) for each task. The target tasks of Whitney's research, and also of the research in *active compliance* [5,7,8] or in the more generic *impedance control* methods [9-11], were assembly and part mating tasks. The objective of impedance control was to regulate the mechanical impedance of robot end-effector. The hybrid position/force control approach to constrained motion [12] cannot be considered in personal applications where the interaction environment is unstructured and not completely known.

This paper presents the theoretical description of two proposed control schemes, the compliant control systems with self-regulating compliance in Cartesian space and in joint space respectively. These are capable to autonomously regulate robot compliance in the free space or in an unplanned constrained motion, without using either the robot dynamic model or the measures of the contact forces. The paper then illustrates how the control

<sup>(1)</sup> Currently JSPS Fellow at the Humanoid Robotics Institute of the Waseda University in Tokyo, Japan.

systems have been developed and implemented on the cable actuated anthropomorphic Dexter robot arm [4].

Finally, the paper reports the comparative experimental trials, which lead to recognizing the compliant control scheme in the joint space as the better of the two controllers, because it can manage both the joint coupling and the accuracy-compliance trade-off. A demonstration of its capability of self-controlling the compliance and the interaction force is provided in the experimental section.

## 2 Theoretical description

Robot dynamics can be synthesized through the following balance of torques:

$$B(q)\ddot{q} + C(q, \dot{q})\dot{q} + F\dot{q} + g(q) = \tau - J^T(q)h$$

where:

- $B(q) \in \mathbb{R}^{n \times n}$  is the joint inertia matrix ( $n$  is the joint space dimension);
- $q$  is the  $n \times 1$  joint vector;
- $\ddot{q}, \dot{q}$  are the joint acceleration and velocity vectors;
- $C(q, \dot{q})\dot{q} = \dot{B}(q, \dot{q})\dot{q} - \frac{1}{2} \left( \frac{\partial}{\partial \dot{q}} (\dot{q}^T B(q) \dot{q}) \right) \in \mathbb{R}^{n \times 1}$  is the vector of centrifugal and Coriolis torque;
- $F$  is the diagonal, positive definite matrix of joint viscosity coefficients;
- $g(q) \in \mathbb{R}^{n \times 1}$  is the vector of joint gravitational torque;
- $J^T(q)h$  is the joint torque vector due to the force  $h$  acting on the end-effector.

The compliant control scheme requires only the knowledge of the gravitational torque vector  $g(q)$ .

The control law can assume one of the two following expressions, depending on the space of definition of the position error [13,14].

$$\tau = J_A^T(q)K_p \tilde{x} - K_D \dot{q} + g(q)$$

is the mathematical formulation of the compliant control system in the Cartesian space, being  $\tilde{x} = x_d - x$  the Cartesian position error.  $x_d$  and  $x$  include respectively the desired Cartesian position vector and orientation vector and the actual Cartesian position vector and orientation vector. The relation  $J_A = H^{-1}J$ , where  $H(\phi_e)$  is depending on the transformation matrix between the end-effector angular velocity and the derivatives of the Euler angles.

Instead,

$$\tau = K_{PQ} \tilde{q} - K_D \dot{q} + g(q)$$

is the compliant control law if the joint space is chosen for the definition of the position error ( $\tilde{q}$  is, in fact, the joint position error).

Both control systems are characterized by a proportional-derivative contribution, added to a term of gravity compensation. The PD term acts directly on the different Cartesian directions through the matrix  $K_p$  in the compliant control scheme in Cartesian space, whereas it acts directly on the robot joints, through  $K_{PQ}$ , in the compliant control system in joint space. The robot is

considered as a mechanical system which presents an  $n$ -dimensional generalized spring, regulated by the rigidity coefficients of the matrix  $K_{PQ}$ . If  $K_{PQ}$  is diagonal the robot can be seen as a system of  $n$  independent springs applied at each joint.  $K_D$ , instead, is a diagonal matrix that controls the damping velocity at each joint.

A self-controlled compliance function can be adopted to satisfy the two targets of automatically varying the level of stiffness during the transition from the free space motion to the constrained space, where an unplanned impact against an obstacle or a person can occur, and of adapting the robot arm positions to the user movements and locations during the execution of personal tasks, such as to comb, to drink, to eat.

A fixed level of compliance can cause a very low accuracy if the compliance is too high, but, vice-versa, high interaction forces and too low adaptability if the compliance is low. So the choice of a variable compliance seems to offer a better level of adaptability, without using an explicit force control scheme, but only exploiting the information about joint position and velocity [15,16].

This corresponds to choosing a  $K_p$  matrix depending on the actual and desired Cartesian position in the controller in Cartesian space and a  $K_{PQ}$  matrix depending on the actual and desired joint position in the compliant control scheme in the joint space:

$$\tau = J_A^T(q)K_p(x, x_d)\tilde{x} - K_D(x, x_d)\dot{q} + g(q) \quad (1)$$

$$\tau = K_{PQ}(q, q_d)\tilde{q} - K_D(q, q_d)\dot{q} + g(q) \quad (2)$$

In both cases, the proportional gain is a diagonal matrix, even if not constant and  $K_D$  is related to it.

Finally, the term of gravity compensation represents a non-linear contribution, evaluated in real-time, to compensate the dynamics due to the gravitational torque. It is expressed by the masses  $m_p$  ( $p=1, \dots, n$ ) and the centers of gravity of each link ( $r_p = [r_{px} \ r_{py} \ r_{pz} \ 1]^T$ ,  $p=1, \dots, n$ ) as  $\tilde{g}(q) = [D_1 \dots D_n]^T$ , where  $D_i = \sum_{p=i}^n \left( -m_p g^T \frac{\partial {}^o T_p}{\partial q_i} r_p \right)$ ,  $g^T = [0 \ 0 \ -g$

$0]$  is the gravity acceleration vector ( $|g| = 9.8062 \text{ m/s}^2$ )

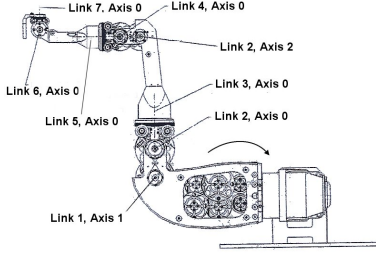
expressed in the base coordinate system and  ${}^o T_p \in \mathbb{R}^{4 \times 4}$  is the homogeneous transformation matrix between the  $p$ -system and the base system.

## 3 The compliant control strategy as applied to the Dexter arm

The two compliant control schemes described in the previous section have been readapted and implemented on the Dexter robot arm [4]. Dexter has an anthropomorphic 8 d.o.f. kinematic structure (8 revolute joints), composed of shoulder, elbow and wrist.  $J_0$ , the base joint, has an horizontal axis and aims at increasing the workspace in the vertical direction (Fig.1).

The arm mechanical configuration is not ever industrial: the 8 joints are not actuated singularly by a motor located on each link, but they are driven so as to generate human-

like movements. In fact, the motors for actuation of joints  $J_2, \dots, J_7$  are all installed on link 1 and for them the mechanical transmission system is realized with pulleys and steel cables. As a consequence a coupling in the degrees of freedom derives.



**Fig.1.** The Dexter mechanical structure

As joint 0 is heavy, dynamically complex and takes part only in a global positioning movement, the two control laws (1) and (2) act only on joints  $J_1, \dots, J_7$ .

A pre-defined trajectory for  $J_0$  has been planned and a PID controller has been used for its control.

The considered 7-joint robot arm has a redundant degree of freedom, since 6 d.o.f. are sufficient to position and orient the end-effector. Dexter redundancy is used to regulate the elbow position, by controlling the so-called ‘arm angle’ [17], denoted by  $\psi$ . The Jacobian matrix is then modified, including also the contribution of each joint to the elbow angle. Its dimension is  $7 \times 7$  if the base joint contribution is not considered.

### 3.1 Compliant control scheme in Cartesian space

Equation (1) is referred to the control of the Dexter arm in Cartesian space. Some variations have been introduced to take into account redundancy and decoupling between the regulation of the Cartesian position and the control of the orientation. An alternative Euler Angles formulation [13] has been used for the definition of the orientation error. The resulting control law regulates the compliance along the three Cartesian directions  $x, y, z$ , and controls the compliance in the orientation and also in the setting of the arm angle:

$$\tau = J^T \begin{bmatrix} K_{pp}(x, x_d) \tilde{p} \\ T_e^{-T}(\tilde{\varphi}) K_{pO} \tilde{\varphi} \\ k_\psi(x, x_d) \tilde{\psi} \end{bmatrix} - K_D(x, x_d) \dot{q} + g(q)$$

$J \in \mathbb{R}^{7 \times 7}$  is the robot Jacobian matrix;

$\tilde{p} = p_d - p$  is the Cartesian position error;

$\tilde{\varphi}$  is the orientation error;

$\tilde{\psi}$  is the elbow angle error;

$T_e = R_e T(\tilde{\varphi})$  and  $T(\tilde{\varphi}) \in \mathbb{R}^{3 \times 3}$  is the transformation matrix in a XYZ representation of Euler angles.

A self-controlled compliance function has been adopted to self-regulate the robot compliance during the motion. The compliance function is an exponential function whose argument is the Cartesian position error. In this way, when an obstacle occurs, compliance increases together

with the position error. Its velocity of decay is regulated by a scalar coefficient  $k$ .

Definitely,  $K_p$  is a block diagonal matrix of exponential functions expressed as:

$$K_p(x, x_d) = \text{block diag} \{ K_{pp}(x, x_d), K'_{pO}(\tilde{\varphi}), k_\psi(x, x_d) \}$$

$$K_{pp}(x, x_d) = \text{diag} [ K_{px} e^{-k_x |x_d - x|}, K_{py} e^{-k_y |y_d - y|}, K_{pz} e^{-k_z |z_d - z|} ]$$

$$K'_{pO}(\tilde{\varphi}) = T_e^{-T}(\tilde{\varphi}) K_{pO}$$

$$k_\psi(x, x_d) = K_\psi e^{-k_\psi |\psi_d - \psi|}$$

where  $K_{px}, K_{py}, K_{pz}, K_\psi$  are the proportional gains when no obstacle occurs, and  $K_{pO}$  has been chosen as a constant diagonal matrix, since the orientation proportional parameters are just low due to the joint coupling.

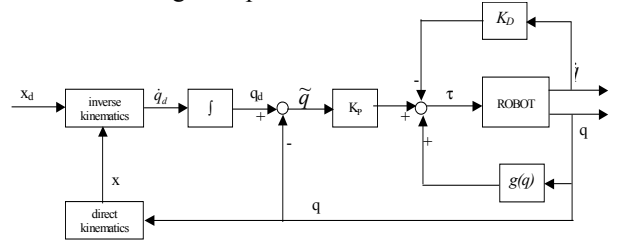
The damping velocity is self-regulated, too. The damping matrix  $K_D$  is directly derived from the  $K_p(x, x_d)$  function as follows:  $K_D(x, x_d) = \alpha J^T K_p(x, x_d) J$ , with  $\alpha$  a positive scalar coefficient. This choice provides a self-adjusted damping to prevent force responses from being too sluggish according to the changes of compliance of the system.

### 3.2 Compliant control scheme in joint space

The development on the Dexter arm of a compliant control scheme in joint space is based on equation (2) and requires an adequate algorithm of inverse kinematics to move from the Cartesian space, where the motion primitives are given, to the joint space, where the controller acts.

Also in the realization of the inverse kinematics, the Dexter robot arm has been considered as a 7 d.o.f. anthropomorphic arm with an extra-joint used to increase the reachable workspace. This choice avoids useless additional computational burden [18].

Joints  $J_1, \dots, J_7$  follow a desired trajectory through an kinematic inversion optimized by the redundancy. The extra degree of freedom, in fact, is used to generate a joint motion that regulates the  $\psi$  elbow angle without changing the end-effector global position.



**Fig.2.** Block scheme of compliant control system in the joint space with kinematic inversion.

The referred inverse kinematics is also robust to the singularities since a damped least-square inverse matrix is used in the inversion. The damping factor defines the trade-off between a zero inversion error and a limited joint velocity.

In view of the interaction environment-robot or human-robot, a self-regulating compliance has been introduced in

the control of joints 1..7 to autonomously vary joint compliance as a function of the position error and consequently of the joint error. In fact the joint position error increases over the time when an unplanned interaction occurs.

The proportional matrix in (2) presents exponential functions on the diagonal, as in the controller in the Cartesian space, but the arguments are the joint errors:

$$K_P(q, q_d) = \text{diag}\{K_{p1}e^{-k_1|q_{1d}-q_1|}, \dots, K_{p7}e^{-k_7|q_{7d}-q_7|}\}$$

$K_{p1}, K_{p2}, \dots, K_{p7}$  are the proportional gains when no obstacle occurs and  $k_i$  defines the velocity of decay of the stiffness at each joint.

The damping velocity is again related to the compliance function, through a positive scalar coefficient  $\alpha$ :

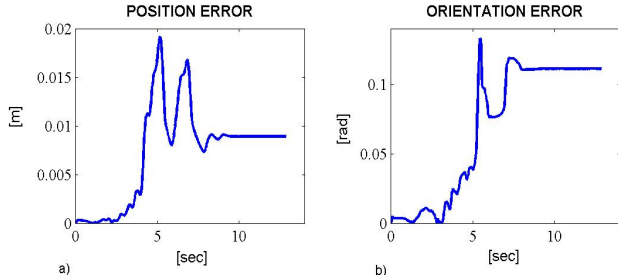
$$K_D(q, q_d) = \alpha K_{PQ}(q, q_d).$$

The two control laws, both in Cartesian space and in joint space, give a joint torque command. By the knowledge of the robot actuation system and the information about the coupling in the mechanical structure, the analog voltage motor commands are evaluated.

#### 4 Experimental comparative results

In order to verify which of the two controllers is more affordable, two sets of experiments have been executed. The first group consists of positioning the end-effector in the free space when the elbow angle is set to zero; the second session, instead, aims at analyzing the robot performance when a non-zero arm angle is required in the positioning task.

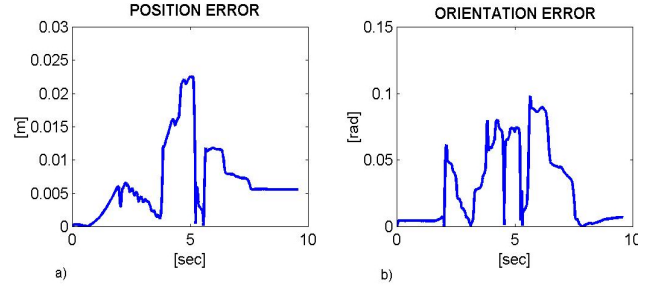
From a theoretical point of view, the development of a controller in Cartesian space is preferred as it is easy to implement, computationally convenient (it does not require any inverse kinematics algorithm) and, above all, it controls the robot directly in the operational space, where the motion actions are specified. In a few words, it would ensure a very smooth and harmonic motion and would be very functional as it provides the possibility of regulating the compliance in each of the Cartesian directions.



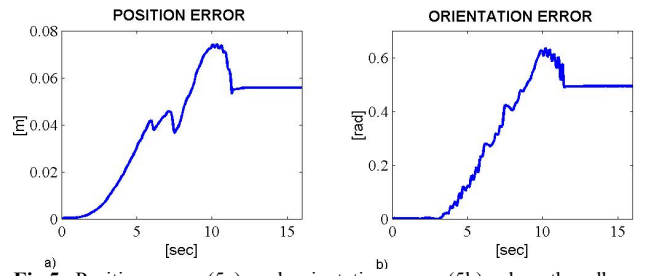
**Fig.3.** Position error (3a) and orientation error (3b) when the elbow angle is zero. The compliant control scheme in Cartesian space is used.

The first set of experimental trials together with the corresponding Figs. 3 and 4 confirms the theoretical considerations on the two control systems. A smoother motion, in addition to the capability of compliance

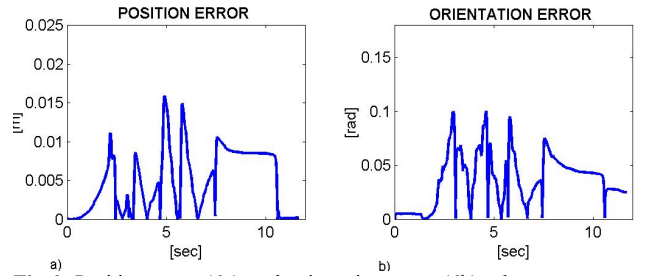
modulation, is confirmed by the use of a compliant control scheme in Cartesian space. Moreover the two control schemes show a similar accuracy in the task of Cartesian positioning and orientation regulation when the desired  $\psi$  angle is zero.



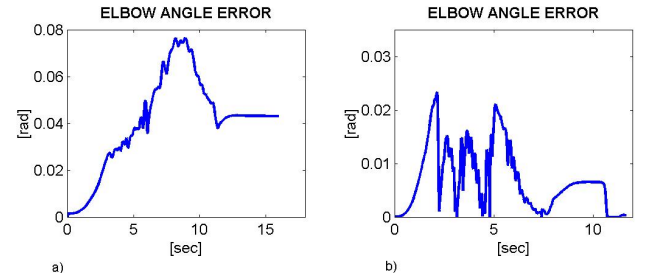
**Fig.4.** Position error (4a) and orientation error (4b) when the elbow angle is zero. The compliant control scheme in joint space is used.



**Fig.5.** Position error (5a) and orientation error (5b) when the elbow angle is different from zero. The compliant control scheme in Cartesian space is used.



**Fig.6.** Position error (6a) and orientation error (6b) when a non-zero elbow angle is set. The compliant control scheme in joint space is used.

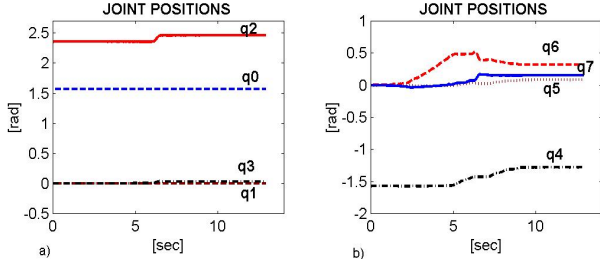


**Fig.7.** Elbow angle error when a non-zero elbow angle is set. A compliant control scheme in Cartesian space (7a) or in joint space (7b) is used.

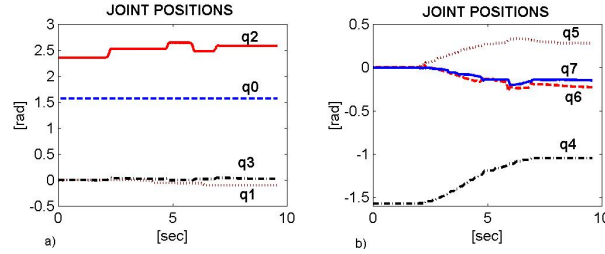
The second session of experimental trials executed on the Dexter arm has revealed unexpected data on the performance of the compliant control schemes in Cartesian space and in joint space, when applied to a structure like the robot under consideration: as shown in Figs. 5-7, performance of the compliant control scheme in

Cartesian space considerably decreases when the desired elbow angle is different from zero.

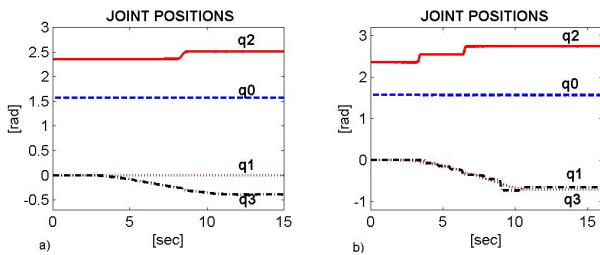
The reason of these results can be traced in the coupling of the degrees of freedom and in the actuation system. As explained previously, Dexter joints are not actuated singularly; their motors are all located on the first link, except for joint 0 and 1. Consequently, their mass decreases while moving from the base to the effector of the arm. When the controller acts in Cartesian space, it acts on the end-effector position error and only indirectly on the joint error. So, it cannot manage the coupling of the joints and, above all, the different weight of each link.



**Fig.8.** Joint positions (8a and 8b) when the elbow angle is zero. The compliant control scheme in Cartesian space is used.



**Fig.9.** Joint positions (9a and 9b) when the elbow angle is zero. The compliant control scheme in joint space is used.



**Fig.10.** Joint positions when the elbow angle is different from zero. The compliant control scheme in Cartesian space is used in Fig.10a) and the compliant control scheme in joint space in Fig.10b).

A direct action in joint space with the second controller ensures the control of the position error at each joint and also regulates the compliance of each of them, taking into account their weight. In fact, the compliant controller in joint space can regulate the position of all the joints, including the heaviest joint  $J_1$  which is not controlled by the controller in Cartesian space.

Figs.8-10 show the time evolution of the joint positions during the two sets of experimental trials. Joint  $J_1$  is always at 0 rad when the control system in Cartesian space is used. A non-moving  $J_1$  causes inaccuracy, since

Dexter cannot position correctly both the end-effector and the elbow angle if a rotation of its torso is not realised.

Definitely, the compliant control scheme in joint space seems to be the more adequate controller for the Dexter arm between the two implemented. However, how functional is its self-compliance control has to be demonstrated.

Control law (2) has been compared with the same control law having constant proportional parameters. The capability of the compliant controller of modulating joint compliance is well-known; in service applications, what is needed is the autonomous regulation of compliance in impact directions. The control in the joint space makes the regulation of the impact in a Cartesian direction more difficult; thus, a certain effort has been devoted to adjust the joint proportional parameters for an optimization of the compliance in the interaction direction.

An impact in the z direction has been implemented. In the free space the robot follows a desired rectangular trajectory but how its behavior changes if an unplanned obstacle occurs on its trajectory has to be studied.

The reference points in the Cartesian space are the vertices  $P_1$ ,  $P_2$ ,  $P_3$  and  $P_4$  of a rectangle in 2D x-z space. The desired trajectory is generated by polynomial algorithms of 5<sup>th</sup> degree (Fig.11a) and  $P_0$  is a generic initial position. The obstacle is located along the z-direction, among the points  $P_2$ ,  $P_3$  and  $P_4$ .

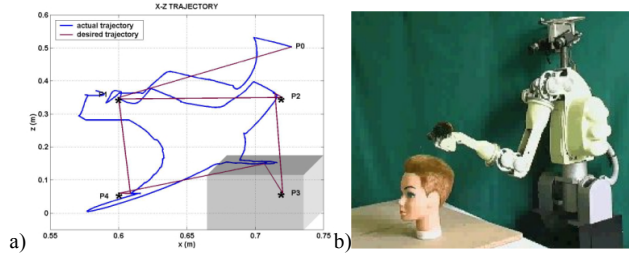
The Cartesian positioning in the free-space follows the desired profile with an accuracy depending on the fixed  $K_{pi}$ , but this accuracy rapidly decreases on the path  $P_2$ - $P_3$ - $P_4$  when the obstacle is met (Fig.11a). In this way, the end-effector changes its Cartesian position in accordance with the shape of the obstacle and the impact force is considerably reduced. As an application, the combing task has been considered (Fig.11b).

A rigid obstacle has been equipped with a load cell in order to measure the impact force in the z-direction. The collision with the obstacle has been repeated with a constant  $K_{PQ}$  matrix and with a self-controlled compliance matrix. The resulting interaction forces have been registered and drawn in a time interval starting at impact time and ending at final contact time (Fig.12).

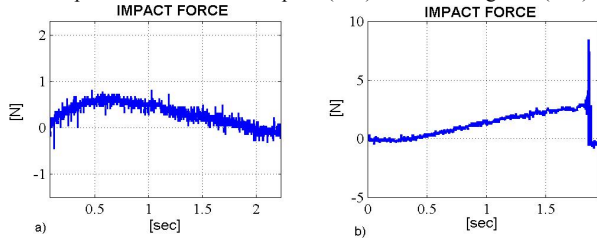
Besides the value of the impact force, it is interesting to observe the force evolution. When a self-regulated compliance is adopted, the force increases until a max of 0.69 N and then decreases at 0 N (Fig.12a). Then the contact ends and the robot starts again reaching the fourth vertex,  $P_4$ . But, when a constant  $K_{PQ}$  matrix, with the same  $K_{pi}$  values is used, the impact is stronger and the force time evolution is completely different (Fig.12b). The force goes on increasing until 4.2 N and the robot, if it can, leaves the contact with a high force impulse without reaching the point  $P_4$  (Fig.12b).

The proportional parameters used in the impact experiments were  $K_{p1}=110$ ,  $K_{p2}=50$ ,  $K_{p3}=55$ ,  $K_{p4}=30$ ,  $K_{p5}=25$ ,  $K_{p6}=4$ ,  $K_{p7}=4$  and, only in the self-regulated

compliant control scheme,  $k_1=1.0$  ,  $k_2=3.5$  ,  $k_3=1.5$  ,  $k_4=3.0$  ,  $k_5=1.2$  ,  $k_6=2.5$  ,  $k_7=2.0$  ,  $\alpha=1.8$ .



**Fig.11.** 2D representation of the actual and the desired trajectory during the interaction with an obstacle on the path.  $P_1$ ,  $P_2$ ,  $P_3$ ,  $P_4$  are the reference points in the Cartesian space (11a). The combing task (11b).



**Fig.12** End-effector impact force along the z direction when a variable compliance (12a) or a constant compliance (12b) is used.

## 5 Conclusions

This paper has presented two compliant control strategies for a robotic manipulator used in personal assistance. The two controllers differ for the space where their control acts, Cartesian or joint space, but both of them aim at realising a functional self-regulated compliance. In particular, their capability of granting a safe transition from an accurate free-space motion to a sudden constrained motion has been developed.

Firstly, a mathematical formulation of the two compliant control schemes with self-regulated compliance is proposed; secondly, how they have been implemented on the steel cable actuated Dexter arm is explained.

An experimental comparison between the two systems has revealed unexpected results, quite far from the standard theoretical considerations that could be done on their expected performance. The reason can be traced in the coupling of the degrees of freedom and in the different weight of each link of the Dexter arm. In fact, the experimental validation has shown the compliant control scheme in the joint space as the more affordable between the two.

A demonstration of its functionality in the unplanned impact was also provided. The control scheme revealed a good capability of ensuring accuracy in the free-space and of adapting the end-effector trajectory to the presence of an unexpected obstacle with a good regulation of the impact force. Anyway, the compliant control scheme in joint space cannot directly control the transients, just ensuring limited errors during the trajectory.

Future research developments will aim at improving the smoothness and the accuracy of the motion, both in the transients and at the equilibrium, possibly using information about the robot dynamics and the interaction force.

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