

Experimental comparative evaluation of compliant control schemes for an anthropomorphic personal robot

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Abstract

This paper investigates the problem of controlling an anthropomorphic robot arm with autonomously variable compliance in order to ensure safety in the interaction with humans and, above all, to increase the robot functionality in tasks of physical interaction, performed in co-operation with humans.

The research work aims at applications in service robotics where the robot arm is 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 the design of the robot and introduces strict requirements on its behavior and control, which has to ensure safety and effectiveness.

Two different compliant control schemes have been developed for the peculiar structure of the Dexter robot arm, an anthropomorphic 8 d.o.f. manipulator, and their performances have been comparatively evaluated through experimental trials. The comparative evaluation of the two control schemes, through the analysis of their different advantages and disadvantages, points out an overall better performance of the compliant control scheme in the joint space, relatively to the management of the mechanics of the robotic system. So, it emerges how the performances of the two control systems are inverted with respect to the theoretical considerations on their accuracy and effectiveness, that could be done on the basis of the classical control theory.

After a brief description of the control models, the paper focuses on the experimental sessions aimed at verifying the level of accuracy, affordability, functionality and safety of the implemented control systems.

1 Introduction

In the history of interaction control main steps have been represented by compliant control, impedance control or hybrid position/force control. The pioneering force control work by Whitney and others [1,2] 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* [1,3,4] or in the more generic *impedance control* methods [5-8], were assembly and part mating tasks. The objective of impedance control was to regulate the mechanical impedance of the robot end-effector. The hybrid position/force control approach to constrained motion [9], instead, is useful in those applications where the interaction environment is structured and well-known.

Control of robots designed and employed in the service of humans, in their everyday life activities and in their

environment, has to face with the very delicate problem of finding a trade-off between personal safety and proper functionality in human-robot interaction and accurate execution of autonomous tasks. Thus, the property to pass from a stiff robot behavior in the free space to the compliant behavior in the constrained motion, by autonomously regulating robot compliance, has been investigated in the work presented in this paper, which proposes two control systems: the compliant control systems with self-regulating compliance in Cartesian space and in joint space respectively. The proposed solution is specifically significant in the implementation on the Dexter manipulator, an anthropomorphic robot arm [10] used in services and personal assistance of human beings [11,12].

A brief theoretical description of the proposed control schemes introduces the basic models of the two control systems implemented on the Dexter arm. A wider attention is posed on the analysis of performance of the two controllers. The comparative evaluation of the experimental results leads to recognizing the compliant control scheme in the joint space as the better of the two, because it can effectively manage both the coupling and the accuracy-compliance trade-off. A demonstration of its functionality and affordability in the interaction is provided in two experimental tasks: opening a microwave oven and combing.

2 Theoretical formulation

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;
- $C(q, \dot{q})\dot{q} = \dot{B}(q, \dot{q})\dot{q} - \frac{1}{2} \left(\frac{\partial}{\partial \dot{q}} (\dot{q}^T B(q) \dot{q}) \right)^T \in \mathbb{R}^{n \times 1}$ is the vector of centrifugal and Coriolis torques;
- 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 can assume two different 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 $H(\cdot)$ is depending on the transformation matrix between the end-effector angular velocity and the derivatives of the Euler angles have been used.

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} . K_D , instead, is a diagonal matrix that controls the damping velocity at each joint.

A rigid robot behavior is clearly not appropriate in personal tasks, such as to comb, to drink, to eat, but also a compliant behavior is not very adequate if a fixed level of compliance is set. In fact, if the compliance is too high, the robot positioning has very low accuracy, but, vice-versa, if the compliance is low, the interaction forces could be high and the adaptability could be too low. So the choice of a variable compliance seems to offer a better level of adaptability, without using an explicit force control scheme [15,16]. It is achievable by choosing a K_p matrix depending on the actual and desired Cartesian position in the controller in the 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 as

$$\tilde{g}(q) = [D_1 \dots D_n]^T, \text{ where } D_i = \sum_{p=i}^n \left(-m_p g^T \frac{\partial {}^o T_p}{\partial q_i} r_p \right) \quad i=1, \dots, n; \quad m_p \text{ and}$$

$r_p = [r_{px} \ r_{py} \ r_{pz} \ 1]^T$ ($p=1, \dots, n$) are the masses and the centers of gravity of each link; $g^T = [0 \ 0 \ -g \ 0]$ is the gravity acceleration vector ($|g|=9.8062 \text{ m/s}^2$) expressed in the base coordinate

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

The two compliant control schemes have been readapted and implemented on the Dexter robot arm [10]. 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 (Figs.4 and 12b).

The arm mechanics 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. The couple motor-reducer of joint 0 is mounted on the mechanical interface between the arm and the base, while that of joint 1 is mounted on link 0. The motors for actuation of joints $J_2, \dots, J_7$, instead, 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.

As joint 0 is characterized by a high weight and a complex dynamics and takes part only in a global positioning movement and not in high precision tasks, 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 to control it.

The redundant degree of freedom of the considered 7-joint robot arm is used to regulate the elbow position, by controlling the so-called ψ 'arm angle' [17]. The Jacobian matrix is then modified to include also the contribution of each joint to the elbow angle. Its dimension is 7×7 if the base joint contribution is not considered.

3 Compliant control scheme in Cartesian space

Equation (1) is referred to the control of the Dexter arm in Cartesian space. An alternative Euler Angles formulation [13] has been used for the definition of the orientation error and a self-controlled compliance function has been adopted to self-regulate the robot compliance during the motion. So, the resulting control law regulates the compliance along the three Cartesian directions x, y, z , 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 arm 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.

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 .

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

$$\begin{aligned} K_p(x, x_d) &= \text{block diag} \{ K_{pp}(x, x_d), K'_{pO}(\tilde{\varphi}), k_\psi(x, x_d) \} \\ K_{pp}(x, x_d) &= \text{diag} \{ K_{px} e^{-k_x |x_d - x|}, K_{py} e^{-k_y |y_d - y|}, K_{pz} e^{-k_z |z_d - z|} \} \\ K'_{pO}(\tilde{\varphi}) &= T_e^{-T}(\tilde{\varphi}) K_{pO} \\ k_\psi(x, x_d) &= K_\psi e^{-k |w_d - w|} \end{aligned}$$

where K_{px} , K_{py} , K_{pz} , K_{ψ} 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 through the matrix $K_D(x, x_d) = \alpha^T K_P(x, x_d) J$, where α is 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.

3.1 Experimental results

The proposed compliant controller has been tested through two sessions of experimental trials, in order to verify its level of accuracy, affordability and functionality. From a theoretical point of view, in fact, 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.

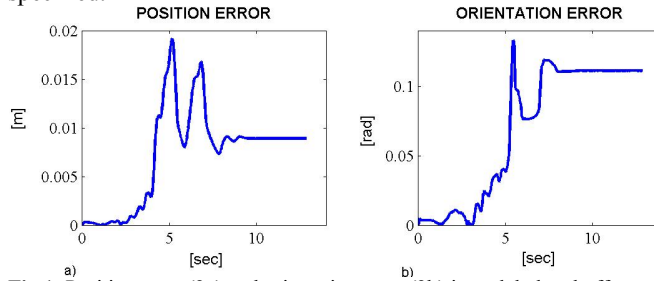


Fig.1. Position error (2a) and orientation error (2b) in a global end-effector positioning with a zero elbow angle. The compliant control scheme in Cartesian space is used.

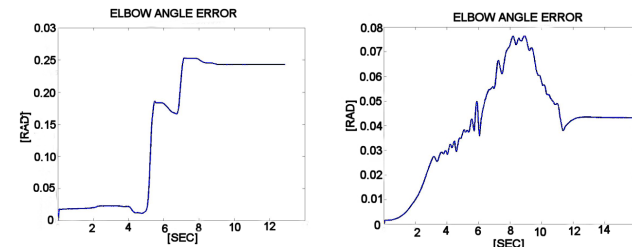


Fig.2. Elbow angle error in a global end-effector positioning with a zero elbow angle (3a) or with a non-zero elbow angle (3b) when a compliant control scheme in Cartesian space is used.

The first group of experimental trials consists of positioning the Dexter arm end-effector in the free space when the elbow angle is set to zero or to a value different from zero. The trials have revealed important data on the performance of the compliant control scheme in Cartesian space when applied to a coupled structure like the robot under consideration: as shown in Figs. 1-3, performance of the compliant control scheme in Cartesian space considerably decreases when the desired elbow angle is different from zero.

For the second session of experimental trials, the task of opening a microwave-oven (Fig.4) was chosen to demonstrate the increased functionality of the compliant controller with respect to a standard stiff controller. This type of task does not require the direct interaction with the user, so the safety for the user is less important, but a good accuracy during the approach to the oven and a high level of adaptability during the opening are required.

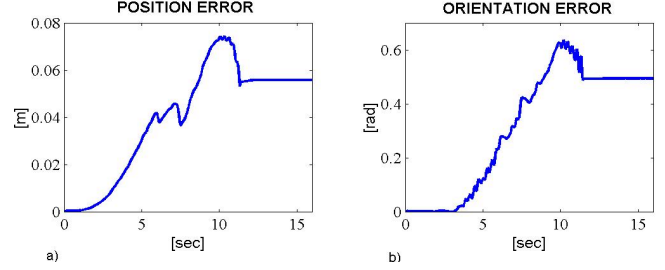


Fig.3. Position error (a) and orientation error (b) during the positioning with a non-zero elbow angle. The compliant control scheme in Cartesian space is used.

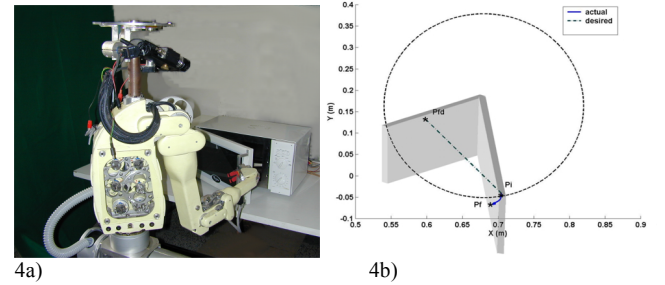


Fig.4. The arm during the execution of the task

Although a standard stiff controller can execute every task with the best accuracy, it stops or fails when imprecise commands are given. It requires the perfect knowledge of the desired trajectory that the robot arm has to follow. So an accurate algorithm of trajectory planning would describe an arc of circumference of 45° having the length of the oven door as radius (Fig.4b). The advantage of the developed control scheme is the good accuracy in the motion when no obstacle occurs as well as a high level of adaptability (regulated through the argument of the exponential function) when some opposing forces are sensed at the end-effector. The trials aim at pointing out that the adaptability of the system can ensure the opening of the oven giving only the final reference point P_{fd} .

Fig.4b) shows the desired trajectory and the actual trajectory, followed by the Dexter arm when controlled by the implemented compliant control. It is evident that the developed compliant control in the Cartesian space is not able to accomplish the desired service task. The opening of the microwave oven requires in fact the change and the control of the elbow angle and, as previously demonstrated, the compliant control scheme in Cartesian space is not able to do that.

4 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.

The inversion algorithm considers the Dexter as a 7 d.o.f. anthropomorphic robot arm with an extra-joint used to increase the reachable workspace. This choice avoids useless additional computational burden [18].

Joint J_0 is characterized by an independent motion along a predefined trajectory. The other joints, instead, follow a desired trajectory through an inverse kinematics optimized by the redundancy. The extra degree of freedom, in fact, is used to

generate a joint motion that regulates the ψ elbow angle without changing the end-effector global position.

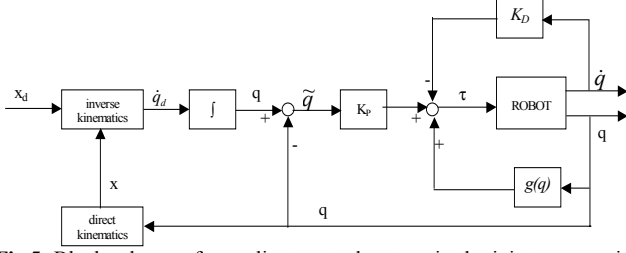


Fig.5. Block scheme of compliant control system in the joint space with kinematic inversion.

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.

Equation (2) presents a self-regulating compliance to autonomously vary joint compliance as a function of the position error and consequently of the joint error:

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

So, accuracy and compliance are ensured when the robot arm operates far from the user or in the unconstrained environment, because the joint position error is very low; however, an increasing compliant behavior is shown when an unplanned interaction occurs. In this case, in fact the joint position error increases over the time.

$K_{p1}, K_{p2}, \dots, K_{p7}$ 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 α :

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

4.1 Experimental results

The two sessions of experiments presented in section 3.2 have been repeated with the compliant controller in the joint space so as to compare the performance of the two controllers. Firstly, the positioning in the free space with a variable elbow angle from zero to a non-zero value is realised.

Figs. 6-7 show the corresponding results. The motion is not very smooth or harmonic, but the robot arm is always able to reach the desired configuration and the error is globally small in both positioning tasks.

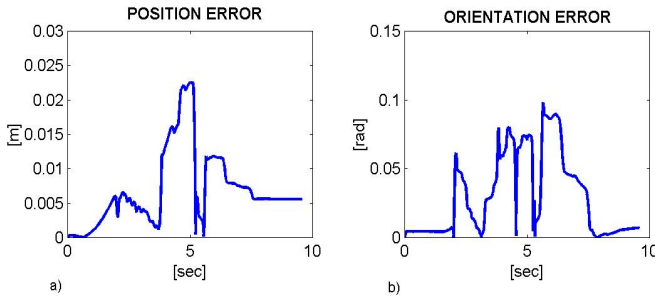


Fig.6. Position error (6a) and orientation error (6b) during the positioning with a zero elbow angle. The compliant control scheme in joint space is used.

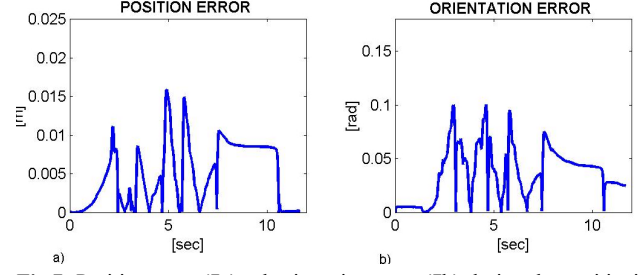


Fig.7. Position error (7a) and orientation error (7b) during the positioning with a non-zero elbow angle. The compliant control scheme in joint space is used.

Then, also the realization of the service task of opening a microwave oven has revealed improved performance. The compliant controller in the joint space can well control the elbow angle position, as demonstrated in Figs. 7-8, since it allows Dexter turning around its trunk (joint 1) and changing the elbow position. The arm now is able to accomplish the task of opening the microwave oven by adapting the current trajectory to the constraints met along the planned motion (that is to say the microwave oven door). So, even a sole command of desired final position is sufficient to move the arm along the bound trajectory.

Fig.8a) shows the desired trajectory, joining point P_i where the oven is completely closed, to point P_{id} , corresponding approximately to the point of max opening of the door, and the actual trajectory, reaching the real final point of opening. The strength of the implemented controller resides in the great flexibility conferred to the system from the compliance, since the desired final point is only a gross indication of the final point of opening, as well as in the great simplicity of use.

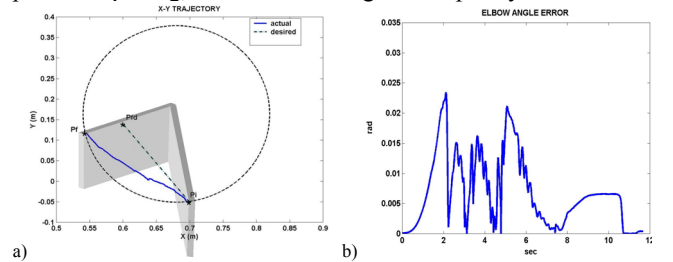


Fig.8. The task of opening the microwave oven (8a). Elbow angle error during the positioning with a non-zero elbow angle (8b) when a compliant control scheme in joint space is used

5 Experimental comparative results

This section aims at analysing the performance of the two implemented compliant control systems and at identifying the more adequate one for the Dexter mechanics and for its applications. To this regard, the previous sections of experimental results are compared.

A comparison between Fig.6 and Fig.1 confirms the theoretical considerations on the two control systems, that is the compliant controller in the Cartesian space can ensure good accuracy as well as smooth motion and control simplicity when the elbow angle is set to zero.

On the contrary, a comparison between Fig.7 and Fig.3 shows a clear decrease of performance for the controller in Cartesian space when a non-zero elbow angle is desired. The controller in joint space seems to ensure globally a smaller position error.

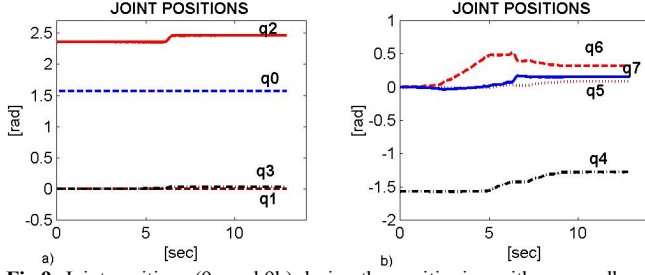


Fig.9. Joint positions (9a and 9b) during the positioning with a zero elbow angle. The compliant control scheme in Cartesian space is used.

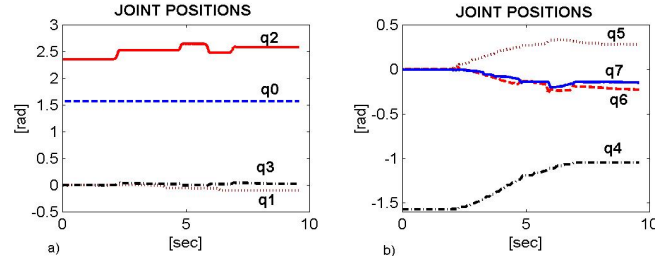


Fig.10. Joint positions (10a and 10b) during the positioning with a zero elbow angle. The compliant control scheme in joint space is used.

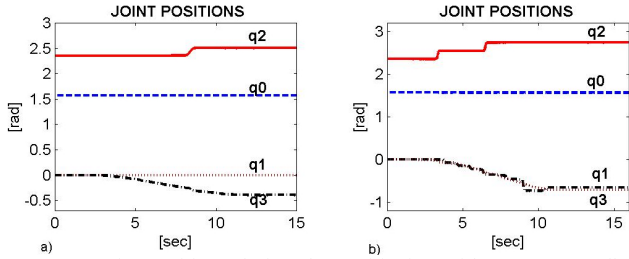


Fig.11. Joint positions during the positioning with a non-zero elbow angle. The compliant control scheme in Cartesian space is used in Fig.11a) and the compliant control scheme in joint space in Fig.11b).

The reason of these results can be found in the coupling of the degrees of freedom and in the actuation system. 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.

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.9-11 show the time evolution of the joint positions during positioning. 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.

As a consequence, the task of opening the microwave oven cannot be accomplished by the controller in Cartesian space. During the opening of the oven, the Dexter arm is bound by the door of the oven which forbids to follow the reference trajectory. The arm feels the opposing force but never becomes unstable. When the compliant control in Cartesian space is tested, the arm stops (Fig.4b) as it is not able to turn around its torso (Figs.11a and 2); when the compliant control in joint

space is performed, the task is well accomplished, as the arm is able to rotate about joint 1, to regulate the elbow (Figs.8b and 11b) and even to adapt the actual trajectory to the opposing force exerted by the microwave oven door (Fig.8a).

Definitely, the compliant control scheme in joint space seems to convey to the robotic platform a better level of affordability and functionality than the compliant controller in Cartesian space.

Moreover, the high level of adaptability and flexibility of the controller in joint space can be used in tasks of personal assistance requiring the strict interaction with the user, like combing. This task in fact requires the autonomous regulation of compliance in the impact direction in order to ensure maximum safety for the user or the environment and for the robot itself. As a demonstration, an impact in the z direction has been implemented and a rigid obstacle has been equipped with a load cell so as to measure the impact force in the z-direction. 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 5th degree (Fig. 12) and P_0 is a generic initial position. The obstacle (the head in the combing) 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. 12). 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.

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 recorded and drawn in a time interval starting at impact time and ending at final contact time (Fig.13).

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 to 0 N (Fig. 13a). 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. 13b). 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. 13b).

The proportional parameters used in the impact experiment 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, $k_1=1.0$, $k_2=3.5$, $k_3=1.5$, $k_4=3.0$, $k_5=1.2$, $k_6=2.5$, $k_7=2.0$, $\alpha=1.8$.

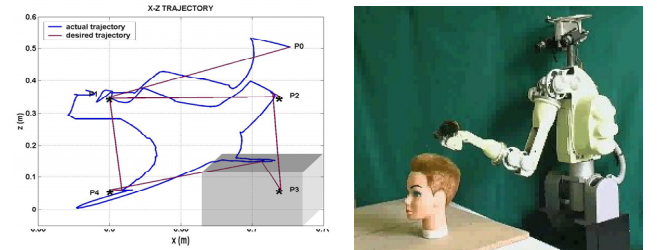


Fig.12. 2D representation of the actual and the desired end-effector trajectory during the interaction with an obstacle (a). The combing task (b)

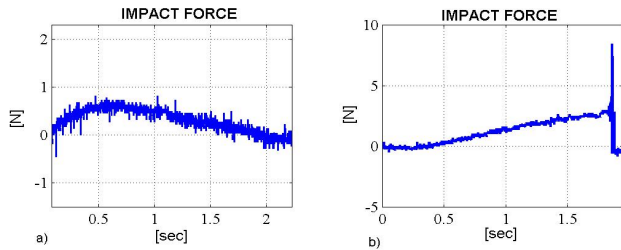


Fig.13 End-effector impact force along the z direction when a variable compliance (12a) or a constant compliance (12b) is used.

6 Conclusions

In this paper two compliant control strategies for a robotic manipulator used in personal assistance have been illustrated. The two controllers differ for the space where their control acts, the Cartesian space or the joint space, but both of them aim at realising a functional self-regulated compliance. In fact, the specific application requires the robot to be capable of moving with good accuracy in the free space as well as of modulating its stiffness when it transits from the free-space to an unplanned constrained environment.

An experimental comparison between the two systems has revealed the compliant control scheme in the joint space as the more affordable between the two. This result is quite far from the standard theoretical considerations that could be done on their expected performance and is due to the coupling of the degrees of freedom and the different weight of each link of the Dexter arm.

The functionality in regulating the robot compliance and the safety ensured by the controller in joint space is further demonstrated in a task of real interaction with the user, like combing. The control scheme can adapt the end-effector trajectory to the presence of an unexpected obstacle with an efficient modulation 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 developments in research on the interaction control 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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