

Functional Compliance in the Control of a Personal Robot

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Abstract

The research in the field of Advanced Robotics is turning its attention more and more to the Man and his assistance, by developing systems such as service robots, personal robots, and even humanoid robots. Interaction control of such robot manipulators is of paramount importance for an effective execution of manipulation and tracking and, over all, for a safe and effective interaction with the humans.

This paper concerns with the problem of the control of an 8 degree of freedom anthropomorphic arm, named DEXTER, mounted on the mobile platform of the MOVAID System, a robotic system for household personal assistance. The goal is to realize a compliant control for this manipulator in tasks of assistance to disabled and elderly people.

On the basis of the control theory applied to Industrial Robotics, a specific compliant control solution has been developed for the DEXTER peculiar mechanical structure and actuation system, which cause a coupled joint configuration. The solution provides the capability of regulating the robot compliance according to the level of stiffness of the interaction environment.

The paper describes the theoretical model of the control system, the implementation on the MOVAID platform and the experimental results in the execution of a set of demonstration tasks.

1. Introduction

The application of robots in personal assistance evolved in accordance with technical advances in robotics in the last couple of decades. The use of robot manipulators in this field of application requires their capability of operating in strict physical interaction with the human user. Personal assistance requires that the system gets in touch with the user, moves him/her or moves things in contact or around him/her, in most cases in accordance with his/her own movements [1-4]. Furthermore, the manipulator has to operate in a variable

and unstructured environment where it has to manipulate objects of variable stiffness (things and persons) and move in a non-completely-known workspace. From these considerations, the need emerges of modulating the robot compliance not only for guaranteeing the user's safety, but also for increasing the system functionality.

The analysis of the solutions for interaction control adopted in Industrial Robotics [5-8] suggested three possible control schemes to be applied in the compliant control of a personal robot arm. They differ for control methodology, required equipment, costs, accuracy, performance and computational burden. The three approaches are: compliant control in joint space [5,6], compliant control in Cartesian space [5,6,9], impedance control [10,11].

In this paper the second approach, compliant control in Cartesian space, is described and how it has been implemented for the DEXTER arm is explained, pointing out how it stands as the best trade-off between simplicity of realization and effectiveness. The adopted scheme controls the robot directly in the operational space, where the motion actions are specified, and it requires neither the robot dynamic model nor the use of sensors but the encoders.

The addressed working environment, household, and the particular task, personal assistance, have determined the peculiarity of the DEXTER arm, i.e. the anthropomorphic physical aspect and the cable mechanical transmission, which provide the system with the best level of safety for the user. The coupled mechanical structure of the arm and the corresponding implementation of compliant control in the Cartesian space are shown in the following sections.

2. Theoretical description of the implemented compliant control system

The compliant control scheme in Cartesian space [5,6] aims at regulating the compliant robot behavior easily and effectively. Its implementation does not require an

accurate knowledge of the robot dynamics, except for the values of the masses of the links and the coordinates of the centres of gravity of each link; in addition, it realizes an interaction control without a direct force measurement, so that the control scheme has no other feed-back loops than the position.

The compliant control scheme in the Cartesian space is a proportional-derivative (PD) control algorithm with gravity compensation. The control law is the result of the proportional and derivative contributions, expressed by the matrices K_P and K_D , which allow the modulation of the robot behavior in the different Cartesian directions. Then, the term of gravity compensation represents a non-linear contribution, evaluated in real-time, to compensate the dynamics due to the gravitational torque.

The mathematical formulation of the PD and gravity compensation control law is given by:

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

where $\tau \in \mathbb{R}^n$ is the torque-vector in the joint space, $g(q)$ is the vector of gravity torque, $J_A \in \mathbb{R}^{m \times n}$ is the manipulator Jacobian matrix, $K_P \in \mathbb{R}^{m \times m}$ and $K_D \in \mathbb{R}^{n \times n}$ are the diagonal matrices of proportional and derivative gains, respectively.

The control action is the combination of three forces:

- 1) a vector of elastic forces in the operational space, $K_P\tilde{x}$, generated by a system of m independent springs with stiffness K_P ,
- 2) a term of dampness which regulates the joint velocity with the K_D matrix,
- 3) a real-time estimation of the gravity force.

This latter term, in the form of a torque, is expressed by the masses m_p ($p=1, \dots, 8$) and the centers of gravity of each link ($r_p = [r_{px} \ r_{py} \ r_{pz} \ 1]^T$, $p=1, \dots, 8$), as in the following equation:

$$\hat{g}(\theta) = \begin{bmatrix} D_1 \\ \dots \\ D_8 \end{bmatrix}$$

where

$$D_i = \sum_{p=1}^n \left(-m_p g^T \frac{\partial {}^o T_p}{\partial q_i} r_p \right) \quad i=1, \dots, 8;$$

$g^T = [0 \ 0 \ -g \ 0]$ 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.

3. Architecture of the experimental system

The DEXTER manipulator is an 8 DOF robot arm developed by Scienza Macchinale s.r.l. (Pisa, Italy) (see Fig.1) and integrated in the MOVAID (MObility and actiVity AssIstance system for the Disabled) mobile robotic system for personal assistance [1,12,13],

outcoming from an EU-funded project completed in 1997.

The on-board architecture is based on an AT platform and two PC104 racks located in the back of the mobile base. The low-level arm controller, realized by means of two MEI 104/DSP-400 board-controllers, runs on one of the two PCs. The control actions are described in C language, using a specific function library, and the communication among CPU, DSP and peripheral units is in binary code on a Data Bus. Fig.2 shows a scheme of the DSP controller.

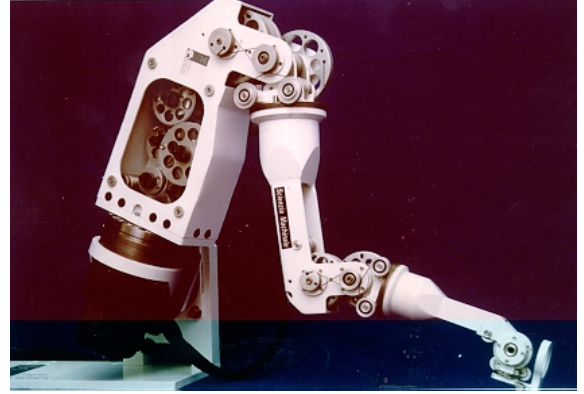


Fig. 1. DEXTER arm

Both the sections dedicated to the implementation of the on-board PID controllers, acting on the 8 axes of the robot, and the I/O coordination functions are realized on the DSP. The axis control boards send 16-bit analog command signals to the DC or brushless servo-motors and high resolution step and direction signals to the steppers. The DEXTER joints are actuated by DC servo-motors, consequently to obtain a good compliant control scheme an efficient management of the analog command signals for these motors is required.

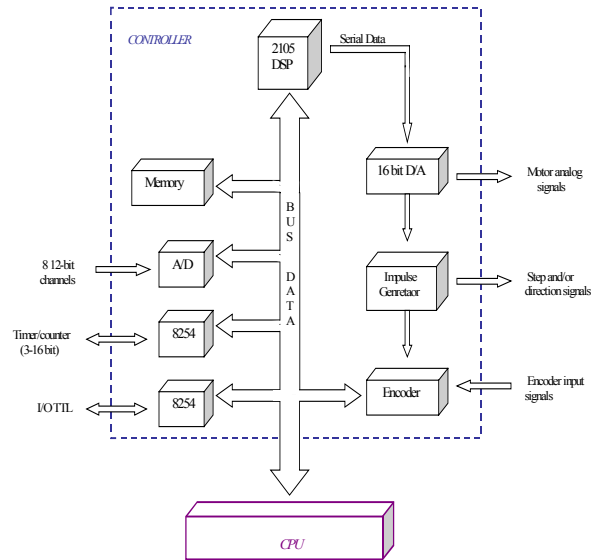


Fig.2. DSP controller functional scheme.

The arm kinematic design has been influenced by the reachable workspace and, thus, by the dimensions and the localization of the furniture and of the objects in the house. The resulting robot structure has 8 joints, $J_0 \dots J_7$, the first of which, J_0 , has an horizontal axis and aims at increasing the workspace in the vertical direction (Fig.3). The horizontal dimension of the workspace, instead, can be regulated with the motion of the mobile base. In short, DEXTER has an anthropomorphic 8 DOF kinematic structure (8 revolute joints), composed of shoulder, elbow and wrist. For the wrist, a roll-pitch-yaw representation is adopted to avoid wrist singularities within the joint range of variability.

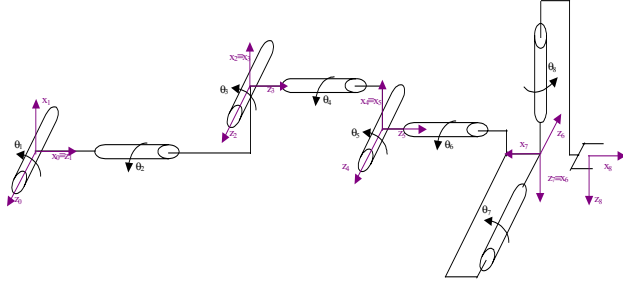


Fig.3. The DEXTER geometrical structure

The DEXTER good performance is not represented by high velocity and accuracy in the end-effector motion, but by the capability of performing the required tasks while ensuring user's safety. It is necessary not only an adequate control architecture, but also low operating velocities (under 0.2 m/s) and a light and flexible structure. Consequently, the arm mechanical configuration is not ever industrial: the 8 joints are not actuated singularly by a motor located on each link (Fig.4), but they are driven so as to generate human-like movements.

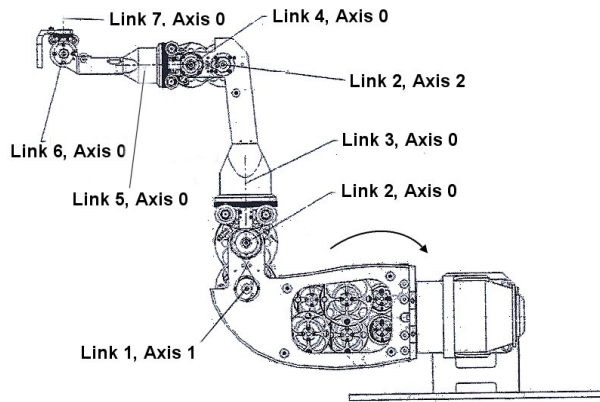


Fig.4. The DEXTER mechanical structure

The joints J_0 and J_1 are actuated by motors and driving gear-boxes directly connected to the articulation axis. The couple motor-reducer of joint 0 is mounted on the mechanical interface between the arm and the mobile base, while that one 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. This type of mechanical structure on one side reduces the heaviness of the moving masses, but on the other side it makes the mechanical drive system quite complex and introduces coupling for the degrees of freedom.

4. The compliant control strategy as applied to the DEXTER arm

The described robot arm represents the focus of the present research work, and thus the adopted compliant control scheme has been adapted to it. Differently from the original model, the control law (1) acts only on joints $J_1 \dots J_7$ and not on the base joint J_0 . This choice is motivated by two orders of reasons:

- joint 0 is characterized by a high weight and a complex dynamics;
- the axis takes part only in a global positioning movement and not in high precision tasks.

So, a pre-defined trajectory for J_0 has been planned and a PID controller has been used to control it.

Using the low operating velocity of the system, it is possible to rewrite (1) as:

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

where the control action in the joint space is determined by the nondiagonal and configuration-dependent matrix $K_P^* = J_A^T K_P J_A$. The diagonal K_P matrix allows robot compliance to be regulated in the different Cartesian directions, depending on the specific task and on the level of stiffness of the interaction environment. In fact, in the steady condition, in presence of a set of forces h acting on the end-effector, the control law becomes $J^T H^{-T}(\varphi_e) K_P \tilde{x} = J^T h$ and, in the hypothesis of Jacobian with full rank, $\tilde{x} = K_P^{-1} h_A$; K_P^{-1} plays the role of active compliance in the Cartesian space. At the equilibrium, the relation $J_A = H^{-1} J$ has been used. $H(\varphi_e)$ is depending on the transformation matrix in a Euler angles representation.

The Cartesian error vector $\tilde{x}$ can be divided into position error and orientation error, both vectors $\in \mathbb{R}^{3 \times 1}$. The consequent steady condition can be expressed as

$$\begin{bmatrix} \Delta p_{de} \\ \Delta \varphi_{de} \end{bmatrix} = K_P^{-1} H^T h = K_P^{-1} H^T \begin{bmatrix} f \\ \mu \end{bmatrix}$$

if $h = \begin{bmatrix} f \\ \mu \end{bmatrix}$ is the vector of the forces f and of the moments

μ in the Cartesian space. The steady condition for the position error is linked only to the active compliance K_P^{-1} , as shown in the relation $\Delta p_{de} = K_{PP}^{-1} f$; the equilibrium for the orientation, $\Delta \varphi_{de} = K_{PO}^{-1} T^T(\varphi_e) \mu$,

instead, is depending on the particular orientation error defined.

The alternative Euler Angles formulation [5] has been used for the definition of the orientation error because it allows avoiding representation singularities. In this way the compliant control law becomes:

$$\tau = g(q) + J^T \gamma - K_D \dot{q}$$

where

$$\gamma = \begin{bmatrix} \gamma_p \\ \gamma_o \end{bmatrix} = \begin{bmatrix} K_{PP} \Delta p_{de} \\ T_e^{-T}(\varphi_{de}) K_{PO} \varphi_{de} \end{bmatrix}$$

$J = [J_1 J_2 J_3 J_4 J_5 J_6 J_7 J_8] \in \mathbb{R}^{6 \times 8}$ is the contribution of all the joints to the position of the end-effector;

$\Delta p_{de} = p_d - p$ is the Cartesian position error;

φ_{de} is the orientation error;

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

Finally, the DEXTER control torque vector is

$$\tau = g(q) + J^T \begin{pmatrix} K_{PP} \Delta p_{de} \\ T_e^{-T}(\varphi_{de}) K_{PO} \varphi_{de} \end{pmatrix} - K_D \dot{q}.$$

In absence of external forces, it ensures reaching the desired posture at the equilibrium:

$$J_A^T(q) K_P \tilde{x} = 0,$$

but, it cannot realize a direct control of the transients. In the case under consideration, however, this problem is not so relevant because the system has a low operating velocity.

From an implementation point of view, the realization of the compliant control scheme in the Cartesian space on the DEXTER manipulator requires the replacement of the velocity controller, the low level PID controller, with the torque controller (Fig.5), expressed by means of (1). It can be possible bypassing the PID axes controller and sending a torque/current command to the motors. That is to say that it is necessary to create a SW/HW communication which, by removing the PID control, can set a digital voltage value suited for the control of the actuation system of joints 1,...,7.

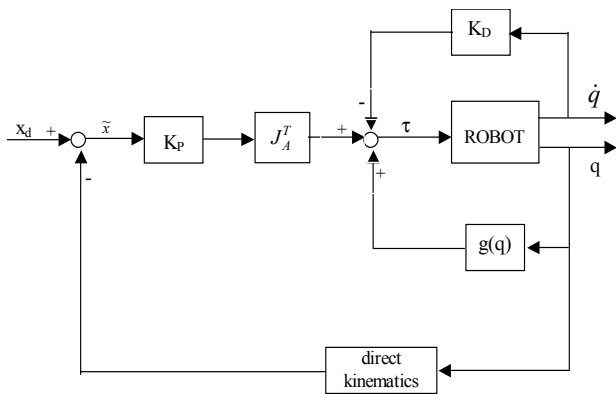


Fig.5. Block scheme of compliant control system in the Cartesian space.

The control law (1) does not give the actuator control command but it evaluates the joint torque vector. The conversion between the joint system and the actuation system is determined by the arm mechanical structure. Due to the mechanical coupling, the reduction matrix is not diagonal. It takes into account the mechanical transmission system, realized in steel cables and responsible of the joint coupling, and the reduction system constituted by the reducers. Consequently, the link between motor velocity and joint velocity is formulated as

$$\dot{q}_m = K_r' A \dot{q}$$

$$K_r = K_r' A$$

where K_r' is the diagonal matrix of reducer coefficients and A is the mechanical coupling matrix. The corresponding torque relation is

$$\tau = K_r^T \tau_m$$

which links the motor torque τ_m to the joint torque τ .

Knowledge of the torque constants of the DC motors and of the current/voltage gains of the servo-amplifiers constitutes a set of significant information to derive the desired analog voltage motor command. Afterwards, a 16-bit conversion is enough to calculate the corresponding digital voltage.

5. Experimental results

The described compliant control scheme in the Cartesian space has been implemented on the DEXTER robot arm and tested. In the testing phase, a considerable effort has been devoted to regulate the proportional and derivative parameters of the control algorithm, because of the coupling in the robot joints and of the anthropomorphic distribution of their masses.

The experimented control algorithm calculates the desired trajectory for the end effector on the basis of the initial Cartesian configuration and the desired final position and calculates the joint command voltage required for the Cartesian positioning motion. The algorithm considers and solves two important aspects: coupling in the joints, and consequently in the conversion from the joint torque to the motor voltage, and a rigid control on the maximum voltage values, in accordance to the prior objective safety.

The experimental trials aim at demonstrating the variable DEXTER compliance provided by the implemented compliant control scheme and at verifying the capability of regulating the end-effector impact force by only varying the K_P parameters.

To demonstrate the first point, the same positioning task has been performed using both high and low proportional parameters. The experimental results show the robot behavior for the Cartesian position regulation and for the end-effector orientation. The initial robot position and orientation are defined as the post-calibration

configuration ($p_i=[72\text{cm } 0\text{cm } 50\text{cm}]$, $o_i=[0^\circ -45^\circ 0^\circ]$). A polynomial algorithm for the trajectory generation is used to define the reference trajectory to the final point, fixed at $p_d=[78\text{cm } -10\text{cm } 25\text{cm}]$, $o_d=[15^\circ -35^\circ 5^\circ]$. Fig.6a) and 6b) show the Cartesian position error relative to the same compliant algorithm, but with two different compliance levels ($K_{pp}=\text{diag}[450 \ 190 \ 250]$ and $K_{pp}=\text{diag}[250 \ 90 \ 150]$). An increase of the compliance causes a higher position error and a slower convergence to zero. The same considerations can be repeated for the orientation error, too (Fig.7a, 7b). An alternative Euler Angles formulation has been used for the orientation error definition.

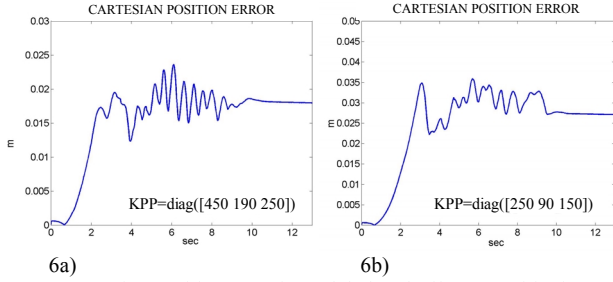


Fig.6. Cartesian position error in a global end-effector positioning task in the free space. The proportional parameters are $K_{pp}=[450 \ 190 \ 250]$ (6a) and $K_{pp}=[250 \ 90 \ 150]$ (6b).

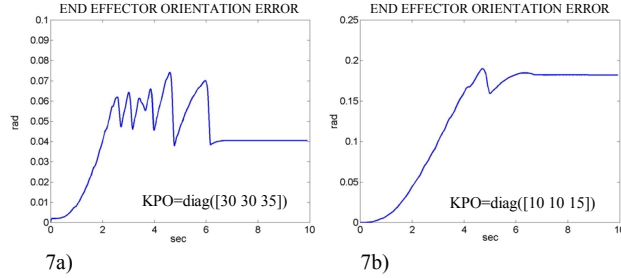


Fig.7. End-effector orientation error in a global positioning task in the free space. The proportional parameters are $K_{po}=[30 \ 30 \ 35]$ (7a) and $K_{po}=[10 \ 10 \ 15]$ (7b).

The position and the orientation time evolution has been compared with the DEXTER stiff behavior, controlled by the PID position controller. As evident from the plots in Fig.8a and 8b, stiffness ensures a higher accuracy by maintaining in total a smaller tracking error.

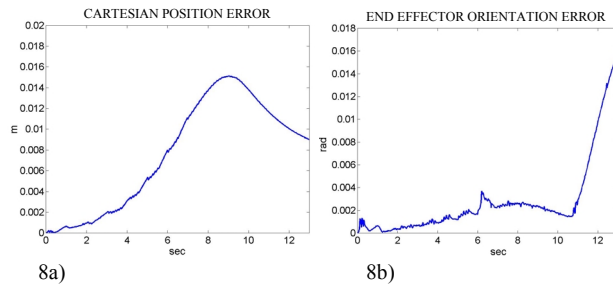


Fig.8. Cartesian position error (8a) and end-effector orientation error (8b) in a global positioning task in the free space. The PID controller is used as position controller.

The second demonstration aims at showing the possibility of controlling the robot-environment interaction force. An impact against a rigid obstacle equipped with a load cell has been experimented, so as to measure the impact force and verify whether the implemented algorithm can indirectly control the interaction force. The experimentation has been repeated on the three Cartesian directions (x, y, z) to measure the impact force along the three axes when the proportional parameters vary. As for the tracking tests, a comparison between the PID and the compliant control is made, too. The following table and Figs.9÷13 show the measured force values for two different sets of proportional parameters and when a PID control is used.

Interaction Direction	Interaction force ($K_{pp}=\text{diag}[450 \ 190 \ 250]$)	Interaction force ($K_{pp}=\text{diag}[250 \ 90 \ 150]$)	Interaction force (PID)
X	2.17 N	1.43 N	4.57 N
Y	1.14 N	0.75 N	4.70 N
Z	2.17 N	1.43 N	9.37 N

Tab.1 Interaction force values in the three Cartesian directions.

Figs.10a), 12 and 13 are particularly interesting: the first shows the force-time evolution when a stiffer behavior is chosen for the compliant system: the arm tries to reach the reference, but in the impact it applies such a great force that it deviates from the obstacle. The same does not happen when K_{pp} is lower (Fig.10b). Figs.12 and 13, instead, draw the high force level originated by a PID stiff behavior. The force is so hard that the system stops for the security solutions adopted in the arm control.

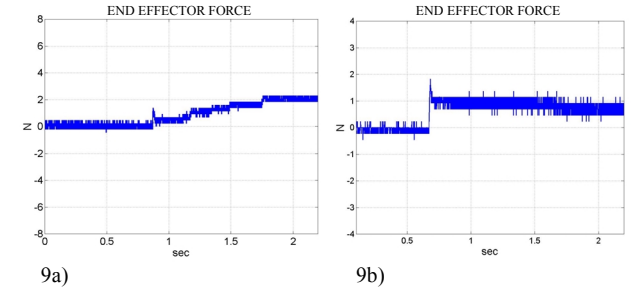


Fig.9 End-effector impact force along the x direction when the proportional parameters are $K_{pp}=[450 \ 190 \ 250]$ (9a) and $K_{pp}=[250 \ 90 \ 150]$ (9b).

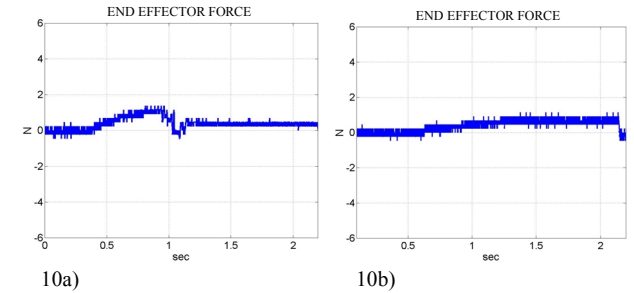


Fig.10 End-effector impact force along the y direction when the proportional parameters are $K_{pp}=[450 \ 190 \ 250]$ (10a) and $K_{pp}=[250 \ 90 \ 150]$ (10b).

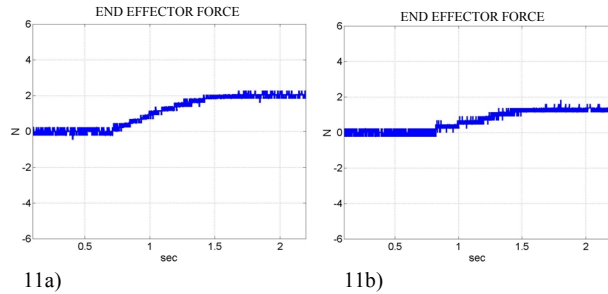


Fig.11 End-effector impact force along the z direction when the proportional parameters are $K_{pp}=[450 \ 190 \ 250]$ (11a) and $K_{pp}=[250 \ 90 \ 150]$ (11b).

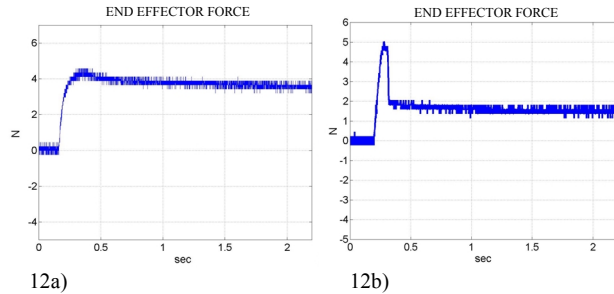


Fig.12 End-effector impact force along the x direction (12a) and the y direction (12b) when a PID controller is used as position controller.

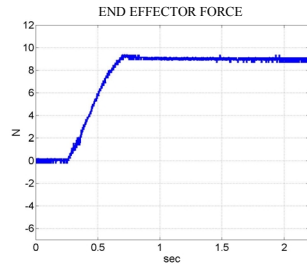


Fig.13. End-effector impact force along the z direction when a PID controller is used as position controller.

6. Conclusions

This paper has presented a compliant control strategy for a robotic manipulator used in personal assistance. The proposed controller acts in the Cartesian space with a PD action and a gravity compensation. It does not require the robot dynamics knowledge except for the masses and the centers of gravity of its links.

The proposed control scheme has been implemented on the DEXTER anthropomorphic arm. Though the theoretical compliant control strategy is simple and well-known in the theory of robot control, its application to the DEXTER robot arm is quite complex because of its anthropomorphism and joint coupling. The choice of the PD parameters, in fact, has to compensate the coupling and the different distribution of the link masses from the base to the end-effector.

An experimental phase tried to identify the parameters that best control the robot and its compliance. The results have shown how the adopted control can regulate robot compliance both in position and in orientation, but the best accuracy in position corresponds to a worst accuracy

in orientation and vice versa, as a consequence of the joint coupling. Moreover, the Cartesian compliant controller cannot directly control the transients, but only the steady state.

Future research will be then addressed to an optimization of the compliant robot behavior aiming at:

- a better dynamic control, both at the equilibrium and in the transients, in addition to a suitable management of the link masses peculiar distribution;
- a direct force control, that is to say the introduction of a force loop in the control feedback.

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