

An experimental study on compliance control for a redundant personal robot arm

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Abstract

Human–robot interaction represents a critical factor in the design of personal robots as well as in the implementation of robot behavior and control. This work investigates and proposes solutions to the problem of controlling an anthropomorphic robot arm for personal assistance, by dealing with the peculiarities of its design, i.e. the mechanics of its cable-actuated, intrinsically compliant structure, and by emphasizing its potential in applications of physical and functional interaction with the environment and with human users.

To satisfy the requirements of increasing the safety in the interaction and the robot functionality in tasks performed in cooperation with humans, three solutions are developed and tested for the considered personal robot. The initial idea is aimed at developing an efficient as well as computational convenient interaction control strategy, i.e. a compliance control scheme in the Cartesian space. The analysis of its limited performance suggests two further control strategies, i.e. a compliance control scheme in the joint space and an impedance–compliance control scheme. Their compared analysis points out that all the three solutions can safely operate in the human environment, but from a functional point of view only the last two schemes can effectively control the personal robot arm in its whole workspace.

The paper describes the mechanics of the considered robot arm, with special regard to its anthropomorphism and cable-actuation and presents in details the three control schemes. They are critically evaluated through the experimental results achieved in tasks of physical and functional interaction with the environment and with human users. The impedance–compliance controller emerges as the more appropriate to the addressed application as well as to the peculiar cable-actuated structure.

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1. Introduction

The advances of robotics research in the last two decades have led to new generations of robotic systems and new scenarios for the application of robots, in closer contacts with human beings. Evidence is given by the research effort devoted to the

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development of humanoid robots worldwide. An interesting overview of research groups and projects in the field of humanoid robotics is given in [20]. The Waseda University in Tokyo has probably the longest tradition in this field, started already in the 1970s. Their current achievements include a full-scale walking robot [11] and robots reproducing other functions of the human body, like manipulation [11,22], mastication, talking and even playing a flute. An interesting work is also being carried out in the generation and expression of emotion through facial movements [33].

In general, Japan is the country devoting the largest effort to the objective of developing humanoid robots, as testified by the “Humanoid Robotics Project of Japan” [13], launched in 1998 and involving most Japanese robotics research groups.

In the USA, too, the development of humanoid robots is receiving more and more attention, especially as physical agents expected to develop human-like intelligence [4].

In Europe, the development of humanoid robots is mostly related to the development of ‘personal robots’, helpful machines in the service of humans [2,10]. Main concrete attempts have been devoted to apply robotic solutions in personal assistance [8,9] in the field of Assistive Robotics, in which robotic systems are used in the assistance to disabled and elderly people [21,36].

Such new scenarios are especially characterized by the introduction of robots in workspaces cohabited by humans, wherein no special arrangement is made for a robot interacting with a human being. Among the many additional requirements that these applications pose to roboticists, safety, effective interaction with humans [3,17,18,29], and capability of operating in partially known and unstructured environments are probably among the most challenging and demanding.

In this paper, it is shown how a compliant behavior for a robot manipulator used in personal assistance can help foster such requirements and improve the interaction between the users and the robotic caregivers. To this regard, an anthropomorphic design for the mechanical structure is considered as the most suitable for tasks and environment conceived for humans.

Compliance is undoubtedly a first basic step to ensure safety when workspace sharing is allowed, but it

can especially help pursue an effective human–robot interaction allowing physical contact and cooperation. In the case of personal robotics, the user may need to be helped by the robotic assistant in the execution of some personal care tasks, such as combing, drinking, eating. All these actions require the adaptability of robot positioning to the user movements, to the relative position between the user’s body and the robot arm, as well as to the shape and current position of his/her body parts, depending on the specific task. This is done by human caregivers in a natural way.

When designing the control of a personal robot manipulator, at least three aspects need to be considered, keeping into account that the operating scenarios can vary from service tasks not requiring a real interaction with the user, to personal care, where a really high level of human–robot interaction is necessary:

- *Safety*. The control system has to guarantee that robot movements are not dangerous for possible injuries to humans, nor to the environment or the robot itself.
- *Human–robot interaction* [3,17,18,29]. Personal care and assistance tasks require that the robotic assistant is 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.
- *Functionality* [38]. 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.

Thus, research on robot control in this application context is focused on the realization of a system representing the best trade-off between safety and effective human–robot interaction, on one side, and accurate execution of autonomous tasks, on the other.

The paper introduces the concept of adaptable functional compliance, then describes the main features of the robotic arm used for the experimental research work, i.e. the 8 degree-of-freedom anthropomorphic Dexter arm, designed for applications of assistance to disabled people and therefore showing peculiarities in the mechanical structure and actuation. The theoretical description of three controllers is presented, with mathematical formulation and the experimental validation of the three controllers is reported with resulting data, which are finally compared.

2. Adaptable functional compliance

Usually, in robot control, either the two issues of human–robot cooperation and accurate execution of desired working tasks in the free space are separately faced or, often, a known and structured environment is assumed.

In the cooperation with humans, safety and human–robot interaction problems are usually managed with an adequate compliance control; instead, in the execution of service tasks, accuracy and precision in positioning and manipulation can be achieved through a stiff robot behavior. But, when the environment is not completely structured, how to manage situations of unexpected transition from unconstrained motion (autonomous mode) to constrained motion (interaction) is a very delicate issue.

The solution to be thought should consider that different situations can require different compliance levels (including stiffness) and the robot needs to be able to modulate its own compliance accordingly. Hence, an adaptable functional compliance is to be achieved.

The research work presented in this paper focuses on the realization of an adaptable functional compliance for a personal robot aimed at helping disabled users in housekeeping and personal care. Different solutions are proposed to be implemented on the robot arm and, particularly, how to achieve maximum flexibility and adaptability in the transition from a stiff robot behavior in the free space to a compliant behavior in the constrained motion is investigated. To this regard, it is worth noting that the extremely variable working environment does not allow to assume fixed force values as reference desired values. The arm should be capable to self-adjust its interaction force in accordance with the environment.

In the history of control, the main approaches to the interaction control are represented by compliant control, impedance control or hybrid position/force control. The pioneering force control work by Whitney and co-workers [23,37] proposed a controller based on shaping of the end-effector impedance (active accommodation matrix) for each task. Whitney's research as well as most of the research in active compliance [23,27,32] or in the more generic impedance control methods [12,14,30] were focused on 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 [26], instead, was a force control in a completely structured environment, where the constraints could be well selected and classified. Evidently, it is not useful in personal applications where the interaction environment is unstructured and not completely known.

Starting from the analysis of the state of the art, three different control schemes have been formulated:

- the compliance control with self-regulating compliance in the Cartesian space;
- the compliance control with self-regulating compliance in the joint space;
- the impedance–compliance control.

They have been thought to cope with two main issues. The first one is the realization of an adaptable functional compliance, as required by the application context (i.e. personal robotics and assistive robotics). The second one concerns the peculiarity of the addressed personal robot. It is an anthropomorphic robot arm actuated through steel cables and having, as a drawback, a mechanical coupling in the degrees of freedom and a notably decreasing inertia from the first link up to the last link.

Moreover, the choice of the control scheme has to answer to the additional requirements of ensuring a maximal simplicity of equipment, a limited cost and a reduced computational burden.

Purposely, the three proposed control schemes avoid using force sensors and try to limit the execution time by computing in the worst case only a reduced dynamic model of the robot.

The three controllers have been implemented on the Dexter robot arm [38,39], experimentally tested and comparatively evaluated.

The first two control schemes are able to autonomously regulate robot compliance in the free space or in an unplanned constrained motion (adaptable functional compliance) without using either the robot dynamic model or the measures of the contact forces coming from a torque/force sensor. The last one, the impedance–compliance control, achieves the same target and improves the performance of the first two controllers by using additional information about the robot dynamics.

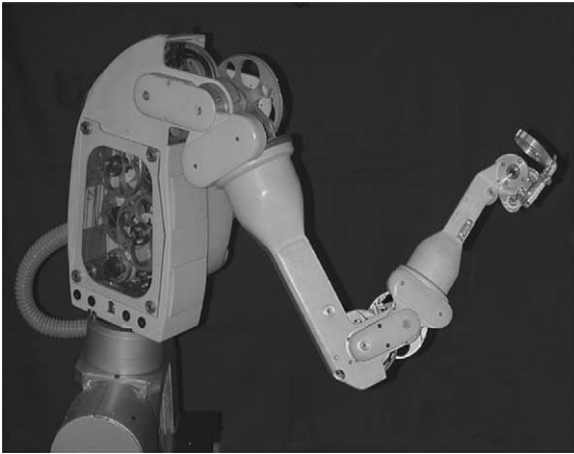


Fig. 1. Dexter arm.

3. The personal robot arm

The Dexter, shown in Fig. 1, is an 8 degree-of-freedom (d.o.f.) anthropomorphic robot arm designed for applications of assistance to disabled and elderly people, in their everyday life environments [1]. It is manufactured by Scienza Machinale s.r.l. (Pisa, Italy) and it has been integrated in the MOVAID (MOBility and actiVity AssIstance system for the Disabled) mobile robotic system for personal assistance [7–9], outcoming from an EU-funded project of the TIDE

(Technology Innovation for the Disabled and Elderly) programme.

Dexter has an 8-revolute-joint kinematic structure, composed of shoulder, elbow and wrist. An anthropomorphic structure has been realized at the mechanical level, so as to mimic human movements in the interaction with the environment.

The kinematic design was influenced by the reachable workspace and, thus, by typical dimensions and localization of the furniture and objects in a house. The resulting robot structure has eight 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. 2). The horizontal dimension of the workspace, instead, can be regulated with the motion of the mobile base on which the arm is supposed to be mounted.

A minimum safety level in interaction is guaranteed by the low operating velocity (under 0.2 m/s) and by the light and flexible mechanical structure. In fact, the joint masses notably decrease from the first link to the last as the steel cable transmission allows the six distal motors to be located on the first link and intrinsically increases the level of user safety in the interaction. Thus, the eight joints are not actuated singularly by a motor located on each link (Fig. 3), like a standard industrial robot, except for joints J_0 and J_1 , which are actuated by motors and driving gear-boxes directly connected to the articulation axis. The couple motor-reducer of joint J_0 is mounted on the mechanical

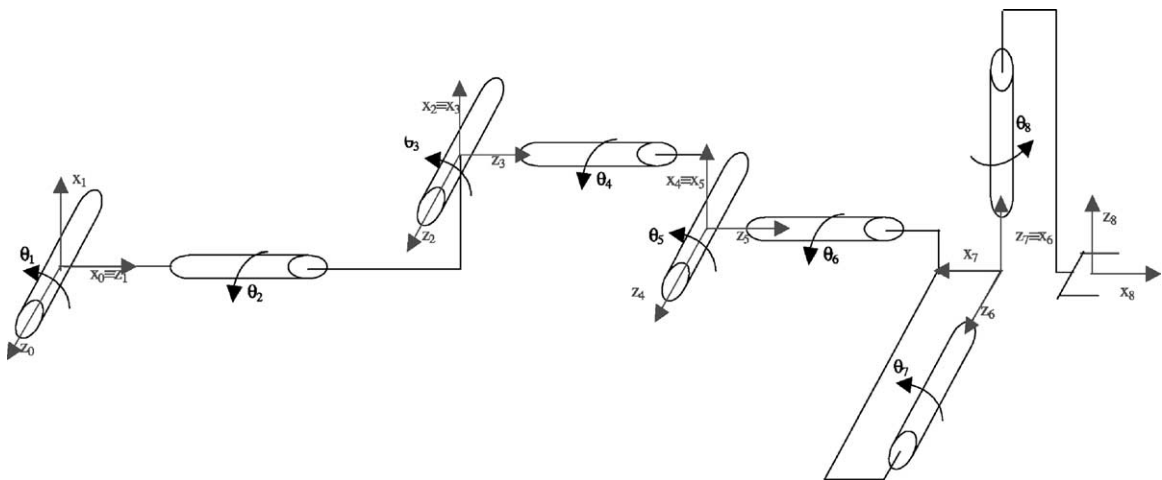


Fig. 2. The Dexter geometrical structure.

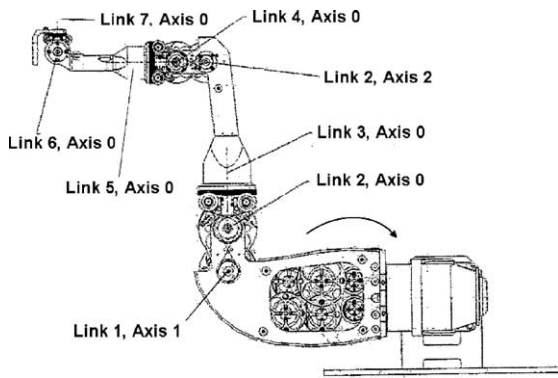


Fig. 3. The Dexter mechanical structure.

interface between the arm and the mobile base, while the one of joint J_1 is mounted on link 0. The motors for the actuation of joints $J_2, \dots, J_7$, instead, are all installed on one side of link 1 and for them the mechanical transmission system is realized with pulleys and steel cables. Although this mechanical solution reduces the weight of the moving masses and decreases the danger in the interaction, it makes the mechanical

drive system quite complex and introduces coupling in the degrees of freedom [6,19,25,35].

The on-board architecture is based on an AT platform and two PC104 racks located in the back of the mobile base on which the arm is mounted, in the MOVAID system. 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. 4 shows a scheme of the DSP controller.

Both the sections dedicated to the implementation of the on-board PID controllers, acting on the eight 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. As regards the Dexter joints, they are actuated by DC servo-motors and controlled in current through the developed compliance controllers.

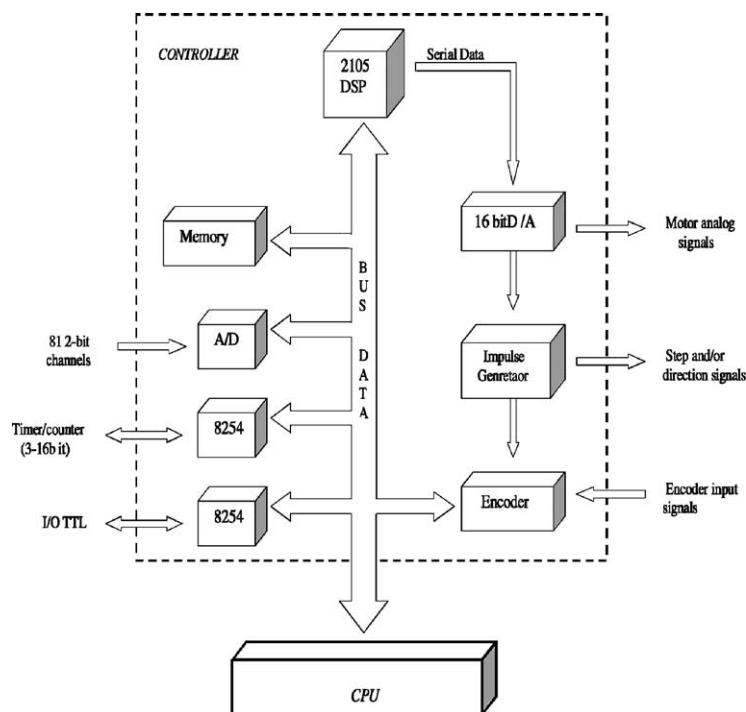


Fig. 4. DSP controller functional scheme.

4. Adaptable functional compliance: an application on a cable-actuated robot

The objective of the experimental research carried out on the Dexter arm and presented in this paper is to regulate the level of the DC motor currents in order to realize the desired adaptable compliant motion, in the joint space or in the Cartesian space. To this aim, three types of torque control systems have been implemented on the robot arm, starting from the dynamic relations between the actuation torques τ and the robot motion, expressed by

$$B(q)\ddot{q} + C(q, \dot{q})\dot{q} + F\dot{q} + g(q) = \tau - J^T(q)h. \quad (1)$$

The contributions to the robot dynamics are:

- the joint inertia matrix $B(q) \in \mathbb{R}^{n \times n}$ (n is the joint space dimension), whose terms take into account the inertia moments acting on each joint i , when the other joints are steady, and the effect of the acceleration of each joint on the joint i ;
- the vector of centrifugal and Coriolis torques

$$C(q, \dot{q})\dot{q} = \dot{B}(q, \dot{q})\dot{q} - \frac{1}{2} \left(\frac{\partial}{\partial q} (\dot{q}^T B(q) \dot{q}) \right)^T \in \mathbb{R}^{n \times 1},$$

which includes the centrifugal and Coriolis effect on each joint i , due to the velocity of the other joints;

- the diagonal, positive definite matrix of joint viscosity coefficients $F \in \mathbb{R}^{n \times n}$;
- the vector of joint gravitational torque $g(q) \in \mathbb{R}^{n \times 1}$;
- the joint torque vector $J^T(q)h$, due to the external force h acting on the end-effector, where J is the end-effector Jacobian matrix.

The vectors q , $\dot{q}$, $\ddot{q}$ represent, respectively, joint position, velocity and acceleration which for the Dexter arm are 8×1 vectors.

The three compliance control laws are derived from (1) and act only on seven joints, $J_1, \dots, J_7$, as joint J_0 is heavy, characterized by a complex dynamics and takes part only in a global positioning movement. Taking into account that J_0 does not act in fine positioning tasks, a predefined trajectory for J_0 has been planned and a PID controller has been used.

The considered seven-joint robot arm has a redundant degree of freedom, since 6 d.o.f.'s are enough to

position and orientate the end-effector. The redundant degree of freedom is used to regulate the elbow position, by controlling the so-called 'arm angle' [16], denoted by ψ . This is defined as the angle between the shoulder–elbow–wrist plane and x – z reference plane, containing the shoulder and the wrist. The Jacobian matrix is then modified, including also the contribution of each joint to the elbow angle. Its dimension is 7×7 as the base joint contribution is not considered.

The paper proposes three control strategies: self-regulated compliance control in the Cartesian space, self-regulated compliance control in the joint space, impedance–compliance control. The primary objective is to control the robot in the interaction with human beings. Hence, the research work was addressed to the analysis of the solutions that effectively allow the control of the Dexter personal robot, including its mechanics, flexibility and coupling, in relation to its role in its working environment, the household. The three proposed control approaches differ for control methodology, costs, accuracy, performance and computational burden.

The self-regulated compliance control in the Cartesian space controls the robot directly in the operational space where the command actions are expressed. In this way, the complexity of the inverse kinematics is avoided and a direct action on the space where the interaction occurs (the Cartesian space) is realized. Furthermore, this control scheme is easy to implement since it does neither require the knowledge of the Dexter dynamics nor the use of force/torque sensors. Consequently, the computational burden is further reduced.

The self-regulated compliance control in the joint space acts at the level of joint commands. It includes the advantages of avoiding the computation of the robot dynamic model and of feeding back force sensor information, too, but it requires the implementation of an inverse algorithm to convert the Cartesian commands in joint commands. It has the advantage, with respect to the controller in the Cartesian space, of controlling each joint independently or, at least, of acting directly on each group of coupled joints, successfully managing the difference in the weight of each joint.

Impedance–compliance control represents a viable third strategy which tries to join the benefits of both previous controllers. In fact, like the first one, it controls the arm in the Cartesian space by functionally

controlling the interaction force in the different Cartesian directions; like the second one, it can move all the joints, both heavy and light. The control strategy has been named “impedance–compliance” because it is based on the estimation of the dynamic parameters of joints J_1, J_2, J_3 only. The other joints are controlled by a compliance controller in the Cartesian space. The computational burden increases with respect to the previous two control attempts, but the effectiveness of the control during the interaction improves, especially in the transients, since the impedance–compliance control realizes a finer control of the end-effector by exploiting the knowledge of the inertia and the masses of the proximal links.

All the three proposed control schemes realize an adaptable compliance through a variable function which allows regulating compliance in accordance with the task requirements.

5. Self-regulated compliance control in the Cartesian space

5.1. Theoretical formulation

The proposed compliance control scheme realizes an indirect force control based only on a static compensation of robot dynamics. It achieves a task space regulation by a proportional-derivative (PD) action plus the estimation of the gravitational torque vector. This compliance controller can act in the Cartesian space or in the joint space, depending on the space of definition of the position error [28,31]. Therefore, a regulation in the Cartesian space can be achieved as well as a regulation in the joint space. A theoretical analysis of problems concerning required equipment, costs, accuracy, performance and computational burden initially suggested the compliance control in the Cartesian space as the best trade-off between simplicity of realization and effectiveness. Thus, the first controller developed and tested on the Dexter arm has been the compliance control scheme in the Cartesian space. The mathematical formulation of the controller is

$$\begin{aligned}\tau &= J_A^T(q) K_P \tilde{x} - K_D \dot{q} + g(q) \\ &= (H^{-1} J)^T K_P \tilde{x} - K_D \dot{q} + g,\end{aligned}$$

where $\tilde{x} = x_d - x$ represents the Cartesian error between the desired position and orientation x_d and the actual position and orientation x , $J(q)$ the Jacobian matrix and the matrix

$$H(\varphi_e) = \begin{bmatrix} I & 0 \\ 0 & T(\varphi_e) \end{bmatrix}$$

is depending on the transformation matrix $T(\varphi_e)$ between the end-effector angular velocity and the derivatives of the Euler angles φ_e .

The torque vector is regulated by a PD term including the proportional matrix K_P and the derivative matrix K_D . The former is a diagonal and positive matrix which acts directly on the different Cartesian directions as a set of springs with rigidity coefficients $K_{P,ii}$. The proportional matrix regulates the robot compliance along x, y, z depending on the level of stiffness of the interaction environment during a specific task. In the steady condition, in presence of a set of forces h acting on the end-effector, the control law reduces to $J^T H^{-T}(\varphi_e) K_P \tilde{x} = J^T h$ and, in the hypothesis of a full-rank Jacobian, $\tilde{x} = K_P^{-1} H^T h$. As announced, K_P^{-1} plays the role of an active compliance in the Cartesian space, modulating the relation between the robot compliance and the acting force.

In absence of external forces, instead, the control law ensures reaching the desired posture at the equilibrium:

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

even though it cannot realize a direct control of the transients.

The sole action on the dynamical behavior of the robot arm during the transients is exerted by the derivative term $K_D \dot{q}$. The diagonal matrix K_D regulates the damping of the system, controlling the velocity at each joint.

The last contribution to the control law is the estimation of the gravitational torque vector. It is a non-linear contribution, evaluated in real time to compensate the effect of the gravitational torques. 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 $g(q) = [D_1, \dots, D_n]^T$, where

$$D_i = \sum_{p=i}^n \left(-m_p g^T \frac{\partial^0 T_p}{\partial q_i} r_p \right), \quad (2)$$

in which $g^T = [0, 0, -g, 0]$ is the gravity acceleration vector ($|g| = 9.8062 \text{ m/s}^2$) expressed in the base coordinate system and ${}^0T_p \in \mathbb{R}^{4 \times 4}$ is the homogeneous transformation matrix between the p -system and the base system.

As said in the previous sections, the particular application context, the household, requires the level of stiffness to be automatically adjusted during the transition from the free-space motion to the constrained space, where an unplanned impact against an obstacle or a person can occur. Further, it is required to adapt the robot arm positions to the user movements and locations during the execution of tasks requiring physical interaction with the human user, such as personal care tasks (e.g. combing, drinking, eating).

Since a fixed level of compliance can cause a very low accuracy if the compliance is too high and, vice-versa, high interaction forces and too low adaptability if the compliance is low, the choice of a variable stiffness seems to provide a certain level of adaptability during a task [15,24] and offers the possibility of realizing an interaction control using only a position feedback and without a direct force measure.

An exponential self-controlled compliance function has been adopted to self-regulate the robot compliance during the motion [39]. The compliance function varies exponentially when the Cartesian position error varies. In this way, when an obstacle occurs, stiffness decreases together with the position error.

The control strategy can be reformulated as follows:

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

or

$$\tau = J^T \begin{bmatrix} K_{PP}(x, x_d) \tilde{p} \\ T_e^{-T}(\tilde{\varphi}) K_{PO} \tilde{\varphi} \\ k_\psi(x, x_d) \tilde{\psi} \end{bmatrix} - K_D(x, x_d) \dot{q} + g(q) \quad (3)$$

if the Dexter redundancy is used to control the elbow angle and the decoupling between the regulation of Cartesian position and the control of the orientation is considered. An alternative Euler angles formulation [31] has been used for the definition of the orientation error because it allows avoiding representation singularities.

In (3), $J \in \mathbb{R}^{7 \times 7}$ is the Dexter 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 an XYZ representation of Euler angles. R_e is the rotation matrix describing the orientation of the end-effector frame with respect to the base frame.

Finally, K_P is a block diagonal matrix of exponential functions expressed as

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

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 coefficients k_x , k_y , k_z define the rate of decay of the stiffness along the three Cartesian directions.

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 α a positive scalar coefficient. This choice provides a self-adjusted damping to prevent force responses from being too sluggish according to the changes of stiffness of the system.

5.2. Implementation and experimental evaluation

The experimental session presents the difficulties faced in implementing the formulated compliance control in the Cartesian space and points to analyze the Dexter behavior during tasks of physical and functional interaction with humans [18].

The compliant behavior was evaluated with respect to three main desired achievements:

- safety in unexpected or purposeful contact with humans;
- increased robot functionality in the execution of some service tasks;
- human–robot cooperation in the execution of personal care tasks.

To this regard, three separate experimental sessions were carried out and their results are reported in the following.

In the testing phase, a considerable effort was 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. In fact, choosing compliance along the three Cartesian directions has not only to take into account the level of compliance required by the task, but even how this level of compliance acts on each joint. For instance, since joints J_2 , J_4 and J_6 are coupled, a too low value for the Cartesian compliance could be adequate to move the lighter joints J_4 , J_6 but not for the heavier joint J_2 .

Hence, the design of K_P matrix is initially based on the desired accuracy in the free space (i.e. when the robot is required to be stiff). Then the coefficients k_x , k_y , k_z , k are regulated in dependence on the rate of variability of compliance required by the task. For instance, for the Dexter arm the K_{PP} matrix presents high initial values for K_{px} , K_{py} , K_{pz} , K_{ψ} ($K_{px} = 220$, $K_{py} = 130$, $K_{pz} = 150$, $K_{\psi} = 200$) and the decay is managed by the position error and the coefficients $k_x = 1.5$, $k_y = 0.8$, $k_z = 1$, $k = 1.5$. In this case a quicker decay of K_{PP} along x is ensured.

The coupling in the degrees of freedom is responsible also for the trade-off between the regulation of the position and the regulation of the orientation of the end-effector. Thus, the proportional matrix for the orientation is characterized by low values ($K_{PO} = \text{diag}\{2, 2, 2\}$) since, on one hand, it acts only on the lighter joints and, on the other, a higher accuracy for

the end-effector position instead of the end-effector orientation is preferred.

Finally, as regards the damping matrix K_D , an experimental value of $\alpha = 0.5$ is set.

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 provides the joint command voltage required for the motion in the Cartesian space. The algorithm considers and tries to solve two important aspects: coupling in the joints, which influences also the conversion from the joint torque to the motor voltage, and regulation of the interaction force. As for the conversion, a coupled reduction matrix is considered and the hardware PID controller is by-passed by sending the control commands directly to the actuators.

A rigorous control on the maximum voltage values is introduced, in accordance to the prior objective of safety.

5.2.1. First session of experimental trials

A preliminary set of trials consisted of positioning the end-effector in the free space in case the elbow angle is set to zero or to a value different from zero [38,39].

A polynomial algorithm for the trajectory generation has been implemented to define the reference trajectory to the final point and an alternative Euler angles formulation has been used for the definition of the orientation error.

Figs. 5 and 6 reveal unexpected data on the performance of the compliance control scheme in the Cartesian space. As the theoretical considerations suggest,

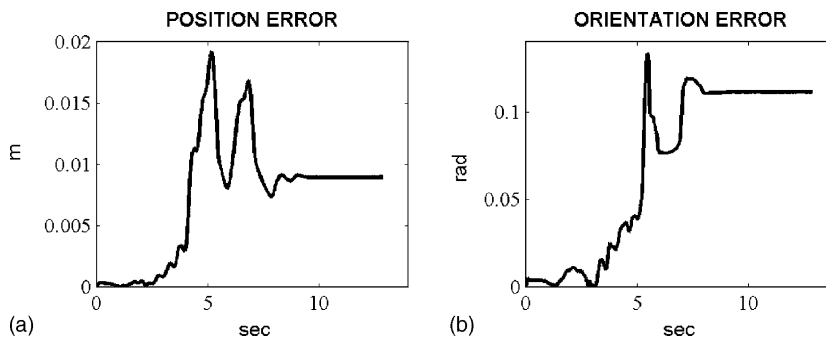


Fig. 5. Position error (a) and orientation error (b) in a positioning task with a zero elbow angle. The compliance control scheme in the Cartesian space is used.

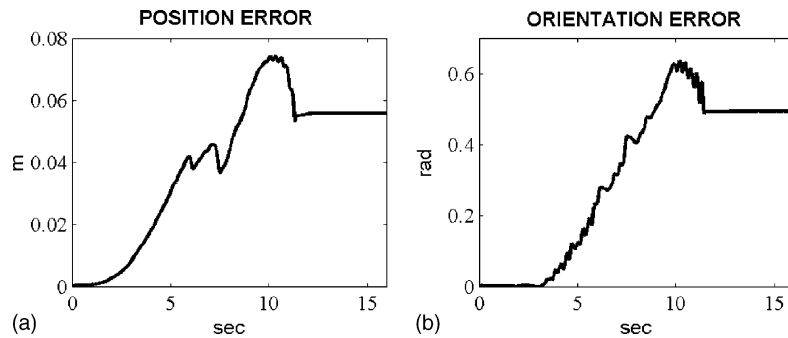


Fig. 6. Position error (a) and orientation error (b) in a positioning task with a non-zero elbow angle. The compliance control scheme in the Cartesian space is used.

the Cartesian controller ensures a very smooth and harmonic motion during the positioning in the free space and, in spite of the joint coupling, the controller shows a good functionality in the regulation of the compliance when an impact occurs on each of the Cartesian directions. But, unfortunately, the Dexter particular robotic structure makes the performance of the compliance control scheme in the Cartesian space considerably decrease when the desired elbow angle is different from zero. Fig. 6 shows how the position and the orientation errors increase when a non-zero elbow angle is desired.

The functionality of Cartesian compliance was then evaluated by recording the time evolution of the interaction forces when the compliance controller in the Cartesian space or the stiff standard PID controller is used to control the Dexter arm.

To measure the impact force and verify whether the implemented algorithm can indirectly control the interaction force, an impact against a rigid obstacle equipped with a load cell has been carried out. The capability of modulating the impact force has been tested by varying the proportional parameters along the three Cartesian directions (x , y , z). The compared analysis between the PID and the compli-

ance control scheme provided the results reported in Table 1.

Figs. 7 and 8 show the measured force values for two different sets of proportional parameters in the compliance control in Cartesian space and Fig. 9 shows the time evolution of the interaction force when a PID control is used.

A note on Figs. 7 and 9 could be particularly interesting. The first one 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. When the K_{pp} is decreased (Fig. 7b), the interaction force is lower and the human–robot interaction is safer. When a PID stiff behavior is chosen (Fig. 9), instead, the force level is not even regulated. The originated force is so hard that the system is halted for the security solutions adopted in the arm control.

5.2.2. Second session of experimental trials

For the second session of experimental trials, the task of opening a microwave oven (Fig. 10a) was chosen to demonstrate the increased functionality of the implemented controller with respect to a standard stiff controller. This type of task does not require the direct

Table 1
Interaction force values in the three Cartesian directions

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

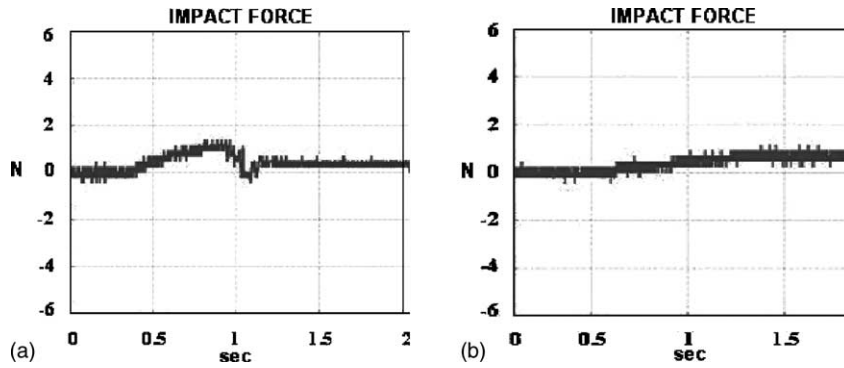


Fig. 7. Impact force along the y-direction when the proportional parameters are $K_{pp} = [450, 190, 250]$ (a) and $K_{pp} = [250, 90, 150]$ (b).

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.

In order to verify the system usability and acceptability, as well, this experimental session was based on user trials [34].

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. Hence an accurate algorithm of trajectory planning would describe an arc of circumference of 45° having the length of the oven door as radius. The advantage of the developed control scheme instead 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 constraints are sensed at the end-effector. The trials aim at verifying that the adaptability of the system can ensure the opening of the oven giving only the final reference point.

Fig. 10b shows the quarter of circle described by the microwave oven door while opening, the reference final point P_{fd} , which should be reached by the arm through the compliance control in the Cartesian space, the desired trajectory from the starting point to P_{fd} and the actual trajectory, followed by the Dexter arm when controlled by the implemented compliance control.

As evident, the developed compliance control in the Cartesian space is not able to accomplish the desired service task. This is not due to the concept of

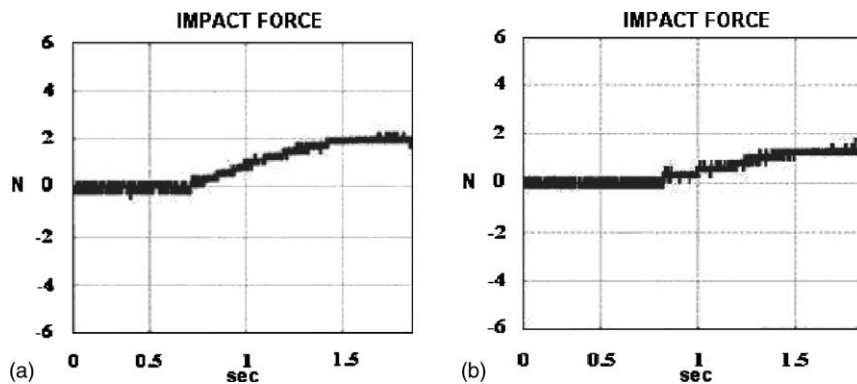


Fig. 8. Impact force along the z-direction when the proportional parameters are $K_{pp} = [450, 190, 250]$ (a) and $K_{pp} = [250, 90, 150]$ (b).

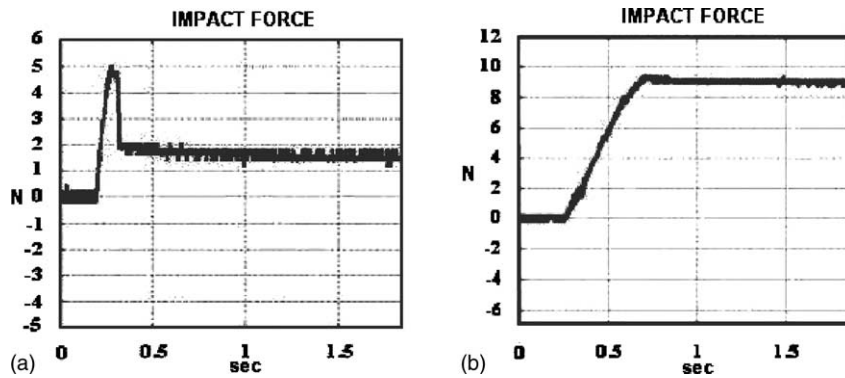


Fig. 9. Impact force along the y-direction (a) and the z-direction (b) when a PID controller is used as position controller.

self-regulating compliance, but it is due to the low performance of the compliance control in the Cartesian space when applied to the Dexter mechanical structure. The real problem in the execution of the task is not the compliance, but the wrong management of the elbow angle. As it will be shown in the next section, opening the microwave oven requires the modification and the control of the elbow angle and, as previously demonstrated, the compliance control scheme in the Cartesian space is not able to do that.

5.2.3. Third session of experimental trials

As a cooperation task, combing was chosen in the third session of experimental trials (Fig. 11a). It appears as a good demonstration of the safety and the

functionality of the self-adjusted compliance. In the combing task, in fact, the variable compliance is helpful to increase the level of safety in the interaction and to convey flexibility to the system avoiding the accurate description of the desired trajectory. To plan an accurate reference trajectory for the combing is useless as the head shape changes from human to human and with human's movement, but to plan an approximate trajectory is sufficient if the robot is made adaptable to the shape of the obstacle met during the task.

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 and the desired trajectory is generated by polynomial algorithms of 5th degree (Fig. 11b). P_0 is a generic initial position. The Cartesian positioning in

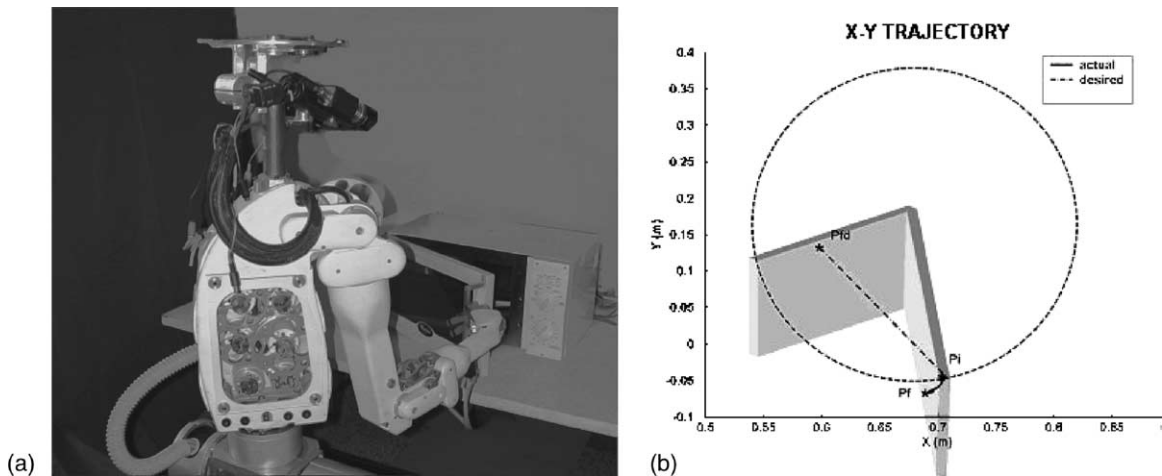


Fig. 10. The arm during the execution of the task (a). The task of opening a microwave oven (b).

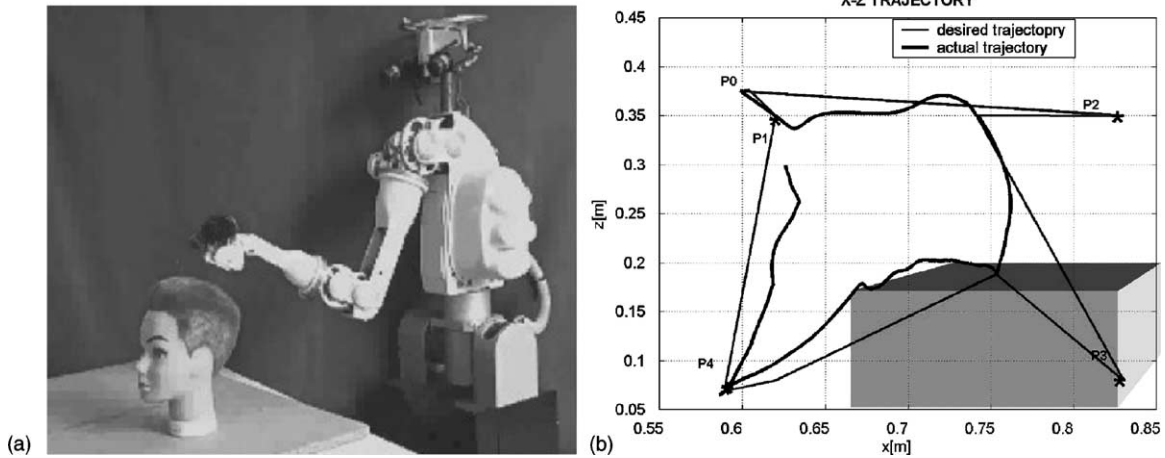


Fig. 11. A view of the experimental combing task (a). The combing task (b).

the free space follows the desired profile with an accuracy depending on the fixed parameters but this accuracy rapidly decreases on the path P_2 – P_3 – P_4 when the user head is met. The end-effector changes its Cartesian position in accordance with the head shape, between P_2 and P_4 . This result is obtained by exploiting the feature of the implemented control scheme of self-regulating the compliance in the different Cartesian directions, which allows imposing a highly variable compliance on the z -direction, as required by the combing task. The K_P parameters are set to an initial value, which ensures a good accuracy in absence of impact, and when an obstacle occurs, their variability over time is regulated through the position error and the scalar coefficient k_x , k_y , k_z . The desired high compliance in the z -direction is obtained by choosing a high value for k_z , which regulates the velocity of decay of the K_{pz} parameter.

The interaction force on the z -direction is measured by a load cell and recorded through an oscilloscope. The combing task has been repeated with a constant K_P matrix, too, in order to evaluate the functionality and the advantage in the use of an exponentially variable compliance. The resulting interaction forces have been recorded and drawn in a time interval starting at impact time and ending at final contact time (the resulting behavior is substantially similar to that obtained through the next controller and shown in Figs. 16b and 17).

6. Self-regulated compliance control in the joint space

6.1. Theoretical formulation

The compliance control scheme in the joint space, like the above controller in the Cartesian space, realizes a compensation only of the gravitational contribution to the robot dynamics (1), but it acts with a PD action on the joint error rather than on the Cartesian error [28,31]:

$$\tau = K_{PQ}\tilde{q} - K_D\dot{q} + g(q), \quad (4)$$

where $\tilde{q} = q_d - q$ is the error between the desired joint position vector q_d and the actual joint position vector q and $g(q) = [D_1, \dots, D_n]^T$ is the gravitational torque estimated through (2).

The PD term acts directly on the robot joints, through K_{PQ} , and acts indirectly on the Cartesian position. The robot is considered as a mechanical system which presents an n -dimensional generalized spring, regulated by the rigidity coefficients of matrix K_{PQ} . If matrix K_{PQ} is diagonal the robot can be seen as a system of n independent springs applied at each joint. The damping velocity at each joint is then controlled through the diagonal matrix K_D .

In the steady condition, in presence of a set of forces h acting on the end-effector, the control law reduces to $K_{PQ}\tilde{q} = J^T h$ and, as K_{PQ} is a positive definite matrix,

the joint error $\tilde{q} = K_{PQ}^{-1} J^T h$ is regulated by the active compliance in the joint space K_{PQ}^{-1} .

In absence of external forces, instead, the control law ensures a zero joint error at the equilibrium:

$$K_{PQ}\tilde{q} = 0.$$

The PD term has been enriched with a variable compliance in order to improve the performance of the robot during the execution of tasks of interaction or cooperation. The self-regulating compliance can autonomously vary the joint compliance as a function of the position error and consequently of the joint error. In fact, the joint position error increases over time when an unplanned interaction occurs.

The control law (4) has been modified in order to take into account the dependency of the K_{PQ} and K_D matrices on the joint error and has been applied to the Dexter robot arm [39]:

$$\tau = K_{PQ}(q, q_d)\tilde{q} - K_D(q, q_d)\dot{q} + g(q). \quad (5)$$

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

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

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

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

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

In the phase of development and implementation of (5) on the Dexter arm, the main features of the robot, such as redundancy and the independence of joint J_0 on the other seven joints, were considered. Hence, an inverse kinematics algorithm is used to move from the Cartesian space, where the motion primitives are given, to the joint space. The Dexter robot arm is 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 [1].

Joint J_0 is characterized by an independent motion from an initial point to a desired final point along a predefined trajectory.

The other joints, $J_1, \dots, J_7$, 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 elbow angle ψ without changing the end-effector global position.

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 (required when the robot is far from the singularities) and a limited joint velocity (necessary in the proximity of a singular region).

6.2. Implementation and experimental evaluation

The same sessions of experimental trials were carried out as for the case of the controller in the Cartesian space.

The design of the controller parameters is basically analogue to the previous controller, as the initial value for K_{PQ} is set in the free space accounting for the desired accuracy. For example, $K_{p1} = 110$, $K_{p2} = 50$, $K_{p3} = 35$, $K_{p4} = 26$, $K_{p5} = 15$, $K_{p6} = 4$, $K_{p7} = 4$ have been chosen and the rate of decay of the proportional coefficients is fixed by $k_1, \dots, k_7$.

In particular, a compliance matrix in the joint space facilitates the control of the stiffness of each joint, but the compliance in the Cartesian directions is indirectly regulated through the experimental setting of $k_1, \dots, k_7$ coefficients. For example, the choice of $k_1 = 1$, $k_2 = 3.5$, $k_3 = 1.5$, $k_4 = 3.0$, $k_5 = 1.2$, $k_6 = 2.5$, $k_7 = 2.0$ allows obtaining a high level of compliance along x , since the compliance in this direction experimentally appears to depend above all on joints J_2, J_4, J_6 .

As for K_D matrix, the experimental value for β is 0.24.

6.2.1. First session of experimental trials

Firstly, the Dexter performance in the regulation of position and orientation as well as in the control of the interaction force has been analyzed.

Figs. 12 and 13 show the time evolution of the position and orientation error during a positioning in the desired location requiring a zero or a non-zero elbow angle, respectively. As can be observed in the graphs, the performance of the Dexter arm does not decrease

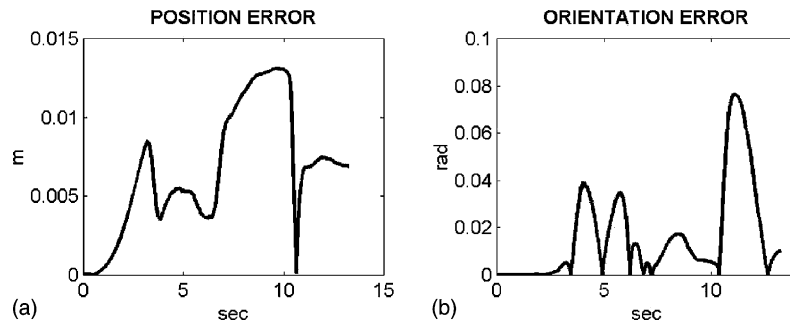


Fig. 12. Position error (a) and orientation error (b) in a positioning task with a zero elbow angle. The compliance control scheme in the joint space is used.

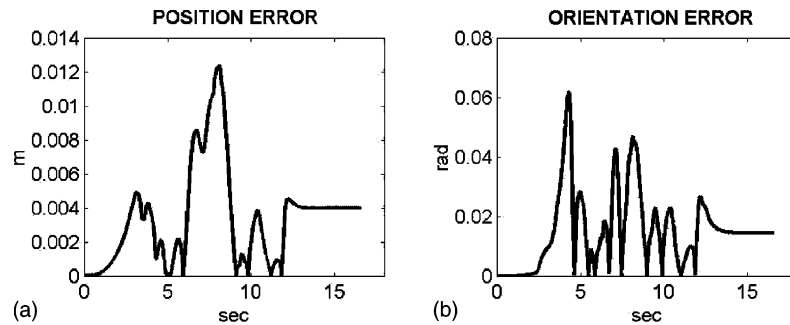


Fig. 13. Position error (a) and orientation error (b) in a positioning task with a non-zero elbow angle. The compliance control scheme in the joint space is used.

when it has to move the angle ψ from zero during the motion. The value of the error in Fig. 13 is comparable with the value in Fig. 12 and the accuracy in the positioning can be increased or decreased depending on the K_{PQ} values.

Table 2 reports the results of the experiments of force measurement during the impact with an object.

The impact has been repeated in the three Cartesian directions, in different conditions of compliance, in order to compare the resulting force with the value generated by a stiff PID controller. The forces during the collision have been measured by means of a load cell and have been recorded through an oscilloscope.

The compliance control scheme in the joint space, as well as the compliance control in the Cartesian space, has shown the capability of regulating the interaction force by varying the proportional matrix (Fig. 14). Like the Cartesian controller, the second implemented controller can considerably reduce the force values that a standard PID controller exerts in the impact and during the interaction.

6.2.2. Second session of experimental trials

Testing of the controller (5) during the execution of the service task of opening a microwave oven has revealed improved performance of the Dexter arm when

Table 2
Interaction force values in the three Cartesian directions

Interaction direction	Interaction force (N) ($K_P = \text{diag}[110, 50, 35, 26, 15, 4, 4]$)	Interaction force (N) ($K_P = [100, 35, 10, 8, 5, 3, 3]$)	Interaction force (N) (PID)
X	3.45	1.64	4.57
Y	2.55	0.91	4.70
Z	3.91	2.36	9.37

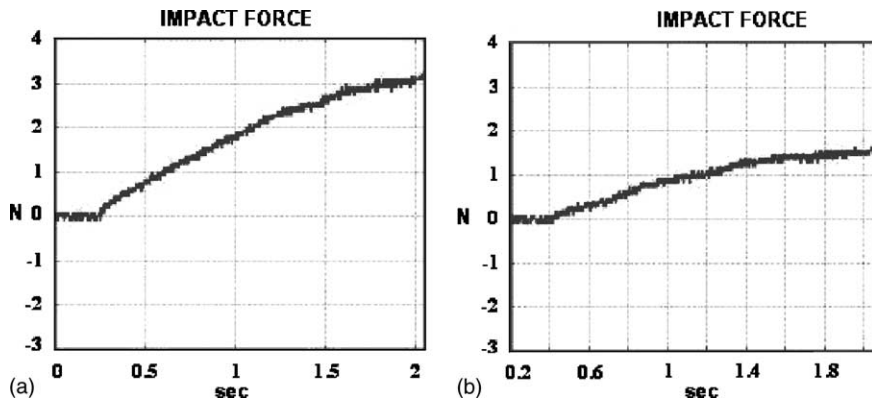


Fig. 14. Impact force along the x-direction when the proportional parameters are $K_{PQ} = [110, 50, 35, 26, 15, 4, 4]$ (a) and $K_{PQ} = [100, 35, 10, 8, 5, 3, 3]$ (b).

controlled in the joint space. The previous experimental session has demonstrated that the compliance controller in the joint space can well control the elbow angle position, since it allows the arm to turn around its trunk (joint J_1) and change the elbow position. This capability allows the controller in the joint space to accomplish the task of opening the microwave oven in one step, consisting of positioning in one desired final configuration.

After the first phase of approach to the oven, in which the proportional parameters are sufficiently high to ensure a good accuracy, a second phase of opening is executed with a lower set of proportional parameters. In this second phase, the robot arm reveals the capability to adjust the current trajectory to the constraints met along the planned motion (i.e. to say the microwave oven door). Thus, it does not require the development of an exact algorithm which plans the positions to reach time to time, but even the sole command of desired final position is sufficient to move the arm along the bound trajectory.

Fig. 15 shows the desired trajectory, joining point P_i , where the oven is completely closed, to point P_{fd} , corresponding approximately to the point of max opening of the door, and the actual trajectory, reaching the real final point of opening. The desired final point is only a gross indication of the final point of opening. It is not realistic that the user calculates exactly the trajectory or even the precise final point reached by the oven door when opened. Thus, the strength of the implemented controller consists in the maximum

flexibility and safety conferred to the system through the compliance. Even if the human indicates the final point very roughly, the system is completely safe: at worst, it can reach a different final point but on the trajectory of the microwave oven door. A further positioning command can follow in order to completely open the oven [34].

6.2.3. Third session of experimental trials

As for the case of compliance control in the Cartesian space, in the combing task [18,39], the reference points are the vertices P_1 , P_2 , P_3 and P_4 of a rectangle

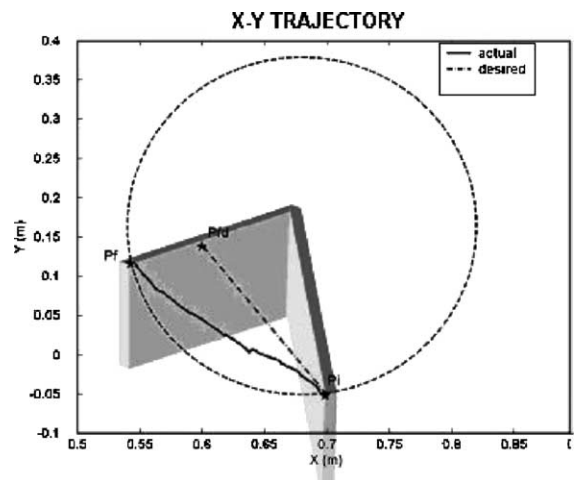


Fig. 15. The task of opening a microwave oven.

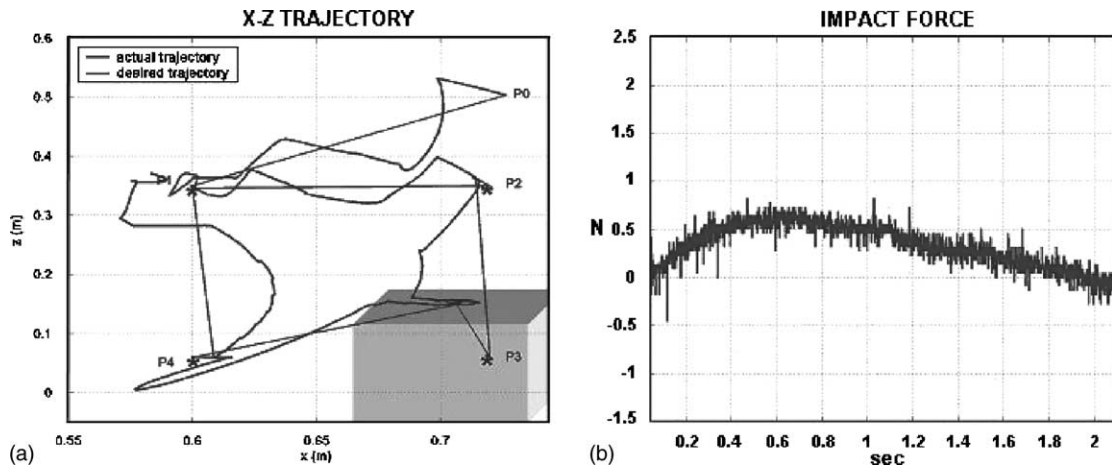


Fig. 16. 2D representation of the actual and the desired trajectory during the interaction with an obstacle on the path. P_1 , P_2 , P_3 , P_4 are the reference points in the Cartesian space (a). Impact force along the z -direction when a self-regulated compliance is used (b).

in 2D x - z space and the obstacle is located along the z -direction, among the points P_2 , P_3 and P_4 . The highly variable compliance required along the z -direction has been generated through an adequate setting of the joint compliance. Particularly, in the Dexter arm, the indirect action on the stiffness in the z -direction has been achieved mainly through a direct control of the compliance of joints J_2 and J_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 head is met (Fig. 16a). In

this way, the end-effector follows the profile of the obstacle (the head) and reduces considerably the force in the impact and during the interaction.

The comparison between the forces exerted by the compliant controller with self-regulating compliance and those generated by the compliant controller with constant compliance (Figs. 16 and 17) during the execution of the same combing task points out the high level of functionality of the implemented controller (4).

In addition to the value of the impact force, it is interesting to observe the time force evolution. When

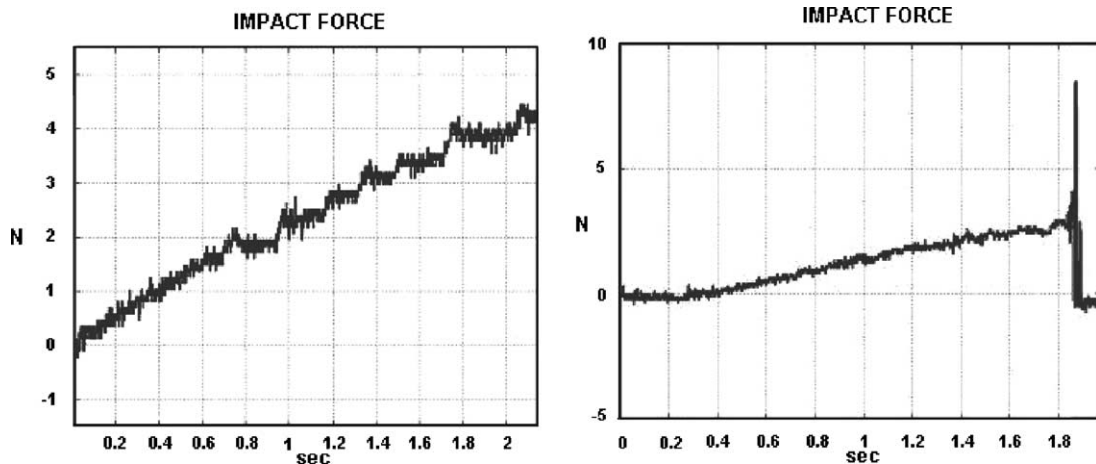


Fig. 17. Impact force along the z -direction when a constant compliance is used.

a self-regulated compliance is adopted, the force increases until a max of 0.69 N and then decreases to 0 N (Fig. 16b). Then the contact ends and the robot starts again reaching the fourth vertex, P₄. 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. 17). 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 point P₄ (Fig. 17b).

7. Impedance–compliance control

7.1. Theoretical formulation

The development of the third interaction control scheme, named “impedance–compliance”, is based on the analysis of the performance of the two compliance control schemes described above. Both of them try to face some critical problems concerning the Dexter structure, such as coupling in the degrees of freedom and the big difference in the inertia of each link. Experimental evidence has shown that the first implemented compliance control scheme, the controller in the Cartesian space, is capable of moving the robot in the Cartesian space only in a limited set of positions of the reachable workspace, since it can manage neither the different weight of each link nor the coupling. Otherwise, the compliance controller in the joint space can effectively control the arm joint by joint, but it does not act directly in the Cartesian space.

The impedance–compliance control scheme is aimed at effectively managing the inertia of the heavy links while controlling the arm directly in the Cartesian space. The resulting control solution acts as an impedance controller on the Dexter J₁–J₂–J₃ sub-system and as a compliance control scheme in the Cartesian space on the J₄–J₅–J₆–J₇ sub-system. In this way it can basically cope with three critical issues.

The first is the management of the high inertia of the proximal links. The knowledge of joints J₁, J₂, J₃ dynamic parameters allows compensating their dynamical behavior and consequently solving the problem of resistance to the motion due to their weight.

The second issue concerns the complexity of Dexter dynamics. Actually, only J₁, J₂, J₃ have been dynamically modeled because they provide the fundamental contributions to the robot motion in its whole workspace. Their control ensures the possibility of generating truly human-like movements, including the torso rotation (joint J₁) and the positioning of the elbow [16].

The last issue concerns the computational complexity. The estimation of the reduced dynamic model and the implementation of the impedance control on the three-joint sub-system means to avoid an excessive increase of the computational burden, due to the complex dynamical model of the whole 8 d.o.f. structure, and to achieve an improvement of the execution time.

Thus, the control law of joints J₁, J₂, J₃ is the classical impedance control strategy based on inverse dynamic control and aimed at linearizing and decoupling robot dynamics by feedback [5,28,31]. The control torques are expressed as

$$\tau_{13} = B_{13}(q)\alpha_{13} + C_{13}(q, \dot{q})\dot{q}_{13} + F_{13}\dot{q}_{13} + g_{13}(q), \quad (6)$$

where α_{13} is the control acceleration vector. All the other contributions to the torque vector are estimation of the terms of the robot dynamics. Hence, $B_{13}(q) \in \mathfrak{R}^{3 \times 3}$, $C_{13}(q, \dot{q})\dot{q}_{13} \in \mathfrak{R}^{3 \times 1}$, $g_{13}(q) \in \mathfrak{R}^{3 \times 1}$ and the 3×1 vector α_{13} is extracted from the α acceleration vector expressed as follows:

$$\alpha = J^+(q)(a - \ddot{J}(q, \dot{q})\dot{q}), \quad (7)$$

where

$$a = \begin{bmatrix} \ddot{p}_d + K_{MP}^{-1}(K_{DIP}\dot{\tilde{p}} + K_{PIP}\tilde{p}) \\ T(\varphi_e)(\ddot{\varphi}_d + K_{MO}^{-1}(K_{DIO}\dot{\tilde{\varphi}} + K_{PIO}\tilde{\varphi})) \\ + \dot{T}(\varphi_e, \dot{\varphi}_e)\dot{\varphi}_e \\ \ddot{\psi}_d + k_{M\psi}^{-1}(k_{DI\psi}\dot{\tilde{\psi}} + k_{PI\psi}\tilde{\psi}) \end{bmatrix},$$

$J \in \mathfrak{R}^{7 \times 8}$ is the Jacobian matrix; $J^+ \in \mathfrak{R}^{8 \times 7}$ is the pseudo-inverse Jacobian matrix; $\tilde{p} = p_d - p$ is the Cartesian position error; $\dot{\tilde{p}} = \dot{p}_d - \dot{p}$ is the linear velocity error; $\ddot{p}_d$ is the desired acceleration vector; $\tilde{\varphi} = \varphi_d - \varphi$ is the orientation error expressed in an Euler angle representation; $T(\varphi_e)$ is the transformation matrix between the angular velocity ω_e and $\dot{\varphi}_e$; $\tilde{\psi} = \psi_d - \psi$ is the elbow

angle error; $K_{PI} = \text{block diag}\{K_{PIP}, K_{PIO}, k_{PI\psi}\}$, $K_{DI} = \text{block diag}\{K_{DIP}, K_{DIO}, k_{DI\psi}\}$, $K_M = \text{block diag}\{K_{MP}, K_{MO}, k_{M\psi}\}$ are 7×7 positive diagonal matrices.

Substitution of (6) in (1) leads to:

$$B_{13}\ddot{q}_{13} = B_{13}\alpha_{13} - J_{13}^T h, \quad \ddot{q}_{13} = \alpha_{13} - B_{13}^{-1} J_{13}^T h,$$

where a non-linear coupling term due to the external forces and moments is present ($J_{13} \in \mathfrak{R}^{6 \times 3}$ is the Jacobian matrix including the contribution of joints 1, 2, 3). Thus the implemented impedance control does neither decouple nor linearize the robot dynamics, because of the absence of a force sensor at the wrist, but the desired mechanical behavior is still ensured. The Dexter sub-system behaves as a mechanical impedance regulated through the matrices K_M , K_{PI} , K_{DI} . The external force exerted on the arm is balanced by a term of mass depending on K_M , a damping term controlled by K_{DI} and an elastic force regulated by K_{PI} . At the equilibrium the elastic term continues to balancing the exerted force even if indirectly.

The orientation part of impedance controller is not used, since the regulation of the end-effector orientation is effectively depending on joints J_4, J_5, J_6, J_7 .

Their contribution to the end-effector position and orientation is controlled by the compliance controller in the Cartesian space (3). The mathematical formulation is updated as follows:

$$\tau_{47} = J_{47}^T \begin{bmatrix} K_{PCp}(x, x_d) \tilde{p} \\ T_e^{-T}(\tilde{\psi}) K_{PCo} \tilde{\psi} \\ k_{\psi C}(x, x_d) \tilde{\psi} \end{bmatrix} - K_{DC}(x, x_d) \dot{q}_{47} + g_{47}(q),$$

where $J_{47} \in \mathfrak{R}^{7 \times 4}$ is the Jacobian matrix for joints $J_4, \dots, J_7$; $\dot{q}_{47}$ is the velocity of joints $J_4, \dots, J_7$ and $K_{PC} = \text{block diag}\{K_{PCp}, K'_{PCo}, k_{\psi C}\}$ and K_{DC} are, respectively, the stiffness and the damping matrices. A self-controlled compliance function can newly be adopted for the gain matrices K_{PC} and K_{DC} in order to convey a high level of compliance variability.

7.2. Implementation and experimental evaluation

Since the idea of implementing an impedance–compliance control strategy arose from the analysis of the experimental performance of the two previous

compliance control schemes, the experimental validation of the impedance–compliance scheme focused on the same parameters of comparison and the same tasks.

As regards the tuning of all the gain matrices, the previous implementation of compliance control in the Cartesian space provided the reference magnitude for them and from there further experimental trials allowed an finer design of the controller for the addressed tasks.

Experimental evidence confirmed that impedance control does not act on the orientation regulation so K_M, K_{PI} and $K_{DI} \in \mathfrak{R}^{4 \times 4}$. More specifically, their values have been set as $K_{MP} = \text{diag}\{1, 0.8, 1\}$, $K_{M\psi} = 1$, $K_{PIP} = \text{diag}\{100, 100, 200\}$, $K_{PI\psi} = 180$, $K_{DIP} = \text{diag}\{30, 15, 27\}$, $K_{DI\psi} = 6$.

Finally, for the control of joints $J_4, \dots, J_7$, the variable compliance function starts from the desired value in the free space ($K_{PCp} = \text{diag}\{100, 100, 120\}$, $K_{PCo} = \text{diag}\{6, 6, 6\}$, $k_{\psi} = 180$) and in case of interaction compliance increases more or less rapidly depending on k_x, k_y, k_z . The value of $k_x = 1.0$, $k_y = 1.2$, $k_z = 2.8$, $k = 1.0$ have been chosen to ensure a quicker decay of K_{PC} along the z-axis.

7.2.1. First session of experimental trials

The first stage of the experimental trials provides the measure of the robot accuracy in tasks of positioning in the free space, both with a zero and a non-zero elbow angle. The temporal evolution of position and orientation error for a fixed set of proportional parameters has been recorded. Figs. 18 and 19 show an efficient robot behavior when the required ψ angle is either zero or different from zero. The compensation of proximal joints inertia leads to increasing the precision in the elbow positioning without notably increasing the position error.

From the point of view of the system functionality in the interaction, the impedance–compliance controller is capable of easily controlling the interaction force in the Cartesian directions, directly regulating the proportional gains K_{PI} and K_{PC} . In fact, the realized control in the Cartesian space for both sub-systems J_1 – J_2 – J_3 and J_4 – J_5 – J_6, J_7 allows acting directly on the level of stiffness along x, y and z , and reducing the impact force in the three directions by decreasing the values of the proportional gains (Fig. 20).

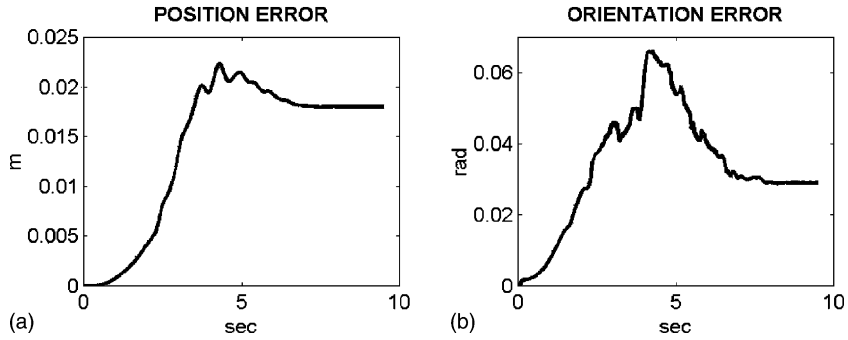


Fig. 18. Position error (a) and orientation error (b) in a positioning task with a zero elbow angle. The impedance-compliance control scheme is used.

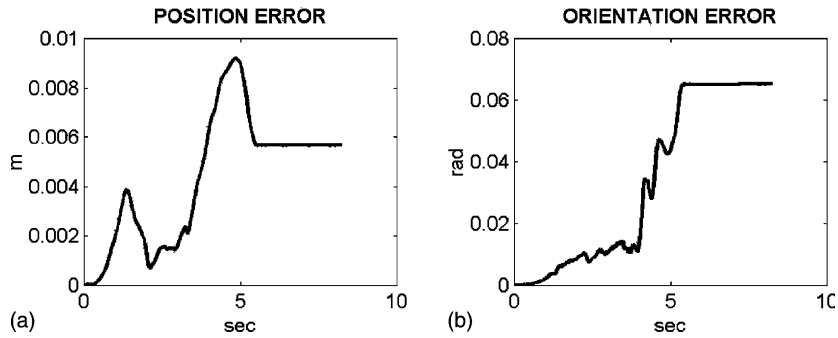


Fig. 19. Position error (a) and orientation error (b) in a positioning task with a non-zero elbow angle. The impedance-compliance control scheme is used.

Table 3 reports the force values measured during the impact with an object and compared with the forces generated by a PID controller accomplishing the same impact task.

The collected data point out the capability of the third implemented control strategy of guaranteeing a safe interaction with humans and objects by regulating both the impulsive force, due to a sudden

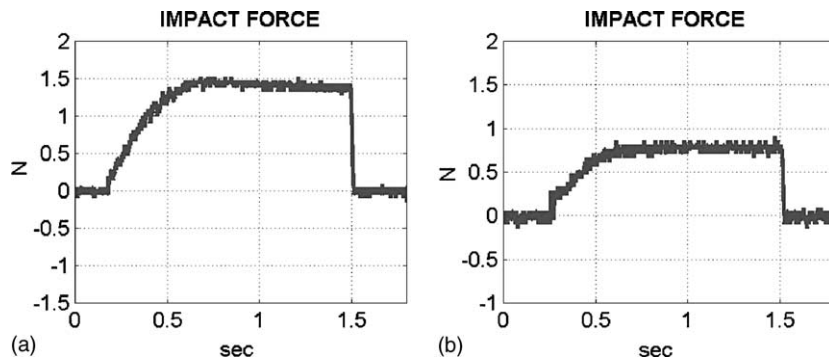


Fig. 20. Impact force along the z -direction when the proportional parameters are $K_{PP} = [300, 300, 300]$, $K_{PC} = [200, 160, 120, 8, 8, 9]$ (a) and $K_{PP} = [200, 200, 200]$, $K_{PC} = [120, 100, 80, 5, 5, 5]$ (b).

Table 3
Interaction force values in the three Cartesian directions

Interaction direction	Interaction force (N) ($K_{PIP} = [300, 300, 300]$, $K_{PC} = [200, 160, 120, 8, 8, 9]$)	Interaction force (N) ($K_{PIP} = [200, 200, 200]$, $K_{PC} = [120, 100, 80, 5, 5, 5]$)	Interaction force (N) (PID)
X	1.33	0.66	4.57
Y	2	0.95	4.70
Z	1.47	0.86	9.37

impact, and the force value during the whole interaction time.

7.2.2. Second session of experimental trials

The service task of opening the door of a microwave oven provides a further evidence of the benefits of the impedance–compliance control with respect to both previous compliant controls (Fig. 21).

The strength of the third proposed controller is the capability of compensating the dynamics of the proximal joints, i.e. to say the joints having the highest inertia and weight. In this way, the robot arm can accomplish the required service task in a truly anthropomorphic manner, by winning the resistance to the motion exerted by the heavier joints and realizing the control of the position time to time along the whole path. Like in a human being, the impedance–compliance control scheme tries to guarantee the accurate control of the position during the transients as well as at the equilibrium, consequently generating fluid and smooth motions during the task.

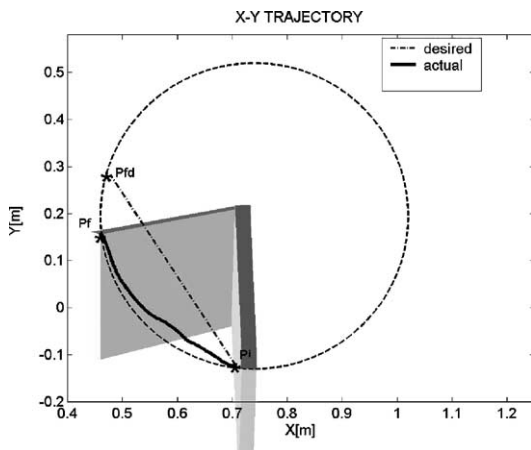


Fig. 21. The task of opening a microwave oven.

As a demonstration, Fig. 21 draws the actual trajectory recorded during the opening of the door of the microwave oven. Like in the experiments performed with the two compliance controllers, one final point, P_{fd} , has been provided as reference. It is outside the range of reachable positions by the door while opening and the corresponding desired trajectory, joining P_i to P_{fd} , is completely different from an arc of circumference. Nevertheless the Dexter arm is capable to accomplish the task and, moreover, the trajectory followed by the end-effector is very near to the quarter of circumference described by the door during the task.

7.2.3. Third session of experimental trials

If opening a microwave oven permits verifying the affordability of the system in term of flexibility and safety for the object (the oven) and the robotic system itself, combing represents the task which demonstrates the capability of ensuring a safe cooperation with the user as well as the functionality of the compliance.

As for the cases of compliance control schemes in the Cartesian and joint space, the realization of the task requires a high level of adaptability of the robotic system in order to fit the robot motions to the different head shapes and movements. The desired trajectory is again a rectangle centered on the human head and the level of adaptability of the actual trajectory to the obstacle sensed during the motion (the human head) is depending on the rate of variability of the self-regulating compliance (Fig. 22). While the J_1 – J_2 – J_3 sub-system is managed by the impedance control, joints J_4 , J_5 , J_6 , J_7 are controlled by the compliance control scheme in the Cartesian space with self-regulated compliance. As a consequence, the first sub-system acts as a mechanical impedance by compensating the robot dynamical contributions and properly balancing the external force and, at the same time, the latter sub-system conveys to the robot

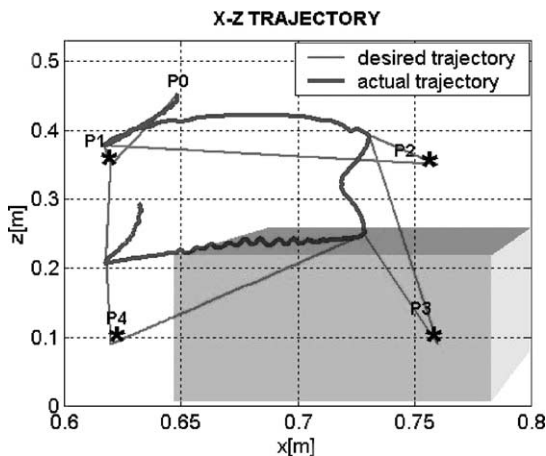


Fig. 22. 2D representation of the actual and the desired trajectory during the interaction with an obstacle on the path. P_1 , P_2 , P_3 , P_4 are the reference points in the Cartesian space.

the necessary level of adaptability to accomplish the task.

The self-regulated compliance is essential to improve the human safety, too, since the interaction force has to be as low as possible not only at the impact time but even after the impact, when the position error increases due to the presence of the obstacle. To this regard, combing task has been executed in two different conditions, with a constant compliance and with a self-controlled compliance for the J_4 – J_5 – J_6 – J_7 sub-system, like for the compliance control in the joint space.

8. Comparative discussion of experimental results

The compared analysis proposed in this section points out the differences in the performance of the three implemented compliance control systems, underlines the complexity of the controlled robotic system and explains the reasons for failure of the system in the execution of some commands [39].

The carried out comparative experimental trials take into consideration three main features as indications of the effectiveness of the control systems: the accuracy in the robot positioning, the capability of modulating the level of compliance, and hence the value of the interaction force, and the affordability of the robotic

system during the execution of tasks of assistance to humans.

8.1. Differences in the control of the elbow and joint J_1

The comparison of the levels of accuracy of the implemented compliance control systems has been based on the position/orientation error recorded in the first session of the experimental trials.

Although the theoretical analysis of the compliance control scheme in the Cartesian space, in the joint space and the impedance–compliance control scheme suggests the first one as the best trade-off between simplicity of implementation and efficacy, the experimental trials have produced unexpected results.

Firstly, a comparison between Figs. 5 and 12 confirms a good accuracy as well as smoothness in the motion and simplicity in the control of the first implemented controller. Furthermore, the performance of the two compliance controllers is comparable when the desired elbow angle is zero. Unfortunately, when a non-zero value is desired for ψ (Figs. 6, 13 and 23a and b), the performance of the compliance controller in the Cartesian space decreases and the controller in the joint space seems to ensure globally a smaller position error.

The reason of these results can be found in the coupling of the degrees of freedom and in the structure of the actuation system. When the controller in the Cartesian space is used, the control acts on the end-effector position error and only indirectly on the joint error. It ensures a smooth motion at the effector, but cannot manage the coupling of the joints and, above all, the different weight of each link. Consequently, the positioning is hardly executed when ψ is different from zero and however, even if ψ is null, the best accuracy in position corresponds to a worst accuracy in orientation and vice-versa, as a consequence of the joint coupling.

A direct action on the joint error with the controller in the joint space ensures the control of the position of each joint by regulating the joint-stiffness. In this way, it can compensate for the irregular distribution of the masses. As shown in Figs. 25 and 28, the compliance controller in the joint space can regulate the position of all the joints, including the heaviest joint J_1 which is never moved by the controller in the Cartesian

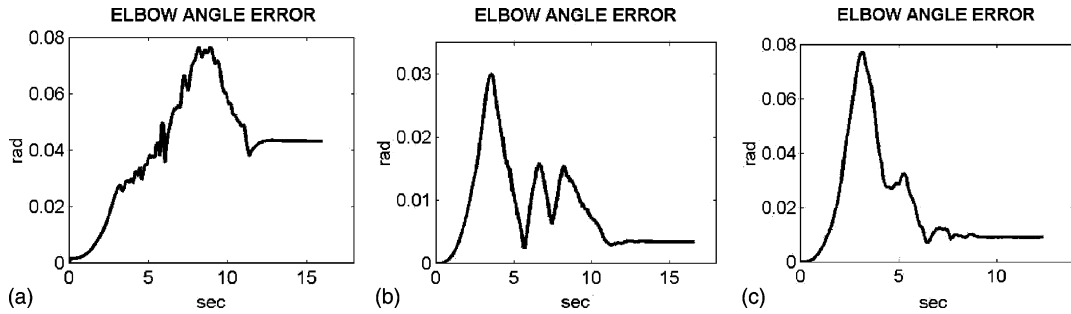


Fig. 23. Elbow angle error in a positioning task with a non-zero elbow angle when a compliance control scheme in the Cartesian space (a), a compliance control scheme in the joint space (b) or an impedance–compliance control (c) is used.

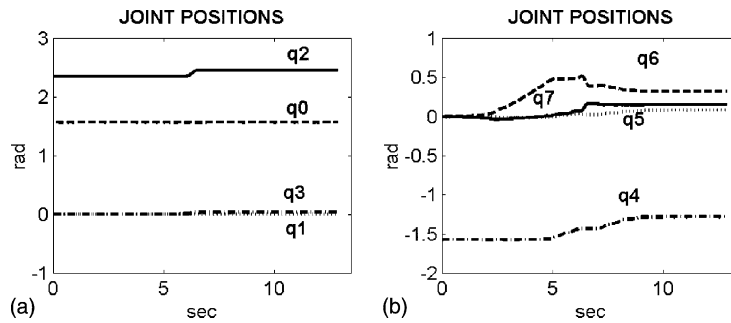


Fig. 24. Joint positions in a positioning task with a zero elbow angle. The compliance control scheme in the Cartesian space is used.

space (Figs. 24 and 27), but its indirect action in the Cartesian space generates an impulsive motion at the end-effector.

The third control, the impedance–compliance scheme, joins the control of the robot actions directly in the Cartesian space to the proper motion of all the joints. In spite of the joint coupling, both position and orientation are well-controlled, without accepting compromises between the two (Figs. 18 and 19),

the motion is globally smooth and all the joints are moved, including the heaviest joint J_1 (Figs. 23c, 26 and 29).

Figs. 24–29 show that joint J_1 is always at 0 rad when the control system in the Cartesian space is used. A non-moving J_1 does not permit a regulation of the position, since Dexter cannot regulate correctly both the end-effector and the elbow angle if a rotation of its torso is not realized.

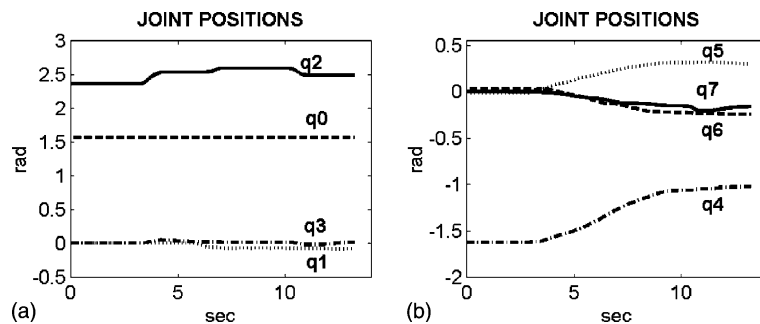


Fig. 25. Joint positions in a positioning task with a zero elbow angle. The compliance control scheme in the joint space is used.

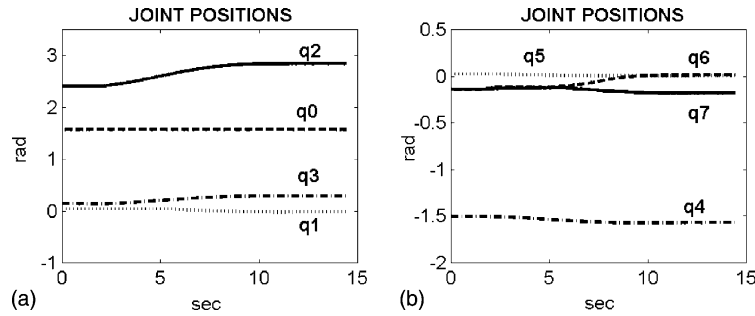


Fig. 26. Joint positions in a positioning task with a zero elbow angle. The impedance–compliance control scheme is used.

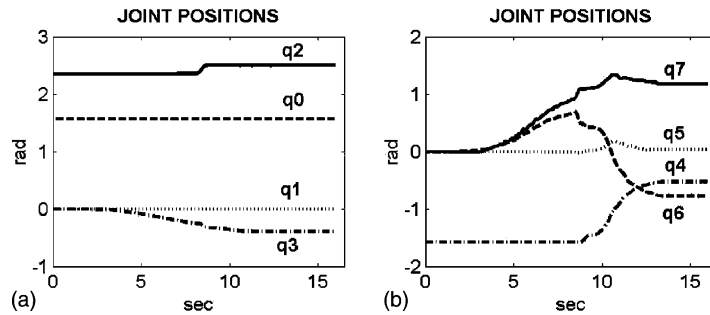


Fig. 27. Joint positions in a positioning task with a non-zero elbow angle. The compliance control scheme in the Cartesian space is used.

8.2. Compared analysis with a standard PID control

As regards the variability of the compliance during the execution of the desired task, both the compliance control schemes in the Cartesian space and in the joint space and the impedance–compliance control scheme can modulate the level of interaction force just varying the value of the proportional parameters. The difference between them concerns the possibility of acting

in the Cartesian space or in the joint space to accomplish the same target of regulating the forces in the Cartesian directions. If the regulation of the K_P parameters is easy and immediate in the Cartesian space (Figs. 7, 8 and 20), in the joint space the action on the compliance in the x – y – z directions is indirect. Particularly, the coupling in the joints and the cable actuation make quite hard the force regulation in the Cartesian space for a controller in the joint space. The empirical trials allow understanding which are the joints

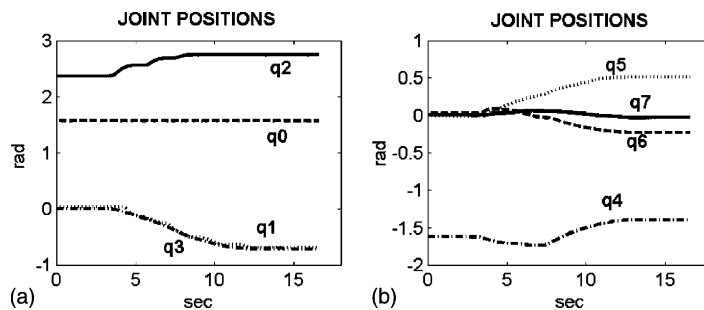


Fig. 28. Joint positions in a positioning task with a non-zero elbow angle. The compliance control scheme in the joint space is used.

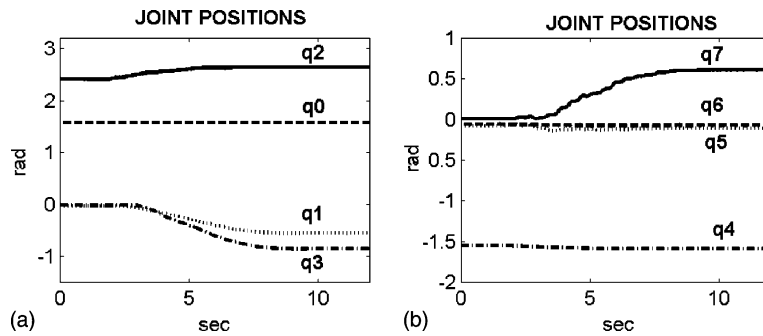


Fig. 29. Joint positions in a positioning task with a non-zero elbow angle. The impedance–compliance control scheme is used.

responsible for the forces exerted on each of the Cartesian directions and, consequently, allow modulating the compliance as in Fig. 14.

8.3. Comparative evaluation of the combing task

The results of the first two set of trials, those for the study of the level of accuracy of the implemented controllers and those for testing the capability of the compliance regulation, constitute the theoretical base for the analysis and the comprehension of the results achieved in the execution of the two tasks of physical interaction and cooperation: combing and opening the microwave oven.

As demonstrated in Sections 3, 4 and 5.2 all the systems can realize the combing task (Figs. 11, 16 and 22). In the three cases, the robot follows a rectangular reference trajectory centered on the human head and adapts its actual trajectory to the obstacle met (the head) with a level of flexibility depending on the imposed parameters for the function of self-regulated compliance. The time evolution of the actual trajectory in the three cases does not differ for the reached final points, but differs for the level of damping during the motion. Unavoidably, the compliance control in the joint space guarantees the tracking of the four vertices, but it does not effectively control the way to reach them.

It might appear strange that even the compliance controller in the Cartesian space is able to accomplish the task. The reason is easily identified in the frontal robot configuration during combing. This means that no rotation on joint J_1 is needed and a contemporary regulation of the end-effector position and the elbow angle is not required.

8.4. Comparative evaluation of the task of opening a microwave oven

The second experimented interaction task, instead, shows the limits of the implemented compliance controller in the Cartesian space. Being the Dexter arm an anthropomorphic robot arm, its attitude in movements is human-like, i.e. to say that its redundancy allows it to turn around its torso and move the elbow from a frontal to a side position like a human arm.

The task of opening the microwave oven can be considered as the real demonstration of the functionality and affordability of the controllers of the robotic system. The functionality is proved by the capability of the system of adapting its actual trajectory to the constraints felt during the execution of the task; the affordability is tested through the analysis of the level of stability of the system when hindered. While opening the oven, the Dexter arm is bound by the door of the oven which forbids the reference trajectory to be followed. The arm feels the opposing force but never becomes unstable.

When the compliance control in the Cartesian space is tested, the arm stops (Fig. 10b) as it is not able to turn around its torso (Figs. 27 and 30a); when the compliance control in the joint space or the impedance–compliance control are performed, the task is always well accomplished, as in both cases the Dexter arm is able to rotate around joint J_1 , to regulate the elbow (Figs. 28, 29 and 30b and c) and even to adapt the actual trajectory to the opposing force exerted by the microwave oven door (Figs. 15 and 21). The advantage of the impedance–compliance control strategy consists again of the easy control of the compliance in the x-direction, as it is required by

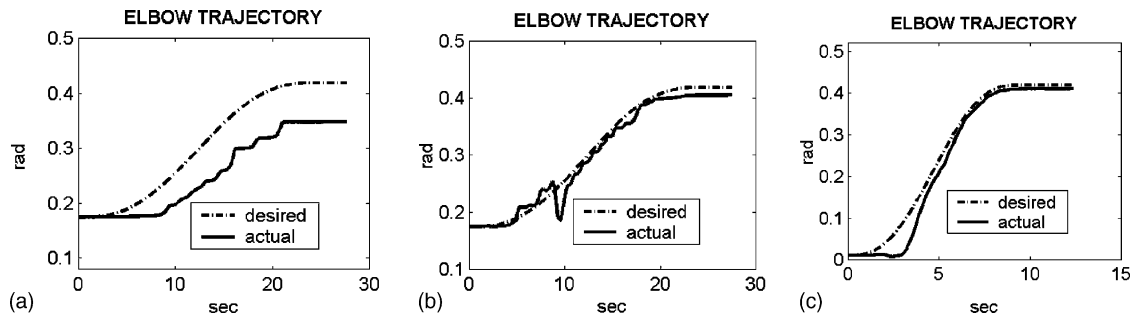


Fig. 30. Elbow trajectory during the opening of a microwave oven. The compliance control scheme in the Cartesian space (a), the compliance control scheme in the joint space (b) or the impedance–compliance control scheme (c) is used.

the task, the full control of the motion in the transients as well as at the equilibrium and consequently the evolution of the described trajectory, i.e. really similar to the trajectory followed by the microwave oven door while opening.

9. Conclusions

The paper has presented a critical analysis of three interaction control schemes implemented on Dexter, an anthropomorphic robot arm which is characterized by a peculiar mechanical design (cable-actuated), realized for a specific application context (personal robotics).

All the three control strategies have been enriched by self-regulated compliance in order to increase the robot functionality in the interaction with objects and persons. Particularly, an error-variable compliance is capable of granting a safe transition from an accurate free-space motion to a constrained motion, hindered by the physical interaction with an object as well as with a person.

As regards the actuation, the Dexter arm poses a series of critical problems, such as non-linear friction, coupling in the degrees of freedom and the anthropomorphic structure, which are differently faced by the three control strategies.

The experimental sessions allow comparing the performance of the three control schemes from the point of view of the robot positioning in free space, the capability of modulating the level of compliance and the affordability of the robotic system during the execution of task of assistance to humans. Even though all

the three implemented control strategies reveal comparable performance as regards the regulation of interaction forces, only the compliance control scheme in the joint space and the impedance–compliance controller can effectively manage the coupling and the anthropomorphism of the robotic structure.

However, the use of a reduced robot dynamic model joined to a self-regulated compliance in the impedance–compliance control resulted as the strategy that effectively satisfies all the requirements, from the cable-actuated structure control up to the cooperation and physical interaction control. Definitely, the last implemented control emerges as the best trade-off between the benefits of the compliance controller in the Cartesian space and the compliance controller in the joint space.

Further researches on the control of the Dexter arm will address the development of new control schemes which, based on the achieved control results and inspired by neuro-biological models, try to reproduce human-like perception-action behaviors in tasks of closer human–robot interaction, cooperation and service applications in general.

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