

An Impedance-Compliance Control for a Cable-Actuated Robot

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Abstract

A research work on the interaction control of a cable-actuated robot arm, the Dexter arm, is presented in this paper.

Firstly, general considerations on the cable-actuated structures and their application potential are provided and then the Dexter structure peculiarities are accurately analyzed in order to develop proper control solutions.

Starting from the analysis of the limitations of the compliance control schemes in Cartesian space and in joint space, previously implemented and experimentally validated on the Dexter arm, a novel control strategy, named impedance-compliance controller, is developed. The proposed control strategy tries to combine the benefits of a compliance control scheme in Cartesian space with the benefits of an impedance control scheme in the operational space by compensating the dynamics of the sole proximal joints.

The impedance-compliance controller is capable to achieve accurate smooth motions while guaranteeing functional control of the whole structure, even though a greater computational complexity is required.

The last section of the paper, dedicated to the experimental results, points out the differences with the previously experimented control solutions and provides some proofs of the increased Dexter functionality.

1 Introduction

The proposed work aims at developing a proper interaction control scheme for a cable-actuated anthropomorphic robot arm. The analyzed robot, called Dexter [1-3], was designed for a specific application domain, i.e. service applications and personal assistance, and for well-identified environments, i.e. residential sites, such as houses or hospitals [4,5]. Consequently, the design was inspired by the idea of a safe and intrinsically compliant structure, realized through a cable actuation system. The main drawback of cable actuation is a

reduced accuracy, which is fully compatible with the addressed environments and tasks.

The classical serial kinematic chains with revolute joints, used in the industrial robot manipulators, ensure high accuracy and precision, but increase the inertia and the weight of the robot. On the contrary, the choice of a compliant structure with steel cables and pulleys decreases the robot accuracy but lightens the mechanical structure. The robot arm becomes less dangerous in the interaction with the human user but more sophisticated in the dynamics, because of the non-linear friction, the coupling in the degrees of freedom and the anthropomorphic structure [6-9].

The proposed research work on the interaction control systems for the Dexter robot arm is the result of a detailed analysis of both the robot kinematic and dynamic characteristics and of the experimental validation of standard interaction control schemes.

Compliant control, impedance control or hybrid position/force control represent the cornerstones in the interaction control research. They range from the force control work by Whitney and others [10,11], which proposed the concept of end-effector impedance (*active accommodation matrix*) for each task, to the research in *active compliance* [10,12,13] or in the more generic *impedance control* methods [14-17], to finally the hybrid position/force control approach to constrained motion [18] or more generally to the force control approach based on force-related information [19]. Most of those works focused on the problem of interaction in industrial applications, such as assembly and part mating tasks, and consequently they started from the assumption that the robot was stiff, heavy, without coupling.

The experience on the Dexter arm has revealed the performance of the interaction controllers on a cable-actuated robot arm, in the hypothesis of negligible elasticity and friction. Previous works have described the compliance control schemes implemented on the Dexter arm and the resulting experimental data [3,20]. Since the

compliance controller in Cartesian space demonstrated a low level of affordability and functionality, a new controller in Cartesian space is presented in this paper. It joins the knowledge on the dynamics of the heaviest joints to the lightness and the low inertia of the last joints in an impedance-compliance control scheme.

Supported by the experimental validation, it is possible to identify the controller proposed in this paper as the scheme that better controls the Dexter arm, because it combines the advantages of a compliance controller in the joint space with those of a controller in Cartesian space.

2 Interaction control strategy

The developed interaction control scheme takes into account the mechanical and dynamical features of the Dexter anthropomorphic manipulator, developed by Scienza Machinale s.r.l. (Pisa, Italy) (Fig.1).

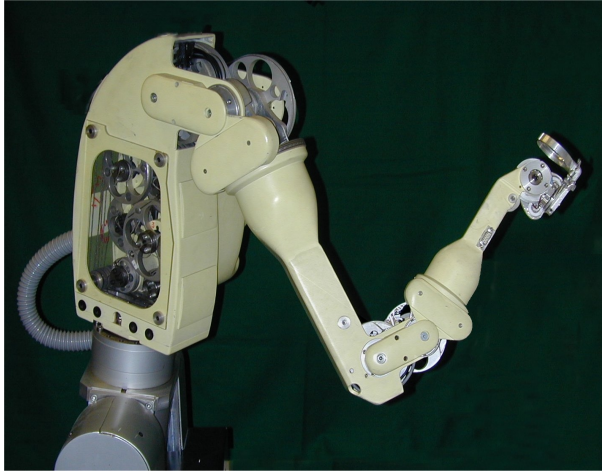


Fig.1 DEXTER arm

Dexter has 8 revolute-joints, the first of which, J_0 , has an horizontal axis which aims at increasing the workspace in the vertical direction (Fig.2). Only 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 the one of joint 1 is mounted on link 0. Joints $J_2, \dots, J_7$, instead, are all actuated by DC-motors installed on one side of link 1 and their transmission system is realized with pulleys and steel cables. This type of actuation allows a human-like distribution of the masses of the links, from the shoulder to the wrist, and a lighter structure than in industrial robots.

From the control point of view, the Dexter structure poses some critical problems, such as the coupling in the degrees of freedom and the big difference in the inertia of each link. The first attempt to face them, namely the compliant control scheme in Cartesian space [3], could manage neither the different weight of each link nor the coupling, even if it could ensure a smooth motion and

easiness of computation. The second attempt, namely the compliant controller in joint space [20], could effectively control joint by joint and thus it could regulate the end-effector position and orientation and the compliance of each joint. The limitation of the controller in joint space was the motion (not very smooth), the transients (not well controlled), and the difficult management of the compliance in the Cartesian directions.

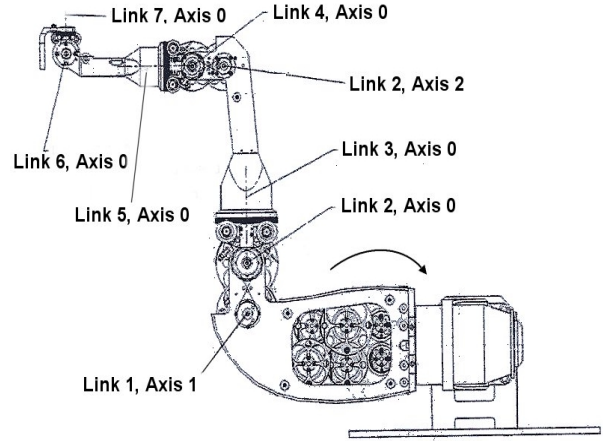


Fig.2 The Dexter mechanical structure

The third attempt, proposed in this work and named impedance-compliance control, tries to join the benefits of both previous controllers. Like the first one, it controls the arm in 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, allowing the rotation of joint J_1 .

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 others are controlled by a compliance controller in Cartesian space. This choice answers three requirements.

The first is the management of the high inertia of the proximal links. The knowledge of joints J_1, J_2, J_3 dynamic parameters allows compensating their dynamical behavior and consequently solves the problem of resistance to the motion due to their weight.

The second requirement concerns the lack of information on the whole Dexter dynamics. Actually, only J_1, J_2, J_3 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 really human-like movements, including the torso rotation (joint J_1) and the positioning of the elbow [21], which enlarge the reachable environment and the range of tasks achievable by the robot.

The last requirement concerns the computational complexity. The estimate of the dynamic model and the implementation of the impedance control on the whole 8-degree-of-freedom structure causes a heavy

computational burden and consequently a notable increase of the execution time. Hence, to implement an impedance control only for three joints and to develop a compliance controller in Cartesian space for the others means to avoid an increase of the computational burden and an improvement of the execution velocity.

3 Mathematical formulation of the impedance-compliance control

The vector of command torques for the 8 joints of the Dexter arm has been derived from the robot dynamic model, expressed in (1):

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

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

Joints J_1, J_2, J_3 are controlled by the impedance control scheme [22, 23]. It is a classical strategy based on inverse dynamic control and aimed at linearizing and decoupling robot dynamics by feedback. The control torques are expressed as:

$$\tau_{13} = B_{13}(q)\alpha_{13} + C_{13}(q, \dot{q})\dot{q}_{13} + F_{13}\dot{q}_{13} + g_{13}(q) \quad (2)$$

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.

The behavior of joints J_4, J_5, J_6, J_7 is regulated by the compliance control scheme in Cartesian space, based on the compensation only of the gravitational torque $g(q)$:

$$\tau_{47} = J_{47}^T(q)K_{PC}\tilde{x} - K_{DC}\dot{q}_{47} + g_{47}(q). \quad (3)$$

Instead, as for joint J_0 , a standard PID controller has been used, because it takes part only in tasks of global positioning and not in fine motion.

Coming back to the first control law, (2) includes the dynamic contributions of the sub-system J_1, J_2, J_3 to the torque vector. Thus, $B_{13}(q) \in \mathbb{R}^{3 \times 3}$, $C_{13}(q, \dot{q})\dot{q}_{13} \in \mathbb{R}^{3 \times 1}$, $g_{13}(q) \in \mathbb{R}^{3 \times 1}$ and the 3×1 vector α_{13} is extracted from the α acceleration vector expressed as follows:

$$\alpha = J^{-1}(q)(a - \ddot{J}(q, \dot{q})\dot{q}) \quad (4)$$

where

$$a = \begin{bmatrix} \ddot{p}_d + K_{MP}^{-1}(K_{DP}\dot{\tilde{p}} + K_{PP}\tilde{p}) \\ T(\varphi_e)(\ddot{\varphi}_d + K_{MO}^{-1}(K_{MO}\dot{\tilde{\varphi}} + K_{PO}\tilde{\varphi})) + \dot{T}(\varphi_e, \dot{\varphi}_e)\dot{\varphi}_e \end{bmatrix}$$

$J \in \mathbb{R}^{6 \times 8}$ is the 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 a Euler angle representation;

$\ddot{\varphi}_d$ is the second derivative of the desired orientation;

$T(\varphi_e)$ is the transformation matrix between the angular velocity ω_e and $\dot{\varphi}_e$;

$K_P = \text{block diag}\{K_{PP}, K_{PO}\}$, $K_D = \text{block diag}\{K_{DP}, K_{DO}\}$, $K_M = \text{block diag}\{K_{MP}, K_{MO}\}$ are 6×6 positive diagonal matrices.

The Dexter sub-system is considered as a mechanical impedance regulated through the matrices K_M, K_P e K_D . The external force acting on the arm is balanced by a term of mass depending on K_M , a damping term controlled by K_D and an elastic force regulated by K_P .

However, because of the absence of a force sensor at the wrist, the implemented impedance control does neither decouple nor linearize the robot dynamics. In fact, the substitution of (2) in (1) leads to:

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

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

where a nonlinear coupling term due to the external forces and moments is present ($J_{13} \in \mathbb{R}^{6 \times 3}$ is the Jacobian matrix including the contribution of joints 1, 2, 3). Anyway, the desired mechanical behavior is still ensured and 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 controlled by the compliance controller in Cartesian space.

The compliance control law in Cartesian space in (3) provides the 4×1 torque vector for J_4, J_5, J_6, J_7 . The mathematical formulation of the implemented control scheme is provided by the following expression:

$$\tau_{47} = J_{47}^T \begin{bmatrix} K_{PCp} \tilde{p} \\ T_e^{-T}(\tilde{\varphi}) K_{PCo} \tilde{\varphi} \end{bmatrix} - K_{DC} \dot{q}_{47} + g_{47}(q).$$

$J_{47} \in \mathbb{R}^{6 \times 4}$ is the Jacobian matrix for joints 4..7; $\dot{q}_{47}$ is the position of joints 4..7 and $K_{PC} = \text{block diag}\{K_{PCp}, K_{PCo}\}$ and K_{DC} are respectively the stiffness and the damping matrices. Detailed information on its implementation on the Dexter arm and its performance can be found in [20].

4 Experimental analysis

The session of experimental trials is aimed at evaluating the level of accuracy, affordability and functionality of the impedance-compliance controller, in

order to compare the resulting data with those concerning the compliance control schemes evaluated in [3,20]. The main target of the trials consists of verifying the system capability of controlling all the joints, although acting in the operational space, since the basic limitations of the compliance control schemes resided in their impossibility of controlling the robot actions directly in Cartesian space as well as of moving properly all the joints.

Therefore, the first step of the experimental session consisted of realizing a set of motions in all the possible configurations in the free space and extracting a measure of robot accuracy. The temporal evolution of position and orientation error for a fixed set of proportional parameters has been recorded and further trials in various conditions of robot stiffness have been accomplished in order to evaluate the dependence of robot behavior on the proportional gains (Figs. 3 and 4).

A decrease of the set of proportional parameters causes an increase of the error (Figs. 3 and 4) and a decrease of the robot stiffness as expected (Figs. 5-7).

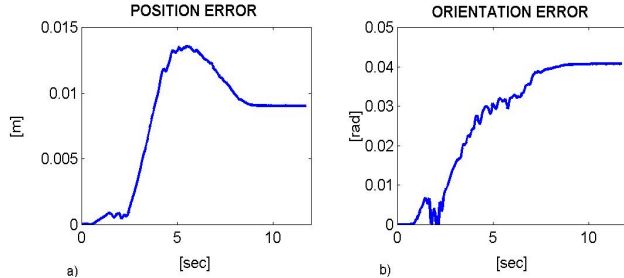


Fig.3. Position (3a) and orientation (3b) error when the proportional parameters are $K_{pp}=[300 \ 300 \ 300]$ and $K_{pc}=[200 \ 160 \ 120 \ 8 \ 8 \ 9]$.

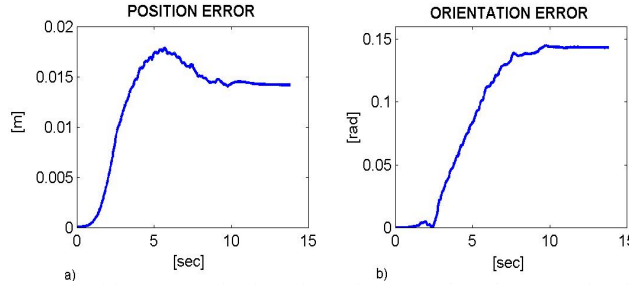


Fig.4. Position (4a) and orientation (4b) error when the proportional parameters are $K_{pp}=[200 \ 200 \ 200]$ and $K_{pc}=[120 \ 100 \ 80 \ 5 \ 5 \ 5]$.

The collected results show a globally affordable behavior of the system; the position error as well as the orientation error are quite small when the robot is stiff, and increase when the robot is less stiff. In spite of the joint coupling, both position and orientation are well-controlled, without accepting compromises between the two. On the contrary, when the sole compliance controller in Cartesian space was used [3,20], the error was globally higher and a higher level of accuracy in the position required a lower level of accuracy in the orientation.

Definitely, the impedance-compliance controller seems to have similar performance to the compliance controller

in joint space, but with respect to it the motion is globally smoother and, moreover, the interaction force is easily controlled by varying the proportional parameters in the Cartesian directions. In fact, the trials on the measure of the impact force against an obstacle equipped with a load cell have pointed out that a variation of the gain along x, y, or z, leads to a variation of the intensity of the force in the same direction (Figs. 5-7).

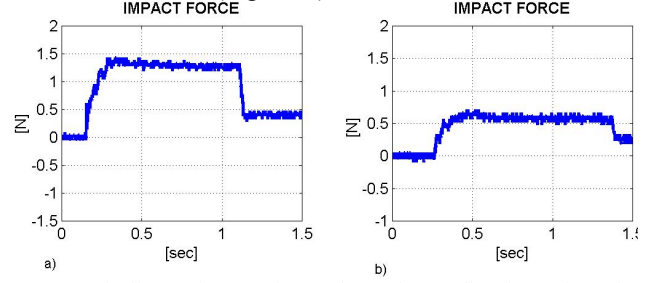


Fig.5 End-effector impact force along the x direction when the proportional parameters are $K_{pp}=[300 \ 300 \ 300]$, $K_{pc}=[200 \ 160 \ 120 \ 8 \ 8 \ 9]$ (5a) and $K_{pp}=[200 \ 200 \ 200]$, $K_{pc}=[120 \ 100 \ 80 \ 5 \ 5 \ 5]$ (5b).

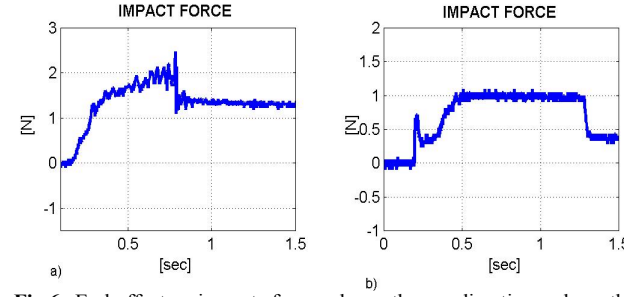


Fig.6 End-effector impact force along the y direction when the proportional parameters are $K_{pp}=[300 \ 300 \ 300]$, $K_{pc}=[200 \ 160 \ 120 \ 8 \ 8 \ 9]$ (6a) and $K_{pp}=[200 \ 200 \ 200]$, $K_{pc}=[120 \ 100 \ 80 \ 5 \ 5 \ 5]$ (6b).

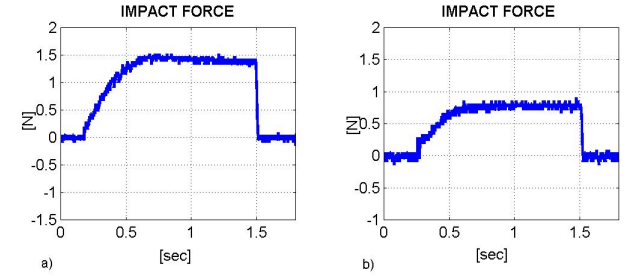


Fig.7 End-effector impact force along the z direction when the proportional parameters are $K_{pp}=[300 \ 300 \ 300]$, $K_{pc}=[200 \ 160 \ 120 \ 8 \ 8 \ 9]$ (7a) and $K_{pp}=[200 \ 200 \ 200]$, $K_{pc}=[120 \ 100 \ 80 \ 5 \ 5 \ 5]$ (7b).

Therefore, from the point of view of the accuracy, the performance of the impedance-compliance controller, acting in Cartesian space, is comparable to the compliance controller acting in joint space and, as regards the management of all the joints, a real improvement has been achieved with respect to the compliance controller in Cartesian space. The impedance-compliance control system revealed capable of moving even the heaviest joints. The strength of the proposed controller is the capability of compensating the dynamics of the proximal joints, that is the joints having the highest inertia, and

consequently of moving all the joints and rotating joint 1 according to the required Cartesian displacement.

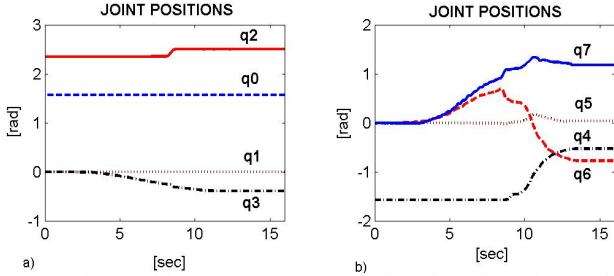


Fig.8 Joint positions (8a and 8b) during frontal motions. The compliance control scheme in Cartesian space is used.

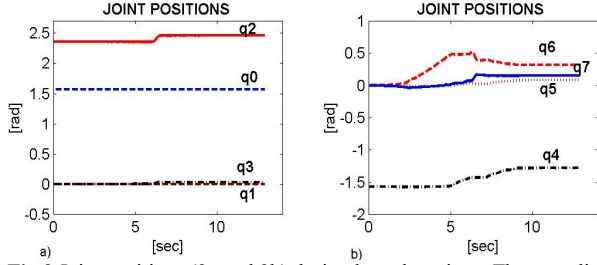


Fig.9 Joint positions (9a and 9b) during lateral motions. The compliance control scheme in Cartesian space is used.

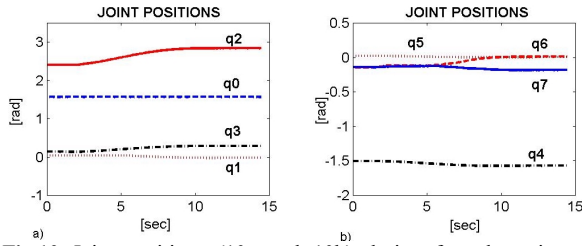


Fig.10 Joint positions (10a and 10b) during frontal motions. The impedance-compliance control scheme is used.

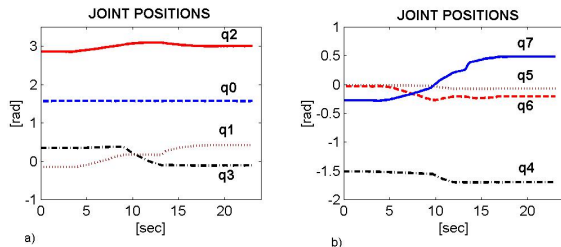


Fig.11 Joint positions (11a and 11b) during lateral motions. The impedance-compliance control scheme is used.

It means that, differently from the pure compliance controller in Cartesian space, even tasks requiring large displacements along the y direction can be realized by rotating J_1 around its axis. As a demonstration, the end-effector has been moved in all the possible locations of its workspace and the path followed by all the joints time to time has been drawn. Of course, the most meaningful result concerns with the position of J_1 over the time. When the compliance control scheme in Cartesian space is used, the joint is never moved, neither for frontal (Fig.8) nor for lateral (Fig.9) motion. That does not

happen when the impedance-compliance controller acts on it (Figs. 10 and 11).

It can be summarized that the Dexter functionality is improved, by allowing the arm executing a series of human tasks which require the torso motion. As an example, opening a microwave oven, a fridge or a door can be cited. In fact, when the precise trajectory followed by the opened door is unknown, a high degree of adaptability of the whole robot is required to execute the task. Like a human, the robot arm needs to adapt its actual configuration to the constraints felt step by step during the motion, not only through a variable compliance but even through the motion of the whole structure. The compliance control scheme in Cartesian space, even having a variable compliance, is not able to open a microwave oven [24] since it cannot move joint 1. Instead, the impedance control scheme, having the capability of properly moving all the joints, can effectively accomplish the task (Fig.12).

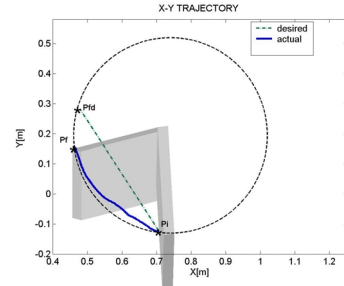


Fig.12 The task of opening the microwave oven

5 Conclusions

The proposed paper is based on a research work investigating the performance of interaction control strategies applied to a cable-actuated robotic system. The work provides a further contribution to the previous experiences in the compliance control of the Dexter anthropomorphic robot arm and allows deriving some general considerations on the structure and its control.

The described impedance-compliance control strategy has the advantage of using a reduced robot dynamic model to solve the basic problems of cable-actuated structures, that are the irregular distribution of the masses and inertia of the robot links and the coupling in the degrees of freedom, as well as to emphasize the lightness and the intrinsic compliance of the structure in service application contexts.

An experimental session has provided the data necessary to demonstrate the level of accuracy of the system and, moreover, the improved Dexter functionality with respect to the previous attempts to control its compliance. Particularly, the strength of the impedance-compliance controller has been proven in a service task of opening a microwave oven.

Future researches on the control of the considered arm will aim at exploiting the achieved results in closer

human-robot interaction and at emphasizing the anthropomorphism of the structure in human-like behaviors, by integrating neuro-biological inspired models.

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