

A Passivity-Based Force/Position Control Scheme for Robot Manipulators

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Abstract

The problem of designing a control scheme for robot manipulators in contact with a compliant surface is considered in this work. A passivity-based force/position control scheme is designed. A keen choice of the reference vector used in the control law is proposed as a function of the end-effector position and velocity errors and the integral of the contact force error. It is demonstrated that the scheme ensures tracking of the unconstrained components of the desired end-effector trajectory with regulation of the desired contact force along the constrained direction. In the imperfect model compensation case, the scheme is made adaptive with respect to a set of dynamic parameters. Numerical case studies are presented for an industrial robot manipulator.

1. Introduction

The use of force sensor measurements is crucial for the success of an interaction task between the manipulator and the environment. A number of schemes using force feedback have been proposed in the literature which are aimed at controlling both end-effector position and contact force. The most common strategy is hybrid force/position control [1]–[4] where either a position or a force is controlled along each task space direction. A different strategy is to control both a position and a force along each task space direction and manage the conflict between force and position by a suitable control design; examples of control schemes of this kind are the inner-outer force/position control [5] and the parallel force/position control [6].

The parallel control scheme is suitable to manage contacts with scarcely structured environments which are known to represent a drawback for hybrid controllers. The performance of a parallel controller with inverse dynamics compensation in the case of contact with an elastically compliant frictionless surface was studied in [7],[8]. Recently a parallel regulator with gravity

compensation has been proposed [9],[10] which guarantees that the force error along the constrained task direction is driven to zero at the expense of a steady-state position error. An adaptive version with respect to gravity parameters has also been developed [11],[12].

This paper is devoted to derive a parallel force/position control scheme in a passivity framework [13]. In comparison with inverse dynamics controllers, passivity-based controllers are expected to have enhanced robustness since they do not rely on the exact cancellation of nonlinear terms [14]. Also, they naturally allow making the controller adaptive in the unknown parameter case.

As in typical passivity-based control schemes for robot manipulators in free space, the resulting control law is formed by a nonlinear model-based term and a linear compensator action. The key contribution of the present work is to establish a functional expression of the reference vector to be used in the controller which is related both to the end-effector position and velocity errors and to the integral of the contact force error. This is conceptually different from previous passivity-based hybrid force/position controllers [15],[16] where each component of the reference vector is related either to a position error or to a force error in respect of the task space direction selection mechanism.

It is demonstrated that the resulting control scheme ensures tracking of the unconstrained components of the desired end-effector trajectory with regulation of the desired contact force along the constrained direction. Also, if uncertainty occurs on the dynamic model parameters, the scheme is made adaptive by introducing a conventional parameter estimate update law.

An industrial robot manipulator is considered to develop numerical examples aimed at analyzing the performance of the proposed scheme both in the known parameter case and when an unknown payload mass is considered.

2. Modeling

The dynamics of a constrained rigid robot manipulator are described in the task space [2] by the following equations

$$\mathbf{B}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\dot{\mathbf{x}} + \mathbf{g}(\mathbf{x}) = \mathbf{u} - \mathbf{f}, \quad (1)$$

where $\mathbf{x}$ is the $(m \times 1)$ vector of task variables (usually end-effector location), $\mathbf{B}$ is the $(m \times m)$ symmetric inertia matrix, $\mathbf{C}\dot{\mathbf{x}}$ is the $(m \times 1)$ vector of Coriolis and centrifugal generalized forces, $\mathbf{g}$ is the $(m \times 1)$ vector of gravitational generalized forces, $\mathbf{u}$ is the $(m \times 1)$ vector of driving generalized forces, and $\mathbf{f}$ is the $(m \times 1)$ vector of contact generalized forces exerted by the manipulator on the environment; all task space quantities are expressed in a common reference frame.

The $(n \times 1)$ vector $\boldsymbol{\tau}$ of joint actuating generalized forces is computed as

$$\boldsymbol{\tau} = \mathbf{J}^T(\mathbf{q})\mathbf{u}, \quad (2)$$

where $\mathbf{q}$ is the $(n \times 1)$ vector of joint variables and $\mathbf{J}$ is the $(m \times n)$ manipulator Jacobian matrix.

In this work, the case of non-redundant ($m = n$) non-singular manipulators is treated. Then the vector $\mathbf{x}$ represents a set of Lagrangian generalized coordinates and the matrix $\mathbf{B}$ is positive definite.

Two notable properties of the dynamic model (1) can be established [15]:

- There exists a choice of the matrix $\mathbf{C}$ such that the matrix

$$\mathbf{S}(\mathbf{x}, \dot{\mathbf{x}}) = \dot{\mathbf{B}}(\mathbf{x}) - 2\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}}) \quad (3)$$

is skew-symmetric. This property is a direct consequence of the passivity of the mapping $\mathbf{u} \rightarrow \dot{\mathbf{x}}$.

- The dynamic model (1) is linear in terms of a suitable set of manipulator and load constant parameters, i.e.

$$\mathbf{B}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\dot{\mathbf{x}} + \mathbf{g}(\mathbf{x}) = \mathbf{Y}(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}})\boldsymbol{\theta} \quad (4)$$

where $\mathbf{Y}(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}})$ is an $(m \times p)$ matrix and $\boldsymbol{\theta}$ is a $(p \times 1)$ vector of manipulator and load parameters.

3. Control design

Consider the following control law

$$\mathbf{u} = \hat{\mathbf{B}}(\mathbf{x})\dot{\mathbf{r}} + \hat{\mathbf{C}}(\mathbf{x}, \dot{\mathbf{x}})\mathbf{r} + \hat{\mathbf{g}}(\mathbf{x}) - \mathbf{K}_D(\dot{\mathbf{x}} - \mathbf{r}) + \mathbf{f}, \quad (5)$$

where $\hat{\mathbf{B}}$, $\hat{\mathbf{C}}$, $\hat{\mathbf{g}}$ are the estimates of $\mathbf{B}$, $\mathbf{C}$, $\mathbf{g}$ respectively, $\mathbf{f}$ is the measured contact force, $\mathbf{r}$ is an $(m \times 1)$

reference vector and $\mathbf{K}_D$ is a symmetric, positive definite gain matrix.

Assuming that $\hat{\mathbf{B}}$, $\hat{\mathbf{C}}$, $\hat{\mathbf{g}}$ have the same functional form of $\mathbf{B}$, $\mathbf{C}$, $\mathbf{g}$ with a $(p \times 1)$ vector of estimated parameters $\hat{\boldsymbol{\theta}}$, the control law (5) can be written as

$$\mathbf{u} = \mathbf{Y}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{r}, \dot{\mathbf{r}})\hat{\boldsymbol{\theta}} - \mathbf{K}_D(\dot{\mathbf{x}} - \mathbf{r}) + \mathbf{f} \quad (6)$$

where the property expressed by (4) has been used. Notice that the matrix $\hat{\mathbf{C}}$ in (5) must satisfy a property analogous to the skew-symmetry of the matrix in (3).

Combining (1) with (6) gives

$$\mathbf{B}(\mathbf{x})\dot{\mathbf{e}} + \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\mathbf{e} + \mathbf{K}_D\mathbf{e} = \mathbf{Y}(\cdot)\tilde{\boldsymbol{\theta}} \quad (7)$$

where $\tilde{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}} - \boldsymbol{\theta}$ and

$$\mathbf{e} = \dot{\mathbf{x}} - \mathbf{r} \quad (8)$$

$$\dot{\mathbf{e}} = \ddot{\mathbf{x}} - \dot{\mathbf{r}}. \quad (9)$$

Consider initially the *known parameter case*, i.e. $\tilde{\boldsymbol{\theta}} = \mathbf{0}$. A simple energy argument exploiting the passivity property of the Lagrange model (7) leads to showing that $\mathbf{e} \in \mathcal{L}_2^m \cap \mathcal{L}_\infty^m$, where $\mathcal{L}_2^m$ and $\mathcal{L}_\infty^m$ are the standard Lebesgue spaces [17]; further, $\mathbf{e} \rightarrow \mathbf{0}$ as $t \rightarrow \infty$ [13].

To obtain a force/position controller, the force and position errors can be obtained as the output of an exponentially stable, strictly proper filter whose input is the reference vector $\mathbf{e} \in \mathcal{L}_2^m \cap \mathcal{L}_\infty^m$ (see the fundamental input/output theorem on p. 59 of [17]).

The parallel control strategy [6] suggests to relate the error vector in (8) to both a position and a force error, without any selection mechanism as in [15], [16] instead. Along the constrained task directions the conflict between the position and force actions must be managed by imposing dominance of the force action over the position one.

Let $\mathbf{x}_d$ denote the *time-varying* desired end-effector position, with $\mathbf{x}_d, \dot{\mathbf{x}}_d, \ddot{\mathbf{x}}_d \in \mathcal{L}_\infty^m$. Let also $\mathbf{f}_d$ denote the *constant* desired force. Then indicate by $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}_d$ the error between the actual and desired end-effector position, and by $\Delta\mathbf{f} = \mathbf{f} - \mathbf{f}_d$ the error between the actual and desired contact force. A keen choice for the error vector in (8) is the following

$$\mathbf{e} = (s + \lambda_1)\Delta\mathbf{x} + \lambda_2 s^{-1}\Delta\mathbf{f} \quad (10)$$

where s is the Laplace variable and $\lambda_1, \lambda_2 > 0$.

By virtue of this choice, from (8) and (9) the reference vector $\mathbf{r}$ and its derivative become

$$\mathbf{r} = \dot{\mathbf{x}} - \mathbf{e} = \dot{\mathbf{x}}_d - \lambda_1\Delta\mathbf{x} - \lambda_2 \int_0^t \Delta\mathbf{f} d\sigma \quad (11)$$

$$\dot{\mathbf{r}} = \ddot{\mathbf{x}} - \dot{\mathbf{e}} = \ddot{\mathbf{x}}_d - \lambda_1\Delta\dot{\mathbf{x}} - \lambda_2\Delta\mathbf{f}. \quad (12)$$

These expressions reveal that the control law (5) requires only joint position and velocity and end-effector contact force measurements.

It is worth noticing that $\Delta \mathbf{x}$ and $\Delta \mathbf{f}$ are not independent since they are constrained by the contact with the environment. Without loss of generality, the case of $m = n = 3$ is taken, i.e. only translational motion and force components are considered. Also the environment is thought of as a frictionless, elastically compliant plane. Hence, the model of the contact force takes on the simple form

$$\mathbf{f} = \mathbf{K}(\mathbf{x} - \mathbf{x}_0), \quad (13)$$

where $\mathbf{x}$ is the position of the contact point, $\mathbf{x}_0$ is a point of the plane at rest, and $\mathbf{K}$ is the (3×3) constant symmetric stiffness matrix that can be expressed as

$$\mathbf{K} = k \mathbf{n} \mathbf{n}^T \quad (14)$$

where $k > 0$ is the stiffness coefficient and $\mathbf{n}$ is the unit vector orthogonal to the contact plane.

Equation (10) can be effectively decomposed into the component along $\mathbf{n}$ and the components on the plane of contact, so that the analysis is reduced to the following three (one + two) equations:

$$e_n = (s + \lambda_1) \Delta x_n + \lambda_2 s^{-1} \Delta f_n \quad (15)$$

$$e_p = (s + \lambda_1) \Delta \mathbf{x}_p - \lambda_2 s^{-1} \mathbf{f}_{dp}, \quad (16)$$

where, with obvious notation, Equation (15) involves the normal components of the force and position vectors, and Equation (16) involves the components parallel to the plane. Notice that the contact model (13),(14) implies $\mathbf{f}_p = 0$; hence it is reasonable to choose $\mathbf{f}_{dp} = 0$. If no information about the plane geometry is available, i.e. the direction of $\mathbf{n}$ is unknown, it is possible to choose $\mathbf{f}_d = 0$.

In view of (13),(14), the position along the normal direction is given by

$$x_n = k^{-1} \Delta f_n + k^{-1} f_{dn} + x_{0n}. \quad (17)$$

From (15),(17) it follows that

$$\Delta f_n = k \left(\frac{s}{s^2 + \lambda_1 s + k \lambda_2} e_n + \frac{s(s + \lambda_1)}{s^2 + \lambda_1 s + k \lambda_2} (x_{dn} - k^{-1} f_{dn} - x_{0n}) \right). \quad (18)$$

Further, Equation (16) with $\mathbf{f}_{dp} = 0$ gives

$$\Delta \mathbf{x}_p = \frac{1}{(s + \lambda_1)} e_p. \quad (19)$$

Because the transfer function between e_p and $\Delta \mathbf{x}_p$ is strictly proper and exponentially stable, by observing that $e_p \in \mathcal{L}_2^2 \cap \mathcal{L}_\infty^2$ and $e_p \rightarrow 0$ as $t \rightarrow \infty$, the theorem on p. 59 of [17] implies that $\Delta \mathbf{x}_p, \dot{\Delta \mathbf{x}}_p \in \mathcal{L}_2^2 \cap \mathcal{L}_\infty^2$ and $\Delta \mathbf{x}_p, \dot{\Delta \mathbf{x}}_p \rightarrow 0$ as $t \rightarrow \infty$.

Regarding the force error along the normal, the transfer function between e_n and Δf_n is strictly proper and exponentially stable but the presence of the second term does not allow in general concluding a similar convergence result as above. In particular, both f_{dn} and x_{0n} are constant whereas the normal component of the desired position may be time-varying. This implies that if x_{dn} is a constant then the second term goes to zero as $t \rightarrow \infty$; hence, observing that $e_n \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and $e_n \rightarrow 0$ as $t \rightarrow \infty$, it follows that $\Delta f_n \in \mathcal{L}_\infty$ and $\Delta f_n \rightarrow 0$ as $t \rightarrow \infty$ in view of a similar argument as above. On the other hand, if x_{dn} is not a constant, $x_{dn} \in \mathcal{L}_\infty$ implies $\Delta f_n \in \mathcal{L}_\infty$ only.

It remains to show that all the signals in the closed-loop system (1),(5) remain bounded. This is easily obtained since from (17)–(19) it follows that $\mathbf{x}, \dot{\mathbf{x}}, \Delta \mathbf{f}, \int \Delta \mathbf{f} d\sigma \in \mathcal{L}_\infty^3$; further from (10)–(12) it follows that $\mathbf{e}, \mathbf{r}, \dot{\mathbf{r}} \in \mathcal{L}_\infty^3$ and from (7),(9) it is $\ddot{\mathbf{x}} \in \mathcal{L}_\infty^3$.

Next, the *unknown parameter case* is treated. Choose the parameter estimate update law as

$$\dot{\hat{\boldsymbol{\theta}}} = -\boldsymbol{\Gamma}^{-1} \mathbf{Y}^T(\cdot) \mathbf{e} \quad (20)$$

where $\boldsymbol{\Gamma}$ is a $(p \times p)$ symmetric, positive definite matrix. This law together with the control law (6) ensures that the mapping $-\mathbf{e} \rightarrow \mathbf{Y} \hat{\boldsymbol{\theta}}$ is passive [13]. As a consequence, $\mathbf{e} \in \mathcal{L}_2^3 \cap \mathcal{L}_\infty^3$, $\hat{\boldsymbol{\theta}} \in \mathcal{L}_\infty^p$. From (19) $\Delta \mathbf{x}_p, \dot{\Delta \mathbf{x}}_p \in \mathcal{L}_2^2 \cap \mathcal{L}_\infty^2$ and $\Delta \mathbf{x}_p \rightarrow 0$ as $t \rightarrow \infty$. From (18) $\Delta f_n \in \mathcal{L}_\infty$ and if x_{dn} is a constant then $\Delta f_n \rightarrow 0$ as $t \rightarrow \infty$. In view of similar arguments as above, it can be shown that $\mathbf{x}, \dot{\mathbf{x}}, \mathbf{r}, \dot{\mathbf{r}} \in \mathcal{L}_\infty^3$ and then $\mathbf{Y}(\cdot) \hat{\boldsymbol{\theta}} \in \mathcal{L}_\infty^3$. Further, from (7),(9) it follows that $\ddot{\mathbf{x}} \in \mathcal{L}_\infty^3$ and in particular $\Delta \ddot{\mathbf{x}}_p \in \mathcal{L}_\infty^2$; this implies that $\Delta \ddot{\mathbf{x}}_p$ is uniformly continuous and in turn, since $\Delta \dot{\mathbf{x}}_p \in \mathcal{L}_2^2$, $\Delta \ddot{\mathbf{x}}_p \rightarrow 0$ as $t \rightarrow \infty$.

In sum, both in the known and in the unknown parameter case, it is possible to design a passivity-based control scheme (with adaptive law) that guarantees tracking of the end-effector position along the unconstrained directions with regulation of the contact force along the constrained direction.

4. Case study

The proposed control scheme was tested in simulation on the industrial robot COMAU SMART-3 6.12R (Fig. 1). Only the first three joints were considered,

constituting an elbow manipulator geometry with zero shoulder offsets. A load of 12 kg mass and zero inertia was added at the end-effector. The complete dynamic model and numerical data of robot parameters are reported in [18]. Simulations were run in MATLAB at a sampling time of 5 ms.

The geometry of the contact plane is characterized by $\mathbf{n} = (1 \ 0 \ 0)^T$ and $\mathbf{x}_0 = (1.07 \ 0 \ 0)^T$ [m]. The gains in (11),(12),(5) were set to $\lambda_1 = 200 \text{ s}^{-1}$, $\lambda_2 = 0.1 \text{ kg}^{-1}$, $\mathbf{K}_D = k_D \mathbf{I}$ with $k_D = 200 \text{ kg s}^{-1}$. This choice guarantees a well-damped behavior both for the unconstrained and constrained motion with an estimate of the stiffness coefficient of the plane $k = 10^5 \text{ N m}^{-1}$.

In the following, simulation results relative to two different tasks are presented. For simplicity a bidimensional task geometry in the xz -plane was considered; thus the sole x - and z -components of position vector and the x -component of the force vector are reported.

In the first task the effectiveness of the control scheme in the known parameter case when an unexpected contact occurs was tested. A motion from $\mathbf{x}_{di} = (1 \ 0 \ 0)^T$ [m] to $\mathbf{x}_{df} = (1.1 \ 0 \ 0.05)^T$ [m] along a rectilinear path was commanded to the end-effector; the trajectory along the path was assigned as a raised cosine time law. A set point $\mathbf{f}_d = \mathbf{0}$ was assigned to the contact force. It can be recognized that a contact occurs at a distance of 0.03 m from the target point $\mathbf{x}_d$ along the x -axis direction. Figure 2 shows the time history of the contact force; it can be seen that the force remains bounded during the contact and goes to zero at steady state, so as desired. Figure 3 shows the desired path (dashed line) and the actual path (solid line) of the end-effector in the xz -plane; notice that only the unconstrained component of the desired position vector, i.e. the z - component, is followed whereas the x -component at steady state reaches that of the environment at rest.

For the second task a stable contact of the end-effector with the elastic plane was first sought, then a motion on the contact surface was commanded by requiring a constant force of 100 N along the normal direction. The orientation of the contact surface was supposed known, but the position of the plane at rest was supposed affected by an uncertainty of 0.01 m. To ensure the contact starting from $\mathbf{x}_{di} = (1 \ 0 \ 0)^T$ [m], the approach phase was managed by imposing a rectilinear path towards $\mathbf{x}_{dm} = (1.08 \ 0 \ 0)^T$ [m]. The force set point was initially set to $\mathbf{f}_d = \mathbf{0}$ and switched to $\mathbf{f}_d = (100 \ 0 \ 0)^T$ [N] as soon as a non-null contact force was sensed. Then, by preserving the force set point, a rectilinear path from $\mathbf{x}_{dm} = (1.08 \ 0 \ 0)^T$ [m] to

$\mathbf{x}_{df} = (1.08 \ 0 \ 0.03)^T$ [m] was assigned. Rised cosine time laws for the reference position trajectories were considered.

Three sets of simulations were carried out with the following controllers:

- (a) control law (5),(11),(12) with compensated load mass;
- (b) control law (5),(11),(12) with non-compensated load mass;
- (c) control law (6),(11),(12) with initially non-compensated load mass and adaptive law (20).

With reference to (4), the dynamic model has been parametrized with respect to the three parameters related to the load. These are the load mass, the first-order moment with respect to joint 3, and the inertia of the load mass with respect to joint 3.

The numerical results are illustrated in terms of the time history of the contact force, the path of the end-effector in the xz -plane, the time history of the z -component of the position tracking error, and the time history of the norm of the parameter error.

Figure 4 shows that the contact force is practically the same in the three cases thanks to the integral action on the force error in the control law.

Figure 5 shows the actual paths in the three cases (solid lines) with respect to the desired path (dashed line). It can be seen that a deviation along the z direction occurs in case (b) which is caused by the non-compensated load mass, whereas good reproduction of the desired path is obtained in the other two cases. Notice also that the actual path along the z -direction is constrained by the presence of the contact plane and thus a deviation from the desired path occurs which is determined by the amount of desired contact force and plane stiffness.

Figure 6 shows how the adaptation mechanism, case (c), allows recovering the tracking position error which affects the behavior of the control law in case (b), and the performance favorably compares with that of the controller with perfect compensation, case (a).

Finally, Figure 7 shows that the norm of the parameter error remains bounded along the trajectory, as anticipated in theory.

5. Conclusions

A passivity-based force/position control scheme for robot manipulators in contact with an elastically compliant surface has been proposed in this work. Inspired by the parallel force/position control framework, the

reference vector used in the control law has been keenly related both to the end-effector position and velocity errors and to the integral of the contact force error. Both theory and simulation results have demonstrated that the scheme ensures position tracking along the unconstrained directions and force regulation along the constrained direction. By virtue of the passivity formulation the scheme has been naturally extended to handle adaptation with respect to a vector of manipulator and load parameters. In particular the simulation results have demonstrated the effectiveness of the control scheme with adaptive law in the case of an unknown load mass.

Experimental tests on the industrial robot COMAU SMART-3 6.12R using an ATI force/torque sensor FT-30/100 will be conducted in the near future.

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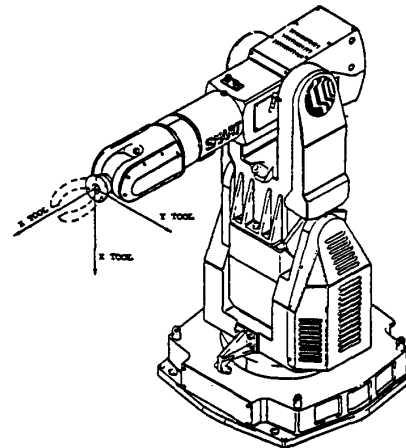


Fig. 1 — The robot COMAU SMART-3 6.12R.

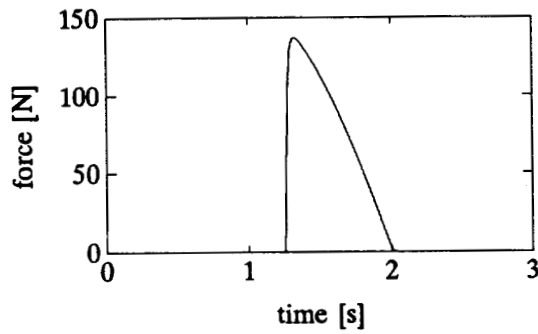


Fig. 2 — Time history of contact force for the first task.

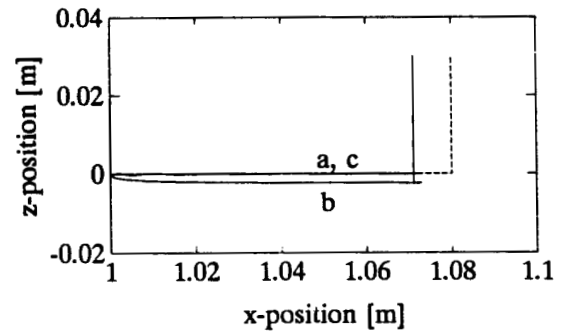


Fig. 5 — Desired and actual paths of the end-effector position in the xz -plane for the second task.

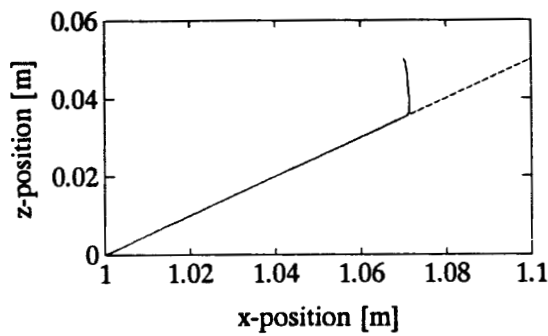


Fig. 3 — Desired and actual paths of the end-effector position in the xz -plane for the first task.

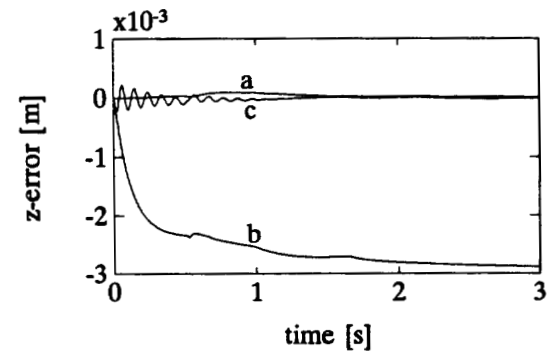


Fig. 6 — Time history of z -component of the position error for the second task.

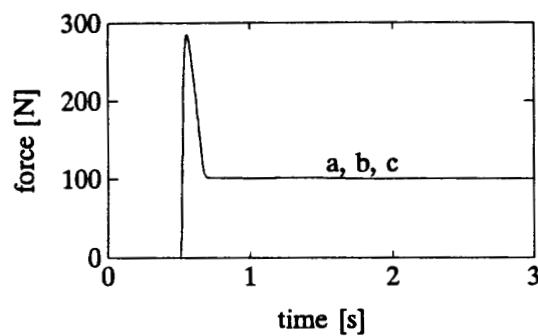


Fig. 4 — Time history of contact force for the second task.

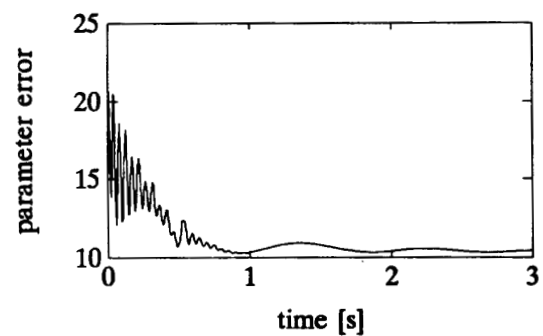


Fig. 7 — Time history of the parameter error norm for the second task.