The Parallel Approach to Force/Position Control of Robotic Manipulators

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***Abstract*—Force/position control strategies provide an effective framework to deal with tasks involving interaction with the environment. In this paper the parallel approach to force/position control of robotic manipulators is presented. It allows a complete use of the available sensor measurements by operating the control action in a full-dimensional space without using selection matrices. Conflicting situations between the position and force tasks are managed using a priority strategy: the force control loop is designed to prevail over the position control loop. This choice ensures limited deviations from the prescribed force trajectory in every situation, guaranteeing automatic recovery from unplanned collisions. A dynamic force/position parallel control law is presented and its performance in presence of an elastic environment is analyzed; simplification of the dynamic control law is also discussed leading to a PID-type parallel controller. Two case studies are worked out that show the effectiveness of the approach in application to an industrial robot.**

I. Introduction

REAL MANIPULATION TASKS involve the interaction of the robot arm with the environment. Typical examples of such tasks are assembly of mechanical parts, contour-following operations, and in general the use of any mechanical tool. Since manipulation implies contact with the environment, the end effector of the robot arm cannot freely move in all directions; therefore, the resulting motion is usually referred to as *constrained motion.* 约束运动

Constrained motion execution by means of purely positional control systems requires a very accurate manipulator model and a very precise knowledge of the geometrical and mechanical characteristics of the environment. As long as every mathematical model is only an approximation of reality, modeling errors arise which cause deviations from the planned contact situation. Since contact with the environment is experienced in the form of interaction forces, large contact forces may result. Typical position control systems are said to be *stiff,* in that they try to follow the commanded position trajectory while rejecting external forces which are considered as disturbances. During constrained motion contact forces are treated as disturbances too; the system attempts to reject them and this results in larger interaction forces. This type of behavior leads to saturation, instability, or even to physical failure [15].

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Proper execution of constrained motion tasks can be achieved using control systems which attempt accomodation of unplanned external forces. Moreover, if direct measurements of the contact force are used in the control strategy, the extra information supplied by the force sensor may help compensate for the lack of knowledge about the real world. Since the contact force is significantly representative of the interaction with the environment, *force control* techniques have been developed.

During past years, fundamental issues such as impact analysis and contact force regulation [23], [25], [30], [33], [35], [36], compliant control [11], [14], [15], [27], [29], and force/position control during constrained motion [5], [9], [17], [22], [24], [28], [31], [32], [34], have extensively been discussed in the literature.

In this paper, the *parallel approach* to force/position control of robotic manipulators, originally proposed in [5] and furtherly developed in [4], [6]–[8], is illustrated in full. The method attempts to combine simplicity and robustness of the impedance and admittance schemes with the ability of controlling both position and force variables typical of the hybrid control approach. The goal is achieved using two controllers acting in parallel, and managing conflicting situations by means of a priority strategy: since the primary aim is to make the resulting system capable to accomodate its motion to environment constraints, the force controller is designed to prevail over the position controller. This choice ensures limited deviations from the prescribed force trajectory in every situation since the adopted strategy is task-independent. Automatic recovery from unplanned impacts is made possible, since no selection mechanism is implemented and sensor measurements are always fully available to each controller. Differently from the hybrid control approach, the task geometry must be accounted at the planning level while only dynamics of the interaction is at issue during the control system design; further, force/position control capability is gained with respect to impedance control schemes.

A dynamic force/position parallel control law is developed and its performance in presence of an elastic environment is analyzed to illustrate the basic properties of the approach. Implemetation issues are discussed and a PID-type parallel controller is derived by simplification of the above dynamic control law. Two case studies are worked out for a three-degree-of-freedom *MANUTEC_R3* industrial robot to demonstrate robustness of the scheme with respect both to knowledge of the stiffness of the environment and to knowledge of the

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task geometry. The results obtained show the effectiveness of the presented approach.

II. Analysis and Control of the Interaction

In this section an overview of the main existing force control approaches is developed. The aim here is to discuss different basic strategies rather than focusing on the details of the single implementations. The main features of each approach are briefly recalled and discussed.

When a manipulator interacts with the environment, the motion of its end effector is subject to external constraints which are experienced in the form of interaction forces. These forces should be accomodated rather than resisted; therefore, the control scheme must suitably handle tracking errors so as to improve the contact.

The control of a single vector variable—such as end effector position or contact force—does not allow to fulfil, or at least to account, both position and force requirements, which happen to be specified in most practical manipulatory tasks. To overcome this drawback, the concept of assigning a dynamic relationship between position and force variables, in addition to commanding and controlling a single vector variable, has been explored by several researchers; it was firstly discussed in [25]. Two dual possibilities can be considered:

- a force history is commanded and in addition a relationship between end effector motion and deviations from the assigned force is given; this approach is termed *admittance control* [25], [33];
- a position trajectory is commanded and in addition a relationship between interaction forces and displacements from the assigned trajectory is given; this approach is termed *impedance control* [14], [15], [29].

The impedance control approach is based on the assumption that, for almost all manipulation tasks, the environment at least contains inertias and kinematic constraints, i.e. systems that accept force inputs and yield motion outputs [14]. This type of systems is defined as admittance. Since two interacting systems must physically complement each other, along any degree of freedom if one is an admittance the other must be an impedance (i.e. a system that accepts motion inputs and yields force outputs). Therefore, if the environment is an admittance, the manipulator must behave as an impedance.

The admittance control approach is obviously generated from a dual development. The basic assumption in this case is that the environment is constituted by elastic and dissipative systems, which are both properly described as impedances; the manipulator, therefore, must behave as an admittance.

It must be pointed out that, in general, the description of a system as an impedance or an admittance is not interchangeable. In principle, it is always possible to exchange input and output variables in a mathematical model, but this involves operations which may be not physically realizable. Therefore, the assumed model can be as simple as possible but it must correctly describe the physics of the represented system. This constitutes the basic criterion in selecting the "best" approach although, by suitably regarding the components of the interaction, some freedom can be gained. For instance, the unavoidable inertial behavior of the manipulator is a constitutive admittance that may be conveniently included either in the manipulator or in the environment model, since it is located at the interaction port.

The impedance control approach allows closed-loop position control capabilities in the free space[1] and in an inertial environment (for instance when carrying a payload); this makes the approach attractive in all those tasks in which the end effector must impose its motion on the environment. If contact with a rigid environment occurs, the impedance approach offers open-loop force control capabilities; in fact, a position set-point gives a steady contact force whose value depends on the stiffness of the environment. On the other hand, the admittance control approach exhibits closed-loop force control capabilities when in contact with a rigid environment[2] and with elastic/dissipative environments (such as in pushing or following a compliant surface); this results in the accomodation of unwanted interaction forces and makes the approach attractive in all those tasks in which the motion of the end effector must be guided by the environment. Dually to the impedance control case, the admittance approach allows open-loop position control capabilities in the free space.

Force control schemes can be devised that close an "outer" force control loop around an "inner" position control loop, which may be the ordinary position control system of the manipulator; this technique is known in the literature as the *external force feedback loop* method [10], [11], [13]. In detail, the force error is converted into a suitable reference trajectory for the inner position controller. Passive compliance at the contact is needed to ensure good performance of the overall system. Only if an integral law is adopted in the outer loop a force set-point can be guaranteed; this can be simply obtained by using a proportional force loop closed around an inner velocity loop. A problem with these schemes is the position control of unconstrained motion components of the end effector.

Manipulation tasks, however, are often specified in terms of direct requirements on both position and force variables; in this case it is necessary to simultaneously perform direct control of the end effector position and of the interaction force.

The basic issue to be considered when using *force/position control* strategies is that it is not possible to simultaneously impose on the environment arbitrarily assigned position and force values along any degree of freedom. Two direct consequences are the following:

- the task requirements to be specified must be compatible with the given task, otherwise overspecification of the problem arises;
- the control of the interaction must be able to handle requirements that are unconsistent with the task being executed.

The specification of compatible requirements needs correct modeling of the task mechanics followed by an accurate task planning. However, the assignment of proper requirements is

[1] In this framework, it is supposed to regard the manipulator inertia as a component of the environmental admittance.

[2] It is assumed that the structural compliance of the manipulator is regarded as a component of the environmental impedance.

only a first step toward the task accomplishment. During task execution deviations from the planned task are always experienced; if those deviations become significant, the planned requirements may be no longer compatible with the actual task. As a consequence, the adoption of control strategies able to handle possibly conflicting requirements is needed.

First of all, a suitable task analysis must derive both the conditions under which the assigned force/position requirements are compatible with the given task and a criterion to choose proper force/position requirements for the task to be executed.

An extensive, essentially static though, task analysis is done in [21]. Among the major conclusions of Mason's study is that, along any degree of freedom, the environment imposes either a position or a force constraint to the manipulator; these constraints are termed *natural constraints* since they are directly determined by the task mechanics. Because of these natural constraints, along any degree of freedom the manipulator can control the sole unconstrained variable; the reference values for these variables are termed *artificial constraints* since they represent the strategy according to which the task will be executed. As a result, a suitable partition of the whole degrees of freedom of the task is obtained: some of them are position controlled while the other are force controlled.

The approach that best fits to the analysis of Mason is well-known in the literature as *hybrid control* [9], [17], [28], [32], [34]. The basic concept of the hybrid approach is that the manipulator controller must take care of the sole artificial constraints while ignoring the natural constraints. This is motivated assuming that there is no need to control variables already subject to constraints by the environment: moreover, if the manipulator is not able to exactly reproduce these constraints, overspecification of the problem arises leading to incorrect behavior.

Two full degree-of-freedom controllers make both a position and a force control action available for each task coordinate; the actual control action is built using a pair of complementary matrices—namely the *selection matrices*—which select the proper contribution to the control law for each task coordinate. In order to ensure stability, the scheme must account dynamic coupling effects arising during manipulator motion [1].

By means of the selection matrices, the structure of the control scheme is changed in such a way to match the task structure. Along each task component the proper control action is active whereas the other one is ignored; this also avoids unwanted interference between the two controllers since force and position control actions are decoupled directly in terms of task components.

In any situation the force/position actions are evaluated by the selection mechanism which is clearly a model-based decision logic. There is no way to modify the behavior of the controller according to what actually happens in the manipulator environment. Moreover, the selection matrices nullify sensor information which is supposed to be negligible, while it could be very helpful just in all those situations in which lack of knowledge about the environment becomes significant. Planning errors may thus affect proper operation of the scheme: a direction along which contact is not expected is position controlled even if contact occurs.

As a major drawback, the hybrid approach results in a control scheme whose structure has to be changed in each phase of a given task. With a changing structure, the continuity of the control law can be ensured only in a perfectly structured world in which the planning can be carried out with mathematical precision. Furthermore, switching is made necessary during the critical transition to a different mechanical behavior of the environment. The need of a changing control structure to guarantee the effectiveness of the scheme points out the strong dependence of the approach on a detailed knowledge of the manipulator environment. Therefore, it is not possible to perform fundamental operations such as self-adjusting of small planning errors or recovery from unexpected impacts where large contact forces may arise.

III. The Parallel Approach

In the following, the *parallel approach* [4], [5] to force/position control of robotic manipulators is developed. The target is to design a force/position control technique which offers some robustness with respect to the uncertanties affecting the knowledge of the environment. The strategy underlying the parallel method is firstly presented.

It has been pointed out in the previous section that the hybrid approach allows force/position control capabilities but it strongly relies on detailed geometric modeling of the environment. Moreover, sensor information, which is directly related to the real task, is subordinated to a selective action which is instead performed on the basis of the planned task. On the other hand, the impedance and admittance approaches exhibit an interesting feature: once the dynamic relationship is assigned, they are each able to deal with a suitable class of environments just controlling the interaction variable; however, they are not able to specify and control both position and force variables. It must be stressed here that the required knowledge of the environment is lower in the latter cases since a *rule* to handle deviations from the planned task is given. A rule-based behavior rather than a control action based on even detailed models of the environment results in a safer and somehow autonomous operation of the robot system.

In the remainder, the possibility of combining the behavior of the impedance and admittance methods with the capability of force/position control characterizing the hybrid approach is explored. To the purpose the components of the interaction are next analyzed.

During constrained motion the robot system is usually regarded as a complete system which interacts with the environment. In this work, instead, it is described as constituted of two interacting systems:

- one system that accepts motion commands and yields the true motion of the robot depending on the reaction from the environment; in the following it will be termed as the *manipulator*;
- the other system that, based on the knowledge of relevant task parameters, transforms the task requirements into commands to the manipulator; in the following it will be referred to as the *controller*.

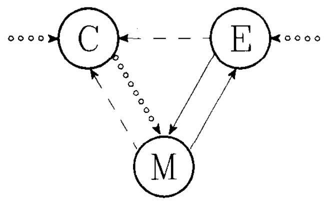


Fig. 1. Graph showing the assumed model of interaction. Dotted lines show command; dashed lines show measurement; solid lines show physical interaction; C, M, and E stand for controller, manipulator, and environment, respectively.

The remaining component of the interaction is obviously the *environment*; its reaction to the manipulator motion can be described by means of suitable interaction variables; in the case of an active environment, the interaction variables depend also on external inputs that can be modelled as external commands. Fig. 1 summarizes the proposed model of interaction by showing the relationships between the interacting systems.

In order to derive the desired system some basic assumptions are needed. The manipulator is supposed to be an admittance; this means that the generalized motion commands are force[3] commands while the robot motion is expressed in terms of position variables.Accordingly, the environment is assumed to be an impedance and the controller output is in terms of force variables. Moreover, a passive environment is considered. It must be noticed that:

a) the assumption that the manipulator is an admittance completly agrees with the inertial nature of the system. The manipulator dynamic behavior, indeed, can be modified but no real controller can eliminate its inertia.
b) the assumption that the environment is an impedance is sufficiently general as it includes the free-space case and the contact with elastic bodies even in presence of friction. Two major cases seem to be excluded:
   ba) the presence of environmental inertias; this case can be treated if the external inertia can be included in the manipulator admittance;
   bb) the contact with a perfectly rigid environment; it can be shown that a rigid contact leads to an intrinsically unstable behavior [9]. On the other hand, real objects are never perfectly rigid. Therefore, the presence of some elasticity at the contact will always be assumed.

The controller structure constitutes the design choice. In the following, two independent parallel systems—a position controller and a force controller—are assumed; they both yield force commands which are simply added since the manipulator admittance acts to sum the forces applied to it and determines its motion in response (cfr. [14]).

As needed by every force/position control strategy, a mechanism to handle inconsistent requirements must be provided. Differently from the hybrid control, that handles conflicts between position and force control actions on the basis of a model, the parallel control philosophy is to design the force control action to be prevailing over the position control action: this means that, when deviations from the planned task occur, priority over position errors is given in weighing force errors. As the chosen strategy is based on a rule, it is task independent; indeed, dominance of the force control loop over the position control loop is aimed at obtaining limited deviations from the prescribed force trajectory and accomodation of unplanned contact forces in every situation.

[3]Throughout the paper *force* stands for both linear force and torque while*position* refers to both translational and angular positional quantities.

An obvious way to implement the desired dominance is to use a PI force control loop working in parallel to a PD position loop; this basic solution is investigated in the following sections. Remarkably, the scheme obtained can be viewed as an extension of both an impedance control scheme (with added direct force control capabilities) and an external force feedback scheme (with improved position control capabilities).

Some general major implication of the chosen priority strategy is next pointed out.

Force and/or position controlled directions do not exist *a priori* in the parallel control case, as instead in the hybrid control case. This implies that sensor measurements are always fully available without any filtering action based on the task planning. As a consequence, the force and position control loops must be designed accounting the dynamics of the interaction in the worst case that the controller is expected to manage, but independently from the geometry of the contact. This feature is actually derived from the impedance/admittance schemes in which, however, either a position or a force loop is present.

The task planning results in force or position reference trajectories along suitably defined task space components, as in the hybrid control case. A perfect planning obviously makes the task successful, but contact is safely handled by the parallel control even in the case of planning errors: in a direction along which contact is not expected, a null reference value for the contact force is assigned giving rise to a force error; priority is given to this error even if it has occurred along a direction that would have been position controlled according to the task planning. Self-adjustment of small planning errors or recovery from unexpected impacts is thus made possible by virtue of the dominance rule.

A block scheme of the overall system is presented in Fig. 2. It can be noted that the position controller is an impedance while the force controller results in a filtering action on the force variables. Although the scheme in Fig. 2 may resemble a hybrid scheme, it must be stressed that the strategy underlying the adopted control makes it essentially different from the hybrid control.

As a final remark, it is worth noticing that different developments—starting for instance from dual assumptions—can be also pursued. This will be mostly appropriate in all those cases in which the assumptions here considered do not properly match the real nature of the interaction.

IV. Dynamic Force/Position Parallel Control Scheme

A dynamic force/position control scheme is developed in this section according to the parallel control concept.

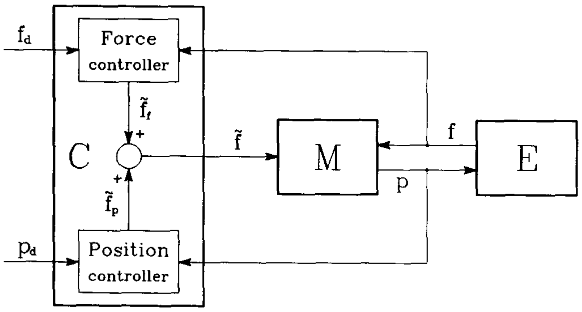


Fig. 2. Block scheme of the system under the assumptions considered.

First the manipulator is considered, for which an open kinematical chain structure with n joints is assumed. If the generalized coordinate vector $q = (q_1 \dots q_n)^{\mathrm{T}}$ denotes the relative displacements q_i between two links at i-th joint, the manipulator equations of motion can be written in the form

$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) = \tau, \tag{1}$$

where $b(q,\dot{q})$ is the $(n \times 1)$ vector of Coriolis and centrifugal terms, $g(q)$ is the $(n \times 1)$ vector of gravitational terms, and τ is the $(n \times 1)$ vector of generalized torques at the joints; $A(q)$ is the $(n \times n)$ symmetric and positive definite joint space inertia matrix.

Since the natural description for end effector trajectories and interaction forces during constrained motion is given in a coordinate frame fixed in a task-oriented space, it appears convenient to use a description of the manipulator dynamics in that space. By assuming a set x of m independent configuration parameters constituting a system of generalized coordinates in a domain of the task space, the end effector equations of motion can be written in the form [3], [16]

$$\Lambda(x)\ddot{x} + c(x,\dot{x}) + p(x) = f_e \tag{2}$$

where $c(x,\dot{x})$ is the $(m \times 1)$ vector of Coriolis and centrifugal terms, $p(x)$ is the $(m \times 1)$ vector of gravitational terms, and f_e is the $(m \times 1)$ vector of generalized forces at the end effector; $\Lambda(x)$ is the $(m \times m)$ symmetric and positive semidefinite operational space pseudo inertia matrix. When $m = n$ and the manipulator is at a nonsingular configuration, x constitutes a set of Lagrangian generalized coordinates; in this case, $\Lambda(x)$ is positive definite and assumes the meaning of a true inertia matrix [17]. In the following we focus our attention on the case $m = n$.

The relationship between the joint space and the task space quantities is established through the following equations:

$$\Lambda(x) = J^{-\mathrm{T}}(q)A(q)J^{-1}(q) \tag{3}$$
$$c(x,\dot{x}) = J^{-\mathrm{T}}(q)b(q,\dot{q}) - \Lambda(x)\dot{J}(q)\dot{q} \tag{4}$$
$$p(x) = J^{-\mathrm{T}}(q)g(q) \tag{5}$$
$$\tau = J^{\mathrm{T}}(q)f_e \tag{6}$$

in which $J(q)$ is the $(m \times m)$ manipulator task Jacobian matrix that is supposed to be nonsingular; this, in particular, excludes the occurrence of both kinematically singular configurations and singularities of the chosen minimal representation of the orientation.

The dynamical model (2) represents a highly nonlinear and strongly coupled system for which the nonlinear dynamic decoupling approach can be adopted [3], [12]. This leads to the following control structure

$$f_e = \widehat{\Lambda}(x)M_d^{-1}\tilde{f} + \widehat{c}(x,\dot{x}) + \widehat{p}(x), \tag{7}$$

where $\widehat{\Lambda}(x), \widehat{c}(x,\dot{x}), \widehat{p}(x)$, respectively represent the estimates of $\Lambda(x), c(x,\dot{x}), p(x)$; $\tilde{f}$ is the command vector of the decoupled end effector, and M_d is the positive definite desired inertia matrix that must be diagonal to ensure dynamic decoupling. With perfect nonlinear compensation and dynamic decoupling (i.e. $\widehat{\Lambda}(x) = \Lambda(x), \widehat{c}(x,\dot{x}) = c(x,\dot{x}),\ \widehat{p}(x) = p(x)$) the manipulator end effector becomes equivalent to an inertia M_d moving in the m-dimensional task space.

When the end effector impacts the environment a term due to contact forces interacts with driving forces in counterbalancing the manipulator dynamical load; at end effector level, therefore, it is

$$\Lambda(x)\ddot{x} + c(x,\dot{x}) + p(x) = f_e - f \tag{8}$$

where f is the $(m \times 1)$ vector of contact generalized forces that the manipulator end effector exerts on the environment. In order to obtain a linear decoupled end effector dynamics for system (8), (7) is modified as follows [2], [5], [14]

$$f_e = \widehat{\Lambda}(x)M_d^{-1}\tilde{f} + \widehat{c}(x,\dot{x}) + \widehat{p}(x) + \widehat{f} \tag{9}$$

where $\widehat{f}$ is the measured contact force vector. It must be noticed that (9) differs from the standard inverse dynamics control as the end effector contact forces are canceled. Remarkably, compensation of the contact forces gives a perfectly stiff behavior to the manipulator independently from the configuration of the arm and from the characteristics of the environment (until power limitation of the actuators come in effect). This choice allows to effectively assign the dynamics of the system both in the free space and during constrained motion.

Equation (9) is the control law of the manipulator; with perfect nonlinear compensation, dynamic decoupling, and contact force compensation, the constrained end effector becomes equivalent to an inertia M_d moving in the $m$ensional task space. In the remainder, exact compensation and decoupling are assumed.

Because of the assumed controller structure (cfr. Fig. 2), it is

$$\tilde{f} = \tilde{f}_p + \tilde{f}_f. \tag{10}$$

Then, a position and a force control action must be designed. To the purpose, let first consider a resolved acceleration position controller [20], namely

$$\tilde{f}_p = M_d\ddot{x}_d + K_v(\dot{x}_d - \dot{x}) + K_p(x_d - x) \tag{11}$$

where x_d denotes the desired end effector position vector. Assuming that the force controller output $\tilde{f}_f$ is a function γ of the force error $e_f = f_d - f$, where f_d is the desired value of the contact force, and combining (8)–(11) yields

$$M_d\ddot{e}_p + K_v\dot{e}_p + K_p e_p + \gamma(e_f) = 0 \tag{12}$$

where $e_p = x_d - x$.

Previous discussion brought to the issue that the force error must prevail over the position error; this leads to conveniently choose $\gamma(e_f)$ as the proportional-integral function

$$\tilde{f}_f = K_f e_f + K_i \int_0^t e_f \, d\tau. \tag{13}$$

Consequently, (12) becomes

$$M_d \ddot{e}_p + K_v \dot{e}_p + K_p e_p + K_f e_f + K_i \int_0^t e_f \, d\tau = 0 \tag{14}$$

which points out how e_f prevails over e_p; in a steady state situation, indeed, the position error may be a constant with a force error equal to zero. This implies that the force control loop dominates over the position control loop in that the overall control system attempts to obtain $f = f_d$ even with a position error that differs from zero.

It must be stressed that, if the task execution identically involves $f_d = f$, the system behaves like the usual resolved acceleration scheme. In particular, this occurs during unconstrained motion if the dynamical load at the force sensor is perfectly compensated by a suitable f_d.

V. Performance Analysis in Presence of an Elastic Environment

So far the dynamic parallel control law (9)–(11), (13) has been developed. We want next to analyze the performance of the proposed control when the manipulator interacts with the environment. To this purpose, the dynamics of the environment must be accounted in order to accomplish the system description.

Accurate modelling of the contact between the manipulator and the environment is usually difficult to obtain in analytic form, due to complexity of the physical phenomena involved during the interaction. It is then reasonable to resort to a simple but significant model, relying on the robustness of the control system in order to absorb the effects of inaccurate modelling. Further, to gain better insight of the system behavior, only translational motion and linear force components are studied, i.e. $m = n = 3$ is assumed.

Following these guidelines, the case of an environment constituted by a rigid, frictionless and elastically compliant plane is considered. The choice of a planar surface is motivated by noticing that it is locally a good approximation to surfaces of regular curvature. Rigidity of the contact plane allows to neglect the effects of local deformation at the contact. The total elasticity, due to end effector force sensor and environment, is accounted through the compliance of the plane. Friction effects are neglected within the operational range of interest.

With the above assumptions, when the end effector is in contact with the plane, the model of the contact force is given by

$$f = K(x - x_0), \tag{15}$$

where x_0 is a point of the plane at rest, and K is a (3×3) constant symmetric *stiffness matrix* [19]; in the following analysis it is supposed that the contact between the manipulator and the environment is not lost after the impact. Moreover we observe that:

- The contact force is orthogonal to the plane for any vector $(x - x_0)$; then, a base of $\mathcal{R}(K)$—the range space of matrix K—is the unit vector n orthogonal to the plane, and $\text{rank}(K) = 1 < 3$.
- All vectors $(x - x_0)$ lying on the plane do not contribute to the contact force; then, a base of $\mathcal{N}(K)$—the null space of matrix K—is a pair of orthogonal unit vectors (t_1, t_2) lying on the plane.
- In force of the symmetry of K, $\mathcal{R}(K) \equiv \mathcal{R}(K^{\mathrm{T}})$, and a convenient choice for (t_1, t_2) is such that the columns of the matrix

$$R = (t_1 \; t_2 \; n) \tag{16}$$

form a set of orthonormal vectors constituting a base of $\mathbf{R}^3$.

According to the above remarks, matrix K can be decomposed as

$$K = R \, \text{diag}\{0, 0, k\} R^{\mathrm{T}} = k n n^{\mathrm{T}} \tag{17}$$

where R, defined in (16), is the rotation matrix from the frame attached to the plane to the reference frame; then k is the *stiffness coefficient*, characterizing the contact along the direction orthogonal to the plane.

By virtue of (15), the following relationship holds

$$e_f = K e_p + f_d - K(x_d - x_0), \tag{18}$$

which substituted in (14) gives

$$\begin{aligned} M_d \ddot{x} + K_v \dot{x} + (K_p + K_f K)x + K_i K \int_0^t x \, d\tau \\ = M_d \ddot{x}_d + K_v \dot{x}_d + K_p x_d \\ + K_f(f_d + K x_0) + K_i \int_0^t (f_d + K x_0) \, d\tau. \end{aligned} \tag{19}$$

Equation (19) represents a third order vector system for which the gain matrices are to be suitably chosen in order to obtain asymptotic stability; since the system is linear, its stability can be discussed in terms of stability of the unforced system

$$M_d \ddot{x} + K_v \dot{x} + (K_p + K_f K)x + K_i K \int_0^t x \, d\tau = 0. \tag{20}$$

One possible choice is to assign a scalar structure—i.e. of the form λI with λ scalar—to the matrices M_d, K_f, K_i, K_p, and K_v so as to allow a decoupled and isotropic behavior of the control law and a simple scalar design of the control gains. To show this, let x_1, x_2, x_n, be the components of x in the frame attached to the plane, defined by the equation

$$\begin{pmatrix} x_1 \\ x_2 \\ x_n \end{pmatrix} = R^{\mathrm{T}} x. \tag{21}$$

Noting that

$$R R^{\mathrm{T}} = t_1 t_1^{\mathrm{T}} + t_2 t_2^{\mathrm{T}} + n n^{\mathrm{T}} = I \tag{22}$$

and exploiting the scalar structure of the control gain matrices, equation (20) can be rewritten as

$$t_1\left[m_d\ddot{x}_1 + k_v\dot{x}_1 + k_px_1\right] + t_2\left[m_d\ddot{x}_2 + k_v\dot{x}_2 + k_px_2\right] + n\left[m_d\ddot{x}_n + k_v\dot{x}_n + (k_p + k_fk)x_n + k_ik\int_0^t x_n\, d\tau\right] = 0. \tag{23}$$

In force of the orthonormality of t_1, t_2, n, equation (23) is equivalent to the system of three scalar equations

$$\begin{aligned} m_d\ddot{x}_1 + k_v\dot{x}_1 + k_px_1 &= 0\\ m_d\ddot{x}_2 + k_v\dot{x}_2 + k_px_2 &= 0\\ m_d\ddot{x}_n + k_v\dot{x}_n + (k_p + k_fk)x_n + k_ik\int_0^t x_n\, d\tau &= 0 \end{aligned} \tag{24}$$

which thus shows that dynamics of system (20) is decoupled in the space of variables x_1, x_2, x_n. A necessary condition of stability is obviously to have all positive gains. Further, it is easily seen that stability of vector system (20) is ensured iff the gains in the sole third scalar differential equation in (24) are properly selected. This can be done with standard techniques in view of other requirements on the system response; an example of design procedure can be found in [4].

As expected, the behavior along the direction normal to the plane is different from the behavior along the tangent directions; remarkably, this anisotropy is purely due to the contact plane, as can be inferred by noting that the x_n component depends—via the matrix R—on the stiffness matrix characterizing the environment. Therefore, the choice of having scalar gain matrices in the parallel control law allows autonomous accomodation of the interaction dynamics (20) to the task directions.

It is important to remark that:

- a decoupled and isotropic behavior of the control law is consistent with the philosophy of the parallel control approach, which do not assume the existence of preferred directions of the task space;
- the decoupled dynamics of system (20) comes from structural properties of the scheme by virtue of measurements of the contact force; it is not imposed by the control law on the basis of models of the environment as in the hybrid control case;
- no exact knowledge of the stiffness matrix K is required, but only an estimate of the stiffness coefficient k is used to tune the feedback gains based on a simple scalar differential equation.
- the design phase can be accomplished mainly looking at the third equation in (24) which is independent from the actual normal direction of the plane. This feature of the parallel control scheme allows to account the sole mechanics of the interaction during the design of the control law, letting the task geometry be accounted at the planning level.

If the prescribed task is the simultaneous achievement of a force set-point f_d^* and a position set-point x_d^*, it results

$$M_d\ddot{x} + K_v\dot{x} + (K_p + K_fK)x + K_iK\int_0^t x\, d\tau = K_px_d^* + K_f(f_d^* + Kx_0) + K_i(f_d^* + Kx_0)t. \tag{25}$$

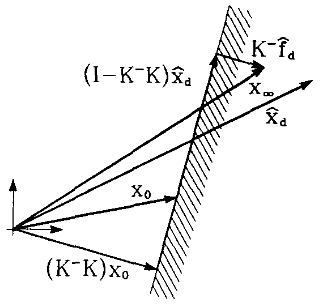


Fig. 3. Construction of the equilibrium point in a 2-D case.

It must be noted that the presence of the manipulator and of the environment imposes constraints between position and force variables, and thus there is no control scheme that can take the system towards arbitrarily given set-points if those violate the physical constraints. In particular, looking at the properties of the elastic contact model (15), the only possibility to obtain a null force error is to assign a set-point $f_d^* \in \mathcal{R}(K)$; on the other hand, this is consistent with the fact that the considered environment can generate reaction forces only along the direction of n. If no information about geometry of the environment is available, i.e. n is unknown, the null vector can be assigned for f_d^* that is anyhow in the range space of any matrix K; in other words, this means that it is always possible to have a null contact force by accomodating the environment constraints.

It can be found that, if $f_d^* \in \mathcal{R}(K)$, the equilibrium point for the system (25) is

$$x_\infty = K^-(f_d^* + Kx_0) + (I - K^-K)x_d^* \tag{26}$$

$$f_\infty = K(x_\infty - x_0) = f_d^* \tag{27}$$

which shows that the system achieves the force set-point. The matrix K^- indicates a generalized inverse of matrix K which, in view of expression (17), can be written in the simple form

$$K^- = R\ \mathrm{diag}\{0, 0, 1/k\}R^{\mathrm{T}} = (1/k)nn^{\mathrm{T}}. \tag{28}$$

For reader's convenience, we remark that the products

$$KK^- = K^-K = R\ \mathrm{diag}\{0, 0, 1\}R^{\mathrm{T}} = nn^{\mathrm{T}} \tag{29}$$

do not affect vector components in $\mathcal{R}(K)$ while cut off vector components outside $\mathcal{R}(K)$.

Equation (26) points out how the system handles a conflicting situation: the target points are projected in two orthogonal complementary subspaces and the equilibrium point is made up by adding the two resulting terms. The first term is needed to the achievement of the force set-point (as (27) brings out), while the other term accounts the sole components of the position set-point which do not affect the force equilibrium. Note, again, that the selection operation on the components of the vector x_d^* is carried out by virtue of structural properties of the scheme on the basis of contact force measurements. Fig. 3 illustrates how the equilibrium point (26) is built in a simple two-dimensional (2-D) case.

If, because of an imperfect trajectory planning, it happens that the desired force vector f_d^* has some component out of $\mathcal{R}(K)$ too, a constant steady solution for system (25) is not possible; the integral-term contribution $K_i K \int_0^t x d\tau$, indeed, is not able to counterbalance the linear time-varying term $K_i(f_d^* + Kx_0)t$. In this case we must look for an equilibrium trajectory rather than for an equilibrium point. It can be found that a steady solution like

$$x_\infty(t) = \bar{x} + \bar{v}t \qquad \bar{v} \in (K) \tag{30}$$

holds, and $\bar{v}$ is given by

$$\bar{v} = K_p^{-1} K_i (f_d^* + Kx_0 - K\bar{x}). \tag{31}$$

As $\bar{v}$ must be in $\mathcal{N}(K)$, it follows that $\bar{x}$ can be written as

$$\bar{x} = K^-(f_d^* + Kx_0) + (I - K^-K)y \tag{32}$$

where y is an arbitrary position vector. Accordingly, it is

$$f_\infty = KK^- f_d^*. \tag{33}$$

Further, substituting (32) into (31) yields

$$\bar{v} = K_p^{-1} K_i (I - KK^-) f_d^*. \tag{34}$$

It is worth noting from (33) that the system achieves the sole component of f_d^* that, belonging to $\mathcal{R}(K)$, can be generated by the environment. On the other hand, $\bar{v}$ is due to the components of f_d^* orthogonal to $\mathcal{R}(K)$. The magnitude of the drift, however, is related not only to the mismatching between the model and the real environment (which decides $\|(I - KK^-)f_d^*\|$), but also to the values assigned to the controller parameters K_p, K_i by setting the factor k_i/k_p (see (34)); it is worth noticing that in normal designs it is $k_p \gg k_i$.

A point to be remarked is that, even in the case of imperfect planning, the equilibrium solution properly aligns with the task directions. As a consequence, f_∞ is only the feasible part of f_d^* and it is always $\|f_\infty\| \leq \|f_d^*\|$. The hybrid control scheme instead, because of the selection mechanism, makes the component of f_∞ in the direction of f_d^* equal to $\|f_d^*\|$; therefore, it is always $\|f_\infty\| \geq \|f_d^*\|$.

Remark 1: The above-developed analysis presents a global stability result in the case of a planar surface. In the case of a curved surface, the rotaion matrix R becomes a nontrivial function of the time-varying contact point and the contact force model (15) can be written in the form [6]

$$f = K\big(x_0(x)\big)\big(x - x_0(x)\big) \tag{35}$$

with

$$K(x_0) = kn(x_0)n^{\mathrm{T}}(x_0). \tag{36}$$

Notice that the stiffness matrix is a function of the rest point —since x_0 decides the direction of the normal to the surface— which in turn depends on the current contact point.

In order to perform a rigorous analysis of system (19, 36) two main difficulties must be solved:

- the relationship between the current contact point and the rest point must be derived in analytic form. This step is crucial since, even for simple regular surfaces, each contact point can be related to different rest points through a possibly transcendent equation; in these cases, the function $x_0(x)$ is not unique and cannot be expressed in analytic form.
- an equlibrium point for the nonlinear system (19, 36) must be found and nonlinear stability analysis methods, such as Lyapunov-type arguments, must be applied. This step is possible only if the function $x_0(x)$ is available in analytic form; even it this case, however, nontrivial computation is expected due to complexity of the relationship involved.

To illustrate modeling and computational complexity induced by model (35), let us consider the case of the sine-shaped surface of equation

$$n = n_s + \Delta z \sin\left(\frac{2\pi}{\ell}(m - m_s)\right) \tag{37}$$

where $x = (l\ m\ n)^{\mathrm{T}}$, n_s is the average height of the surface and Δz, ℓ, and m_s respectively are the amplitude, period and shift of the sine-wave along the m direction [6]. If the rest point $x_0 = (l_0\ m_0\ n_0)^{\mathrm{T}}$ is searched out as the point such that the normal to the surface at x_0 passes through the contact point x, first the equation

$$\left(n - \Delta z \sin\left(\frac{2\pi}{\ell}(m_0 - m_s)\right)\right) \cdot \Delta z \frac{2\pi}{\ell} \cos\left(\frac{2\pi}{\ell}(m_0 - m_s)\right) = m_0 - m \tag{38}$$

must be solved with respect to m_0, then l_0 is set equal to l, and n_0 is assigned the value of (37) at $m = m_0$ [6]. A closed form solution to (38) is not available; however, if x_0 is computed in simulation e.g. via numerical methods, the following expression for the normal to the surface at the rest point can be derived [6]

$$n(x_0) = \frac{1}{\sqrt{1 + \left(\Delta z \frac{2\pi}{\ell} \cos\left(\frac{2\pi}{\ell}(m_0 - m_s)\right)\right)^2}} \cdot \begin{pmatrix} 0 \\ -\Delta z \frac{2\pi}{\ell} \cos\left(\frac{2\pi}{\ell}(m_0 - m_s)\right) \\ 1 \end{pmatrix} \tag{39}$$

that allows computation of the stiffness matrix via (36).

On the other hand, if the surface is smoothly curved the analysis developed for the planar case can be revived to predict local stability of an equilibrium point: in a sufficiently small neighbourhood of the equilibrium point, indeed, the tangent plane at the point is a good approximation to the surface and R can be considered to be constant. Also, if desired trajectories are assigned such that R is slowly varying with respect to the overall system's dynamics, quasi-static analysis can be developed in respect of a succession of locally stable next equilibrium points. In this framework, an edge-following task is worked out in the case study section.

Remark 2: The results that have been obtained in the above with reference to a three-dimensional (3-D) task space can be suitably extended to the general six-dimensional case when the environment can be modeled as a *generalized spring*; this is an element that connects two rigid bodies and reacts to their relative displacement with a generalized force [19]. With a suitable choice of the task-space components, a generalized spring can be modeled in the form (15), where K is a 6×6 symmetric matrix that we can further assume to be constant. Equations (26), (27), (30)–(34) hold, but it is no longer possible to give a simple interpretation in terms of normal and tangent directions to the contact surface.

VI. Implementation Issues

The choice of designing a dominant force control loop results in the accomodation of the manipulator motion to the geometrical constraints imposed by the environment without requiring the task description during the design of the control law. Nevertheless, when the force error cannot be driven to zero a drift arise; this can be due not only to planning errors, but also to implementation problems such as uncompensated loads at the sensor or force sensor bias.

The occurrence of planning errors has been discussed in the previous section. It is our belief that, when a wrong target is assigned to the manipulator, safe behavior of the system overcomes performance. On the other hand, if the manipulator is somehow commanded to push against the air, it is not so strange that it starts drifting (maybe any human being would do the same). Moreover, in a real contact, friction forces are not negligible; the drift does not quite occur until f_d^* is inside the friction cone characterizing the contact.

Inexact estimate of the gravity term in (9) gives, as usual, a steady error on the end effector location. More dangerous is the presence of uncompensated loads at the sensor, due to gravity and dynamics of the mass beyond the sensor itself. The gravity load is especially problematic, as it causes a downward drift of the end effector. If this term is due to the manipulator structure (for instance to the links and/or to a tool beyond a wrist sensor) its compensation can be reasonably pursued; the residual compensation error, if sufficiently small, can be cut off by imposing a threshold on the force measurement. If the manipulator is required to carry payloads it is not advisable to have them beyond the force sensor. It must be stressed that the parallel control approach has been especially devised to handle constrained motion of the end effector and therefore it does not represent the best solution for pick-and-place operations or trajectory following tasks in the free space. In any case, it is preferable to measure the force as close as possible to the contact point.

To counteract force sensor bias, calibration of the sensing device is required; if this is properly done, a threshold again will cut off sensor noise and bias compensation errors. Another reason for force threshold is to prevent limit cycling in the force control loop.

In summary, two cases can be distinguished:

- The end effector is in the free space.—During unconstrained motion of the end effector the force set-point is zero; therefore, the adoption of a threshold on the force measurement might be useful to avoid drift of the end effector.
- The end effector is in contact with the environment.—A nonzero value for the force set-point is assigned if the end effector has to manipulate the environment or to follow its surface. If the planning is sufficiently correct, the measured force vector is mainly aligned to the surface normal and pointing inward the contact plane; the smaller tangential component is to a certain extent counteracted by dry friction, which thus acts as a selective threshold. We remark, however, that in this case it is of primary concern to maintain a stable contact and to guarantee accomodation of the environment constraints rather than ensuring accurate tracking of possibly wrong trajectories.

Direct implementation of (9) is computationally inefficient in view of calculation of the joint torques through (6); laws (6, 9) are thus suitably replaced by the control law

$$\tau = \widehat{A}(q)J^{-1}(q)\left(M_d^{-1}\tilde{f} - \dot{J}(q)\dot{q}\right) + \widehat{b}(q,\dot{q}) + \widehat{g}(q) + J^{\mathrm{T}}(q)\widehat{f} \tag{40}$$

which is still, however, computationally demanding.

A crucial problem with either (9) or (40) arises from the contact force compensation term: in the case of a high-stiffness environment direct unfiltered force feedback tends to be nonrobust with respect to the time delay in the force measurement. A remedy for this comes from the integral force action in (13) which is embedded in laws (9, 40) through (10); to avoid instability, the integral gain must be chosen sufficiently small [31].

The effects of time delays in the control loop on the behavior of the overall system can be analyzed following the guidelines of [18]; this allows derivation of stability boundaries to be taken into account in the design of the controller parameters.

VII. PID Force/Position Parallel Control Scheme

A major source of implementation problems is due to law (9) which is, instead, attractive from a theoretical viewpoint and thus is widely adopted in the literature.

In view of practical real-time implementation, a computationally cheaper parallel control law can be developed starting from (9) by removing the dynamic decoupling filter and the compensation of the Coriolis and centrifugal terms; these, indeed, constitute the major computational burden of the control algorithm. A PD position controller and a PI force controller are still used to ensure dominance of the force loop over the postion loop; as usual in the case of PD position control, compensation of gravitational terms is needed to avoid steady-state position errors. Finally, the contact force compensation term can suitably be replaced by feed-forwarding the desired contact force. With these assumptions the following parallel control law is obtained [7]

$$f_e = -K_v\dot{x} + K_p e_p + \widehat{p}(x) + f_d + K_f e_f + K_i \int_0^t e_f \, d\tau. \tag{41}$$

Notice that, as in the case of the dynamic parallel control law (9–11, 13), no exact knowledge of the stiffness matrix is required by the control law (41).

As demonstrated in [7], for given force and position set-points system (8) under the control (41) with scalar gain matrices asymptotically achieves the equilibrium state (26, 27) if the force set-point belongs to $\mathcal{R}(K)$; therefore, under these assumptions, the simple control law (41) recovers the same steady-state performance as the dynamic control law (9–11, 13).

The stability proof in [7] follows an energy-based Lyapunov argument which has later been improved in [8]. In detail, local asymptotic stability of system (8, 41) at the equlibrium (26, 27) is demonstrated, and a set of simple conditions is derived that provide design guidelines for the gains in (41). Further modification of the Lyapunov function has been proposed in [8] to prove local exponential stability of system (8, 41) at the same equilibrium. Remarkably, this result allows to find out an upper bound on the rate of convergence of system (8, 41) toward the equilibrium (26, 27), but involves more complex conditions to be satisfied by the gains of the control law.

The performance of the PID parallel control law (41) when an unplanned impact against a planar surface is experienced has also been analyzed in [8]. Complete recovery from the collision with perfect accomodation of the end effector position to the (unknown) location of the surface and with a null steady contact force is observed also in the case of underestimation of the stiffness coefficient.

VIII. Case Studies and Simulation Results

An industrial robot with elbow geometry is considered, namely the *MANUTEC_R3* manipulator [26]; this is a six-joint robot, but the wrist is supposed to be frozen and only linear forces and translational displacements are of interest. The actual torque and joint-velocity limits of the manipulator have been accounted in the simulation; this anyway constitutes an approximation to reality, due to the unmodeled effect of backlash, friction, actuator/sensor dynamics, etc. However, within a reasonable range, the approximation is useful in predicting the manipulator behavior [31].

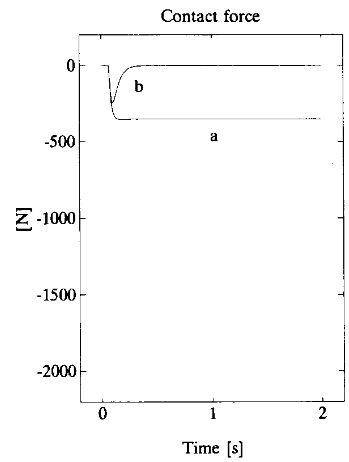
The environment is constituted by a rigid, frictionless, and elastically compliant surface for which either model (15) or model (35) holds when in contact. The sole environment data used for designing the controller is an estimate of the stiffness coefficient of the surface.

Case 1: This case is aimed at illustrating the basic properties of the parallel control. In order to gain better comprehension, the linearizing and dynamically decoupling parallel control law (9)–(11), (13) is considered; to reduce the effects of discrete time implementation, a sampling interval of 0.5 ms is used.

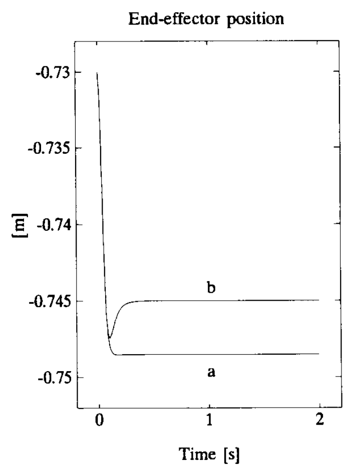
A planar surface is considered, characterized by the vectors $n = (0\,-1\,0)^{\mathrm{T}}$ and $x_0 = (0\,-0.75\,0)^{\mathrm{T}}$ m. A step motion from $x(0) = (0\,-0.73\,0)^{\mathrm{T}}$ m to the set point $x_d^* = (0\,-0.75\,0)^{\mathrm{T}}$ m is commanded to the manipulator's tip, leading to the occurrence of an (unplanned) impact. A null contact force is desired, i.e. $f_d^* = 0$ N. Because of the simple task geometry, only the second component of the end effector position and of the contact force are reported.

In a first run (Case 1A), the true stiffness coeffcient of the environment is 10^5 N/m and a correct estimate of k is assumed.

Initially, the behavior of a pure position controller is studied; this is representative either of an hybrid control scheme experiencing an unexpected impact or of an impedance control scheme. The control law (7), (10), (11) is thus used with $\tilde{f}_f = 0$ (i.e. no force loop) and with $m_d = 1$ kg, $k_v = 200$ Ns/m, $k_p = 5000$ N/m. Then, the parallel control law (9)–(11), (13) is applied with the same position loop settings as before and with the force loop gains $k_f = 0.04$-, $k_i = 1.11$ s^{-1}. The results are reported in Fig. 4. It can be recognized that the position controller achieves an equilibrium state characterized by both a position error and a nonnull contact force. The steady contact force value is related through the stiffness coefficient to the depth of the end effector into the surface, which in turn depends on k_p; lower contact forces can be obtained by decreasing the stiffness of the position loop, but this degrades the tracking performance in the free space. The parallel controller, instead, shows a complete recovery from the impact with perfect accomodation of the end effector position to the (unknown) location of the surface and with a null steady contact force.



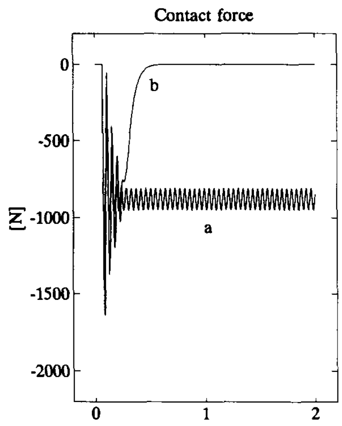
(a)



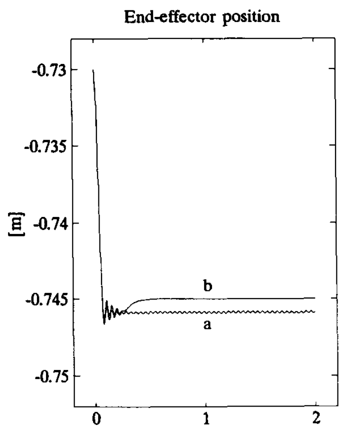
(b)

Fig. 4. Time histories for Case 1A. (a) Impedance control. (b) Parallel control.

To investigate robustness with respect to knowledge of the stiffness coefficient, a second simulation has been run with the



(a)



(b)

Fig. 5. Time histories for Case 1B. (a) Impedance control. (b) Parallel control.

same controller design as in the previous run while the true stiffness coeffcient of the environment is raised to 10^6 N/m.

The results are reported in Fig. 5. Due to high stiffness of the environment, even small displacements into the surface generate high contact forces that cause saturation of the joint actuators; this leads the position controller to enter a persistent oscillation. On the other hand, the parallel controller performs a damped oscillation at the beginning of the impact; then, the integral term in the force loop yields a recovery action and, again, the manipulator end effector is driven to the rest position of the surface with null steady contact force.

Case 2: A second case study is presented to demonstrate the application of the parallel control technique to a nontrivial constrained motion task a in poorly structured environment; this is also aimed at investigating robustness of the scheme with respect to the knowledge of the task geometry. The dynamic parallel control law (9)–(11), (13) is again applied to the *MANUTEC_R3* robot with a sampling time of 2 ms.

The sine-shaped surface (37) is considered in Case 2A, characterized by $n_s = 0$ m, $\Delta z = 0.09$ m, $\ell = 1.8$ m, $m_s = 0.45$ m. The contact force model (35, 36) is used with the true stiffness coefficient equal to 10^5 N/m. A correct estimate of k is assumed and the parameters of the scheme are set as follows: $m_d = 1$ kg, $k_v = 50$ Ns/m, $k_p = 60$ N/m, $k_f = 5.4 \cdot 10^{-3}$[-], $k_i = 2.1 \cdot 10^{-2}$ s^{-1}.

The precise shape and location of the surface is unknown to the task planner and to the controller designer; however, an approximate model of the surface is available as the plane $n = 0$, whose height is an estimate of the average height of the actual surface. Since the exact profile of the environment is unknown, a bound on the possible displacement of the actual edge from the nominal surface is considered; in the case at issue, the maximum displacement from the nominal surface has been evaluated as 0.1 m in the n direction.

The task to be performed requires to move the end effector toward the surface and, once in contact, to follow its contour. Following the guidelines in [6], a simplified force-based planning strategy can be adopted.

The initial location of the end effector is at the point $A = (0.60, -0.90, 0.12)$ m which is close to the surface but not in contact with it even in the worse case expected.

To approach the environment, the position set-point A and the force set-point $f_d^* = (0\,0 - 30)$ N are assigned; in other words, point A should be held but the robot is commanded to push toward the surface. The unbalanced force set-point yields a drifting motion of known velocity $(k_i/k_p)f_d^*$ until contact is achieved; this makes unnecessary to estimate the location of the surface and allows direct specification of the nominal impact force.

After steady contact is detected, the contour-following phase is started. A trapezoidal velocity profile positional trajectory from A to $B = (0.60, 1.10, 0.12)$ m of duration 42 s and cruise velocity 0.05 m/s tog ether with the force set-point $f_d^* = (0\,0 - 100)$ N are assigned.

The results are shown in Fig. 6, where the trace in the (mn) plane of the actual end effector trajectory confronted with the surface at rest and the time history of the contact force norm are reported. The deviation of the contact force from its nominal value is mainly due to coupling between force and velocity arising when the planned task is inconsistent with the actual task; if planning cannot be improved, the sliding velocity of the end effector onto the surface should be decreased. Another effect of coupling between force and velocity components is the time distorsion of the commanded velocity profile. As can be inferred from the contact force histories obtained, indeed, the motion of the end effector is faster during the peak-to-valley transition, while is slower during the valley-to-peak transition. This effect, which is likely to be of minor concern if following the edge of an unknown environment, becomes more evident when lower velocity/force ratios are used.

The same planning and the same controller design as in Case 2A is used in Case 2B to execute the task, but the relative location of the surface respect to the robot is significantly changed by setting $m_s = -0.45$ m. Fig. 7 reports the results obtained that simply show a longer approach phase with respect to Case 2A.

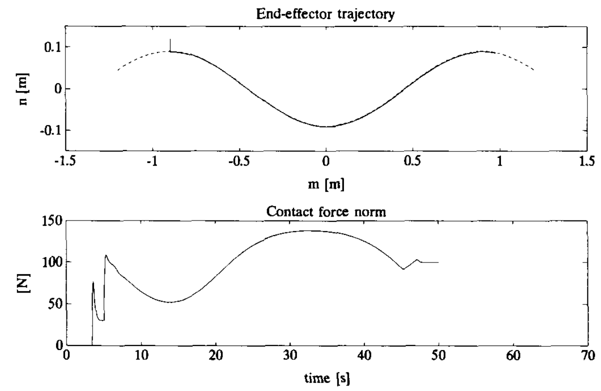


Fig. 6. end effector trajectory and contact force history for Case 2A.

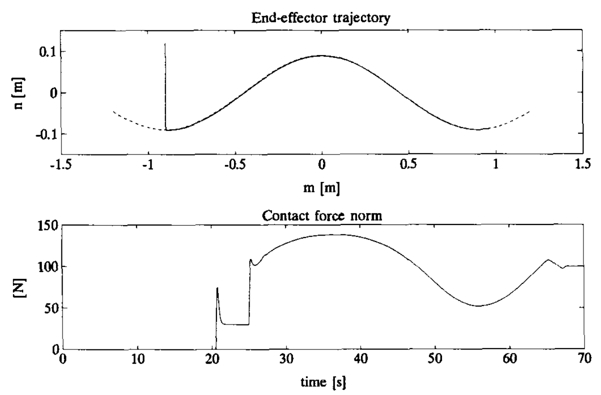


Fig. 7. end effector trajectory and contact force history for Case 2B.

IX. Conclusion

Constrained motion execution demands the adoption of control strategies which properly handle both the dynamic interaction of the manipulator with the environment and the fulfillment of force/position requirements. With respect to both needs, the inherent advantage of rule-based controllers over model-based controllers has been recognized.

The parallel control approach has been developed starting from the analysis of the different components of the interaction. Each component has been characterized in terms of its function and relation to the others. This led to distinguish two different aspects in the overall control strategy: the control of the manipulator motion itself and the control of the interaction with the environment. The latter suitably converts manipulation goals into motion commands accounting information from the actual task.

The above analysis offers a general framework to handle constrained motion problems. Suitable assumptions allowed to proceed toward the design of an effective parallel control scheme. Different assumptions, however, can be devised to pursue different design developments.

One major issue of the parallel control approach is that it allows to account geometric and dynamic characteristics of the environment at different levels in the system design. This feature is appealing as it gives proper roles to each component of the control system. It seems to be effective, indeed, to control the dynamics of the interaction while letting the geometry of the task be accounted at the planning level. An impact is mostly due, indeed, to (unavoidable) planning errors and then it cannot be handled by any strategy that uses the same information on which the task planning is based. Accordingly, no information about the location and orientation of the environment is required in the design of a parallel controller. As usual, the achieved robustness is paid in terms of reduced dynamic performance; e.g. the dynamic scheme presented in this paper result in a third-order system which yields slower dynamics—besides a more complex design—than the corresponding hybrid control scheme.

Two parallel control laws have been presented showing the basic features of the approach at different implementation complexity. The robustness properties of the scheme with respect both to knowledge of the stiffness of the environment and to knowledge of the task geometry have been tested in two case studies.

It has been shown that even if the environmental stiffness is one order of magnitude underestimated, the behavior of the scheme is satisfactory. Recovery from (unpredictable) irregular operation of the manipulator caused by planning errors in high-stiffness environment is achieved despite the occurence of saturation of the joint actuator torques.

In a perfectly structured environment with perfectly planned trajectories the hybrid control scheme and the parallel control scheme can be designed to exhibit equivalent behavior. However, since the design of a parallel controller can be accomplished without requiring geometric description of the environment, execution of complex tasks as contour following operations is made possible with a minimal task planning based on a rough geometric model of the environment. Proper operation of the scheme was obtained in a case study, whereas other control techniques might suffer from stability problems or might not be used at all.

Finally, it must be stressed that the proposed structure of the controller is only an example (not necessarily the best) of how a parallel controller can be implemented. Further research efforts will be devoted to the development of new parallel controllers able to handle more complex tasks.

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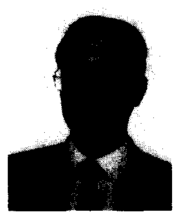

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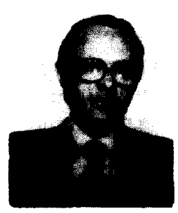

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