

DYNAMIC FORCE/MOTION CONTROL OF COOPERATIVE ROBOT SYSTEMS

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ABSTRACT

A new approach to designing a dynamic controller for multiple cooperating robotic manipulators is presented. A suitable kineto-static formulation for multi-arm systems provides an effective framework to analyze the coordination problem. This gives a global task space description of external and internal forces and, dually, absolute and relative velocities. The objective is to control absolute motion of the object held by the two arms and internal forces acting on the object. Differently from earlier works aimed at designing static controllers, the scheme here proposed does take into account the multiple arm dynamics. A nonlinear action is designed first to compensate for the dynamic terms which decouples the system. Then a linear action achieves prescribed force/motion behavior.

INTRODUCTION

Cooperative manipulation by multiple robots has lately attracted many researchers in the robotics community. Proper execution of advanced manipulation tasks demands for effective coordination of multiple robots. Handling heavy or non-rigid objects, mating mechanical parts, servicing in hazardous environments are some examples of tasks that may require more than a single arm. The potential offered by cooperative manipulation, however, is counterbalanced by the increased complexity of the coordination problem for multiple robots.

A master-slave (or leader-follower) strategy was developed by Luh and Zhen'g (1987) for the simple case of two-arm systems. In this approach, the desired motion is defined for the leader arm, which is motion-controlled, and the motion of the follower arm, which is force-controlled, is derived via a set of constraints allowing for coordinated control of the system. This approach seems to be impractical since it is naturally sensitive to modeling errors and system uncertainties, as it was experimentally demonstrated by Kopf and Yabuta (1988).

As opposed to the above method, a number of approaches have been presented which exploit object task space coordinates defined for the global multi-arm system. A technique was proposed by Hayati (1986) which extends the hybrid position/force control concept to the case of multiple arm system. Tarn, Bejczy, and Yun (1987) derived a closed-chain dynamic model of a two-arm system adopting the nonlinear decoupling technique to linearize and control the system in object coordinates. The object dynamics is taken into account in (Khatib, 1988), where a dynamic model for the multi-effector/object system is derived, and motion and active force control is achieved via dynamic decoupling. One shortcoming of all the above approaches is that they do not explicitly embed the internal forces and relative motions into the object task space defining the variables to be controlled.

On the other hand, a dynamic coordinated control was designed by Li, Hsu, and Sastry (1988) which achieves not only tracking of a desired object trajectory but also stabilization of a desired (internal) grasping force. A conceptually similar approach was independently proposed by Kreutz and Lokshin (1988); a stability analysis for that controller can be found in (Wen and Kreutz, 1988).

Differently from these latter methods which consider internal forces at the end-effectors level, the perspective here is to control the internal forces at the object level. It is argued that this approach better reflects the natural way of specifying a set of independent internal forces for the system regarded as a whole. It should be mentioned that a similar approach has recently been followed by Walker, Freeman, and Marcus (1989).

The global task space formulation proposed by Dauchez and Uchiyama (1987) is adopted — and here generalized to the multiple arm case — to describe external and internal forces as well as absolute and relative motions at the object level. A control scheme based

on this formulation was designed by Uchiyama, Iwasawa, and Hakomori (1987), and later refined by Uchiyama and Dauchez (1988). These schemes, however, are only static control schemes since they do not explicitly account for the dynamics of the multiple arms. This represents a severe limitation for high performance cooperative robot control systems.

This work is intended to provide a systematic framework for the design of a dynamic force/motion control for cooperative robot systems, based on the above global task space formulation. The resulting controller is obtained in two stages: First a nonlinear decoupling action, based on the estimates of the dynamic terms and the measures provided by end-effector force sensors, is designed which linearizes the system. Then a standard linear control action allows to achieve prescribed force/motion behavior. Remarkably, the approach pursued in this work naturally avoids the use of selection matrices, typical of hybrid controllers, since the choice of controlling the absolute motion of the object and the internal forces on the object is made in advance. The orthogonality between force and motion task directions is ensured by the global task space formulation adopted.

GLOBAL TASK SPACE FORMULATION

The formulation of task space coordinates required for describing cooperative tasks is derived by regarding the multiple arms and the grasped object as *one integrated system* with respect to the degrees of freedom provided by the joints of each arm.

The assumption is made to consider *tight grasp* and *rigid object*. Other types of contact have been considered in the literature, e.g. sliding (Cole, Hsu, and Sastry, 1989) and rolling (Cole, Hauser, and Sastry, 1989). An elastic model of the object has been considered in (Nakamura, 1988).

According to (Dauchez and Uchiyama, 1987), the cooperative task is described in terms of a set of absolute coordinates and a set of relative coordinates. The formulation has recently been generalized to the case of multiple arms (Walker, Freeman, and Marcus, 1989; Chiacchio, Chiaverini, and Siciliano, 1990) and is briefly summarized in the following. Consider a cooperative system with K arms grasping an object. Let m be the dimension of the task space of interest and

$$\mathbf{h}_i = \begin{bmatrix} \mathbf{f}_i \\ \mu_i \end{bmatrix} \quad \mathbf{h}_i \in \mathbb{R}^m \quad i = 1, \dots, K \quad (1)$$

denote the vectors of generalized contact forces (forces \mathbf{f}_i and moments μ_i) at the multiple end-effectors, all expressed with respect to the base frame. The above vectors

can be compacted into

$$\mathbf{h} = \begin{bmatrix} \mathbf{h}_1 \\ \vdots \\ \mathbf{h}_K \end{bmatrix} \quad \mathbf{h} \in \mathbb{R}^M \quad (2)$$

where $M = Km$ is the dimension of the *contact space*, that is the Cartesian product of the task spaces associated with each arm. Let then

$$\mathbf{h}_a = \begin{bmatrix} \mathbf{f}_a \\ \mu_a \end{bmatrix} \quad \mathbf{h}_a \in \mathbb{R}^m \quad (3)$$

denote the vector of *external forces* applied at the center of mass of the object — expressed in the base frame — described in the *global task space*. It can be shown that the mapping from the contact space onto the global task space is described by

$$\mathbf{h}_a = \mathbf{W}\mathbf{h} \quad (4)$$

where $\mathbf{W} \in \mathbb{R}^{M \times M}$ is the grasp matrix given by

$$\mathbf{W} = [\mathbf{W}_1 \quad \dots \quad \mathbf{W}_K] \quad (5)$$

The grasp sub-matrices $\mathbf{W}_i \in \mathbb{R}^{m \times m}$ are

$$\mathbf{W}_i = \begin{bmatrix} \mathbf{I} & \mathbf{O} \\ \mathbf{R}_i & \mathbf{I} \end{bmatrix} \quad i = 1, \dots, K \quad (6)$$

where \mathbf{I} and \mathbf{O} respectively denote identity and null matrices of appropriate dimensions, and \mathbf{R}_i are the matrices performing the vector product $\mathbf{r}_i \times \mathbf{f}_i = \mathbf{R}_i \mathbf{f}_i$ with \mathbf{r}_i denoting the vector pointing from the object center of mass to the i -th end-effector. In the most general case of $m = 6$, it is

$$\mathbf{R}_i = \begin{bmatrix} 0 & -r_{ix} & r_{iy} \\ r_{ix} & 0 & -r_{iz} \\ -r_{iy} & r_{iz} & 0 \end{bmatrix} \quad i = 1, \dots, K \quad (7)$$

Since \mathbf{W} is a low-rectangular matrix, it can easily be recognized that \mathbf{W} possesses a non-empty null space $\mathcal{N}(\mathbf{W})$. According to the perspective of regarding the system as a whole, the vector of *independent internal forces* is defined as $\mathbf{h}_r \in \mathbb{R}^{M-m}$. A solution to eq. (4) can then be written as

$$\mathbf{h} = \mathbf{W}^\dagger \mathbf{h}_a + \mathbf{V}\mathbf{h}_r \quad (8)$$

where $\mathbf{V} \in \mathbb{R}^{M \times (M-m)}$ is a matrix whose range spans the null space of the grasp matrix, i.e. $\mathcal{R}(\mathbf{V}) \equiv \mathcal{N}(\mathbf{W})$. For example, for a three-arm system ($K = 3$) with a six-dimensional global task space ($m = 6$): \mathbf{W} is a (6×18) matrix and \mathbf{V} is a (18×12) matrix.

At this point, the choice of \mathbf{V} is related to the physical characterization of the internal forces \mathbf{h}_r of the system.

The vector of independent internal forces \mathbf{h}_r can be partitioned as

$$\mathbf{h}_r = \begin{bmatrix} \mathbf{h}_{r1} \\ \vdots \\ \mathbf{h}_{r,K-1} \end{bmatrix} \quad \mathbf{h}_{ri} \in \mathbb{R}^m \quad (9)$$

Accordingly, the matrix \mathbf{V} is chosen as

$$\mathbf{V} = [(\mathbf{V})_1 \quad \dots \quad (\mathbf{V})_{K-1}] \quad (10)$$

where the j -th block column is

$$(\mathbf{V})_j = \begin{bmatrix} \vdots \\ \mathbf{V}_k \\ \vdots \\ -\mathbf{V}_l \\ \vdots \end{bmatrix} \quad (\mathbf{V})_j \in \mathbb{R}^{M \times m} \quad (11)$$

\mathbf{V}_k and \mathbf{V}_l denote the sole non-null sub-matrices defined as

$$\mathbf{V}_i = \begin{bmatrix} \mathbf{I} & \mathbf{O} \\ -\mathbf{R}_i & \mathbf{I} \end{bmatrix} \quad i = 1, \dots, K \quad (12)$$

Notice that, in force of the above relations, \mathbf{h}_{rj} identifies the internal forces between the k -th and the l -th end-effectors. Nonetheless, any choice of \mathbf{V} that corresponds to a physical description of the internal forces can be made as long as it guarantees that $\mathbf{WV} = \mathbf{O}$.

Once the static formulation has been established, the differential kinematic relationship can be derived in a similar manner. Let

$$\mathbf{v}_i = \begin{bmatrix} \dot{\mathbf{p}}_i \\ \omega_i \end{bmatrix} \quad \mathbf{v}_i \in \mathbb{R}^m \quad i = 1, \dots, K \quad (13)$$

denote the vectors of end-effector velocities (linear velocities $\dot{\mathbf{p}}_i$ and angular velocities ω_i), all expressed in the base frame. These can be compacted into

$$\mathbf{v} = \begin{bmatrix} \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_K \end{bmatrix} \quad \mathbf{v} \in \mathbb{R}^M \quad (14)$$

Let then

$$\mathbf{v}_a = \begin{bmatrix} \dot{\mathbf{p}}_a \\ \omega_a \end{bmatrix} \quad \mathbf{v}_a \in \mathbb{R}^m \quad (15)$$

denote the vector of absolute velocities of the object. Analogously to the definition of internal forces, the vector of independent relative velocities $\mathbf{v}_r \in \mathbb{R}^{M-m}$ is defined as

$$\mathbf{v}_r = \begin{bmatrix} \mathbf{v}_{r1} \\ \vdots \\ \mathbf{v}_{r,K-1} \end{bmatrix} \quad \mathbf{v}_{ri} \in \mathbb{R}^m \quad (16)$$

At this point, in force of the duality between forces and velocities which follows from the principle of virtual work in mechanics, it can be shown that

$$\begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_r \end{bmatrix} = \mathbf{U}^T \mathbf{v} \quad (17)$$

where $\mathbf{U} = [\mathbf{W}^\dagger \quad \mathbf{V}]$ is specified as in (8).

DYNAMIC MODELING

Hereafter, a six-dimensional task space will be considered without loss of generality. The dynamics of the multiple arms in the task space can be written as (Khatib, 1987)

$$\Lambda_i(\mathbf{x}_i)\ddot{\mathbf{x}}_i + \mathbf{n}_i(\mathbf{x}_i, \dot{\mathbf{x}}_i) = \gamma_i + \eta_i \quad i = 1, \dots, K \quad (18)$$

where \mathbf{x}_i is the vector expressing position and orientation of the end-effector, Λ_i is the positive definite inertia matrix, \mathbf{n}_i is the vector containing centrifugal, Coriolis, gravitational forces and viscous terms, γ_i is the vector of input forces, and η_i is the vector of forces acting from the environment onto the end-effector; all those terms are defined with respect to an inertial base frame. Notice that a minimal representation of end-effector orientation is implicitly used for \mathbf{x}_i , i.e.

$$\mathbf{x}_i = \begin{bmatrix} \mathbf{p}_i \\ \phi_i \end{bmatrix} \quad i = 1, \dots, K \quad (19)$$

where \mathbf{p}_i is the end-effector position vector and ϕ_i is any set of orientation angles (Euler, RPY); in fact, integration of end-effector angular velocities ω_i defined in (13) does not give a unique definition of orientation. More specifically, one has

$$\mathbf{v}_i = \mathbf{E}(\mathbf{x}_i)\dot{\mathbf{x}}_i \quad i = 1, \dots, K \quad (20)$$

where the matrix $\mathbf{E}(\mathbf{x}_i)$ is invertible almost everywhere in the arm's workspace. In particular, $\mathbf{E}(\mathbf{x}_i)$ can be expressed as

$$\mathbf{E}(\mathbf{x}_i) = \begin{bmatrix} \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{E}_o(\phi_i) \end{bmatrix} \quad i = 1, \dots, K \quad (21)$$

where \mathbf{E}_o is an orientation Jacobian matrix mapping $\dot{\phi}_i$ into ω_i .

Applying again the duality principle, the following relations hold

$$\gamma_i = \mathbf{E}^T(\mathbf{x}_i)\mathbf{d}_i \quad i = 1, \dots, K \quad (22)$$

$$\eta_i = \mathbf{E}^T(\mathbf{x}_i)\mathbf{h}_i \quad i = 1, \dots, K \quad (23)$$

Notice that the transformations in (20,23) are needed to relate end-effector angular velocities and torques to the

corresponding quantities defined in (13,1); the transformation in (22) is introduced accordingly.

Plugging (22,23) into (18), the dynamic models of the multiple robots become in compact form

$$\Lambda(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{n}(\mathbf{x}, \dot{\mathbf{x}}) = \mathbf{E}^T(\mathbf{x})[\mathbf{d} + \mathbf{h}] \quad (24)$$

where $\mathbf{x} = [\mathbf{x}_1^T \ \dots \ \mathbf{x}_K^T]^T$, $\Lambda = \text{block diag}(\Lambda_1, \dots, \Lambda_K)$, $\mathbf{n} = [\mathbf{n}_1^T \ \dots \ \mathbf{n}_K^T]^T$, $\mathbf{E} = \text{block diag}(\mathbf{E}_1, \dots, \mathbf{E}_K)$ with $\mathbf{E}_i = \mathbf{E}(\mathbf{x}_i)$ for $i = 1, \dots, K$, $\mathbf{d} = [\mathbf{d}_1^T \ \dots \ \mathbf{d}_K^T]^T$, and \mathbf{h} defined as in (2).

In (24) it is assumed that sensors are available for measuring the contact forces \mathbf{h} exerted by the multiple end-effectors on the object. This overcomes the drawback of needing an accurate object dynamic model to determine the contact forces, as opposed to previous approaches (Li, Hsu, and Sastry, 1988; Kreutz and Lokshin, 1988).

DYNAMIC FORCE/MOTION CONTROL

Based upon the kineto-static and dynamic formulations presented in the above two sections, an approach to designing a force/motion control for cooperative robot systems is presented in the remainder.

It is intuitive to recognize that, when multiple robots are employed to manipulate an object, the capability of exerting external forces is enhanced no matter what are the configurations of the single arms. On the other hand, the capability of generating absolute velocities is penalized by that arm which is in the least favourable configuration to accomplish the object motion in the required direction. In force of the duality concept — at the basis of the above-described global task space formulation — it can be inferred that the capability of sustaining internal forces along a given direction is limited by the weakest arm of the system, whereas the capability of giving rise to relative motion between each pair of arms along a given direction is improved. These considerations have been confirmed by recent studies on the manipulability of multi-arm systems aimed at deriving global task space ellipsoids (Chiacchio et al., 1989; Chiacchio, Chiaverini, and Siciliano, 1990).

From the control point of view, it can be deduced that the choice of motion-controlling the absolute coordinates of the object while force-controlling the relative coordinates between pairs of end-effectors naturally copes with the physics of the system. The manipulability ellipsoids relative to these variables, indeed, are always smaller in size than the corresponding single-arm ellipsoids; this allows finer control of the chosen variables. Another point in favor of this approach is that the structural orthogonality between absolute and relative variables implied in the above global task space formulation relieves the user from the task of adopting selection matrices which is typical of most hybrid force/motion control techniques.

In turn, with this control strategy, the robots can carry the object with high accuracy while exerting desired internal forces (e.g. twisting, bending, pushing, pulling or shearing) on it. Such approach was also followed in (Uchiyama, Iwasawa, and Hakomori, 1987), but only a simple static control scheme was designed. In the following, a dynamic force/motion control scheme is proposed based on the nonlinear decoupling feedback technique which is equivalent to the well-known computed-torque method for single robot control.

The key point of the approach is to define the output of the variables to be controlled. In view of the above-discussed concepts, it is reasonable to choose as output to the overall system the vector of absolute velocities of the object ${}^a\mathbf{v}_a$ and internal velocities between end-effector pairs expressed in the object frame ${}^a\mathbf{v}_r$, i.e.

$$\mathbf{y} = \begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_r \end{bmatrix} \quad (25)$$

The choice of velocities (linear + angular) in lieu of locations (position + orientation) overcomes the problems related to eqs. (19–21) (De Luca, Manes, and Nicolò, 1988). Also, it is convenient to describe the internal force task in the object frame rather than in the base frame (Uchiyama and Dauchez, 1987); given the (3×3) matrix ${}^a\mathbf{R}_o$ transforming a vector from the base frame to the object frame, the output vector \mathbf{y} can be expressed as

$$\mathbf{y} = \begin{bmatrix} \mathbf{I} & \mathbf{O} \\ \mathbf{O} & {}^a\mathbf{A}_o \end{bmatrix} \begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_r \end{bmatrix} = \mathbf{R} \begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_r \end{bmatrix} \quad (26)$$

with ${}^a\mathbf{A}_o = \text{block diag}({}^a\mathbf{R}_o, {}^a\mathbf{R}_o)$. Furthermore, it will be shown next how selecting motion variables for the internal force task allows to prescribe a satisfactory dynamic behavior along the directions to be force-controlled.

At this point, nonlinear decoupling theory requires that the output vector be related to the state vector of the dynamic system to be controlled. In this process, it may be necessary to derive the output vector as many times until the input vector explicitly appears (Hirschorn, 1979). In the context of the present work, the outlined procedure translates into the following steps. Plugging (17) in (26) gives

$$\mathbf{y} = \mathbf{R}\mathbf{U}^T\mathbf{v} \quad (27)$$

Accounting for eq. (20) leads to

$$\mathbf{y} = \mathbf{T}(\mathbf{x})\dot{\mathbf{x}} \quad (28)$$

with $\mathbf{T} = \mathbf{R}\mathbf{U}^T\mathbf{E}$. The dynamic models in (24) can be solved for the end-effector accelerations as

$$\ddot{\mathbf{x}} = -\Lambda^{-1}(\mathbf{x})\mathbf{n}(\mathbf{x}, \dot{\mathbf{x}}) + \Lambda^{-1}(\mathbf{x})\mathbf{E}^T(\mathbf{x})[\mathbf{d} + \mathbf{h}] \quad (29)$$

which suggests deriving once eq. (28), i.e.

$$\dot{\mathbf{y}} = \dot{\mathbf{T}}(\mathbf{x})\dot{\mathbf{x}} + \mathbf{T}(\mathbf{x})\ddot{\mathbf{x}} \quad (30)$$

Substituting then (29) in (30) yields

$$\dot{y} = \dot{T}(x)\dot{x} + T(x)[-A^{-1}(x)n(x, \dot{x}) + A^{-1}(x)E^T(x)[d+h]] \quad (31)$$

Let α denote a new input vector. The input-output decoupling control vector d can be chosen so as to compensate for the nonlinear dynamic terms, i.e.

$$d = E^{-T}(x)\hat{\Lambda}(x)T^{-1}(x)[\alpha - \dot{T}(x)\dot{x}] + E^{-T}(x)\hat{n}(x, \dot{x}) - \hat{h} \quad (32)$$

where " $\hat{\cdot}$ " indicates the estimates of the dynamic terms and " \sim " the available sensor measures of the generalized contact forces with the object. With perfect compensation, the system (31) becomes

$$\dot{y} = \alpha \quad (33)$$

which is a linear and decoupled system (equivalent to $6K$ independent integrators) in the absolute/relative space defined by the output (25).

The goal now is to prescribe a desired behavior for the system (33) in terms of the absolute motion of the object and the internal forces acting on the object. Let v_{ad} denote a desired absolute velocity vector. Let also h_{rd} denote a desired vector of internal forces. The new input vector α can suitably be selected as

$$\alpha = \begin{bmatrix} \dot{v}_{ad} + K_v(v_{ad} - v_a) + K_p e_a \\ -M^{-1}[(^a h_{rd} - ^a h_r) + D^a v_r] \end{bmatrix} \quad (34)$$

where the absolute location error vector is chosen as

$$e_a = \begin{bmatrix} P_{ad} - P_a \\ \frac{1}{2}(n_{ad} \times n_a + s_{ad} \times s_a + a_{ad} \times a_a) \end{bmatrix} \quad (35)$$

which is consistent with $\dot{e}_a = v_{ad} - v_a$ (Luh, Walker, and Paul, 1980). The diagonal positive definite matrices K_p and K_v characterize the desired dynamics of the absolute location error control loop. Also M and D denote a mass matrix and a damping matrix determining the behavior of the internal force control loop (Hogan, 1985).

The resulting controller is schematically illustrated in Fig. 1. It can be recognized that all the quantities needed for the computation of the control law (32,34) can be derived from the sole sensor measurements which are assumed to be available, that is the joint displacement vector $q = [q_1^T \dots q_K^T]^T$, the joint velocity vector \dot{q} and the contact force vector h . The transformations required are:

$$x = g(q) \quad (36)$$

where $g = [g_1^T \dots g_K^T]^T$ is the direct kinematic function for the multiple robots,

$$\dot{x} = J(q)\dot{q} \quad (37)$$

where $J = \text{block diag}(J_1, \dots, J_K)$ is the usual Jacobian matrix, v is computed according to (20), v_a and v_r are computed via (17). Also, h_r is solved for from (8) with $h_a = 0$; then v_r and h_r are respectively transformed into ${}^a v_r$ and ${}^a h_r$ by the matrix ${}^a A_o$, as in (26). Finally, the actual vector of torques $\tau = [\tau_1^T \dots \tau_K^T]^T$ delivered at robot joints can be derived as

$$\tau = J^T(q)E^T(x)d \quad (38)$$

CONCLUDING REMARKS

A new dynamic force/motion controller has been designed for multiple cooperative robot systems. The absolute motion of the object held by the robots, described with respect to the base frame, and a set of independent internal forces between end-effector pairs, described with respect to the object frame, are suitably controlled. The scheme can be considered as the natural dynamic extension of a previous static control scheme; both of them are based on an effective kineto-static formulation for multiple arms. A nonlinear action which compensates for the dynamic model terms has been designed based on the assumption of disposing of joint displacement and velocity measures as well as of end-effector contact force measures. The resulting decoupled linear system allows the design of standard motion tracking and force impedance control actions.

Since the proposed control strategy relies on the data provided by sensors, it is argued that a crucial point is to investigate the robustness of the scheme to imperfect robot modeling, inaccurate modeling of the contact between the multiple end-effectors and the object. In view of a practical on-line implementation, another issue to deal with is the computational burden required by the overall controller. Ongoing research work is oriented to perform extensive simulations and experiments for typical case studies.

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