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OBJECT LEVEL MANIPULATION

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Abstract

The paper discusses basic methodologies developed within the operational space framework for the analysis and control of robot systems involving combinations of serial and in-parallel mechanical structures. First, we present the fundamentals of the operational space framework and describe the unified approach for motion and active force control of manipulators. For serial structures such as a macro-/mini-manipulator, the effective inertial characteristics of the combined system are shown to be dominated by the inertial properties of the micro-manipulator. This result is the basis for the development of a new approach for dextrous dynamic coordination. In this approach, the combined system is treated as a single redundant manipulator. Dexterity is achieved by minimizing deviations from the neutral (mid-range) joint positions of the micro-manipulator. In the case where several arms, i.e., in-parallel structures, are involved in manipulation of the object, the multi-effector/object system is treated as an augmented object representing the total masses and inertias perceived at some operational point, and actuated by the total effector forces acting at that point. This model is used for the dynamic decoupling, motion, and active force control of the system. Individual manipulator control forces are calculated using a criterion based upon minimization of the overall actuator effort.

Introduction

Motion control of robot mechanisms has generally been viewed from the perspective of the manipulators' joint motions. The architectures of robot control systems which are developed within the joint space framework are typically organized following the three levels of task specification, joint space task description, and joint space control. At the highest level, tasks are specified in terms of end-effector or manipulated object motions.

At the second level, these specifications are transformed into descriptions of joint motions. This involves using the inverses of the geometric and kinematic models. Finally, at the lowest level, the robot is controlled in joint space.

Task specification for motion and contact forces, dynamics, and force sensing feedback, are most closely linked to the end-effector's motion, or more generally to the manipulated object's motion. The issue of dynamic modeling and control at the manipulated object level is yet more acute for tasks that require simultaneous motion and contact-force control of the object. The inability of joint space models to deal with effector or object dynamic control has resulted in force control methodologies that have been essentially based on *kinematic and static* considerations. The performance of the resulting implementations is obviously limited when dynamic effects need to be considered. In free motion, the effects of dynamics increase with the range of motion, speed, and acceleration at which the robot is operating. In part mating operations, the effects of dynamics also increase with the rigidity of the mating objects.

There is clearly a need for a description of the end-effector dynamics and for the dynamics of the object and its interaction with the environment. This has been precisely the motivation behind development of the *operational space formulation* [2,4]. In this framework both forces of motion and active forces are addressed at the same level of end-effector or manipulated object control. This provides a unified approach for the dynamic control of end-effector motions and forces.

Limitations of the joint space framework for control are yet more severe for robot systems involving an increased number of degrees of freedom. In quest of increased capabilities and higher performance, robot systems are advancing beyond the traditional single six-degree-of-freedom serial chain mechanism. Recent research and ongoing developments show a clear trend toward robot systems with mechanical structures which use a larger number of degrees of freedom distributed between multiple arms [1,8,10]. Research also shows an increasing interest in the incorporation of lightweight mini-manipulators [7,9] to increase performance.

In this paper, we are concerned with evaluation of the dynamic characteristics of macro-/mini-manipulator and multi-arm systems, determination of the impact which these characteristics will have on their performance, and design of dynamic coordination strategies for their control.

Basic Concept

The basic idea behind the operational space approach is to control motions and contact forces through the use of force commands that act directly at the end-effector level. Generation of these control forces is realized by the application of corresponding joint torques to each actuator of the manipulator.

For instance, submitting the end-effector to the gradient of an attractive potential field (through application of the corresponding actuator joint torques) will result in joint motions that position the effector at the configuration corresponding to the minimum of this potential field. This type of control can be shown to be stable. However, the dynamic performance of such control will clearly be limited by the inertial interactions between moving links.

High performance control of end-effector motions and contact forces requires construction of a model describing the dynamic behavior as perceived at the end-effector or more precisely, at the point on the effector where the task is specified. This point is called the *operational point*.

A coordinate system associated with the operational point is used to define a set of *operational coordinates*. Then, a set of operational forces acting on the end-effector is associated with the system of operational coordinates which describe the position and orientation of the end-effector. Construction of the end-effector dynamic model is achieved by expressing the relationship between its positions, velocities, and accelerations with the operational forces acting on it.

End-effector control is based on selection of the operational forces generated at the end-effector as a command vector. These operational forces are produced by submitting the manipulator to the corresponding joint forces, using a simple force transformation.

The operational space robot control system is organized in a hierarchical structure, as shown in Figure 1, which uses three control levels:

- *Task Specification Level*: at this level, tasks are described in terms of motion and contact forces of the manipulated object or tool.

- *Effector Level*: associated with this level is the end-effector dynamic model; the basis for the end-effector's motion and force control. The output here is a vector of joint forces and torques to be produced by the joint level. These forces and torques are computed so as to generate the required operational-space forces and moments associated with the end-effector command vector.

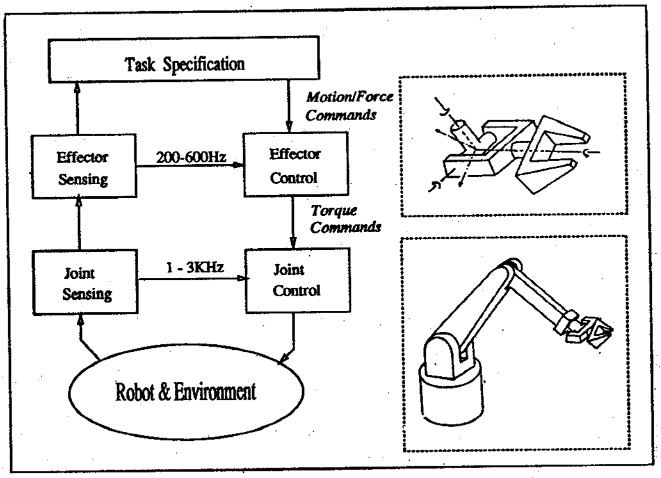

Figure 1: Operational Space Control Structure

- *Joint Level*: this level is formed by the set of individual joint torque controllers, allowing each joint to produce its assigned torque component for producing the vector of joint torques corresponding to the end-effector command vector.

Single Manipulator System

In this section, the operational space framework for a single manipulator is summarized.

Effector Equations of Motion

The end-effector position and orientation with respect to a reference frame $\mathcal{R}_O$ of origin O is described by the relationship between $\mathcal{R}_O$ and a coordinate frame $\mathcal{R}_\odot$ of origin $\odot$ attached to this effector. $\odot$ is called the *operational point*. It is with respect to this point that translational and rotational motions and active forces of the effector are specified. An *operational coordinate system* associated with an m-degree-of-freedom effector and a point $\odot$, is a set $\mathbf{x}$ of m *independent* parameters describing the effector position and orientation in a frame of reference $\mathcal{R}_O$. For a non-redundant n-degree-of-freedom manipulator, i.e., $n = m$, these parameters form a set of of *generalized operational coordinates*. The effector equations of motion in operational space [4] are given by

$$\Lambda(\mathbf{x})\ddot{\mathbf{x}} + \Pi(\mathbf{x})[\dot{\mathbf{x}}\dot{\mathbf{x}}] + \mathbf{p}(\mathbf{x}) = \mathbf{F}; \tag{1}$$

where $\Lambda(\mathbf{x})$ designates the kinetic energy matrix, and $\mathbf{p}(\mathbf{x})$ and $\mathbf{F}$ are respectively the gravity and the generalized operational force vectors. $\Pi(\mathbf{x})$ represents the $m \times m(m+1)/2$ matrix of centrifugal and Coriolis forces. With $J(q)$ being the Jacobian matrix associated with the generalized operational velocities $\dot{\mathbf{x}}$, the kinetic energy matrix $\Lambda(\mathbf{x})$ is related to the $n \times n$ joint space kinetic energy matrix, $A(\mathbf{q})$ by

$$\Lambda(\mathbf{x}) = J^{-T}(\mathbf{q})A(\mathbf{q})J^{-1}(\mathbf{q}). \quad (2)$$

The generalized joint forces Γ required to produce the operational forces $\mathbf{F}$ are

$$\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F}; \quad (3)$$

This relationship is the basis for the control of manipulators in operational space. Dynamic decoupling and motion control of the manipulator in operational space is achieved by selecting the control structure

$$\mathbf{F} = \widehat{\Lambda}(\mathbf{x})\mathbf{F}^{\star} + \widehat{\Pi}(\mathbf{x})[\dot{\mathbf{x}}\dot{\mathbf{x}}] + \widehat{\mathbf{p}}(\mathbf{x}); \quad (4)$$

where, $\widehat{\Lambda}(\mathbf{x})$, $\widehat{\Pi}(\mathbf{x})$, and $\widehat{\mathbf{p}}(\mathbf{x})$ represent the estimates of $\Lambda(\mathbf{x})$, $\Pi(\mathbf{x})$, and $\mathbf{p}(\mathbf{x})$. With a perfect nonlinear dynamic decoupling, the end-effector becomes equivalent to a *single unit mass*, I_m, moving in the m-dimensional space,

$$I_m\ddot{\mathbf{x}} = \mathbf{F}^{\star}. \quad (5)$$

$\mathbf{F}^{\star}$ is the input of the decoupled end-effector. This provides a general framework for the selection of various control structures.

Active Force Control: The operational space formulation provides a natural framework for integrating motion control and active force control in a unified manner. In part mating operations, both motions and active forces need to be controlled simultaneously. Such operations typically involve motion control in some directions and active force control in the orthogonal directions For this purpose, we have introduced the concept of generalized specification matrices, Ω and its complement $\overline{\Omega}$ [4]. Using these matrices, the unified control vector for end-effector motion and active force control is:

$$\mathbf{F} = \Omega\ \mathbf{F}_{\text{Motion}} + \overline{\Omega}\ \mathbf{F}_{\text{Active-Force}}; \quad (6)$$

where $\mathbf{F}_{\text{Motion}}$ is given as in equation (4) and $\mathbf{F}_{\text{Active-Force}}$ is the active force control vector [4]. The control system is developed following a two-level architecture: a low-speed dynamic parameter evaluation level updating the dynamic parameters; and a high-speed servo control level which computes the command vector using the updated dynamic coefficients.

Redundant Manipulators

Redundancy is a source of freedom in task execution. Positioning and orienting the end-effector of a redundant manipulator can be accomplished with an infinity of postures of the mechanical structure. This also implies that the description of the end-effector position and orientation does not allow one to determine the complete configuration of the redundant mechanism. Thus, a set of operational coordinates is not sufficient to completely specify the configuration of a redundant manipulator. For this reason, the dynamic behavior of the entire system is impossible to describe by a dynamic model in operational coordinates. The dynamic behavior of the end-effector itself, nevertheless, can still be described, and its equations of motion in operational space can still be established. In fact, the structure of the effector dynamic model is identical to that obtained in the case of non-redundant manipulators (equation 1). In the redundant case, however, the matrix Λ should be interpreted as a *"pseudo kinetic energy matrix"*. This matrix is related to the joint space kinetic energy matrix by

$$\Lambda(\mathbf{q}) = [J(\mathbf{q})A^{-1}(\mathbf{q})J^T(\mathbf{q})]^{-1}; \quad (7)$$

Another important aspect of redundancy is concerned with forces. End-effector forces are affected by the joint torques delivered by the redundant actuators. Determining how generalized joint torques are reflected at the end-effector is crucial in tasks that involve active force control.

Consistent Null Space: End-effector motions are controlled by operational forces, $\mathbf{F}$, created by the application of a set of generalized joint forces, $\mathbf{\Gamma}$, given by $\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F}$. For redundant manipulators, the previous relationship becomes incomplete. At a given configuration, there is an infinity of elementary displacements of the redundant mechanism that could take place without altering the configuration of the effector. Those displacements correspond to motion in the null space associated with a generalized inverse of the Jacobian matrix.

In terms of forces, there are also an infinity of joint force vectors that could be applied without effecting the resulting forces reflected at the end-effector. Those are the joint forces acting within the null space. The general expression for the relationship between end-effector forces and generalized joint forces is

$$\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F} + [I - J^T(\mathbf{q})J^{\#^T}(\mathbf{q})]\mathbf{\Gamma}_0; \quad (8)$$

where $\mathbf{\Gamma}_0$ is an arbitrary generalized joint force vector. While $\mathbf{F}$ is used for end-effector control, the joint torque vector $\mathbf{\Gamma}_0$ provides means to control the manipulator internal joint motions.

The previous relationship (8), which is based only on static considerations, provides a freedom in the selection of the generalized inverse ($J^{\#}$ such that $J = JJ^{\#}J$). Taking into account the effector's dynamics results in an additional constraint which reduces this freedom. The additional constraint is concerned with end-effector accelerations. Analysis of equations of motion shows that the effector acceleration corresponding to the application of a joint torque vector $\mathbf{\Gamma}$ is $J(\mathbf{q})A^{-1}(\mathbf{q})\mathbf{\Gamma}$. In order for the dynamic effects of the joint forces associated with null space to be canceled, it is necessary for the null space to satisfy

$$J^T(\mathbf{q})A^{-1}(\mathbf{q})[I - J^T(\mathbf{q})J^{\#^T}(\mathbf{q})]\Gamma_0 = 0. \quad (9)$$

The null space associated with a generalized inverse satisfying the above constraint is said to be dynamically consistent.

Theorem 1: *(Dynamic Consistency)*

A generalized inverse that is consistent with the dynamic constraint of equation (9), $\overline{J}(\mathbf{q})$, is unique and given by

$$\overline{J}(\mathbf{q}) = A^{-1}(\mathbf{q})J^T(\mathbf{q})\Lambda(\mathbf{q}). \quad (10)$$

$\overline{J}(\mathbf{q})$ in equation (10) is actually a generalized inverse of the Jacobian matrix corresponding to the solution that minimizes the manipulator's instantaneous kinetic energy.

Control of Redundant Manipulators: Just as in the case of non-redundant manipulators, the dynamic decoupling and control of the end-effector can be achieved by selecting an operational command vector of the form (4). The manipulator joint motions produced by this command vector are those that minimize the instantaneous kinetic energy of the mechanism. Analysis shows the system to be stable. However, even though the end-effector is asymptotically stable, the manipulator joints can still move in the nullspace. Asymptotic stabilization of the entire system can be achieved by the addition of dissipative joint forces. In order to prevent any effect of the additional forces on the end-effector and maintain its dynamic decoupling, these forces must be selected to only act in the dynamically-consistent nullspace associated with $\overline{J}(\mathbf{q})$. These additional stabilizing joint forces must be of the form

$$\mathbf{\Gamma}_{ns} = [I_n - J^T(\mathbf{q})\overline{J}^T(\mathbf{q})]\mathbf{\Gamma}_s. \qquad (11)$$

In the actual implementation, the global control vector will be developed in a form [4] that avoids the explicit evaluation of the expression of the generalized inverse of the Jacobian matrix.

Macro-/Mini-Manipulator Systems

We now consider the case of systems resulting from serial combinations of two manipulators. The manipulator connected to the ground will be referred to as the "macro-manipulator". It has n_M degrees of freedom and its configuration is described by the system of n_M generalized joint coordinates $\mathbf{q}_M$. The second manipulator, referred to as the "mini-manipulator", has n_m degrees of freedom and its configuration is described by the generalized coordinates $\mathbf{q}_m$. The resulting structure is an n degree-of-freedom manipulator with $n = n_M + n_m$. Its configuration is described by the system of generalized joint coordinates $\mathbf{q} = [\mathbf{q}_M^T\ \mathbf{q}_m^T]^T$. If m represents the number of effector degrees of freedom of the combined structure, n_m is assumed to provide the mini-manipulator with the full freedom to move in the m-dimensional operational space. The macro-manipulator part must have at least one degree-of-freedom. That is,

$$n_M \geq 1 \text{ and } n_m \geq m.$$

Let Λ_{mini} be the kinetic energy matrix associated with the mini-manipulator considered alone, and Λ the pseudo kinetic energy matrix associated with the combined mechanism, i.e., macro-mini-manipulator.

Theorem 2: *(Reduced Effective Inertia)* The operational space *pseudo kinetic energy matrix* Λ satisfy [6]

$$\frac{1}{1+\eta\cdot\lambda_k(\Lambda_{\text{mini}})} \leq \frac{\lambda_k(\Lambda)}{\lambda_k(\Lambda_{\text{mini}})} \leq 1; \quad k = 1, 2, \ldots, m$$

where $\eta \geq 0$, and $\lambda_k(.)$ denote the k^{th} largest eigenvalue of $(.)$, i.e., $\lambda_m(.) \leq \ldots \leq \lambda_1(.)$.

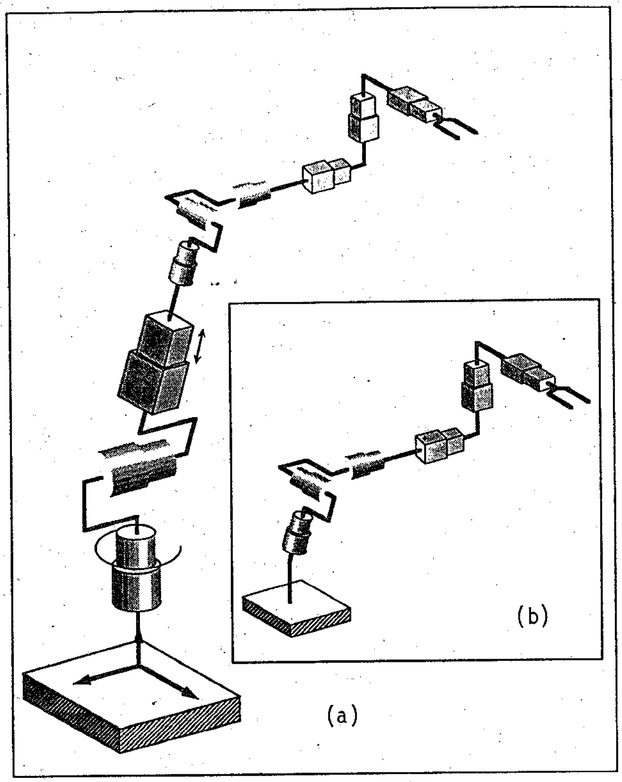

Figure 2: Reduced Effective Inertia

Figure 2.a shows a nine degree-of-freedom manipulator The magnitude of the inertial characteristics of this manipulator are bounded by the inertial characteristics of the six degree-of-freedom mini manipulator shown in Figure 2.b.

Dextrous Dynamic Coordination

The previous results show that the inertial characteristics of the combined system are upper bounded by (and, for prismatic structure, identical to) those of the mini-manipulator. Given the mechanical limits on the range of joint motions of the mini-manipulator, these characteristics are only useful within this available range.

The operational space control of a macro-/mini-manipulator treated as a single redundant manipulator will result in fast dynamic response, which will be essentially due to the high bandwidth of the mini-structure. These dynamic characteristics are maintained until the mini-structure's joints reach their limits. Maximizing the mini-manipulator's available range of motion is therefore essential for extending this performance to tasks requiring a large range of motion.

The proposed *dextrous dynamic coordination* is based on minimization of deviations from the neutral (mid-range) joint positions of the mini-manipulator. This minimization is achieved using joint forces selected from the dynamically consistent null space associated with $\overline{J}(\mathbf{q})$. This will preclude any effects of the additional forces on the primary task.

Let $\overline{q}_i$ and $\underline{q}_i$ be the upper and lower bounds on the i^{th} joint position q_i. We construct the potential function

$$V_{\text{Dextrous}}(\mathbf{q}) := k_d \sum_{i=n_M+1}^{n} (q_i - \frac{\overline{q}_i + \underline{q}_i}{2})^2; \qquad (12)$$

where k_d is a constant gain. The gradient of this function

$$\boldsymbol{\Gamma}_{\text{Dextrous}} = -\nabla V_{\text{Dextrous}}; \qquad (13)$$

provides the required attraction [3] to the mid-range joint positions of the micro-manipulator. The interference of these additional torques with the end-effector dynamics is avoided by selecting them from the null space. That is,

$$\boldsymbol{\Gamma}_{nd} = [I_n - J^T(\mathbf{q})\overline{J}^T(\mathbf{q})]\boldsymbol{\Gamma}_{\text{Dextrous}}. \qquad (14)$$

To avoid joint limits, we can use an "artificial potential field" function [3]. Asymptotic stabilization of the redundant mechanism requires additional dissipative joint forces which should also be selected from the dynamically consistent null space.

It is essential that the ranges of motion of joints associated with the mini-structure allow accommodation for the relatively slower dynamic response of the arm. A sufficient motion margin is a requirement for achieving dextrous dynamic coordination.

Multi-Effector Robot System

Let us consider the problem of manipulating an object with a system of N robot manipulators, as illustrated in Figure 3. The effectors of each of these manipulators are assumed to have the same number of degrees of freedom, m, and to be rigidly connected to the manipulated object. Let $\odot$ be the selected operational point attached to this object. This point is fixed with respect to each of the effectors. Let $\Lambda_{\mathcal{L}}(\mathbf{x})$ be the kinetic energy matrix associated with the object's load alone, expressed with respect to $\odot$ and the operational coordinates $\mathbf{x}$. Being held by N effectors, the inertial characteristics of the object as perceived at the operational point are modified. The N-effector/object system can be viewed as an ***augmented object*** [5] representing the total inertias perceived at $\odot$. Let $\Lambda_i(\mathbf{x})$ be the kinetic energy matrix associated with the i^{th} effector.

Theorem 3: ***(Augmented Object)*** The kinetic energy matrix of the augmented object is [5]

$$\Lambda_{\oplus}(\mathbf{x}) := \Lambda_{\mathcal{L}}(\mathbf{x}) + \sum_{i=1}^{N} \Lambda_i(\mathbf{x}).$$

The augmented object equations of motion are

$$\Lambda_{\oplus}(\mathbf{x})\ddot{\mathbf{x}} + \Pi_{\oplus}(\mathbf{x})[\dot{\mathbf{x}}\dot{\mathbf{x}}] + \mathbf{p}_{\oplus}(\mathbf{x}) = \mathbf{F}_{\oplus}; \qquad (15)$$

where the matrix $\Pi_{\oplus}(\mathbf{x})$, of centrifugal and Coriolis forces, the vector $\mathbf{p}_{\oplus}(\mathbf{x})$, of gravity forces, and the generalized operational forces $\mathbf{F}_{\oplus}$ also possess the additive property.

The augmented object represents the total masses and inertias perceived at the operational point and actuated by

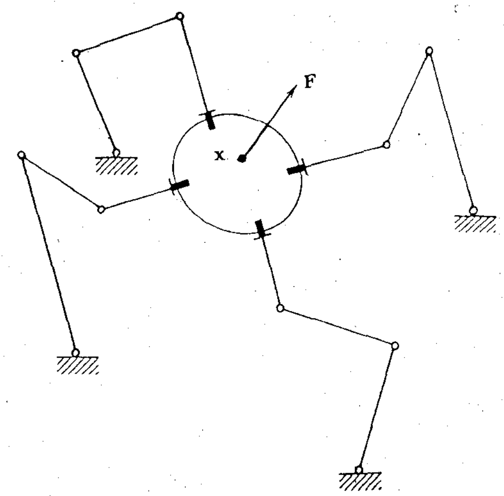

Figure 3: A Multi-Effector/Object System

the total effector forces acting at that point. Based on this model, a control structure similar to (4) has been used to achieve the dynamic decoupling and control of the combined system. The criterion used in the allocation of forces has been based on minimization of the total joint actuator efforts [5].

Allocation of Effector Forces

The force vector, $\mathbf{F}_i$, to be produced by the i^{th} effector is selected to be aligned with $\mathbf{F}_{\oplus}$ and to act in the same direction,

$$\mathbf{F}_i = \alpha_i \mathbf{F}_{\oplus}; \quad \text{with} \quad \alpha_i > 0. \qquad (16)$$

In addition, the set of N positive numbers α_i must satisfy

$$\sum_{i=1}^{N} \alpha_i = 1. \qquad (17)$$

The actuator joint torques required by the i^{th} manipulator is

$$\boldsymbol{\Gamma}_i = \alpha_i J_i^T(\mathbf{q}_i)\ \mathbf{F}_{\oplus}.$$

The set of N positive numbers, $\alpha_1, \alpha_2, \ldots, \alpha_N$ are selected such that the overall effort of the actuators is minimized.

The evaluation of α_i's involves the computation for each manipulator of the vector joint torques τ_i corresponding to the total operational forces $\mathbf{F}_{\oplus}$

$$\tau_i = J_i^T(\mathbf{q}_i)\ \mathbf{F}_{\oplus};$$

which represents the actuator joint torques that would be assigned to the i^{th} manipulator, if this manipulator alone were to produce the total operational force $\mathbf{F}_{\oplus}$.

Actuator joint torques are limited. The magnitude of the maximal bounds on the j^{th} actuator force of the i^{th} manipulator is noted $\overline{\gamma}_{ij}$. If τ_{ij} denotes the j^{th} component of τ_i, the number $|\tau_{ij}|/\overline{\gamma}_{ij}$ represents a measure of the effort that will be required by the j^{th} actuator if the i^{th} manipulator alone produced the total operational forces $\mathbf{F}_\oplus$.

The effort of the i^{th} manipulator is characterized by

$$r_i = \max_j\{|\tau_{ij}|/\overline{\gamma}_{ij}\};$$

which corresponds to the greatest effort. r_i is a positive number, which would be greater than one if the requested joint forces cannot be achieved by the i^{th} manipulator alone. In order to minimize the overall effort, the weighting numbers α_1, α_2, ..., and α_N will be selected so that the effort is equally distributed, that is

$$\alpha_1 r_1 = \alpha_2 r_2 = ... = \alpha_N r_N.$$

Using equation (17), this corresponds to the solution

$$\alpha_i = \frac{\beta_i}{\beta_1 + \beta_2 + ... + \beta_N}; \tag{18}$$

where

$$\beta_i = \frac{r_1.r_2...r_N}{r_i}. \tag{19}$$

The above control structure only uses the necessary forces, i.e. net force, required to achieve the dynamic decoupling and control of the system. Compared to control structures where joint motions or effector motions are individually decoupled and controlled, the proposed control system represents a significant reduction in actuator activities. Indeed, in this approach, the inertial coupling, centrifugal, and Coriolis forces acting on one effector are used to compensate for parts of the coupling forces acting on the others. The actuator joint force activity is further minimized by the criterion used for the allocation of effector forces.

Conclusion

Dynamic analysis of mechanisms with serial structures has shown their inertial properties to be upper-bounded by the properties associated with the set of last links spanning the effector's operational space. The effective inertias of a macro-/mini-manipulator are bounded by those of the lightweight mini-manipulator alone.

Treating the manipulator and its mini-manipulator as a single redundant system, a *dextrous dynamic coordination* based on minimizing the deviation from the neutral (mid-range) joint positions of the mini-manipulator has been proposed. In order to eliminate any effect of the forces used to achieve spatial dexterity on the primary task, this minimization uses joint forces selected from a dynamically consistent null space.

The augmented object model presented in this paper constitutes a natural approach for dynamic modeling and control of multi-effector/object systems. In this approach, the control structure only uses the necessary forces, i.e., net force, required to achieve the dynamic decoupling and control of the system. This methodology constitutes a powerful tool for dealing with the problem of object manipulation in multi-arm systems.

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