Decentralized Cooperation between Multiple Manipulators

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Abstract

Mobile manipulation capabilities are key to many new applications of robotics in space, underwater, construction, and service environments. This article discusses the ongoing effort at Stanford University for the development of multiple mobile manipulation systems and presents the basic models and methodologies for their analysis and control. We present the extension of these methodologies to mobile manipulation systems and propose a new decentralized control structure for cooperative tasks. The article also discusses experimental results obtained with two holonomic mobile manipulation platforms we have designed and constructed at Stanford University.

1 Introduction

A central issue in the development of mobile manipulation systems is vehicle/arm coordination. This area of research is relatively new. There is, however, a large body of work that has been devoted to the study of motion coordination in the context of kinematic redundancy. In recent years, these two areas have begun to merge, and algorithms developed for redundant manipulators are being extended to mobile manipulation systems [1][2][3][4].

Typical approaches to motion coordination of redundant systems involve the use of pseudo- or generalized inverses to solve an under-constrained or degenerate system of linear equations, while optimizing some given criterion. These algorithms are essentially driven by kinematic considerations and the dynamic interaction between the end effector and the manipulator's internal motions are ignored.

Our approach to controlling redundant systems is based on two models: an *end-effector dynamic model* [5] obtained by projecting the mechanism dynamics into the operational space, and a *dynamically consistent force/torque relationship* [6] that provides decoupled control of joint motions in the null space associated with the redundant mechanism.

These models form the basis for the dynamic coordination strategy we are implementing on the mobile manipulation platforms. With this strategy, the vehicle/arm system can be viewed as the mechanism resulting from the serial combination of two subsystems: a "macro" structure with coarse, slow, dynamic responses (the mobile base), and a relatively fast and accurate "mini" device (the manipulator).

Another important issue in mobile manipulation concerns cooperative operations between multiple vehicle/arm systems [7][8][9][10][11]. Our research in cooperative manipulation has produced a number of results which provide the basis for the control strategies we are developing for mobile manipulation platforms. Our approach is based on the integration of two basic concepts: The *augmented object* and the *virtual linkage* [12]. The *virtual linkage* characterizes internal forces, while the *augmented object* describes the system's closed-chain dynamics. These models have been successfully used in cooperative manipulation for various compliant motion tasks performed by two and three PUMA 560 manipulators.

While providing accurate description of cooperative manipulation, the *augmented object* and *virtual linkage* models have been implemented in an architecture that requires some level of centralized control, which is not quite suited for autonomous mobile manipulation platforms. The article presents a new strategy based on the *augmented object* and *virtual linkage* models for decentralized cooperative operations between multiple mobile manipulation platforms.

2 Vehicle/Arm Coordination

2.1 Dynamics

The joint space dynamics of a manipulator are described by

$$A(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \Gamma; \qquad (1)$$

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where $\mathbf{q}$ is the n joint coordinates and $A(\mathbf{q})$ is the $n \times n$ kinetic energy matrix. $\mathbf{b}(\mathbf{q}, \dot{\mathbf{q}})$ is the vector of centrifugal and Coriolis joint-forces and $\mathbf{g}(\mathbf{q})$ is the gravity joint-force vector. $\mathbf{\Gamma}$ is the vector of generalized joint-forces.

The operational space equations of motion of a manipulator are [5]

$$\Lambda(\mathbf{x})\ddot{\mathbf{x}} + \mu(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{p}(\mathbf{x}) = \mathbf{F}; \qquad (2)$$

where $\mathbf{x}$, is the vector of the m operational coordinates describing the position and orientation of the effector, $\Lambda(\mathbf{x})$ is the $m \times m$ kinetic energy matrix associated with the operational space. $\mu(\mathbf{x}, \dot{\mathbf{x}})$, $\mathbf{p}(\mathbf{x})$, and $\mathbf{F}$ are respectively the centrifugal and Coriolis force vector, gravity force vector, and generalized force vector acting in operational space.

2.2 Redundancy

The operational space equations of motion describe the dynamic response of a manipulator to the application of an operational force $\mathbf{F}$ at the end effector. For non-redundant manipulators, the relationship between operational forces, $\mathbf{F}$, and joint forces, $\mathbf{\Gamma}$ is

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

where $J(\mathbf{q})$ is the Jacobian matrix.

However, this relationship becomes incomplete for redundant systems. We have shown that the relationship between joint torques and operational forces is

$$\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F} + \left[I - J^T(\mathbf{q})\overline{J}^T(\mathbf{q})\right]\mathbf{\Gamma}_0; \qquad (4)$$

with

$$\overline{J}(\mathbf{q}) = A^{-1}(\mathbf{q})J^T(\mathbf{q})\Lambda(\mathbf{q}); \qquad (5)$$

where $\overline{J}(\mathbf{q})$ is the *dynamically consistent generalized inverse* [6]. This relationship provides a decomposition of joint forces into two dynamically decoupled control vectors: joint forces corresponding to forces acting at the end effector ($J^T\mathbf{F}$); and joint forces that only affect internal motions, $\left([I - J^T(\mathbf{q})\overline{J}^T(\mathbf{q})]\mathbf{\Gamma}_0\right)$.

Using this decomposition, the end effector can be controlled by operational forces, whereas internal motions can be independently controlled by joint forces that are guaranteed not to alter the end effector's dynamic behavior. This relationship is the basis for implementing the dynamic coordination strategy for a vehicle/arm system.

The end-effector equations of motion for a redundant manipulator are obtained by the projection of the joint-space equations of motion (1), by the *dynamically consistent* generalized inverse $\overline{J}^T(\mathbf{q})$,

$$\begin{aligned} &\overline{J}^T(\mathbf{q})\,[A(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{\Gamma}] \\ &\quad\Longrightarrow\quad \Lambda(\mathbf{q})\ddot{\mathbf{x}} + \mu(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{p}(\mathbf{q}) = \mathbf{F}; \end{aligned} \qquad (6)$$

The above property also applies to non-redundant manipulators, where the matrix $\overline{J}^T(\mathbf{q})$ reduces to $J^{-T}(\mathbf{q})$.

2.3 Inertial Property

A mobile manipulator system can be viewed as the mechanism resulting from the serial combination of two sub-systems: a "macro" mechanism with coarse, slow, dynamic responses (the mobile base), and a relatively fast and accurate "mini" device (the manipulator).

The mobile base referred to as the *macro structure* is assumed to be holonomic. Let Λ be the *pseudo kinetic energy matrix* associated with the combined macro/mini structures and Λ_m the operational space *kinetic energy matrix* associated with the mini structure alone.

The magnitude of the inertial properties of macro/mini structure in a direction represented by a unit vector $\mathbf{w}$ in the m-dimensional space can be described by the scalar [6]

$$\sigma_{\mathrm{w}}(\Lambda) = \frac{1}{(\mathbf{w}^T\Lambda^{-1}\mathbf{w})};$$

which represents the effective inertial properties in the direction $\mathbf{w}$.

Our study has shown [6] that, *in any direction* $\mathbf{w}$, *the inertial properties of a macro/mini-manipulator system are smaller than or equal to the inertial properties associated with the mini-manipulator in that direction:*

$$\sigma_{\mathrm{w}}(\Lambda) \leq \sigma_{\mathrm{w}}(\Lambda_m). \qquad (7)$$

A more general statement of this *reduced effective inertial* property is that the inertial properties of a redundant system are bounded above by the inertial properties of the structure formed by the smallest distal set of degrees of freedom that span the operational space.

2.4 Coordination Strategy

The reduced effective inertial property shows that the dynamic performance of a combined macro/mini system can be made comparable to (and, in some cases, better than) that of the lightweight mini manipulator. The idea behind our approach for the coördination of macro and mini structures is to treat them as a single redundant system. High dynamic performance for the manipulated object task (motion and contact forces) can be achieved with an operational space control system using essentially the fast dynamic response of the mini structure[6]. However, given the mechanical limits on the mini structure's joint motions, this would rapidly lead to joint saturation of the mini-structure degrees of freedom.

The *dynamic coordination* we propose is based on combining the operational space control with a minimization of deviation from the midrange joint positions of the mini-manipulator. This minimization must be implemented with joint force control vectors selected from the *dynamically consistent* null space of equation (4). This will eliminate any effect of the additional control forces on the end-effector 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

$$V_{\text{Coordination}}(\mathbf{q}) = k_c \sum_{i=n_M+1}^{n} \left(q_i - \frac{\overline{q}_i + \underline{q}_i}{2} \right)^2 \quad (8)$$

where k_c is a constant gain and n_M is the macro structure's number of degrees of freedom. The gradient of this function

$$\mathbf{\Gamma}_{\text{Coordination}} = -\nabla V_{\text{Coordination}}; \quad (9)$$

provides the required attraction to the mid-range joint positions of the mini-manipulator. The interference of these additional forces with the end-effector dynamics is avoided by projecting them into the null-space of $J^T(\mathbf{q})$. This is

$$\mathbf{\Gamma}_{\text{Null-Space}} = \left[I - J^T(\mathbf{q})\overline{J}^T(\mathbf{q}) \right] \mathbf{\Gamma}_{\text{Coordination}} \quad (10)$$

3 Cooperative Manipulation

3.1 Augmented Object

The *augmented object* model provides a description of the dynamics at the operational point for a multi-arm robot system. The simplicity of these equations is the result of an additive property that allows us to obtain the system equations of motion from the equations of motion of the individual mobile manipulators.

The *augmented object* model is

$$\Lambda_{\oplus}(\mathbf{x})\ddot{\mathbf{x}} + \mu_{\oplus}(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{p}_{\oplus}(\mathbf{x}) = \mathbf{F}_{\oplus} \quad (11)$$

with

$$\Lambda_{\oplus}(\mathbf{x}) = \Lambda_{\mathcal{L}}(\mathbf{x}) + \sum_{i=1}^{N} \Lambda_i(\mathbf{x}); \quad (12)$$

where $\Lambda_{\mathcal{L}}(\mathbf{x})$ and $\Lambda_i(\mathbf{x})$ are the kinetic energy matrices associated with the object and the i^{th} effector, respectively. $\mu_{\oplus}(\mathbf{x}, \dot{\mathbf{x}})$, $\mathbf{p}_{\oplus}(\mathbf{x})$, and $\mathbf{F}_{\oplus}$ also have the additive property.

3.2 Virtual Linkage

Object manipulation requires accurate control of internal forces. Recently, we have proposed the *virtual linkage* [12], as a model of internal forces associated with multi-grasp manipulation. In this model, grasp points are connected by a closed, non-intersecting set of virtual links (Figure 1.)

The relationship between applied forces, their resultant and internal forces is

$$\begin{bmatrix} \mathbf{F}_{res} \\ \mathbf{F}_{int} \end{bmatrix} = \mathbf{G} \begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_N \end{bmatrix} \quad (13)$$

where $\mathbf{F}_{res}$ represents the resultant forces at the operational point, $\mathbf{F}_{int}$ the internal forces and $\mathbf{f}_i$ the forces applied at the grasp point i. $\mathbf{G}$ is called the grasp description matrix, and relates forces applied at each grasp to the resultant and internal forces in the object. Furthermore, $\mathbf{G}$ can be written as

$$\mathbf{G} = [\, \mathbf{G}_1 \mathbf{G}_2 \ldots \mathbf{G}_N \,];$$

where each $\mathbf{G}_i$ represents the contribution of the i^{th} grasp to the resultant and internal forces felt by the object. Also, $\mathbf{G}_i$ can be further decomposed

$$\mathbf{G}_i = \begin{bmatrix} \mathbf{G}_{res,i} \\ \mathbf{G}_{int,i} \end{bmatrix};$$

where $\mathbf{G}_{res,i}$ is the contribution of $\mathbf{G}_i$ to the resultant forces in the object and $\mathbf{G}_{int,i}$ to the internal ones.

The inverse $\mathbf{G}^{-1}$ provides the forces required at the grasp points to produce the resultant and internal forces acting at the object.

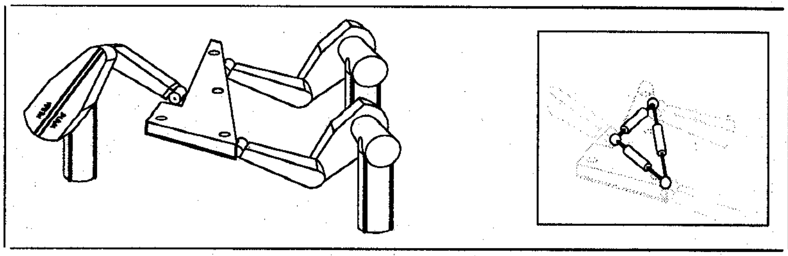

Figure 1: The Virtual Linkage

$$\begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_N \end{bmatrix} = \mathbf{G}^{-1} \begin{bmatrix} \mathbf{F}_{res} \\ \mathbf{F}_{int} \end{bmatrix}. \qquad (14)$$

Similarly, $\mathbf{G}^{-1}$ can be written as

$$\mathbf{G}^{-1} = \begin{bmatrix} \overline{\mathbf{G}}_1 \\ \vdots \\ \overline{\mathbf{G}}_N \end{bmatrix};$$

with

$$\overline{\mathbf{G}}_i = [\, \overline{\mathbf{G}}_{res,i} \;\; \overline{\mathbf{G}}_{int,i} \,];$$

where $\overline{\mathbf{G}}_{res,i}$ represents the part of $\overline{\mathbf{G}}_i$ that correspond to the resultant forces at the object; and the matrix $\overline{\mathbf{G}}_{int,i}$ represents the part corresponding to the internal forces.

3.3 Decentralized Control Structure

For fixed base manipulation, the *augmented object* and *virtual linkage* have been implemented in multiprocessor system using a centralized control structure. This type of control is not suited for autonomous mobile manipulation platforms. Before presenting the decentralized implementation, we begin with a brief summary of the centralized control structure. The overall structure of the centralized implementation is shown in Figure 2.

In a multiple mobile robot system, each robot has real-time access only to its own state information and can only infer information about the other robots' grasp forces through their combined action on the object. In the decentralized control structure we propose, the object level specifications of the task are transformed into individual tasks for each of the cooperative robots. Local feedback control loops are then developed at each grasp point.

The task transformation and the design of the local controllers are accomplished in consistency with the *augmented object* and *virtual linkage* models. The overall structure of the proposed decentralized control structure is shown in Figure 3.

The local control structure at the i^{th} grasp point is

$$\mathbf{f}_i = \mathbf{f}_{motion,i} + \mathbf{f}_{force,i}. \qquad (15)$$

The control vectors, $\mathbf{f}_{motion,i}$, are designed so that the combined motion of the various i^{th} grasp points results in the desired motion at the object operational point. On the other hand, the vectors $\mathbf{f}_{force,i}$ create forces at the grasp points, whose combined action produces the desired contact and internal forces on the object.

The motion control at the i^{th} grasp point is

$$\mathbf{f}_{motion,i} = \hat{\Lambda}_{\oslash,i} \Omega \mathbf{f}^*_{motion,i} + \hat{\mu}_{\oslash,i} + \hat{p}_{\oslash,i}; \qquad (16)$$

with

$$\hat{\Lambda}_{\oslash,i} = \hat{\Lambda}_{g,i} + \overline{\mathbf{G}}_{res,i} \hat{\Lambda}_{\mathcal{L}} \overline{\mathbf{G}}^T_{res,i}; \qquad (17)$$

where $\hat{\Lambda}_{g,i}$ is the kinetic energy matrix associated with the i^{th} effector at the grasp point. The second term of equation (17) represents the part of $\hat{\Lambda}_{\mathcal{L}}$ assigned to the i^{th} robot and described at its grasp point.

The vector, $\hat{\mu}_{\oslash,i}$, of centrifugal and Coriolis forces associated with the i^{th} effector is

$$\hat{\mu}_{\oslash,i} = \hat{\mu}_{g,i} + \overline{\mathbf{G}}_{res,i} \hat{\mu}_{\mathcal{L}}; \qquad (18)$$

where $\hat{\mu}_{g,i}$ is the centrifugal and Coriolis vector of the i^{th} robot alone at the grasp point. $\overline{\mathbf{G}}_{res,i}\hat{\mu}_{\mathcal{L}}$ represents the part of $\hat{\mu}_{\mathcal{L}}$ assigned to the i^{th} robot and described at its grasp point. Similarly, the gravity vector is

$$\hat{p}_{\oslash,i} = \hat{p}_{g,i} + \overline{\mathbf{G}}_{res,i} \hat{p}_{\mathcal{L}}; \qquad (19)$$

where $\hat{p}_{g,i}$ is the gravity vector associated with the i^{th} end effector at the grasp point. $\overline{\mathbf{G}}_{res,i}\hat{p}_{\mathcal{L}}$ represents the part of $\hat{p}_{\mathcal{L}}$ assigned to the i^{th} robot and described at its grasp point.

The sensed forces at the i^{th} grasp point, $\mathbf{f}_{s,i}$, combine the contact and internal forces felt at the i^{th} grasp point, together with the acceleration force acting at

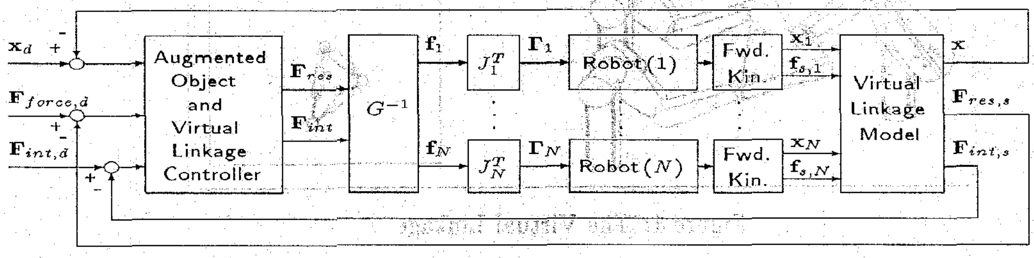

Figure 2: Centralized Control Structure

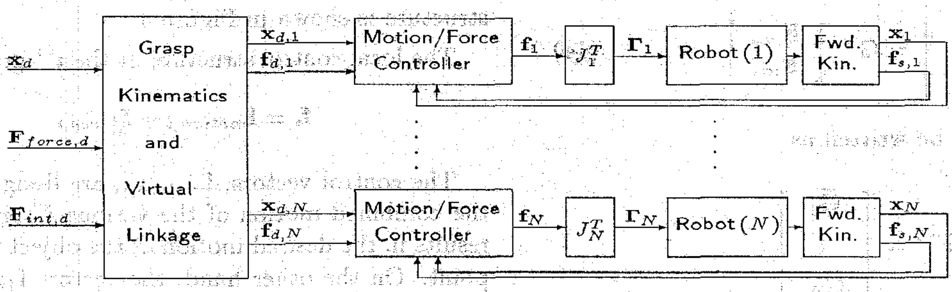

Figure 3: Decentralized Control Structure

the object. The sensed forces associated with the contact and internal forces alone, $\mathbf{f}_{\bar{s},i}$, are therefore obtained by subtracting the acceleration effect from the total sensed forces

$$\mathbf{f}_{\bar{s},i} = \mathbf{f}_{s,i} - \overline{\mathbf{G}}_{res,i}\left(\hat{\Lambda}_{\mathcal{L}}\ddot{\mathbf{x}}_d + \hat{\mu}_{\mathcal{L}} + \hat{p}_{\mathcal{L}}\right). \tag{20}$$

Here, the object desired acceleration has been used instead of the actual acceleration, which would be difficult to evaluate.

The force control part of equation (15) is

$$\mathbf{f}_{force,i} = \hat{\Lambda}_{\oslash i}\mathbf{f}^*_{force,i} + \mathbf{f}_{\bar{s},i}; \tag{21}$$

where $\mathbf{f}^*_{force,i}$ represents the input to the decoupled system associated with the contact forces and internal forces. $\mathbf{f}^*_{force,i}$ can be achieved by selecting

$$\mathbf{f}^*_{force,i} = -\mathbf{K}_f(\mathbf{f}_{\bar{s},i} - \mathbf{f}_{d,i}) - \mathbf{K}_{vf}\mathbf{f}_{\bar{s},i} \tag{22}$$

The vector $\mathbf{f}_{d,i}$ is the desired force assigned to the i^{th} mobile manipulator. Using equation (14), this vector is

$$\begin{bmatrix} \mathbf{f}_{d,1} \\ \vdots \\ \mathbf{f}_{d,N} \end{bmatrix} = \mathbf{G}^{-1}\begin{bmatrix} \mathbf{F}_{res,d} \\ \mathbf{F}_{int,d} \end{bmatrix}; \tag{23}$$

where the desired resultant forces are

$$\mathbf{F}_{res,d} = \overline{\Omega}\mathbf{F}_{contact,d}; \tag{24}$$

where $\mathbf{F}_{contact,d}$ is the desired contact force vector.

The assumptions in the above control structure is that the object is rigid and that there is no slippage at the grasp points. Gripper slip in the real system will result in errors in the grasp kinematic computation and inconsistencies with the *virtual linkage* model. To compensate for these effects, some level of communication between the different platforms will be needed for updating the robot state and modifying the task specifications. The rate at which this communication is required is much slower than the local servo control rate. Such communication can be achieved over a radio Ethernet link (at 10-20 Hz).

4 Experimental Platforms

We have built two autonomous mobile manipulation platforms (Figure 4). These platforms were developed in collaboration with Oak Ridge National Laboratories and Nomadic Technologies. Each platform consists of a PUMA 560 arm mounted on a holonomic mobile base.

The arm is equipped with a 6-axis wrist force sensor and an electric two fingered gripper. The base consists of three "lateral" orthogonal universal-wheel assemblies which allow the base to translate and rotate holonomically [13]. The base houses two PCs, motor amplifiers, and batteries.

The above control strategies have been successfully implemented in the two platforms. Motion and

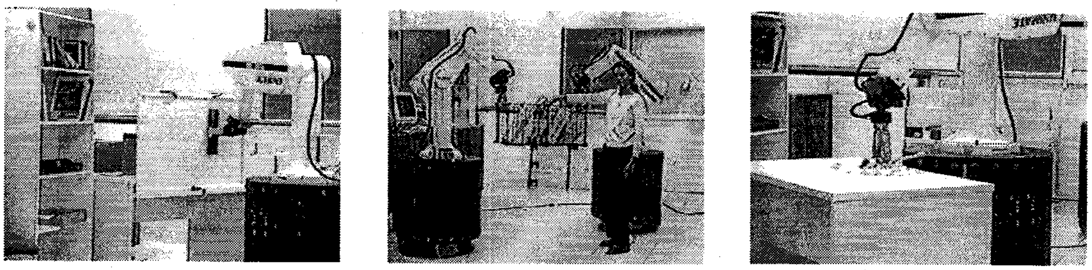

Figure 4: Experiments with the Mobile Platforms

Erasing a whiteboard, cooperating in carrying a basket, and sweeping a desk are examples of tasks demonstrated with the Stanford Mobile Platforms.

force control performance are comparable to results obtained with fixed base PUMA arms.

5 Conclusion

We have presented extensions of various operational space methodologies for fixed-base manipulators to mobile manipulation systems. A vehicle/arm platform is treated as a macro/mini structure. This redundant system is controlled using a dynamic coordination strategy, which allows the mini structure's high bandwidth to be fully utilized. For cooperative operations, we have developed a new decentralized control structure based on the *augmented object* and *virtual linkage* models that is better suited for mobile manipulator systems. Vehicle/arm coordination and cooperative operations have been successfully implemented on two mobile manipulator platforms developed at Stanford University.

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