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Mobile manipulation: The robotic assistant

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Abstract

Mobile manipulation capabilities are key to many new applications of robotics in space, underwater, construction, and service environments. This paper discusses the development of robotic "assistance" capabilities to aid workers in the accomplishment of a variety of physical operations and presents various control strategies developed for vehicle–arm coordination, compliant motion tasks, and cooperative manipulation between multiple platforms. These strategies have been implemented on two holonomic mobile platforms designed and built at Stanford in collaboration with Oak Ridge National Laboratories and Nomadic Technologies. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Coordinated mobility and manipulation; Multiple robot cooperation; Human–robot interaction; Service robotics

1. Introduction

A new field of robotic applications is emerging. Robots are today moving towards applications beyond the structured environment of a manufacturing plant. They are making their way into the everyday world that people inhabit – hospitals, offices, homes, construction sites [1–3], and other such cluttered and uncontrolled environments. While advancing into these new areas, the current generation of service and field robots suffer major shortcomings because of their limited abilities for manipulation and interaction with humans. Their operations are mostly concerned with transportation, and rarely involve more than the simplest manipulation tasks.

The successful introduction of robotics into human environments will rely on the development of competent, practical systems that are dependable, safe, and easy to use. The value of their contribution to the work environment will have to be unquestionable and their task performance as reliable as that of a human worker. Typical operations are composed of various tasks, some of which are sufficiently structured to be autonomously performed by a robotic system, while many others require skills that are still beyond current robot capabilities. Today, these tasks can only be executed by a human worker. The introduction of a robot to assist a human in such tasks will reduce fatigue, increase precision, and improve quality; whereas the human can bring experience, global knowledge, and understanding to the task. The synergy of the human/robot team can greatly increase the overall performance by fully utilizing their complementary abilities in the completion of the task.

Advances towards the challenge of robotics in human environments will depend largely on the full integration of mobility and manipulation. Central to the development of mobile manipulation is vehicle–arm coordination. This area of research is relatively new. There is, however, a large body of work that has

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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 [4–7]. Typical approaches to motion coordination of redundant systems rely on 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 effort in this area has resulted in a *task-oriented* framework for the *dynamic coordination* [8] of mobile manipulator systems. The dynamic coordination strategy we developed is based on two models concerned with the effector dynamic behavior [9], and the robot self-posture description and control. The *effector dynamic behavior* model is obtained by a projection of the robot dynamics into the space associated with the effector task, while *the posture behavior* is characterized by the complement of this projection. To control the two behaviors associated with this decomposition, a consistent control structure is required. Our study revealed a unique control structure that guarantees *dynamic consistency* and decoupled posture control [10], while providing optimal responsiveness at the effector.

Another important issue in mobile manipulation concerns the development of effective cooperation strategies for multiple robot platforms [11–14]. An example of cooperative operations involving multiple vehicle–arm systems in construction tasks is illustrated in Fig. 1. Our earlier work on multi-arm cooperation established the *augmented object* model, describing the dynamics at the level of the manipulated object [15], and the *virtual linkage* model [16], characterizing internal forces. These models provided the basis for an effective control structure for cooperative manipulation skills. For fixed-base robots, cooperative manipulation can be effectively implemented in a centralized control structure, given the easy access to high-rate force sensory feedback in these environments. Access to this feedback is difficult and often impractical for mobile platforms. Addressing this problem, we have developed a decentralized cooperation strategy [8]. With this strategy, cooperative tasks are accomplished in a manner consistent with the *augmented object* and *virtual linkage* models, thereby preserving the overall performance of the system.

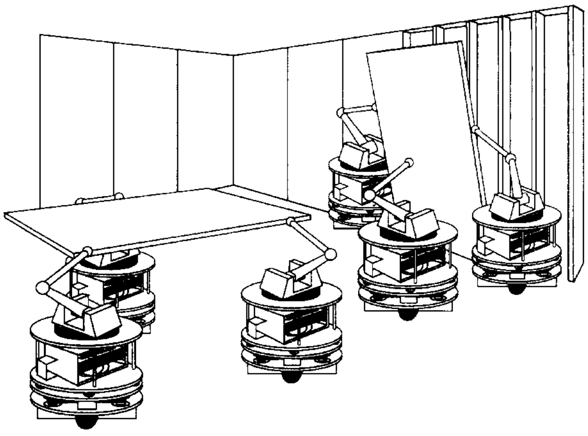

Fig. 1. Robotics in construction: drywall.

A practical robotic assistant must be capable of sufficient level of competence to avoid obstacles during motion. Even when a path is provided by a human or other intelligent planner, sensor uncertainties and unexpected obstacles can make the motion impossible to complete. Our research on the artificial potential field method [17] has addressed this problem at the control level to provide efficient real-time collision avoidance. Due to their local nature, however, reactive methods are limited in their ability to deal with complex environments. Our investigation of a framework to connect real-time collision avoidance capabilities with a global collision-free path has resulted in the *elastic band* approach [18], which combines the benefits of global planning and reactive systems in the execution of motion tasks. Our ongoing investigation in this area has recently lead to a novel approach, the *elastic strip*, which allows the robot's free space to be represented, and more efficiently computed, in its workspace rather than the much higher dimensional configuration space. Details on the elastic strip approach can be found in [19].

The discussion in this paper focuses on the various methodologies developed for the integration of mobility and manipulation, the cooperation between multiple robotic platforms, and the interaction between humans and robots.

2. Integration of mobility and manipulation

A robotic assistant must be able to interact with the environment; grabbing, lifting, pushing, and manipulating objects, while maneuvering to reach, avoid collision, and navigate in its workspace. In addition to the complex kinematic coordination this involves, a full integration of mobility and manipulation must also address the dynamic interactions associated with these two action modalities.

We have developed a general framework for the dynamic coordination and control of vehicle–arm systems. This framework provides the user with two basic task-oriented control capabilities: end-effector task control and platform self-posture control. The major characteristic of this control structure is the dynamic consistency it provides in implementing these two primitives: the robot posture behavior has no impact on the end-effector dynamic behavior. While ensuring dynamic decoupling and improved performance, the resulting control structure provides the user with a higher level of abstraction in dealing with task specifications and control.

The dynamic coordination strategy we developed is based on two models concerned with the effector dynamic behavior, and the robot self-posture description and control. The *effector dynamic behavior* model is obtained by a projection of the robot dynamics into the space associated with the effector task, while the *posture behavior* model is characterized by the complement of this projection. To control the two behaviors associated with this decomposition, a consistent control structure is developed. Our study revealed a unique control structure that guarantees *dynamic consistency* and decoupled posture control, while providing optimal responsiveness at the effector.

We first present the basic models associated with the end-effector and self-posture behaviors. In a subsequent section we present the posture control strategies.

2.1. Effector dynamic behavior

The joint space dynamics of a manipulator are described by

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

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

2.1.1. Non-redundancy

For a non-redundant manipulator the effector dynamic behavior is described by the operational space equations of motion [9]:

$$\Lambda(\boldsymbol{x})\ddot{\boldsymbol{x}} + \mu(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \boldsymbol{p}(\boldsymbol{x}) = \boldsymbol{F}, \tag{2}$$

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

2.1.2. Interaction with the environment

The operational space model provides the foundation for a unified approach to task-level motion and force control. The operational forces are produced by submitting the manipulator to the corresponding joint-forces, using a simple force transformation. The relationship between operational forces, $\boldsymbol{F}$, and joint-forces, $\boldsymbol{\Gamma}$, is

$$\boldsymbol{\Gamma} = J^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{F}, \tag{3}$$

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

The use of the forces generated at the end effector to control motions leads to a natural integration of active force control. In the operational space framework, simultaneous control of motions and forces is achieved by a unified command vector for controlling both the motions and forces at the operational point.

By the nature of coordinates associated with spatial rotations, operational forces acting along rotation coordinates are not homogeneous to moments, and vary with the type of representation being used (e.g., Euler angles, direction cosines, Euler parameters, quaternions). The homogeneity issue is addressed by establishing the end-effector dynamic model in terms of linear and angular velocities and accelerations [9].

Compliant motion and contact operations involve motion control in some directions and force control in the other directions. Such tasks are described by the *generalized selection matrix* Ω and its complement

$\overline{\Omega}$ associated with motion control and force control, respectively [9].

With respect to linear and angular motions, the end-effector/sensor equations of motion can be written as

$$\Lambda_0(\boldsymbol{x})\dot{\vartheta} + \mu_0(\boldsymbol{x}, \vartheta) + \boldsymbol{p}_0(\boldsymbol{x}) + \boldsymbol{F}_{\text{contact}} = \boldsymbol{F}_0. \tag{4}$$

The vector $\boldsymbol{F}_{\text{contact}}$ represents the contact forces acting at the end effector. ϑ is the vector of end-effector linear and angular velocities and $\boldsymbol{F}_0$ is the vector of end-effector forces and moments. The end-effector dynamic decoupling, motion, and active force control is achieved by selecting the control structure

$$\boldsymbol{F}_0 = \boldsymbol{F}_{\text{motion}} + \boldsymbol{F}_{\text{active-force}}, \tag{5}$$

where

$$\boldsymbol{F}_{\text{motion}} = \widehat{\Lambda}_0(\boldsymbol{x})\Omega\boldsymbol{F}^*_{\text{motion}} + \widehat{\mu}_0(\boldsymbol{x}, \vartheta) + \widehat{\boldsymbol{p}}_0(\boldsymbol{x}), \tag{6}$$

$$\boldsymbol{F}_{\text{active-force}} = \widehat{\Lambda}_0(\boldsymbol{x})\overline{\Omega}\boldsymbol{F}^*_{\text{active-force}} + \boldsymbol{F}_{\text{sensor}}, \tag{7}$$

and where $\widehat{\cdot}$ represents estimates of the model parameters.

The vectors $\boldsymbol{F}^*_{\text{motion}}$ and $\boldsymbol{F}^*_{\text{active-force}}$ represent the inputs to the decoupled system. With perfect estimates of the dynamic parameters and perfect sensing of contact forces (i.e., $\boldsymbol{F}_{\text{sensor}} = \boldsymbol{F}_{\text{contact}}$), the closed loop system is described by the following two decoupled sub-systems:

$$\Omega\dot{\vartheta} = \Omega\boldsymbol{F}^*_{\text{motion}}, \tag{8}$$

$$\overline{\Omega}\dot{\vartheta} = \overline{\Omega}\boldsymbol{F}^*_{\text{active-force}}. \tag{9}$$

The above control structure provides a *basic primitive* for object motion and force control. This primitive is parametrized by compliance frames, the operational point, generalized selection matrices, and desired motion and forces.

$$\boldsymbol{F} = \boldsymbol{F}(\text{Operational-Point, Compliant-Frame,}\ \text{Desired-motions, Desired-Forces}).$$

By selecting these parameters appropriately, one can instantiate this basic control model in many different ways to adapt to the needs of specific tasks.

2.2. Vehicle–arm dynamics

An important characteristic of mobile manipulator systems is the macro/mini structure they possess: the "macro" mechanism, with coarse and slow dynamic responses (the mobile base), and the relatively fast and accurate "mini" device (the manipulator). A dynamic coordination strategy that allows full utilization of the mini structure's high bandwidth is essential for achieving effective task performance, particularly in compliant motion operations.

Our study has shown [10] that, *in any direction, the inertial properties of a macro/mini-manipulator system are smaller than or equal to the inertial properties associated with the mini structure in that direction.* A more general statement of this 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. 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 structure. The increase in the responsiveness of the robotic system is achieved by a control structure similar to the controller used in the non-redundant case.

The dynamic behavior at the end effector of a mobile manipulator is obtained by the projection of its joint-space dynamics (1) into operational space

$$\overline{J}^{\mathrm{T}}(\boldsymbol{q})[A(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{b}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \Gamma] \\ \Longrightarrow \quad \Lambda(\boldsymbol{q})\ddot{\boldsymbol{x}} + \mu(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{p}(\boldsymbol{q}) = \boldsymbol{F}, \tag{10}$$

where

$$\overline{J}(\boldsymbol{q}) = A^{-1}(\boldsymbol{q})J^{\mathrm{T}}(\boldsymbol{q})\Lambda(\boldsymbol{q}), \tag{11}$$

$\overline{J}(\boldsymbol{q})$ is the *dynamically consistent generalized inverse*, [10], which minimizes the robot kinetic energy, and

$$\Lambda(\boldsymbol{q}) = [J(\boldsymbol{q})A^{-1}(\boldsymbol{q})J^{\mathrm{T}}(\boldsymbol{q})]^{-1}. \tag{12}$$

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

For redundant robots, the operational space control structure (5) produces joint-motions that minimize the robot's instantaneous kinetic energy. This is essentially accomplished using the fast dynamic response of the mini structure. However, given the mechanical limits on the mini structure's joint-motions, this would rapidly lead to joint-limitations at the mini structure's degrees of freedom.

The integration of mobility and manipulation is based on combining the effector task control with a control of the robot posture through a minimization of a desired posture criterion. However, it is critical for the posture control to be dynamically decoupled from the end effector. This is accomplished by the following decomposition of joint-torques:

$$\boldsymbol{\Gamma} = J^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{F} + N^{\mathrm{T}}(\mathbf{q})\boldsymbol{\Gamma}_{\text{posture}}, \tag{13}$$

with

$$N(\boldsymbol{q}) = [I - \overline{J}(\boldsymbol{q})J(\boldsymbol{q})]. \tag{14}$$

This relationship provides a decomposition of joint-forces into two dynamically decoupled control vectors: joint-forces corresponding to forces acting at the end effector, $J^{\mathrm{T}}\boldsymbol{F}$; and joint-forces that only affect internal motions, $N^{\mathrm{T}}\boldsymbol{\Gamma}_{\text{posture}}$.

Using this decomposition, the end effector can be controlled by operational forces, whereas self-motions can be independently controlled by joint-forces that are guaranteed not to alter the end effector's dynamic behavior.

2.3. *Posture control*

The above decomposition provides the two basic task-oriented control behaviors: end-effector task control and platform self-posture control. The major characteristic of this control structure is the dynamic consistency it provides in implementing these two behaviors: the robot posture behavior has no impact on the end-effector dynamic behavior.

The posture can be for instance controlled by a minimization of the deviation from the mid-range joints of the mini structure. Let $\overline{q}_i$ and $\underline{q}_i$ be the upper and lower bounds on the ith joint position q_i. We construct the potential function

$$V_{\text{mid-range}}(\boldsymbol{q}) = k \sum_{i=n_M+1}^{n} \left(q_i - \frac{\overline{q}_i + \underline{q}_i}{2}\right)^2, \tag{15}$$

where k is a constant gain and n_{M} is the macro structure's number of degrees of freedom. The gradient of this function,

$$\boldsymbol{\Gamma}_{\text{posture}} = -\nabla V_{\text{mid-range}}, \tag{16}$$

provides the required attraction to the mid-range joint positions of the mini manipulator.

Other posture behaviors can be similarly designed. Collision avoidance can be also included in the posture control [19]:

$$\boldsymbol{\Gamma}_{\text{posture}} = -\nabla(V_{\text{desired-posture}} + V_{\text{obstacles-avoidance}}). \tag{17}$$

The interference of these additional forces with the end-effector dynamics is avoided by projecting them into the dynamically consistent null space of $J^{\mathrm{T}}(\mathbf{q})$, i.e., $N^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{\Gamma}_{\text{posture}}$.

With the robot posture behavior presented above, the explicit specification of the associated motions is avoided, since desired behaviors are simply encoded into specialized potential functions for various types of operations of the robotic assistant, e.g., transportation, human cooperation, motion with contact.

3. Cooperative manipulation

The development of effective cooperation strategies for multiple robot platforms is an important issue in mobile manipulation. Our approach to cooperative manipulation is based on the integration of two basic concepts: the *augmented object* [15] and the *virtual linkage* [16]. 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 [16].

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 overall dynamic model from the equations of motion of the individual mobile manipulators. The *augmented object* model is

$$\Lambda_{\oplus}(\boldsymbol{x})\ddot{\boldsymbol{x}} + \boldsymbol{\mu}_{\oplus}(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \boldsymbol{p}_{\oplus}(\boldsymbol{x}) = \boldsymbol{F}_{\oplus}, \tag{18}$$

with

$$\Lambda_{\oplus}(\boldsymbol{x}) = \Lambda_{\mathcal{L}}(\boldsymbol{x}) + \sum_{i=1}^{N} \Lambda_i(\boldsymbol{x}), \tag{19}$$

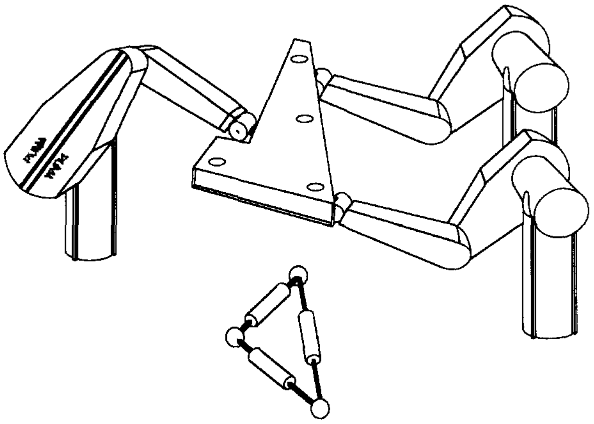

Fig. 2. The virtual linkage.

where $\Lambda_{\mathcal{L}}(\boldsymbol{x})$ and $\Lambda_i(\boldsymbol{x})$ are the kinetic energy matrices associated with the object and the ith effector, respectively. The vectors $\mu_{\oplus}(\boldsymbol{x}, \dot{\mathrm{x}})$ and $\boldsymbol{p}_{\oplus}(\boldsymbol{x})$ also have the additive property.

The generalized operational forces $\boldsymbol{F}_{\oplus}$ are the resultant of the forces produced by each of the N effectors at the operational point:

$$\boldsymbol{F}_{\oplus} = \sum_{i=1}^{N} \boldsymbol{F}_i. \tag{20}$$

The dynamic decoupling and motion control of the augmented object in operational space is achieved by selecting a control structure similar to that of a single manipulator. The dynamic behavior of the augmented object of Eq. (18) is controlled by the net force $\boldsymbol{F}_{\oplus}$. Due to the actuator redundancy of multi-effector systems, there is an infinity of joint-torque vectors that correspond to this force.

3.2. *Virtual linkage*

Object manipulation requires accurate control of internal forces. We proposed the *virtual linkage* [16] 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, as illustrated in Fig. 2 for a three-grasp task.

In the case of an N-grasp manipulation task, a *virtual linkage* model is a $6(N-1)$ degree of freedom mechanism that has $3(N-2)$ linearly actuated members and N spherically actuated joints. Forces and moments applied at the grasp points of this linkage will cause forces and torques at its joints. We can independently specify internal forces in the $3(N-2)$ members, along with $3N$ internal moments at the spherical joints. Internal forces in the object are then characterized by these forces and torques in a physically meaningful way.

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

$$\begin{bmatrix} \boldsymbol{F}_{\mathrm{res}} \\ \boldsymbol{F}_{\mathrm{int}} \end{bmatrix} = \boldsymbol{G} \begin{bmatrix} f_1 \\ \vdots \\ f_N \end{bmatrix}, \tag{21}$$

where $\boldsymbol{F}_{\mathrm{res}}$ represents the resultant forces at the operational point, $\boldsymbol{F}_{\mathrm{int}}$ the internal forces and f_i the forces applied at the grasp point i. $\boldsymbol{G}$ is called the grasp description matrix, and relates forces applied at each grasp to the resultant and internal forces in the object.

3.3. *Decentralized cooperation*

For fixed base manipulation, the *augmented object* and *virtual linkage* have been implemented in a multiprocessor system using a centralized control structure. However, this type of control is not suited for autonomous mobile manipulation platforms.

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. Recently, we have developed a new control structure for decentralized cooperative mobile manipulation [8]. In this structure, 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.

3.4. *Human–robot interaction*

In addition to its ability to perform the autonomous portion of the assistance mission, the robotic assistant must also be capable of interacting and cooperating

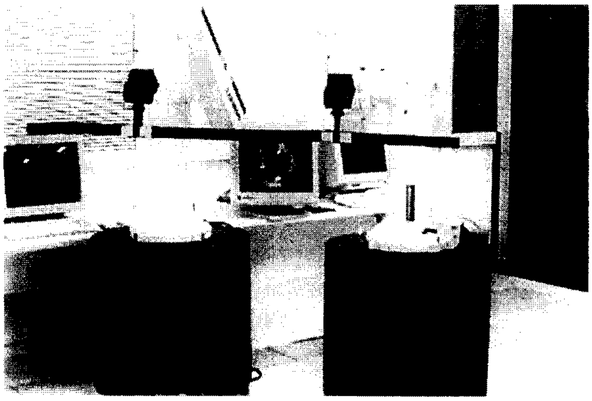

Fig. 3. The Stanford Robotic Platforms.

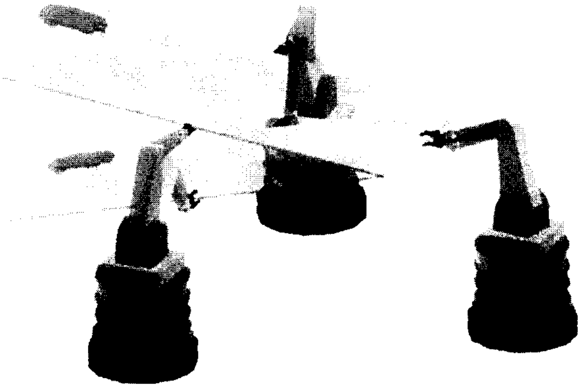

Fig. 4. Human–robot interaction. The human guide, represented by the floating hand, is guiding the board, constrained to rotate only about a specific axis.

with a human. Guided motions involve tight cooperation performed through compliant motion actions, as illustrated in Fig. 4, or "looser" free-space motion commands. The robot, for instance, may support a load while being guided by the human to an attachment, or visually following the guide to a destination. The issues involved in human–robot cooperation have similarities with those associated with multi-robot cooperation. The development of guided-motion primitives is based on the decentralized control behaviors developed for cooperative robots. In the decentralized cooperation discussed above, each robot relies on two models: the "augmented load" that takes into account the inertial properties associated with other robots, and the virtual linkage model associated with the grasp description. The integration of a model of the human arm inertial properties and a description of the human grasp allows the integration of the human factors in these models for effective human–robot cooperation.

4. Experimental platforms

Experimental platforms for the study of the interaction of manipulation with mobility have more complex requirements than those developed for navigation alone. In collaboration with Oak Ridge National Laboratories and Nomadic Technologies, we designed and built two holonomic mobile manipulator platforms, shown in Fig. 3. Each platform is equipped with a PUMA 560 arm, various sensors, a multi-processor computer system, a multi-axis controller, and sufficient battery power to allow for autonomous operation. The base consists of three "lateral" orthogonal universal-wheel assemblies [20] which allow the base to translate and rotate holonomically in relatively flat office-like environments.

The Stanford Robotic Platforms have been used in the implementation and verification of the different strategies discussed above. We have shown vehicle–arm coordination in a variety of manipulation tasks, such as ironing and vacuuming, as illustrated in Fig. 5. We have also demonstrated real-time collision avoidance with coordinated vehicle–arm motion, and cooperative tasks involving operator-directed compliant motion [21].

The dynamic coordination strategy has allowed full use of the relatively high bandwidth of the PUMA. Object motion and force control performance with the Stanford mobile platforms are comparable with the results obtained with fixed base PUMA manipulators.

5. Conclusion

Advances in real-world autonomous robots largely depend on the development of robotic systems that fully integrate mobility and manipulation. We have presented a basic framework for the coordination and control of vehicle–arm systems. This framework provides the user with two basic task-oriented control primitives: end-effector task control and platform self-posture control. The major characteristic of this control structure is the dynamic consistency it provides in

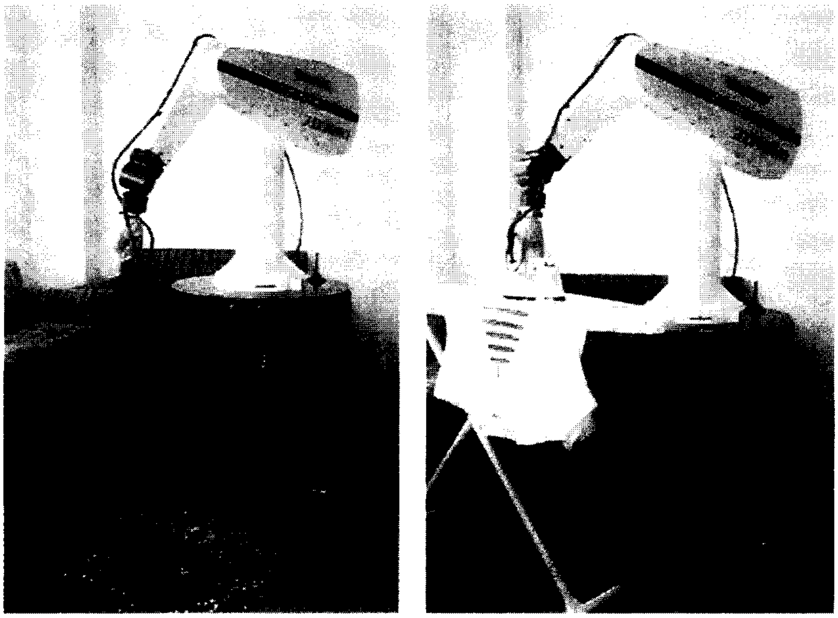

Fig. 5. Experimentals with the Stanford Mobile Platforms. Vacuuming and ironing are examples of tasks demonstrated with the Stanford mobile platforms.

implementing these two primitives: the robot posture behavior has no impact on the end-effector dynamic behavior. While ensuring dynamic decoupling and improved performance, this control structure provides the user with a higher level of abstraction in dealing with task specifications and control. Cooperative operations between multiple platforms rely on the integration of the *augmented object*, which describes the system's closed-chain dynamics, and the *virtual linkage*, which characterizes internal forces. These models are the basis for the decentralized control structure presented in [8]. Vehicle–arm coordination and cooperative operations have been implemented and demonstrated on the two mobile manipulator platforms developed at Stanford University.

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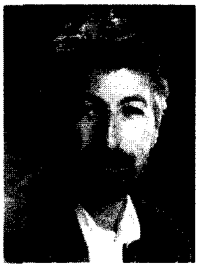

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