Robots in Human Environments

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Abstract

This article discusses the basic capabilities needed to enable robots to operate in human-populated environments for accomplishing both autonomous tasks and human-guided tasks. These capabilities are key to many new emerging robotic applications in service, construction, field, underwater, and space. An important characteristic of these robots is the "assistance" ability they can bring to humans in performing various physical tasks. To interact with humans and operate in their environments, these robots must be provided with the functionality of mobility and manipulation. The article presents developments of models, strategies, and algorithms concerned with a number of autonomous capabilities that are essential for robot operations in human environments. These capabilities include: integrated mobility and manipulation, cooperative skills between multiple robots, interaction ability with humans, and efficient techniques for real-time modification of collision-free path. These capabilities are demonstrated on two holonomic mobile platforms designed and built at Stanford University in collaboration with Oak Ridge National Laboratories and Nomadic Technologies.

1 Introduction

A new field of robotics 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 [6, 22, 23], and other 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 and 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 must be 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 execution of task. During an assistance task, the robot must be capable of performing basic autonomous operations involving both navigation and manipulation. For more elaborate and delicate operations, the assistant, in its supporting role, must be able to interact and cooperate with the human when performing a guided task. The discussion in this article focuses on the basic capabilities needed for manipulation and posture behaviors, cooperation between multiple robots, interaction with the humans, and efficient techniques for real-time collision-free path modifications.

The development of robots in human environments will depend largely on the full integration of mobility and manipulation. Mobile manipulation is a relatively new research area. There is, however, a large body of work 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 [28, 4, 19]. 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

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robot's self motions are ignored.

Our effort in this area has resulted in a *task-oriented* framework for the *dynamic coordination* [14] of mobile manipulator systems. The dynamic coordination strategy we developed is based on two models concerned with the effector dynamics [11] and the robot self-posture behavior. The *effector dynamic behavior* model is obtained by a projection of the robot dynamics into the space associated with the task, while *the posture behavior* is characterized by the complement of this projection. To control these two behaviors, a consistent control structure is required. The article discusses these models and presents a unique control structure that guarantees *dynamic consistency* and decoupled posture control [12], while providing optimal responsiveness at the effector.

Another important issue in mobile manipulation concerns the development of effective cooperation strategies for multiple robots [25, 7, 24, 1, 8]. Our earlier work on multi-arm cooperation established the *augmented object* model, describing the dynamics at the level of manipulated object [15], and the *virtual linkage* model [26], characterizing internal forces. Effective implementation of cooperative manipulation relies on the availability of a high-rate force sensory feedback from the cooperating robots to the controller. While force feedback is easily accessible for multi-arm systems, the access to this data is difficult for mobile platforms. The article presents a *decentralized* cooperation strategy that is consistent with the *augmented object* and *virtual linkage* models, preserving the overall performance of the system.

A robotic system 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 [10] has addressed this problem at the control level to provide efficient real-time collision avoidance. Due to their local nature, however, reactive methods [10, 17, 2, 18] are limited in their ability to deal with complex environments. Using navigation functions [16] the problems arising from the locality of the potential field approach can be overcome. These approaches, however, do not extend well to robots with many degrees of freedom, such as mobile manipulators [5, 29]. Our investigation of a framework to integrate real-time collision avoidance capabilities with a global collision-free path has resulted in the *elastic band* approach [21], which combines the benefits of global planning and reactive systems in the execution of motion tasks. The concept of elastic bands was also extended to nonholonomic robots [9]. The article discusses our ongoing work in this area and presents a novel approach, the *elastic strip* [3], which allows the robot's free space to be computed and represented directly in its workspace rather than in its high-dimensional configuration space. The resulting algorithms are computationally efficient and can easily be applied to robots with many degrees of freedom.

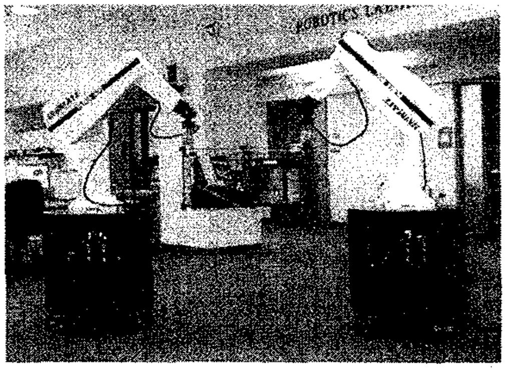

Figure 1: The Stanford Robotic Platforms

The discussion in this article focuses on the various methodologies developed for the integration of mobility and manipulation, the cooperation between multiple robotic platforms, the interaction between humans and robots, and for the real-time modification of collision-free paths. The article also presents the implementation of these developments on the Stanford robotic platforms, shown in Figure 1.

2 Mobility and Manipulation

The ability to interact with the environment is an important capability for robotic systems; grabbing, lifting, pushing, and manipulating objects, while maneuvering to reach, avoid collision, and navigate in the workspace. The control of the two functionalities, mobility and manipulation, must address both their complex kinematic coordination, and their strong dynamic interaction and coupling. Another critical aspect of mobile manipulation dynamics is the higher requirements manipulation tasks have on the robot responsiveness compared with those of mobility.

Mobile manipulator systems share many of the characteristics of macro/mini structures [12]: coarse and slow dynamic responses of the mobile base (the macro mechanism), and the relatively fast responses and higher accuracy of the manipulator (the mini device). Inspired by these properties of macro/mini structures, we have developed a framework for the coordination and control of mobile manipulator systems. This framework provides a unique control structure for decoupled manipulation and posture control, while achieving optimal responsiveness at the effector. This control structure is based on two models concerned with the effector dynamic behavior and the robot self-posture behavior. The *effector dynamic behavior* model is obtained by a projection of the robot dynamics into the space associated with the effector task, and the *posture behavior* model is characterized by the complement of this projection.

We first present the basic models associated with the end effector. In a subsequent section we present the vehicle arm coordination strategy and posture control behavior.

2.1 Effector Dynamic Behavior

The joint space dynamics of a manipulator are described by

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

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

For a non-redundant robot, the effector dynamic behavior is described by the operational space equations of motion [11]

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

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.

Based on this model, the control structure for end-effector dynamic decoupling and motion control is

$$\mathbf{F} = \widehat{\Lambda}(\mathbf{x})\mathbf{F}^{\star} + \widehat{\mu}(\mathbf{x}, \dot{\mathbf{x}}) + \widehat{\mathbf{p}}(\mathbf{x}), \tag{3}$$

where $\widehat{\Lambda}(\mathbf{x})$, $\widehat{\mu}(\mathbf{x}, \dot{\mathbf{x}})$, and $\widehat{\mathbf{p}}(\mathbf{x})$ represent the estimates of $\Lambda(\mathbf{x})$, $\mu(\mathbf{x}, \dot{\mathbf{x}})$, and $\mathbf{p}(\mathbf{x})$. The vector $\mathbf{F}^{\star}$ represents the input to the decoupled system. The generalized joint forces $\mathbf{\Gamma}$ required to produce the operational forces $\mathbf{F}$ are

$$\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F}. \tag{4}$$

where $J(\mathbf{q})$ is the Jacobian matrix. With perfect estimates of the dynamic parameters, the closed loop system is described by the

$$I\ddot{\mathbf{x}} = \mathbf{F}^{\star}.$$

where I is the identity matrix. The use of the forces generated at the end effector to control motions leads to a natural integration of motion and force control [11].

2.2 Vehicle/Arm Dynamics

An important characteristic of mobile manipulator systems is the macro/mini structure they possess. Our study has shown [12] 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 *reduced effective inertial* property is that the inertial properties of a redundant robot 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 states that the dynamic performance of a vehicle/arm system can be made comparable to and, in some cases, better than that of the manipulator arm alone. 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. 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

$$\begin{aligned} &\overline{J}^T(\mathbf{q})\left[A(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{\Gamma}\right] \\ &\quad\Longrightarrow \quad \Lambda(\mathbf{q})\ddot{\mathbf{x}} + \mu(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{p}(\mathbf{q}) = \mathbf{F}; \end{aligned} \tag{5}$$

where

$$\overline{J}(\mathbf{q}) = A^{-1}(\mathbf{q})J^T(\mathbf{q})\Lambda(\mathbf{q}); \tag{6}$$

$\overline{J}(\mathbf{q})$ is the *dynamically consistent generalized inverse*, [12], which minimizes the robot kinetic energy, and

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

In the case of non-redundant manipulators, the matrix $\overline{J}^T(\mathbf{q})$ reduces to $J^{-T}(\mathbf{q})$.

The increase in the responsiveness of the robotic system is achieved by a control structure identical to the one used in the non-redundant case. For redundant robots, this control structure produces joint motions that minimize the robot's instantaneous kinetic energy. As a result, a task at the effector will be carried out by the combined action of the set of joints that possess the smallest effective inertial properties. This gives a prominent role to the arm of a mobile manipulator for performing the effector task. However, typical operations of a mobile manipulator extend much beyond the limited workspace of the arm, giving the mobile base an important role in providing coverage of wide areas of the workspace.

2.3 Posture Control Behavior

The posture, the robot's relative configuration to the mobile base, is key to extending the workspace of a mobile manipulator. An important consideration in the development of posture control behaviors is the interactions between the posture and the effector. It is critical for the effector to maintain its responsiveness and to be dynamically decoupled from the posture behavior. The posture can then be treated separately from the effector task, allowing intuitive task specifications and effective robot control. In our approach, the overall control structure for the integration of mobility and manipulation is based on the following decomposition of joint torques

$$\mathbf{\Gamma} = J^T(\mathbf{q})\mathbf{F} + N^T(\mathbf{q})\mathbf{\Gamma}_{\text{posture}}, \tag{8}$$

with

$$N(\mathbf{q}) = [I - \bar{J}(\mathbf{q})J(\mathbf{q})] \tag{9}$$

This relationship provides a decomposition of joint forces into two control vectors: joint forces corresponding to forces acting at the effector, $J^T\mathbf{F}$, and joint forces that only affect the robot posture, $N^T\mathbf{\Gamma}_{\text{posture}}$. To control the robot for a desired posture, the vector $\mathbf{\Gamma}_{\text{posture}}$ will be selected as the gradient of a potential function constructed to meet the desired posture specifications. The interference of this gradient with the end-effector dynamics is avoided by projecting it into the dynamically consistent null space of $J^T(\mathbf{q})$, i.e. $N^T(\mathbf{q})\mathbf{\Gamma}_{\text{posture}}$.

Collision avoidance can be also integrated in the posture control as discussed in section 4. With this posture behavior, the explicit specification of the associated motions is avoided, since desired behaviors are simply encoded into specialized potential functions for various types of operations. This is illustrated in the simulation results for a 24-degree-of-freedom humanoid system shown in Figure 2, whose task was generated from simple manipulation and posture behaviors.

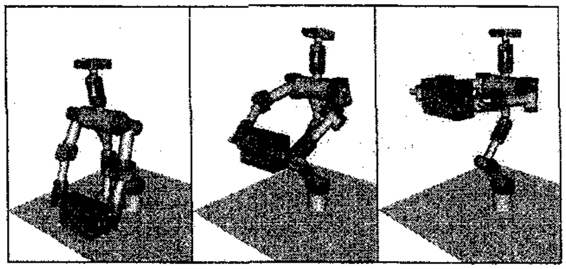

Figure 2: Manipulation and Posture Behaviors: *a sequence of three snapshots from a dynamic simulation of a 24-degree-of-freedom humanoid system, whose task is generated from simple manipulation and posture behaviors.*

3 Cooperative Manipulation

The development of effective cooperation strategies for multiple robot platforms is an important issue for both the operations in human environments and the interaction with humans. Human guided motions may involve tightly constrained cooperation performed through compliant motion actions or less restricted tasks executed through simpler free-space motion commands. Several cooperative robots, for instance, may support a load while being guided by the human to an attachment, or visually following the guide to a destination. In this section, we focus on constrained cooperation between multiple robots and describe our approach for a decentralized strategy for robot cooperation.

Our approach is based on the integration of two basic concepts: The *augmented object* [15] and the *virtual linkage* [26]. 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 fixed-base PUMA 560 manipulators [27]. First we will present these two models and the corresponding cooperation control strategy. The extension to mobile manipulators, presented in a subsequent section, is based on a *decentralized* cooperation strategy that is consistent with the *augmented object* and *virtual linkage* models.

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

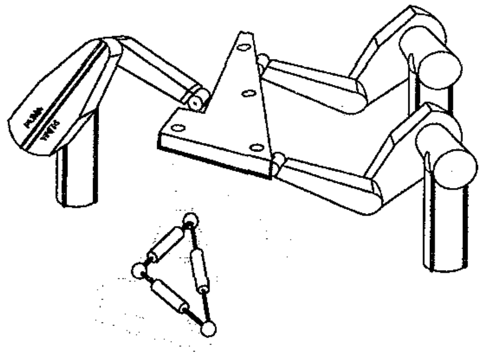

Figure 3: The Virtual Linkage: *for a three-grasp manipulation task, a twelve-degree-of-freedom mechanism (three spherical joints and three prismatic joints) is used to describe the internal forces.*

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

$$\Lambda_{\oplus}(\mathbf{x})\ddot{\mathbf{x}} + \mu_{\oplus}(\mathbf{x},\dot{\mathbf{x}}) + \mathbf{p}_{\oplus}(\mathbf{x}) = \mathbf{F}_{\oplus}; \qquad (10)$$

with

$$\Lambda_{\oplus}(\mathbf{x}) = \Lambda_{\mathcal{L}}(\mathbf{x}) + \sum_{i=1}^{N} \Lambda_i(\mathbf{x}); \qquad (11)$$

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. The vectors, $\mu_{\oplus}(\mathbf{x},\dot{\mathbf{x}})$ and $\mathbf{p}_{\oplus}(\mathbf{x})$ also have the additive property. The generalized operational forces $\mathbf{F}_{\oplus}$ are the resultant of the forces produced by each of the N effectors at the operational point.

$$\mathbf{F}_{\oplus} = \sum_{i=1}^{N} \mathbf{F}_i. \qquad (12)$$

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 equation (10) is controlled by the net force $\mathbf{F}_{\oplus}$. 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 have proposed the *virtual linkage* [26], as a model of object internal forces associated with multi-grasp manipulation. In this model, grasp points are connected by a closed, non-intersecting set of virtual links (Figure 3.) For an N-grasp manipulation task, the *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. By applying forces and moments at the grasp points we can independently specify internal forces in the $3(N-2)$ linear 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

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

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

3.3 Decentralized Control Structure

The *virtual linkage* and *augmented object* models have been successfully used in the cooperative control of two and three fixed PUMA arms. For these fixed-base (non-mobile) robots, the control structure was implemented using a *centralized* control scheme. In a centralized control setup, each arm sends its sensory data to a central controller which then commands the motion of each arm based on information from all the arms in the system. However, this type of control is not suited to the more autonomous nature inherent in mobile manipulation systems, where a *decentralized* control scheme is more appropriate.

For systems of a mobile nature, a *decentralized* control structure is needed to address the difficulty of achieving high-rate communication between platforms. We have developed a new control structure for decentralized cooperative mobile manipulation [14]. 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 [15, 26].

4 Path Modification Behaviors

To perform motion tasks, a robot must combine the abilities of planning motions and executing them. Since a planned motion is based on a priori knowledge of the environment, it is difficult to carry out such a motion when uncertainties and unexpected obstacles are to be considered. Reactive behaviors sought to deal with dynamic environments are, by their local nature, incapable of achieving global goals. Our investigation of a framework to connect real-time collision avoidance capabilities with a global planning system has resulted in a new approach based on the *elastic band* concept [21]. This approach becomes computationally demanding, however, as the dimension of the configuration space associated with the robot increases. the specification of tasks for robots is most naturally done in workspace. Elastic bands, however, represent a path in the configuration space.

The *elastic strip* [3] operates entirely in the workspace. The characterization of free space becomes more accurate in the workspace than that in configuration space, resulting in a more efficient description of trajectories. In addition, by avoiding configuration space computation, the framework becomes applicable to robots with many degrees of freedom. The trajectory and the task are both described in workspace. An elastic strip represents the workspace volume that is swept by the entire robot along its trajectory. The basic idea of the elastic strip is to incrementally modify this workspace volume as if it were elastic, expanding and contracting in order to maintain a short and smooth path. Objects in the environment exert repulsive forces, ensuring a safe distance to obstacles.

To represent the free space associated with the elastic strip, we use a series of three-dimensional spheres in the workspace around some configurations along the elastic strip. A single configuration is covered with a set of such spheres forming a *protective hull* of that configuration. The overlapping protective hulls along the trajectory form an *elastic tunnel*, which represents the local free space along the entire path. This is illustrated in Figure 4, where three consecutive protective hulls cover the trajectory of the robot. The initial and the final configuration are shown. An obstacle is reducing the size of the intermediate protective hull.

An elastic strip can be seen as a grid of links and springs. The internal forces acting on the elastic strip are generated by the virtual springs attached to control points in subsequent configurations along the trajectory. These forces cause the elastic strip to contract, maintaining a constant ratio of distances between every three consecutive configurations. The external forces are caused by a repulsive potential associated with the obstacles.

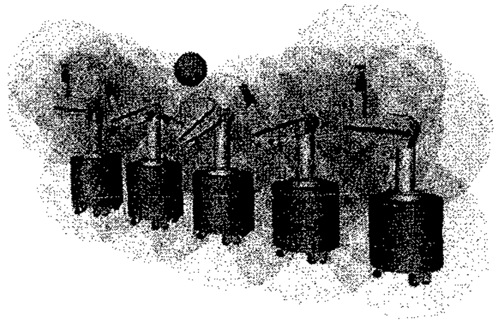

Figure 4: Elastic Tunnel: ***the protective hulls covering a trajectory for the Stanford robotic platforms form an elastic tunnel of free space.***

4.1 Motion Behaviors

Given a planned motion, the elastic strip allows a robot to dynamically modify its motion to accommodate changes in the environment. For a mobile manipulator this modification is not uniquely determined and may be chosen depending on the task. A transportation task for a mobile manipulator, for instance, can be described by the motion of the mobile base, while only a nominal posture of the arm and load are specified. For a manipulation task, the description consists of the motion of the end effector and its contact forces, while only a nominal posture of the mobile base and arm is given. In both cases some degrees of freedom are used for task execution, while others can be used to achieve task-independent motion behavior.

The elastic strip also provides an effective approach for executing partially described task. If only those degrees of freedom necessary for execution have been specified, reactive obstacle avoidance combined with an attractive potential to the desired posture can complete the robot control in real-time. With a partial plan, however, the elastic strip can be subjected to local minima.

The framework for combining motion behavior and task execution relies on the effector/posture control structure discussed above in 2.3. Simple obstacle avoidance behavior can be easily augmented by specifying a desired posture for the robot. This posture can be chosen according to some optimization criterion. This is achieved by selecting

$$\Gamma_{\text{posture}} = -\nabla(V_{\text{desired-posture}} + V_{\text{obstacle-avoidance}}); \tag{14}$$

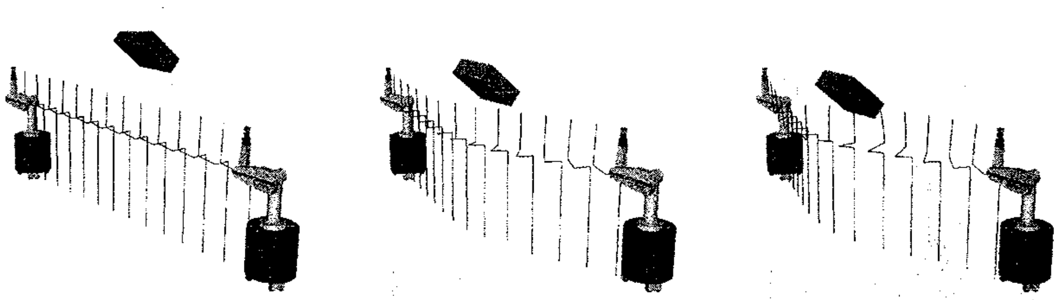

Figure 5: Elastic Strip:*the initial plan for the Stanford robotic platform is incrementally modified by a moving obstacle.*

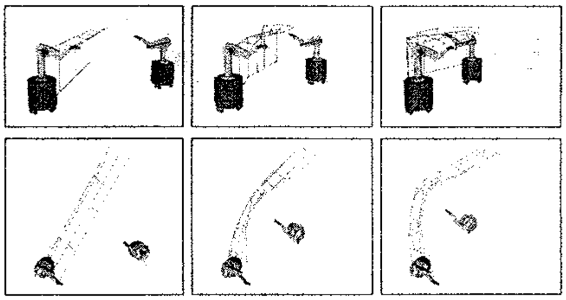

Figure 6: Interaction between the two Platforms: *the elastic strip of the first platform is modified incrementally in order to maintain a valid path while avoiding the second moving platform.*

and projecting these torques in the dynamically consistent null space to guarantee that the posture control torques will not alter the end-effector's dynamic behavior.

An example of the the elastic strip implementation is shown in Figure 5. In this example, all links of the robot are subjected to the moving obstacle. The elastic strip is represented by a set of intermediate configurations, displayed as lines connecting joint frames. The approaching obstacle deforms the elastic strip to ensure obstacle avoidance. As the obstacle moves away, internal forces cause the elastic strip to assume the straight line trajectory.

The elastic strip framework was also implemented and tested on the Stanford robotic platforms. For example, one robot was commanded to perform a straight line motion, while keeping the arm's posture. During the execution of this plan an unforeseen obstacle, the second platform, forces the first robot to deviate from its original plan. Two different perspectives of the simulated modification of the trajectory are shown in Figure 6. A sequence of snapshots from the execution on the real robot can be seen in Figure 7.

Figure 7: Experimental Execution of a Plan: *the path of the first platform is modified in real-time to avoid the second moving platform.*

5 Stanford Robotic Platforms

In collaboration with Oak Ridge National Laboratories and Nomadic Technologies, we designed and built two holonomic mobile manipulator platforms. Each platform is equipped with a PUMA 560 arm, various sensors, two computer systems, 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 demonstrated real-time collision avoidance with coordinated vehicle/arm motion, and cooperative tasks involving operator-directed compliant motion [13].

The Stanford robotic platforms have been also used in a variety of mobile manipulation tasks including ironing, opening a door, and vacuuming, as illustrated in Figure 8. The dynamic strategy for integrated mobility and manipulation discussed above has allowed full use of the bandwidth of the PUMA manipulator. Object motion and force control performance with the Stanford robotic platforms are comparable with the results obtained with fixed base PUMA manipulators.

Figure 8: Experiments with the Stanford Robotic Platforms: *Vacuuming, opening a door, and ironing are examples of tasks demonstrated with the Stanford robotic platforms.*

6 Conclusion

Advances toward the challenge of robotics in human environments depend on the development of the basic capabilities needed for both autonomous operations and human/robot interaction. In this article, we have presented methodologies for the integration of mobility and manipulation, the cooperation between multiple robots, the interaction between human and robots, and the real-time modification of collision-free path to accommodate changes in the environment.

For vehicle/arm coordination and control, we presented a framework that 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 guarantees 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, this control structure provides the user with a higher level of abstraction in dealing with task specifications and control.

For cooperative operations between multiple platforms we have presented a decentralized control structure. This structure relies on the integration of the *augmented object* which describes the system's closed-chain dynamics, and the *virtual linkage* which characterizes internal forces. This decentralized cooperation approach provides the basis for an effective strategy for human/robot interaction.

The notion of an elastic strip encapsulates what must be known about the environment for both executing global motions and adjusting them to dynamic changes and unforeseen circumstances quickly and safely. The generality of this notion makes it the appropriate abstraction at all levels in the control of a team of cooperating robots. An elastic strip represents the workspace volume swept by a robot along a preplanned trajectory. This representation is incrementally modified by external repulsive forces originating from obstacles to maintain a collision-free path. Internal forces act on the elastic strip to shorten and smoothen the trajectory.

Vehicle/arm coordination, cooperative operations, human/robot interaction, and the elastic strip approach have been demonstrated on the mobile manipulator platforms developed at Stanford University.

Acknowledgments

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