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A New Control Structure for Free-Flying Space Robots

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Abstract

The zero-drag nature of space heightens the importance of dynamic effects during manipulation. This is especially true for *redundant* space manipulators, which are often characterized by macro-mini structures and floating bases – characteristics that result in highly dynamic internal motions. This paper discusses the dynamic characteristics of such redundant manipulators and proposes a new approach based on a *dynamically consistent* control decomposition that decouples the control of the end-effector from the control of the internal motions of the robot. The proposed method accurately accounts for the dynamic coupling between the internal motions of the redundant structure and the end-effector. Selection of an appropriate internal motion control scheme enables the robot to assume the form of macro-mini coordination that best supports the particular task to be performed at the end-effector. This is exceptionally useful for space robots, which must assume a large variety of control configurations in order to maximize their array of on-orbit manipulation capabilities. Three sample internal motion control schemes are presented along with simulation results.

1 Introduction

As our presence in space expands, dextrous robots that are capable of handling a wide variety of tasks such as assembly, maintenance, and repair will be needed to reduce astronaut extra-vehicular activity (EVA) hours during routine operations. Such robots must be capable of performing a variety of dynamically complex tasks that are difficult for humans to manage. The recent Endeavor experience in which American astronauts encountered complications while grappling a disabled satellite demonstrates the difficulty that humans have in manipulating objects in a zero-drag, zero-gravity space environment.

The Endeavor mission has highlighted the importance of dynamics in space manipulation. The absence of damping in a zero-drag environment makes dynamic effects much more significant than for manipulation on Earth. Slight force errors at the end-effector due to incomplete characterization of manipulator dynamics can result in poorly managed contact with floating objects and subsequent undamped object rotation and translation. This misapplication may also result in poor tracking during manipulation of objects already acquired.

In addition, space robots must operate from a non-fixed base, and are consequently characterized by much more active dynamics. Redundant manipulators (as are most space robots) will have significant internal dynamics that will couple to the end-effector if not properly compensated for in the internal motion control of the robot. When used alone, kinematics and quasi-static considerations will fail to account for these dynamics. The paper outlines a new method for the control of redundant space robots that addresses this dynamic coupling problem. This method is based on a ***dynamically consistent*** decomposition of the control of *redundant* manipulators.

In the last several years, much of the work in the area of space robotics has centered on manipulator/vehicle coordination and redundancy (Ullman and Cannon 1989; Koningstein, Ullman, and Cannon 1989; Umetani and Yoshida 1989). Developed concurrently with this work has been a large body of generic research on redundant manipulation (Liegois 1977; Fournier 1980; Hanafusa, Yoshikawa, and Nakamura, 1981). More recently, these two fields of work have begun to merge (Papadopoulos and Dubowsky 1991).

For a mechanism involving a large number of degrees of freedom, the dynamic properties and interactive forces of the links of the manipulator become a major concern. Addressing these dynamic issues, our investigation (Khatib 1990) has focused on the analysis of the inertial properties of macro-/mini-manipulators and on the development of general techniques for their coordination and control.

The first major result of our work concerns the magnitude property of the effective inertia of macro-/mini-manipulator systems. Our analysis has shown the effective inertia of a macro-/mini-manipulator system to be less than or equal to the inertia associated with the lightweight mini-manipulator structure.

The second basic result is a new control technique for a dextrous dynamic coordination of macro-/mini-manipulators. In this technique, the vector of control torques, Γ, is expressed as the sum of two control vectors:

$$\Gamma = \Gamma_{\textbf{End-Effector}} + \Gamma_{\textbf{Internal-Motion}}.$$

The first, $\Gamma_{\textbf{End-Effector}}$, acts at the end-effector to provide fast dynamic response while the second, $\Gamma_{\textbf{Internal-Motion}}$, is designed to continuously control the internal configuration of the redundant robot in accordance with some desired criterion (i.e. maximize the mini-manipulator's range of motion, avoid singularities, etc). The dynamic interaction between the above two tasks is eliminated by the use of a dynamically consistent relationship between the joint torques and the end-effector forces. This relationship provides a decomposition of joint torques into two dynamically decoupled control vectors:

$$\Gamma = J^T F + [I - J^T \bar{J}^T]\Gamma_o,$$

where $J^T F$ is the joint torques corresponding to the operational space forces acting at the end-effector, and $[I - J^T \bar{J}^T]\Gamma_o$ is the joint torques that only affect the internal motions of the system. F refers to the operational space control forces acting on the end-effector; Γ_o refers to the desired internal motion control torques intended to resolve the redundancy of the manipulator; and $[I - J^T \bar{J}^T]$ is the null space mapping that ensures that only those components of Γ_o that do not dynamically couple to the end-effector will be incorporated into the control of the manipulator.

$\bar{J}$, the *dynamically consistent generalized inverse*, is defined as $\bar{J}(q) = A^{-1}(q) J^T \Lambda(q)$, where $A(q)$ is the joint space inertia matrix, $J(q)$ is the system Jacobian, and $\Lambda(q)$ is the operational space inertia matrix. $\bar{J}$ is unique because it incorporates inertial, and hence dynamic, information into the null space mapping corresponding to the internal motions of the redundant system.

2 Application to Free-Flying Space Robots

This technique is being incorporated into the control of a free-flying robot prototype developed at the Stanford Aerospace Robotics Laboratory (Ullman, 1989). This robot, shown in Figure 1, floats on an air bearing over a large, flat granite surface plate, simulating to great precision in 2D the zero-drag nature of space. The robot maneuvers by means of cold-gas thrusters, and manipulates free-floating objects with three degree of freedom electrically-actuated manipulators. A simulation of the dynamics of the base and one of the manipulators has been developed. The simulated robot has six degrees of freedom. Since the robot operates in a plane, it has three redundant degrees of freedom.

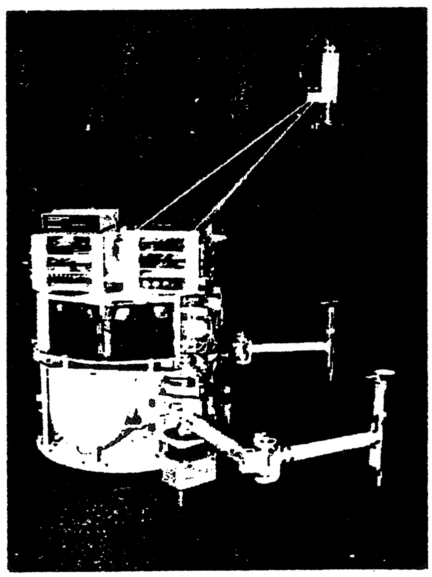

Figure 1: Stanford ARL Free-Flying Space Robot

The following sections summarize the essential features of the proposed method for the control of space robots. First, the section on *Dynamically Consistent Control* motivates the importance of selecting the control of internal motions from a dynamically consistent null space. The second section, *Dynamic Decomposition*, shows the effects of the proposed control decomposition on the dynamics of the end-effector and internal motions. The third section, *Internal Motion Control*, presents three examples of internal motion control schemes. Finally, *End-Effector Control Issues* discusses how to bound the the end-effector during extended motions.

3 Dynamically Consistent Control

The selection of internal motion control torques from a dynamically consistent null space ensures that dynamic coupling will not occur between the internal motions of the manipulator and the end-effector. This selection is achieved via the use of the dynamically consistent generalized Jacobian inverse, $\overline{J}$. This choice of generalized inverse incorporates inertial, and hence dynamic, information into the null space mapping, $[I - J^T\overline{J}^T]$. The control of the manipulator therefore properly accounts for inertial coupling at the end-effector. Any other choice of generalized Jacobian inverse will result in the selection of a different null space, and the dynamics of the end-effector and the internal motions of the system will not be decoupled.

Figure 2 compares control methods that differ in their selection of a generalized Jacobian inverse. The internal motion control of the robot on the left incorporates the dynamically consistent generalized inverse in its null space mapping, while the internal motion control of the robot on the right uses the Penrose Pseudo-Inverse, $J^{\dagger} = J^T(JJ^T)^{-1}$. All other parameters in both the dynamic models and the control algorithms for the robots are identical.
In this example the pair of robots have been instructed to maintain their end-effector in a stationary position while moving their bases quickly (peak velocity at 0.2 m/s). The internal motion requested of the robots during this slew is highly dynamic. As is evident from the time histories in Figure 2, the robot with the dynamically consistent control has no difficulty with this task, while the robot on the right is unable to account for the accelerations that couple to the end-effector.

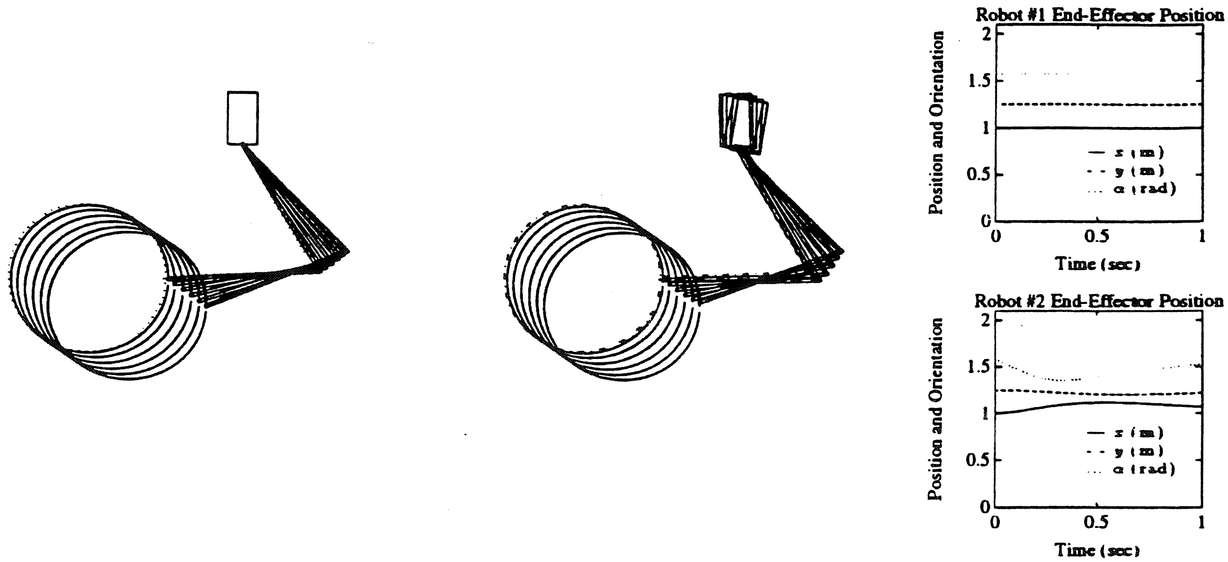

Figure 2: **End-Effector Performance for (a) Dynamically Consistent Internal Motion Control and (b) Kinematic Internal Motion Control**

The redundant space robot under dynamically consistent internal motion control (left) accurately accounts for dynamic coupling at the end-effector when internal motions of the system are excited. The redundant robot on the right, whose internal motion control is only kinematic, fails to account for this dynamic coupling.

For sufficiently static motions, coupling effects are small enough that feedback control may treat them as small, unmodeled nonlinear disturbances. As the dynamic activity of the manipulator increases, however, these nonlinearities exceed the disturbance rejection capabilities of the manipulator and result in unacceptable behavior.

3.1 Dynamic Decomposition

The spectral separation between end-effector and base is illustrated in Figure 3. Upon command, the robot responds to a step response change in the desired location of the end-effector. In this example, where saturation of velocity or acceleration have not yet been added, both the end-effector and base execute ideal second-order responses. The bandwidth of the end-effector, however, is approximately three times higher, and the settling time is accordingly much shorter. In brief, under decoupled control the end-effector is largely free of domination by the slower dynamics of the base for slews that are within the workspace of the base.

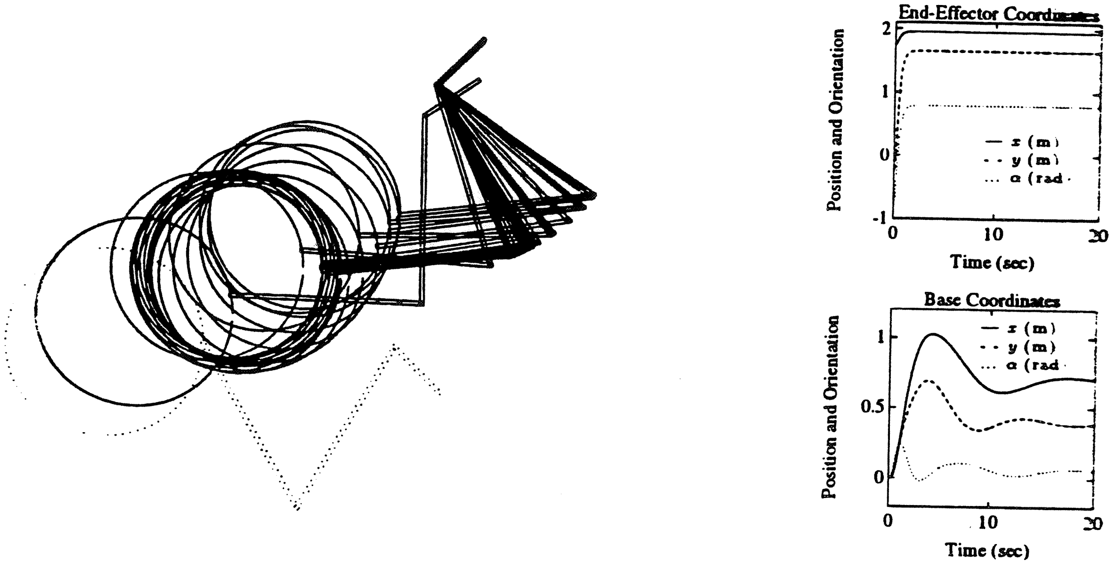

Figure 3: Space Robot Executing Quick End-Effector Slew Under Dynamically Decomposed Control

The dynamic properties of the end-effector are much faster than the dynamic properties of the base. The base has been underdamped to accentuate its slower dynamics.

4 Internal Motion Control

The joint force vector Γ_o may be used to control the behavior of the internal motions of the redundant system in accordance with any number of criteria, such as base (macro) navigation, configuration control, avoidance of obstacles and singularities, minimization of actuator effort, and control of effective inertia at the end-effector. This is achieved by selecting Γ_o as the product of the joint space inertia matrix, A, and the negative gradient of a quadratic potential function of joint angles, $V_{Internal\ Motion}(q)$:

$$\Gamma_o = -A(q)\nabla V_{\text{Internal Motion}}(q).$$

The weighting of the gradient by the inertia matrix is necessary to ensure that the internal motion control torques will be weighted to take into account the inertial properties of the robot.
Interference of these internal motion control torques with the end-effector dynamics is avoided by selecting them from the dynamically consistent null space:

$$\Gamma_{\text{Internal Motion}} = [I - J^T \bar{J}^T]\Gamma_o.$$

Asymptotic stabilization of the internal motions of the redundant mechanism is achieved by also selecting dissipative joint forces from the dynamically consistent null space.
The simulated robot has six degrees of freedom. $\Gamma_{\text{Internal-Motion}}$ will correspondingly have six elements, corresponding to the contribution of each actuator to the internal motion of the robot. As the end-effector control constrains three degrees of freedom by specifying the position and orientation of the last link, the internal motion control can only specify three additional constraints. There are numerous ways in which the joint force vector $\Gamma_{\text{Internal-Motion}}$ can be selected to achieve different types of internal motion behavior. To illustrate the ease with which various types of internal motion control may be implemented, three examples are described below in the context of space robots.

4.1 Macro Navigation

Perhaps the simplest internal motion scheme for a space robot is to impose motion control on the three degrees of freedom corresponding to the base, while damping all of the joints. In this control scheme F specifies the control of the end-effector, while Γ_o specifies the desired control of the base. For example, if $x_{\text{base-desired}}$, $y_{\text{base-desired}}$, and $\alpha_{\text{base-desired}}$ are the desired position and orientation of the base of the robot in inertial space, and q_1, q_2, and q_3 are the actual x, y, and α coordinates of the base in inertial space, one may select the control law

$$\Gamma_o = -A(q)\begin{pmatrix} k_{p_1}(q_1 - x_{\text{base-desired}}) + k_{v_1}(\dot{q}_1) \\ k_{p_2}(q_2 - y_{\text{base-desired}}) + k_{v_2}(\dot{q}_2) \\ k_{p_3}(q_3 - \alpha_{\text{base-desired}} + k_{v_3}(\dot{q}_3) \\ k_{v_4}(\dot{q}_4) \\ k_{v_5}(\dot{q}_5) \\ k_{v_6}(\dot{q}_6) \end{pmatrix}$$

k_{p_1}, k_{p_2}, and k_{p_3}, are the position gains for each joint, and k_{v_1}, k_{v_2}, and k_{v_3}, are the velocity gains. The velocity dependent terms are inserted to add desired damping properties to the system. For this particular control law, only the first three joints are under position control. While the end-effector of the robot will respond to the end-effector control. F, the base of the robot will slew to the desired base position. This location and orientation will be reached perfectly because there are three excess degrees of freedom to position the base without violating the required performance of the end-effector.

4.2 Configuration Control

Similarly, the control law

$$\Gamma_o = -A(q)\begin{pmatrix} k_{v_1}(\dot{q}_1) \\ k_{v_2}(\dot{q}_2) \\ k_{v_3}(\dot{q}_3) \\ k_{p_4}(q_4 - q_{4_{desired}}) + k_{v_4}(\dot{q}_4) \\ k_{p_5}(q_5 - q_{5_{desired}}) + k_{v_5}(\dot{q}_5) \\ k_{p_6}(q_6 - q_{6_{desired}}) + k_{v_6}(\dot{q}_6) \end{pmatrix};$$

will attempt to maintain a particular internal configuration of the robot. It may be desired, for example, to keep the joints bent away from singularities. Configuration control has the additional feature of causing the lower links of the robot – in this case, the base – to follow the end-effector without the need to explicitly plan or specify the location of the lower links in inertial space. The ability to specify the behavior of the internal motions of the system as a function of end-effector behavior is extremely useful for tasks in which the sole function of the macro is to support the end-effector in the most useful manner possible. Numerous extensions are immediate.

4.3 Control of End-Effector Effective Inertia

More sophisticated internal motion control schemes are possible. For example, the internal configuration of the robot may be controlled to modify the effective inertia of the end-effector. The instantaneous effective inertia of the end-effector, Λ, is a function of the configuration of the robot.

In the case of serial macro-/mini-structures, it has been demonstrated that the effective inertia of the mini when mounted on a macro is less than or equal to its effective inertia when mounted on a perfectly massive rigid base (Khatib 1987). Thus by proper management of the configuration of the robot, it is possible to change the effective inertia of the end-effector over a large dynamic range.

Figure 4 shows an example of a robot operation where the reduced effective inertia property is useful. In this figure, the space robot brings an object into contact with a stiff surface. Clearly, it is desirable to have the joints of the arm of the robot bent sharply during contact, with as much of the mass of the robot spread away from the line of action as possible. This configuration will result in a much more compliant end-effector than if the robot made contact with its arm extended.

It is worth noting that the base of the robot is still in the midst of its slow transient response while the end-effector makes contact and maintains a constant contact force. The selection of dynamically consistent internal motion torques ensures that force control at the end-effector will not be degraded by coupling with the lower links.

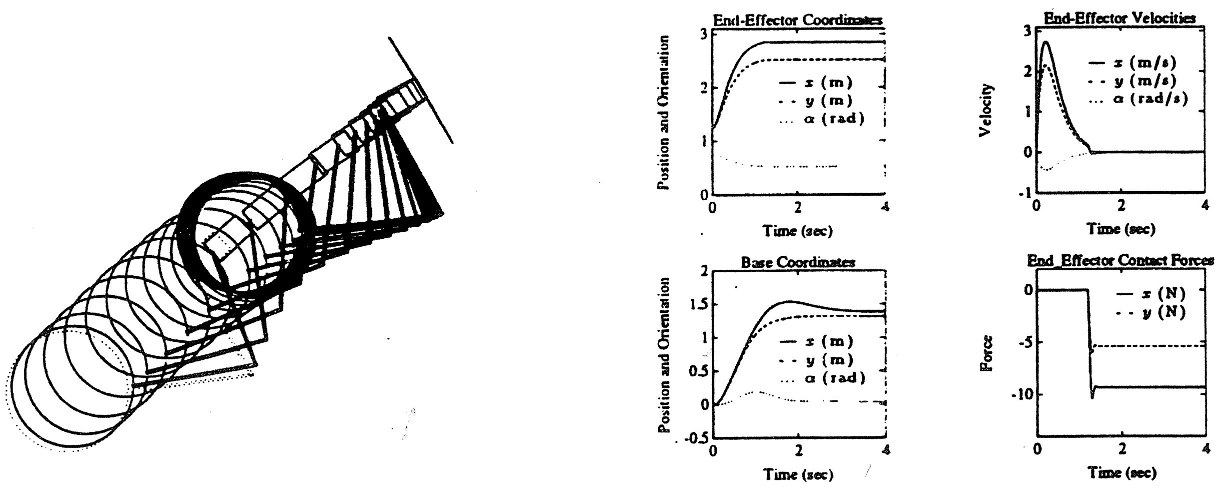

Figure 4: Space Robot Coming Into Controlled Contact with Hard Surface

Decomposition of control permits the end-effector to make compliant contact with a surface and execute high bandwidth, fine control while the much slower base is still in the middle of a transient response. The space robot comes into contact with the surface with the arm bent to increase end-effector compliance (reduce effective inertia and increase bandwidth).

5 End-Effector Control Issues

The addition of a mini-manipulator to a macro-manipulator is desirable because it provides a robot with the high bandwidth and low effective inertia of a lightweight structure while maintaining the large workspace of a more substantial structure. Within a limited range, the end-effector may move very quickly with little concern for the slower dynamics of the macro. During long slews, however, the desired goal location is sufficiently far away that the speed with which the end-effector can approach the goal is largely limited by the speed at which the macro can carry it there.

Measures must be taken to ensure that the end-effector will not outpace the lower links of the robot and extend to singularity. One method is to have the mini simply regulate a standard position in its workspace until the macro moves the mini's workspace over the desired goal location. The mini then snaps into action to acquire the desired target. While this method is functional, it requires the system to execute control logic and switch modes. The dynamic performance of this method also suffers because the end-effector moves very quickly toward the goal within the last few instants of the slew, and then must decelerate quickly to match the velocity of the desired target.

The application of the artificial potential field method (Khatib 1986) to contain the end-effector within some range of the macro can significantly simplify the solution to this problem and improve the dynamic performance. A simple application of this concept for the simulated space robot is illustrated in Figure 5.

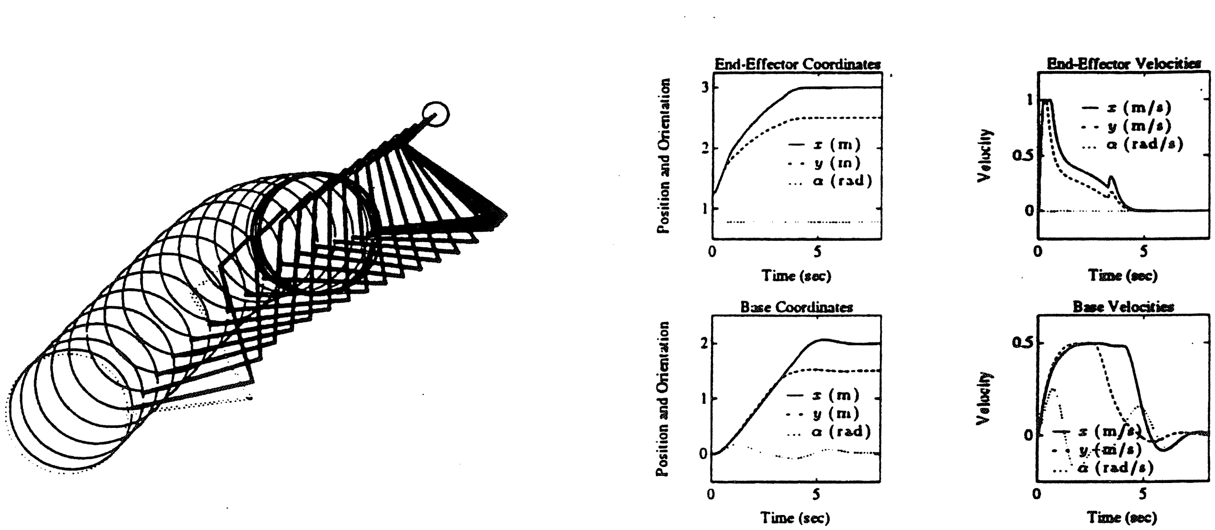

Figure 5: **Space Robot Executing Long Slew**

During long slews, measures must be taken to ensure that the end-effector will not outpace the slower links of the robot. The use of a repulsive potential field at the outer edge of the robot workspace can help to bound the end-effector in a natural and effective manner.

A repulsive potential field has been constructed at a radial distance from the shoulder joint of the robot arm. This repulsive potential field is deadbanded over most of the useful workspace of the mini, so as not to interfere with the performance of the end-effector during local manipulation, but rises steeply near the outer regions of this workspace. Upon introduction of a distant goal location, the end-effector will begin to traverse its available workspace in the direction of the goal. At some distance away from the base of the robot, the attractive potential of the desired goal location on the end-effector will be offset by the repulsive potential designed to bound the range of the end-effector. The internal motion control of the robot, in turn, instructs the lower links (in this case the base) to follow the end-effector at a distance that is smaller than the distance between the end-effector and the base. The result of this control structure is that the end-effector "leads" the base toward the desired goal at the maximum rate the base will permit.

There are several benefits to this control structure. The first is that there is no need to explicitly characterize the range to the target. The second is that the end-effector may demonstrate desirable dynamic behavior during acquisition of the target.

For example, the extension of the arm during the middle portion of the long slew permits the end-effector to decelerate at the end of the slew to a small velocity relative to the target while the base still has significant velocity. The end-effector does not need to acquire the target while in the midst of a sharp dynamic transient. The base velocity is saturated to ensure that it will be capable of decelerating within the distance spanned by the arm.

Other potential fields may be constructed to accommodate additional criteria. For example, the end-effector may require a minimum available bandwidth when it acquires a target. This bandwidth may be directly related to the configuration of the robot (as discussed above) and hence to the maximum allowable extension of the end-effector from the base.

6 Conclusion

A new approach for the dynamic control of redundant, macro-/mini-structures has been applied to the space manipulation problem. With this approach internal motions of the redundant robot are decoupled from the dynamics of the end-effector. The dynamic behavior of the end-effector may then be analyzed independently of the manner in which the redundancy is resolved. The three different internal motion control schemes presented in the paper illustrate the simplicity with which different control schemes can be created to implement different types of manipulation tasks. Lastly, we have presented the use of an artificial potential field to bound the range and improve the performance of the end-effector during extended slews. This methodology is being implemented on Stanford's free-flying robot prototype.

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