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An Operational Space Formulation for a Free-Flying, Multi-Arm Space Robot

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1 Summary

The number of hours of assembly and maintenance required on-orbit to construct and service space-based platforms has highlighted the important role that space robotics must play. Tasks that robots will perform on a future space platform will include assembly, repair, maintenance, and service. While a number of these anticipated tasks may be accomplished by fixed-base, single end-effector manipulators, many more tasks will require robotic systems that possess characteristics such as mobility, multiple arms, autonomy and dexterity.

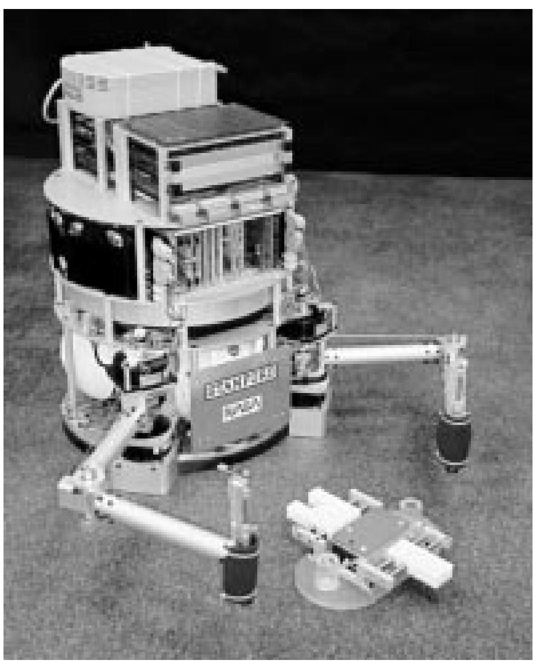

Figure 1: **ARL Free-Flying Space Robot**

The Aerospace Robotics Laboratory at Stanford University has developed experimental platforms to research issues in dynamics and control, advanced manipulation, and high-level control of free-flying, multi-arm space robots. The ARL's facility has three free-flying space robot prototypes, such as that shown in Figure 1, with which it has been conducting experiments in the areas of dynamics and control, advanced manipulation, and assembly. The robots float using a frictionless air bearing over a granite surface plate. Each robot features thrusters and a momentum wheel for locomotion, two DC motor-driven manipulators with pnuematic grippers, force sensing, real-time vision, on-board computation and power, and wireless communications. These platforms provide an excellent environment for the development of mobile, multi-arm space robotic systems.

2 Theoretical Development

Free-flying, multi-arm robotic systems inherently demonstrate dynamic characteristics that are relevant to any application where mobility and multiple end-effectors are combined. Characteristics such as macro-mini coordination, redundancy, and force control are particularly significant. These characteristics are exacerbated by the low-damping environment of space, which can make dynamic effects that are less significant on earth much more important on-orbit.

One issue that is important in the dynamics and control of mobile, manipulation systems is that the performance of the end-effector(s) *in inertial space or relative to a work site, not relative to the manipulator base*, is critical. Especially in the case of free-flying systems, where the dynamic performance of the base of the robot is typically sluggish and inaccurate, it is important to express *the dynamics* as well as the control of the robot in the physical, operational space at the end-effector(s), not in the joint space of the robot. The operational space formulation is a well known method for expressing exactly this, but until recently has only been developed for single end-effector systems. A mobile, multi-arm robot, however, has several end-effectors which are dynamically coupled through a common set of lower links (the base).

A second important issue is the dynamically consistent decomposition and control of the redundancy of the robot. In the low-drag environment of space, kinematic methods of redundancy control that assume acceleration terms to be small begin to suffer from degraded performance. This is especially true of robotic systems with multiple, coupled arms and a mobile base.

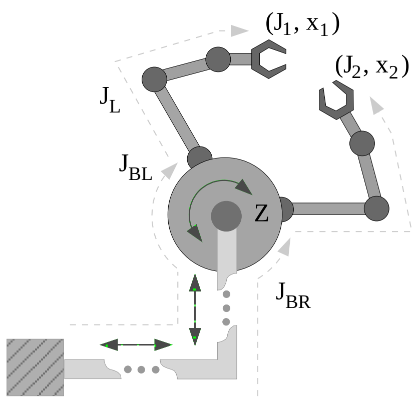

Figure 2: **Model for a Free-Flying, Two-Arm Space Robot**

To address these important dynamic issues, the operational space formulation has been recently extended to this wider class of manipulators, where two or more manipulator chains branch from a common set of lower links or base. The extended operational space formulation incorporates and extends the concepts of dynamically consistent decomposition and control of redundant systems, internal motion control, and augmented object control. The concepts of Unified Motion/Force Control are preserved.

3 Experimental Results

The extended operational space formulation has been experimentally implemented and tested on the ARL free-flying robots. Key theoretical concepts of the framework – such as dynamic decomposition and control of a multi-limb, redundant manipulator; internal motion control; and independent arm control and augmented object control from a mobile base – have been experimentally validated.

In addition, the framework has been modified to address non-ideal space robot characteristics, including unactuated degrees of freedom in the wrist joints and on-off thrusters on the robot base. Unactuated wrist joints introduce constraints on possible torque selections for the robot, while on-off thrusters introduce discrete actuation, underactuation of the base, and deadbands. The impact of these characteristics on redundancy control, dynamic decoupling, and end-effector accuracy will be described and quantified, with suggestions made for future space robot hardware design and control.

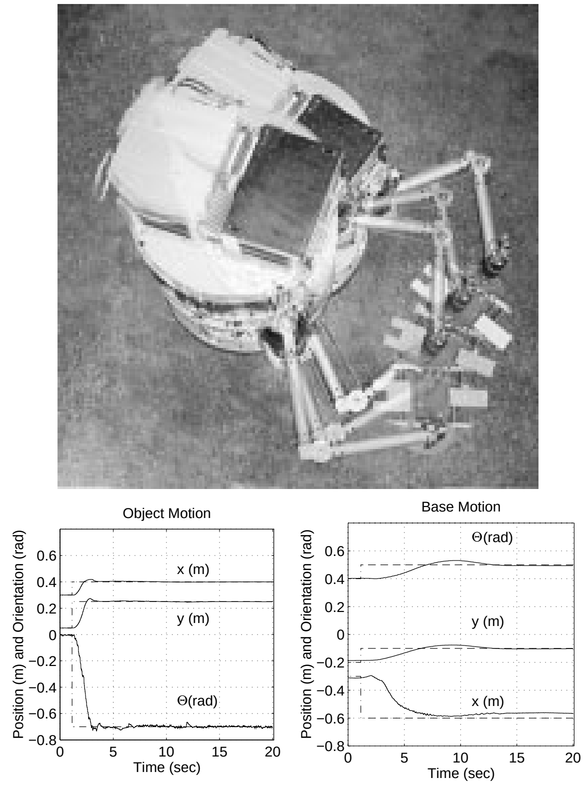

Figure 3: **Slew Under Extended Augmented Object Control**

Figure 3 is an example of the type of results that this paper will use to motivate discussion. The photo at the top of the figure depicts a floating, two-armed robot slewing an object under extended augmented object control. The plots below the photo record the position and orientation history of the object and the robot base, respectively. The robot is able to move the object with nearly ideal behavior, while the robot base continues to move and settle with slower dynamics. These plots simultaneously demonstrate the macro-mini nature of the robot and the level of dynamic decoupling that can be achieved between the object control and the control of the internal motions of the robot.

Video footage of space robots performing in an operational scenario will be presented at the conference.

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