N94- 34036

# HARDWARE INTERFACE FOR ISOLATION OF VIBRATIONS IN FLEXIBLE MANIPULATORS—DEVELOPMENT AND APPLICATIONS*

**Davoud Manouchehri**
**Thomas Lindsay, Ph.D.**
**Rockwell International, Space Systems Division**
**12214 Lakewood Blvd.**
**Downey, CA 90241**

**David Ghosh, Ph.D.**
**NASA Langley Research Center**
**Hampton, VA 23665-5225**

## ABSTRACT

NASA's Langley Research Center (LaRC) is addressing the problem of isolating the vibrations of the Shuttle remote manipulator system (RMS) from its end-effector and/or payload by modeling an RMS flat-floor simulator with a dynamic payload. Analysis of the model can lead to control techniques that will improve the speed, accuracy, and safety of the RMS in capturing satellites and eventually facilitate berthing with the space station.

Rockwell International Corporation, also involved in vibration isolation, has developed a hardware interface unit to isolate the end-effector from the vibrations of an arm on a Shuttle robotic tile processing system (RTPS). To apply the RTPS isolation techniques to long-reach arms like the RMS, engineers have modeled the dynamics of the hardware interface unit with simulation software.

By integrating the Rockwell interface model with the NASA LaRC RMS simulator model, investigators can study the use of a hardware interface to isolate dynamic payloads from the RMS. The interface unit uses both active and passive compliance and damping for vibration isolation. Thus equipped, the RMS could be used as a telemanipulator with control characteristics for capture and berthing operations. The hardware interface also has applications in industry.

## INTRODUCTION

NASA's Langley Research Center and Marshall Space Flight Center (MSFC) have joined forces to study berthing operations between the Shuttle remote manipulator system and Space Station *Freedom* (SSF) by constructing the Coupled, Multibody Spacecraft Control Research Facility at MSFC (Reference 1). This flat-floor test bed is composed of a two-link, three-joint manipulator arm that simulates the RMS and a large, controlled mass that simulates the SSF. The SSF model is equipped with air jets and a torque wheel to simulate the reaction jets and control moment gyro (CMG). Experimental runs on the test bed determined system parameters and natural frequencies. From these parameters, a software model of the flat-floor test bed, generated by Matrix$_X$ software, was validated against the actual performance of the system.

One of the important problems to be solved with this test bed is the isolation of vibrations between the SSF and RMS during berthing operations. The RMS has long, flexible links that are susceptible to unwanted

---

*This work was partially funded by NASA Langley Research Center Contract NAS1-19243 to Rockwell International's Space Systems Division and monitored by Dr. Raymond Montgomery of LaRC Spacecraft Controls Branch.

vibrations. Shuttle, RMS, and SSF motions, as well as force impacts, can induce vibrations. A system that decouples the dynamics between the RMS and SSF can increase the speed, accuracy, and safety of berthing operations.

Rockwell International's Space Systems Division has developed a mechanical interface unit to decouple the dynamics between two coupled systems (Reference 2). Kennedy Space Center (KSC) is developing a robotic device for Shuttle reprocessing operations. After each flight, each tile on the underside of the Shuttle orbiter must be injected with a hazardous fluid that prevents the tiles from absorbing water. Approximately 17,000 of the tiles can be processed by a mobile robotic vehicle that locates each tile, moves into contact, and injects the tile with the rewaterproofing compound. The elevation arm of the robotic tile processing system lifts the end-effector and brings it near the underside of the Shuttle. The Rockwell interface unit then positions a rewaterproofing nozzle in contact with the Shuttle tiles. As the rewaterproofing compound is injected into each tile, the interface unit must maintain the proper force between the nozzle and the tile, regardless of any vibrations the arm may impart to the interface unit. The interface unit uses active and passive compliance and damping to decouple the vibrations of the arm from the nozzle and the Shuttle tile. A Matrix$_x$ software model of the interface unit was developed to test control algorithms and validate interface unit operations under various loading conditions.

As a feasibility study for using the Rockwell interface unit in the LaRC/MSFC flat-floor test bed, Rockwell and LaRC integrated the Matrix$_x$ software simulators of the test-bed facility and the interface unit. Simulations to date show very promising results, and plans are under way to integrate the hardware unit into the test bed. This paper describes the interface unit hardware, the combined Rockwell/LaRC simulator, and results of the simulations. Future plans and applications are also addressed.

## THE ROCKWELL INTERFACE UNIT

The Rockwell interface unit combines one degree of linear actuation (z-direction) with three degrees of passive compliance (linear in the z-direction and rotational about the x- and y-axes). A direct-drive stepper motor with microstepping capability rotates a drive link and connector link that impart motion to the upper platform of the unit. A six-bar linkage is designed to constrain the upper platform to straight-line motion. Springs mounted on the upper platform provide the compliance and a small degree of damping. Mounted on top of the springs, a force/torque sensor sends feedback to the interface unit controller. The payload is mounted to the force/torque sensor. For the RTPS, this payload is the rewaterproofing nozzle. Figure 1 shows the interface unit developed for the RTPS. The total extension length for actuation is 2 inches (49.0mm), and the total travel for the springs is 0.192 inch (4.88mm), allowing for a maximum rotation of 8.40 degrees (0.147 radian). These parameters, as well as the spring constants, are the main variables to be optimized for interfacing with the LaRC/MSFC test bed.

The interface unit developed for the RTPS has been tested under a variety of loading conditions, including vibrations of the interface base while the nozzle is in contact with a solid surface (simulating the Shuttle tile). The interface unit performs quite well and maintains a seal between the nozzle and tile under all operating conditions. However, because the control objectives for the rewaterproofing task differ from the current LaRC/MSFC test-bed operation objectives, a new controller was developed, which is described later.

## INTEGRATION OF SYSTEM MODELS

The LaRC/MSFC flat-floor test bed was modeled by LaRC with Matrix$_x$ software. Similarly, Rockwell modeled its interface unit with Matrix$_x$ software. These two software models were integrated, and the combined models are used to simulate the integrated system. Figure 2 illustrates the location of the interface unit in the combined system.

C-4.

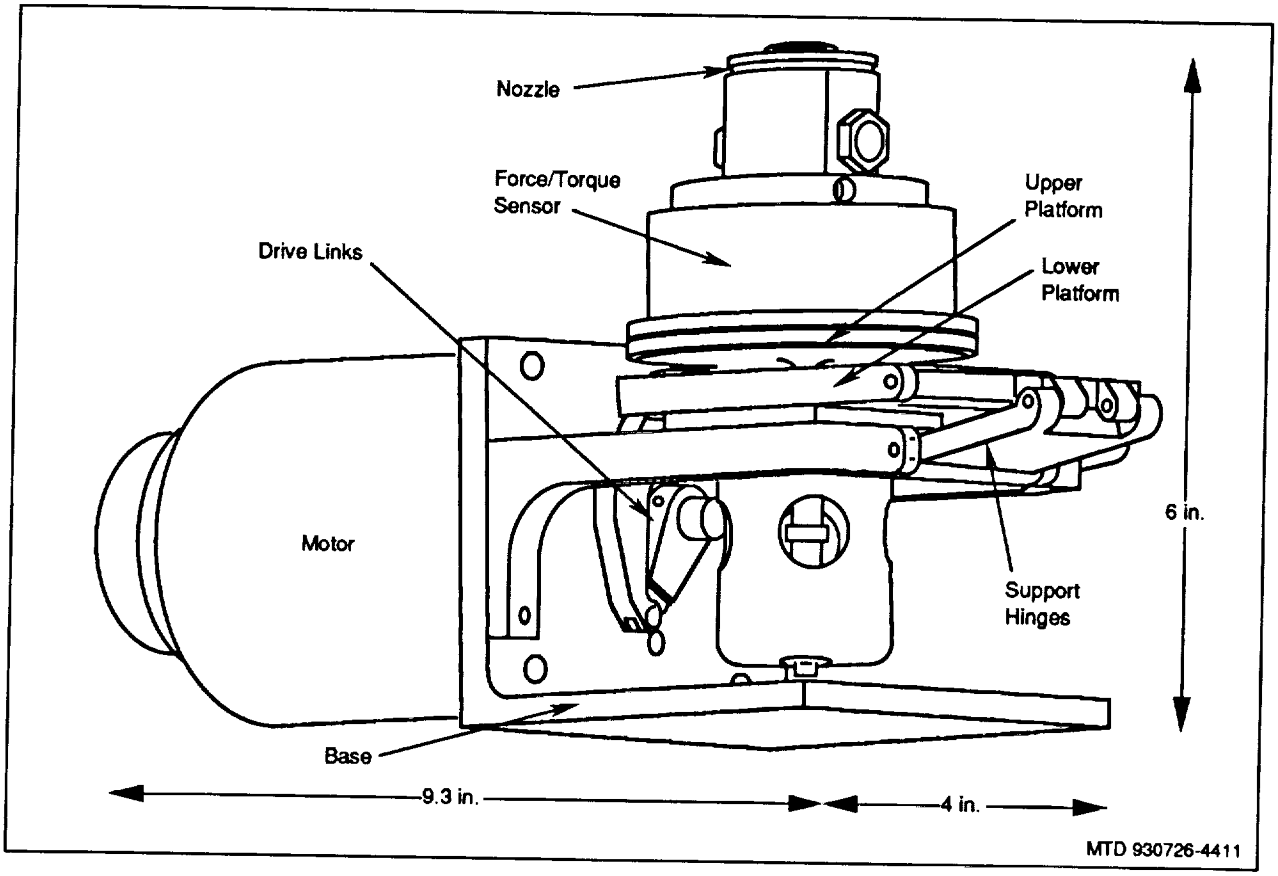

*Figure 1—The Rockwell Interface Unit*

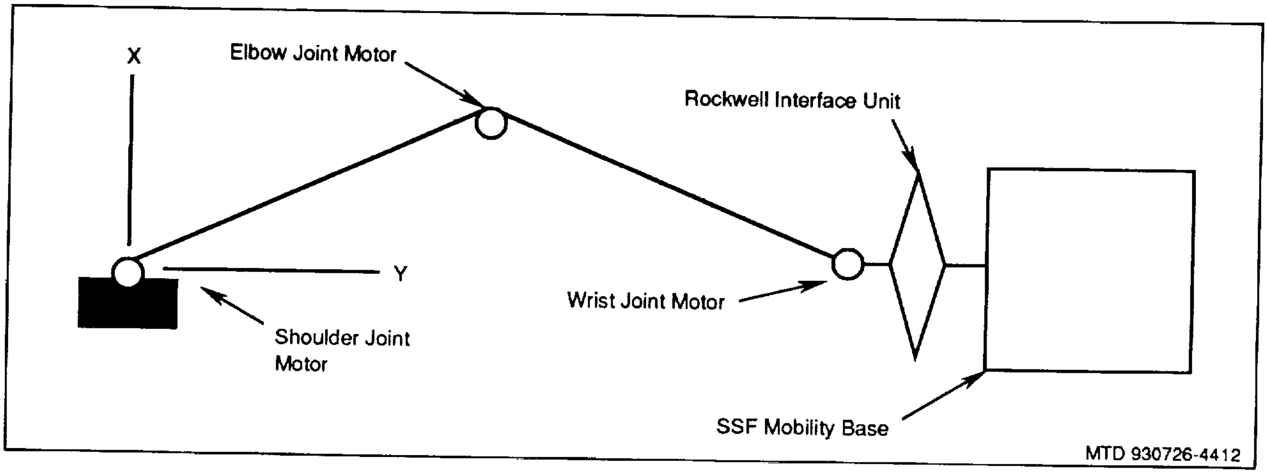

*Figure 2—Combined System Layout*

The LaRC model is composed of a two-link manipulator with three joints (shoulder, elbow, and wrist), including full motor models, gearing, etc., and a controlled payload mass. To increase computation speed, the dynamics of the payload are calculated along with the dynamics of the manipulator links in a software code block. However, to incorporate the Rockwell interface model, the payload mass was split from the arm dynamics. The interface unit was then installed between the arm and payload.

The Rockwell model began as a stand-alone simulator, and the interface unit was modeled in all three dimensions. Data lines to and from the unit were created, and the model was reduced to two dimensions for faster performance in the two-dimensional flat-floor simulator. The interface unit is subjected to a rotational torque from the manipulator wrist motor, as well as the x- and y-motion of the manipulator end-point. The interface unit applies a rotational torque to the payload and to the length of extension. The payload model returns the rotational position and velocity to the interface, and the interface then returns its rotational position and velocity to the wrist motor. The loading force is also returned from the interface unit to the manipulator arm. Internally, the interface controller responds to the force sensed by the force/torque sensor to control the length of extension.

## CONTROL STRUCTURE

The interface unit controller is the most important subject in the ongoing project. One major issue to be resolved is the nature of the control objectives. The first iteration of the interface controller is an attempt to meet two objectives: to minimize the force sensed at the interface and to maintain the position of the interface near its center position. For this controller, only direct readings of the force at the interface and the extension of the interface are needed.

$$\begin{aligned} vel_c &= -F_{f/t} * pgain_f + pgain_p * ((z_{mid}/(z_{max} - z))^2 - 1.0) \quad \text{if } z > z_{mid} \\ &= -F_{f/t} * pgain_f + pgain_p * ((z_{mid}/(z - z_{min}))^2 - 1.0) \quad \text{if } z \le z_{mid} \end{aligned} \tag{1}$$

$$pgain_f = gain * (z_{mid} - |z - z_{mid}|)/z_{mid} \tag{2}$$

where

$vel_c$ = commanded rotational velocity to interface unit motor

$F_{f/t}$ = z-force from force/torque sensor

$z$ = current extension of interface unit

$pgain_f$ = proportional gain for force feedback

$pgain_p$ = proportional gain for position feedback

$z_{mid}$ = middle position for actuator

$z_{max}$ = maximum extension for actuator

$z_{min}$ = minimum extension for actuator

Toward the extremes of the actuator motion, the effect of a load force diminishes, while the command to restore the central position increases. A steady load force causes the unit to maintain an off-center equilibrium point.

This control algorithm meets two control objectives: attempt to zero out load forces while attempting to maintain a center equilibrium position. These objectives could provide good performance characteristics for many operations. However, meeting other control objectives may become important. For example, if the manipulator arm performance degrades only for certain load-force frequencies, it may be beneficial to scan sensor inputs for these frequencies and attempt to isolate or damp only these problem frequencies. As another example, monitoring the sensor inputs to determine the load impedance would allow the controller to adapt its gains to either match or mismatch the impedance, depending on the goals of the operation. As a final example, a capture operation may require the interface unit to first comply completely with load forces but then slowly attempt to damp out any vibrations while stiffening the actuator until it finally becomes locked. The most useful interface unit would be completely self-contained, requiring no operator input. However, for different operations it may be necessary to switch manually between control modes.

## SYSTEM SIMULATION

The results presented here are from the combined system using the first-iteration controller, as described above. The combined system is compared with the original LaRC simulator model without an interface unit. The results are extremely promising.

An example run is shown in Figure 3. In it, the manipulator arm is fully extended in the x-direction (all joint angles initially zero). The joint 3 motor is commanded with a step torque of 100 N•m for 2 seconds, a step torque of -100 N•m for 2 seconds, and then a zero input for 4 seconds. Figure 4 compares the resultant joint angles for the system with and without the interface unit. Joints 1 and 2 are free to rotate, and the results indicate that these joints are much less affected by the motion of the payload with the

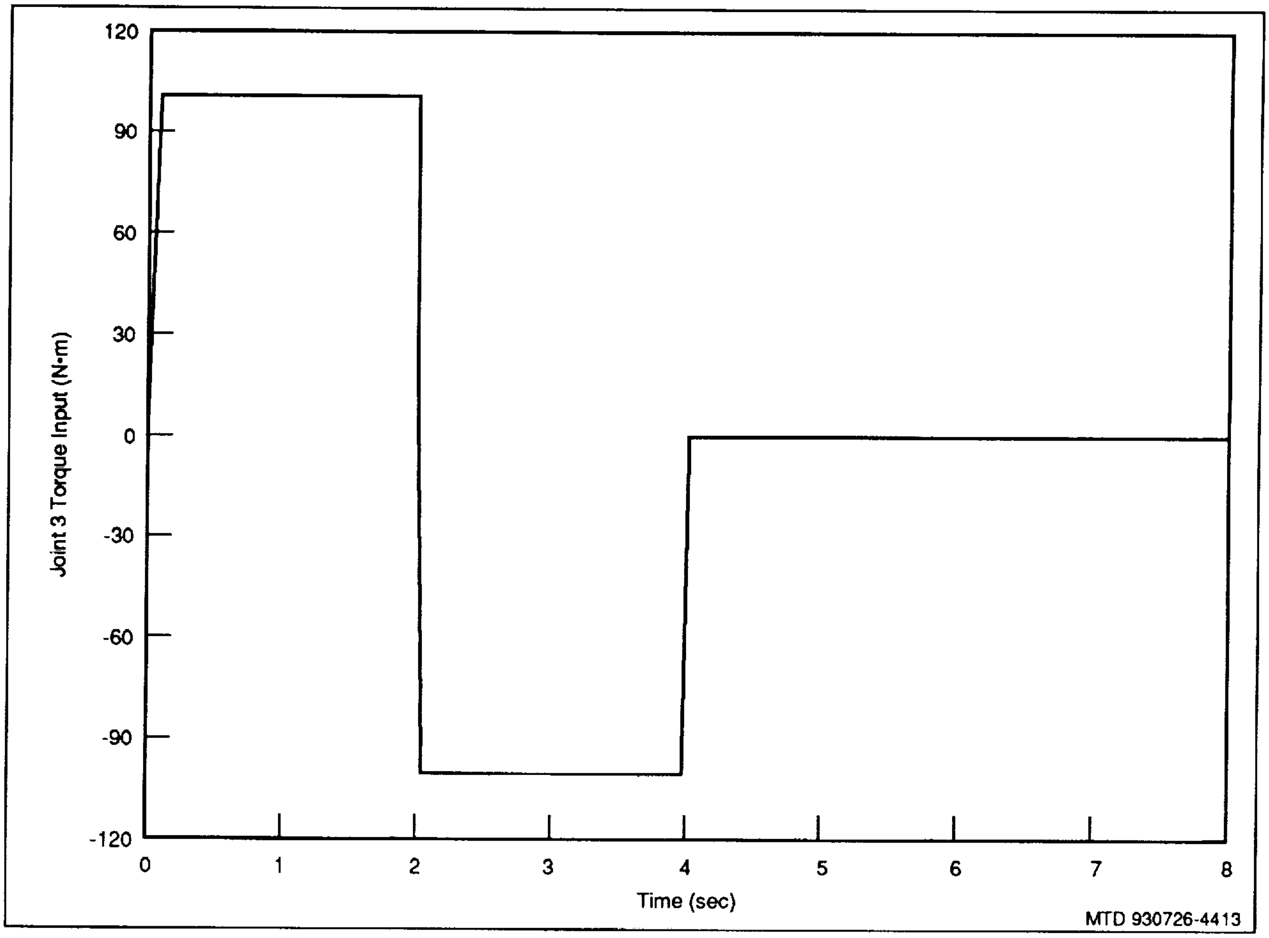

*Figure 3—System Input*

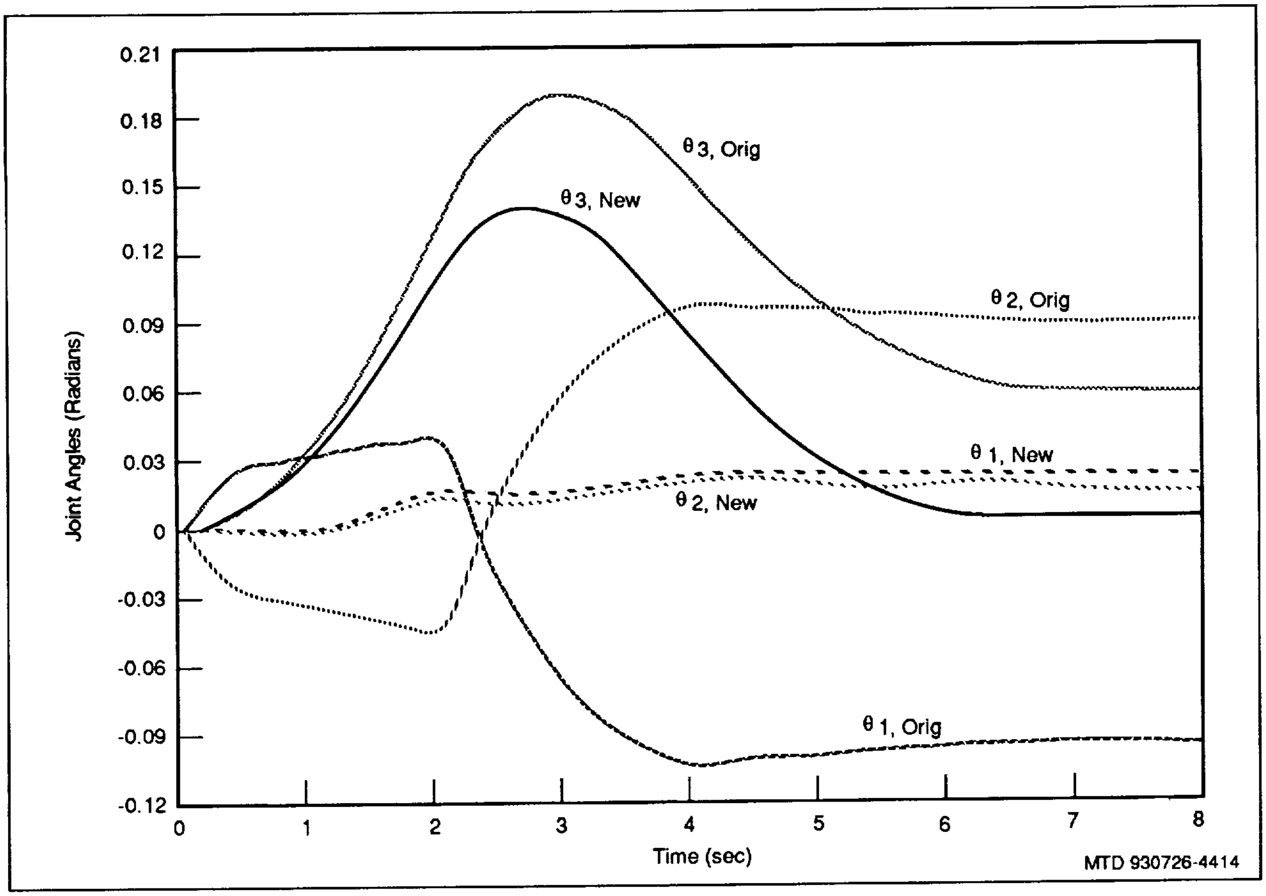

*Figure 4—System Response Comparison*

interface unit than without. Joint 3 is also less affected by the inertial movement of the payload with the interface unit.

## CURRENT AND FUTURE WORK

The software model is currently being updated through the use of a combined dynamic software code structure. This will make the combined model more dedicated to the current task but should increase the computational speed of the simulator and the sensitivity of the simulator to numerical integration instabilities.

The interface unit is being redesigned for integration into the LaRC/MSFC test bed. New control structures are being implemented in the simulation model and then tested with the existing interface unit. An integrated test will soon be performed in the LaRC/MSFC test bed. The results will be used to validate the software simulation and to iterate the interface design for a unit to be permanently integrated into the test bed. Positive results from the test bed unit will prompt the design of a prototype unit for testing on Shuttle missions.

## APPLICATIONS

The utility of the interface unit on the Shuttle RMS is evident from the above discussions. However, similar vibration isolation/control and dynamic system decoupling are also needed for other applications of long manipulator arms, including Department of Energy waste cleanup as well as industrial uses. The device may also prove beneficial for reducing vibrations and impact forces in devices with less accurate control, such as cranes and winches. The implementation of a passive or near-passive interface device for these applications will improve system performance without intelligent human interaction or advanced system control techniques. Further space applications of the device include isolation of antennas and solar panels from a satellite and isolation of payloads from Shuttle vibrations during ascent flight.

## REFERENCES

1. Montgomery, Raymond, Tobbe, Patrick, Weathers, John, Ghosh, Dave, and Garrison, James, "A Testbed for Research on Manipulator-Coupled Active Spacecraft," to appear in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Monterey, California, August 9-11, 1993.

2. Manouchehri, Davoud, Hansen, Joseph, Wu, Cheng, Yamamoto, Brian, and Graham, Todd, "Robotic End-Effector for Rewaterproofing Shuttle Tiles," *Proceedings of the SPIE OE/Technology '92 Conference*, Boston, Massachusetts, November 15-20, 1992.

# Session R7: ROBOTIC OPERATIONS: SPACE TERRESTRIAL

---

Session Chair: Mr. Charles Shoemaker