➤ M. Nahon
➤ C. Damaren
➤ A. Bergen
➤ J. Goncalves

A Test Facility for Multi-armed Space-based Manipulators

ABSTRACT

■ Canada's planned contribution to the International Space Station entails the design, testing, and construction of the Mobile Servicing System (MSS). The robotic components that constitute the MSS can only undergo limited testing prior to launch due to the Earth's gravitational field, and it is therefore difficult to ensure *a priori* that the system will perform well in space. At the University of Victoria, a facility has been constructed to allow testing of a planar robotic system with no gravitational effects. The facility consists of two arms, each with three degrees of freedom, supported by air pads on a glass-topped table. One arm is powered by high-torque variable reluctance brushless servomotors used in a direct-drive configuration, while the second arm utilizes brushed DC motors with harmonic drives. The motor controllers allow position, velocity, or torque setpoints to be commanded. The links of the arms are interchangeable and can be rigid or flexible. High-accuracy position sensing is included at each joint, and the flexible links are equipped with resistive strain gauges, thereby allowing the determination of the state of the arm at all times. The modularity of the system allows a wide range of experiments to be performed, and some of these are described. Future enhancements to the facility will include more sensors and the addition of a small rigid manipulator on the end of one of the existing arms.

RÉSUMÉ

■ La contribution prévue du Canada à la station spatiale internationale comprend la conception, l'essai et la construction du système d'entretien mobile (SEM). Les éléments de robotique qui constituent le SEM ne peuvent subir qu'un nombre limité d'essais avant le lancement en raison du champ gravitationnel de la terre et il est donc difficile d'assurer *a priori* que le système fonctionnera bien dans l'espace. À l'université de Victoria, on a construit une installation pour permettre l'essai d'un système robotique planaire sans effets gravitationnels. Cette installation comprend deux bras qui ont chacun trois degrés de liberté et qui sont supportés par des tampons pneumatiques sur une table recouverte de verre. L'un de ces bras est ac-

➤ Department of Mechanical Engineering, University of Victoria, Victoria, British Columbia, Canada

INTRODUCTION

Construction of the International Space Station is presently scheduled to begin in 1997. One of the first elements to be launched will be Canada's contribution to the project: the Mobile Servicing System (MSS), since it will be used to help assemble the station. In the longer term, the MSS will be used to perform maintenance tasks on the station and to repair satellites. Two of the principal elements of the MSS are shown in **Figure 1**: the long Space Station Remote Manipulator System and the two-armed Special Purpose Dextrous Manipulator[1] — both state-of-the-art robotic devices. Other space robotic systems are planned in the U.S.[2] and Japan[3], though some of these projects have been scaled back lately.

Among the difficult problems facing designers of these systems will be the paucity of means to evaluate their numerical models and planned control techniques. Because of the lightweight design inherent in space-based robots, they cannot be tested on Earth since they are unable to support their own weight. This has created a need for test facilities that will allow the concepts to be evaluated. In answer to this, a number of facilities have been built in Canada, Japan, Europe, and the U.S., which allow for testing of at least certain aspects of space robots. These can be conveniently partitioned into three categories:

- Systems that mimic the kinematic arrangement of space robots but are subject to gravitational effects.[4,5,6] These systems are useful for verifying kinematic control. However, since they are dominated by gravitational effects, these systems cannot incorporate the dynamic behaviour that would be characteristic of a robot operating in space.
- Systems designed to operate in a plane perpendicular to gravity[7,8] allow the incorporation of dynamic behaviour similar to that in space, but cannot be used to investigate the characteristics of motion in 3-D.
- Neutrally buoyant underwater systems, such as the one at University of Maryland,[9] allow three-dimensional motion with no gravitational effects. However, the dynamics of such a system would be substantially different from a space-based system due to viscous frictional effects of the water.

The reader is directed to a comprehensive existing overview of Earth-based space simulation facilities[10] for further information on the variety of facilities in existence.

tionné par des servomoteurs à couple élevé, sans balais et à réluctance variable dans une configuration à entraînement direct. Le second bras utilise des moteurs c.c. à balais et à réducteur à planétaire. Les contrôleurs de moteur permettent de commander la position, la vélocité ou les points de réglage de couple. Les liaisons des bras sont interchangeables et peuvent être rigides ou flexibles. Chaque articulation comprend une détection de position de haute précision et les liaisons flexibles comportent des extensomètres relatifs qui permettent de déterminer la position du bras à n'importe quel moment. La conception modulaire du système se prête à une grande variété d'expériences possibles dont certaines sont décrites. Par la suite, on pense pouvoir ajouter davantage de détecteurs et un petit manipulateur rigide au bout de l'un des bras existants.

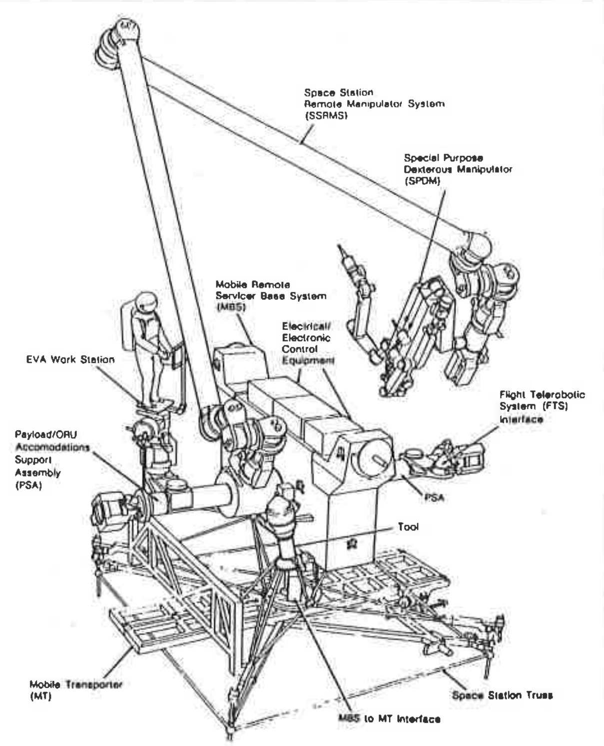

Figure 1.
The Mobile Servicing System (MSS).

The experimental facility discussed in this paper is of the second type. It was designed to allow the verification of numerical models of structurally flexible and co-operating manipulator systems, which we have already developed, and to evaluate new methods for the control of these systems. In particular, it is intended that this facility will allow us to validate general (3-D) dynamics simulation programs for motion in a plane, and that these programs will then in turn be used as design tools for the more complex 3-D systems. The facility is modular and allows a wide variety of experiments to be performed, reflecting the interests of a number of researchers.

The facility (**Figure 2**) consists of two planar three-degree-of-freedom manipulators supported on air bearings on a large 2 m by 4 m glass-topped table. Each manipulator is anthropomorphic — with a 'shoulder,' an 'elbow,' and a 'wrist' — but is constrained to move in a plane. Each joint is driven by a rotary electric motor. The arms are asymmetric in that one arm is driven by high-torque, low-friction servomotors in a direct-drive configuration, while the second arm is constructed using more conventional DC servomotors with harmonic drives. Both motor types can be easily driven with position, velocity, or torque commands, thereby allowing the use of a broad range of control techniques. The asymmetric design will allow the evaluation of various control strategies with significantly different actuation techniques for space-based applications.

Two long links interconnect the three joints on each arm, yielding an inter-joint separation of about 0.75 m. The link characteristics can be altered by changing their properties (mass, stiffness, length, for example). A full complement of rigid and flexible aluminum links has been manufactured. The rigid links are 38 mm box-section beams, while the flexible links are of a 63 mm by 6 mm rectangular section. The modular coupler and interchangeable link design allows links to be exchanged in a few minutes. The third link, which is attached to the wrist, is a short rigid assembly used to fasten a gripper or payload.

The elbow and wrist actuators are supported by air bearings, which ride on the glass tabletop. The shoulder or base motor is held in place by a vacuum pad, which allows the arms to be positioned at any location and orientation on the table. It is envisaged that this will allow studies on completely freely-floating arms later. The supporting table is adjustable to compensate for small- and large-scale construction inaccuracies. As a result, the supporting surface can be levelled precisely to eliminate any gravitational effects on the robot arms.

Control of the system is based on an IBM-compatible 486DX66 personal computer (PC). A high-speed board based on the Texas Instruments TMS320C30 Digital Signal Processing (DSP) chip is connected to the PC bus. Its 33 MFlop capability allows it to execute complex control algorithms at very high update rates. Sensor and actuator signal processing is performed by specialized motion control cards and custom interface boards. These, in turn, communicate with the motor controllers through analog and serial data links.

A number of sensors are mounted on the system to provide feedback for use in control algorithms. Each motor is equipped with adjustable external home and limit sensors and a built in high-resolution resolver or optical encoder to measure joint position. Resistive strain gauges are mounted on all flexible links to measure structural deflections. A force/torque sensor can be mounted at one of the wrists to provide force information during contact tasks. Two additions will be made to the facility in the near future: a system to measure end-point position or acceleration from an inertial reference frame; and a small rigid micro-manipulator mounted on the end of one of the exiting arms.

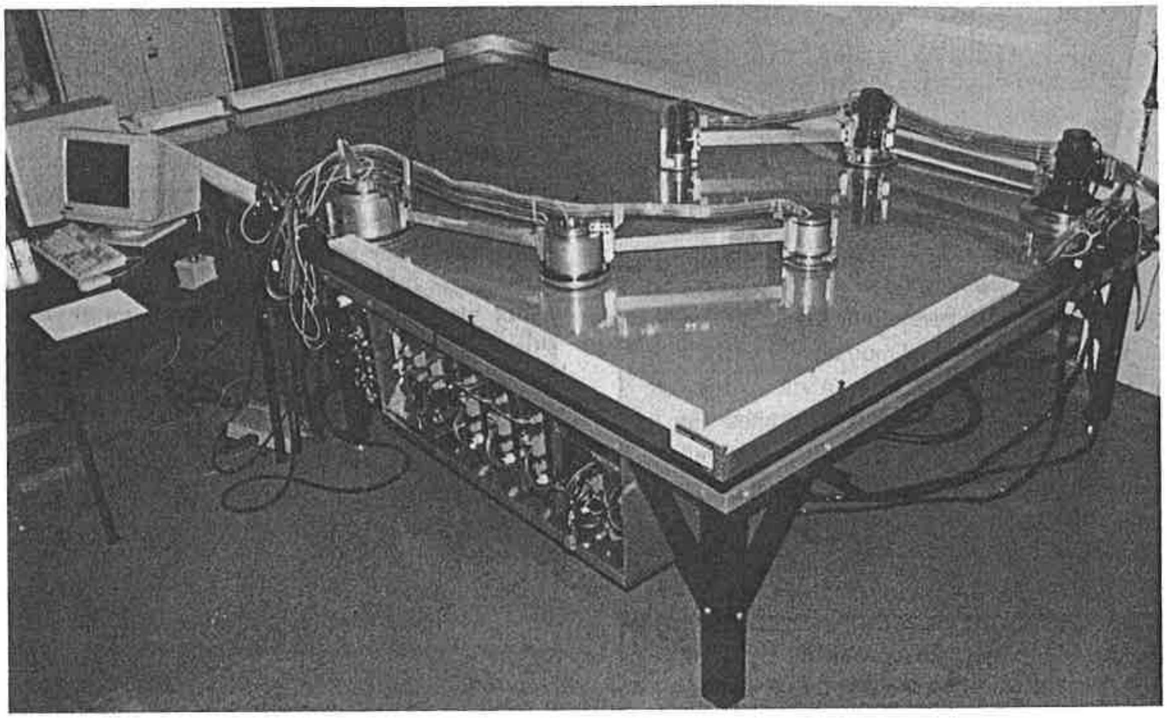

Figure 2.
The University of Victoria facility.

This equipment will allow a wide range of experiments to be performed, including:

- validation force-balancing strategies for two-armed manipulation of objects;[11]
- development of control techniques for multi-armed robotic systems;[12]
- validation of dynamic models for robots with flexible links;[13]
- development of control systems for robots with flexible links and joints;[14] and
- development and validation of collision avoidance for robot manipulators.[15]

This paper provides a detailed description of the two-armed robotics facility at the University of Victoria. Mechanically, attention is focused on the choice of actuators and the design of the links, couplers, and support table. Novel design features are noted, and their utility in the present application is highlighted. A detailed description is then given of the control hardware structure, with an emphasis on the features that extract high performance from this complex electromechanical system.

ACTUATORS

Electric actuators were chosen to power the arms since they are the current standard for space robotic applications — and are likely to remain so for the foreseeable future. A wide range of such actuators is available, and these are usually classified according to the type of gearing used, method of commutation, location of windings, and magnet type. Most robots for space and industrial applications use DC servo motors with gear reduction due to the high torque-to-weight ratio these units can provide. However, the gearing system tends to introduce significant flexibility and backlash — thereby causing positioning errors — and degraded repeatability and control of the robot arm. High-torque motors, used without gear reduction, are more recent and have gained popularity in robotic applications. With these actuators, the load is attached directly to the motor rotor. This results in greater mechanical stiffness, more precise positioning, better repeatability, and lower friction and rotor inertia than in a geared system. In addition, modelling of the joint characteristics, such as friction and flexibility, is easier than for a geared actuator. The major drawback of gearless actuators is their lesser torque-to-weight ratio; though newer models are improving rapidly.

To gain experience with both types of motors and to enable them to be compared in identical situations, both types of actuators have been incorporated in the new robotics facility. The direct-drive arm, with its zero-backlash, highly rigid joints will allow the validation of dynamics models for flexible links, with little or no contamination from joint non-linearities. Once these models are validated, the effect of non-ideal joints can then be investigated on the geared-drive arm. Furthermore, a primary objective of the intended research work is to develop and validate control algorithms. Comparing the results of a given controller implemented on these two distinct manipulators will provide a sound basis to determine the controller's robustness to changes in motor characteristics. Finally, it is expected that the use of both drive technologies will enhance and diversify the research opportunities available in the future.

The high-torque motors selected for this facility were the NSK Megatorque series variable reluctance brushless motors (**Figures 2** and **3**). These were connected to their load in a direct drive configuration. The geared brushed servomotors chosen (**Figures 2** and **4**) were built by HD Systems Inc. and are equipped with 50:1 gear ratio harmonic drives. Both types of actuators were purchased with dedicated amplifier/controller units, which handle power conversion and allow the actuators to be commanded in position, velocity, or torque modes. The control units also include a comprehensive range of alarms, limit switch inputs, and monitor signals. Each actuator has a built-in resolver from which position and velocity information can be obtained.

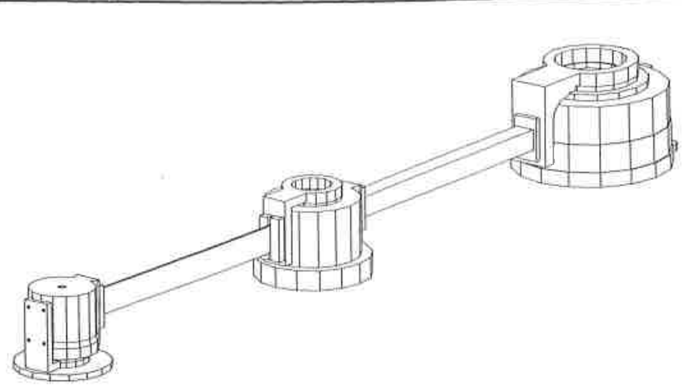

Figure 3.
NSK arm.

To choose the specific actuator models for this facility, a baseline maneuvre was chosen to represent the system's desired performance. In this maneuvre, all the joints of the manipulator were simultaneously rotated through 90° in two seconds using 0.75 m links and a 2 kg payload. A rigid-link inverse dynamics simulation allowed the determination of the maximum actuator torques required at each joint to accomplish this maneuvre. The process of choosing appropriate actuators was iterative since the inertial parameters of the actuators themselves had a dramatic effect on the peak torques required. Thus, a less powerful but lighter motor set might result in similar arm performance to that obtained with a more powerful but heavier set. **Table 1** shows the characteristics of the NSK Megatorque models chosen for the direct-drive arm, as well as for the HD Systems models selected for the geared arm. A quick comparison of the physical dimensions and torque capabilities of these motors clearly indicates that the geared arm is significantly more powerful than the direct drive arm. Since the geared arm is also lighter, it is able to perform the baseline maneuvre faster than required. However, the next smaller set of actuators available proved incapable of performing this maneuvre in two seconds.

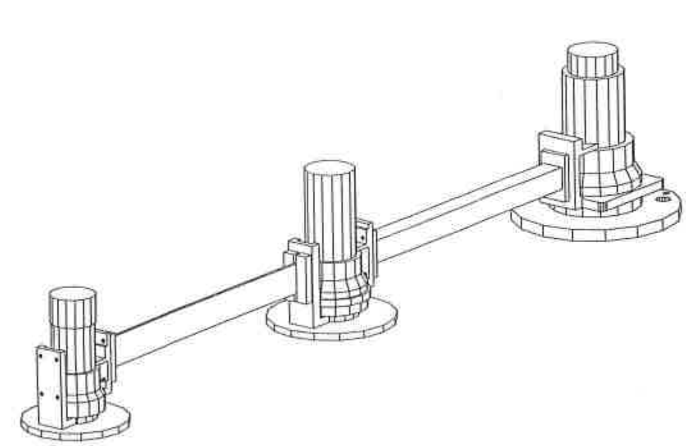

Figure 4.
HD arm.

The motors in the two arms have significantly different features. It will be revealing to investigate how these affect overall arm performance. Among these characteristics: a torque-to-weight ratio that is about five times higher for the geared actuators than for the high-torque direct drive configuration; brushes for commutation on the geared actuators, while the brushless high-torque motors have their commutation performed electronically within their controllers; and the high-torque motors are almost completely freely backdrivable, while the geared motors require substantial effort to be backdriven.

One of the more interesting design choices to be made was the determination of which side of each motor (rotor or stator) should be attached to which link (proximal or distal) at that joint, and whether the output rings (rotors) should face up or down. These decisions were based primarily on a desire to maintain the vertical position of the motors' mass centres as uniform as possible for both arms. The differing conditions at the joints resulted in non-uniform configurations. The final configurations chosen for all six actuators are illustrated in **Figures 3** and **4**. On the HD arm, all three actuators are positioned with their harmonic drives (the bulge in motor diameter) facing the supporting table in order to minimize the vertical distance from the motors' mass centres to the table. The HD shoulder actuator is configured differently than the

Table 1.
Motor characteristics.

Arm	Location	Model	Max. Cont. Torque (N–m)	Mass (kg)	Diameter (mm)	Controller Voltage Input
Direct Drive	Shoulder	RS 1010FN002	150	40	320	3 ϕ 220 V
	Elbow	RS 0608FN001	40	14	215	3 ϕ 220 V
	Wrist	BS 0408FN001	10	6.5	130	1 ϕ 110 V
Geared	Shoulder	RFS-32-6030	216	11.5	165	1 ϕ 110 V
	Elbow	RFS-25-6018	98	6.4	130	1 ϕ 110 V
	Wrist	RFS-20-6007	56	3.6	110	1 ϕ 110 V

elbow and the wrist in that its rotor is attached to the proximal link while the stator is attached to the distal link. The opposite configuration is used for the other motors. This greatly simplified the design and allowed full 360 degree motion of the actuator. On the NSK arm, the shoulder output rings (rotors) face upward on the shoulder and elbow actuators, while that of the wrist motor faces downward. Generally, these actuator configurations tended to eliminate the need for motor support structures to adjust the mass centre locations, thus reducing overall joint mass and complexity. Although the HD actuators are significantly taller than the NSK motors, the vertical location of the mass centres is almost the same for all moving actuators (elbow and wrist). As a result, interchanging actuators will not introduce undesirable torsional moments due to a variation in the heights of the motors' mass centres.

LINK DESIGN

To allow easy exchange of links and actuators between the arms, the entire system was designed to consist of 'link modules' and 'actuator modules,' which would be fully interchangeable. Thus, any link can be placed at any position on either arm, as can any actuator. This can be accomplished simply by unbolting and bolting the appropriate components in the desired locations and rerouting the wiring. In addition, this also allows a planar arm with up to six axes to be configured, for example, to study methods for the control of kinematically redundant arms. The decision to maintain a modular design had a significant impact on the link design. Among the issues addressed in the mechanical design of the links were: the method of attachment, including adjustment capability; link cross-section for rigid and flexible links; link lengths; and material used. Each of these factors, in turn, had an impact on the coupler design and the manipulator workspace.

The requirement for modularity led to the use of vertical flanges on both links and couplers as a means of connecting the links and actuators. This resulted in a standard interface of simple construction, which was mechanically stiff and did not impose limitations on the geometric cross-section of the link that could be used. Although other methods were considered, each was deficient in one or more of these areas. The links presently being used on the test-bed are shown in **Figure 5**. The left-most link is 'flexible,' while the other three are considered 'rigid.' All four links have the same flange bolt pattern, which allows the link to be attached to the coupler face plate using four hex-head screws. In the case of the rigid links, the flanges are welded to the link, while the flexible link flanges are composed of two pieces that simply clamp the link. The flange bolt holes are elongated in certain directions to allow small adjustments to be made to the link positions. This capability was found to be essential to allow proper operation of the arm. In particular, the arm is very rigid in bending about a horizontal axis. If the links are tightened in place with the air pads turned off, this rigidity tends to impose an additional load to be lifted by the air pads when they are turned on. It has been found that all final alignments are best done with the arm on the table and the air pads turned on. We have not yet devised an acceptable method for introducing compliance in bending about a horizontal axis, without also introducing (undesirable) compliance in bending about the vertical axis.

During the preliminary design of the manipulator, the need to maintain height of the mass centres of all the arm components as uniform as possible was crucial. Other configurations that would have allowed full 360° motion of the elbow were considered, but they entailed so many performance compromises, including large out-of-plane moments, that they were abandoned. This then dictated that the link heights should all be the same, and the width of the rigid links became the prime determinant of the workspace of the manipulators. In other words, the factor that prevents full rotation of the shoulder and wrist joints is the point at which the proximal link interferes with the distal link. This would tend to drive the link width to be as narrow as possible. However, the width of the

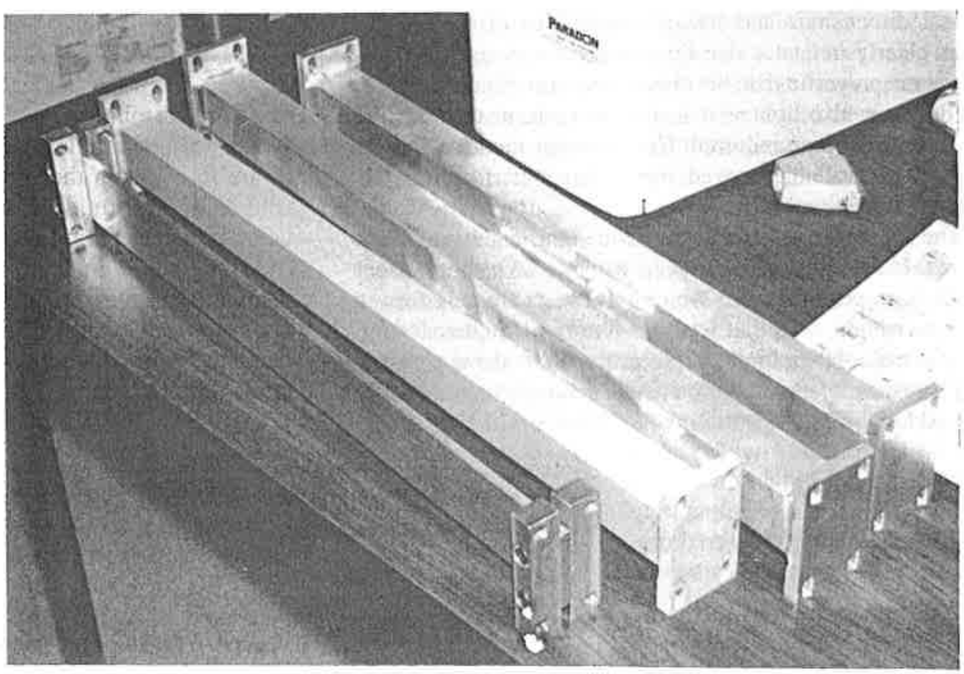

Figure 5.
Rigid and flexible links.

rigid links is also the prime determinant of their structural flexibility. As a compromise between workspace and flexibility, a maximum link and coupler width of 50 mm was chosen. The section shape determines the bending stiffness to mass ratio, which should be kept large. A wide-flange I-beam would be ideal in this case, but was not available in the small-size aluminum required. The most appropriate available material was a square hollow box section, 38 mm on each side with a 3 mm wall thickness. Assuming 0.5 m link length between coupler faces, simulations showed that the manipulator tip deflection due to structural bending would be less than 1 mm during the baseline maneuvre described in the previous section. As well, it was determined that the lowest natural frequency of the link would be greater than 100 Hz. These specifications were deemed acceptable and allowed coupler face plate widths of 50 mm to be used. The lengths of the rigid links were chosen to give the same distances between joint axes as that obtained with the flexible links.

The length of the flexible links was determined primarily by the system's resulting natural frequencies and the effect on overall size of the test facility. Longer links have the benefit of having lower natural frequencies, which makes sensing and control tasks easier. Our space limitations dictated that a flexible link length of 0.5 m could be accommodated, while still allowing 180° motion of a single outstretched arm with two flexible links, placed at the centre of one of the long sides of the table. Once the couplers, motor diameters, and end effectors are accounted for, each arm may be up to 2 m long. The flexible links are constructed of simple aluminum plate, 6 mm wide by 63 mm high, to facilitate their modelling. The width was chosen to be large enough to ensure that the yield point would not be reached in either link during the baseline maneuvre. The resulting first four natural frequencies of the complete arm, with two flexible links, in bending are 9, 18, 26, and 51 Hz. In the future, it is expected that links of more complex shapes or alternative materials could be accommodated if desired.

COUPLER DESIGN

The design of the couplers tended to follow logically once the actuator orientations, method of link attachment, and link dimensions had been chosen. Each elbow and wrist motor required a special-purpose proximal and distal coupler to be designed, while the shoulder motors required only distal couplers. To accommodate the constraints of minimum size and mass, many of the couplers were of fairly intricate shape. It therefore became expedient to fabricate them from multiple pieces, which were assembled later. All coupler components were constructed from 6061-T6 aluminum to reduce joint mass while maintaining high structural rigidity and to ease the required machining.

The maximum range of joint rotation available is limited by the angles at which the proximal and distal couplers come into contact. This, in turn, is determined by the width of the coupler face plate and its distance from the joint axis. The width of each coupler face plate was chosen as 50 mm to accommodate the 38 mm wide rigid link as well as the weld bead attaching the flange to the link. Since this constant face plate width will cause less interference when it is further from the joint axis, the motion of the larger motors is less constrained than that of the small ones. In the final implementation, the range of joint motion available was as follows: NSK elbow, 305°; NSK wrist, 282°; HD elbow, 275°; and HD wrist, 253°. Both NSK and HD shoulder motors are capable of full 360° rotation since they have no proximal couplers to interfere with their distal couplers.

The proximal couplers are simply brackets rigidly attached to the motor stator at several points by means of hex-head screws. Each of these brackets has a vertical face plate with the appropriate four-bolt pattern, to which the proximal link flange can be attached. By contrast, most of the distal couplers are more elaborate because each actuator's output ring (rotor) axis is vertical, while the link that it drives is in the horizontal plane. This necessitated the fabrication of L-shaped couplers with inset corner gussets to increase their rigidity.

On the NSK arm (**Figure 3**), the shoulder and elbow distal couplers can be seen emanating from the top of the motors and bending 90° downward to present a vertical face plate to which the distal link flanges are bolted. The NSK wrist distal coupler emanates from the bottom of the motor and bends 90° upward to present an analogous vertical face. The elbow and wrist distal couplers of the HD arm (**Figure 4**) have a similar configuration to the NSK wrist because their output rings are also facing the table. By contrast, the HD shoulder has the distal link attached to its stator (as described in the preceding section), and the distal coupler of that motor is, in fact, quite similar to the proximal couplers of the other motors.

MANIPULATOR SUPPORT SYSTEM

The function of the supporting system is to provide a near-frictionless surface for the motion of the arms, as well as constraining that motion to a horizontal plane. In addition, the system must allow for omni-directional motion within that plane, including two degrees of freedom in translation and one in rotation.

Several support concepts were investigated before the choice to use an air pad system was made. Magnetic and mechanical bearing systems were discarded due to their excessive complexity and poor friction characteristics. By contrast, pneumatic bearings can support large loads, operate cleanly, are simple and inexpensive to construct, and have extremely low friction characteristics. A pneumatic bearing supports a compression load on a thin film of air between two bearing surfaces. The main drawback to this system is the continuous supply of compressed air required to maintain the pressure gradient across the pad.

Air Pad System

The large workspace of the manipulators and the concentrated loads of the motors precluded the use of a table with pinholes through which pressurized air would be injected. Instead, active air pads, in which air is injected through holes in the pads, were chosen to support the manipulator. In effect, this configuration allows the air to be routed only where it is really needed — under the motor. The air pad design chosen for the facility was driven partly by the work described in Reference 16 and partly by tests conducted in-house. All air pad prototypes were constructed of plexi-glass, which is flat, smooth, and easy to machine. During our experimental investigation, the overall hover height, smoothness of operation, and load-carrying capacity (both vertical load and off-centre moment) were evaluated. In all cases, tests were conducted with a shop air supply, a load ranging up to 40 kg, and on a variety of surfaces. Test results indicated that the simplest air pad designs tended to have the best overall performance. The active air bearing — a disk with air injected at the centre — was the simplest design and offered the best performance. A simple refinement on this simple design — adding a small recess area of approximately 15% of the pad diameter around the injection point — improved the load-carrying capacity and eliminated slight vibrations.

When installed on the NSK wrist and the HD elbow and wrist, the air pads are attached to an aluminum disk mounted to the bottom of the distal couplers. The disks are the same diameter as the air pads and provide added stiffness and mechanical protection in the event of collision with another object. In the case of the NSK elbow, the air pad is mounted to an aluminum disk on which the motor casing (stator) sits.

In contrast to the elbow and wrist motors, which must float as freely as possible, the two shoulder motors must be constrained from moving. Initially, this was to be done by supplying a number of bolt locations along the perimeter of the support table to which they could be bolted. However, it was determined that a more elegant solution would be to use a vacuum system for the shoulder motors that would be analogous to the bearing system of the other motors. The significant advantage is that the shoulder motors can be positioned at any location and orientation on the table. Shoulder pads were constructed from aluminum disks with an O-ring embedded at the perimeter to enhance the vacuum seal and mounted under each shoulder motor. When evacuated, these pads can produce a clamping force in excess of 10,000 N. A simple ejector pump is used to generate the vacuum required to clamp the base motors to the table. Once the vacuum is drawn and locked in, it will remain for a period of days, thereby avoiding the frequent use of this noisy device. Lift can also be generated by pressurizing the shoulder pads so that the manipulator can be easily repositioned by hand. This base mounting system maximizes versatility and avoids both the mechanical complexity and loss of workspace associated with other mounting techniques.

The air distribution system supplies pressurized air, at 550 kPa, to the shoulder and wrist pads and vacuum to the shoulder pads when the manipulators are in operation. The operation of the air system system is shown in **Figure 6** for three modes of operation: evacuating the shoulder pads; normal operation; and emergency shutdown. Each actuator is fed by an individual supply line connected to a distribution header by either a needle valve or a plug valve for flow control or isolation. These control valves can be seen on the air control panel on the left in **Figure 7**. If an emergency stop situation is detected, power to the actuators is turned off and the shoulder and wrist pads are evacuated by drawing a vacuum at the distribution header. This is accomplished by controlling the air flow through the same ejector as used to evacuate the shoulder pads. A strong braking force is then generated between the pad and the table, which immediately stops all motion. A vacuum switch mounted on the header senses if the shoulder motors have adequate vacuum

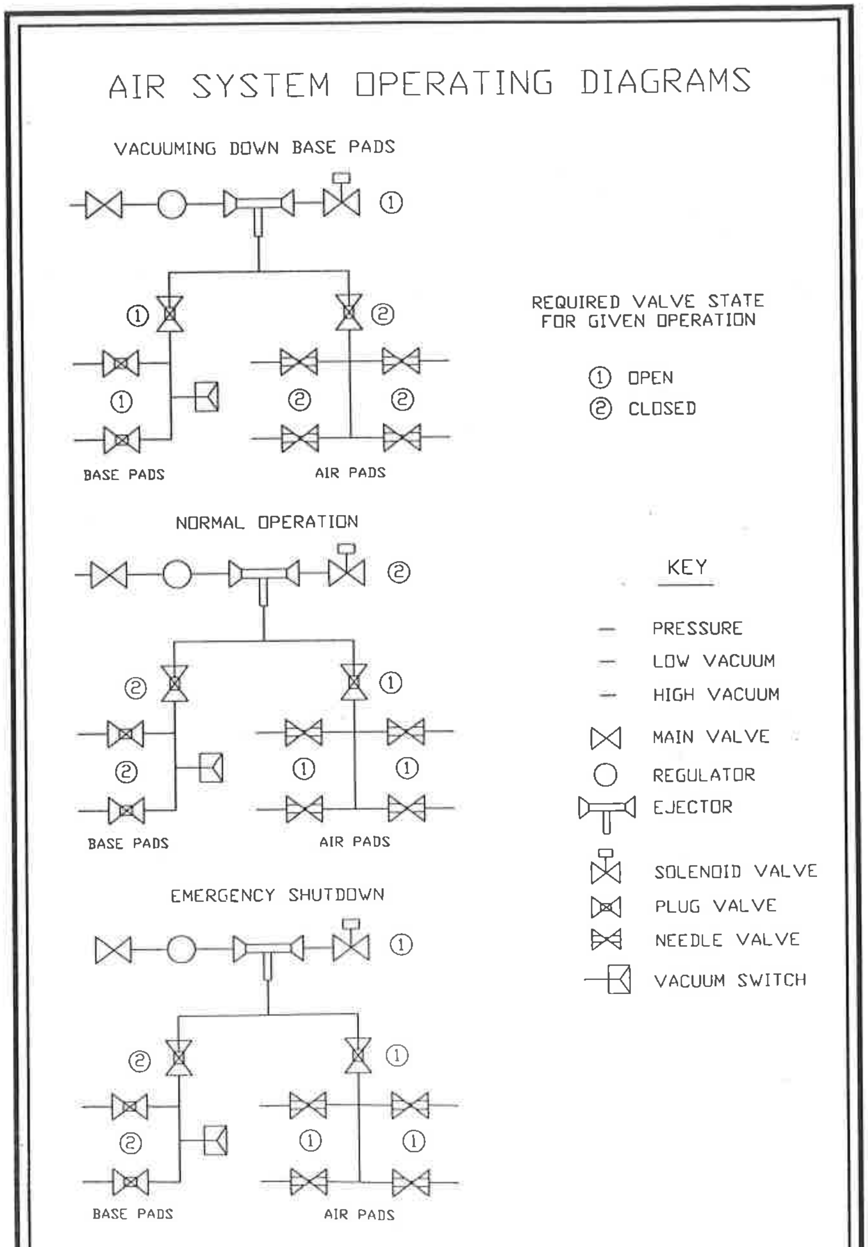

Figure 6.
The air system.

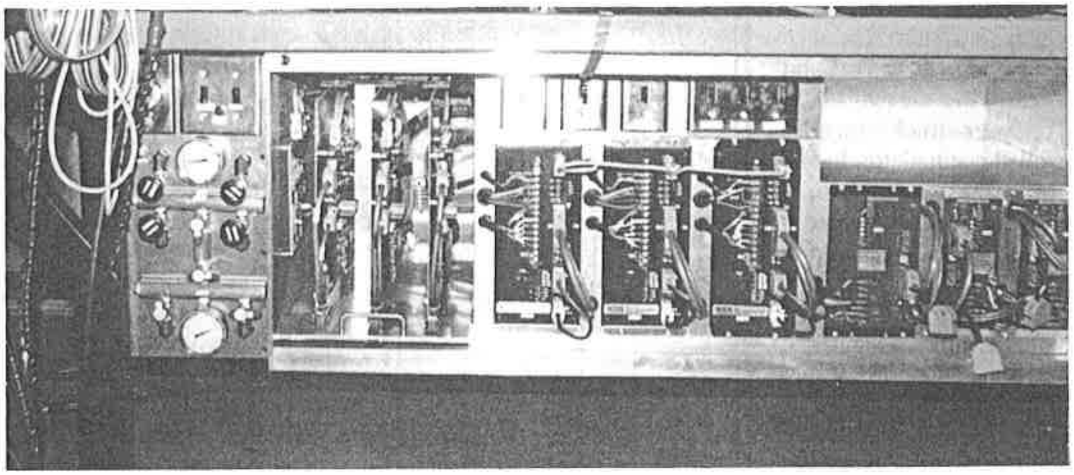

Figure 7.
The air controls and motor controllers.

and will trigger an emergency stop condition if that vacuum is lost.

Supporting Surface

The air bearing performance is critically dependent on the smoothness and flatness of the lower bearing surface. Any irregularities on the air pad or the bearing surfaces may result in contact between the two, which then leads to high friction. Tests using granite, arborite, aluminum, steel, and glass for the lower bearing surface were performed. The results of these tests indicated that plate glass provided the smoothest operation. The decision to use glass as a bearing surface implied that a separate support structure would have to be designed. To ensure ease of use of the facility, the support structure was also used as a means of raising the glass surface to an appropriate working height. As well, the tendency of a large piece of glass laid horizontally to conform to the shape of the surface on which it rests required that a continuous supporting surface be provided, and that levelling of that surface had to be incorporated. Thus, the supporting table, broken down according to functionality, consisted of three major components: a glass bearing surface; a plywood supporting surface; and a steel substructure. These are clearly shown in **Figure 8**.

Safety glass was used to reduce the danger of flying shards in the event of a catastrophic failure. The glass is therefore composed of two sheets, each 5 mm thick, bonded together by a clear laminate. The

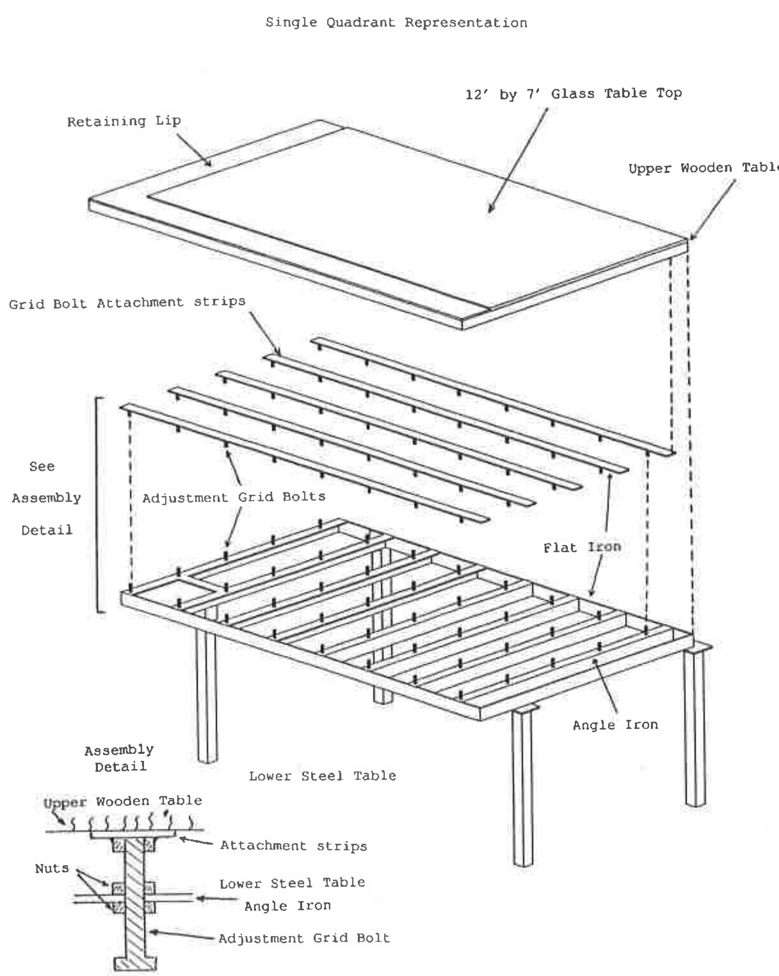

Figure 8.
The support table.

glass sheet is held in place by an L-section aluminum rail, which extends around the perimeter of the table. A 15 mm clearance was left between the bottom of the rail and the glass sheet to ensure that the two would not impact if the rail were struck violently, say by an uncontrolled manipulator. In one year of use, the glass has suffered some minor scratches. When this problem becomes severe enough, it should not be difficult to flip the glass, thereby restoring a clean surface for a time. In the long term, the glass will have to be replaced regularly. The 2 m by 4 m plywood-supporting surface was built up from two thicknesses of 12 mm thick 1.2 m by 2.4 m sheets bonded together. When laying out the overlay pattern, care was taken to ensure that no joints from the upper layer would be coincident with joints from the lower layer. The upper surface was then smoothed with wood filler, sanded, and painted. The steel substructure was fabricated of mild steel angle and box sections, welded together and powder-coated. A grid of jacking bolts (with a 0.4 m separation between bolts) between the plywood-supporting surface and the steel substructure allows fine adjustments to be made. In addition, jacking bolts are provided in each table leg to allow coarse height adjustment. During the final stages of facility construction, both systems were used to level the table to within 0.1 mm over the entire surface. The procedure used to do this was as follows:

After allowing two months of settling, including vigorous use of the robot arms, spirit level readings were taken at a few locations. The leg supports were then adjusted to level the table as much as possible, on average.

A 2 m rigid straight edge was laid on the table surface, along a line of jacking bolts. A feeler gauge was used to detect high and low spots along the edge. The grid jacking bolts were used to completely or partially remove these, while avoiding extreme adjustment of any single bolt. This was repeated for each line of jacking bolts and along both perpendicular directions.

A single motor supported by an air pad was placed at various locations on the table, and its tendency to drift in any particular direction was noted. The leg supports were readjusted as a consequence. This technique was used in preference to the spirit level as it proved to be more sensitive and accurate.

The second and third steps were repeated in succession until no further improvement could be obtained.

The entire procedure required five person-days to complete. Since then, the adjustment has been checked regularly and found to require little re-work.

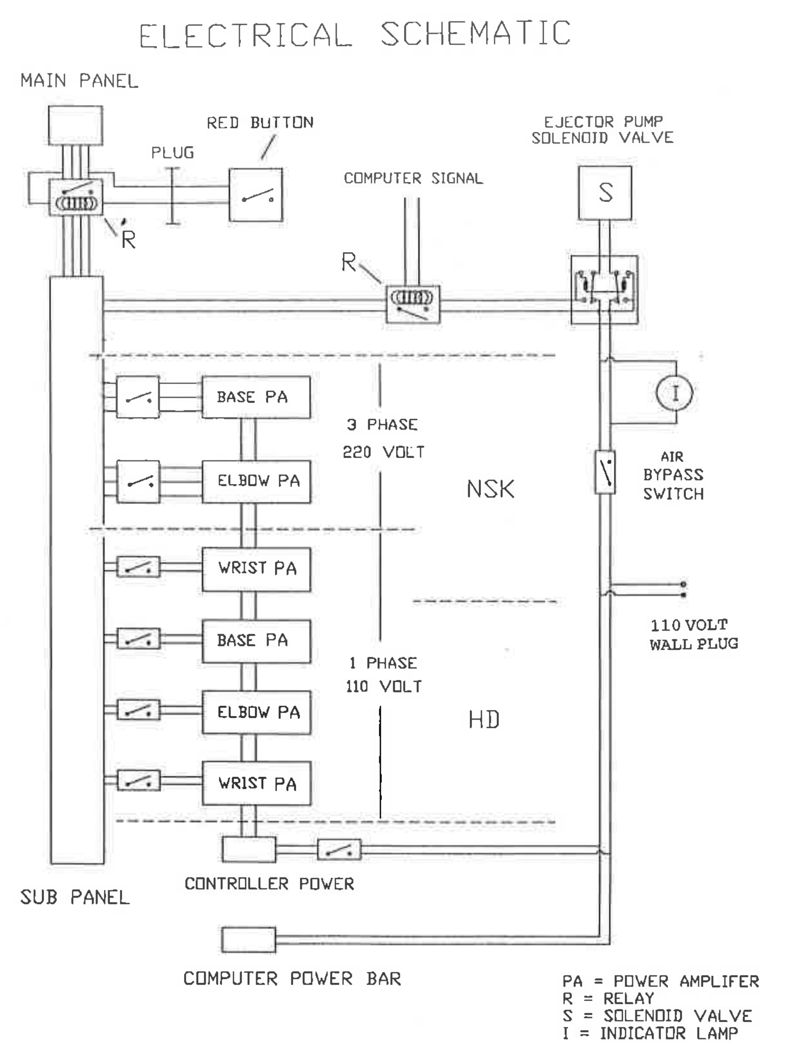

Figure 9.
Electrical system.

ELECTRICAL SYSTEM

The electrical system, shown schematically in **Figure 9**, supplies power to the various components in the facility. The air solenoid valve, computer, motor power amplifiers, and motor controllers are the principal devices requiring high voltage power. The power amplifiers of the NSK shoulder and elbow motors require three-phase 220 volt power, while the remaining components require single-phase 110 volts. Three-phase 220 volt power is supplied from the main panel in the electrical control room adjacent to the laboratory. A red mushroom emergency stop button allows the user to remotely control power to the sub-panel, which supplies the motive power to the facility. Each power amplifier is connected to this sub-panel by individual breakers and isolation switches (shown at the top of the control panel in the middle of **Figure 7**).

The sub-panel is also one of the power sources for the ejector pump solenoid valve. If the user initiates an emergency stop by depressing the stop button, power to the power amplifiers and to the ejector solenoid valve is cut off. This latter action creates a vacuum at the air distribution header, thus braking the arms, as described in the sub-section "Air Pad System." A solid-state relay inserted in the solenoid power line allows the computer to shut off power to the solenoid valve in case of a hardware-generated shutdown (from a joint limit, for example). A separate 110-volt circuit supplies power to the computer, the motor controllers, and the solenoid valve. This allows passive operation of the facility, with the emergency stop button depressed, during hardware or software development. As well, since the electrical system uses two separate power sources, the computer and electronic hardware are electrically isolated from the power amplifiers.

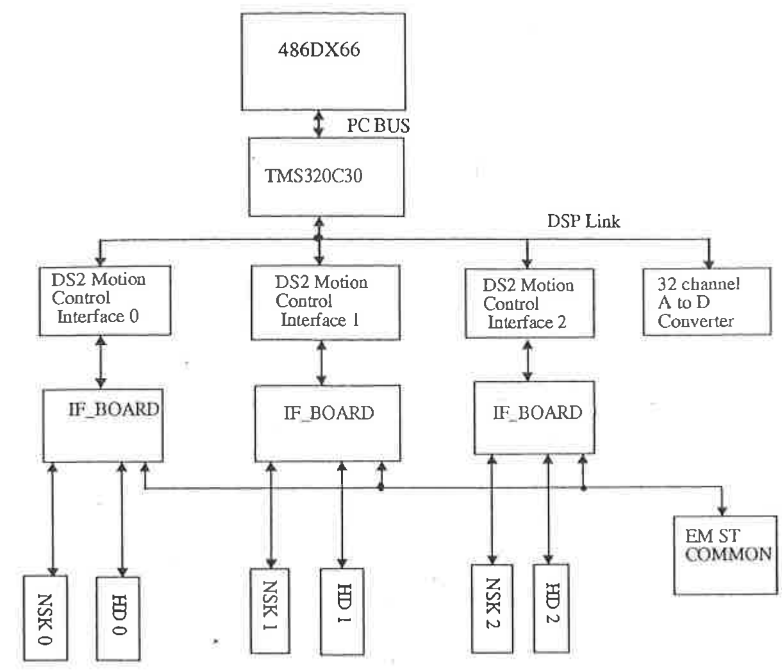

Figure 10.
Control hierarchy.

COMPUTER CONTROL AND INTERFACE

To extract the full performance capabilities of the complex electromechanical system described in the preceding sections, a sophisticated computer control system is required. The control laws required to control flexible systems or force-controlled systems are often complex and usually need to be executed at high update rates. A great deal of computational power was therefore needed, along with the capability to operate the system at precisely controlled real-time intervals. In addition, these requirements had to be attained at a reasonable cost. The computer system chosen to accomplish this task is shown diagrammatically in **Figure 10**.

Computer Hierarchy

The IBM-compatible 486DX66 personal computer is used as a software development platform, user interface, and data display station. Code development is performed using the C language and is facilitated by the debugging tools available on that platform. This code includes all necessary forward and inverse kinematics, trajectory planning, feedback control laws, and real-time I/O. Once the code is ready to be evaluated, it is compiled on the PC using the cross-compiler supplied by Texas Instruments and then downloaded onto the DSP board for real-time execution. The PC is also used to monitor the system during real-time operation, accept user inputs to control the experiment, and display any data desired. This is accomplished by software running on the PC, which communicates with the DSP through dual-port memory.

The PC communicates through the PC Bus with a Spectrum TMS320C30 DSP board, the system's main computing engine. This board is capable of performing 33 MFlop and runs a SPOX real-time operating system. The DSP board is responsible for real-time execution of the control algorithms, including all timing, interrupts, and I/O. The DSP is the primary means enabling one to obtain the high sampling rates desired. To date, the system has been operated using simple control laws at rates of up to 500 Hz, with substantial capacity remaining. Bench testing will be performed in the future to determine the maximum sampling rate available.

The DSP board communicates, in turn, with three IMI DS2 motion-control boards via the DSP Link. These boards are specially designed to interface with the Spectrum board, and their function is to provide the specialized functions required for motion control, including two encoder interfaces, two D/A channels, two A/D channels, and various bit I/O. Each DS2 board handles two motion axes — one NSK motor and one HD motor — thus allowing full control of the system using three boards. All functions on the DS2 are memory-mapped to the DSP. These memory locations can be accessed by the control algorithms that execute on the DSP. Also attached to the DSP Link is a 32-channel Analog-to-Digital (A/D) converter, which allows sampling of any analog signals that cannot be accommodated by the DS2 boards. At present, this board is dedicated to the processing of strain gauge signals.

Corresponding to each DS2 board is an Interface Board, designed in-house, which contains the homing and conditioning circuitry for the HD motor's analog signals. These boards also monitor the emergency stop signal, which can be generated by any of the six motors. If one of these is triggered, the Emergency Stop Common board will receive that signal and retransmit it to the other motion axes, thus halting all motion and triggering the ejector pump to evacuate the air pads. Finally, each Interface Board sends and receives commands to one NSK controller and one HD controller.

System Operation

The NSK and HD controllers allow the motors to be controlled in three modes: position, velocity, or torque. The first two of these are closed-loop feedback modes, which apply a factory supplied algorithm to force the measured position or velocity to match the corresponding value commanded by the user. Since these modes inherently contain dynamics over which we have no control, they will rarely be used during experiments. By contrast, the torque mode simply sends an open-loop torque command to the actuators. Since most robot controllers tend to be formulated in terms of the motor torque as the command variable, this latter mode is the one that will be used most frequently. This allows us to design and implement our own control algorithms at a lower level than might otherwise be possible.

Motor actuation is accomplished by sending an analog voltage command to the controllers, which convert this to a drive current for each motor. Sensing of motor position is accomplished by reading quadrature pulses emitted by the encoders or digitized resolver outputs. Each of these signals is connected to the Interface Board, which performs various logical and level-shifting operations and provides a central tie-down for all control signals.

SENSING

At present, the installed sensing capability consists of a high-precision resolver or encoder, as well as home and limit switches at each joint; resistive strain gauges on the flexible links; a six-axis force-torque sensor; and a vacuum sensing switch in the shoulder motor header. Future planned additions to the sensing capability include manipulator end-point position or acceleration sensing.

Both the high-torque and geared motors were purchased equipped with position sensing devices whose resolution allows for excellent accuracy. The NSK shoulder and elbow motors have resolvers whose output is digitized to a resolution of 614,400 pulses per revolution (ppr), while the wrist resolver generates 409,600 ppr. The encoders in the HD motors all have a resolution of 204,800 pulses per revolution of the harmonic drive output shaft (1024 ppr encoder X 50:1 gear ratio X 4 for quadrature effect). Of course, in the case of the HD motors, the presence of backlash and flexibility mean that an accurate encoder reading does not necessarily imply an accurate knowledge of the output shaft angle. Velocity can be computed from the position signals using a differencing algorithm or may be obtained from an analog voltage signal, which is available on each motor controller.

Each flexible link is equipped with three strain gauges, each in a full-bridge configuration, positioned to maximize their mode-identification capability. The low-power signal from the strain gauge is routed off the arm and amplified by Analogic Signal Conditioners.

An Assurance Technologies model 30/100 force/torque sensor is available for mounting on the wrist of one of the end-effectors. This device can measure three force components, up to 133 N, and three moment components, up to 11.3 N-m. The disk-shaped sensor is 74 mm in diameter, 29 mm in length, and has a mass of 180 g. It is based on silicon strain gauge technology and can be sampled at up to 300 Hz through a parallel communication line. In the future, a purpose-made unit may be constructed to measure only the three components of force and torque that exist at the end-effector, thereby allowing higher sampling frequencies and better control over the instrument electronics.

A vacuum switch mounted on the shoulder motor header senses whether the shoulder motors have sufficient vacuum and triggers an emergency stop procedure if that vacuum is lost. The pressure/vacuum state of the distribution header is controlled by the computer and the user. Both must acknowledge that no emergency situation exists for the air pads to have pressure; otherwise, the system remains in vacuum mode. A manual bypass exists to allow the user to reposition the arm, which requires pressure at all the pads, when the computer system is not operational.

Home and Limit Switches

Home and limit switches have been incorporated into each joint to sense a home position and to generate an emergency stop situation if a joint rotation limit has been exceeded. The triggering positions can be easily adjusted to tailor the joint limits to the configuration of the manipulators and the nature of the experiment. The homing sequence is necessitated by the fact that the position sensors fitted to both types of actuators are not absolute sensors — they only sense the joint position relative to the position at which the system is initialized. Thus, at the start of each experiment, the sensor outputs must be zeroed at a fixed known 'home' position, which is achieved using the position control mode of each motor.

Both home and limit switch functions have been implemented using optical rather than mechanical switches. Reflective optical switches, which combine an infrared LED and a photo darlington transistor in a single housing, were installed at each joint. The photo transistor is triggered by changes in the reflectivity of the object placed in front of the sensor pair. These switches were mounted at appropriate locations on the actuator body and pointed at the output coupler. The target surface (in most cases, the top of the air pads) is covered in transparent material with black ink marks at the desired switching locations. The switching point can be altered by simply changing the location of the ink marks. The physical location of the switches varies sightly among the six actuators, but in each case, the switches are mounted in protective enclosures and the sensing surface is easily accessible to change the switching locations.

USE OF THE FACILITY

At present, four researchers are actively using the facility, and it is anticipated that further experiments and researchers will be accommodated in the future. A wide variety of experiments is planned, of which some have already begun.[17] The principal areas on which these experiments will focus are as follows:

Validation of flexible link/flexible joint dynamics models. In particular, we plan to investigate several approximate models, including one that incorporates the *geometric stiffening effect*, for manipulators with structurally flexible links.[13] The direct-drive arm of the experimental facility is being used for this purpose. For example, **Figure 11** shows a comparison of the measured and predicted (using a single- and a seven-element model) strain one-third of the way along the second link during a point-to-point maneuvre. Also under way is an investigation of the dynamics of manipulators with flexible joints. The work, which is being performed using the geared arm with rigid links, will act as a preliminary step to the validation of the complete simulation models for manipulators with flexibility in the links and joints.[18]

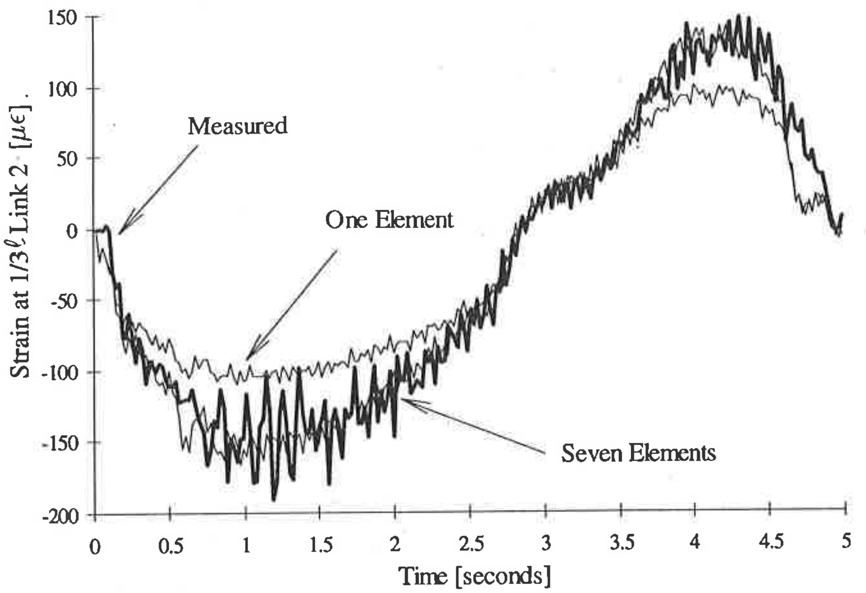

Figure 11.
Strain for Link 2.

Evaluation of force optimization techniques for multi-armed manipulators. This involves the implementation of real-time optimization techniques to provide force setpoints for multi-armed robotic system. These setpoints are intended to allow synergy of the two manipulators; reduce power consumption; and prevent crushing or tearing of the grasped object. A number of techniques have been developed to accomplish this,[11] and these will be evaluated on the facility. More recently, methods have been developed to use the redundant actuation inherent in multi-armed systems to suppress the vibrations of the links.[19] These methods will be implemented and evaluated.

Evaluation of control methods for flexible single and dual-arm robots. Special properties of these systems have been uncovered and shown to hold numerically for detailed models. Principal among these is passivity of a certain input-output mapping.[14] The control system design has been predicated on the powerful passivity theorem, which states that any strictly passive feedback controller will stabilize a passive system. Control laws that include both feedforward and feedback control have been developed. Their performance has been promising in simulation studies of a model of the Shuttle Remote Manipulator System and justifies further experimental study. A detailed simulation model of the co-operating manipulator test-bed is presently being generated.

Macro/micro manipulation. The installation of a small manipulator on the end of one of the existing arms will allow the investigation of systems comprising a large, flexible manipulator with a small, rigid robot attached to its end. These macro/micro manipulators are being proposed for hazardous applications, such as toxic waste clean-up, and operations in space. Among the ideas to be investigated are: the potential for using the short-reach manipulator to damp out the vibrations in the flexible manipulator supporting it;[20] and motion planning strategies for the short-reach robot.

Development and evaluation of improved methods for collision prediction and detection for robot arms. These methods are based on the use of optimization algorithms to find the minimum distance between moving objects. These algorithms are similar to those developed for off-line application in MDSF — SPAR Aerospace's in-house simulation facility.[21] However, they are extended and optimized for use in real-time applications, such as collision detection[15] and motion planning systems. The test-bed will allow experimental validation of the algorithms in both these applications.

CONCLUSIONS

Research into co-operative task manipulation and the dynamics and control of structurally flexible manipulators is important in the development of space manipulators, such as the Mobile Servicing System. The new planar robotics facility constructed at the University of Victoria is a valuable tool for conducting investigations on the behaviour of such systems. The two-armed facility mimics a space environment by supporting the manipulators on air bearings and constraining the motion to a horizontal plane. The manipulators use high-torque and geared actuators controlled by an integrated computer system. Modular joint design allows a variety of link sections to be used, thus maximizing the possible system configurations. Initial testing of the manipulators has demonstrated that each subsystem is functioning as required and the facility is ready for use by the research group. A number of improvements to the facility are expected in the near future. A small 3-dof micro-manipulator will be mounted on the end of one of the arms for use in investigating macro/micro manipulation tasks.

ACKNOWLEDGEMENTS

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