A COMPARISON OF THE SHUTTLE REMOTE MANIPULATOR SYSTEM AND THE SPACE STATION FREEDOM MOBILE SERVICING CENTER

Edith C. Taylor
Lyndon B. Johnson Space Center
Houston, Texas 77058

Michael Ross
Lockheed Engineering & Sciences Co.
Houston, Texas 77258

ABSTRACT

The Shuttle Remote Manipulator System is a mature system which has successfully completed 18 flights. Its primary functional design driver was the capability to deploy and retrieve payloads from the Orbiter cargo bay. The Space Station Freedom Mobile Servicing Center is still in the requirements definition and early design stage. Its primary function design drivers are the capabilities to support Space Station construction and assembly tasks; to provide external transportation about the Space Station; to provide handling capabilities for the Orbiter, free flyers, and payloads; to support attached payload servicing in the extravehicular environment; and to perform scheduled and un-scheduled maintenance on the Space Station. This paper discusses the differences between the two systems in the areas of geometric configuration, mobility, sensor capabilities, control stations, control algorithms, handling performance, end- effector dexterity, and fault tolerance.

1. INTRODUCTION

The Shuttle Remote Manipulator System (RMS) was the first generation space manipulator. It was designed in the late 1970's and had its first flight on STS 2 in November 1981. It is now a mature system which has successfully completed 18 flights. The Shuttle RMS was developed by the National Research Council of Canada with their prime contractor, SPAR Aerospace of Toronto, Canada.

The Space Station Freedom Mobile Servicing Center (MSC) will be the second generation space manipulator. Currently, it is still in the requirements definition and early design stage. The MSC consists of two flight elements : the Mobile Transporter and the Mobile Remote Servicer. The Mobile Transporter is being developed by NASA/Johnson Space Center with its Space Station contractor McDonnell Douglas in Huntington Beach, California. The Mobile Remote Servicer is being developed by the National Research Council of Canada and they are again using SPAR Aerospace as their prime contractor.

This paper will begin by discussing the functions for which the Shuttle RMS has been used and then the functional requirements for the Station MSC. The paper will then discuss the differences between the two systems in the areas of geometric configuration, mobility, sensor capabilities, control stations, control algorithms, handling performance, end-effector dexterity, and fault tolerance.

2. MANIPULATOR FUNCTIONS

The primary functional design driver for the Shuttle RMS was the capability to retrieve and deploy payloads to and from the Orbiter cargo bay. The Shuttle RMS has successfully deployed two payloads to low earth orbit : the Long Duration Exposure Facility (LDEF) on Shuttle Flight STS 41-C and the Earth Radiation Budget Satellite (ERBS) on STS 41-G. And the Shuttle RMS has successfully retrieved two payloads and returned them to earth : the PALAPA and the WESTAR, two communication satellites which failed to function on their original deploy missions, on STS 51-A.

An equally important utilization of the Shuttle RMS has been in the assistance of payload flight experiments. The Shuttle RMS has been used to position payloads at specific data collection points. The Plasma Diagnostics Package (PDP) on STS 3 and the Induced Environmental Contamination Monitor (IECM) on STS 4 were positioned by the arm to take measurements of electric and magnetic fields and plasma characteristics in the environment of the Orbiter (PDP) and the concentration of particles and gases emitted by the Space Shuttle (IECM). In both cases the payload was maneuvered through a sequence of preprogrammed positions without releasing the payload from the arm. For other payload flight experiments, the Shuttle RMS was used to deploy and then later retrieve the payload experiment on the same mission. The SPAS (STS 7) and the SPARTAN (STS 51-G) fall into this later category.

The Shuttle RMS has also proved to be a valuable general purpose tool for observation, positioning astronauts, and applying a little shove at a critical point. The end-effector camera is routinely used for inflight visual inspections of payloads, Orbiter thermal tiles and second stage motor burns. A Manipulator Foot Restraint (MFR) has been attached to the arm to provide a stable platform for astronauts to repair satellites (Solar Maximum Satellite on STS 13, WESTAR/PALAPA on STS 51-A, and SYNCOM on 51-I) and to construct prototype Space Station truss structures (EASE/ACCESS experiment on ST 61-B). Finally, the Shuttle RMS has been used to push a stuck SIR-B antenna closed (STS 41-G), knock off an ice chunk which had formed coming out of the waste water dump nozzle (STS 41-D), and to hit a switch on the SYNCOM satellite (STS 51-D).

The Station MSC has been assigned the responsibility of playing the predominant role in the following Space Station functions: attached payload servicing (external), Space Station assembly, Space Station maintenance (external), transportation on the Space Station, deployment and retrieval, and EVA support.

To satisfy these responsibilities, the MSC must provide two new functions, which are not provided by the Shuttle RMS. The first is transportation. The MSC is required to transport payloads, EVA crew members, Space Station Program Elements and systems, Orbital Maneuvering Vehicles, and Orbital

Replacement Units (ORU's) to all locations as required to support Space Station and payload operations. This requirement drives the design to a manipulator with a base which can move up and down the truss. The Mobile Transporter is this moving base. The second requirement is dexterity. To play the predominant role in assembly, servicing and maintenance requires a device with much more finesse and dexterity than the Shuttle RMS. The problems with fine motions arise from the lightweight long flexible links comprising these manipulators. The design solution to meet this requirement is to develop a separate robotic device which will operate from the end of the manipulator arm. The Special Purpose Dexterous Manipulator (SPDM) is this robotic device. Although programmatically the SPDM is a separate flight element from the MSC, for the purposes of this paper, it will be included with the MSC system.

3. DESIGN CHARACTERISTICS

This section discusses the differences between the Shuttle RMS and the Station MSC in the areas of geometric configuration, mobility, sensor capabilities, control stations, control algorithms, handling performance, end-effector dexterity, and fault tolerance.

3.1 GEOMETRIC CONFIGURATION AND MOBILITY

The geometric configuration of the Shuttle RMS is shown in Figure 1. The arm is approximately 50 feet long with six in-line joints (shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, wrist yaw, and wrist roll). All joints except the wrist roll have travel limits less than +/- 180 degrees. The effective reach envelope of the Shuttle RMS is approximately 35 feet from the base of the arm. The long booms are 12" diameter thin-walled tubes of composite material with internal stiffeners. The shoulder end of the Shuttle RMS arm is bolted to the Orbiter longeron and an end-effector is mounted onto the other end. The end-effector is the device that attaches (grapples) to the object to be manipulated, and uses a grapple fixture and an ingenious snare-wire device to rigidly attach to the grapple fixture. The grapple fixture is an 11" long pin with a nob on the end, attached to and protruding out from the payload. Affixed to the grapple fixture is a target pin, which lines up with the end-effector camera when the end-effector is properly aligned for capture. The grappling mechanism is also shown in Figure 1.

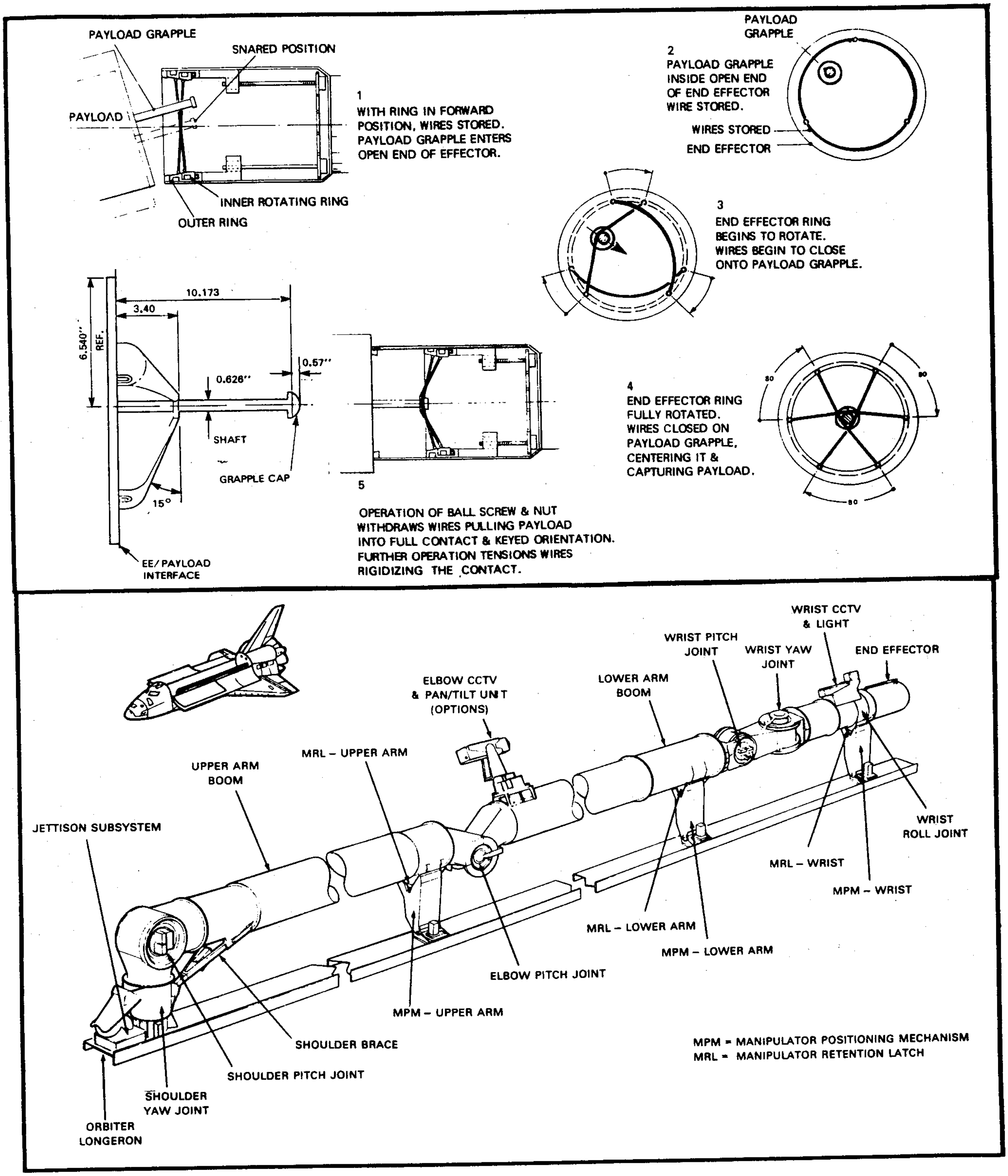

Figure 1. Shuttle RMS Configuration

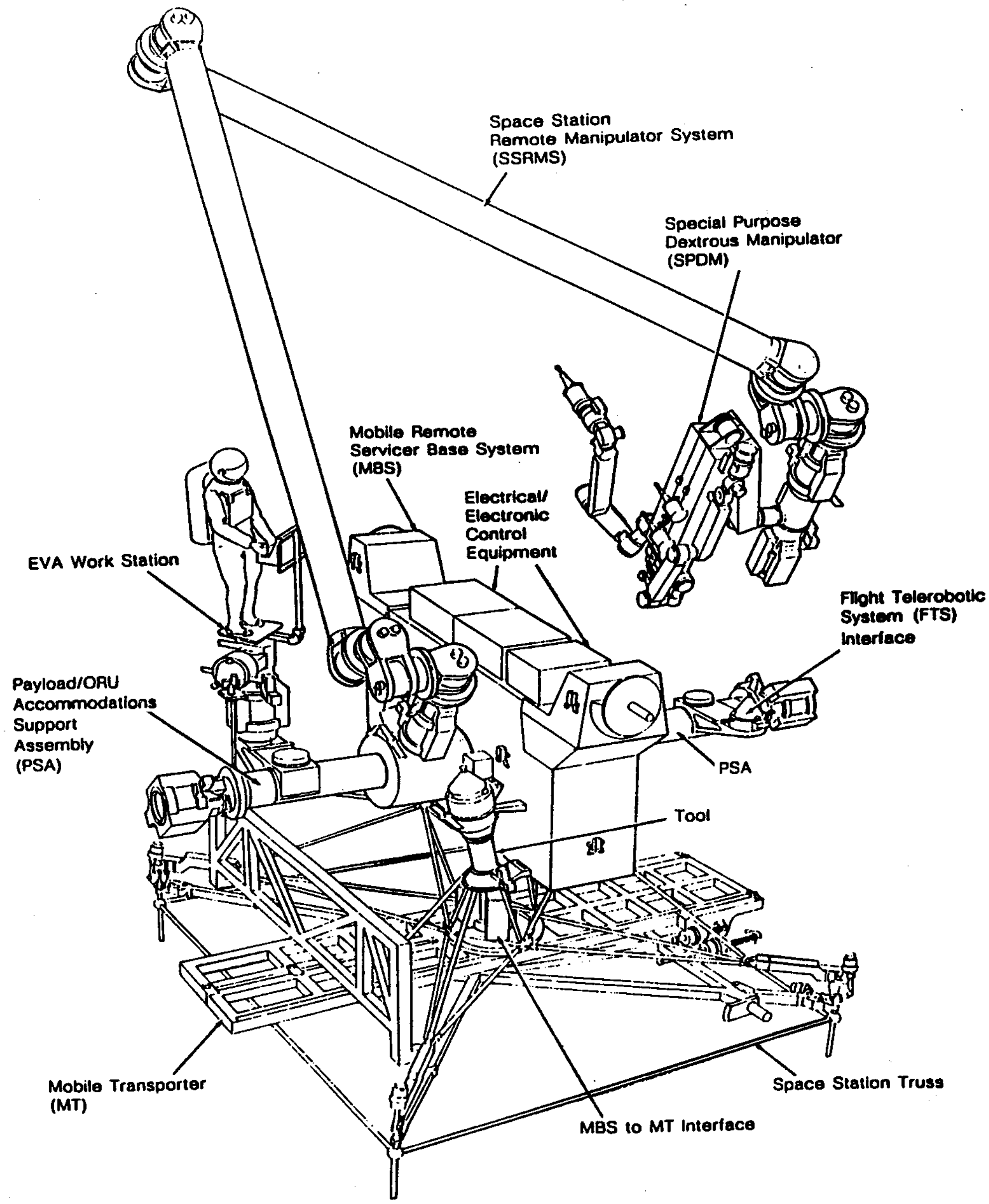

Figure 2. Space Station MSC Configuration

The Mobile Servicing Center is physically composed of four parts as shown above in Figure 2. At the bottom riding on the Station truss is the Mobile Transporter (MT). Sitting on top of the MT is the Mobile Remote Servicer (MRS) base. Attached to the MRS base through a power data grapple fixture (PDGF) is the MSC manipulator, the Space Station Remote Manipulator System (SSRMS). And finally, attached to the end-effector of the SSRMS is the Special Purpose Dexterous Manipulator (SPDM), the robotic end-effector for the MSC. The MSC can be operated with or without the SPDM.

The Mobile Transporter (with or without the MRS base on top) will be able to translate up and down, turn corners and change planes on the station truss. The MT itself will have an early role in the assembly of the Space Station Freedom, as it will be mounted in the Shuttle bay to hold and extend the truss assembly as each 5 meter bay is assembled.

The MSC manipulator is approximately 55 feet long with seven offset joints. It is symmetrical about the middle (elbow) joint with an end-effector on each end. These end-effectors will be similar to the current design, but will have additional structural latches and will transfer power and data across the interface. Either end-effector can attach itself to the power data grapple fixture on the MRS base. The offset joints will allow each joint to have +/- 270 degrees of travel.

The SSRMS has a relocatability feature. Either end-effector can attach itself to and operate from a power data grapple fixture located anywhere on the station. Current plans call for power data grapple fixtures mounted along the truss and perhaps also one mounted on one of the Space Station modules. This gives the MSC manipulator the ability to walk end over end down the truss in an "inchworm" motion. This type of mobility would preclude the carrying of payloads, however.

With the combined mobility of the Mobile Transporter and the SSRMS relocatability feature, the MSC reach envelope covers most of the Space Station external structure.

3.2 SENSORS

The Shuttle RMS has limited sensor data available. The motor tachometer rates and joint encoder angles are measured and fed back into the control algorithms. In the early Shuttle test flights, the Shuttle RMS was instrumented with strain gauges to provide load data at the shoulder and wrist, but the instrumentation was removed after the arm become operational. There are two cameras located on the Shuttle RMS, one at the elbow (with pan and tilt controls) and the other fixed at the wrist. Their views are displayed back to the Shuttle RMS operator at the Orbiter aft flight deck crew workstation, but there is no integration of the video data into the control loop except through the human operator.

The MSC manipulator will add force/moment sensing, vision sensing and vision data processing to the control loop. The force/moment sensor will be mounted at each end of the arm. Vision data will come from two cameras fixed at either end, with two more pan-and-tilt cameras mounted on the booms at the elbow joint, looking in opposite directions. The vision data will yield the state of the end-effector (position, attitude, rate). These additional sensors will reflect the advance of the state-of-the-art in manipulator control.

3.3 OPERATOR WORKSTATIONS

The Shuttle RMS is operated by a crewman at a station in the aft of the cabin, looking out through the rear windows onto the cargo bay. Control of the RMS is effected through two hand-controllers, one for translational motion and the other for rotational motion. The operator has control (pan, tilt, and zoom) of the closed-circuit television cameras (CCTV) located at each corner of the cargo bay (as well as special mission-specific locations). The operator also controls the lights illuminating the bay.

Another workstation is the Manipulator Foot Restraint (MFR), which is a platform grappled by the arm for suited crewpersons to "stand" on and work from while the RMS provides any necessary mobility. No RMS controls exist at this station, however, so all motion must be commanded by the operator in the Shuttle at the request of the crewperson on the MFR.

In contrast, the MSC will have numerous workstations. The operator will have a choice of controlling all the MSC's functions from the base of the arm, the tip of the arm, inside the station module, and from inside the Shuttle. The stations outside on the MSC will be referred to as extravehicular activity (EVA) workstations, while those used inside the pressurized environment are intravehicular activity (IVA) workstations. Of the IVA workstations, some are to be portable, enabling control of the MSC from the Shuttle (for possible berthing operations in which the MSC captures the Shuttle) or elsewhere.

3.4 CONTROL ALGORITHMS

The Shuttle RMS's design was mostly finalized in the late 1970's, involving more effort than any manipulator or robot built prior to that time. The RMS was also the first dexterous "space robot", and its control algorithms, while state-of-the-art in 1978, have become dated in the decade since. The main control algorithm involves commanding a desired rate for the payload. The joint rates necessary for this command then become the input rate command to each individual joint servo. Since the RMS has six joints to achieve 6 degrees of freedom at the end-effector, conversion from end-effector states to joint states is a simple matter. No true end-effector position control is possible, although a rate command designed to hold a joint position constant can be generated by the flight software. Holding joints still does not guarantee the end-effector will not move, however, since the joint encoders do not sense changes in the booms (like flexure or thermal warpage).

The MSC will have seven joints, which gives much more freedom of control while making that control much more complex. The method of converting from six end-effector degrees of freedom to the seven joint states requires input of some other constraint, usually minimization of some quantity like total kinetic energy in the arm.

Along with having seven joints, the MSC is expected to be able to sense and control end-effector position, rates, and forces. This will add greatly to the types of tasks which can be feasibly accomplished.

3.5 HANDLING PERFORMANCE

The Shuttle RMS was designed to handle payloads up to 65,000 lbm., while maintaining a tip positioning accuracy of 2 inches and one degree. A recent study sponsored by Johnson Space Center involving SPAR Aerospace and three independent contractors was conducted to determine the ability of the current RMS design to handle payloads outside of its design range (up to 250,000 lbm.). The results of this study, yet to be released, indicate the Shuttle RMS's performance is degraded by the increased mass, but not greatly. The greatest problems foreseen in such a situation stem from potential control system instabilities, where the position or rate of the payload oscillates about a desired point. All other handling characteristics were not seriously impacted, however.

The MSC's design range will extend to the massive payloads expected for the Space Station Freedom. The handling performance specifications are not known yet, but are expected to be more stringent since the improved sensors will enable higher-resolution control. The seven-joint arrangement will aid in obstacle avoidance, since an infinite number of arm configurations is available for a particular end-effector position and attitude.

Another improvement in the performance will come from the collision avoidance algorithms expected to be implemented in the control scheme. This should allow the operator to concentrate on the task, and pay less attention to the arm's configuration. The collision avoidance algorithm is expected to be based on a world model of the environment, rather than proximity sensors.

3.6 END-EFFECTOR DEXTERITY

The RMS's end-effector position and rate are determined by the joint encoders and tachometers. This causes problems, as stated previously, because using joint data assumes perfectly constant links connecting the joints, i.e. no change from the ideal. This is not generally true for space manipulators, because of their relatively flexible lightweight links.

The MSC manipulator control scheme will utilize vision data to determine the actual position and rates of the end-effector, and will close the loop around this information, rather than around the individual joints. This method will lead to an improvement in the accuracy of the end-effector's trajectory, and therefore its dexterity.

In addition to this improved positioning accuracy, even more dexterity will be obtained using the Special Purpose Dexterous Manipulator (SPDM). This item will be a tool attached to the end-effector (or elsewhere) which will use two small seven-joint manipulators with cameras to perform tasks which require highly precise motion, like module changeouts, adjustments, testing, and cleaning.

3.7 FAULT TOLERANCE

Fault tolerance is a measure of the ability of a system or component to function despite failures of subsystems. Redundant and/or backup subsystems are used to ensure this tolerance. A system may be fail-safe, which means a safe shutdown (not an out-of-control machine), or it could be fail-operational, which means operation of the device may continue (perhaps in a degraded mode) despite that failure.

A weak point in the design of the Shuttle's RMS lies in its fault tolerance. The RMS has some redundant equipment and backup control modes which can be used in event of certain failures, however unrecoverable failure scenarios do exist. The end-effector has several failure points which can completely disable it, effectively disabling the arm. This is because the RMS was designed to be fail-safe, instead of fail-operational.

The MSC, however, is expected to be designed to a philosophy of one-fault tolerance as a minimum, which implies a functional redundancy of two (two redundant strings of functional elements). Any functional capabilities of the MSC which may be essential to crew safety or Space Station survival shall be two-failure tolerant, i.e., the system will be able to continue operation after two failures, and the third failure will cause a safe shutdown.

4. CONCLUSIONS

The Shuttle RMS was the world's first manipulator designed and tested almost completely by computer. Its first flight on STS-2 was the first time it was able to operate, since it was too weak to operate under gravity. While the technology of robotics today has surpassed the RMS's mid-seventies design, much has been learned from this first manipulator. Armed with this experience, the United States and Canada are expected to jointly produce a final design which will serve the needs of the Space Station Freedom for years after its construction. The design, construction and operation of the MSC will yield valuable experience in the field of space robotics and control. Perhaps even more important are the potential benefits to ground-based robotic technology, artificial intelligence and information processing which are bound to result from the research required for this ambitious project.