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SPACE ROBOTICS AND MANIPULATORS – THE PAST AND THE FUTURE

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Abstract. This paper presents the current state of the technology in space robotics. Some historical developments and the experience gained during those projects have been discussed. The challenge of space exploration and related danger requires even larger use of robotic devices. Many tasks and jobs are being automated. The exploration of the Moon and Mars requires autonomous, mobile robots to gather various information, measurements and data. The introduction of the Space Shuttle and related activities required an efficient robotic manipulator for in orbit operations. The Space Station Mir (in-orbit) and especially Space Station Freedom or Alpha (planned for the very near future) require advanced robots and manipulators. The Space Station Remote Manipulator System (SSRMS) and Special Purpose Dextrous Manipulator (SPDM) have been shown and briefly reviewed.Those and other robots for future missions are discussed in this paper.

Keywords. Robotics; manipulators; space robots; aerospace control; automation; automatic control.

1. INTRODUCTION

Space exploration requires extensive use of robotics. This has been done in the past and will be done in the future on much and ever larger scale. Robotic devices in space could be divided into three groups:

- mobile robots;
- flying robots;
- robots and manipulators.

The second group may be considered as a subset of the first group but because of its distinctive features flying robots have been grouped as a separate entity.

Robots in Space can operate in three different modes:

- manual;
- automatic;
- teleoperation.

Mobile robots operating in an automatic mode can be further divided into autonomous and nonautonomous. From a locomotion point of view robots may be divided into rovers (wheeled), walking and other. In the past mobile robots have been used in several unmanned missions. The best known are Lunokhod 1 and Lunokhod 2, used in the Luna 17 and 21 missions respectively. Both used wheels as locomotion (8 wheels). Their respective weights were 456 and 539 kilograms. "Lunokhods" were designed to perform technical and scientific research on the Moon's surface. Flying robots can be divided into two groups: first - flying orbital probes like Mariners and Vikings (USA) or Lunas and Mars (Russia); second - flying teleoperators like the Flight Telerobotic Servicer (FTS). Robots and manipulators are used on board spacecraft (Space Shuttle) or space stations (Mir and Freedom - planned).

2. ROBOTS AND MANIPULATORS

Robots and manipulators in space are designed to perform the following operations: capture, maneuvering, berthing/deberthing, support of Extra-Vehicular Activities (EVA), positioning and release. One of the most important features of all robots deployed in space is their flexibility. Robots and manipulators used in space are built out of light materials, and very often their links deflect. Those robots are considered to be flexible. The first robot used in space was the Remote Manipulator System (RMS) mounted on the Space Shuttle. This robot was used for the first time on 12 November 1981 in the Columbia Shuttle. It is 15 meters long, has three hinged joints for pitch and three other for yaw and roll which makes a total of six degree of freedom (DOF). The Remote Manipulator System is shown in Fig. 1 and its kinematics in Figure 2 (Scott and Dameo, 1991). The Space Station Remote Manipulator System (SSRMS) which has been designed for use in the Space Station "Freedom" is shown in Fig.3. It is more than 17 meters long, has seven degrees of freedom and is a redundant DOF manipulator. The seventh degree of freedom has been introduced to avoid singularities in some specific but important positions.

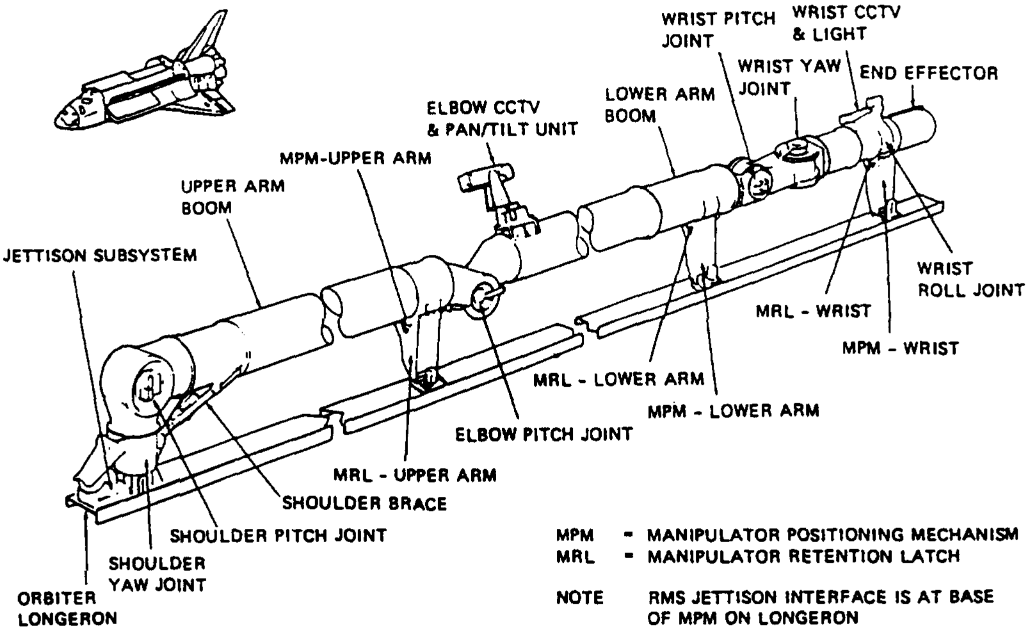


Fig. 1 Space Shuttle Remote Manipulator System (RMS).

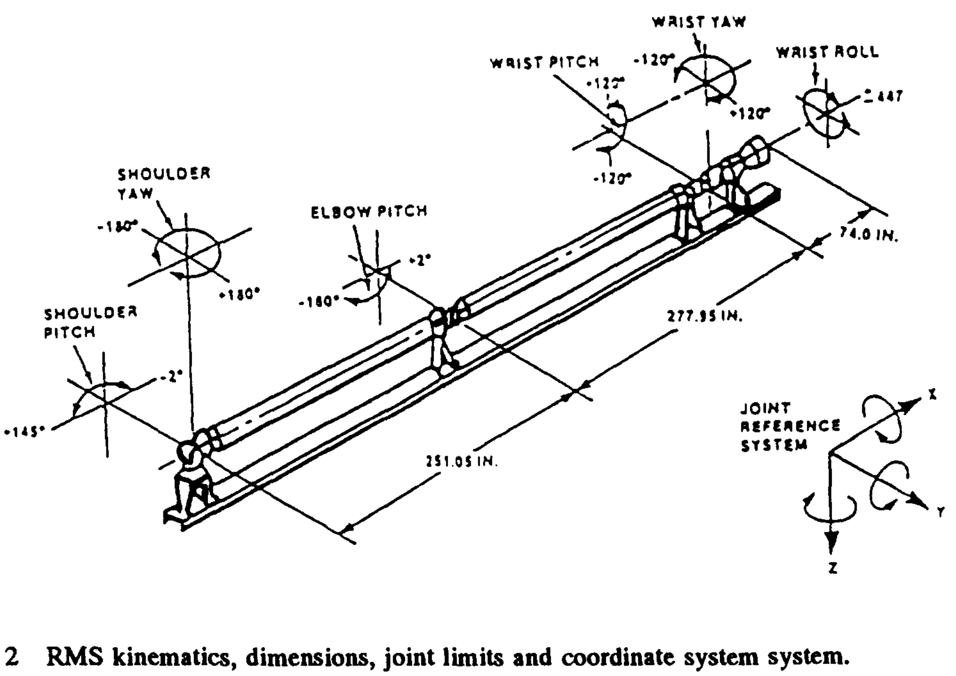


Fig. 2 RMS kinematics, dimensions, joint limits and coordinate system system.

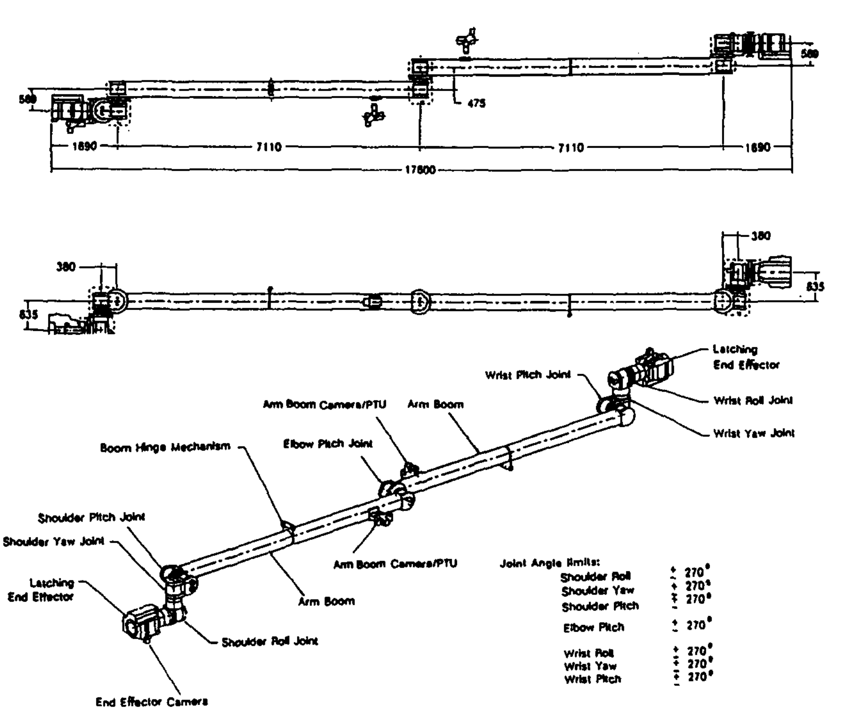


Fig. 3 The Space Station Remote Manipulator System (SSRMS).

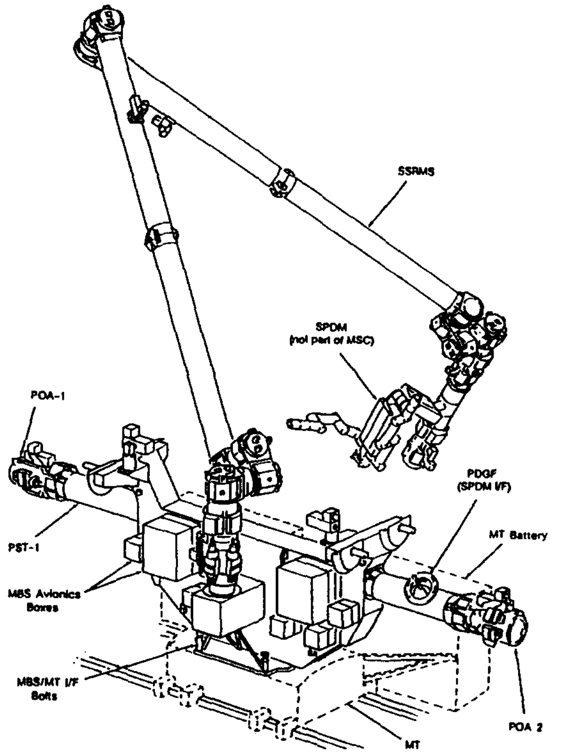


Fig. 4 The Mobile Servicing Centre (MSC).

The SSRMS is a part of a larger system called the Mobile Servicing Centre (MSC), shown in Fig.4 (Dignard, 1991). The Special Purpose Dextrous Manipulator (SPDM) shown in Figs 5 and 6 (Ravindram, 1990) is a two-arm manipulator designed for the Space Station "Freedom" application. The SPDM has two 7 DOF arms (Fig.6) and will be placed at the end tip of SSRMS. The length of each arm is 1.99m.

3. LESSONS LEARNED FROM THE PAST

The Space Shuttle Remote Manipulator System was originally planned to be used in two modes: manual and automatic (computer controlled). In practice RMS is being used only in the manual mode. There are numerous problems related to the use of the RMS in Space. One of the most important problems is related to its positioning. As was already mentioned, this manipulator is built out of light materials to minimize the launch cost which is ~$118K per kilogram for geostationary orbit (Wertz and Larson, 1991). The RMS may be considered as a very flexible manipulator, which means that its links deflect substantially. When the arm is accelerated and stopped, large vibrations occur which makes the positioning of the tip very difficult. The astronauts' experience while handling Space Shuttle cargo or satellites indicates that one has to wait several minutes for the manipulator's tip to stabilize. If more-complex assembly tasks or operations are being performed on the orbit, the cumulative settling time before the arm's tip vibrations damp down to within 1 inch amplitude's margin could be 10-20 hours or more for 15 Space Station Freedom (SSF) related flights. That has a major impact on efficiency of any operation in the orbit. There are two main methods of improving positioning accuracy of the RMS: passive and active. The passive methods are focused on redesigning the manipulator and application of different materials. This alone could bring a substantial improvement in the robot's dynamics performance. The drawback of this method is that it would increase the manufacturing

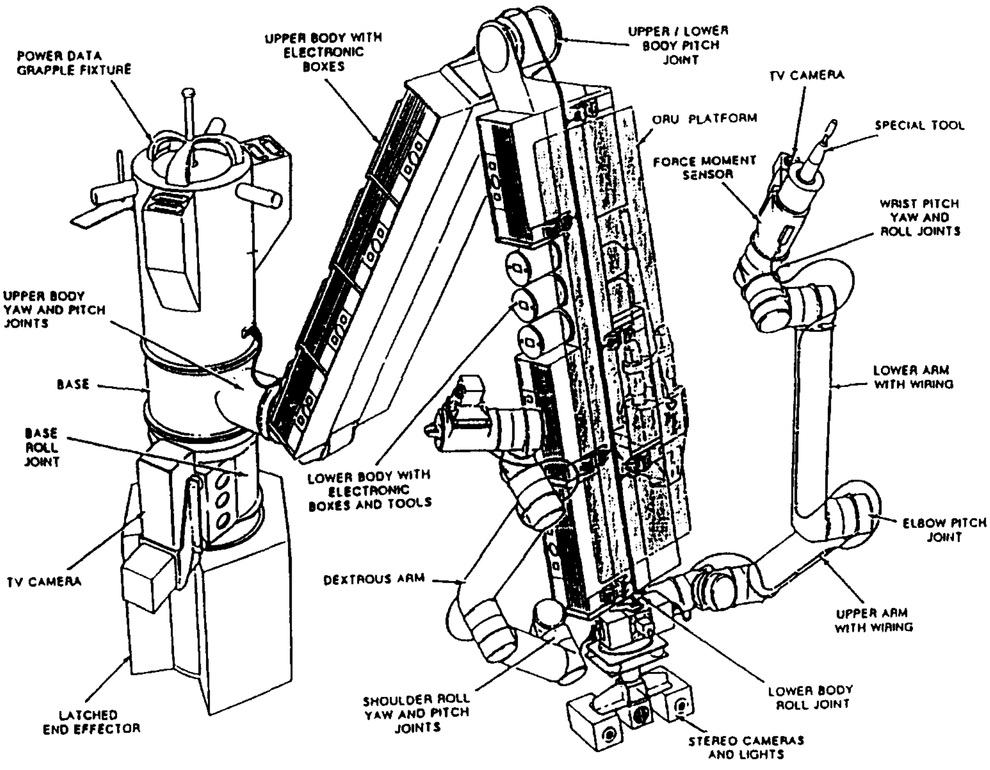


Fig. 5 The Special Purpose Dextrous Manipulator (SPDM).

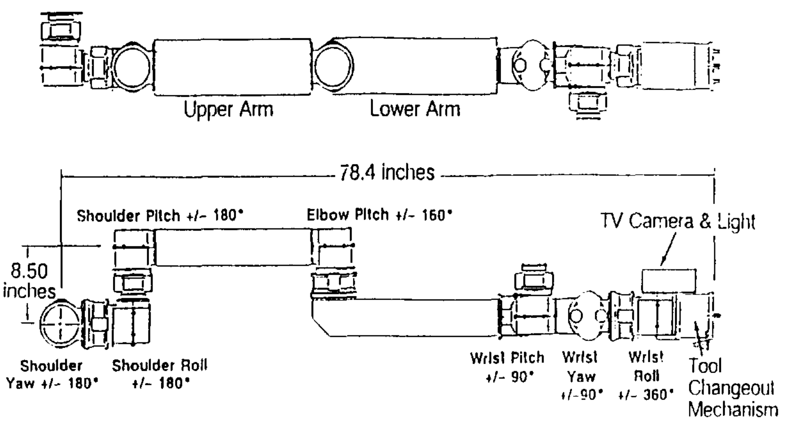


Fig. 6 SPDM Arm Configuration.

cost of the arm. The performance of the manipulator would improve but that could be limited only to certain types of operations.

The second, an active method, has more potential for improving the positioning of the arm's tip in various situations. There are two different methods to reduce the tip oscillations caused by commanded motions: first, the command input is preshaped and second, using position, velocity or force feedback to derive joint commands which are designed to damp oscillations. The "preshaped input" method is simpler, because it does not require identification of parameters like frequency, damping and friction. The drawback of this method is that it cannot take into account disturbances coming from the shuttle attitude changes. The "feedback " method may allow better damping but it requires the knowledge of the system in the form of a mathematical model and its parameters. There were several studies done on active vibration damping control (Dameo, 1990; Scott and Dameo, 1991) for the RMS. They all bring substantial improvement of positioning accuracy and they reduce the settling time. Scott and Dameo (1991) show the typical free responses (Figs 7, 8) which follow 10-second rotation command to the shoulder-yaw joint. The other joints are held fixed. Results obtained by Scott and Dameo (1991) and shown in Figures 9 and 10 (Scott and Dameo, 1991) indicate that the active control significantly improves damping (by factor of 3) and reduces the demand for peak joint torque (by factor of 2). The numerous experiments indicate that the velocity feedback (from tachometers) and the acceleration feedback (from accelerometers) are needed for accurate and fast position control of the RMS. A simple PID control or optimal control might not be satisfactory and more research is being done on adaptive control (Sasiadek and Srinivasan, 1989) and other types of control.

The Shuttle Remote Manipulator System often handles fragile payloads and a force control loop would greatly enhance its capabilities. Nguyen (1991) described his concept of force accommodation control. Another viable option for the RMS position control is to couple both methods: passive and active. It calls for better structural design but it also requires an implementation of one or more feedback control loops.

The following lessons have been learned from 11 years' use of the Remote Manipulator System:

- speed of manipulation should be drastically improved;
- the positioning accuracy is one of the most important issues in day-to-day operations;
- the new manipulators should be designed to include passive vibration control capabilities;
- new, active vibration control should be added in order to improve the positioning accuracy and shorten the settling time;
- the new force loop could add significantly to the capabilities of the manipulator.

4. FUTURE MISSIONS AND SYSTEMS

The planned assembly of Space Station "Freedom" creates new challenges for Space applications of robotics. Large payloads and main assembly operations will be performed with the help of newly designed SSRMS. The SSRMS is designed for payload capability up to 116,000 kg. The maximum tip velocity is 0.37 m/s. Its kinematics have been shown in Fig.2 . This figure also shows range limits for the manipulator's joints. The tip positioning accuracy is 4.5 cm with respect to the shoulder.

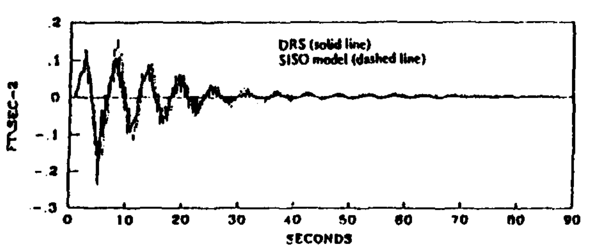


Fig. 7 Results for the Tip Accelorometer (from Scott and Dameo, 1991; with the AIAA permission).

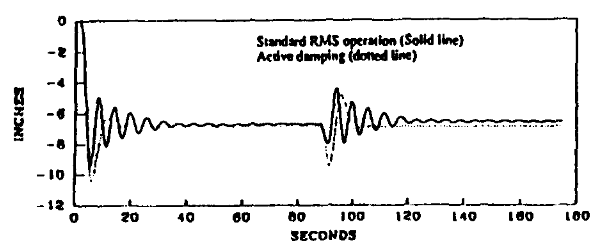


Fig. 9 RMS Tip Position during standard operation (from Scott and Dameo, 1991; with the AIAA permission).

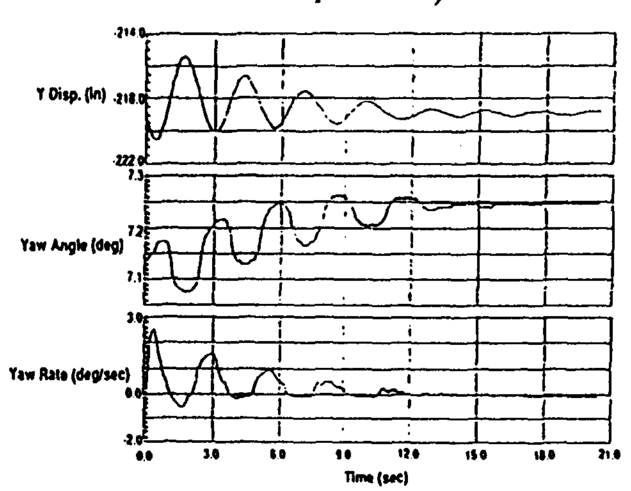


Fig. 8 Free Response of RMS (from Scott and Dameo, 1991; with the AIAA permission).

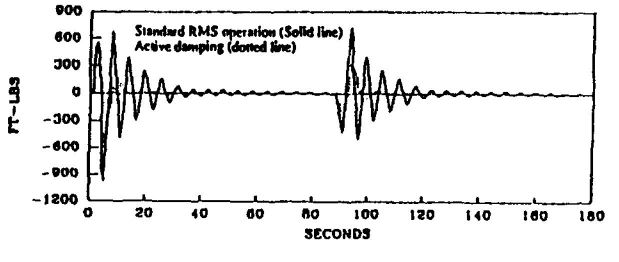


Fig. 10 RMS Shoulder Yaw Servo Torque during standard operation (from Scott and Dameo, 1991; with the AIAA permission).

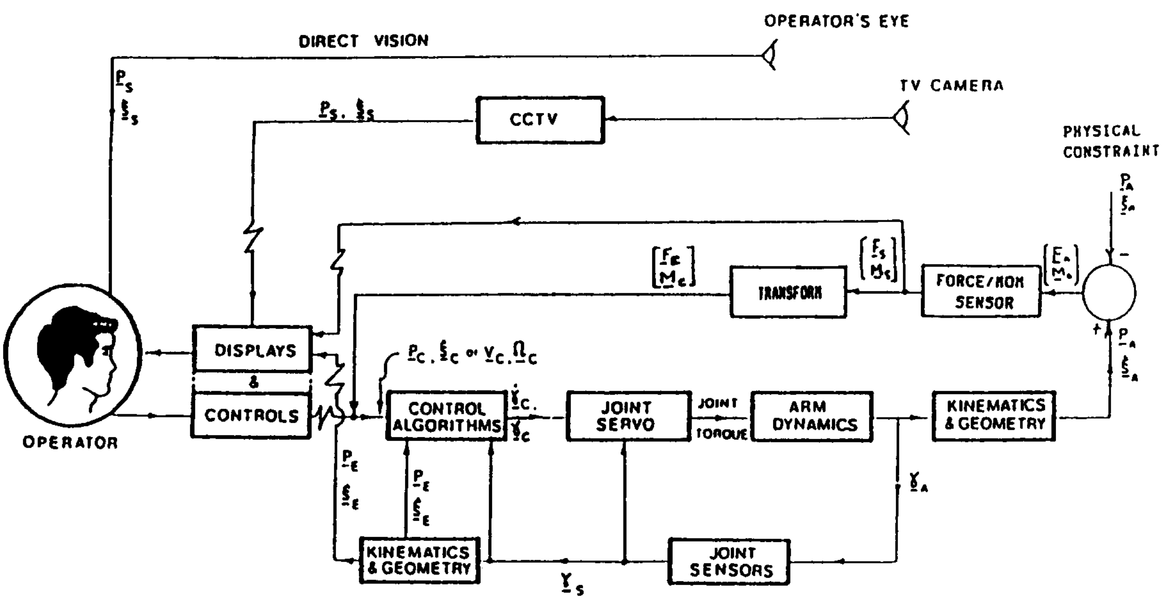
The control system for the SSRMS has been shown in Fig.11 . As was already mentioned, the SSRMS is part of Mobile Servicing Centre (MSC). The MSC, together with the SPDM and the Mobile Maintenance Depot (MMD), form the Mobile Servicing System (MSS) responsible for the majority of assembly and maintenance operations. The flow of information and data management architecture in the MSS has been shown in (Dignard, 1991). The MSS is controlled and operated from the pressurized environment and its human/machine interface is provided by the MSS Control Equipment (MCE).

The MCE is composed of the Hand Controller Assembly (HCA), Human-Computer Interface Software (IHS), the MSS Computing and Control Facility (MCCF), the Artificial Vision Unit (AVU), the Backup Drive Control Software (BDCS) and the Backup Drive Human-Computer Interface Software (BDIHS).

The SPDM is a two-arm robot which will be placed at the end of the SSRMS. Its payload capacity is 600kg. Unloaded manipulators could be positioned with an accuracy of 0.6cm . The SPDM is planned to be used for operations where higher accuracy is needed. It also handles much lower payload than the SSRMS.

Some aspects of SPDM and SSRMS control systems have been discussed by Stieber and Fung (1991). The control system for SPDM is quite sophisticated. It involves simultaneous position/force control of a dual-arm manipulator in complex tasks and hostile environment. The basic concept of dual-arm adaptive control has been discussed by Sasiadek and Srinivasan (1987). Two of the most important issues are the position/force control and grasping control.

The original plans for the Space Station Freedom (SSF) called for the Flight Telerobotic Servicer (FTS) which could fly in space in close proximity to the SSF and service the area difficult to reach for the SSRMS and SPDM. The FTS has two arms built on a flying base. That introduces at least three additional degrees of freedom and makes the design of the control system even more challenging. Flying robots will have to be moving much faster than an average spacecraft. Positioning and orientation of space-based robots will require more reliance on thrusters than in spacecraft. Thrusters used in these robots have to be very efficient from a fuel point of view and frequent refueling will be required. Other technologies developed for spacecraft such as the "momentum wheel" will be also used, but their design will be changed to accomodate the need for faster movemants. It is expected that space-based robots will be refueled from the Space Station



P = END-EFFECTOR POSITION
ξ = END-EFFECTOR ORIENTATION
V = END-EFFECTOR LINEAR VELOCITY
F = END-EFFECTOR FORCE
M = END-EFFECTOR MOMENT
Ω = END EFFECTOR ANGULAR VELOCITY
γ = JOINT ANGLE
γ̇ = JOINT ANGLE RATE
C = COMMANDED
E = ESTIMATED(COMPUTED)
S = SENSED
A = ACTUAL

Fig. 11 SSRMS Control System.

itself. The latest changes in the design concept of the Space Station, especially the change from the Station "Freedom" to the Station "Alpha" will make refueling difficult as there is not much room for fuel tanks in the latest version of the Space Station. Almost all known concepts of flying robots are kinematically redundant which improves their manipulability and makes them suitable for broader range of tasks. Robots in space will have an advanced guidance and navigation system. This includes a "dead reckoning" system for path tracking and navigation along prescribed trajectories, and a collision-avoidance system to avoid obstacles such as parts of the station's structure. An interesting problem to be solved is the momentum and vibration transfer from objects which have been intercepted and grasped by flying robots. Here, the theory and practice of non-holonomic systems control should be very helpful.

The following problems are considered the most important and challenging in the future development of space robots:
- increasing autonomy of space robots;
- broad application of telerobotics;
- improved and more efficient position and force control systems;
- development of new free flying robots;
- design of new, autonomous mobile robots for exploration of planets.

5. CONCLUSIONS

The exploration of space poses new problems and requirements for development of robotic devices. Space voyages will take more time and astronauts will spend longer time in space. However, before man is sent to other planets or systems, a thorough exploration has to be done using various kind of robots. The characteristic feature of the development of Space Robots is that two main streams are being pursued simultaneously; one related to autonomous robots and second involving telerobotics with force feedback. This may help astronauts to perform various tasks and operations without leaving the pressurized environment.

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