Space Tele-Robotics

by

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Abstract of the Dissertation
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The International Space Station (ISS) has been under assembly since 1998. During the build phase and after Permanently Manned Capability (PMC), the Mobile Servicing System (MSS) will be used as a tool to assist the crew in the assembly and maintenance of the ISS. The operation of the MSS will be executed and controlled by the crew of the ISS, which will impact the limited crew resources. The current plan specifies that the MSS will not be operable when the crew is not present.

Simulations have been conducted to quantify the maintenance workload expected over the life of the ISS. These simulations predict a peak in maintenance demand occurring even before PMC is achieved. The MSS is key to executing those maintenance tasks, and as a result the demands on MSS crew resources will likely exceed availability, thereby creating a backlog of Maintenance Actions (MA) and negatively impacting ISS effectiveness.

Ground Operated Telerobotics (GOT), the operation of the MSS from the ground has been proposed as an approach to reduce the anticipated maintenance backlog as well as reduce the crew workload when the MSS can be used for simple or repetitive tasks both when the ISS is occupied and not.

An extensive review of the literature revealed factors critical to the successful implementation of GOT and various simulation and design considerations. The resulting design requirements were generalized for any teleoperated robot situation from ocean to interplanetary.

CONTENTS

TOC \O "1-3" LIST OF TABLES

iv

LIST OF FIGURES

PAGEREF _Toc468104074 \h v

ACKNOWLEDGEMENTS

PAGEREF _Toc468104075 \h vi

INTRODUCTION

PAGEREF _TOC468104076 \H 1

BACKGROUND OF THE PROBLEM

PAGEREF _TOC468104077 \H 1
Assembly and servicing
PAGEREF _Toc468104078 \h 1
Payload Actuation and Manipulation
PAGEREF _Toc468104079 \h 1
Exploration
PAGEREF _Toc468104080 \h 2
Robot vs. Man
PAGEREF _Toc468104081 \h 2

STATEMENT OF THE PROBLEM

PAGEREF _TOC468104082 \H 3

PURPOSE OF THE STUDY

PAGEREF _TOC468104083 \H 4

DEFINITION OF TERMS

PAGEREF _TOC468104084 \H 4

LIMITATIONS OF THE STUDY

PAGEREF _TOC468104085 \H 6

REVIEW OF THE LITERATURE

PAGEREF _TOC468104086 \H 7

ROBOTICS ACTIVITIES THROUGHOUT THE WORLD

PAGEREF _TOC468104087 \H 7
France
PAGEREF _Toc468104088 \h 7
Germany
PAGEREF _Toc468104089 \h 8
Italy
PAGEREF _Toc468104090 \h 9
The Netherlands
PAGEREF _Toc468104091 \h 10
Belgium
PAGEREF _Toc468104092 \h 10
Spain
PAGEREF _Toc468104093 \h 10
Japan
PAGEREF _Toc468104094 \h 10
Russia (RKA)
PAGEREF _Toc468104095 \h 11
USA
PAGEREF _Toc468104096 \h 12

TECHNOLOGY

PAGEREF _TOC468104097 \H 19
Control Modes
PAGEREF _Toc468104098 \h 19
NASREM.
PAGEREF _Toc468104099 \h 20

Kinematics
PAGEREF _Toc468104100 \h 23
Robot Motions
PAGEREF _Toc468104101 \h 35
Trajectory Planning and Object Avoidance (TPOA) system
PAGEREF _Toc468104102 \h 42

INTERNATIONAL SPACE STATION

PAGEREF _TOC468104103 \H 49
Overview
PAGEREF _Toc468104104 \h 49
Mobile Servicing System (MSS)
PAGEREF _Toc468104105 \h 50
Japanese Experimental Module Remote Manipulator System
PAGEREF _Toc468104106 \h 65
Design issues
PAGEREF _Toc468104107 \h 72
Simulation
PAGEREF _Toc468104108 \h 75
The Future.
PAGEREF _Toc468104109 \h 78

APPLICATIONS

PAGEREF _TOC468104110 \H 79
Space-Based Scientific Platform (Space Station)
PAGEREF _Toc468104111 \h 79
Servicing In Space (SIS)
PAGEREF _Toc468104112 \h 80
Planet Explorations
PAGEREF _Toc468104113 \h 81

METHODOLOGY

PAGEREF _TOC468104114 \H 89

RESULTS

PAGEREF _TOC468104115 \H 90

ACCURACY, REPEATABILITY AND LATENCY

PAGEREF _TOC468104116 \H 90
Thermal Expansion or Contraction
PAGEREF _Toc468104117 \h 90

FAIL SAFE

PAGEREF _TOC468104118 \H 93

MOTION OPTIMIZATION

PAGEREF _TOC468104119 \H 93

SIMULATION DISPLAY REQUIREMENTS

PAGEREF _TOC468104120 \H 94

ROBOT ENVIRONMENT

PAGEREF _TOC468104121 \H 95

ERROR DETECTION AND REPORTING

PAGEREF _TOC468104122 \H 95

REFERENCES

PAGEREF _TOC468104123 \H 97

LIST OF TABLES

Page
TOC \h \z \c "Table" HYPERLINK \l "_Toc50961162" Table 1. RMS characteristics (joint issues)
PAGEREF _Toc50961162 \h 15
HYPERLINK \l "_Toc50961163" Table 2. Comparison of algorithms
PAGEREF _Toc50961163 \h 33
HYPERLINK \l "_Toc50961164" Table 3. SSRMS Design Parameters.
PAGEREF _Toc50961164 \h 52
HYPERLINK \l "_Toc50961165" Table 4. SSRMS Control Modes
PAGEREF _Toc50961165 \h 55
HYPERLINK \l "_Toc50961166" Table 5. JEM-RMS Arm Specification
PAGEREF _Toc50961166 \h 70

LIST OF FIGURES

Page
TOC \h \z \c "Figure" HYPERLINK \l "_Toc50961135" Figure 1. Functional block diagram of robot system
PAGEREF _Toc50961135 \h 6
HYPERLINK \l "_Toc50961136" Figure 2. Space Vision System
PAGEREF _Toc50961136 \h 18
HYPERLINK \l "_Toc50961137" Figure 3. Control Modes
PAGEREF _Toc50961137 \h 20
HYPERLINK \l "_Toc50961138" Figure 4. NASREM Architecture
PAGEREF _Toc50961138 \h 21
HYPERLINK \l "_Toc50961139" Figure 5. Joint dynamics reference frames.
PAGEREF _Toc50961139 \h 41
HYPERLINK \l "_Toc50961140" Figure 6. TPOA System Conceptual Framework
PAGEREF _Toc50961140 \h 43
HYPERLINK \l "_Toc50961141" Figure 7. TPOA Methodologies
PAGEREF _Toc50961141 \h 44
HYPERLINK \l "_Toc50961142" Figure 8. International Space Station.
PAGEREF _Toc50961142 \h 49
HYPERLINK \l "_Toc50961143" Figure 9. The Mobile Servicing System (MSS)
PAGEREF _Toc50961143 \h 51
HYPERLINK \l "_Toc50961144" Figure 10. The Space Station Remote Manipulator System (SSRMS)
PAGEREF _Toc50961144 \h 54
HYPERLINK \l "_Toc50961145" Figure 11: SSRMS Handoff Operation with SRMS
PAGEREF _Toc50961145 \h 59
HYPERLINK \l "_Toc50961146" Figure 12. The Special Purpose Dexterous Manipulator (SPDM).
PAGEREF _Toc50961146 \h 63
HYPERLINK \l "_Toc50961147" Figure 13. SPDM ORU Tool Change-out Mechanism (OTCM) & SPDM Tools
PAGEREF _Toc50961147 \h 64
HYPERLINK \l "_Toc50961148" Figure 14. Japanese Experimental Module
PAGEREF _Toc50961148 \h 67
HYPERLINK \l "_Toc50961149" Figure 15. JEM Remote Manipulator System (JEM-RMS)
PAGEREF _Toc50961149 \h 69
HYPERLINK \l "_Toc50961150" Figure 16. Typical Grapple Fixture
PAGEREF _Toc50961150 \h 74
HYPERLINK \l "_Toc50961151" Figure 17. Latching End Effector
PAGEREF _Toc50961151 \h 75

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INTRODUCTION

Background of the Problem

Space is a hostile environment for human beings. At great expense humans are sent into space to perform tasks that are innately suited to them and for which there is no practical alternative. Even when protected from the vacuum and radiation of space, the physiological effects of zero or low gravity limits the amount of time an astronaut can remain in space. Consequently, astronauts are regularly cycled back to Earth.

Astronauts are called upon to construct and maintain their habitat in space as well as conduct various experiments. Eventually product production activities will be included among the many astronaut tasks. Given the high cost of transporting astronauts to space and sustaining them there, their numbers are limited, so the work demanded from them is often excessive.

There are three main areas where robots may replace or augment astronauts in space:

Assembly and servicing

Attached or free-flying robots can repair small satellites, the assemble space structures and service external space platform payloads.

Payload Actuation and Manipulation

Robots can be used inside astronaut-occupied environments (pressurized living spaces) to maintain and service payloads. This capability reduces the requirements for intensive astronaut maintenance of these payloads, and permits operation of the payloads during periods when the astronauts may not be present.

Exploration

Robots can be used as reconnaissance and surveying systems for the exploration of the other planets. During those missions, potential landing sites and areas of scientific interest are explored, science instruments are placed, and samples for analysis are gathered and possibly returned to Earth.

Robot vs. Man

Humans are better at the following tasks:

Detecting small amounts of visual, auditory, or chemical energy
Perceiving patterns of lights or sounds
Improvising and using flexible procedures
Storing information for long periods of time, recalling appropriate parts of that information and reasoning inductively
Exercising judgment (strategic, tactical and moral).

Machines are better at the following tasks:

Responding quickly to control signals or feedback
Applying great force smoothly and precisely
Storing information briefly and erasing it completely
Reasoning deductively

Performing many complex operations at once

Many of these and future space robots could be remotely controlled twenty-four hours a day, seven days a week, 365 days a year by multiple shifts of operators on Earth. Such “teleoperators” would free astronauts to do more work that cannot be done by a machine, or reduce the number of astronauts needed in space for the duration of a mission, and, hence, reduce the cost of the mission.

Statement of the Problem

There are difficulties associated with robots, their teleoperation and their teleoperation over long distances such as those encountered in Earth to space operations.

General problems

Degrees of freedom – The required motion trajectory may be impossible to follow if the ability of the robot translate and rotate objects is limited to anything less than six degrees of freedom.

Motion optimization – Robots can be less efficient if the trajectory of movement is not optimized.

Spatial resolution – Accuracy may suffer if the minimim measurable unit is too large for the task.

Accuracy – Payload placement or orientatoin may be incorrect if the net accuracy of the robot does not matach its resolution.

Repeatability – Placement or orientation may be incorrect if the robot cannot repeatedly move to the same position and orientaton in time.

Stability – Unintended motion could result in collisions with objects near the intended trajectory of motion. Slowly damped oscillations will waste time while the operator waits for a stable arm before conducting the next move, or worse, an operator may attempt a motion under the misguided impression that a robot apendage is at a specific poition in space and cause a collesion. If the robot is dynamically unstable, it could destroy itself as well as objects withing its reach.

Compliance – If the robot does not respond as its controller intended, unintended collisions could occur.

Teleoperation problems - Observation difficulty

Teleoperations in space - Telecommunication time delay

Purpose of the Study

The intent of this study is to demonstrate the practicality of teleoperated robots in space, and propose methods of eliminating the problems associated with it

Definition of Terms

Automation

The automatically controlled operation of an apparatus, a process or a system by mechanical or electronic devices that substitute for human organs of observation, decision, and affect.

Robot

A programmable multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable motions for the performance of a variety of tasks. It may be automated to the extent that it performs functions ordinarily ascribed to human beings or operates with what appears to be almost human intelligence.

Pick-and-place robots: These robots perform the operation of grasping individual parts in a known location and placing them in a known location. Typically no reorientation of parts is required.

Assembly robots: These robots adapt to part position and orientation variations, significantly change the position and orientation of parts as they are assembled, and may include accessories to fix the part in place using multiple end effectors (screw drivers, riveters, adhesives, arc welder).

Adaptive robots: These robots are able to sense their environment and modify their actions in response to the information sensed.

Robotics

The science and art of designing and using robots.

Robot System

The typical robot system consists of the following major subsystems:

Manipulator system: Typically a mechanical arm mechanism, consisting of a series of links and joints that perform the motion by moving the end-effector through space. It closely resembles a human arm and consists of a base, shoulder, elbow, and wrist. Each joint couples two links in one motion plane. Multiple joints at the same location increase the degrees of freedom of the associate link (simultaneous angular motion in all three spatial coordinates, linear motion along any angle, rotational motion at any angle or linear position).

End-effector: Typically a device that can grasp various end-effector tools as needed for various tasks (hand),

Actuator power drive: Provides electric, hydraulic or pneumatic energy to move the manipulator arm and end-effector.

End-effector tool: Anything from a screw or nut driver to a welder or another robot that makes it possible for the robot to perform a specific task.

Fixtures: The fixed jigs and other tooling that facilitate or make more accurate the activities of the end-effector.

Controller: Converts simple motion commands into device driver commands for all the robot components involved in the movement.

Sensor: Provides pressure (contact, force, torque), photon (visual) acoustic (proximity or process) or thermal (proximity, process) feedback to the controller so it can iterate movement as a function of the sensed information.

Interface: Allows external systems to communicate gross or specific commands to the controller.

Figure 1 shows how the subsystems interact.

EMBED Visio.Drawing.6

Figure SEQ Figure * ARABIC 1. Functional block diagram of robot systems

Teleoperator
A machine that extends a person's sensing and/or manipulating capability to a location remote from that person.

Teleoperation
The direct and continuous control of the teleoperator.

Telerobot
An advanced form of teleoperator, the behavior of which a human operator supervises through a computer intermediary.

Telerobotics
The supervisory control of a teleoperator.

Limitations of the Study

This study was primarily a broad literature search and detailed review of the literature. The results derived from that review are limited to requirements for the viable teleoperation of robots in space.

REVIEW OF THE LITERATURE

Robotics Activities Throughout the World

France

France is funding robotics activities primarily in three different areas, extra-vehicular robotics, internal robotics and planetary robotics.

Extra-Vehicular Robotics

Development of a large extravehicular robot arm technology model (Maquette Fonctionnelle de Bras - MFB). This program partly overlaps the ESA's SMS (Service Manipulator System) development and will undergo further improvements. SMS focused more on technology development and pre-design, whereas MFB was oriented towards a system test bed (primarily for control and dynamics).

Internal Robotics

The development of an internal payload servicing test bed (BAROCO) and the ESA/CAT (Centre d'Avancement Technologique) facility functionally overlap. However, they are complementary in technology, because BAROCO is focusing more on advanced teleoperation whereas CAT mainly implements supervised automatic control. Centre Nationale d'Etude Spatiale (CNES) has shown interest in the BioRob experiment, and is prepared to support its ground segment by reusing MATRA's developments for CAT and BAROCO.

Planetary Rovers

In 1996 a first CNES/Russian planetary rover was planned to land on Mars (MARSOSHOD ’96), for which CNES is developing the camera, vision system and navigation control. Moreover, another cooperative program for an instrumented mars rover, called VAP (Véhicule Autonome Planétaire) has been studied and is now entering the technology preparation phase (I-ARES, ground demonstrator). Mostly French companies and institutes, but also Russian, Hungarian and Spanish partners, participate in VAP.

Apart from direct development work for these three application fields, CNES also has a substantial technology preparation program, which constitutes the prime activity for the robotics section of CNES Toulouse. In this forum, CNES is studying a Japanese offer for cooperation on NASDA experiments in robotics whereby NASDA test beds at Tsukuba space center can be operated from CNES Toulouse and vice versa.

Germany

The main activities in space automation and robotics (A&R) Deutsche Agentur fur Raumfahrtangelegenheiten (DARA) include the following:

The “Robotic Technology Experiment” (ROTEX) flew on the Spacelab mission D2 (planned and executed in March 1993). ROTEX is a technology demonstration experiment whereby an anthropomorphic robot arm performs representative tasks, such as Orbit Replacement Unit (ORU) exchange and object grappling, under different control modes. The novelties of ROTEX are the multi-sensory gripper and the computer-assisted telemanipulation control. ROTEX will be the first European space robot to be operated in space. Using this equipment, the multi-sensory gripper and its control algorithms could be of direct relevance for the Columbus Advanced Meteorological & Temperature System (AMTS) development. So far, no subsequent application is foreseen for ROTEX.

The MARS/ARCOS development: ARCOS is a development of an Automation and Robotics Control System and is proposed for harmonization with ESA. The Man-Tended Free Flyer (MTFF) Automation & Robotics Servicing test bed (MARS) is an internal payload servicing test bed. It therefore covers the same applications as CAT, but concentrates more on technology investigations, such as interfaces to the station and data control, while CAT emphases utilization support and complete operations.

Italy

Agenzia Spaziale Italiana's (ASI) funding for A&R activities is focused towards channeling the valuable existing robotic expertise in the country to space applications. Apart from creating a nucleus of competence for technology development, ASI plans to start an ambitious program called SPIDER (Space Inspection Device for Extra-vehicular Repairs) for the development of a free-flying robotized service vehicle operating in the vicinity of, or docked to, the Space Station, and also adaptable to other orbits. The plan is separated into the following two lines of action:

SPIDER: a phase A was concluded in 1991 showing the feasibility of such a vehicle, and a phase B is in preparation for the overall design of the fully autonomous spacecraft. An early, simplified version of this spacecraft was offered to European Space Agency (ESA) as a chaser in the AR&C (Automatic Rendezvous and Capture) demonstration program.

Bread-boarding (an experimental model, especially of an electric circuit; a prototype) activities in different directions and ground test beds and facilities. Some of these bread-boarding activities are complementary to ESA activities, such as the CAT development and the SPARCO (Space Robot Controller) development.

ASI also funds the robotic part of Robotic Servicing Demonstrator (ROSED), an Italian-Belgian harmonization program.

The Netherlands

The National Aerospace Laboratory (NLR) has started a development of an intra-vehicular payload operations test bed known as the Automation and Robotics for Microgravity Applications Demonstrator (ARMADE) that partially overlaps with CAT. No plan for implementation exists yet, but harmonization with CAT is being discussed.

NIVR has also shown interest in the BioRob experiment for some of the payload element developments.

Thanks to the astronomy user community of The Netherlands, there was strong interest in the technology preparation activities for robotic EVA servicing on the External Viewing Platform (EVP), which is attached to the free docking port of the APM.

Belgium

Belgium has no space robotic program of its own but contributes (on a 50/50 basis with Italy) to the ROSED program. Its industrial involvement is primarily with the equipment that complements the robot, such as sensor instrumentation, gripper, and work cell, and integration and testing.

Spain

So far, the Spanish national space program has undertaken limited space robotics activities, but CDTI (Centreo para el Desarrollo Tecnológico e Industrial) has shown interest in entering the area, especially in robotic engineering and in subsystem elements such as end effectors.

Japan

NASDA currently concentrates its robotic activities in the following areas:

The robot arm development and fine manipulator for the Japanese Experiment Module (JEM) contribution to the International Space Station: A number of ground test beds for the JEM arm already exist, both in NASDA and in industry, and the technology seems to be very close to the Canadian developments. Both systems are utilized on International Space Station (ISS), based on telemanipulation with a direct view on the worksite by the operator.

Japan, and especially the Japanese Post, Telephone and Telegraph (PTT), is very interested in the servicing of geostationary satellites.

Russia (RKA)

Surface roving and planetary exploration technologies are being developed, but little information is known about robotic manipulator developments for the Mir space station or other applications.

A robot arm for the Buran space plane was developed and a flight model exists. This robot is very similar to the US Shuttle Remote Manipulator System (SRMS).

Mir currently has two "robots." One is used to re-berth a previously docked module to another docking interface. The other is a slender beam manually operated by the crew in external activities to support transportation of material and other crewmembers. Plans exist to elaborate the berthing arms into six degrees of freedom (6-DOF) robots for active berthing because of the distinct advantages of berthing over direct docking in certain cases.

Russia has a long tradition in planetary roving vehicles, and activities are currently focused on the Mars '96 mission. This mission, including CNES among its international partners, will deploy a semi-autonomous six-wheel Mars rover (MARSOHOD) carrying a soil drill, seismic radar, and other scientific instruments.

USA

The National Aeronautics and Space Administration (NASA) has been successfully operating the SRMS for many years and in a wide variety of missions. Because of its operational flexibility, this manipulator is now used for many more tasks than anticipated in the beginning. Since its first mission in November 1981, the RMS, which features the 850 lb., 50-ft. long remote manipulator arm, or Canadarm, has become one of the most versatile and successful components of the shuttle configuration. NASA includes the arm on about five out of every six shuttle flights, even when it has no specific plans to use it.

Shuttle Remote Manipulator System

The SRMS is the result of a cooperative program between the Canadian Space Agency (CSA) and NASA. It consists of the arm, a display and control panel (including two hand controllers), and a manipulator controller unit that interfaces with the shuttle computer. The arm may be installed on either the port or starboard side of the shuttle. So far, however, it has only been used on the port side.

The SRMS is designed to perform payload deployment and retrieval as well as vehicle breathing tasks in and around the shuttle cargo bay when the shuttle is in orbit. The manipulator assembly consists of seven rotational joints, namely, shoulder swing-out, shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, wrist yaw, and wrist roll. The swing-out joint is a roll joint, which allows the arm to deploy from its inboard storage position to the outboard operational position. Optically commutated, brushless DC motors, driven by servo power amplifiers inside the arm, power each joint. The 13-inch diameter upper and lower arm booms of the RMS, which together weigh less than 120 lbs, are thin-walled tubes of multi-ply graphite epoxy. Their stiffness keeps the arm's tip from moving more than 1 in. under a 10-lib force. A combination of closely fitting insulating blankets, thermostatically controlled heaters, and radiation surfaces protect the arm from the intense heat and cold of space.

The most complex mechanism of the arm is its cylindrical end effector, which is a wire-snare device at the end of the arm. When a payload is captured, the wire noose is tightened, and pulls the payload snuggly against the rim of the end effector. The payload is released by opening the snare wires. Ultimately, other tools may be used to provide greater dexterity than even the human hand.

Operations

A mission specialist operates the manipulator system by standing at the control panel mounted on the aft bulkhead of the crew compartment. Usually a second flight crewmember assists with television camera operations. The astronaut looks directly into the shuttle cargo bay through two windows in the aft bulkhead and above the shuttle through two more windows overhead. The astronaut controls the arm from the display and control panel by using software contained in a general-purpose computer through a manipulator controller interface unit. The interface unit disseminates information among the display and control system, RMS software in the computer, and the manipulator arm itself. The astronaut moves the two hand controllers to operate the arm, either one joint at a time or all six moving in a coordinated motion. The arm can also be programmed to work automatically, with the operator using the keyboard to enter destination coordinates or a pre-programmed sequence of trajectory points. Astronauts monitor the arm's operation through a system of television cameras and lights on the arm and in the cargo bay.

Measures

The RMS arm is 50 feet, 3 inches long and 15 inches in diameter and has six degrees of freedom. The arm weighs 905 pounds. It and its peripheral systems weigh 994 pounds. It is capable of deploying or retrieving payloads weighing up to 65,00 pounds.

The RMS can be operated only in a zero-gravity environment, since the arm DC motors are unable to move the arm's weight under the influence of earth's gravity. Each of the six joints has an extensive range of motion, allowing the arm to reach across the payload bay, over the crew compartment, or to areas on the undersurface of the shuttle. Arm joint travel limits are announced to the flight crew arm operator before the actual mechanical hard stop for a joint is reached.

For example, the pitch joint can be physically moved to ± 121.4 degrees to the mechanical hard stop. At ± 114.4 degrees the software warns the RMS operator by activating the yellow "reach limit" light, the "master alarm" push button indicator and tone on the control panel, and a reach limit indication on the cathode ray tube (CRT) monitor. If the RMS operator continues driving the joint past the reach limit, the next warning is the joint's soft stop. At this point (± 116.4 degrees for the wrist pitch joint), the "software stop talkback" shows a barber pole. The arm drops out of mode (if it was being driven in one of the computer-augmented modes) and is unable to be driven further without operator action. The arm can only be operated in the single, direct, or backup modes after it reaches a soft stop. If one continues to drive the joint in this direction, motion will stop at ± 121.4 degrees for wrist pitch because a joint cannot be driven past its hard stop. All joint angles equal zero degrees when the arm is cradled. Table 1 summarizes the characteristics of the RMS joint.

Table SEQ Table * ARABIC 1.

RMS characteristics (joint issues)

Joint	Reach Limit Location (degrees)	Soft Stop Location (degrees)	Mechanical Stop Location (degrees)	Singularity Location
Shoulder yaw	+175.4	-177.4	+180.0	
Shoulder pitch	+140.4	+142.4	+145.0	
Elbow pitch	-155.6	-157.6	-161.0	-7.6
Wrist pitch	-114.4	-116.4	-121.4	-75/-105
Wrist yaw	-114.6	-116.6	-121.3	+75/+105
Wrist roll	-440.0	-442.0	-447.0	

The two lightweight boom segments are named the “upper arm” and “lower arm.” The upper boom connects the shoulder and the elbow joints, and the lower boom connects the elbow and wrist joints. The booms are made of graphite epoxy. They are 13 inches in diameter by 17 feet and 20 feet, respectively, in length and are attached by metallic joints. The composite in one arm weighs 93 pounds. The joint and electronic housings are made of aluminum alloy.

End-Effector

The standard end effector is considered the hand of the RMS. It is a hollow, can-like device attached to the wrist roll joint at the end of the arm. Payloads to be captured must be equipped with a grapple fixture. To capture a payload, the fight crew operator aligns the end effector over the grapple fixture probe to capture it.

The end effector snare consists of three cables that have one end attached to a fixed ring and one attached to a rotating ring. An end effector capture and release rocker switch on the RMS rotational hand controller initiates a capture by depressing the bottom half of the rocker switch, which causes the inner cage assembly to rotate its three wire snares around the payload-mounted grapple fixture probe, and centers the payload grapple fixture in the end effector. The RMS Rotational Hand Controller (RHC) end effector switch must be engaged until the payload-mounted grapple fixture is centered.

The RMS RHC end effector capture switch is powered only if the end effector mode switch is in the automatic or manual positions. Its activation causes a jackscrew to draw the snare assembly inside the end effector, pulling the payload tightly against the face of the end effector and making the arm and payload assembly rigid. During this process, electrical current limit commands are sent to each joint motor to relax the arm, allowing the arm to move and compensate for misalignment errors. Wrist roll can still be commanded with a limp arm. One dual-end motor produces all the motion in the end effector. The end effector electronics unit processes the end effector commands to produce the appropriate motor, clutch, and brake commands.

The rigidize sequence can be accomplished automatically or manually. The flight crew operator selects the mode with the end effector mode switch (“Auto”, ”Off”, ”Man”). Positioning the switch to “auto” causes the rigidize sequence to proceed automatically. If the switch is set to “man,” the end effector manual control switch must be positioned to

"Rigid." To release a payload, the snare mechanism moves outward until there is no force pulling the payload against the end effector. This is known as *derigidizing*. If the end effector mode is set to "Auto, lifting the RMS RHC switch guard and depressing the top half of the rocker switch commands a release. Derigidization automatically occurs, the snares of the end effector rotate open, and the payload grapple fixture is released. If the switch is set to "man," the end effector "Man" control switch must be positioned to "derigid."

Vision system

The Canadian Space Vision System senses and calculates the exact position of a payload 30 times every second. This allows astronauts to determine quickly and precisely whether their payload is moving in the correct speed range to permit capture. The system also makes shuttle-docking operations with satellites and the Space Station safer, quicker, and more accurate, especially when huge satellites that obliterate all direct views need to be berthed. The vision system is based on a technique called "real-time single camera photogrammetry." For the Space Vision System, this involves the computerized analysis of video images generated by a TV camera at a rate of 30 frames per second. To identify the target (a pattern of dots attached to the payload) for the Space Vision System computer, the operator views the object on a TV monitor and touches a light pen to each of the target dots. This causes the dots on the display to be highlighted by rectangles called "aperture windows." The computer then calculates the positions of these dots. The camera transmits analog signals to a “video sampling processor,” where only the visual data within the aperture windows of each video frame is sampled and the rest is ignored. Data extracted frame-by-frame from the aperture windows is fed into the vision system computer. The vision system computer is programmed with the relative position of the target dots with respect to each other, and the target's position on the object, as well as the optical characteristics of the TV camera. It finds the precise location and orientation of the target, and therefore the object that it is attached to, by calculating the geometric relationships of the moving images of the dots. Figure 2 shows the Space Vision System in operation.

Figure SEQ Figure * ARABIC 2. Space Vision System

Future

The next generation SRMS will be an arm installed on the ISS. It is to be used on the section of the Space Station where spacecraft will dock for the purpose of providing the replacement parts, fuel and other consumables. The SRMS will also be used for repairs and scheduled maintenance, and helping in the assembly of the Space Station in years ahead.

Flight Telerobotic Servicer (FTS)

NASA canceled the Flight Telerobotic Servicer (FTS) and OMV (Orbital Maneuvering Vehicle) programs, and does not have any concrete robotic project running. The Jet Propulsion Laboratory (JPL) is doing impressive work on surface rovers and planetary exploration technologies for which they have several full-scale demonstrators. The Johnson Space Center (JSC) is concentrating on service manipulators in support of manned systems. The Goddard Space Flight Center (GSFC), which was responsible for the FTS program, is now putting more emphasis on the Automatic Rendezvous and Capture Demonstration and low-cost robotic demonstrators. Although the Marshall centers claim to have activities in this field, little work is being done on ISS internal automation. Intra-Vehicular Automation & Robotics (IVAR) is gaining interest.

Technology

Control Modes

The human control of a robot occurs in the following three modes:

Manual

Supervised

Automatic

Figure 3 provides a graphic representation of the human/machine interaction.

EMBED Word.Picture.6

Figure SEQ Figure * ARABIC 3. Control Modes

NASREM.

The NASA Standard Reference Model (NASREM) task/computer hierarchical architecture, as proposed by Albus, McCain, and Lumina (1987), is a reference model telerobot control system architecture consisting of a hierarchy of six levels of sensory processing, world modeling, and task decomposition. Their proposal, originally conceived for computer-aided manufacturing and more recently applied to spacecraft, is really a qualitative taxonomy of hierarchical levels, based in part on the Albus (1975) model of the animal cerebellum and how it mediates control. Figure 4 is a diagram of the NASREM architecture where:

G is a Sensory Processing Component
M is a World Modeling Component
H is a Task Decomposition Component

Figure SEQ Figure * ARABIC 4. NASREM Architecture

A global data store is accessible by the sensory processing module at any level, and each sensory processor receives new data from the next-lower-level sensor system. The task-decomposition modules at each level receive commands as appropriate from the human supervisor and from the next-higher-level task-decomposition module. The arrows show other inter-module communication. The level breakdown is as follows.

Level 1, the bottom-most or servo level, is assigned the most primitive closed-loop servo-hardware control; sensor data is compared against commands and signals given to actuators to nullify the differences. Kinematic coordinate transforms are also handled at this level, as are interpolations of actual trajectory points between servo command updates.

Level 2, the primitive level, generates smooth, dynamically efficient trajectories in a convenient coordinate frame. The criteria for dynamic efficiency can vary but would most likely be some function of the time, the maximum force, and the energy used. This is the level at which a single arm-hand, vehicle, or sensor mechanism would be commanded to make a limited continuous movement.

Level 3, the elemental move (E-move) level, transforms symbolic commands for movement into intermediate poses of one or a combination of arm-hands, mobility devices, or sensors in such a way that these poses define pathways free of collisions with obstacles and kinematic singularities. World models at this level would be specific to manipulation in general, to the mobility generally (vehicle control), or to a single category of extroceptive sensing, such as vision or touch, which includes the actuators that position and focus the sensors.

Level 4, the task level. At this level transforms the goals specified in Level 4 into control-system actions designed to achieve these goals. This is the level at which a single complete telerobot would be commanded to perform a relatively straightforward and constrained task. The world model at this level would include manipulative control as well as control of the vehicle.

Level 5, the service level, deals with a larger set of tasks to be performed at one location.

Level 6, the mission level, deals with an entire mission and all telerobotic and computational elements that participate.

Kinematics

Robots with general geometry can work in either redundant or nonredundant situations. The situations are based on Newton's method but offer substantially better accuracy for a given step size by making use of the continuity properties of the curve. The following sections present four simple algorithms, each designed to perform an inverse-kinematics transform on a parameterized curve representing a path or trajectory in space.

The trajectory is assumed to be a continuous, parameterized curve, given as a sequence of points at equally spaced values of a trajectory parameter. The problem is to find a corresponding sequence of points in joint space. It is assumed that these points are sufficiently closely spaced that the trajectory curve can be reconstructed by interpolation.

The algorithms described here will find just one solution, although the user can control which solution is found by choosing appropriate starting conditions and, in the case of redundancy, by adding null-space perturbations to avoid obstacles, singularities, and so on.

Four algorithms are described: the midpoint method, two algorithms using integral terms (one in task space, one in joint space), and a type of predictor-corrector method. All are simple modifications of Newton's method, and in all cases the modification makes use of the assumed continuity of the trajectory to improve the accuracy of the first iteration. They work for redundant as well as nonredundant robots, but they do not work at singularities, or in situations where the robot is unable to follow the trajectory exactly, such as when it is out of reach, and is being asked merely to follow it as closely as possible.

In this project there is a task space, X, a joint space, EMBED Equation.3 , a kinematics function EMBED Equation.3 and a parameterized curve in the task space, EMBED Equation.3 , representing the trajectory. The general problem is to find a curve EMBED Equation.3 in joint space that satisfies equation (1):

EMBED Equation.3 EMBED Equation.3

(1)

where EMBED Equation.3 represents an ordered sequence of points, EMBED Equation.3 , where EMBED Equation.3 , and EMBED Equation.3 is the step size or spacing of the points. The problem is to find a corresponding sequence EMBED Equation.3 such that EMBED Equation.3 for all EMBED Equation.3 . It is assumed that EMBED Equation.3 is small enough that EMBED Equation.3 can be reconstructed sufficiently accurately from EMBED Equation.3 by a suitable curve-fitting method, and similarly that EMBED Equation.3 can be constructed from EMBED Equation.3 . It is also assumed that EMBED Equation.3 , the first member of EMBED Equation.3 , is given or has been determined separately. Generally, equation (1) has multiple solutions, and the value of EMBED Equation.3 influences which solution is found.

If the trajectory describes the motion of a rigid body, such as a robot's end effector, then the elements of EMBED Equation.3 are rigid-body displacements. Therefore, it is assumed that EMBED Equation.3 is the Euclidean group, or a subgroup thereof, and the notation of group theory will be used in the descriptions below. The expression EMBED Equation.3 is the composition of displacements EMBED Equation.3 and EMBED Equation.3 , executed in left-to-right order.

Newton's Method

Newton's method finds a solution to the equation EMBED Equation.3 through the iteration EMBED Equation.3 , starting from initial guess, EMBED Equation.3 , and continuing until EMBED Equation.3 is less than some specified value. In the context of solving the equation EMBED Equation.3 , this formula becomes as shown in equation (2):

EMBED Equation.3

(2)

EMBED Equation.3

EMBED Equation.3 ,

where EMBED Equation.3 is the number of iterations, EMBED Equation.3 is the Jacobian of EMBED Equation.3 , EMBED Equation.3 is the matrix inverse of EMBED Equation.3 , EMBED Equation.3 , is the inverse of the group element EMBED Equation.3 , and EMBED Equation.3 converts a group element to a vector representation. If the mechanism is redundant with respect to the task space, then the pseudo-inverse of EMBED Equation.3 may be used instead of the inverse.

The initial guess is given by equation (3):

EMBED Equation.3

(3)

The validity of this formula depends on EMBED Equation.3 being continuous, EMBED Equation.3 being small, and the mechanism not being close to a singularity. The first two conditions allow us to assume that EMBED Equation.3 is close to EMBED Equation.3 , and the third allows us to infer that EMBED Equation.3 is close to EMBED Equation.3 .

Ideally, the number of iterations should be kept as small as possible to minimize the amount of computation. If we set EMBED Equation.3 , then equation (2) and (3) simplify to equation (4):

EMBED Equation.3

(4)

where EMBED Equation.3 and EMBED Equation.3 . The accuracy of this equation is EMBED Equation.3 because the error in approximating EMBED Equation.3 with EMBED Equation.3 is EMBED Equation.3 , and Newton's method produces quadratic convergence –the error after each iteration is proportional to the square of the error before the iteration. The second iteration results in an EMBED Equation.3 error.

For the sake of simplicity, the algorithm embodied in equation (4) is referred to in subsequent discussions as "Newton's Method," which is often referred to as "Jacobian control" in the robotics literature.

The Midpoint Method

An algorithm called the midpoint method is used for solving differential equations. It is identical to Euler's method, except that it uses the derivative at a point to calculate a step from point EMBED Equation.3   to EMBED Equation.3 , rather than from EMBED Equation.3   to EMBED Equation.3 . The result is more accurate than Euler's method, having a EMBED Equation.3   truncation error per step compared with EMBED Equation.3   for Euler's method.

The obvious formula suggested by this analogy is shown in equation (5):

EMBED Equation.3

(5)

This differs from equation (4) by only two subscripts. This equation does indeed produce the result, giving EMBED Equation.3   accuracy at no extra cost, but only if the task space is linear, such as a pure translation.

A formula that works for any task space is shown in equations (6), (7), and (8), where EMBED Equation.3   is the truncation error for equation (4).

EMBED Equation.3

(6)

EMBED Equation.3

(7)

EMBED Equation.3

(8)

Equation (8) follows from the fact that EMBED Equation.3   is EMBED Equation.3   and thus can be expressed as a power series EMBED Equation.3

Substituting for EMBED Equation.3   in equation (6) gives equation (9):

EMBED Equation.3

(9)

where EMBED Equation.3   has been substituted for EMBED Equation.3   to compensate for errors in the calculated value of EMBED Equation.3 .

Equation (9) is the formula for the midpoint method for performing a trajectory transformation, and it is accurate to EMBED Equation.3 . It simplifies to equation (5) if group composition can be equated to vector addition and group inverse to negation.

Integral-Term Methods

In linear control theory, adding an integral term can increase the accuracy of a proportional controller. The same tactic can be applied to improve the accuracy of Newton's method using one of the following approaches:

Estimate and compensate for the task-space tracking error of Newton's method

Predict the value of EMBED Equation.3   and use it as the starting point for an iteration of Newton's method

The integral term method refers to these algorithms as EMBED Equation.3   and EMBED Equation.3 , respectively, where EMBED Equation.3   is the number of integral terms.

In EMBED Equation.3 , an offset is added to EMBED Equation.3 that is the inverse of the expected error in using equation (4) to calculate EMBED Equation.3 , so that a more accurate value can be obtained by aiming at the modified trajectory point. The simplest way to calculate the offset is to use the group sum (integral) of past tracking errors, which results in the formula in equations (10) and (11):

EMBED Equation.3

(10)

EMBED Equation.3

(11)

EMBED Equation.3

(12)

EMBED Equation.3

(13)

EMBED Equation.3

(14)

This method achieves EMBED Equation.3 accuracy, assuming that both EMBED Equation.3 and EMBED Equation.3 are continuous and that EMBED Equation.3 . Both EMBED Equation.3 and EMBED Equation.3 should be set to zero at the start of the trajectory. The extension to three or more terms is straightforward.

It is also possible to add integral terms to the mid-point method. The addition of one term results in the algorithm shown in equations (15) and (16):

EMBED Equation.3

(15)

EMBED Equation.3

(16)

Predictor-Corrector Methods

The name "predictor-corrector" is usually associated with a class of algorithms used to solve initial value problems. It has been proposed that the inverse kinematics problem be couched as a differential equation and solved using these algorithms. Another class of predictor-corrector methods were developed for curve-following-in-continuation or homotopy applications (and presumably elsewhere). The algorithm presented here is of this latter type. The difference between them lies in the job of the corrector. In an initial-value problem, an infinite number of curves can satisfy the differential equation, and the corrector must find the one that is most consistent with previously calculated values. In contrast, the corrector in a curve-following problem has a fixed curve for which it can aim, independent of previously calculated values.

The algorithm described here uses polynomial extrapolation to predict the value of EMBED Equation.3 , followed by an iteration of Newton's method, which serves as the corrector. We shall refer to it as EMBED Equation.3 , where EMBED Equation.3 is the degree of the predictor. EMBED Equation.3 is also a predictor-corrector algorithm, differing from EMBED Equation.3 only in its method of prediction. The formula for EMBED Equation.3 is shown in equations (17) and (18):

EMBED Equation.3

(17)

EMBED Equation.3

(18)

The predictor is a linear extrapolation through points EMBED Equation.3 and EMBED Equation.3 . Higher-order methods fit polynomials of higher degree through a larger number of points, but all use the same corrector formula. The predictor for EMBED Equation.3 is shown in equation (19):

EMBED Equation.3

(19)

If the first EMBED Equation.3 derivatives are continuous, n-degree polynomial extrapolation predicts the value of EMBED Equation.3 with an EMBED Equation.3 error, and one iteration of the corrector formula reduces the error to EMBED Equation.3 , so the accuracy of EMBED Equation.3 is EMBED Equation.3 , where EMBED Equation.3 is the integral term, which should be set to zero at the start of a new trajectory (EMBED Equation.3). This algorithm, EMBED Equation.3 , assumes that EMBED Equation.3 continuous in EMBED Equation.3 and that EMBED Equation.3 , where

EMBED Equation.3 . If EMBED Equation.3 , then a settling period of approximately 3-6 iterations occurs as the integral term converges to the correct value for the new trajectory. The tracking accuracy of this algorithm is EMBED Equation.3 , except during the settling period. It is possible to improve the accuracy by adding more integral terms. The formula for EMBED Equation.3 is shown in equations (12), (13), and (14), which achieves EMBED Equation.3 accuracy under the same trajectory assumptions as for EMBED Equation.3 .

Although the task-space composition operator is not commutative for displacements, it is nearly commutative for small displacements. The integral terms in the above formulas are small, so it does not make much difference if, for example, we use the formula EMBED Equation.3 instead of EMBED Equation.3 .

In EMBED Equation.3 , integral terms are used to predict the value of EMBED Equation.3 based on past differences between the predicted and calculated values. The predicted value is then used as the starting point for an iteration of Newton's method. The accuracy of EMBED Equation.3 is EMBED Equation.3 . This is because EMBED Equation.3 , and the error after one iteration of Newton's method is proportional to the square of the error before. EMBED Equation.3 assumes that the first EMBED Equation.3 derivatives of EMBED Equation.3 are continuous in EMBED Equation.3 and zero-valued at EMBED Equation.3 . If the trajectory does not meet these conditions, then errors will occur at the places of discontinuity, followed by settling periods as the integral terms adjust to new values. The magnitude of the tracking error during these periods depends on the severity of the discontinuity.

Both EMBED Equation.3 and EMBED Equation.3 become less stable as the number of integral terms is increased and require progressively smaller step sizes to stabilize them. The practical upper limit seems to be around EMBED Equation.3 or EMBED Equation.3 , but it may be lower for particular applications, depending on circumstances. For a given value of EMBED Equation.3 , EMBED Equation.3 appears to be less stable than EMBED Equation.3 .

Redundancy

If the degree of freedom of the mechanism is greater than the dimension of the task space, then the mechanism is redundant with respect to the task. This means that, in general, an infinite number of joint-space trajectories can map to the given task-space trajectory. It also means that the Jacobian is rectangular and therefore non-invertible. One popular solution is to use the pseudo-inverse of the Jacobian in place of the inverse. This produces a minimum-norm solution in the sense that EMBED Equation.3 is the vector with the smallest Euclidean norm satisfying EMBED Equation.3 , where EMBED Equation.3 is the pseudo-inverse of EMBED Equation.3 .

If EMBED Equation.3 is substituted for EMBED Equation.3 in Newton's method (equation (4)), then the resulting formula minimizes EMBED Equation.3 at each step. This is a good strategy from both a numerical and a physical point of view.

Physically, it locally minimizes the amount of joint motion required to execute the task, while numerically it minimizes the size of the step from EMBED Equation.3 to EMBED Equation.3 , which improves both the accuracy and stability of the calculation. If the resulting trajectory is not to the liking or the user, then a small null-space vector can be added to the pseudo-inverse solution, which the user can manipulate to steer the trajectory away from obstacles, singularities, joint motion limits, and so on. This null-space vector is usually incorporated as the product of an arbitrary vector, EMBED Equation.3 with the null-space projection matrix, EMBED Equation.3 , where EMBED Equation.3 is the identity matrix. Incorporating the pseudo-inverse and the null-space vector into equation (4) produces the formula shown in equation (20) for Newton's method:

EMBED Equation.3

(20)

calculating the value of EMBED Equation.3 that minimizes EMBED Equation.3 .

EMBED Equation.3 may be treated in the same way as Newton's method, but the other algorithms exhibit unstable behavior in the null space: the midpoint method produces zigzag trajectories, while EMBED Equation.3 and EMBED Equation.3 exhibit a build-up of null-space velocity. Both can be corrected by the addition of a null-space offset. In the case of the midpoint method, the required offset is EMBED Equation.3 , and the modified equation is shown in equation (21):

EMBED Equation.3

(21)

In the case of EMBED Equation.3   and EMBED Equation.3 , the offset is EMBED Equation.3 , and the modified equation (corrector formula) is shown in equation (22):

EMBED Equation.3

(22)

In both cases, the effect of the offset is to minimize EMBED Equation.3 , thus mimicking the stable behavior of Newton's method. (EMBED Equation.3   may be removed if not needed.) If these equations are to be used as part of a multiple-iteration algorithm, then the offset may be applied only on the first iteration.

Comparison of the Algorithms

Table 2 shows the order, continuity requirement, calculation requirement, and starting conditions for each algorithm.   EMBED Equation.3   stands for Newton's method, EMBED Equation.3   for the midpoint method, and EMBED Equation.3   for the midpoint method with one task-space integral term.

The continuity requirement (3rd column) refers to the number of derivatives of EMBED Equation.3   that are assumed to be continuous in the interval EMBED Equation.3 .

Table SEQ Table * ARABIC 2

Comparison of algorithms

Algorithm	Order	Continuity	Calculation	Start
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3
EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3	EMBED Equation.3

All of the algorithms assume that the trajectory itself is continuous. If the trajectory does not satisfy these conditions, then errors may occur, such as spikes in the graph of tracking error versus EMBED Equation.3 , and, if the algorithm uses integral terms, a settling period may occur after the error, before normal tracking resumes.

The calculation requirement (4th column) refers to the number of evaluations of the forward kinematics EMBED Equation.3 function and the Jacobian EMBED Equation.3 needed per point on the trajectory. Included with EMBED Equation.3 is the cost of solving a set of linear equations and, where appropriate, the addition of a null-space term. Other calculations, such as composition of task-space elements, or addition of joint-space vectors are assumed to be much less time-consuming, and are therefore ignored. An extra EMBED Equation.3 is shown in parentheses for EMBED Equation.3 and EMBED Equation.3 , because an extra evaluation of the kinematics function is needed if the user wishes to monitor the tracking accuracy. Monitoring is necessary if the user wishes to control the accuracy by varying the step size or number of iterations per point. The accuracy of the other algorithms should be easy to monitor.

The final column describes the starting conditions, which are the number of points on the trajectory EMBED Equation.3 for which the corresponding join point of space must already be known, and the number of derivatives EMBED Equation.3 that must be zero at the start of the trajectory. The latter are required by algorithms using integral terms, and are needed in order to avoid large initial tracking errors. The result of EMBED Equation.3 for EMBED Equation.3 should be rounded up to the nearest integer.

Dynamics

The dynamic is the analysis that deals with forces and their relation primarily to the motion, but sometimes also to the equilibrium of bodies.

The dynamic performance of a manipulator is the ability to start, move, and stop with well-defined and predictable operation under all conditions of arm length and weight loading. This performance is described in the next paragraph under both static and dynamic conditions.

A dynamic analysis of a manipulator needs to consider many of the following parameters:

Gravity vector

Mass

Center of mass

Matrix of inertia

This section identifies an example of dynamic calculation of a manipulator with two degrees of freedom. It demonstrates that the complexity increases dramatically with the number of degrees of freedom.

Robot Motions

Degrees of Freedom

The manipulator system of a robot as described in the previous paragraph performs the motion by moving the end-effector tooling through space.

Pitch, yaw, and roll are the basic motions referred to as degrees of freedom. Six degrees of freedom are necessary to emulate the motion of a human arm and wrist. The human upper arm, moving at the shoulder joint, has two degrees of freedom, because it can rotate up and down, and forward and backward in two angular directions. The lower arm, moving at the elbow joint, is the third degree of freedom. Wrist rotation is the fourth, wrist movement up and down is the fifth, and wrist movement left and right is the sixth. Operation of the fingers and thumb provides other degrees of freedom.

The Space Station Remote manipulator System (SSRMS) has seven degrees of freedom distributed across three joints: three degrees at the shoulder, one at the elbow and three at the wrist.

Motions and optimizations

The many factors to consider in moving the SSRMS include the following:

Ensure the safety of any astronaut near the SSRMS.

Move the SSRMS only inside a safety envelope to be sure not to hit any part of the Alpha or other devices.

Keep the movement simple.

Avoid the angular limitations.

Keep the SSRMS and its target in the field of view of the operator or the cameras at all times.

Quality of a manipulator

The quality of the manipulator can be described in terms of the following five parameters, which combine the effects of the arm geometry, accuracy, and quality of the point servomechanism providing location feedback and the computer programs written to direct the robot through its desired tasks.

Accuracy

Repeatability

Stability

Spatial resolution

Compliance

The human body is a good analog to study the effects on the manipulator as weight is moved from one point to another. It is easy to visualize the areas on the skeletal frame where the forces will be most felt: knees twisting under the load, the waist bending, the shoulder, elbow, and wrist joints all taking part of the stress. The human control system is extremely well damped and approaches its rest points smoothly and surely compared to a loaded manipulator, whose ability to stop on target will be some form of damped oscillation around rest until motion ceases.

As with the human skeleton, loads are handled best with the least strain when the arms are bent close to the body, and loads are most difficult to lift and control when the arms are fully extended. Like the human, the manipulator will find it impossible to perform some tasks at arm's length. Unless directed otherwise, or provided with automated feedback, the robot may try to do the impossible with catastrophic consequences.

Accuracy – Repeatability

It is very difficult to define accuracy without bringing resolution into the discussion. Accuracy implies the capability to hit the mark, reach the point in space, or get the correct answer. Repeatability is the act of duplicating an action or a result.

A repeatable act does not need to be an accurate one. A target shooter may have a group of shots at the six o'clock position on the target, and have excellent repeatability, but no accuracy, because the pattern missed the bulls-eye.

The shooter can achieve both repeatability and accuracy if the shot pattern remains clustered as before, but shifts to fall accurately within the bulls-eye. Without repeatability, one may occasionally achieve accuracy, but it will be unpredictable and therefore undesirable for a manipulator, whose job is to faithfully repeat an action.

Repeatability for robots implies the capability to return precisely to the position where it is sent. The accuracy of that position depends to a great degree on the measurement resolving powers of the servomechanisms. During a short-term movement, temperature variations that may contract or expand the robot components are not a serious concern, but during a long-term movement, they affect accuracy. One might expect these types of variations to be most critical in precision requiring extremely high accuracy. To achieve the accuracy required may necessitate some form of temperature control in the work area or automated temperature compensation as part of each link.

Accuracy of the machine is achieved (or lost) by three elements of the robot system: the resolution of the control components previously mentioned, the inaccuracies or imprecision of the mechanical linkages, gears, and beam deflections under different load conditions, and the minimum error that must be tolerated to operate the arm under closed servo loop operation.

Stability

Stability is a quality referring to that feature of the robot that keeps it from breaking into oscillation (or vibration) as it moves from point to point or when at rest. An undamped system oscillates in an unbounded manner until the servomechanism or part of the manipulator is damaged as it is forced through severe angular accelerations in trying to react to the commands of the controller. An over-damped system, however, causes the arm to follow the commands of the controller in a sluggish way. A critically damped servo system provides an optimum situation in which the arm is steady at rest, but responds to commands with a minimum overshoot when moving from point to point along the work trajectory.

A servo sensor must detect an error between the present position and the next position on the path. An optimum approach to movement would be one in which the servo responds to large errors with faster movements, and as the error is reduced, that is, as the arm is nearing its next point, the arm moves more slowly.

Spatial resolution

Spatial resolution, another significant parameter in robot design, refers to the minimum or smallest dimension to which the system can define the workspace. This resolution determines the smallest error that can be made by the robot. This limit can be placed by the minimum resolution of the controller or the minimum resolving increment of the servo system, whichever is less. A microprocessor using 8-bit words can resolve to one part in 256, while a 16-bit machine can resolve to one part in 65,336. Selecting the minimum resolution required for the application can minimize cost.

Compliance

Manipulator compliance is an indication of displacement in response to the force or torque exerted on it. A high compliance means the manipulator moves a good deal when it is stressed and therefore would be termed *spongy* or *springy*. Low compliance is characterized by a stiff system. Compliance involves a complex set of variables that are dependent on where forces are applied, the sticking and sliding friction of couplers and gears, the effect of the power source, and even the frequency of the force exerted.

Compliance can be theoretically calculated, but it can only be accurately measured after the robot has been put in place and exercised. Like the other variables affecting accuracy and precision, each becomes more important as stringent repeatability and accuracy requirements are imposed.

Compliance is a feature that can be good or bad depending on where it occurs and whether its sequence is desirable. A spongy, compliant robot arm would not be desired for grinding or milling since the part would oppose the grinder, and would essentially try to hold the robot back from the part being serviced. On the other hand, in a situation where the robot was meeting some unpredicted opposition, the robot could destroy itself if it were to remain non-compliant, and oppose this force. Clearly, there are conditions where both high compliance and low compliance are appropriate responses.

Dynamics in Space

The RMS can only be operated in a zero gravity environment, because the DC arm motors are unable to move the arm's weight under the influence of Earth's gravity.

The dynamic performance of a robot contact motion depends on the following environment parameters:

> The force response at low stiffness is sluggish.
>
> High stiffness gives rise to bouncing and instability (compromise between

speed response and stability).

The environment disturbance forces, such as aerodynamics and gravity gradient, are much less significant than the control system forces.

Two main concerns require analyses:

Controller arm structural dynamics interactions

Controller-controller interactions

The SRMS and the SSRMS arms do not have uniform mass and stiffness distributions. Most of their masses are concentrated at the joints.

From a global dynamics point of view, the SRMS arm can be represented by a number of structural bodies, (see EMBED Equation.3 in Figure 5.). A joint separates each structural body.

<u>Figure SEQ Figure * ARABIC 5</u>. Joint dynamics reference frames.

The dynamical characteristics of each segment are defined by its inertial and structural properties in joint reference frames. The inertial properties of each segment are defined in terms of its mass EMBED Equation.3 , mass center location EMBED Equation.3 , and second mass moments about its mass center EMBED Equation.3 .

Primarily the bending and torquing stiffness of its structural elements define the structural properties of the SRMS. Other secondary properties, such as elongation, shear and rotary inertia effects are negligible.

To maintain the arm's structural integrity, loads induced in the arm must be kept below design limits, which require operational constraints to be placed on the space vehicle propulsion and attitude control systems.

Trajectory Planning and Object Avoidance (TPOA) system

The TPOA system structure adopted for preliminary development has been retained for the consolidation development as shown in Figure 6. The Conceptual Framework allows for the integration of the various methodologies, thus ensuring further development potential and compatibility with complementary methodologies. Refer to Figure 7 regarding the methodologies, and note that some of its elements will be described further in following sections. The Geometric Approaches in the Methodologies diagram decomposes into the following subclasses:

Configuration space approach
Graph representation for configuration space
Cell decomposition methods
Retraction approach
Local optimization of a distance measure
Quaternion representation for collision detection
Heuristic motion planning
Back projection for planning with uncertainty
Moving obstacle avoidance

EMBED Visio.Drawing.6

Figure SEQ Figure * ARABIC 6. TPOA System Conceptual Framework

The adopted installation of this Conceptual Framework consists of the following features:

Path Planning is performed for the end-effector considered as a single point, not for the arm as a whole.

A trajectory is generated in task space (2-D in this case) for interconnecting the end-effector path points.

The Redundancy Resolution algorithm transforms the end-effector trajectory into a joint trajectory (position and velocity) for all the joints. Redundancy resolution, using the extra degree of freedom is employed to ensure collision avoidance at the link-level with static and moving objects in the workspace, and to avoid self-collision . To keep the joints within their operating angular ranges, joint limiting is enabled.

EMBED Visio.Drawing.6

Figure SEQ Figure * ARABIC 7. TPOA Methodologies

In this scheme, static and moving Object Avoidance is distributed over Path Planning and Redundancy Resolution functions. The Path Planning module provides low-level collision avoidance for the end-effector. The Redundancy Resolution module, together with joint limiting, provides low-level collision and self-collision avoidance at the link-level. The human operator supplies the high-level Path Planning capability. The new desired end-effector position(s) can be calculated by the system while the arm is moving.

Path Planning and Obstacle Avoidance

The Path Planning Module (PPM) performs path planning for the end-effector. The PPM implements the following variant of Artificial Potential Field (APF) methodology:

"The manipulator moves in a field of forces. The position to be reached is an attractive pole for the end-effector, and obstacles are repulsive surfaces for the manipulator parts."

Utilizing similar ideas, several authors have applied APF to the Path Planning and Collision Avoidance problem. The reported details of implementations are quite different, mostly in the particular choices of potential functions, both for the attractive and repulsive force fields, and in the representation of objects. One approach is based on the use of a super-quadric function.

Trajectory Generation

The trajectory generation for the end-effector is determined using the X-spline technique. The X-spline is a generalization of the conventional cubic spline in which the continuity condition on the second derivative is not enforced at the data points. For real-time trajectory generation, the data points are provided sequentially from the path-planning scheme in some specified time period. By using the X-spline function for trajectory interpolation, the local curve can be determined once the next two or three look-ahead data points are provided. This eliminates the need to compute the entire trajectory along the path before the manipulator can start moving. This method is simple, suitable for telecommunicated implementation, and provides good trajectory approximation even though only local information is used.

Robot Interactions with the Environment.

The following are some key points for robot interactions with the environment using an adaptive hybrid force or position control scheme:

> The controller must be able to deal with non-repetitive tasks in unknown or uncertain environments.
>
> The controller must be able to recover from unexpected contact motion during a trajectory move.
>
> The dynamic performance of a robot contact event depends on the environment parameters.
>
> The force response at low stiffness is sluggish.

High stiffness gives rise to bouncing , instability and a compromise between speed response and stability.

An adaptive scheme, such as Adaptive Impedance Control or Adaptive Force Control improves the performance and enhances stability at high stiffness by rendering the behavior independent of the environment.

Adaptive Control Scheme

Equations 23 through 27 define an adaptive control scheme.

EMBED Equation.3   prediction error

(23)

EMBED Equation.3

(24)

EMBED Equation.3

(25)

EMBED Equation.3

(26)

Recursive Least Square in Continuous Domain

EMBED Equation.3

(27)

slow system EMBED Equation.3 rapid system

Modified Impedance Control Concept

This section gives an overview of some important concepts in the control concept for the robotic arms of SPDM.

The robot dynamic control equation is given in equation (28):

EMBED Equation.3

(28)

During a gross motion, the external forces EMBED Equation.3 . In the impedance control technique, the virtual impedance between the end-effector current pose and a destination pose is defined to produce EMBED Equation.3 with the desired dynamics shown in equation (29):

EMBED Equation.3

(29)

where EMBED Equation.3 are EMBED Equation.3 positive definite matrices of the desired impedance.

In the modified scheme, the governing equations are modified as shown in equation (30):

EMBED Equation.3

(30)

and after several substitutions, in equation (31) for the computed torque command,

EMBED Equation.3

(31)

and in equation (32):

EMBED Equation.3

(32)

The total virtual torque loading associated with the impedances for avoidance of singular configurations as well as for dealing with the joint limits can be written as shown in equation (33):

EMBED Equation.3

(33)

To avoid collisions between the robot links and the obstacles, the robot links are made discrete, and the impedance in equation (34) has been generated between the EMBED Equation.3 point on the robot link and the closest point on the surface of the pre-specified influence zone of an obstacle:

EMBED Equation.3

(34)

In the modified impedance control concept, the total force vector produced by the defined impedance can be stated as shown in equations (35), (36), and (37):

EMBED Equation.3

(35)

EMBED Equation.3

(36)

EMBED Equation.3

(37)

International Space Station

Overview

The International Space Station (ISS), shown in Figure 8, is the largest cooperative space endeavor ever undertaken. It involves the participation of the United States (NASA), Russia (RKA), Canada (CSA), Europe (ESA), and Japan (NASDA). The ISS was scheduled to be built between 1995 and 2002, at which point Permanently Human Capability (PHC) was to be achieved. The ISS will be in operation for 10-15 years.

Figure SEQ Figure * ARABIC 8. International Space Station.

Mobile Servicing System (MSS)

The assembly of the Space Station involved the installation of many different components at various locations. The tasks were decomposed into several generic activities: track and capture, maneuvering, berthing, unberthing, deployment, positioning, and handoffs among manipulators. The Mobile Servicing System (MSS) is the unit that accomplishes all these tasks. The MSS is comprised of the mobile servicing center (MSC), the mobile servicing system maintenance depot (MMD), and the (define SPDM) SPDM. The MSS is a unique system in that it is a largely autonomous robotic system capable of self-maintenance (with SPDM). The MSS is therefore one of the most complex systems on the Space Station.

The MSC is the mobile portion of the MSS. It consists of the Mobile Remote Servicer (MRS) mounted on the mobile transporter (MT) element. The MRS includes the MRS base system (MBS), and the SSRMS. The MRS, along with the SPDM, traverses from one end of the Space Station to the other on the MT.

The MBS not only serves as a structural carrier for the SSRMS and the SPDM, but also provides the mechanisms for the support of and attachment of the SSRMS and the

SPDM, which includes power, data linkage and video signal routing through the MSC utility ports and the power data grapple fixtures (PDGFs).

SPDM has two possible locations of operation, attached to the SSRMS, or to the MBS itself. This is reflected in the diagram of the MSS in Figure 9:

Figure SEQ Figure * ARABIC 9. The Mobile Servicing System (MSS)

Mobile Servicing Center (MSC)

The MSC is the mobile portion of the MSS. It consists of the MRS mounted on the mobile transporter (MT) element.

The MT element provides the physical interfaces between the MRS and the Space Station integrated truss assembly (ITA). The mobile transporter can translate along the rails located on the front face of the truss and stop at any one of the ten designated mobile transporter worksites. Batteries supply electrical power for translation mobility, “keep-alive,” and safe storage or positioning (safeing) part of the transporter energy storage system (TESS). Data communications are provided by a trailing umbilical.

The MRS includes the MRS base system (MBS), which forms the primary base from which the SSRMS operates. The system has four strategically oriented power data grapple fixtures (PDGFs), which give the operator different options for basing the SSRMS. The MBS is attached to the MT, which provides another way to relocate the SSRMS and its payloads.

Space Station Remote Manipulator System (SSRMS)

The Space Station Remote Manipulator System (SSRMS) is a large-scale, symmetric, seven-jointed manipulator (arm) that is intended to be used primarily for payload transporting and maneuvering and shuttle berthing and deberthing around the Space Station. As with the ISS, the SSRMS is being designed to remain in orbit for the projected 15-year operational period.

The SSRMS is capable of manipulating large payloads up to the mass of a fully loaded shuttle, some 116,000 kg, as demonstrated in Table 3, along with some other SSRMS design parameters. The SSRMS system consists of a seven-jointed arm, terminated at each end with an end effector, as shown in Figure 10, and it is functionally symmetrical about the central elbow joint.

Table SEQ Table * ARABIC 3.

SSRMS Design Parameters.

Design parameter	SSRMS
Reliability requirement	Fail-operational
Mobility	Self-relocatable
Maximum payload (kg)	116,000
Stopping distance (m)	Payload & operation dependent (1.25)
Power budget (W)	915 (keep alive) 2,000 (operation)
On-orbit mass budget (kg)	1,334
Stiffness budget – straight-out (N/mm)	0.67
Positioning accuracy (m and deg)	0.065 and 0.7
Data transfer rate (ms)	once every 50
Nominal bus DC voltage (V)	120

A unique feature of the SSRMS is its ability to be relocated by virtue of its symmetry and identical latching end effectors (LEE), either of which can act as a shoulder or wrist to the SSRMS. This feature allows operation of the SSRMS with either end effector acting as the reference base of the arm, and so the SSRMS can "walk" along the ISS, from one power data grapple fixture to the next, alternately converting the end effector to the operating base. The SSRMS can relocate onto PDGFs either on the MBS or strategically located on the ISS. Video cameras, pan and tilt units (PTUs), lighting are provided to monitor SSRMS operations.

Figure SEQ Figure * ARABIC 10. The Space Station Remote Manipulator System (SSRMS)

SSRMS Control Modes

The SSRMS provides manual and automatic operating modes similar to those provided by the SRMS. In addition, the SSRMS provides an automatic operator commanded joint mode, pre-stored joint mode, and greater flexibility for specifying operating coordinate systems. Other control features include an Artificial Vision Function (AVF) tracking mode and a force moment accommodation capability. Table 4 shows the control modes for SSRMS.

The SSRMS's displays and controls subsystem has cathode ray tube (CRT) displays, a mouse, a keyboard and hand controllers. Different pages of displays and controls can be displayed on the monitor screen. Commands are affected through contact to the touch screen, like selecting a switch displayed on the screen. The SSRMS displays and controls subsystem does not have a fixed number of components and physical location. For example, the SSRMS can be commanded from a ground control station. During ground control, hand controller operations are prohibited. The SSRNS can also be controlled from a Space Station intra-vehicular activity (IVA) multipurpose application console (MPAC). Each MPAC workstation is capable of displaying control and command data and consists of display monitors for video views, and hand controllers. Using display pages, the IVA operator can select suitable operating modes for the SSRMS in both manual and automatic modes.

In manual mode, the operator can command the Point of Resolution (POR) of the arm to any allowable position in the workspace as well as command individual joints to rotate at various rates. In automatic mode, the operator can choose to initiate pre-stored sequences for joint or POR movement, command the joints or POR to predetermined points, or allow the SSRMS to be semi-autonomous with the assistance of the artificial vision system (AVS). The AVS is capable of automatically tracking targets to reduce operator workload.

Table SEQ Table * ARABIC 4.

SSRMS Control Modes

Control Mode	Commanded Motion
Human in the Loop	
Manual Augmented	Manipulator receives hand controller data and moves selected POR at the specified rate

Single Joint Rate	Movement on joint-by-joint basis. Other joints in Joint Position Hold.
Automatic Trajectory	
Operator Commanded Joint POR	Control of POR from its current position to operator-specified destination
Operator Commanded Joint Position	Control of joints from current position to operator-specified destinations
Pre-stored POR Auto Sequence	POR commanded along predefined trajectory
Pre-stored Joint Position Auto Sequence	Joints move in a predefined joint position sequence.
AVF Supported Tracking	Manipulator responds to relative position information generated by AVF and provided by MCCF.

SSRMS Subsystems

The SSRMS has a computer subsystem distributed over three different units: the arm computer unit (ACU), the LEE electronics unit (LEU), and the joint electronic unit (JEU), each of which is dedicated to special processing functions. At the heart of the subsystem is the ACU, which is responsible for arm mode control, arm tip position and rate control, arm health monitoring and safe storing, force and moment accommodation, data collection, local bus control, and video distribution unit (VDU) control. The LEU performs force moment sensor processing, monitors LEE health and status, and controls the LEE operations. The JEU provides joint position and rate control, and monitors joint health and status. The ACU communicates with the LEU, the JEU, and its higher-level controller, the MSS computing and control facility.

The SSRMS vision subsystem consists of two camera and light units mounted on each LEE. Two camera and light units are also mounted on pan and tilt units located on the two arm booms. Four VDUs are mounted in the vicinity of each camera and light unit. All cameras are identical color cameras with a maximum zoom ratio 8.5:1 and maximum wide field of view of 52 degrees. The pan and tilt unit is controlled within +90 deg in tilt and 0-350 degrees in pan. The light unit is capable of providing a minimum illumination level of 380 foot-candles at a distance of 0.68 meters, and 3.5 foot-candles at a distance of 10 meters. Each VDU transfers power and command from the ACU to its associated light, camera, pan, and tilt unit. It receives video signals and status, such as camera setting, pan and tilt angles, and then distributes them onto SSRMS and Space Station video lines.

SSRMS Uses

The SSRMS must perform various functions, in the assembly and maintenance of the Space Station: load and unload the shuttle, transport payloads, maneuver payloads, capture, berth, and de-berth the shuttle, provide power, data, and video to end-of-arm users, and provide EVA crew positioning. The following two examples show the use of SSRMS. The first example of SSRMS use involves handoff operations as performed in its first nominal operation in the installation of the MBS onto the MT on Flight 6A. Figure 11 shows a handoff operation. The SSRMS operates from its initial location, while the SRMS reaches into the cargo bay, grapples the MBS, and then positions itself so that the SSRMS can take this payload in a handoff maneuver. Once the SSRMS has grappled the MBS payload, the SRMS releases it, and moves clear so that the SSRMS can berth the MBS to its final location on the MT. On completion of the MBS installation, the SSRMS relocates onto the MBS. After a full examination of the SSRMS and MBS on Flight 6A, the SPDM/MMD payload was also installed onto the MBS in a handoff maneuver using the SRMS and the SSRMS.

The second example of SSRMS use involves the ability of the SSRMS to relocate itself for pressurized logistics module (PLM) change-out. The PLM is a module carried in the shuttle that contains consumable supplies for the crew and spares and equipment for the scientific experiments. PLMs are exchanged on a one-for-one basis, where the spent module returns waste products, equipment for repair, and completed scientific experiments. Once the MSC (SSRMS and MBS) is activated and evaluated, the SSRMS steps from the MBS to the underside of the lab module, latches onto the PDGF, and releases from the MBS. The SSRMS arm then maneuvers its free end to the shuttle payload bay, aligns with the target on the PLM, and grapples the PLM. Having established that the PLM has been correctly grasped, the shuttle payload latches are released, the PLM is taken from the shuttle and positioned beneath the vacant node. The PLM is berthed to the node using an active berthing interface. After the release of the new PLM, the SSRMS maneuvers over to the spent PLM, grapples it, and places it in the shuttle payload bay. To complete the mission, the SSRMS steps onto the MBS and returns to its "keep-alive" and storage position.

Figure SEQ Figure * ARABIC 11: SSRMS Handoff Operation with SRMS

Special Purpose Dexterous Manipulator (SPDM)

The SPDM is a teleoperated robotic device that will conduct both nominal and contingency operations in the unpressurized environment onboard the Space Station. Primary missions and tasks involve removing and replacing ORUs on the space station. Currently, almost 300 ISS ORUs are fulfilling various functions designed to be compatible with the SPDM for removal and replacement. In addition to the removal and replacement of ORUs, other maintenance actions that the SPDM is expected to fulfill include adjustment, maintenance, support of EVA operations, and inspection of the ISS components and hardware over the 30-year operational life of ISS.

The SPDM will operate either from the end of the SSRMS or attached to a PDGF on the MBS. The PDGF serves as the connector outlet delivering all required power, robot command signals, and video links to and from the SPDM at appropriately located utility sites. Four PDGFs are located on the MBS as well as at additional sites located elsewhere on the ISS as determined by access requirements for performing the Space Station maintenance tasks.

The SPDM will have the dexterity to manipulate hinged panels and doors, mate and demate connectors, operate jackscrews, and change orbital replacement units. These operations are facilitated by the incorporation of force moment sensing devices in the ORU tool change mechanisms terminating each arm. The SPDM will also have three zoomable cameras, lights, and two pan and tilt control units that make it a key asset for viewing and inspection tasks on the Space Station.

The SPDM will feature capabilities that will allow it to successfully complete ISS servicing and MSS maintenance tasks. A major goal of the SPDM is to reduce astronaut EVA hours, which are potentially hazardous and time consuming,, and requires at least two suited crew members cooperating in the EVA and a third crew member monitoring them.

SPDM Configuration

The SPDM consists of a single-degree of freedom base body roll segment incorporating a PDGF for SSRMS attachment and a LEE to provide for attachment to the MBS. The SPDM is intended be capable of operating from any one of the four MBS PDGFs from the end of the SSRMS, or from a PDGF located on the Space Station itself. The physical mass allocation for the SPDM and tools is 815 kg. The SPDM body section is attached to the base by a roll joint, incorporates onboard avionics, has provisions for the stowing of four tools, and also has two ORU temporary storage locations. The body will have three cameras, two mounted on PTUs and the third attached to the LEE for attaching the SPDM's LEE to a PDGF when transported by the SSRMS. AVF is a planned feature of the SPDM, which will allow it to automatically lock onto and track a target and orient the SPDM's arm for final grappling by the IVA teleoperator.

Two 7-DOF arms are attached to the SPDM body. Both are composed of two equal boom segments housing their joints, ORU tool change-out mechanism (OTCM) and associated electronics to yield an overall arm length of 136.34 inches and a weight of 644 lbs. Each arm has seven offset joints and seven joint electronics units (JEUs), which provide the electronics control. Each joint is housed in an 8-inch diameter structure and has a rated torque of 150 ft-lbs. The two arms mounted above the roll joint will be able to rotate 360 degrees with respect to the LEE and ORU accommodation platforms.

As shown in Figure 12, the SPDM consists of a body and two dexterous arms, which have the following features:

Body

Can be attached to PDGFs for storage and operation of SPDM on MBS or ISS

Can be attached to a LEE for operation from the end of SSRMS

Can act as an extension to SSRMS for payload handling

Incorporates a roll joint to position the shoulder assembly

Provides accommodations for transport of ORUs and holsters for storage of four tools

Incorporates two cameras with lights on pan-tilt units to supplement viewing

Has dexterous arms

The two arms are identical to OTCM end effectors.

Each arm has seven joints (RYPPPYR) – Roll, Yaw, Pitch

All joints are offset for maximum dexterity.

End effectors incorporate a standardized gripper interface.

A camera with lights is in each end effector.

Six-axis force moment sensors are located in the base of each end effector.

Power, data, and video connections are provided at each end effector.

One arm is used for stabilization at the worksite.

Figure SEQ Figure * ARABIC 12. The Special Purpose Dexterous Manipulator (SPDM).

The SPDM can accomplish the above tasks with its ORU Tool Change-out Mechanism (OTCM), along with the various tools it can attach to and use for the dexterous operation at hand. The OTCM of the SPDM, along with various SPDM tool types, are shown in Figure 13.

EMBED PBrush

Figure SEQ Figure * ARABIC 13. SPDM ORU Tool Change-out Mechanism (OTCM) & SPDM Tools

SPDM Uses

The SPDM must perform various dexterous functions in the maintenance and servicing of the payloads, the MSS, and the Space Station, like remove or replace ORUs, manipulate, install, or remove ORU sub-carriers, attach or detach interfaces and covers, inspect and monitor ISS payloads, ORUs and equipment, engage “bare” bolts with tools, provide lighting and monitoring of work areas for EVA and IVA crew and transport, and position equipment to assist EVA crew. The following example better describes the use of the SPDM.

In this example, the dexterous manipulator's task is to replace the SSRMS Arm Controller Unit (ACU). The SSRMS and the SPDM are individually powered and examined. The SSRMS is maneuvered to the SPDM base PDGF, where it attaches and latches itself to the SPDM. Together they are manipulated to the spare ACU location, where they acquire the spare ACU and temporarily stow it on the SPDM base ORU 1 location. The SSRMS deposits the SPDM back on the MBS and then the SSRMS is stowed in its shoulder roll ACU maintenance configuration. The failed ACU is disconnected by the SPDM, then removed and temporarily stowed on the SPDM base 2 ORU locations. The replacement ACU is removed from its temporary stowage at base location 1, fitted to the SSRMS, and electrically connected and checked. The failed ACU is removed from its temporary stowage, and placed in long-term storage with keep-alive power connected, using the same SSRMS and SPDM combination. The manipulators are stowed in their normal operating configurations and powered down.

SPDM Control Modes

The SPDM is intended to be controlled telerobotically from a workstation inside the IVA environment known as the IVA control station (IVA-CS). The SPDM can be operated in three distinct modes. The first SPDM mode is the manual augmented mode, during which the IVA operator inputs commands through two 3-DOF hand controllers that cause the selected arm to move to a particular POR within the task space area. The second

SPDM mode is the single joint mode in which each of the 19 individual joints SPDM can be commanded, such as to reposition the base body joints for better access to the ACU ORU. The third SPDM mode is the automated trajectory mode, which commands the SPDM along prescribed trajectories generated from previously stored information, or as determined from POR target coordinates or vision system tracking signals.

Japanese Experimental Module Remote Manipulator System

As part of its contribution to the ISS, the Japanese Space Agency, NASDA, is providing a Japanese Experimental Module (JEM), shown in Figure 14. JEM is a manned, multi-purpose space experiment laboratory attached to the Space Station and consists of a pressurized micro-gravity laboratory (PM), two external exposed facilities (EF) for attaching scientific experiments, an experiment logistics module (ELM), a large manipulator known as the main arm, and a small fine arm (SFA) for dexterous activities around the exposed facilities. The complete robotic system with the control equipment and computing facilities in the pressurized module is known as the JEM remote manipulator system (JEM-RMS).

The PM is a cylinder-shaped, multi-purpose laboratory in which material processing experiments and life science experiments are conducted in the micro-gravity environment. The EF is a working station exposed to space, in which scientific observations, communications experiments, science and engineering experiments, and material processing experiments are conducted mainly by remote manipulation. The ELM is a container that is used to store and supply experimental specimens, various gases, consumables, and so on, and to transport materials between the JEM and the earth.

Figure SEQ Figure * ARABIC 14. Japanese Experimental Module

JEM-RMS Configuration

The operation of the JEM and the experiments in the JEM will be performed by one crewmember. To increase the productivity, safe, and reliability of the JEM, it is necessary to apply automation and robotics technologies to replace human intelligence. The JEM Remote Manipulator System (JEM-RMS) is attached to the PM to handle the ELM, the EF, and the Orbital Replacement Units (ORUs), including mission equipment, to support implementation of experiments, and to monitor a worksite and the Extra-Vehicular Activities (EVA).

The JEM-RMS has two configurations: a main-arm configuration and a small-fine-arm configuration. The main arm handles large payloads, such as the EF, by grasping the grapple fixture with the end effector, whereas the small fine arm, attached to the end effector of the main arm, handles relatively small payloads, such as the ORUs, or executes dexterous work with a gripper end effector or special tools.

As shown in Figure 15, the JEM-RMS consists of the main arm, the small fine arm, a vision system and operation and management equipment. The main arm has six degrees of freedom that are packaged in three physical joints (shoulder, elbow, and wrist) with a full length of about 10 m (including the end effector). The small fine arm (SFA) also has six degrees of freedom that are packaged in the three physical joints (shoulder, elbow, and wrist) with full length of about two meters (including a grapple fixture and an end effector). The JEM-RMS arm specifications are detailed in Table 5. The small fine arm is connected electrically and mechanically with its grapple fixture to the end effector of the main arm, through which it is controlled from the PM. Since the manipulator control system forms a man-in-the-loop system, visual information is essential for its operation. The visual information is obtained either by direct view through the window of the PM or by TV cameras. Two sets of TV cameras are mounted on the elbow and wrist of the main arm. Five sets are mounted on the PM and the pedestals of the EF. Stereoscopic TV cameras are mounted on the small fine arm.

Figure SEQ Figure * ARABIC 15. JEM Remote Manipulator System (JEM-RMS)

The main arm attached to the aft end cone of the pressurized module (PM) has the capability to reach out over the exposed facilities for payload and experiment placement and retrieval. The main arm is terminated in an end effector similar to the SRMS interface, which can attach itself to the small fine arm. In fact, Spar has a contract to provide the end effector for the JEM arm.

The SFA would normally be stored on the exposed facility and picked up when needed. The SFA is terminated at one end with a grapple fixture that can be interfaced with

Translation/rotation speed (mm/s)

the main arm end effector and at the other end by a gripper for dexterous tasks around the exposed facility workspace.

JEM-RMS Control Modes

The control console is situated close to the airlock and window at the aft end of the JEM PM. At the control console, the operator can input commands to the RMS using a 6-DOF hand controller with video viewing being available. Manual control is a master-slave arrangement, and automatic trajectories can be selected.

Table SEQ Table * ARABIC 5.

JEM-RMS Arm Specification

Item	Main arm	Small fine arm
Structural Type	Main Arm and Small Fine Arm type	
Degrees of freedom	6	6
Length (m)	Nearly 9.9	Nearly 1.7
Payload handling weight (kg)	Max. 7,000	Max. 300
Positioning accuracy (mm) (degree)	Translation 50(+/-)	Translation 10(+/-)
	Rotation 1(+/-)	Rotation 1(+/-)

Translation/rotation speed (mm/s) (mm/s) (mm/s)	60 (P/L: less than 600kg)	50 (P/L: less than 80kg)
	30 (P/L: less than 3,000kg)	25 (P/L: less than300kg)
	20 (P/L: less than 7,000kg)	-
Maximum tip force (N)	More than 30	More than 30
Life	Over 10 years	

The small fine arm is also equipped with force moment sensing (FMS) and force moment accommodation (FMA) that provides feedback to the operator regarding the forces and moments developed at the tip of the SFA. Force moment sensing (FMS) and accommodation allows faster berthing of payloads and prevents the potentially damaging buildup of forces in the arm structure. FMS also allows the SFA to feel its way into passive berthing mechanisms.

JEM-RMS Design Status

NASDA will develop the JEM operational capability in Japan. System study and coordination with NASA are currently underway. The operation system in Japan includes an Engineering Support Center that supports planning and real-time monitoring, a User Support Center that supports user payload integration, a JEM operation training facility, a logistics support facility, and an information network system.

NASDA is planning to construct the Space Station Integrated Program (SSIP) center in Tsukuba Space Center, a NASDA research and development center. The SSIP center will have four buildings, the space experiment building, a JEM building, a crew operation support building, and a mission operation building.

SSIP's space experiment building will be for user support and experiment equipment preparation and testing, while the JEM building will be for JEM final assembly and testing, JEM training, payload physical integration, and JEM operations simulation. The SSIP crew operation support building will be for basic crew training and crew health maintenance: a weightless environment test facility for JEM operational procedure verification and crew familiarization in a weightless environment. Finally, the SSIP mission operation building will be for operation planning, real-time monitoring, and engineering support to SSCC.

Each partner independently develops the space station elements. To achieve efficient, effective, and safe operation, interoperability among the elements must be established. Many items must be taken into account for commonality and interoperability. Typical examples are the international standard payload rack and the data management system.

Several interface coordination meetings on the payload rack were successfully conducted, and an interface control document is being established to satisfy interoperability requirements. To ensure clean, minimal data management system interfaces between the JEM and the Space Station core, and to reduce the risks for the development, specific responsibilities were defined. NASDA is responsible for JEM system development, while NASA is responsible for the overall space station. Based on this principle, interoperability among the elements is being pursued. Network protocol and database access are being coordinated. The coordination, including responsibility sharing between partners, is continuing successfully.

Design issues

ISS Robot design issues include interfaces, grapple fixtures, end effectors, simulation and commonalities from which advantage can be had.

Interfaces

The use of the ISS robotic devices previously described requires a variety of specialized mechanical and electrical interfaces. The types of robotic interfaces, where these interfaces can be positioned on the payload, and how the manipulator attaches itself to this device must be investigated.

Grapple Fixtures

All current large manipulator devices use a grapple fixture (GF) for interfacing with the payload. Four different types of grapple fixtures were planned for the ISS. Functionally, each grapple fixture interface provides a slightly different capability. It is important to note that the SRMS, SSRMS, and JEM main arm can use any of these grapple fixtures as a mechanical interface to the payload, but they do not have the same electrical connectivity.

Physically, each grapple fixture has an abutment plate, three cam lobes, a grapple shaft, and a three-dimensional target as shown in Figure 16. As the target rod projects upward from the center of a circle, parallax effects help the manipulator operator align the end effector with the grapple fixture, with proper alignment being achieved when the rod appears centered within the circle when viewed through the end effector camera.

The location must be appropriately positioned relative to the payload center of mass to minimize inertia effects that can degrade remote manipulator system control performance. The grapple fixture location must provide acceptable manipulator kinematics, from payload unloading to installation on the ISS.

Figure SEQ Figure * ARABIC 16. Typical Grapple Fixture

End-Effectors

The end effector provides a physical interface between the manipulator arm and its payload. The SRMS, SSRMS, and JEM end effectors are designed for use with payloads or tools with attached grapple fixtures. Mechanically, the end effectors of these manipulators are functionally equivalent and use a snare to achieve a soft capture and a retraction mechanism that aligns and enhances the interface rigidity.

The capture and rigidity sequence has several steps, including placing the grapple shaft in the end effector canister, rotating the snare cables around the grapple fixture shaft to align the interface, and pulling the shaft into the end effector to form a rigid interface. The SSRMS additionally engages a set of collet latches, which allows for the transfer of higher loads and reduces snare cable lifetime concerns. Figure 17 shows the latching end effector.

Figure SEQ Figure * ARABIC 17. Latching End Effector

Simulation

The characteristic software and hardware simulation of kinematics and dynamics can categorize simulation facilities into four main types. MAGIK is the manipulator analysis graphic interactive kinematic, SES the systems engineering simulation, MDF the manipulator development facility, MRMDF the mobile remote manipulator development facility, SDTS the six-degree-of-freedom test system, and SSAIAF, the space systems automated integration and assembly facility. Trick is not an acronym but a dynamic software simulation of manipulator system that works in tandem with the MAGIK program. CIM station is a commercial program primarily utilized for kinematic simulations, but it also has some dynamic capabilities.

Kinematic simulations are used to describe the movement of the robotics device, while dynamic simulations describe the flexibility of the robotics manipulator's structural members and joints. Software simulations present robotics equations of motion in a visual manner for evaluation, but no actual hardware is used. Hardware simulations use representative components for both kinematic and dynamic evaluations.

The design iterations required to develop the ISS assembly sequence were completed mainly using the MAGIK program. MAGIK is the primary kinematic analysis tool used by the ISS robotic analysts at the Johnson Space Center. It allows users to conduct man-in-the-loop analyses to evaluate space robotic operations, including issues of reach, clearance, viewing, and control. MAGIK can be used to model, specify, simulate, analyze, and modify n-jointed type manipulators and their respective control algorithms. The MAGIK simulation currently implements kinematic models of all robotic devices currently based on the ISS. In 1988, MAGIK was hosted on a Silicon Graphics Iris series workstation, where the solid surface graphics rendering became fast enough that analysts could interactively control virtual robotic systems. A generic manipulator could be operated in coordinated motion while viewing the operations from any chosen perspective or orthogonal view. This capability allowed excellent insight into the problems that would be faced by the crew as they attempted to perform space station assembly and maintenance operations. MAGIK has proven to be an invaluable tool, without which development of the assembly planning work previously presented would have been much more difficult.

Commonalities

Canada is developing the SPDM, but due to recent budgetary cutbacks, as well as the U.S. request that Canada make a full commitment to building SPDM, its completion has come into question. As of 1994 Canada has agreed to, at the very least, design SPDM, but as for building it, that remains unknown. To assist in SPDM completion at lower cost, suggestions have been made that SPDM does not necessarily need to be created "from scratch," and that it could be built based on commonalities it has with the SSRMS, which are presented here from a report presented to the Canadian Space Agency in January 1995.

The development of the SPDM builds upon SSRMS development by use of SSRMS hardware elements, software, and facilities.

Operation of the SPDM benefits from commonality with SSRMS in the following areas:

Operating philosophy

User interface

Control modes

Compatibility with on-orbit assets provided by MSS

SPDM system cost and risk are reduced during all stages of the system life cycle by commonality with SSRMS in the following ways:

Design, development, and verification

Maintenance and logistics (on-orbit)

Training of crew and ground personnel

The following SPDM components are common with SSRMS (Figure 10), and hence at a mature state of development with attendant low risk:

Latching End Effector (LEE)

LEE Electronics Unit (LEU) with resident software

Body Joint (=SSRMS Arm Joint)

Arm Computer Unit (ACU) with resident software

Camera, Light, and Pan/Tilt Assembly (CLPTA)

Video Distribution Unit (VDU) with resident software

Joint Electronics Unit (JEU) with resident software (Re-Packaged)

OTCM Electronics Unit (OEU) (Re-Packaged LEU)

Common SPDM and SSRMS Facilities:

MSS Avionics Integration Facility (MAIF)

System Integration and Test Facility (SITF)

Manipulator Development & Simulation Facility (MDSF)

MSS Operations & Training Simulator (MOTS)

Other (Test Equipment)

The Future.

If the Space Station grows significantly, a second SSRMS and SPDM will be desirable to provide robust servicing capability. Redundant manipulators would allow continued robotic capability, even when a manipulator is withdrawn from operational use for maintenance. The first operational requirement to be met before any manipulator upgrades are initiated would be to replace the manipulator to be withdrawn from service. Therefore, a second SSRMS and SPDM would first be upgraded on the ground before launch with the latest improvements. After installation and checkout of the upgraded SSRMS and SPDM on orbit, the original SSRMS and SPDM could be withdrawn from operations for upgrading and refurbishing. This upgrade could be performed in orbit, but it may be more easily performed on the ground.

Aside from the possible upgrade and refurbishment of the existing manipulators, additional capabilities could be added to the MSS. These capabilities include ground-controlled telerobotics, collision detection using tactile sensors, advanced vision systems and tactile sensing. The potential of using two SSRMSs or two SPDMs simultaneously also exists with the ramifications of coordinated control of two manipulators, and the increased need for collision prediction and avoidance.

Applications

This section describes three possible uses of teleoperated robots.

Space-Based Scientific Platform (Space Station)

The following three robotic devices will be on the Space Station:

> The European Robotic Arm (ERA), which is a relocatable ten-meter manipulator that has been designed for the Russian segment of the ISS, and is therefore technically compatible with it. Largely self-contained, it has a small impact on the Russian resources and internal accommodations.
>
> The MSS, which includes two robots, a Space Station Remote Manipulator System (SSRMS) and Special Purpose Dexterous Manipulator (SPDM). The

SSRMS is a large (17 meter) manipulator that is designed to operate from fixed bases (PDGFs) with IVA control. It would have a larger impact on resources and internal accommodations, provided that additional design changes, hardware, software, engineering, and training are provided, the modified MSS elements could perform the robotics tasks on the Russian segment. Early delivery of the MSS elements might potentially enable the MSS to also assist NASA assembly operations on early flights.

The Japanese Experimental Module Remote Manipulator System (JEMRMS) consists of a Main Arm and a Small Fine Arm in the exposed environment. The Main Arm is ten meters long, has six degrees of freedom, and has a maximum tip velocity of 20 mm/sec. The Small Fine Arm is 2.2 m long and has 6 degrees of freedom.

Servicing In Space (SIS)

Despite the somewhat inauspicious history of space servicing, there is more interest than ever in SIS with initiatives underway in the USA, Japan, and Europe. These involve market studies, economic analyses, mission requirements definitions, trade studies, concept designs, and technology demonstrations in preparation for the development and implementation of pay-for-service systems.

Interest in servicing spacecraft in orbit dates back more than two decades. A primary objective in the development of the US Space Shuttle was to reduce space program costs by replacing expendable launch vehicles (ELV) with a fully reusable system capable of maintaining, refurbishing and upgrading payloads. Unfortunately, projected high development costs forced a reduction of the Shuttle servicing capabilities and provided no means of accessing high altitude orbits or high inclination Low Earth Orbits (LEO). Consequently, the need for the SIS has occurred and a few proposals have been presented, such as the following:

> Experimental Servicing Satellite (ESS): This program was started in 1993 in Germany to demonstrate unmanned external servicing in an experimental way. As a preliminary target for this Servicing Experiment, a defunct geostationary satellite, TV Sat-1, was selected.
>
> Miniman: Several Spanish research institutions are cooperating to develop a space manipulation demonstrator for operation in LEO (Low Earth Orbits) satellites.

Planet Explorations

Sending mobile robots to accomplish planet exploration missions is scientifically promising though technologically challenging. The following aspects make planet exploration a demanding and difficult problem for robotics:

> The robot must operate in a natural, unstructured and à priori unknown environment.
>
> Continuous interaction with the robot is impossible due to significant delays in

communications and low bandwidth.

The information about the robot and the environment is mostly acquired through the robot's own sensors. These limitations have been partially tested and validated.

Because of time delays and low bandwidth, direct teleoperation is either impossible or very cumbersome. Telerobotics approaches need a rather accurate model of the working space and are therefore not applicable as such. The robot clearly requires important autonomous capabilities.

An option is to send one or more simple and completely autonomous robots without any control from a ground station. Such robots, using a behavior based control scheme, would accomplish an imaging, measurement, or sample collection mission. However, it is not possible in this scheme to interact with the robot to designate a precise site to which the robot has to navigate or to send different missions. Even in this case, reaching a precise site needs capabilities with which such robots cannot be endowed.

A different approach is necessitated by the following considerations:

The landing site may be remote from areas of interest to the scientists, mainly because it will be selected for its safety whereas the interesting areas are often undesirable for landing. Hence, the robot has to travel some distance (tens of kilometers or more) from the landing site to reach a specific region of interest.

The mission is not defined once and for all. According to returned data, the scientists on Earth should be able to decide on the exploration of one site instead

> of an other, the analysis of certain samples, and so on. Hence, it is necessary to send new missions to a planetary exploration robot. To do that it is necessary to know where is the robot and what it is doing.
>
> When the environment is poorly known, the mission can only be defined at a task-level in general and not in every detail, except in very special cases, such as collecting a specified rock. Hence, the robot must be able to interpret the mission according to its actual context during its autonomous execution. One or more "observation robots" could provide a view of the primary robot and its environment to scientists on Earth to alleviate this problem.
>
> The robot could experience difficult situations wherein its perception, interpretation or decision-making capacities are insufficient, and human intervention is necessary.

Accordingly, a global architecture was developed in two main parts for a robotic exploration system: a ground station for mission programming and supervision, and a remote robot able to interpret the mission and execute it autonomously.

The Ground Station

The Ground Station includes the necessary functions to allow a human to build a mission that can be interpreted and executed by the robot, and supervise its execution, taking into account the delays and communication constraints. Such a mission is called an *executable mission*, as opposed to a higher-level description of objectives as planet scientists may express them.

The process of building an executable mission is decomposed into the following two phases that correspond to two different levels of abstractions and to different planning techniques:

A phase called *mission planning*, which produces a mission plan defined as a set of ordered steps with temporal constraints that allow the robot to achieve a given goal.

A phase called *teleprogramming*, which consists of refining a step in the mission in terms of tasks that can be interpreted and then executed by the robot. Depending on the nature of the mission and its difficulty, and on the amount of information available at planning time, an executable mission can be composed of a variable number of relatively detailed steps.

Mission planning

Mission planning can be conducted with the help of a planning system able to consider temporal and resource constraints as they can be foreseen. For example, a planning system called Ix-Tet was developed that can reason with symbolic and numeric temporal relations between time instants. It produces a set of partially ordered tasks with temporal constraints. The explicit representation of time allows for a representation of planning operators that specifies information concerning the duration of actions, the relative time when the consequences of an operation become true, the conditions that must remain true during execution and its net effect with other operators executed in parallel.

At the mission planning level, the operator describes the mission in terms of results to be achieved, temporal relations, numerical constraints, and so forth. The planner produces a set of tasks according to that description to develop a nominal plan.

Task Level Teleprogramming

Depending on the nature of the task and on its difficulty with respect to environmental conditions, and depending on the robot decision and operational capacities, a task selected by the planner can be sent directly to the robot, or it may have to be further refined at the ground station. This process is the teleprogramming phase. It uses all the information and expertise available at the ground station that may help the robot in performing its task. The result of this phase can be a more or less detailed program together with a set of execution modalities that provide a convenient representation for a class of conditional plans.

These execution modalities are expressed in terms of constraints or directions to be used by the robot control system for executing the mission and each of its tasks. The execution modalities are also expressed in terms of a description of situations to monitor and the appropriate reactions should such a situation occur. Such reactions are immediate reflexes, local correcting actions, or requests for re-planning a task.

Necessary indications need to be introduced to the robot to take into account failures and unexpected events. A specific procedure is used to interactively build the final plan by appending other tasks. At this point, the plan skeleton is complete, but the tasks need to be refined. It is important to note that the robot, instead of using its own data, can take advantage of other observations [by what/whom – example] to execute its autonomous navigation. In addition, execution modalities can be added to the task to authorize the robot to make its own decisions. Such modalities include constraints and indications for selecting the adequate actions.

When a task is not already defined, the operator must develop a program for the task. The version of the mission program of the robot includes the final mission plan, the modalities, the description of new tasks and all necessary data. The plan is expressed as a data structure, consisting of a set of tasks, defined with their arguments, temporal constraints and modalities, connected by transitions labeled with internal and external events.

Telesupervision

Telesupervision in this context has both a mission monitoring role and a troubleshooting role. Because of communication constraints, specific supervision commands, such as status reports and data on mission execution, must be included in the mission itself. In case of a problem encountered during execution, the robot must decide to call for help or to continue the mission according to the given modalities.

The mobile robot

Because the robot is in a remote and poorly known environment, and communications constraints prevent a continuous exchange of data with it, it is generally not possible to plan its actions in detail. Therefore, the robot control system should be able to interpret the tasks in terms of actions to be executed while considering the actual state of the system and its environment. Mission execution is completely autonomous and controlled on-board, without any interaction operators on Earth unless it is planned. The exchange of data with the Ground Station occurs as planned in the mission unless the execution of a task fails.

The robot control architecture is derived from the architecture for complete autonomy in which the task-planning component is deported to the operator station, which has computers that are more powerful as well as computer-aided facilities and human expertise at its disposal. The architecture is organized into three levels. The higher level is composed of a mission supervisor that interacts with the operator station and the next level. The second level is composed of a task refinement planner and a task supervisor. The activity of the supervisors consists of monitoring plan execution at their level by detecting situations, assessing them and taking appropriate actions in real time. To achieve this, the supervisor utilizes deliberation algorithms bounded by time and compatible with the dynamics of the controlled system.

The lowest level includes the robot modules that perform perception and action execution. The response time of these modules is bounded, because they use polynomial time algorithms. This level is managed and controlled by a central executive. It executes the actions requested by the task supervisor. The executive is a time-bounded system; its reactions to events are part of a predetermined, precompiled structure.

A robot module embeds primitive robot functions that share common data or resources. An internal control process called a module manager is responsible for receiving requests to perform these functions from the robot controller and for otherwise managing the module. Such an architecture allows a level of robot autonomy that is essentially dependent upon the environment and the difficulty of the task. The autonomy is determined by the procedures implemented on the refinement level and the algorithms within the module functions.

Mission Execution

On-board plan supervision consists of sequencing the tasks according to expected events specified in the plan as well as unspecified events. In case of a conflict between two tasks, the plan supervisor is responsible for deciding which task should be executed or interrupted for decision enforcement. Each task in the plan corresponds to the execution of one or several procedures. According to the tasks and to the execution context, the procedures are either selected because they are explicitly designated in the task plan, and are then instantiated for execution, or they are selected as a result of the designated goals

The choice of the best procedure among several candidates, is made by a meta-procedure that reasons on applicability criteria. Procedure selection is an iterative process. The execution of a procedure may produce several outcomes. The plan explicitly provides the desired chaining between the tasks according to some of these outcomes. If this chaining is not explicit in the plan, default procedures are selected and executed by the supervision system. Usually, such procedures will put the robot in a safe and stable situation, and attempt to communicate with the ground station.

Conclusion

The presented approach is based on a generic architecture for intervention robots that has been developed for highly demanding applications such as planet exploration. It has been partially implemented and demonstrated using a mobile robot performing autonomous navigation tasks in an unknown natural environment.

METHODOLOGY

Extensive literature was analyzed in detail to ascertain all the problems that might discourage the use of teleoperated robots in space. Each concern was delineated and resolved with requirements that would eliminate or at least mitigate the concern to the extent that it would not be an impediment to the implementation of teleoperated robots.

RESULTS

A number of important teleoperated robot requirements were derived from a review of the literature and an extrapolation into other environments.

Accuracy, Repeatability and Latency

The robot control system must be able to accurately position and orientate the end effector and it tools. The more accuracy, the less adaptable need be the end effector tools and the less specialized need be its payloads, i.e. grappling points need not be added to every payload. An accuracy of plus and minus 0.05 mm ????? is desirable.

Similarly, the robot control system must be able to accurately repeat the same movements to within plus and minus 0.05 mm ??????.

The time it takes for a motion to begin after it is started, and the time it takes for a motion to end after it is stopped is the latency delay caused by the less than perfect fit of the parts (tolerances) and inertial overrun of the drive mechanism. Latency must be minimized or anticipated if the accuracy and repeatability requirements are to be met.

Thermal Expansion or Contraction

Links will lengthen or shorten and bend according to their exposure to the radiant energy of a star, particularly if there is no gaseous environment to dissipate the heat. Non-uniform heating of a robot will adversely affect its accuracy and repeatability.

Longitudinal

To achieve the accuracy required may necessitate some form of temperature control in the work area. While this may be feasible within crew quarters, it is not feasible in the vacuum of space. There an adaptive structure would be required.

Active

Telescoping links could actively compensate for thermal expansion/contraction of the links. A laser range-finding system internal to the link (graphite tube) or external to it could actively drive a rack and pinion system to shorten/lengthen the arm as it is heated/ cooled, respectively to maintain a nominal length.

Passive

The links could be passively lengthened/shortened with an internal piston driven by a liquid whose volumetric response to thermal variations exceeds that of the link.

Bending

Extended exposure to solar energy on one side of a link will cause it to expand while the shaded side contracts, causing the link to bend. Adaptive or passive compensation as described above could be employed to actively or passively maintain straight links, however the forces required to counteract such bending may be impractical to achieve. A highly thermally conductive surface would mitigate bending, but not likely eliminate it, so a jacket with a circulating fluid may be required to thermally balance links and limit their bending to amounts that do no compromise accuracy or repeatability. If the fluid were cooled/heated to maintain a constant as well as uniform temperature, then it would eliminate the need for active or passive longitudinal compensation schemes as well.

Conclusion

Robot links exposed to the vacuum of space or an atmosphere too tenuous to attenuate thermal effects must be kept at a constant temperature with a circulating fluid. Otherwise the end effector must use sensors to constantly seek a position designated by a local positioning system much like the now familiar Global Positioning System.

Control

The robot control system must include the ability to be switched between a command source in its vicinity, i.e. a local operator like a space station flight crew member, and a remote command source, like a ground operator.

When operated by a local operator, commands are sent directly to the robot. When operated from the ground, operator commands are sent to a robot simulator on the ground that forwards the commands to the robot. To make ground control operators feel physically present at the work site, animations and force feedback from the simulator must be provided to the operator as an indication of real time robot activity while awaiting time-delayed video, force and position and orientation data telecommunicated from the robot. The force, position and orientation data must be used to correct the simulation. Repetitive errors must be used to refine the simulation algorithms just as empirical tests were used to refine the simulation before the robot was deployed.

A three-dimensional animation of the simulation not only provides replicas of the local robot video camera views, but also provides any additional views the operator wants on separate monitors, including the views seen by those in the vicinity of the robot through their windows. Although time delayed, these animations can also be useful to local operators by providing views of robot activity that are not available from their windows or video cameras. When robot motion has stopped for a period equal to or greater than the time delay (data: 9 seconds, video: 6 seconds for ground to earth orbit situation), the actual video can be overlayed on the simulator display to provide the remote operator, or "teleoperator" with a dose of reality, and an opportunity to see objects that may be unknown to the simulator.

These simulator algorithms must include the various limits of the robot so the actual robot limits are not exceeded by the teleoperator. The limits also provide the data needed by the simulator to mitigate gross teleoperator commands, and decelerate robot motions as the limits are approached to minimize robot fatigue and wear.

The teleoperator controls the robot by controlling its animation and feeling the forces provided by the simulation.

Fail Safe

To protect the robot from dangerous commands from an operator or simulator, sensors on the robot must cause the robot to halt if an out-of-range condition is detected. The robot accordingly notifies the teleoperator of the situation, and relies on the operator to devise a remedy, because reverting to a "safe state" may involve automated moves that exacerbate the problem, or create new problems.

Sensors must also be used to protect the payload from damage by the end effector or one of its tools. Prior to a mission or operation, the crush and tear limits of the payload must be entered into the robot controller as well as the simulation, so should the operator or simulation fail to consider the fragility of the payload, the robot will halt before damaging the payload.

Motion optimization

Simulator data should be analyzed to discover repetitive moves that are worthy of optimization and encoding as a single command, like transfer commodity ABC-1 from a shuttle to space station port PQR-2. In this manner a long series of tedious operator commands can be executed with the push of a button or a menu selection. The longer the telecommunication time delays, the more important is motion optimization and encoding.

Simulation Display Requirements

The simulator monitors and the data driving them must be of sufficient fidelity to display joint angles with simulated meters at each joint. Color can be used to display the bending and torque loads experienced by the robot by coloring the surface of the robot animation according to the calculated or measured stress. Simulated torque and pressure meters may be required at the end effector to precisely indicate to the operator the forces being exerted on the payload. To avoid obscuring the end effector or its tool or payload, these meters must be small, yet readily readable. This may place additional demands on monitor resolution.

Local operators would also benefit from seeing robot component stress distribution displayed as color variations on an animation of the robot. Hence, the local operators should also indirectly control the robot by driving a simulator animation while the simulator directly drives the robot. Having both local and remote operators using simulators as intermediaries has a number of other advantages. It simplifies training. It avoids the confusion that would be caused by different operational modes. It provides another means of validating the simulations and correcting one by comparing the position and orientation data generated by the local and remote simulators with a third simulator when communication delays make comparisons with the actual robot position and orientation impossible. Finally, it allows robot operations to be conducted in darkness without continuous artificial lighting of the robot environment.

Robot Environment

To avoid damaging the robot or objects within its environment, the simulation must include three-dimensional models of everything within range of the robot.

In the case of an unknown environment, a robot must first survey it with it with an electromagnet or acoustic mapping end effector tool to create a three-dimensional model of its environment that can be telecommunicated to the simulator(s). Only then can the animations of the simulator(s) include the environment of the robot.

Error Detection and Reporting

Teleoperated robots must work autonomously for the duration of the telecommunication time delay plus the reaction time of a worst case ground operator. Depending on the distances involved, the period of autonomous behavior can range from seconds to hours. Although the MSS Failure Management Architecture provides an essential framework for failure detection for teleoperators, it is not designed to cover non-equipment errors related to the inability of the robot to autonomously complete a task. Teleoperated robot operators require yet another layer of task error detection and response capability.

In addition to the pressure and torque sensors needed to prevent the robot from performing motions dangerous to itself or its payload, proximity sensors are required on the robot with enough range to allow it stop, or plan and execute an avoidance maneuver after detecting an unexpected object within its path. Simply halting would be practical in an orbital situation, but it may cause significant task delays when the telecommunication time delay is interplanetary. Furthermore, the unexpected object may be moving, so simply halting would be unacceptable even in an orbital situation. A sophisticated object avoidance system is required regardless of the circumstance. The robot must detect an object in its environment, determine its trajectory and accordingly plan and execute a maneuver or a deviation of its current maneuver to avoid contact with the object.

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