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REMOTE SYSTEMS DEVELOPMENT

by
R. Olsen, O. Schaefer, and J. Hussey
Space and Electronics Division
Grumman Aerospace Corporation
Bethpage, New York 11714

ABSTRACT

Potential space missions of the nineties and the next century require that we look at the broad category of remote systems as an important means to achieve cost-effective operations, exploration and colonization objectives. This paper addresses such missions, which can use remote systems technology as the basis for identifying required capabilities which must be provided. The relationship of the space-based tasks to similar tasks required for terrestrial applications is discussed. The development status of the required technology is assessed and major issues which must be addressed to meet future requirements are identified. This includes the proper mix of humans and machines, from pure teleoperation to full autonomy; the degree of worksite compatibility for a robotic system; and the required design parameters, such as degrees-of-freedom. Methods for resolution are discussed including analysis, graphical simulation and the use of laboratory test beds. Grumman experience in the application of these techniques to a variety of design issues are presented utilizing the Telerobotics Development Laboratory which includes a 17-DOF robot system, a variety of sensing elements, Deneb/IRIS graphics workstations and control stations. The use of task/worksite mockups, remote system development test beds and graphical analysis are discussed with examples of typical results such as estimates of task times, task feasibility and resulting recommendations for design changes. The relationship of this experience and lessons-learned to future development of remote systems is also discussed.

INTRODUCTION

The inherent capacity of humans reaches its full potential when we learn to extend our reach beyond our immediate environment. Whether it be by humans traveling into space or by sending our intellect and physical capacities via robotic vehicles, while we remain behind, our species must always explore and develop the next frontier. These philosophical reasons for human involvement in space encourage us to develop ways to extend our reach while maintaining safety, practicality, and the use of resources within acceptable bounds. It is for these reasons that *remote systems*, i.e. systems that operate with a degree of self-contained intelligence to perform useful functions for humans but at a location removed from the presence of humans, have been a "growth" area since the beginning of the space program. Within the framework of this definition of remote systems, the human can provide varying degrees of control of the remote elements - ranging from simple changes of commands, e.g. between two positions of an antenna gimbal drive, to highly interactive control of a robot manipulator which sends measured force information to a remote human operator, to a fully autonomous robot which carries out a complete task or even a complete mission at the request of a human. Remote systems, in this context, apply to a wide range of applications (Fig. 1) from low earth orbit (LEO) through geostationary earth orbit (GEO) to lunar and planetary missions, and include "robots" which perform manipulation functions, and "remote vehicles" which provide translation capability.

This paper is concerned with how these systems are developed through a process of mission analysis, identification of design issues, and the use of various available techniques for their resolution. It also illustrates how the remote tasks proposed for future space missions correspond closely to a myriad of potential applications on the earth (Fig. 2).

Grumman has been involved since the 1970s with the development of remote systems beginning in an "inner space" application with robot arms on the Ben Franklin submersible and remote maintenance devices for the nuclear industry to involvement in the 1980s with space systems for satellite servicing, remote military ground vehicles and flexible assembly systems for aircraft manufacture. The emphasis has generally been on a wide variety of tasks in an unstructured environment.

REMOTE SYSTEMS

A remote system as defined above does not begin to have real meaning until the definition is expanded in the form of the general system architecture presented in Fig. 3. This figure presents the concept of a human, the user, in one location or environment controlling effectors and tools which are the means of performing desired functions or tasks, in some other location or environment and utilizes sensors for task control and user feedback. The sensors provide the spatial/temporal information of the gaming area for remote control of mechanisms and the remote sensory perceptions of the user. The degree of perception of task conduct and completion is a key to the strategy of using remote mechanisms intelligently.

The user receives sensory information and enters commands through a user interface while information is controlled and manipulated between the two environments by processing elements. The processing, as illustrated, is gen-

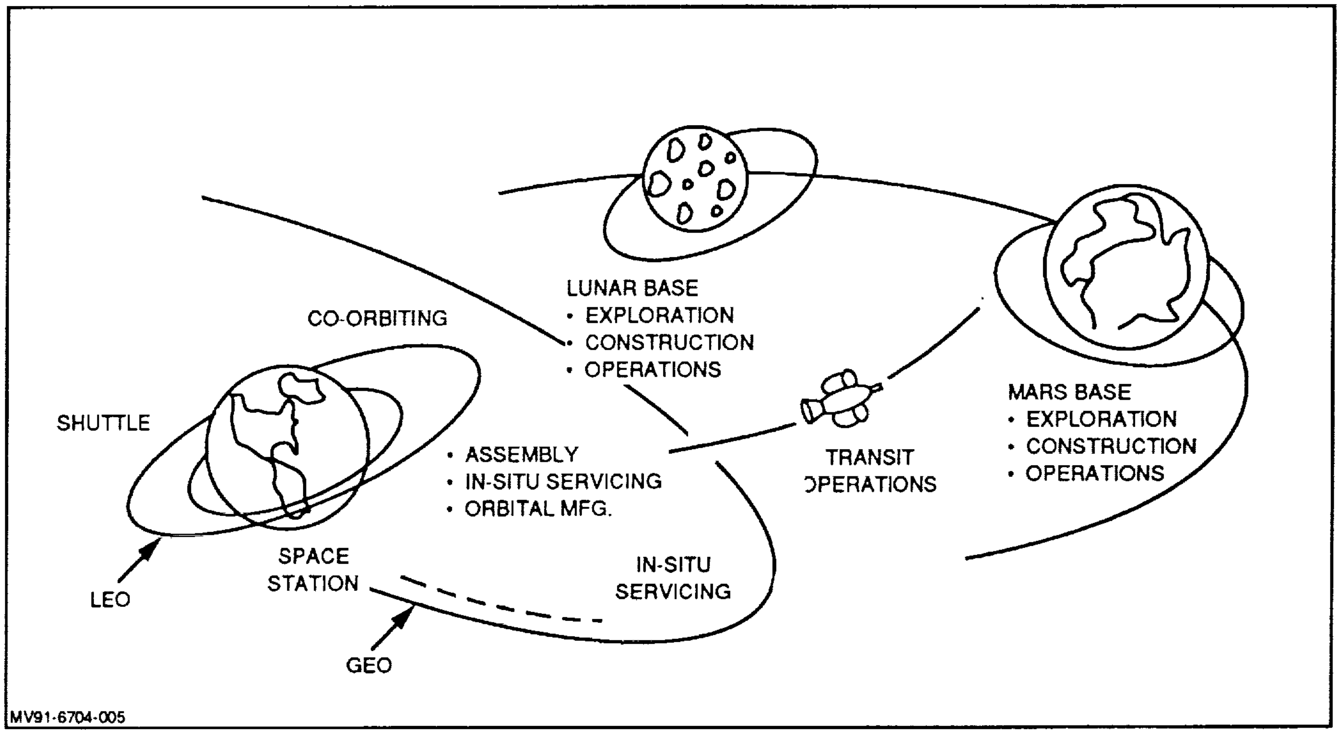

Fig. 1 Future Remote Systems Scenarios

erally divided between the two environments, with the processing complexity in either location being a function of the quantity of information and the level of sophistication of the computations required. When most of the processing is at the user location, the control approach is described as teleoperation. When almost all of the processing takes place at the remote site, the system is described as autonomous. In the latter case, the user is mostly a periodic observer of the task being performed with the ability to redirect or take charge at any time.

The communications element between the processing in the two environments, which is shown in the figure, provides for the passage of signals and commands. In some cases, this element may be nothing more than a cable

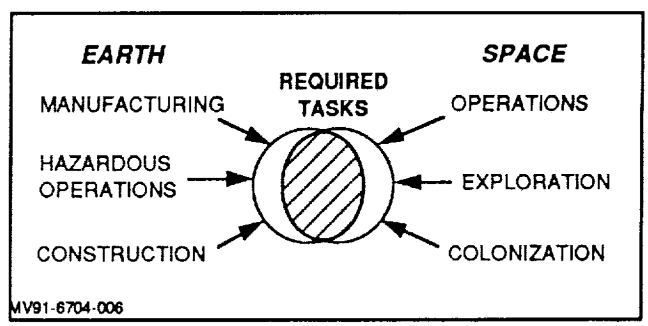

Fig. 2 Similarity Between Earth & Space Remote Systems Tasks

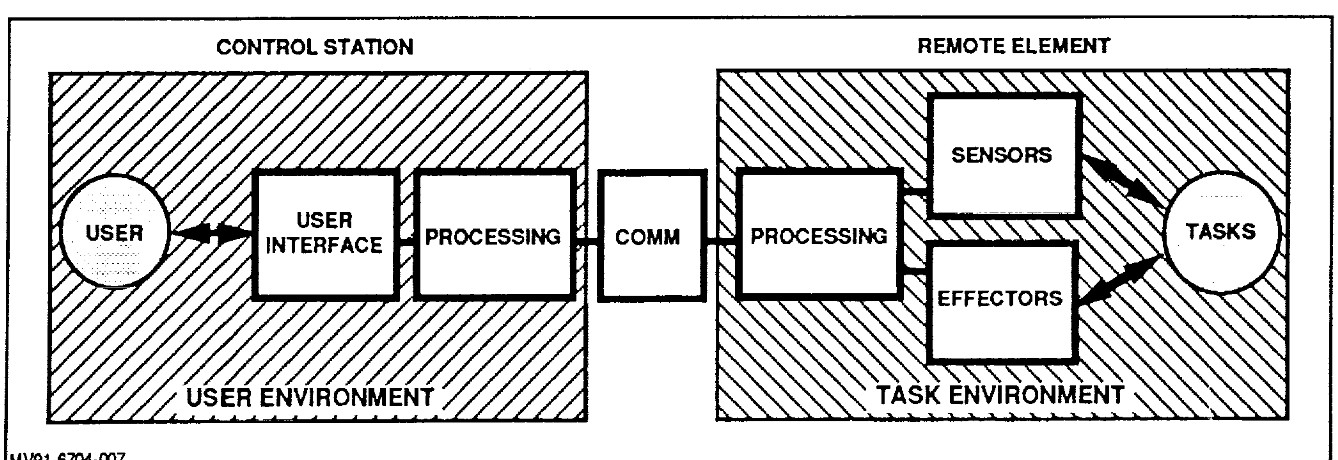

Fig. 3 Remote System General Architecture

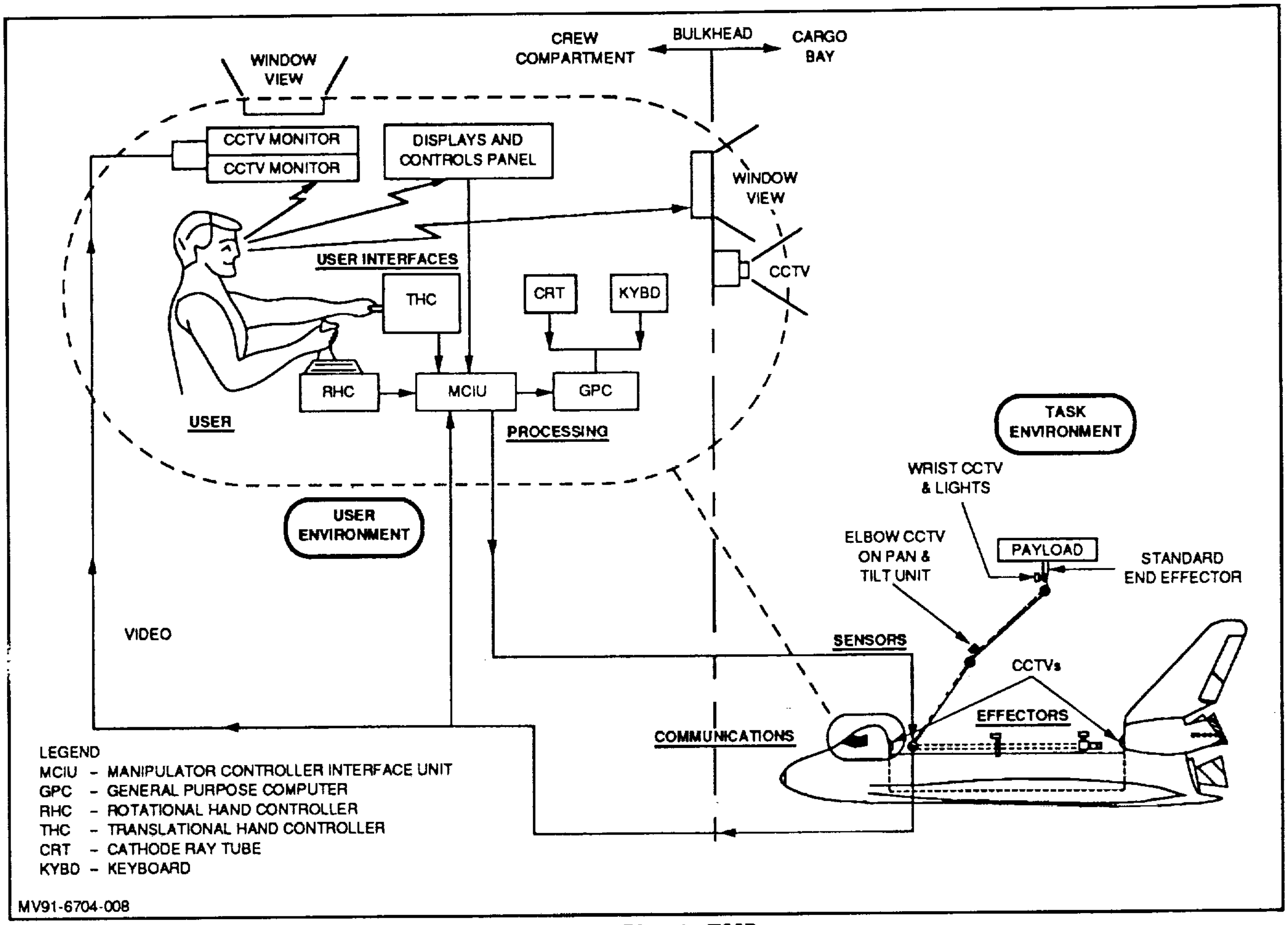

Fig. 4 Shuttle RMS

between the two environments. It becomes especially important when long distances are envolved such that wireless communication is required. Often the communications link is characterized by a long time delay which may be a significant factor in developing a remote system.

Figure 4 illustrates the above architecture applied to a specific remote system, the shuttle's Remote Manipulator System (RMS), with the system elements identified.

FUTURE MISSIONS

The development of remote systems for space is very dependent on the wide range of anticipated future missions (Fig. 5). These missions can generally be grouped into three categories: operations, exploration and colonization. The operations missions have already begun as exemplified by the use of the shuttle RMS for a variety of deployment and servicing support functions in more than 20 missions. The 1990s will see an increase in operations with shuttle and space station tasks carried out by U. S. and foreign remote systems such as the Canadian Special Purpose Dexterous Manipulator and the Japanese Small Fine Arm. It is difficult to project too far into the future but it appears that in addition to increasing operations functions, the exploration and, eventually, the colonization functions will rely on remote systems to achieve objectives in a cost-effective manner.

Potential applications of remote systems for these missions are presented in Fig. 6 which also identifies some of the key technologies required to provide the capability. There is also a group of related applications of remote systems required on earth (Fig. 7). Much of the technology required is generally the same although specific differences may exist because of unique environmental or functional requirements. Nevertheless, it is believed that the development of remote systems for earth and space applications should take place in concert to a large extent. The methodology for such development, presented in subsequent sections for space remote systems, is applicable to terrestrial systems and, in fact, benefits can be obtained through joint efforts in selected areas.

REQUIREMENTS/ISSUES

The development of remote systems (Fig. 8) starts with the decomposition of the mission requirements into goals, tasks and subtasks, and the characteristics of the mechanism and user/work environments. The functional decomposition lends itself to development of a relational data base that will maintain traceability through the design concept development stage. This initial stage of decomposition must characterize the performance indexes, constraints, time functions, data items, and components. To achieve this de-

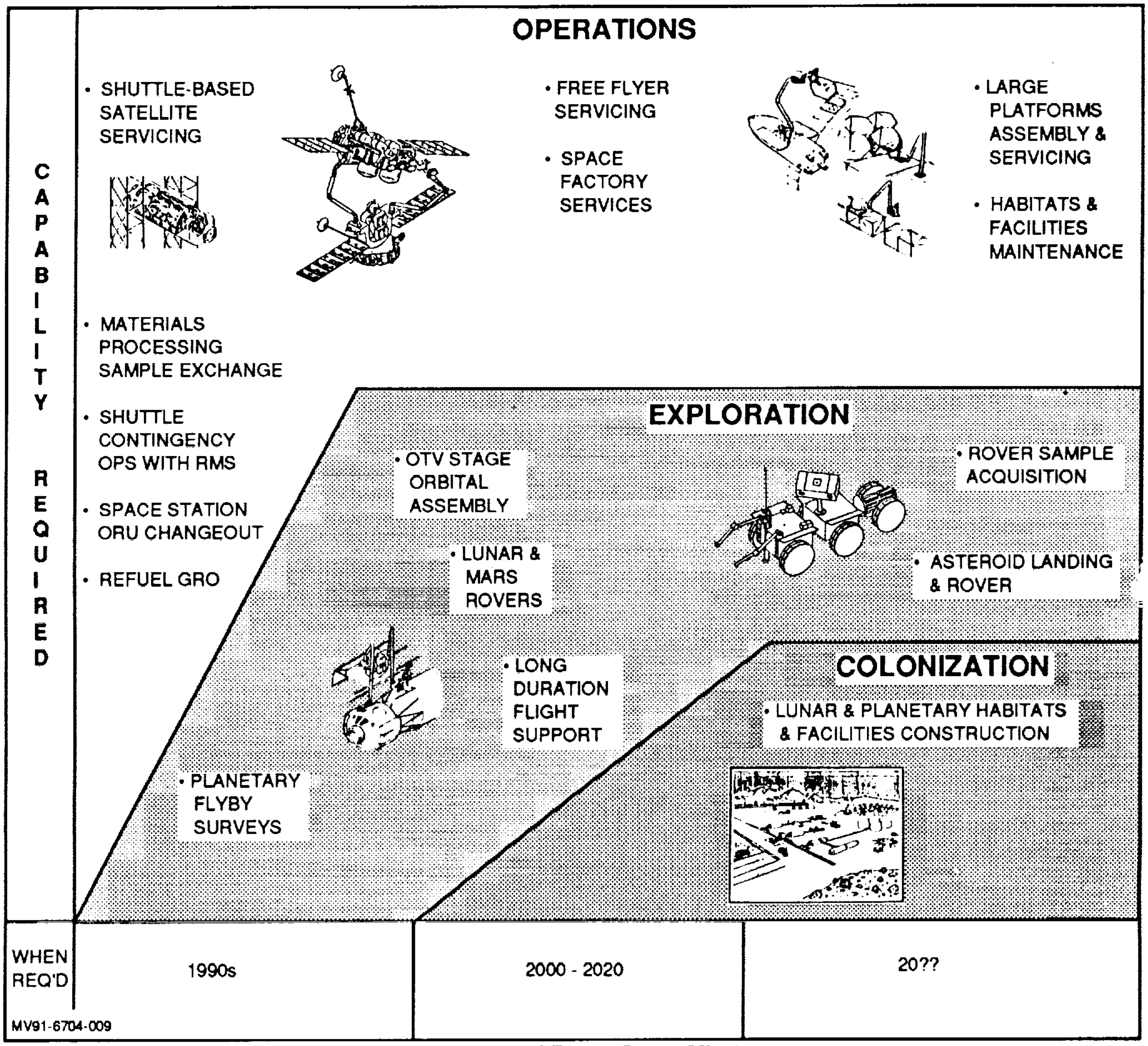

Fig. 5 The Range of Future Space Missions

composition, the mission definition must therefore characterize the payload size, operational volume, physical constraints, task environment characteristics, and any special functions/characteristics that are germaine to the proposed mission.

The objective is to develop a set of requirements that define the boundaries within which the remote system must function to accomplish the mission tasks.

From this base a series of trades can be conducted to establish the global or architectural issues of the design. Although the structured environment of the factory is ideal, the generally more unstructured environment of space systems can be viewed as similar, but with more interactions required to address the uncertainties (i.e. constraints).

The development of system requirements requires careful consideration of the fundamental design issues relative to the mission-related factors which establish remote system requirements. Figure 9 indicates which design factors for remote systems are affected by five mission factors which generally cover all system requirements. Payload size includes not only the volume but unusual shapes and configurations. Operational volume is the volume at the task site which must be reachable physically by the manipulator arms and visually by the sensors. At the control station, the volume requirement impacts the design of controllers which require operator movement.

Physical constraints refer to all types of mission factors which may limit or prevent some performance capabilities of the system design. An example relative to the manipulator arms would be task site characteristics which require reaching around obstacles to perform a task. Relative to the control station, a physical constraint would be an existing display panel design the prevents the easy incorporation of some display features especially suitable for telerobotic operations.

Task environment factors include items such as natural lighting conditions at the task site which may have a major impact on sensor performance requirements. Another task environment example is physical separation between the robot and control station which results in significant transmission time delay.

The special functions category is meant to cover unique mission requirements which do not fit into the previous categories but which may have a significant effect on system design. Examples are missions requiring handling of cryogenic equipment and operations with hazardous fluids.

There are many issues associated with remote systems design which emanate from the above system requirements and which generally must be resolved before a design can be finalized. Major issue areas (Fig. 10) are the mix of humans and machines, the particular remote system's characteristics, the compatibility of the worksite with the remote system elements, and the required workstation features. Each of these areas is discussed below in terms of specific items which may require resolution.

The *mix of humans and machines* is of special interest because it involves reaching a balance between human capabilities and the limitations of technology relative to the human intellect. The level of autonomy/processing of the remote system must be sufficient to meet the mission requirements and is dependent on the specific tasks and the range of variations in the task environment. High levels of autonomy require that the capabilities of the remote systems technology be sufficiently developed to properly characterize the dynamic task environment from sensor information, to compute the necessary response to carry out the mission, and to provide the means for creating this response. The level of feedback/communications to the human from the remote system is another important element because it significantly impacts the communications link requirements. The decision level of the human in the performance of the remote tasks is another factor which can vary from a high level that only decides on the next task to be performed based on successful completion of a task, to low level decision making such as the path planning choices made during a task.

An important element determining the mix of humans and machines concerns the evaluation of hazards which can affect mission success, especially relative to systems where humans are present. The mix will be different if the tasks involve operations which can threaten humans if not performed properly or under failure conditions.

The *remote system characteristics* area basically concerns the design parameters for the remote system relative to the particular functions to be performed. It is primarily described by the physical size and capacity of the effectors, degrees of freedom of mechanisms such as manipulators, end effectors/tools for interfacing with the tasksite, and vision/lighting capabilities. The goal is a remote system which provides the needed performance levels without excessive capacity.

USER GROUP	APPLICATIONS	TECHNOLOGY REQUIREMENT
PERIODIC ORBITAL OPERATIONS	• S/C SERVICING AND MAINT. • S/C ASSEMBLY IN ORBIT • CONTINGENCY OPERATIONS	• TELEOPERATED SYSTEMS • BILATERAL FORCE-REFLECTING, DEXTEROUS 2-ARM MANIPULATOR • VISION/LIGHT SENSORS
PERMANENT SPACE OPERATIONS	• MATERIALS PROCESSING OPERATIONS • HABITAT MAINTENANCE • PAYLOAD ADJUSTMENTS & RECONFIGURATION	• AUTONOMOUS SERVICING SYSTEMS • PRECISION MANIPULATORS • ADVANCED SENSORS
EXPLORATION MISSIONS	• PLANET MAPPING & INTERPRETATION • ROVER VEHICLE PLANETARY EXPLORATION • EARLY SURFACE CONSTRUCTION TECHNIQUES	• ADVANCED TELEOPERATED SYSTEMS • HIGH RESOLUTION TV TRANSMISSION • HIGH RELIABILITY SYSTEMS • MOBILITY SYSTEMS
COLONIZATION MISSIONS MV91-6704-010	• SURFACE MINING • CONSTRUCTION • TRANSPORTATION VEHICLES	• AUTONOMOUS SERVICING SYSTEMS • PRECISION MANIPULATORS • ADVANCED SENSORS

Fig. 6 Remote Systems Applications – Space

The *tasksite compatibility* area concerns the characteristics of the task environment which have a direct bearing on the remote system design. It includes the nature of the terrain for mobile remote systems. Cooperative features refer to physical characteristics which simplify the design of the remote system for performing the required functions such as easily accessible attachment fittings at all tasksites.

The variations and characteristics of work articles, i.e. items to be handled in some way by the remote system, are very important measures of tasksite compatibility. Safety of the remote system is a function of the compatibility of the tasksite in terms of avoiding tasksite features which may inadvertantly damage the remote system during its operation. Remote systems working in proximity to humans is a special case which must be addressed.

USER GROUP	APPLICATION	TECHNOLOGY REQUIREMENT
SURGERY & REHABILITATION UNITS	• ISOLATION WORK OPERATIONS • MICROSURGERY • AUTOMATED SURGERY IN EMERGENCY • HAZARDOUS MATERIAL HANDLING • PATIENT REHABILITATION SERVICES	• ADVANCED TELEOPERATED SYSTEMS • BILATERAL, FORCE-REFLECTING, DEXTEROUS TWO-ARM MANIPULATOR • HIGH RESOLUTION VIDEO
NUCLEAR POWER	• PLUTONIUM MANUFACTURING • SPENT FUEL REPROCESSING • STEAM GENERATOR INSPECTION • DECONTAMINATION • ASSEMBLY, DISASSEMBLY, REPAIR	• TELEOPERATED SYSTEMS • BILATERIAL FORCE REFLECTION • HIGH RESOLUTION TV TRANSMISSION • VACUUM COMPATIBLE MANIPULATOR
ELECTRONICS	• HIGH-SPEED ASSEMBLY OF "BOTTLENECK" PARTS • CLEAN ROOM OPERATIONS	• TELEOPERATED SYSTEMS • ADVANCED TRANSDUCERS & SERVO CONTROLS • VISION SENSORS FOR REGISTRATION
OIL EXPLORATION	• OFF-SHORE OIL RIG MAINTENANCE • WELL HEAD MAINTENANCE • INSPECTION	• TELEOPERATED BILATERAL FORCE REFLECTING SYSTEM FOR HIGH-PRESSURE, CORROSIVE ENVIRONMENT • REMOTE SENSORS/VISION SYSTEMS
MINING	• UNDERGROUND OPERATIONS • HIGH-WALL SURFACE MINING • OPERATIONS • THIN SEAM MINING OPERATIONS • DRILL BIT AND BOLT INSTALLATION	• TELEOPERATED SYSTEM • DEXTEROUS HEAVY DUTY MANIPULATORS • ROBUST TV TRANSMITTING SYSTEM • ADVANCED LIGHTING SYSTEMS
CHEMICALS	• TOXIC MATERIAL HANDLING • LABORATORY OPERATIONS	• TELEOPERATED SYSTEMS • BILATERAL FORCE REFLECTION • HIGH RESOLUTION TV AND VISION PROCESSING
CONSTRUCTION	• BRIDGE MAINTENANCE • STRUCTURAL ASSEMBLY OPERATION • UNDERWATER STRUCTURAL ASSEMBLY • HIGH RISE BUILDING & BRIDGE ASSEMBLY	• TELEOPERATED BILATERIAL FORCE REFLECTION SYSTEM • HEAVY DUTY, HIGH STRENGTH 2-ARM MANIPULATOR • ROBUST VISION SYSTEMS
FIRE FIGHTING & EMERGENCY UNITS MV91-6704-011	• OPERATING IN RESTRICTED HOSTILE ENVIRONMENT • MUNITIONS REMOVAL	• LOW COST, RELIABLE, TELEOPERATED BILATERIAL FORCE REFLECTION SYSTEMS • LOW COST MULTISPECTRUM VISION SYSTEM

Fig. 7 Remote Systems Applications – Earth

The area of *control stations* essentially covers all the issues associated with the design of the remote system at the location of the human user. It includes the types, quantities and configuration of controllers, the types, quantities and arrangement of displays, and the human factors aspects of the control station design.

SYSTEMS TECHNOLOGY

Remote system concept designs are very heavily influenced by the cost and availability of technology. A summary of required technology availability is shown in Fig. 11. To ease the introduction of new technology, remote systems should utilize open architectures with robust interfaces, for example, the NASA/NBS Standard Reference Model (NASREM) software architecture. Such a functional architecture imposes standard requirements on module interfacing, synchronization, communications and global memory access to support a hierarchal development, by levels, from Task Planner, to Path Planner to Trajectory Planner to Servo Control Level. It is designed to incorporate all levels of remote system automation. The standard interfaces provide the software hooks necessary to incrementally upgrade remote systems as new capabilities develop in processing, sensors, effector mechanisms and autonomous systems.

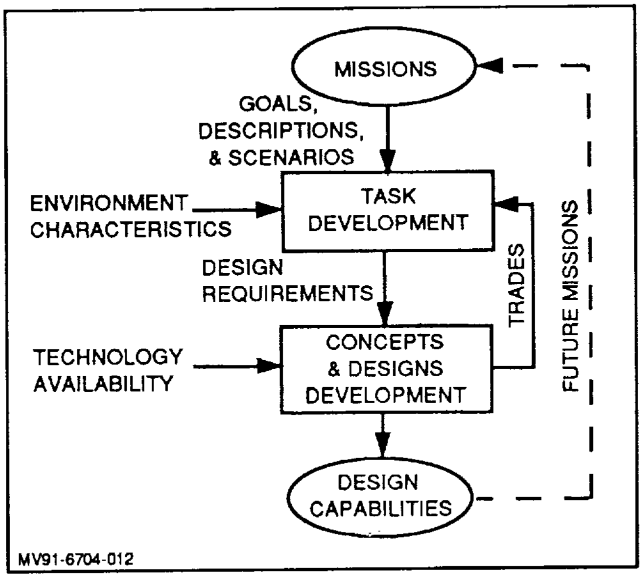

Fig. 8 Remote Systems Design Tradeoff Process

In the hardware area, the use of standards provides the guidelines for minimum levels of performance and functionality and tends to improve availability and reduce costs. It is also the driving force behind the third-party vendor products so heavily relied on. The present state-of-the-art in processors is being driven by the tri-service Joint Integrated Avionics Working Group (JIAWG) selections of 32 bit Instruction Set Architecture (ISA) standards for Reduced Instruction Set Computers (RISC) namely the MIPS R3000 and Intel i960 VLSI chips that produce 50 MIPS and the Parallel Intermodule Bus (PI Bus) wide bandwidth data bus specifications. These specifications are particularly meaningful since high-speed, low-power and wide bandwidth computations capabilities are the core technologies necessary to solve the remote system technology problems.

Another area requiring increased advanced development is the field of computation algorithms, that are targeted at the low-level parallelism available in matrix/vector processing architecture, for inverse kinematics/dynamics, sensor signal processing and sensor fusing. At present an order of magnitude speedup over state-of-the-art systems is needed. The tasks of work environment feature extraction and identification are presently mired in visible bandwidth vision system processing. The ultimate solution probably lies in a sensor fusion approach that requires a multi-spectrum sensor and/or a near field range/range rate sensor to augment the diffraction/disperson problems inherent in feature sensors. These technology areas are a key to remote system motion planning and execution.

Last but not least is the human interface. All too often we attempt to solve our technology problems by "letting the operator do it" without full knowledge of the cognitive work load/overload we create. The human problems of motion and depth perception, detection and recognitiion, and general task knowledge when added to the environment problems of communications delays, sensor perception, lighting and work area uncertainties have created a human factors nightmare. Therefore, there must be a concerted development effort to transition from skill-based operation to rule-based expert system operation to knowledge-based autonomous system operation (Fig. 12) to alleviate this bottleneck in the next decade.

	DESIGN FACTOR	MISSION FACTOR: PAYLOAD SIZE	OPERATIONAL VOLUME	PHYSICAL CONSTRAINTS	TASK ENVIRONMENT	SPECIAL FUNCTIONS
REMOTE ELEMENT	MANIPULATOR ARM - SIZE/GEOMETRY - KINEMATICS	•	•	•		
REMOTE ELEMENT	NO. OF ARMS - DEXTEROUS - STABILIZING	•	•	•		•
REMOTE ELEMENT	VISIBILITY - TV - LIGHTING	•	•	•	•	•
REMOTE ELEMENT	END EFFECTORS - SPECIAL/ALL PURPOSE - TOOLS - STOWAGE	•		•		•
REMOTE ELEMENT / CONTROL STATION	CONTROL TECHNIQUES - FEEDBACK - PRECISION - TIME DELAY CAPABILITY			•	•	•
REMOTE ELEMENT / CONTROL STATION	CONTROL ELECTRONICS - DISTRIBUTION/CENTRALIZED - SOFTWARE	•		•	•	•
CONTROL STATION	CONTROLLERS - REPLICA/NON-REPLICA - ANTHROPOMORPHIC		•	•		•
CONTROL STATION	DISPLAYS - MULTIFUNCTION - DEDICATED			•	•	•

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Fig. 9 Influence of Mission Factors on Design

Once the design requirements have been established and technology trades have been completed, the next step in the process is the resolution of identifed issues and the verification of the design concepts. The various methods to resolve issues are presented in Fig. 13 and the applicability of these methods to the issues discussed above is shown in Fig. 13A.

The numerical analysis is performed at the system specification level after functions have been assigned to hardware and software design elements. Analysis software such as Ascent Logic's Requirements Driven Design (RDD) -100 can be used to develop functional design requirements and contains function behavior models that can be linked into concept design segments for time-function execution analysis. This program is capable of developing performance time lines and computation and communications estimates for initial design verification and sizing exercises.

As the design definition matures, the graphical analysis and computation analysis tools are used to verify the performance and constraints of the architectural elements. The graphical analysis tools such as IGRIP permit analysis of the geometry of the remote system in the work environment. It is an initial verification of geometric and kinematic performance of the mechanisms and task performance/time lines. It is especially useful in resolving remote system and worksite characteristics and compatibilities.

The computer simulation tools are used to develop the engineering performance of the system/subsystem elements. A typical set of tools includes analysis of weight, power, thermal, structural, and control systems. The simulation models are usually transfer function level models, with detailed design parameters, subjected to the stimulus of nominal/worst case environment parameters. The objective is to evaluate the element performances and verify the system budgets and performance allocations.

The hardware test/simulation phase is usually conducted at the full system level and utilizes engineering breadboard hardware/transform function models, prototype algorithms/software and environment mockups operated in real time. It is usually the first time human factors and hardware/software performance are evaluated in the operational environment as a total system. The decision to simulate at reduced scale or full scale depends on the fidelity of the interfaces

ISSUE AREA	ELEMENTS FOR RESOLUTION
MIX OF HUMANS & MACHINES	DECISION LEVELS HAZARDS EVALUATION LEVEL OF AUTOMONY/ PROCESSING LEVEL OF FEEDBACK/COMM
REMOTE SYSTEM CHARACTERISTICS	PHYSICAL SIZE & CAPACITY DEGREES OF FREEDOM END EFFECTORS & TOOLS VISION/LIGHTING
TASKSITE COMPATIBILITY	TERRAIN COOPERATIVE FEATURES WORK ARTICLES SAFETY
CONTROL STATIONS	CONTROLLER(S) DISPLAY(S) HUMAN FACTORS

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Fig. 10 Issue Areas

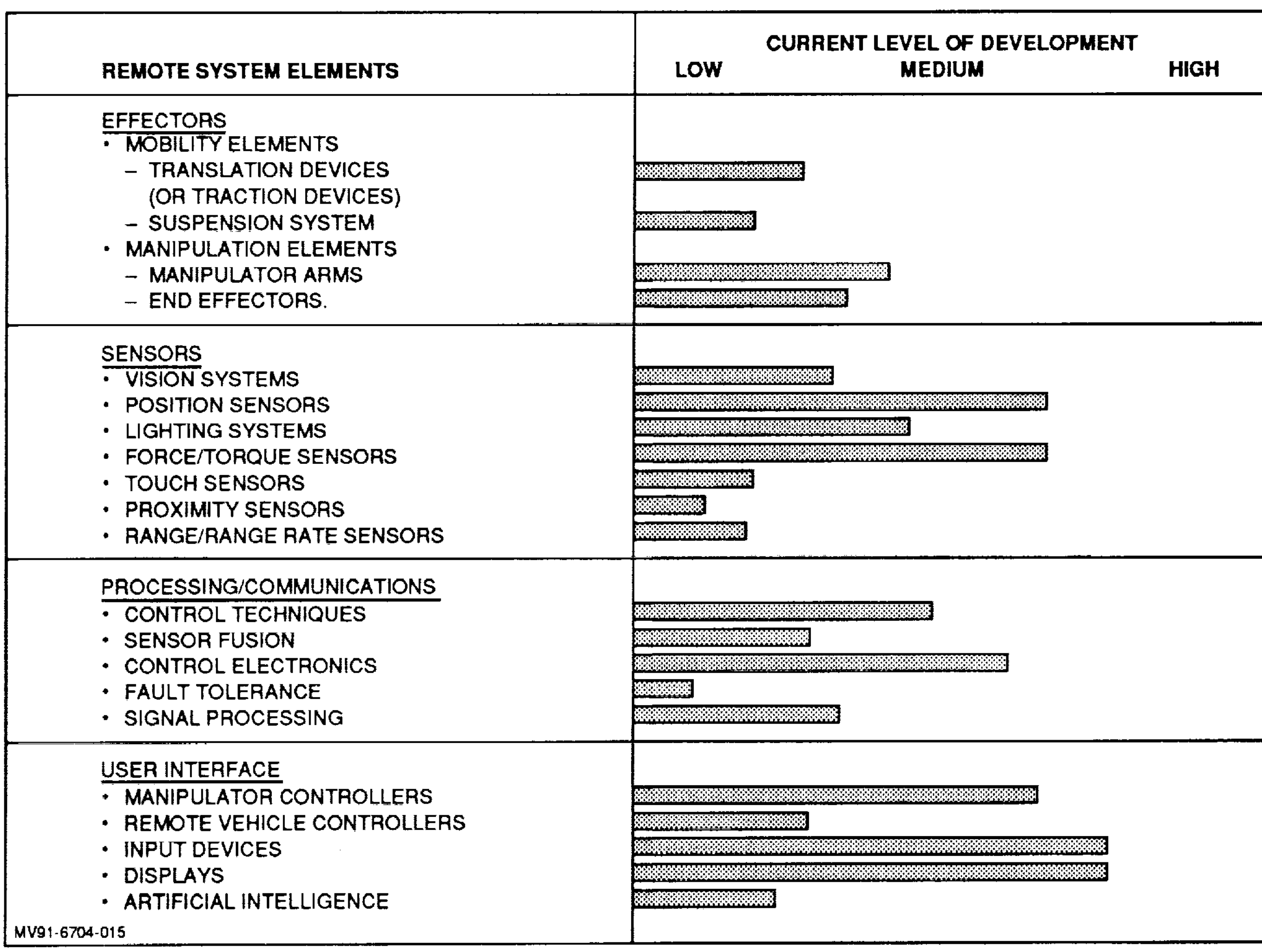

Fig. 11 Technology Requirements for Space Application

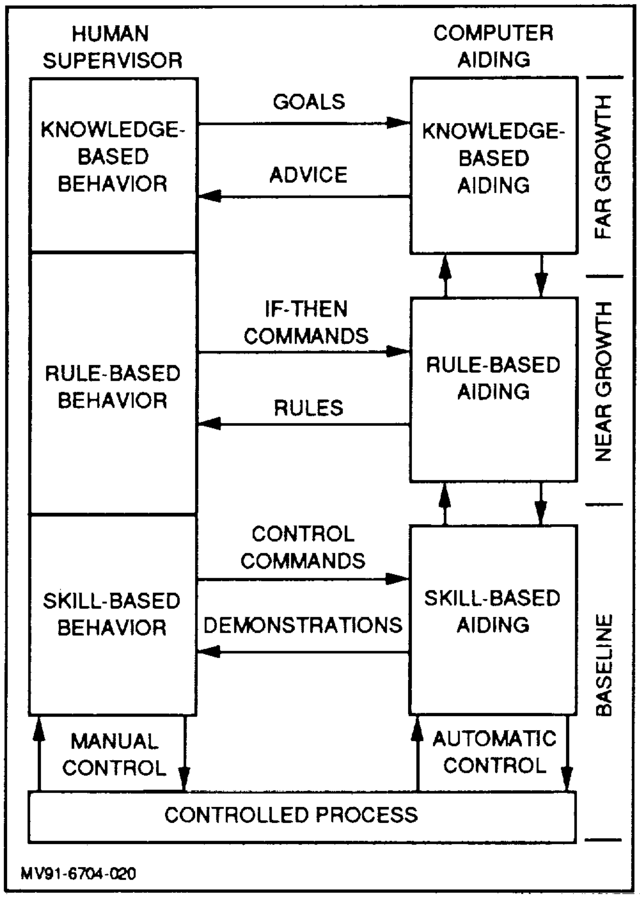

Fig. 12 Operator Interface

necessary to achieve system performance verification. Testing capabilities such as Grumman's Simulation Center are required; the Large Amplitude Space Simulator (LASS), the Advanced Space Workstation Lab and the Telerobotics Development Lab are needed for either full scale or scaled real time simulations for final remote system design concept verifications. The LASS contains a six-degree-of-motion device in a 50 ft x 50 ft x 20 ft high gaming area. The motion device can be programmed to emulate a space transport vehicle or a large scale robotic mechanism. The models that drive the motion device are real time dynamic kinematic models. The motion device is capable of supporting up to 1000 lbs (usually only the end effector of the vehicle or mechanism) at linear velocities of + 15 FPS and angular velocities of ±80 DPS. The gaming area can be provisioned with full scale mockups of the environment work articles. An additional 5 DOF motion can be added to test articles by mounting them on a Handling and Position Aid (HPA) capable of supporting 1000 lbs of payload. The HPA is a 5 DOF stiff, robust arm with morphology similar to the human arm. The applications of such approaches to resolve issues are discussed in the next section.

APPLICATION OF RESOLUTION APPROACHES

The issue resolution approaches discussed above are generally used to accelerate the development process while reducing the risk. Figure 14 shows how this resolution methodology can be used in an integrated fashion in the space hardware development process. In this section, we will show, by taking examples from various projects and the Grumman Telerobotics Development Laboratory, how these

METHOD	DEFINITION	ADVANTAGE	DISADVANTAGE
NUMERICAL ANALYSIS	COMPUTATION OF PERFORMANCE LEVELS FROM TASKS REQMTS AND ENVIRONMENTAL CHARACTERISTICS	FAST, VERY ACCURATE, INEXPENSIVE	NOT ALWAYS FEASIBLE FOR COMPLEX ISSUES
GRAPHICAL ANALYSIS	GEOMETRIC STUDIES OF PHYSICAL ENVIRONMENT & CONCEPTS USING COMPUTER GRAPHICS	FAST, RELATIVE ACCURATE, MODERATELY EXPENSIVE	NOT ALWAYS FEASIBLE FOR INTRICATE SYSTEMS, SUBJECT TO SOME INTERPRETATION
COMPUTER SIMULATION	MATHEMATICAL MODELING OF PHYSICAL BEHAVIOR OF A SYSTEM	PRECISE FOR CERTAIN PROBLEMS, MODERATELY EXPENSIVE, EASY PARAMETER VARIATIONS	DEPENDENT ON FIDELITY OF MATH MODEL
HARDWARE TEST/SIMULATION-REDUCED SCALE	USE OF REPRESENTATIVE REDUCED SCALE PHYSICAL MODELS IN CONJUNCTION WITH COMPUTER MODELS	REALISTIC OPERATIONS, SOME HARDWARE EFFECTS, HUMAN FACTORS INCLUDED	MODERATELY COSTLY, POTENTIAL SCALING ERRORS
HARDWARE TEST/SIMULATION-FULL SCALE	USE OF REPRESENTATIVE FULL SCALE MODELS OF SYSTEM ELEMENTS IN CONJUNCTION WITH COMPUTER MODELS	CLOSEST TO REAL OPERATIONS, INCLUDES HARDWARE NONLINEARITIES, HUMAN FACTORS INCLUDED	COSTLY, LONGER SCHEDULE TIME, LIMITED PARAMETER VARIATIONS

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Fig. 13 Issues Resolution Methods

ISSUE AREA	ELEMENTS FOR RESOLUTION	RESOLUTION APPROACHES: NUMERICAL ANALYSIS	GRAPHICAL ANALYSIS	COMPUTER SIMULATION	HARDWARE TEST/SIMULATION -REDUCED SCALE	HARDWARE TEST/SIMULATION -FULL SCALE
MIX OF HUMANS & MACHINES	DECISION LEVELS	•	•	•	•	•
	HAZARDS EVALUATION		•	•	•	•
	LEVEL OF AUTONOMY/ PROCESSING	•		•		•
	LEVEL OF FEEDBACK/COMM	•		•		•
REMOTE SYSTEM CHARACTERISTICS	PHYSICAL SIZE & PERFORMANCE	•	•	•	•	•
	DEGREES OF FREEDOM		•		•	•
	END EFFECTORS & TOOLS		•	•	•	•
	VISION/LIGHTING		•		•	•
TASKSITE COMPATIBILITY	TERRAIN		•		•	•
	COOPERATIVE FEATURES	•	•	•		•
	WORK ARTICLES					•
	SAFETY		•	•	•	•
CONTROL STATIONS	CONTROLLER(S)		•	•	•	•
	DISPLAY(S)		•		•	•
MV91-6704-017	HUMAN FACTORS		•		•	•

Fig. 13A Resolution Approaches

approaches have been used in the remote system development process.

Graphical and Computer Analysis

Math models of candidate remote systems elements, such as a manipulator arm, can be developed using data from automated drafting programs. Using a Silicon Graphics high-resolution, three-dimensional workstation and a Deneb Robotics software package IGRIP, a solid model with moving joints can be developed, as shown in Fig. 15 for a 3-arm capture mechanism for a tumbling satellite retrieval system, to determine task feasibility (e.g. collision potential) and design viability (e.g. reach requirements). It provides real-time, kinematic simulation of sufficient fidelity to support task scenario development, operator interface and procedures training, system kinematics display, camera views, and realistic operations. Candidate control algorithms from control systems analysis programs such as PROTOBLOCK can be input into the IGRIP simulation for evaluation.

Another example of graphical modeling of a concept is presented in Fig. 16, which shows a robot performing a servicing operation on a space platform. Such modeling

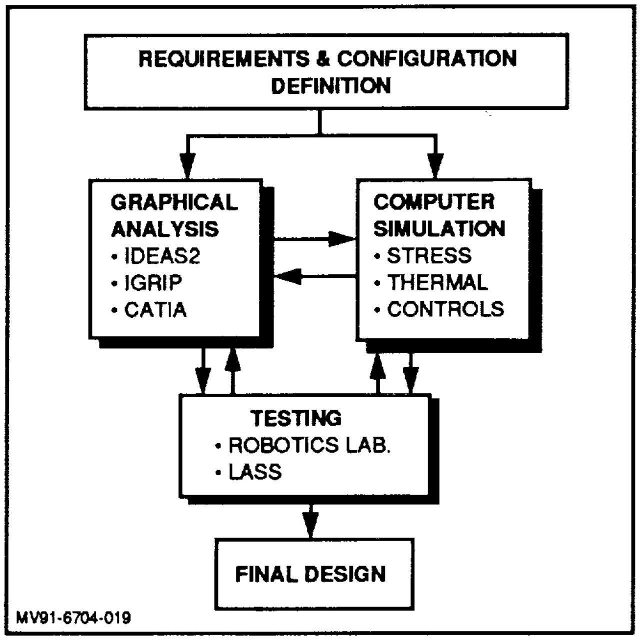

Fig. 14 Integration of Issue Resolution Methodologies into a Program

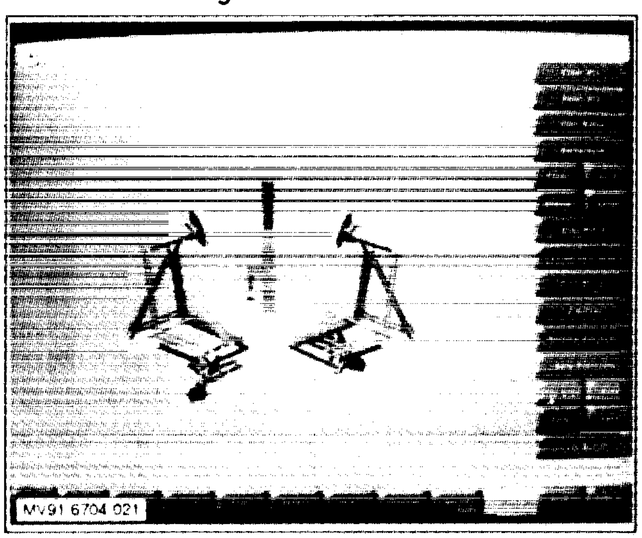

Fig. 15 3-Arm Capture Kit IGRIP Solid Model

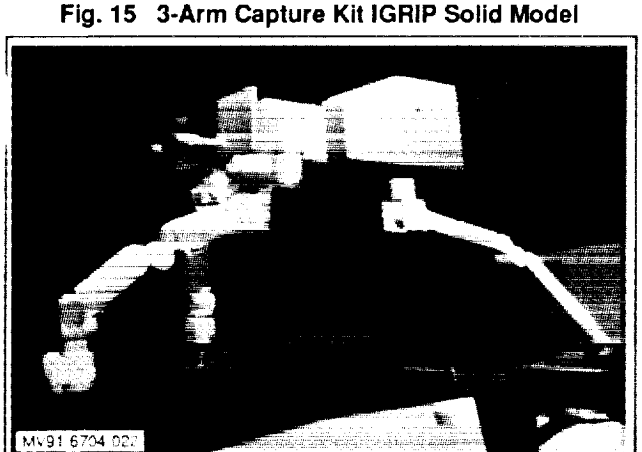

Fig. 16 Typical IGRIP Robot Scenario

analysis, when performed prior to initial hardware fabrication, enables lessons learned to be applied during the design phase, before commitments to hardware are made. The available computerized, geometrical data base can also then be transformed into finite element models for dynamic and thermal analyses.

Testing

Testing of remote systems, in full and partial scale, can be described using four general categories: large robots, small robots, remote vehicles, and EVA astronaut/robot operations as further described below. All tests involve interfaces with and direction from a control station. In general, the testing results in measures of system performance such as task times, identification of design improvements, and suggested changes to the task environment.

Large Robots - Large robots, i.e. manipulator arms significantly longer than 10 ft with associated sensors, in conjunction with a control station, can be tested using computer simulation approaches and actual test articles. The shuttle's Remote Manipulator System (RMS) has been tested using a simulation approach in Grumman's Large Amplitude Simulator (LASS) as shown in Fig. 17 for placement of a plasma diagnostics package on a spacelab pallet. A dynamics and kinematic model of the RMS has been installed in the LASS. This enables the RMS end effector motion to be emulated by the LASS platform. A functional block diagram of the facility as it is utilized for simulation of the RMS is illustrated in Fig. 18. The RMS software and dynamics are contained in the hybrid computer. It receives its input commands from the rotational and translational hand controllers located in the shuttle aft flight deck control station mockup in the laboratory (Fig. 19).

In another simulation (Fig. 20) a space erectable radiator element was inserted into a receptacle by the RMS. In this test, the operator was able to to successfully insert a simulated 50 ft radiator test article in an evaporator slot with a vertical clearance of 0.25 inch and horizontal clearance of ± 1 inch. The test runs were made with a tactile sensor which enabled the operator to detect a touch before the force built up to 5 lbf. An augmented grapple target and an enlarged slot opening (±1 in both directions) enabled 40 test runs to be completed with only 6 recorded touches.

Testing of a large robot using a test article is exemplified in Fig. 21 by the handling and positioning aid (HPA) which was a candidate manipulator for moving and holding large, heavy payloads within the servicing envelope of the shuttle payload bay. In this case, the HPA with a simulated snare end effector and TV camera is shown aligning to a grapple fitting with control from a remote console.

Small Robots - Small robots, i.e. one or more arms generally less than 10 ft long with associated control stations, can be tested using computer graphics and test article. Fig. 22 illustrates the Deneb IGRIP graphics, discussed above, used to simulate a two-armed robot which is being controlled by two 6-DOF hand controllers.

Early testing using a pair of master/slave manipulators is shown in Fig. 23 with the operator performing a simulated satellite servicing task. Simulations of small robots carried by a large robot have been performed using the LASS platform which now creates a positioning system simulation with its 6 DOF capability. The RCS module changeout task, as performed telerobotically on the LASS, is shown in Fig. 24. The subtasks included attaching the protective covers over the nozzles, attaching a tether, untightening the fasteners, extracting the module, and installing the replacement module. The object being manipulated must also be off-loaded to work properly within the design capacity of the robots; this also provides the capability for "zero-g" simulation.

A more advanced two-arm robot (Fig. 25), each arm having 7-DOF, which also has an additional 3-DOF "torso"

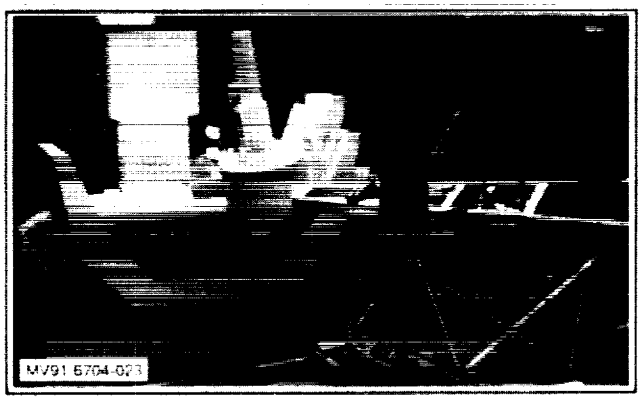

Fig. 17 Experiment Simulation on LASS

for a total of 17 DOF, is another test article which can be controlled by a pair of mini-master controllers as shown in Fig. 26. These controllers can be used to evaluate limited operating volume applications, e.g. within a one ft cube (Fig. 26) and to evaluate performance with candidate displays (Fig. 27). This robot has been used to investigate tasks requiring a capability to reach around obstacles such as truss structure (Fig. 28) and then use a camera installed close to the end effector to perform inspections of a truss joint as shown in Fig. 29. Another example of the use of such a test article is shown in Fig. 30 which shows an off-loaded hydrazine fuel coupling being installed using the two arms.

Remote Vehicles - We view remote vehicles as vehicles which translate on a planetary surface or in space, controlled remotely. The LASS, in conjunction with appropriate control consoles, has been used to simulate free flying spacecraft. Fig. 31 shows a special inspection vehicle, the Maneuvering TV (MTV) with a snare end effector, as a half scale model, on the LASS simulator aligning to capture a mockup of the Long Duration Exposure Facility spacecraft. The motion of the Orbital Maneuvering Vehicle (OMV) has also been simulated, including the capture of a satellite with a three-point docking ring shown separately in Fig. 32 and on a full scale OMV mockup in Fig. 33. Early tumbling satellite capture concepts were tested (Fig. 34) using a two arm capture concept on a simulated OMV with the HPA used to position a spinning target satellite.

This combined capability has been used more recently to simulate capture of a tumbling satellite using a specially designed OMV front end kit (Fig. 35). In this case, the LASS simulated all motions of the OMV, based on inputs from the

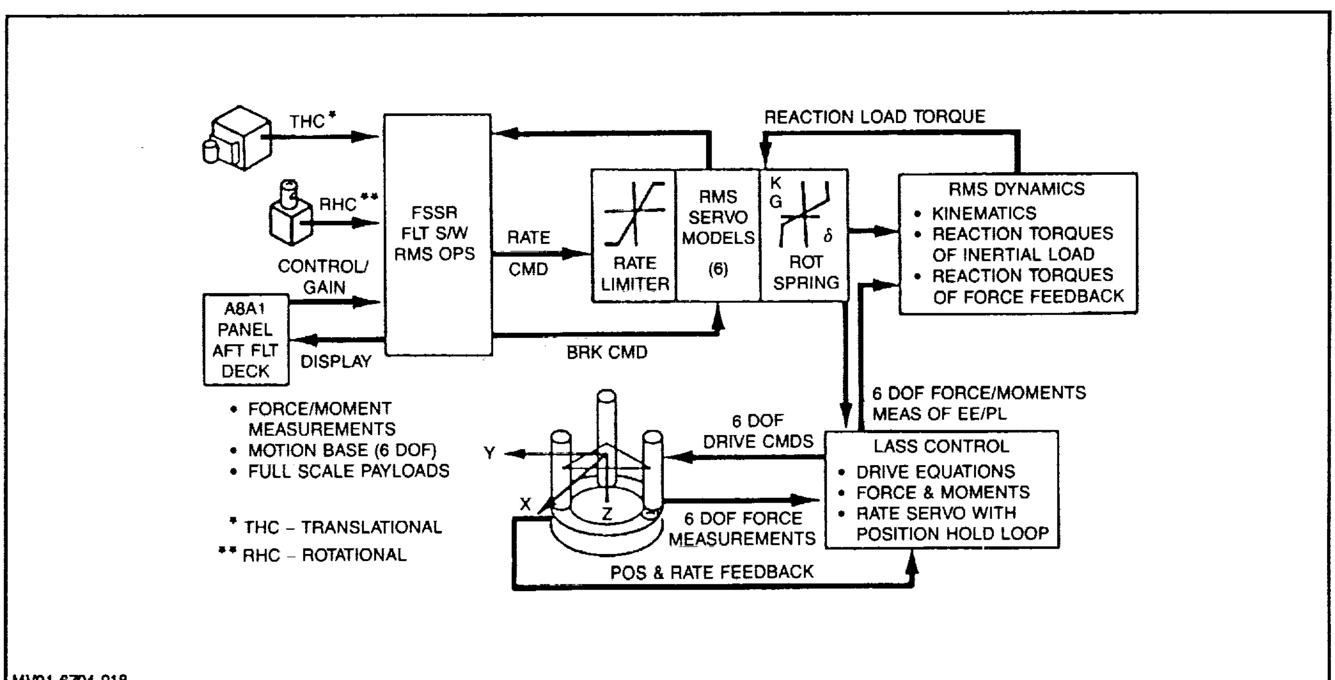

Fig. 18 LASS RMS Block Diagram

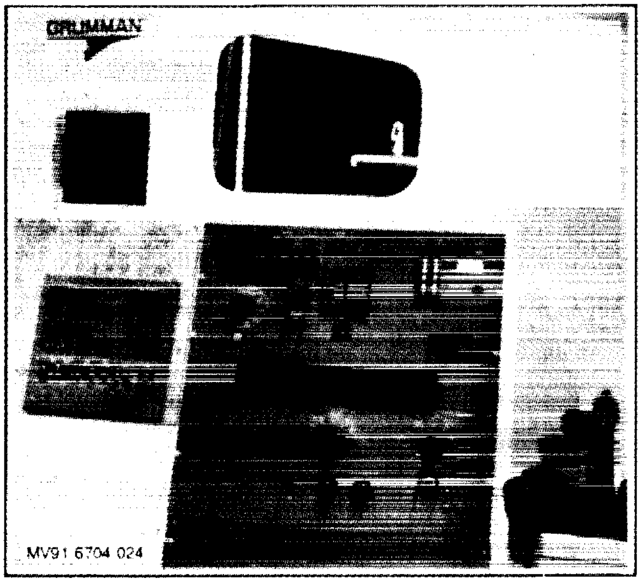

Fig. 19 Shuttle RMS Control Station Mockup

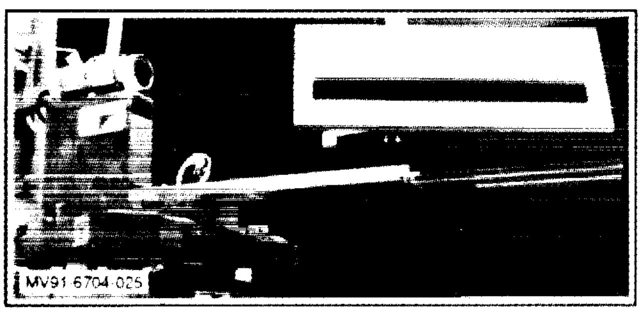

Fig. 20 Space Radiator Insertion Test on LASS

remote control console. The kit, a three dual-link arm device installed on the LASS platform, performed the capture of the satellite being held by the HPA.

A control console from which such teleoperation mission feasibility tests are performed is shown in Fig. 36. Controls and display graphical aids added to the console enhance operator human factor performance of the mission.

EVA Astronaut/Robot Operations - EVA astronaut/robot operations refer to the special case of extra vehicular activity (EVA) where astronauts operate in close proximity to robots, and is broken out as a separate category because of the safety issues involved. The Manipulator Foot Restraint (MFR) which is a platform at the end of the RMS which supports an astronaut is one example. The MFR was developed by Grumman using the LASS as a development tool and a scale model (Fig. 37) based on functional and operational requirements. This model and task simulations led to the development of test hardware (Fig. 38), which was evaluated on the LASS by suited astronauts (Fig. 39). With the MFR on the LASS simulating the dynamics of the RMS, a wide variety of servicing scenarios were simulated (Fig. 40). This testing has significantly aided the resolution of safety concerns which otherwise would not have been identified early in the design process. In addition to evaluation of astronaut tools, equipment and tasks, the RMS control

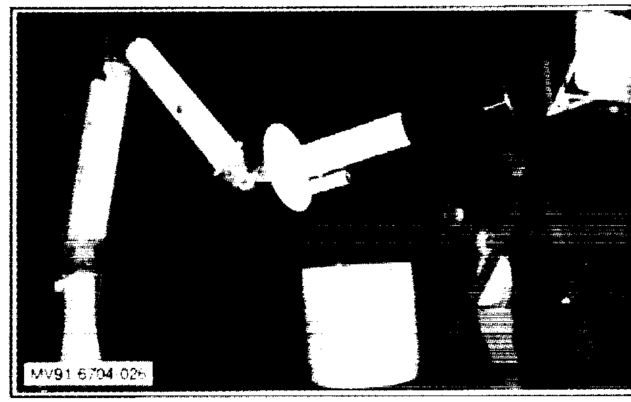

Fig. 21 Moving Heavy Payloads with HPA

Fig. 22 Simulations Using a Workstation

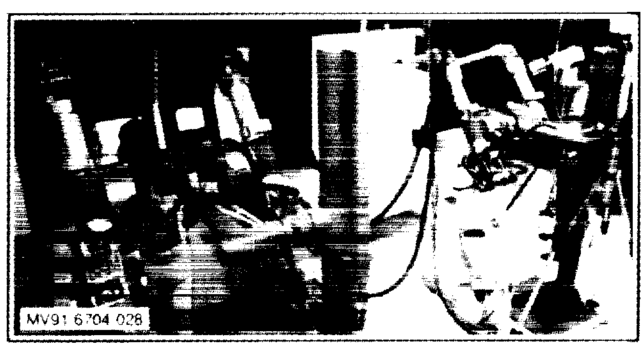

Fig. 23 Simulations Using Master/Slave Manipulators

system interaction with a suited astronaut was evaluated. Soft and breakaway mock-ups were used to prevent damage to equipment or injury to test subjects in case of an unchecked runaway. The further use of scale models is shown in Fig 41 which shows a small robot operating in conjunction with an EVA astronaut on a MFR.

The use of extensive testing of the types discussed above are essential in the development of satisfactory, low-risk remote systems.

Summary & Conclusions

Future space activities are expected to rely more and more on remote systems. These systems and the technology used have counterparts in many future terrestrial applications. Their development is best accomplished by using graphical analysis and test articles early in the process to resolve design issues before commitments are made to a design. Such issues have been discussed and the methods of resolution have been described with examples given based on many years of remote systems development experience. The "lessons learned" from such techniques contribute to the identification of technology advances, accelerate the development process, and lower the risks associated with the eventual final design.

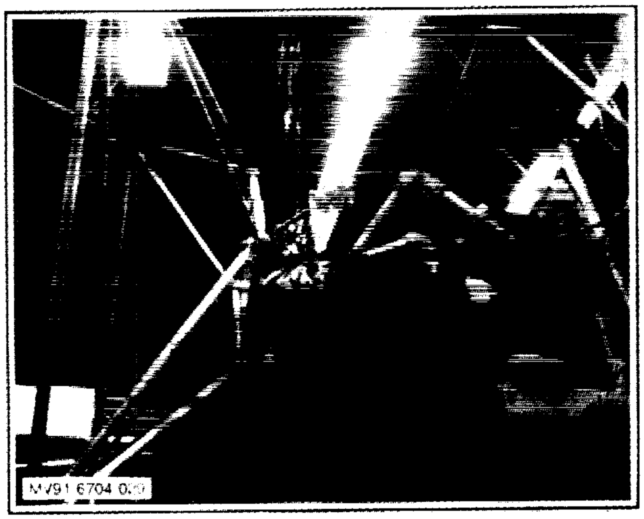

Fig. 24 RCS Module Changeout Using Robotics

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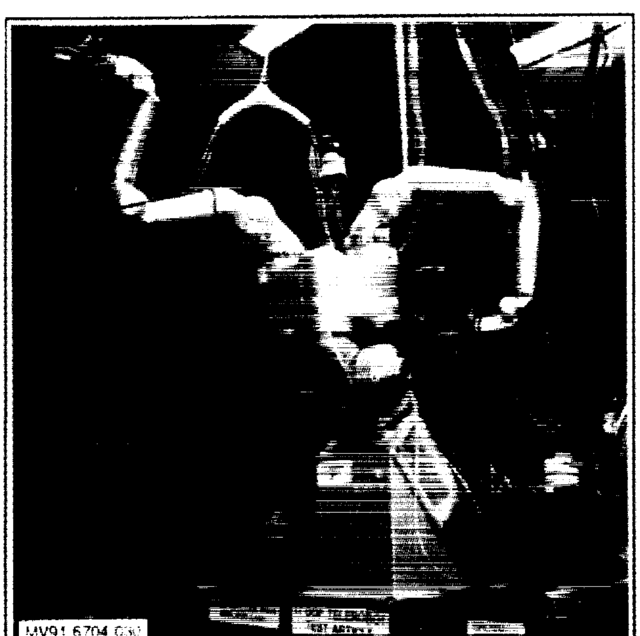

Fig. 25 17-DOF Laboratory Robot

Fig. 26 Simulations with Mini-Masters

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Fig. 27 Display/Task Performance Evaluation

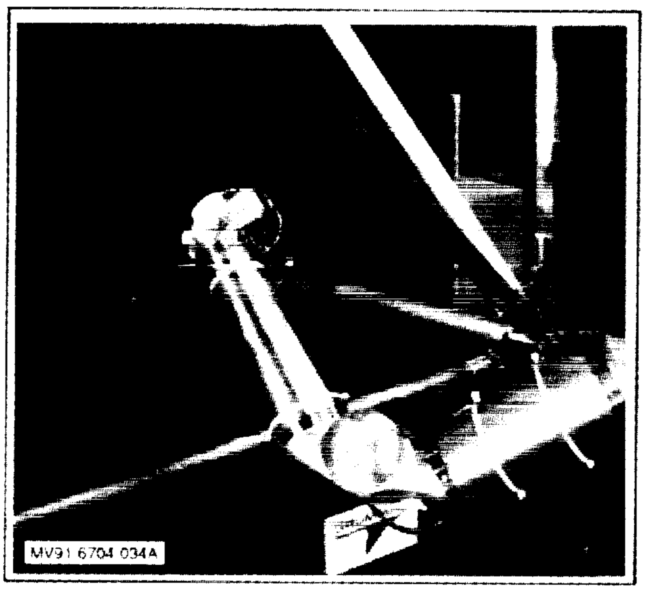

Fig. 28 Joint Inspection Around Obstacles


Fig. 29 Inspection – Wrist Camera View

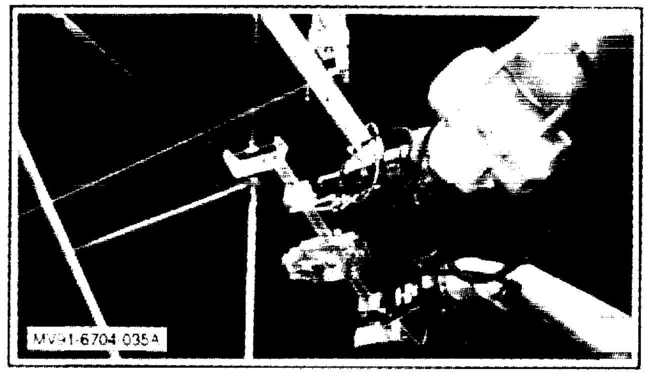
Fig. 30 Robotic Fuel Coupling Installation

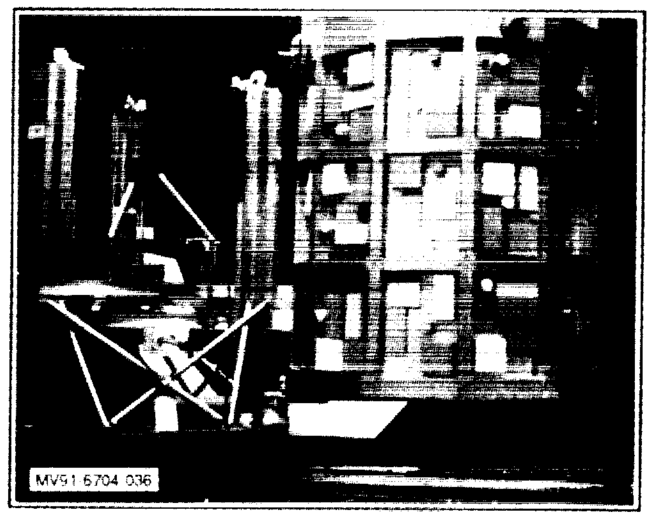

Fig. 31 LDEF Inspection Simulation with MTV

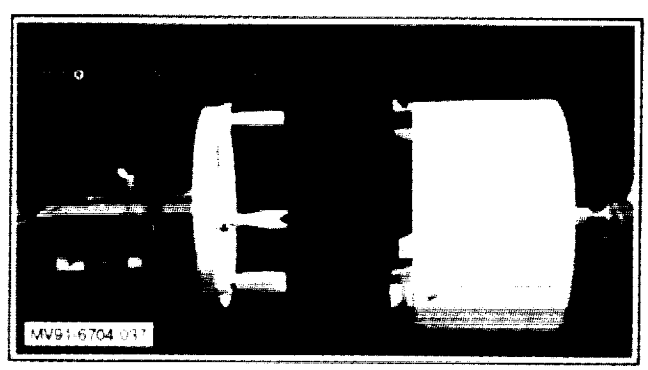
Fig. 32 3-Pt. Docking Mechanism Simulation

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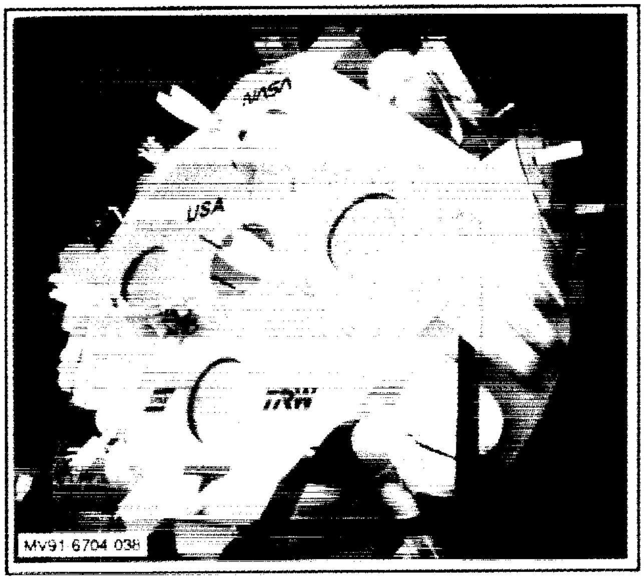

Fig. 33 Full Scale Mockup of OMV/3-Pt. Mechanism

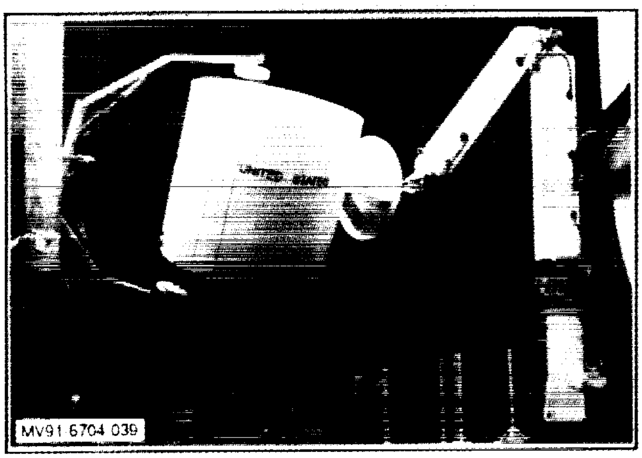

Fig. 34 Early TSR Capture Simulation on LASS

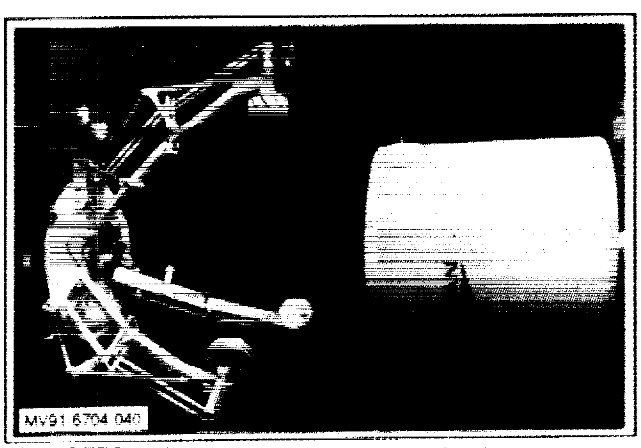

Fig. 35 3-Arm Kit Capture Simulation on LASS

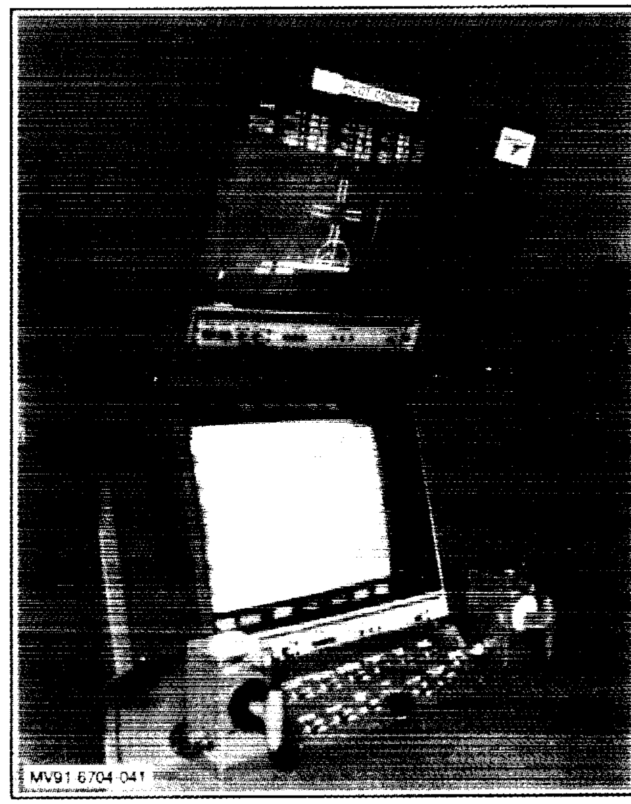

Fig. 36 OMV/Front End Kit Control Console

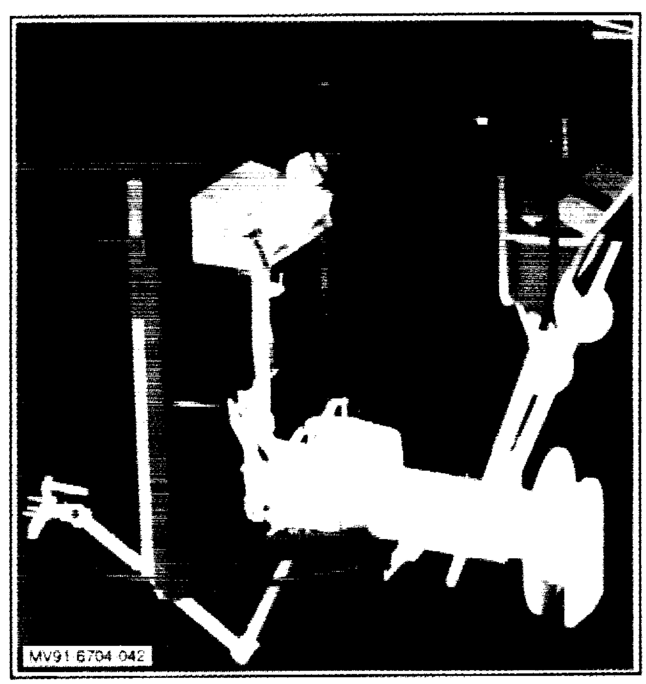

Fig. 37 Early Scale Model of MFR

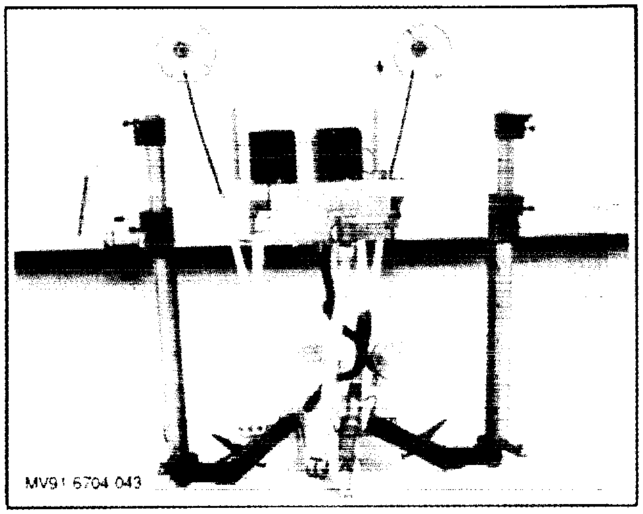

Fig. 38 MFR Development Test Article

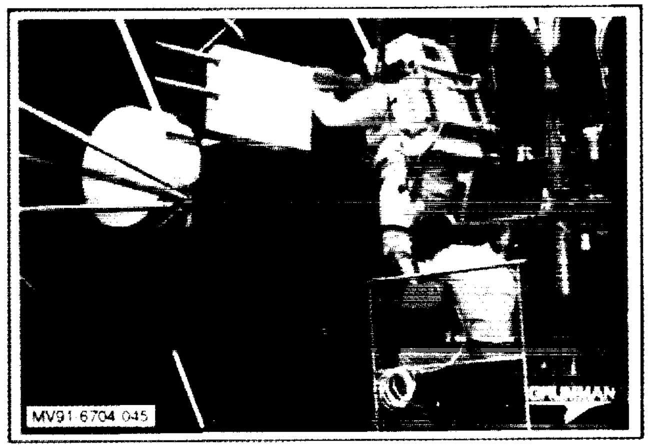

Fig. 40 Thermal Bus Assembly Simulation

Fig. 39 Astronaut MFR Simulations on LASS

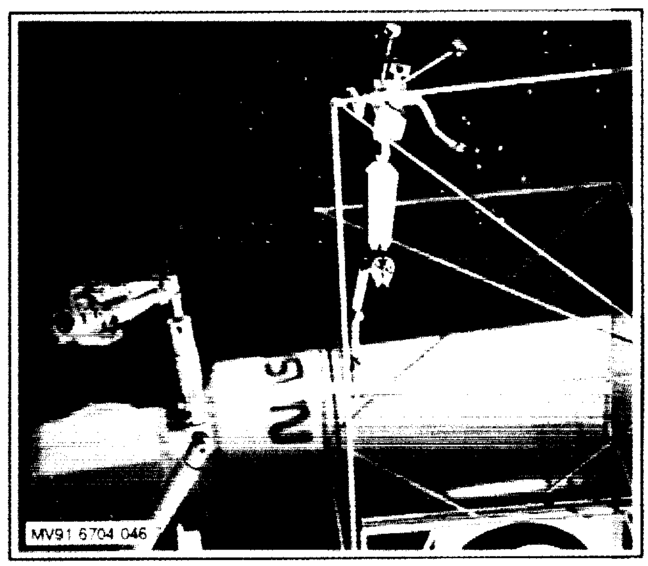

Fig. 41 Combined Astronaut/Robot Operations

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