

THE FLIGHT TELEROBOTIC SERVICER PROJECT AND SYSTEMS OVERVIEW

Harry G. McCain and James F. Andary
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771, U.S.A.

Abstract

The Flight Telerobotic Servicer (FTS) Project is developing an advanced telerobotic system to assist in and reduce crew extravehicular activity (EVA) for Space Station Freedom. The FTS will provide a telerobotics capability to the Freedom Station in the early assembly phases of the program and will be employed for assembly, maintenance, servicing, and inspection throughout the lifetime of Freedom Station. A planned evolution of the FTS capabilities will take place over time with technology transfer between U.S. industry, universities, and other Government agencies as an integral part of the program.

The initial implementation of the FTS will be accomplished with existing technology derived from relatively mature NASA, industry, and university research and advanced development projects. The early FTS technical challenge is the development and integration of existing technology elements into a spaceflight quality system capable of performing the required Space Station Freedom tasks. This paper will give a brief overview of the FTS program and will explore some of the technical and system engineering issues associated with the development of the FTS.

Introduction

During review of the Space Station Freedom conceptual development and preliminary design activity (Phase B studies) it became evident that demand for crew EVA would exceed availability during Freedom assembly and operational phases. Each of the individual S.S. Freedom Work Package Phase B studies identified a need for some type of robotic device to augment crew EVA requirements. NASA determined that these efforts should be consolidated into a single telerobotic system that could satisfy the majority of the requirements identified. In the spring of 1986, NASA Goddard Space Flight Center (GSFC) (as a part of its S.S. Freedom Work Package 3 activities) was given the responsibility for developing a multipurpose, dextrous telerobotic manipulator system, the Flight Telerobotic Servicer (FTS). The FTS has significant Congressional interest and support and is the focal point for the advancement of space robotic capabilities.

The objectives of the FTS Project are to:

- Provide an alternative for crew EVA by supporting the crew in Freedom assembly, maintenance, and servicing activities
- Improve crew safety by performing hazardous tasks such as spacecraft refueling, thermal, and power system maintenance, and remote inspection before manned EVA
- Increase crew availability for problem solving, supervising, supporting contingency operations, and supporting scientific studies by reducing the amount of time the crew has to spend on simple, repetitious tasks
- Provide in situ maintenance and servicing capability for platforms when the FTS is operated from the Orbital Maneuvering Vehicle (OMV)
- Accelerate robotic technology transfer from research to industry

The primary elements of the FTS that will be delivered for Freedom Station use from the Project are: (1) the telerobot and its various end-effectors and tools, (2) operator workstations for FTS operation from both the Shuttle and Freedom, (3) all operating software and procedures, and (4) sustaining engineering and operations support to the Space Station Freedom Program. Additionally, the FTS Project will provide a continuing program for the technological enhancement of the FTS system leading to increased autonomous capabilities for future operations.

The FTS is to be delivered in time for the first Freedom Station assembly flight of the Space Shuttle (currently January 1995). Before this delivery, the FTS development includes two space test flights to be flown as attached payloads on the Space Shuttle.

The first of these test flights is currently scheduled for August 1991 and is called the FTS Development Test Flight (DTF-1). This flight will consist of a partial FTS configuration composed of prototype elements. The primary objectives of this flight test will be to verify FTS design approaches and human-machine interfaces in the zero-g environment.

The second of these test flights, the FTS Demonstration Test Flight (DTF-2), is currently scheduled for early 1993. This flight will consist of a mature version of the entire FTS system that will demonstrate the FTS capabilities to perform actual Freedom Station tasks and will act as a dry run for upcoming Freedom Station applications.

Project Status

Since its inception in the spring of 1986, the FTS Project has completed Phase A and Phase B studies and is currently completing the competitive procurement activity for the FTS hardware build contract (Phase C/D).

The Phase A study was done in-house at GSFC, with the participation of many of the other NASA field centers and other Government agencies. The results of the Phase A study produced an early FTS concept called the "Strawman." This concept served as the basis for the Request for Proposal (RFP) for multiple Phase B study contracts. Six Phase B study proposals were received, and two study contracts were awarded at the end of 1987. These contracts were awarded to Grumman Aerospace, Bethpage, NY, and Martin Marietta, Denver, CO. These contracts were for a 9-month duration and were completed at the end of September 1988.

In parallel with the Grumman and Martin Marietta studies, GSFC conducted an in-house Phase B study to serve as a basis of comparison to the contractor studies. This study produced a more mature FTS concept called the "Tinman." The details of this concept are discussed in the first two references [1, 2].

The Request for Proposal for the FTS C/D contract has been released and proposals are due before the end of calendar year 1988. The FTS Phase C/D contract is currently scheduled for award in the spring of 1989.

System Requirements Development

Even though Freedom Station designs have not been made final, development schedules for the FTS called for the development of a rational and comprehensive set of FTS functional requirements, so that the program could proceed. The approach that should be used for the development of these requirements was not immediately obvious. For example, the functional capability requirement used by several contractor teams during the Freedom Station Phase B studies was "man equivalence." Unfortunately, "man equivalence" does not have an adequate definition from which to build a space hardware system. Also, it is generally accepted that the state of robotic technology now and in the foreseeable future will not match the abilities of a human to process visual data or to plan tasks and motions, especially in contingency situations.

Therefore, it was decided that the functional requirements for the FTS should be derived from the "work to be done." To circumvent the problems posed by the immaturity of the Freedom Station design, a statistical approach to developing a requirements data base was developed [3]. A representative set of tasks, called the Robotic Assessment Test Set (RATS), was assembled for detailed analysis [4]. The NASA Centers responsible for S.S. Freedom definition were consulted in choosing the

U.S. Government work not protected by U.S. copyright.

task set that could provide a representative sample of activities for determining the "tall pole" design requirements and for assessment of competing design approaches. Activities included in the RATS are:

- Assembly
 - Truss Assembly
 - Utility Line Connection
 - Solar Dynamic Array Assembly
- Maintenance and Servicing
 - Solar Power Converter Orbital Replaceable Unit (ORU) Changeout
 - High-Resolution Solar Observatory Film Canister Changeout
 - Solar Power Converter Changeout
 - Solar Maximum Mission Main Electronics Box Replacement
 - Hubble Space Telescope (HST) Axial Instrument Changeout
 - HST Reaction Wheel Assembly Changeout
 - Electrical Connector Inspection
 - Gamma Ray Observatory Refueling
 - In situ Platform/Free Flyer ORU Changeout

In order that the needed information could be developed, the tasks included in the RATS were required to have the following two characteristics:

- Concepts were sufficiently advanced that dimensions and drawings were available.
- Tasks were representative of the actual tasks that will be performed on the Freedom Station.

Each of the RATS tasks was subjected to a detailed analysis to derive the specific functional requirements for a telerobotic system. This analysis of the RATS tasks was done without regard for the system that might actually perform the task. That is, the tasks were decomposed into the individual steps necessary for completion without assuming anything about the manipulating system, which could be an astronaut, a robot, or some special purpose device.

Each task was decomposed to a series of the following building blocks: MOVE, ATTACH/RELEASE, LOCATE, and MANIPULATE. Task specific engineering numbers were then applied to each of these individual steps such as distances to be moved, insertion forces, fastener torques, and required clearances. This information became the data base for the development of the FTS functional requirements.

FTS Technology Utilization

The FTS technical challenge is the following:

- To support technology transfer to U.S. industry
- To engineer and integrate state-of-the-art robotic technology components into a reliable spaceflight quality system
- To design a system capable of technological evolution

One of the primary goals of the FTS Project is the development and transfer of robotic technology to U.S. industry. Ultimately this will be the case. However, the technology components for the initial implementation of the FTS will come from U.S. industry. The eventual contribution that FTS expects to make toward advancing the state-of-the-art in robotics will be at the system level through the integration of various technology elements into a robotic system more sophisticated and advanced than currently exists.

Figure 1 depicts the FTS development process. The figure shows that the primary source of manipulator technology will be derived from the manufacturing, nuclear, and undersea industries. This will be integrated with the other technology elements, such as computers, sensors, and vision

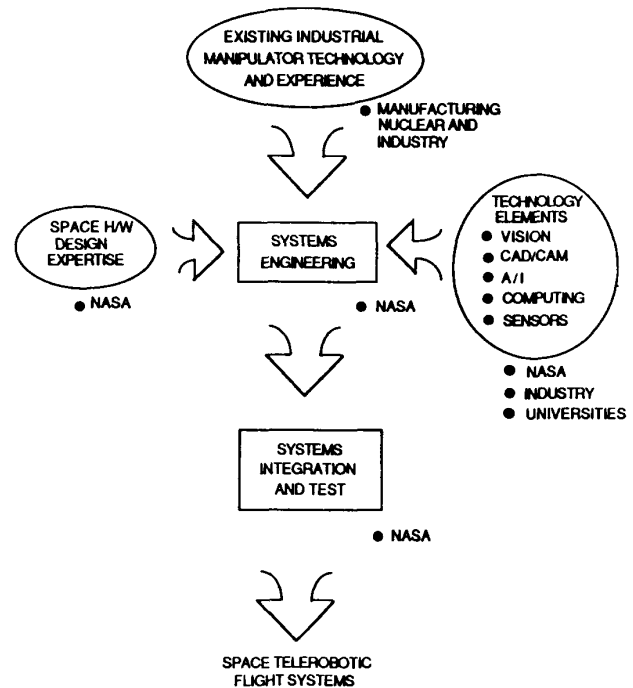


Figure 1. Flight Telerobotic Servicer (FTS) Development

systems, necessary for advanced robotic applications. What NASA contributes is expertise in the areas of space hardware and software design, and system engineering.

At this point, it is important to emphasize the issue of space hardware and software development. The FTS is a system for use in space. The constraints and demands on such a system are many. It must operate in the harsh space environment with thermal extremes and radiation. It must survive the launch environment. It must be extremely safe and reliable. Systems and hardware that will operate in this environment and meet these requirements are not available off the shelf, but will require extensive design and testing over and above that already accomplished for current state-of-the-art products.

Figure 2 displays approximate times for the process of bringing systems of varying complexity and at varying states of development to a state of spaceflight readiness. The specific example highlighted in Figure 2 shows that a moderately complex system, such as a force and torque sensor with a conceptual design that has been tested analytically or experimentally, would take approximately 3 years to be brought to the state of a prototype/engineering model that had been tested in a space environment. This, of course, is only the component or subsystem level. Time for full-up system level testing and flight qualification must also be added to the process. The FTS schedule, therefore, dictates that selection of technology elements and components be made carefully so that the entire system will be ready in time for Freedom Station. Fortunately, needed technology elements already exist in a state of readiness that will enable the FTS Project to develop a sophisticated and useful system.

In the future, new technology will become available to significantly enhance the autonomous capabilities of the FTS. The initial design of the FTS must include an evolutionary capability, so that the system can be incrementally upgraded without reconfiguration of the entire system.

A key to this evolutionary capability is the initial adoption of a functional control architecture that supports growth to more autonomous operation as the technology becomes available. The FTS Project has adopted the NASA/National Bureau of Standards (NBS) Standard

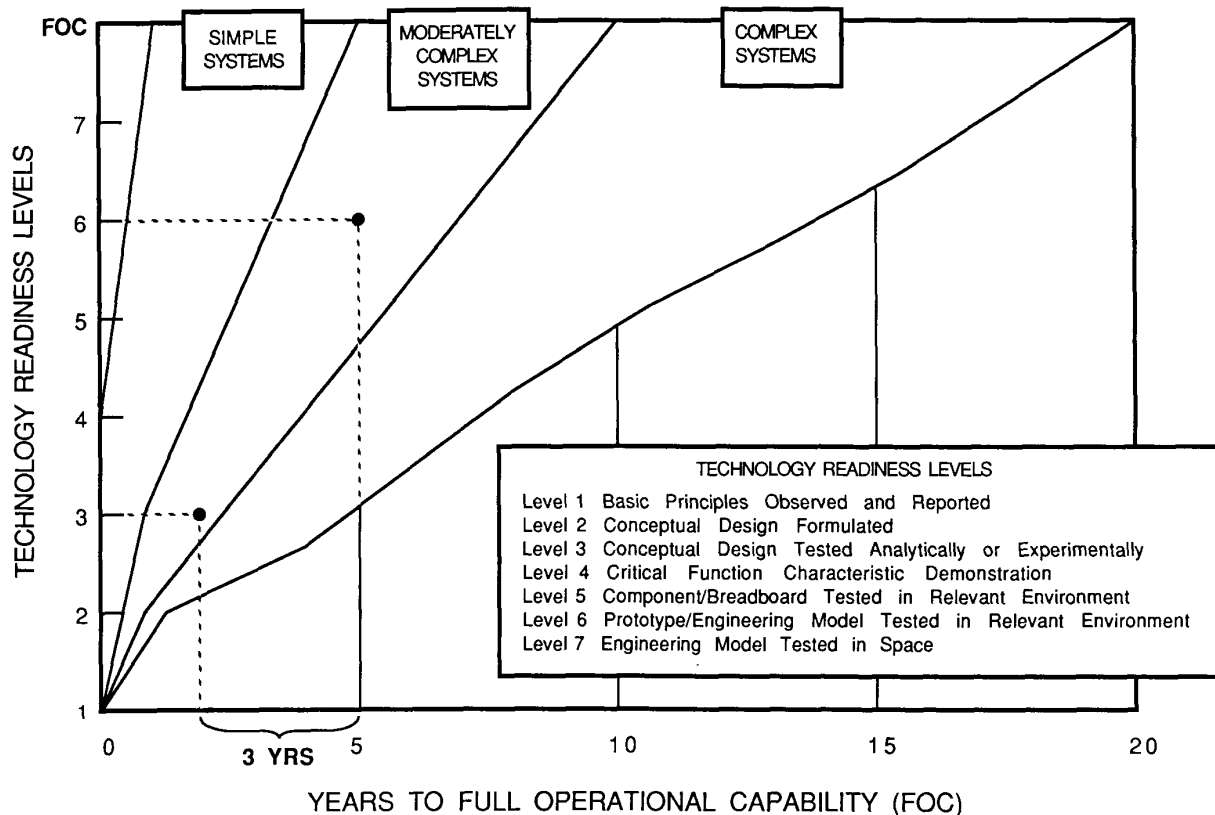


Figure 2. Technology Readiness for Spaceflight Use

Reference Model for Telerobot Control System Architecture (NASREM). NASREM defines a logical control architecture for telerobotics, derived from a number of concepts developed in previous and ongoing research programs, including the NASA Office of Aeronautics and Space Technology (OAST) telerobotics research program at the Jet Propulsion Laboratory and the Langley Research Center, work at the Johnson and Marshall Space Flight Centers, the artificial intelligence program at the Ames Research Center, the Intelligent Task Automation Program sponsored by Defense Advanced Research Projects Agency (DARPA) and Wright Patterson Air Force Base, supervisory control concepts pioneered by Sheridan at Massachusetts Institute of Technology (MIT), and the Hierarchical Control System developed for the Automated Manufacturing Research Facility at NBS. The principal developer of NASREM, Albus, is at NBS. NASREM is discussed in more detail in the Architecture section and in a reference [5].

Design Drivers

In addition to the flight qualification aspects of the FTS Project, there are several other requirements that significantly drive the design of the FTS. The following paragraphs will discuss the primary of these design drivers.

Teleoperation and Autonomous Capabilities

As briefly discussed earlier, robotic technology has a long way to go to even approach the capabilities of the human in the areas of vision processing and task planning, and even though robotic manipulators have become quite advanced, the dexterity and control of the human hand will not be matched for some time to come. In acknowledgment of these limitations, the FTS must be designed to keep the human operator in the loop in a teleoperative mode, except when the task environment can be sufficiently structured to permit autonomous operation.

The control mode in which each motion of a robotic manipulator is directly controlled by a remote operator viewing the task site directly or from video displays is called teleoperation. The operator employs a master hand controller (usually a joy stick type device for rate control or some form of robot replica device for position control) to control the motions of the slave manipulator that is performing the actual task. This mode of operation allows the operator to accomplish work at a relatively unknown or unstructured worksite in a hostile environment like space while he or she remains in a shirt sleeve environment. Teleoperation systems have been developed primarily by the nuclear industry for repair and maintenance of nuclear reactors and by the undersea industry for offshore gas and oil rig assembly, maintenance, and repair, as well as for undersea salvage operations.

In contrast to the direct human control of the teleoperated system, the manufacturing industry typically operates its robotic systems autonomously. That is, the robot performs its tasks automatically, without human intervention. This is possible because a factory floor environment can be set up in a structured and accurate way. The tasks performed by robots in the manufacturing environment are generally repetitious (e.g., pick and place operations) and must be done rapidly to support high productivity.

The systems that have been designed for the teleoperation and manufacturing environments have different attributes, as shown in Figure 3. In particular, the manipulator designs contrast sharply. Manipulators designed for teleoperation purposes have relatively low weight and inertia and are fairly compliant, so that little or no damage will be done if the operator makes an error. The inaccuracies of this "sloppier" design are easily compensated for by the operator by means of visual and force feedback. In contrast, manipulators designed for manufacturing operations are required to be highly repeatable and hence very stiff and massive.

TELEOPERATED (NUCLEAR/UNDERSEA)	ROBOTIC (FACTORY)
MANIPULATOR	
LOW-WEIGHT/INERTIA FLEXIBLE/COMPLIANT NONREPEATABLE	MASSIVE VERY STIFF HIGHLY REPEATABLE
OPERATOR INTERFACE	
DEXTRous HAND CONTROL CAMERAS/VIDEO FORCE FEEDBACK	TEACH PENDANT PROGRAMMABLE
CONTROLS	
LOW-LEVEL SERVOS MANUAL OPERATION OPERATOR ALWAYS IN LOOP	LOW-LEVEL SERVOS HIGH-LEVEL SERVOS STRUCTURED/REPETITIVE

Figure 3. Existing System Attributes

The FTS design will incorporate the capabilities for both teleoperation and autonomy, as shown in Figure 4. This is why FTS is termed a "telerobotic" system. The design will allow for a spectrum of control modes from pure teleoperation to complete autonomy. These control modes (see Architecture section) will be easily transitioned at the sub-task level to permit varying degrees of supervised autonomy and shared control.

A manipulator system that combines the capabilities of the currently existing teleoperated and robotic systems has never been built, although research has been done in this field. To accomplish this goal, the FTS design must apply sophisticated sensor-driven control techniques, such as active compliance (impedance control) to support good teleoperability and still maintain repeatable autonomous capabilities. Additionally, FTS must employ a control structure that supports a methodical representation of task decomposition, task description, task performance and human interaction to control the manipulator in a shared manner. This control structure is already developed in the form of the NASREM Architecture.

Force Reflection

For teleoperation, there are a number of workstation operator control methods, including resolved motion rate control, replica master control, hybrid control, non-force-reflecting control, and force-reflecting control. An excellent discussion is presented on each of these in one of the references [6]. A force-reflecting system enables the operator to feel, by means of the master hand controller, the contact forces of the slave arm at the worksite. Experienced operators say that the addition of this capability to the teleoperation system greatly enhances their productivity and reduces their errors, especially when executing a task for the first time.

Unfortunately, the addition of a force reflecting capability to a system adds considerable complexity. It adds complexity to the hand controller(s), because they must include actuators to impart forces to the operator. This in turn adds much complexity to the control system, because the hand controller is now effectively a robot and must be controlled as such.

Another major system constraint that comes with the addition of force-reflecting capabilities is in the area of data communications. With a force-reflecting system, the operator/hand controller is an integral part of the control loop and can effect the stability of the system. In order for the force reflection to be effective, the control loop gains must be set high enough for the operator to feel the forces. This requires a reasonably high sampling rate (at least 50 Hz), which dictates a low data latency time between the master and the slave. On Freedom Station, the FTS master and slave will have to communicate across the Freedom Station Data Management System, which is effectively a local area network with nondeterministic data latency times. This presents a problem that has not been completely solved at this time.

Mobility

There are two basic types of mobility required for the FTS: global and local. Global mobility is defined as the mobility required to get the telerobot portion of the FTS system to the worksite. Local mobility is the mobility required at the worksite to properly position the telerobot arms to the task.

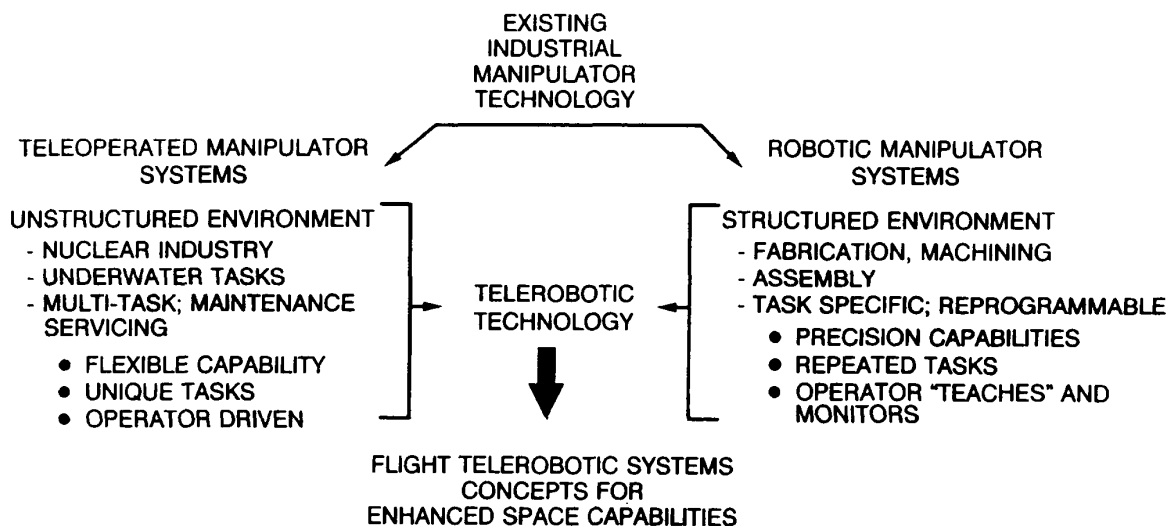


Figure 4. FTS will Incorporate Teleoperation and Autonomous Capabilities

There is no requirement for the telerobot to provide its own global mobility by walking down the Freedom Station truss or employing some other form of self-mobility. This would add unwarranted complexity to the FTS System, since there are already systems on the Space Shuttle and S.S. Freedom that can provide this mobility. When operating from the Shuttle during the early Freedom Station assembly phases, the Shuttle Remote Manipulator System (RMS) will provide global mobility. When operating on the Freedom Station, global mobility will be provided by the Space Station Remote Manipulator System (SSRMS), which will be attached to a transport device such as the Mobile Servicing Centre (MSC) (to be supplied by Canada).

Some form of local mobility is required as an integral part of the FTS design. This will probably take the form of additional degrees of freedom at the base or torso of the telerobot. The "Tinman" concept for local mobility is shown in Figure 5.

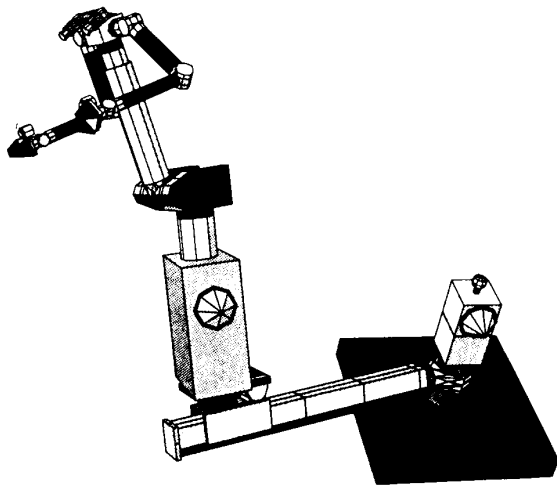


Figure 5. "Tinman" Concept for Local Mobility

Safety

Safety is of primary importance in the design and operation of any robotic system and is especially critical to the FTS. It is, therefore, required that safety be an overt consideration in the FTS system design. The following paragraphs describe the system safety requirements for the FTS.

The telerobot is considered to be in a safe state when all motion has stopped, and the position of the telerobot and its attachment to the worksite and the workpieces are securely maintained.

The FTS system will have the capability to detect failures and automatically assume a safe state. This capability will be two-fault tolerant. That is, the FTS subsystems supporting this safety capability will be able to sustain two failures and still operate properly. These capabilities will reside physically in the telerobot portion of the FTS in case of interruption of power or data.

The workstation portion of the FTS will provide a secondary safing function that will monitor and detect unsafe conditions and alert the operator. Any EVA astronaut working in the vicinity of the telerobot will also have shutdown control over the telerobot implemented by means of a direct link from the EVA astronaut to the telerobot.

Architecture

For the FTS to achieve its design goals, an appropriate functional architecture must be adopted at the outset of the project and followed faithfully throughout the life of the project.

The FTS functional architecture must:

- Allow for incremental evolution as technology advances
- Provide for varying degrees of teleoperation, supervisory, and autonomous control
- Permit the integration of subsystems developed by different groups or organizations

As discussed earlier, the NASREM architecture has been adopted by the FTS Project to fulfill these requirements.

Figure 6 shows the NASREM architecture at its highest level of abstraction. NASREM defines a set of standard modules and interfaces that facilitate software design, development, validation and test, and make possible the integration of telerobotic components from a wide variety of sources. Standard interfaces also provide the "hooks and scars" necessary to incrementally upgrade the FTS as new capabilities develop in computer science, robotics, and autonomous system control. NASREM does not represent a specific computer system architecture and can, in fact, be implemented with many different computer hardware and software configurations, as long as the standard NASREM module interfaces are explicitly maintained.

NASREM is hierarchically structured into multiple levels, as shown in Figure 6, such that a different fundamental mathematical transformation is performed at each level. At level 1, coordinates are transformed and outputs are servoed. At level 2, mechanical dynamics are computed. At level 3, obstacles are observed and avoided. At level 4, tasks on objects are transformed into high level motions. At level 5, tasks on groups of objects are sequenced and scheduled. At level 6, tasks that require parallel activities of multiple robotic systems are sequenced and scheduled.

NASREM is also horizontally structured into three sections: Task Decomposition, World Modeling, and Sensory Processing. Task Decomposition includes planning and task monitoring, servo control, and interfaces for operator input commands. World Modeling includes computer-aided design (CAD) models of objects and structures, maps of areas and volumes, lists of objects with their features and attributes, and tables of state variables that describe both the system and the environment. Sensory Processing includes signal processing, detection of patterns, correlation and differencing of observations versus expectations.

The NASREM levels provide logical interfaces for an operator to the control. The operator can essentially supply commands at any level and replace the levels above.

The initial implementation of FTS will obviously not include all of these levels of activity, but NASREM provides the required framework for future growth.

Conclusions

The FTS is being developed in response to a recognized need to augment available astronaut EVA capabilities on the Space Station Freedom. The FTS Project has completed Phase A and multiple Phase B studies, and will have a Phase C/D contract in place in the spring of 1989. The FTS Program includes two Shuttle test flights to verify the design concept and to demonstrate its capabilities to perform Freedom Station assembly, maintenance, servicing, and inspection tasks in a space environment.

The FTS development process will space qualify and integrate state-of-the-art technology elements into a unique system that includes both teleoperation and autonomous capabilities. The early applications of the

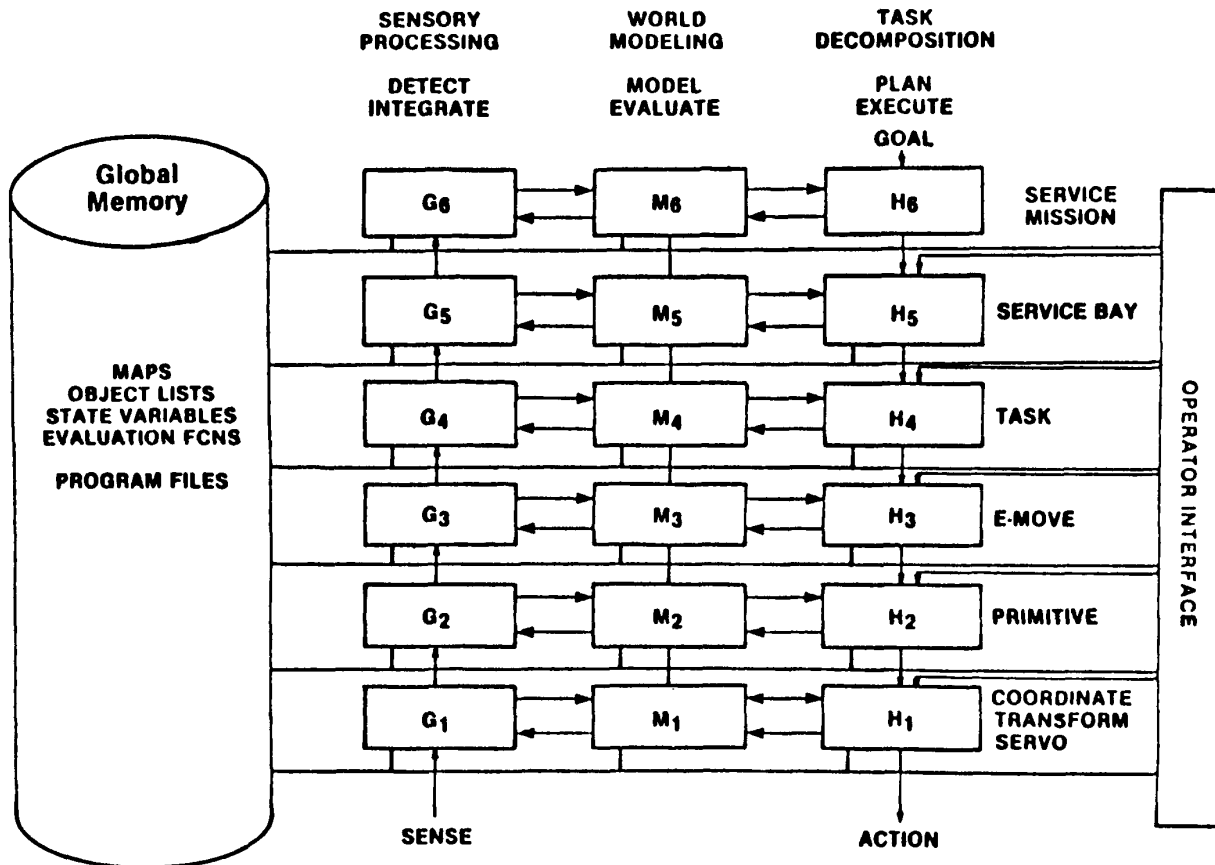


Figure 6. NASREM Architecture

FTS will be primarily teleoperated with limited autonomy. Evolution to more advanced technology that will enable more autonomous operation is a planned part of the FTS Program. A key to the evolutionary capability of the FTS design is the NASREM architecture. This architecture provides the framework for future growth and permits a logical blend of teleoperation and autonomous operations as required.

References

- [1] J. Andary, S. Hinkal, and J. Watzin, "Design Concept for the Flight Telerobotic Servicer (FTS)," presented at the 2nd Space Operations Automation and Robotics Workshop, Dayton, Ohio, July 1988.
- [2] "FTS In-House Phase B Study Final Report," September 1988.
- [3] J. Oberright, H. McCain, and R. Whitman, "Space Station Flight Telerobotic Servicer Functional Requirements Development," Proceedings of SPIE - The International Society of Optical Engineers, November 1987.
- [4] "Robotic Assessment Test Sets: Levels 1, 2, & 3," SS-GSFC-0029, 1987.
- [5] J. Albus, H. McCain, and R. Lumia, "NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)," SS-GSFC-0027, December 1986.
- [6] L. Martin, P. Satterlee, and W. Appleton, "Development of Dual-Arm Robotic Manipulator Control Based on Teleoperation Manipulation Methods," prepared for NASA Langley Research Center, Contract No. NAS1-18423, August 1987.