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THE FLIGHT TELEROBOTIC SERVICER AND TECHNOLOGY TRANSFER

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ABSTRACT

The Flight Telerobotic Servicer (FTS) Project at the Goddard Space Flight Center is developing an advanced telerobotic system to assist in and reduce crew extravehicular activity (EVA) for Space Station Freedom (SSF) [I]. The FTS will provide a telerobotic capability in the early phases of the SSF Program and will be employed for assembly, maintenance, and inspection applications. In mid-1989, the FTS Project entered the flight system design and implementation phase (Phase C/D) of development with the signing of the FTS prime contract with Martin Marietta Astronautics Group in Denver, Colorado. The basic FTS design is now established and can be reported on in some detail.

The current state of space technology and the general nature of the FTS tasks dictate that the FTS be designed with sophisticated teleoperational capabilities for its initial primary operating mode. However, technologies, such as advanced computer vision and autonomous planning techniques, would greatly enhance the FTS capabilities to perform autonomously in less structured work environments. Another objective of the FTS program is to accelerate technology transfer from research to U.S. industry.

SYSTEM DESCRIPTION

The FTS flight system consists of the telerobot, two workstations -- one for the shuttle orbiter and one for Space Station Freedom -- and a facility for on-orbit storage, called the Storage Accommodation Equipment (SAE).

The Telerobot

The telerobot [figure 1] has two 7 degree-of-freedom (DOF) manipulators and an attachment, stabilization, and positioning subsystem (ASPS) or "leg" mounted on a compact body. The body contains internal electronic boxes that provide the power, data management, and data processing functions. The boxes are designed as orbital replaceable units (ORUs) that can be replaced by an astronaut on extravehicular activity (EVA) or another telerobot. Also mounted on the body are a camera positioning assembly with two head cameras and holsters for storing tools and end effectors. On each manipulator wrist actuator is mounted a camera for close-up viewing. At the end of the wrist roll actuator is a force-torque sensor for measuring forces and torques produced at the tool plate. Attached to the force-torque sensor is the end effector changeout mechanism, which will accommodate a variety of tools and end effectors.

Workstations

The shuttle and space station workstations will provide the operator with similar interfaces, including color video displays, text and graphics overlay capability, and two six-DOF force reflecting handcontrollers for teleoperation of the FTS manipulators. During operation, a sequence of events is displayed which the operator will use as a checklist. As commands are issued, displays provide status information and command menus. Anomalous events result in automatic caution and warning displays to the operator, along with fault diagnostics and recommended corrective action.

Storage Accommodation Equipment

The FTS will be stored on orbit at the SAE which will be attached to the space station truss on the nadir facing side. Also stored in the SAE will be the telerobot's ORUs and tools. The SAE has power, data, and video interfaces with the SSF, and an EVA station to support EVA maintenance of the FTS.

The weight of the telerobot and workstation will be approximately 1500 pounds. The average on-orbit power is planned to be less than 1000 watts with a peak power of approximately 2000 watts . The system is designed for an indefinite on-orbit life through periodic maintenance.

Operating Modes

The FTS can operate while attached to a worksite or while attached to a transport device [figure 2]. The way the FTS is attached to a worksite is with its ASPS. If it is at an "improved" worksite, the telerobot connects to the power, data and video systems through a worksite attachment fixture (WAF) which also gives the telerobot mechanical support. If it is at an "unimproved" worksite, the telerobot will receive its power, data and video utilities through an umbilical that will be connected to a nearby utility port. In this case the worksite only provides mechanical support. In the transporter-attached mode, the telerobot is attached to a shuttle or space station remote manipulator system (RMS) via a grapple fixture mounted on the back of the FTS body.

Test Flights

Two test flights -- a Development Test Flight (DTF-1) and a Demonstration Test Flight (DTF-2) -- precede the deployment of the initial operational FTS system at first element launch (FEL) in 1995. DTF-1, scheduled for launch in 1992, will validate the performance of the FTS manipulator design in a zero-gravity environment [figure 3]. Data obtained will also be used to evaluate human-machine interfaces, assess servicing interfaces with work elements, and establish the correlation between simulation and analysis results and flight performance data. DTF-2, scheduled for launch in 1994, will validate the full servicing capabilities of the FTS. Following DTF-2, the DTF-2 flight hardware will be refurbished, updated as required, and installed at the Goddard Space Flight Center as an engineering test system to support operation and evolution of the FTS.

CURRENT FTS TECHNOLOGY

Engineering and integrating the different telerobotic technologies into an operational system that combines teleoperation and autonomy and that meets stringent performance requirements is the challenge of the FTS project. The following paragraphs summarize the major elements of these technologies.

Manipulator Technology

The FTS manipulator [figure 4] comprises harmonic drive actuators with brushless d.c. torque motors commutated by Hall effect sensors. The transmissions have 100:1 speed reduction and incorporate fail-safe brakes for safety purposes. Table 1 shows manipulator performance specifications. A force-torque sensor attached to the manipulator tool plate measures the forces and torques exerted at the worksite and provides feedback to force reflecting handcontrollers at the workstation. It also allows the telerobot to control the forces and torques generated by the manipulators using a position-based, impedance control algorithm. This compliance control also allows the manipulators to automatically compensate for misalignments. The operator may select position or resolved-rate control, or in special situations, single-joint control. Coordinated dual-arm control will be useful in handling large components on Space Station Freedom.

Three microprocessors are imbedded in the manipulator links to control the seven joints and the end effector. Flat conductor cables carry hundreds of electrical signals through the actuators and back to the central processor in the telerobot body where the bus controller routes the commands and signals between the workstation and the telerobot. Several types of signals, including a 1553 data bus and the video channel from the wrist camera mounted to the wrist roll actuator, are passed through the actuators.

Control System Technology

The NASA/NBS Standard Reference Model (NASREM) control system architecture, which has been selected for FTS, allows teleoperation and autonomous operations. Its architecture is a three-legged hierarchy of computing modules (figure 5). The first leg plans and executes the decomposition of high level goals into low level actions. The second leg remembers, estimates, predicts, and evaluates the state of the world surrounding the telerobot. The third leg recognizes patterns, detects events, and filters and integrates sensory information. The sensory system compares the world model predictions with observations. Each level in the hierarchy has a specific function, and receives commands from the next higher level. The first four levels of NASREM will be implemented in the FTS system. Level 4 decomposes tasks into sequences of movements. Level 3, the elementary move level, plans all aspects of the manipulation. The primitive level, or Level 2, generates the time sequence of desired state vectors to produce dynamic trajectories. The servo level, or Level 1, contains the servo control loops for the actuators.

The FTS flight software, coded in Ada, interprets the operator inputs and controls the telerobot's motion, monitors health and status, and ensures the safety of the FTS. The primary control loop operates at 50 Hz, which means that all the control computations and the data transfer from the handcontrollers to the manipulators back to the handcontrollers must be accomplished in 20 milliseconds, including data transmission delays.

FTS GROWTH TECHNOLOGY

In the unstructured working environment of the FTS, current technology dictates the FTS operational mode be primarily teleoperation. However, technologies, such as artificial intelligence planning and advanced computer vision, are evolving from the research phase and could significantly enhance FTS capabilities to perform tasks autonomously in space. Therefore, the capability to evolve is designed into the FTS. In the meantime, it must use the operator for those tasks for which the human is better suited, such as vision processing and manipulator path planning [2].

The FTS project relies on a number of sources for the development of the growth technologies which will be needed for the FTS evolution. The primary sources of these advanced technologies are NASA's Office of Space Station (OSS) Advanced Development Program and the Telerobotic Development and Demonstration Program of the Office of Aeronautics and Space Technology (OAST). The FTS project works directly with these organizations to establish technology requirements. The most promising technologies will then be considered for incorporation into the FTS system as part of its planned evolution process.

Preliminary Requirements

One example of the evolutionary planning that is being conducted by the FTS project is a recent study [3] that assessed the impact of future (1999) requirements on the FTS data management and processing system (DMPS). A set of preliminary requirements were generated based on an estimate Of available state-of-the-art technology without regard to current flight qualification status and without power, weight, redundancy, and safety considerations. These preliminary requirements will be refined into a coherent, viable set that will be used to focus the technology development process. The following paragraphs summarize these preliminary requirements.

Control. The telerobot will be able to operate at NASREM level 4. Head cameras will automatically track specified objects. End effectors will incorporate "smart" 6-DOF micromanipulators. Other growth requirements include coordinated automation and teleoperation, control with time delay (e.g., ground control), increased speed, and control by implementing different manipulative algorithms. Improved collision avoidance techniques using geometric models and proximity sensor data will also be incorporated.

Vision. Requirements for presenting stereo vision to the operator and for color in autonomous processing are being studied. Autonomous image processing to identify and track objects at the worksite will be incorporated, which will resolve ambiguities with information from a CAD world model.

Sensors. Sensor upgrades could include laser range imaging, proximity sensors and special purpose sensors.

Operator Interface. The operator's interaction with FTS will be enhanced with stereo vision; video image overlays, including a shaded graphics figure of the robot superimposed on a CAD view of the worksite; displays of sensor data; monitoring of the activity stream at all NASREM levels; speech recognition; and simulation of command sequences.

Safety. System monitoring will be increased to be consistent with the increased autonomy. In addition, a separate "watchdog" system will monitor the main system and output warnings or initiate system shutdown. Monitoring for imminent object collision will be included.

System Impact

A study [4] assessed the impacts of meeting these requirements:

200 Hz Around the Loop Control Rate. This rate will improve servo control, control loop stability, and force reflection "crispness."

Increased Autonomy. This feature will increase system efficiency and minimize operator load. It will affect processing throughput, worksite modelling, and sensor systems.

Image Data Processing. Processing of image data in real-time requires special purpose hardware and associated software.

Simulation. Requirements for generation of graphic images containing a million polygons at a 6 Hz update rate require extremely fast computers and/or special purpose graphic engines.

CAD Data Interface. This interface with Space Station Freedom will provide the worksite geometric information to support the FTS world model.

CURRENT RESEARCH PROGRAMS

Much of the technology planned for use on the space station FTS and on the test flights is relatively new and untested. To provide the answers needed to design safe, reliable, and fully functional robotics for flight, Goddard Space Flight Center is developing a unique space robotics facility. This highly sophisticated facility will be used by the Goddard robotics team to create, test, and evaluate new robotic technologies required to support Space Station Freedom, and to perform complex maintenance and construction operations for the challenging missions being planned by NASA in the 21st Century.

With help from universities, industry, and other NASA centers, Goddard is presently integrating techniques for task planning, robot motion control, operator interface, sensor integration, advanced end effectors, and safety.

During the past several years, a number of tests and demonstrations were successfully conducted. Some highlights include the autonomous removal of an ORU, assembly of an attached payload structure, vision controlled docking that permits the robot to find an object and dock to it for removal, and voice control of cameras that can free an operator's hands for control of the robot.

Work that is presently underway include detailed task performance with mockups of space station hardware, implementation of higher levels of the NASREM architecture, research into advanced collision avoidance schemes, improvements in operator interfaces, control algorithm development, and prototype work with advanced mechanisms for end effectors, tools and worksite attachment mechanisms.

FTS TECHNOLOGY TRANSFER

As dictated by Congress, a key objective of the FTS project is to enhance the United State's expertise in automation and robotics and, thereby, contribute to this nation's economic competitive advantage. To capitalize on the emerging FTS technologies that are relevant to ground and space applications, Martin Marietta Space Systems Company and the Goddard Space Flight Center have established a Commercial Applications program to disseminate these technologies to industry. This program involves outreach to companies and organization with a potential interest in FTS technologies, including industries, small business, entrepreneurs, the Centers for the Commercial Development of Space, NASA's Industrial Applications Centers, various U.S. government organization, universities, and NASA-sponsored centers. Also, information is being collected in databases which are available to the user community.

Since first-hand interactions between the users and developers of technology are crucial to smooth and timely transfers, a high level of interactive support is being provided to complete the technology transfer process. These processes are being tailored to fit the requirements of the-recipient.

An industrial briefing of the FTS technologies is planned in early December 1990. Interested parties that could benefit from these technologies or any aspect of the commercial applications activity should plan to attend.

CONCLUSION

The FTS provides a versatile capability for long-term space station maintenance. The basic FTS design is now established and plans for the first development test flight in 1992 are well underway. Although the initial design primarily involves the integration of existing technologies, plans for evolution and growth will incorporate the products of on-going research -- bridging the gap between the NASA's research arm and its flight programs. Through the commercial applications program the mechanisms are being established now to transfer the FTS technology products directly into U.S. industry.

REFERENCES

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2. Lumia, Ronald: Short Term Evolution for the Flight Telerobotic Servicer, GSFC Internal Report, 13 October 1989.

3. Ring, Michael: FTS Requirements for Data Management and Processing, Phase I Report. Advanced Technology and Research Corporation, prepared for GSFC, 23 March 1990.

4. Data Management and Processing Subsystem Alternate Architecture Study, FTS Contract NAS5-30689, Exhibit 2, Task 3, prepared by Martin Marietta Astronautics Group, 15 June 1990.

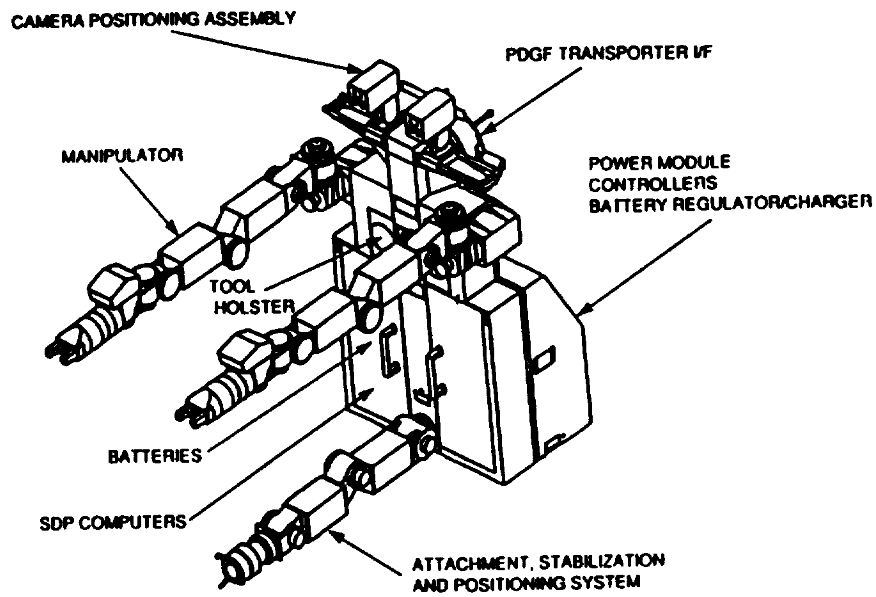

FIGURE 1. THE FLIGHT TELEROBOTIC SERVICER

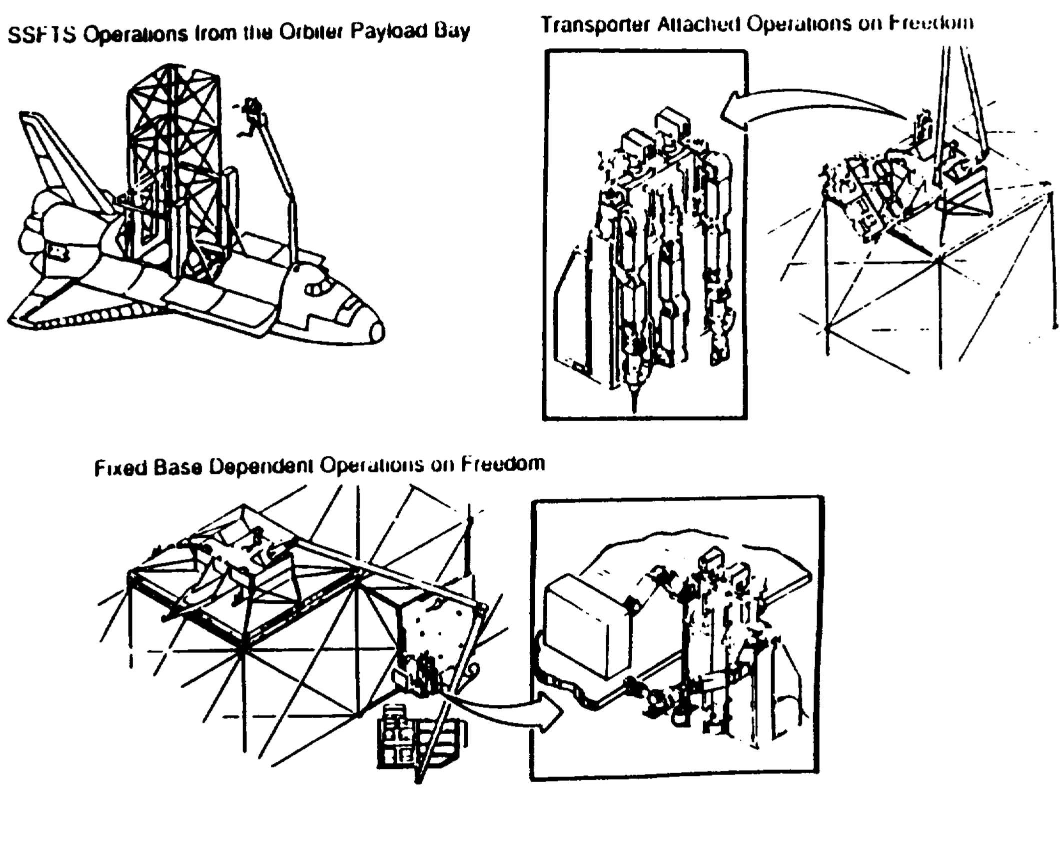

FIGURE 2. FTS OPERATIONS MODE

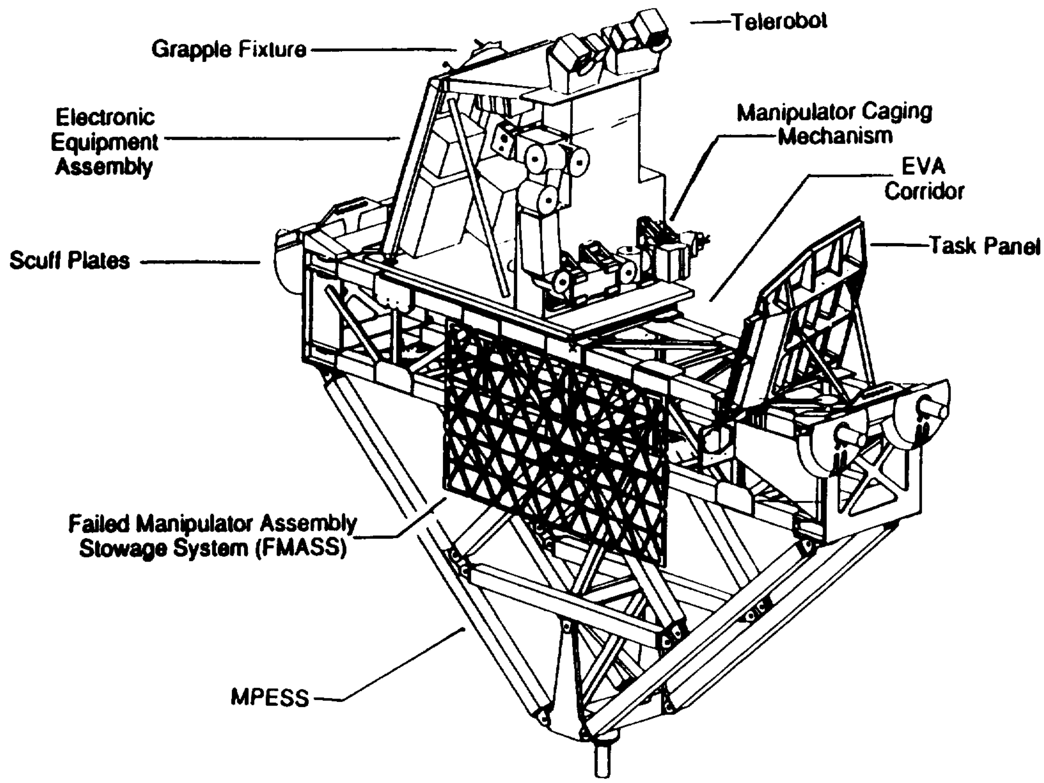

FIGURE 3. DTF-1 CONFIGURATION

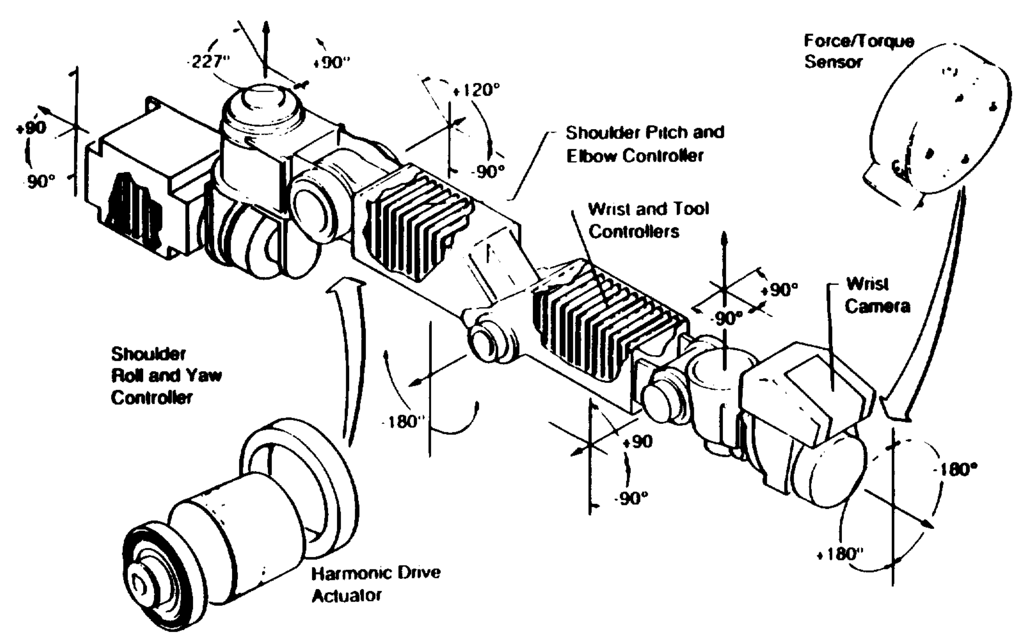

FIGURE 4. FTS MANIPULATOR

- Tip Force At Tool Plate: 20 lb Minimum In Any Direction Or Configuration
- Tip Torque At Tool Plate: 20 ft-lbs Minimum
- Incremental Motion At Tool Plate: <0.001 in, < 0.01deg
- Repeatability At Tool Plate (Constant Thermal Environment): <0.005 in, <0.05 deg
- Translation Rate At Tool Plate, Fully Extended: 24 in/sec Minimum No Load
6 in/sec Minimum With 2.8 Slug Load
- Accuracy At Tool Plate, Relative To Manipulator/Body Interface: <1.0 in, <3.0 deg
- Actuator Position Sensor Resolution: Shoulder Joints: 22 bits
Elbow Joints: 21 bits
Wrist Joints: 20 bilts
- All Cable Is Internally Routed
- Manually Releasable Fail-Safe Brakes And Backdrivable Actuators Allow Manual Stowage
- Hardwire Control Allows Backup Operation Of Actuators Using Secondary Motor Windings

TABLE 1. KEY MANIPULATOR CAPABILITIES

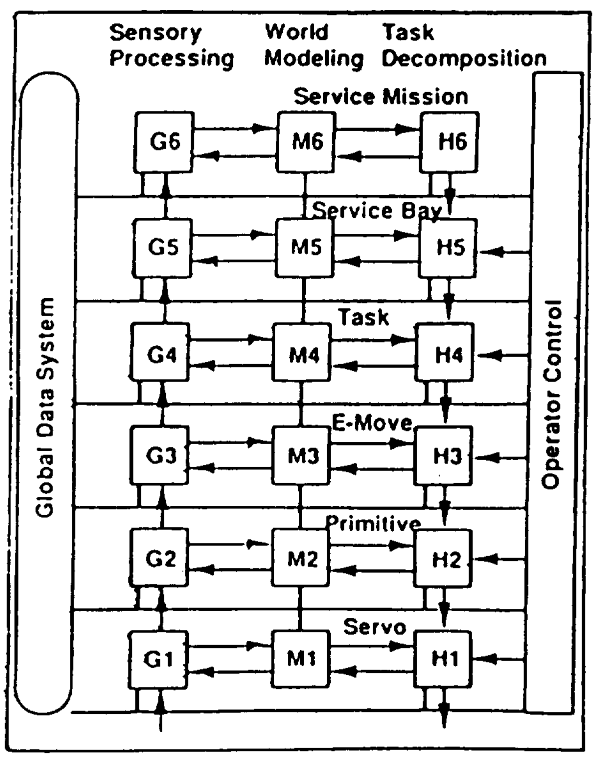

FIGURE 5. NASREM ARCHITECTURE SCHEMATIC