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THE SPACE STATION FLIGHT TELEROBOTIC SERVICER AND THE HUMAN

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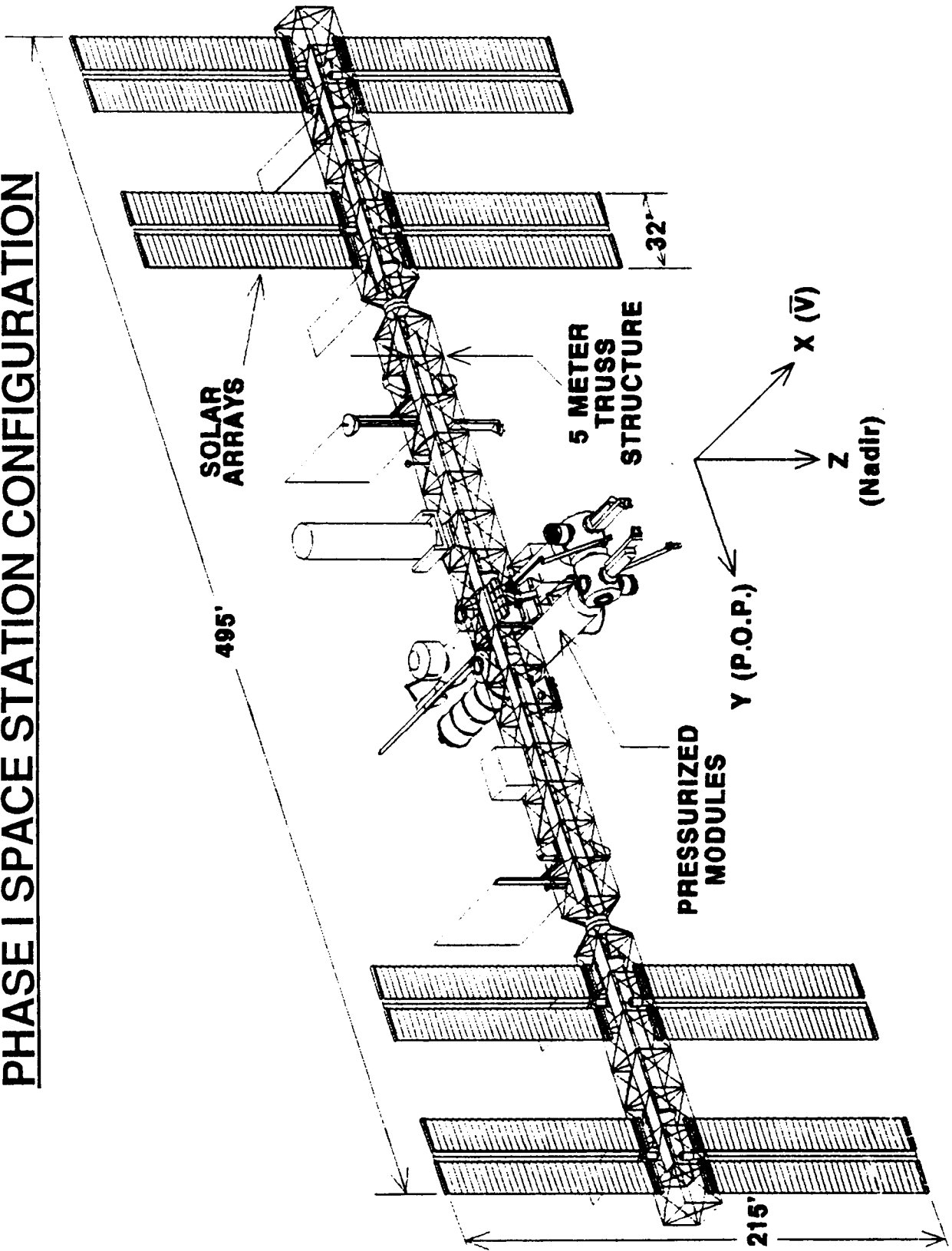
INTRODUCTION

This paper describes the Space Station Flight Telerobotic Servicer (FTS) and its human-machine interaction issues. This was a presentation for the Second International Conference on Human-Computer Interaction in August 1987 held in Honolulu, Hawaii, and reflects the FTS program up until that time. Included in this paper is a discussion of the FTS strawman concept and the FTS workstation human factors issues.

SPACE STATION PHASE I

In 1984, the National Aeronautics and Space Administration (NASA) was directed by President Reagan to develop a permanently inhabited Space Station for scientific and commercial use within a decade. The Station will be assembled in space over many flights, the first of which, at the time of this presentation, was scheduled for early 1994. The Station assembly will be performed over two major blocks of time or phases. At the end of Phase I, about four years after the first launch, the Station will have two laboratory modules, one habitat module, a logistics module (all 40 feet long and 14 feet diameter), a 75 kW solar array power system, all of which are connected on a single truss structure, and the Flight Telerobotic Servicer (FTS). The Phase I configuration is shown below.

PHASE I SPACE STATION CONFIGURATION



FTS INITIATION

In 1985, Congress mandated NASA to develop a flight telerobotic system which is to be available at the time of the first assembly element launch of the Space Station. This system is to be compatible with a mobile remote manipulator and to be used for Space Station assembly and maintenance. It should also be adaptable as a smart front end for the orbital maneuvering vehicle (OMV) for remote operations and servicing.

The development of this telerobotic system, called the Flight Telerobotic Servicer, or FTS, is being managed by NASA Goddard Space Flight Center, whose program began in May 1986. The FTS will include a telerobot, space based workstations, and ground support systems. This paper reviews the FTS program and a strawman FTS concept, as of August 1987, but with particular emphasis on the human/machine interfaces of the FTS workstations.

FLIGHT TELEROBOTIC SERVICER

INITIATION

- Congressional mandate to NASA
November, 1985
- "Specifically, the Committee of Conference directs that . . . be used for delivery of a flight telerobotic system at the time of initial Space Station operational capability for a mobile remote manipulator for station assembly and maintenance and a smart front end on the orbital maneuvering vehicle for remote operations and servicing."
- NASA Goddard Space Flight Center selected in May 1986 as lead Center for development of the Flight Telerobotic Servicer (FTS)

GENERAL FTS REQUIREMENTS

There are six general requirements that the FTS must meet which are listed below. First, it will be a multipurpose tool to reduce, assist and compliment astronaut extravehicular activity (EVA). The FTS will be working outside of the Space Station pressurized modules and will have EVA crewmembers as a contingency. The FTS tasks will include aid in assembly, servicing, maintenance, and inspection of the Station and its payloads. To do these tasks, it will be capable of operating in both a teleoperated or autonomous mode, whichever is best for the task. At first, the FTS will be limited to teleoperation, indirect manipulation or remote control by a person, but will have autonomous capabilities by the time the Phase I Station is completely assembled. Autonomous operation means that the FTS can operate on its own for periods of time without the person constantly commanding it, but acting as a supervisor instead. The FTS will be operable from both within the Space Station and the Shuttle. At first, control will be from the Shuttle to support the assembly of the Station. The Station should be capable of supporting FTS operation after about the fourth assembly flight. Eventually, the FTS may be controlled from the ground. However, time delay problems must be overcome or the FTS must be completely autonomous. The FTS will interface with the Space Station mobile servicing center and servicing facility manipulator, the Shuttle remote manipulator system (RMS), and the OMV. This requires some degree of commonality or interchangeability for how the FTS handles multiple power, data, and communication systems, all of which are different for each of the host devices. Lastly, but probably most importantly, the FTS must operate safely and fail in a manner which is both safe and recoverable.

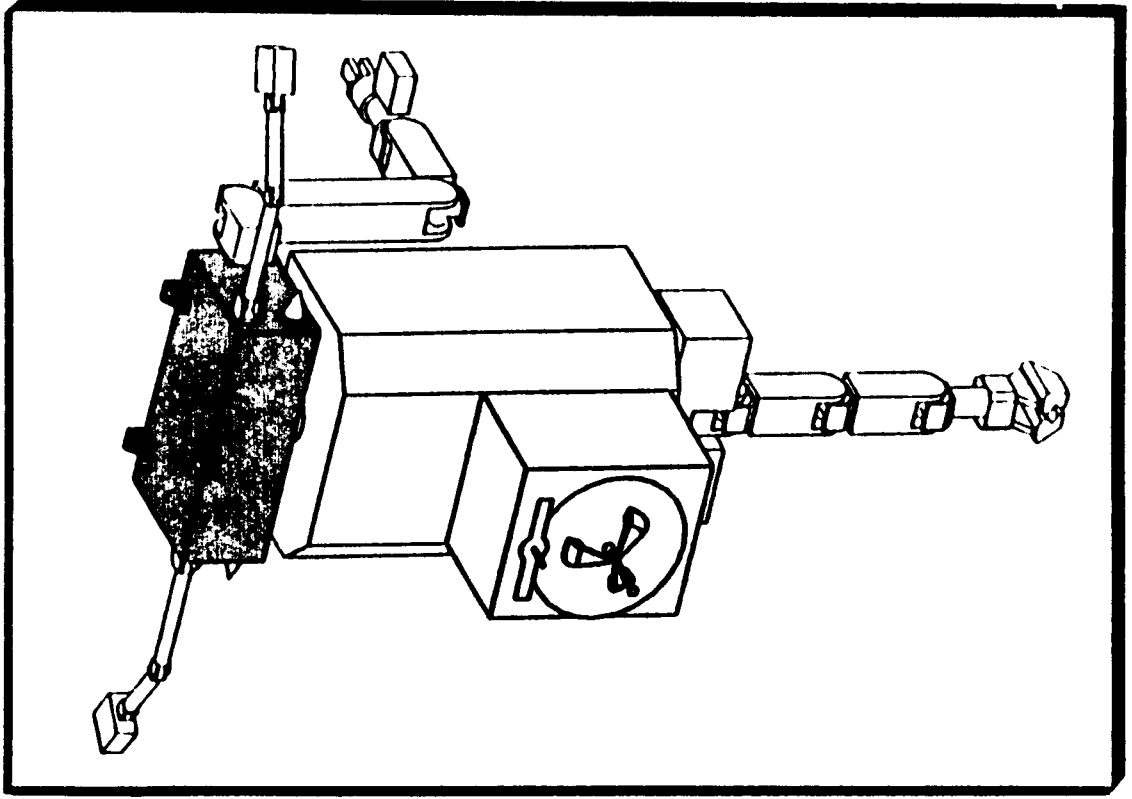
GENERAL FTS REQUIREMENTS

- Multipurpose tool to reduce, assist and compliment Astronaut Extravehicular Activity (EVA)
- Aid in assembly, servicing, maintenance, and inspection of Space Station and its payloads
- Capable of both teleoperation and autonomous operation
- To be operable from within the Space Station and the Shuttle
- Interface with the Space Station mobile servicing center and servicing facility manipulator, the Shuttle Remote Manipulator System (RMS), and the Orbital Maneuvering Vehicle (OMV)
- Safe operation and fail safe/recoverable

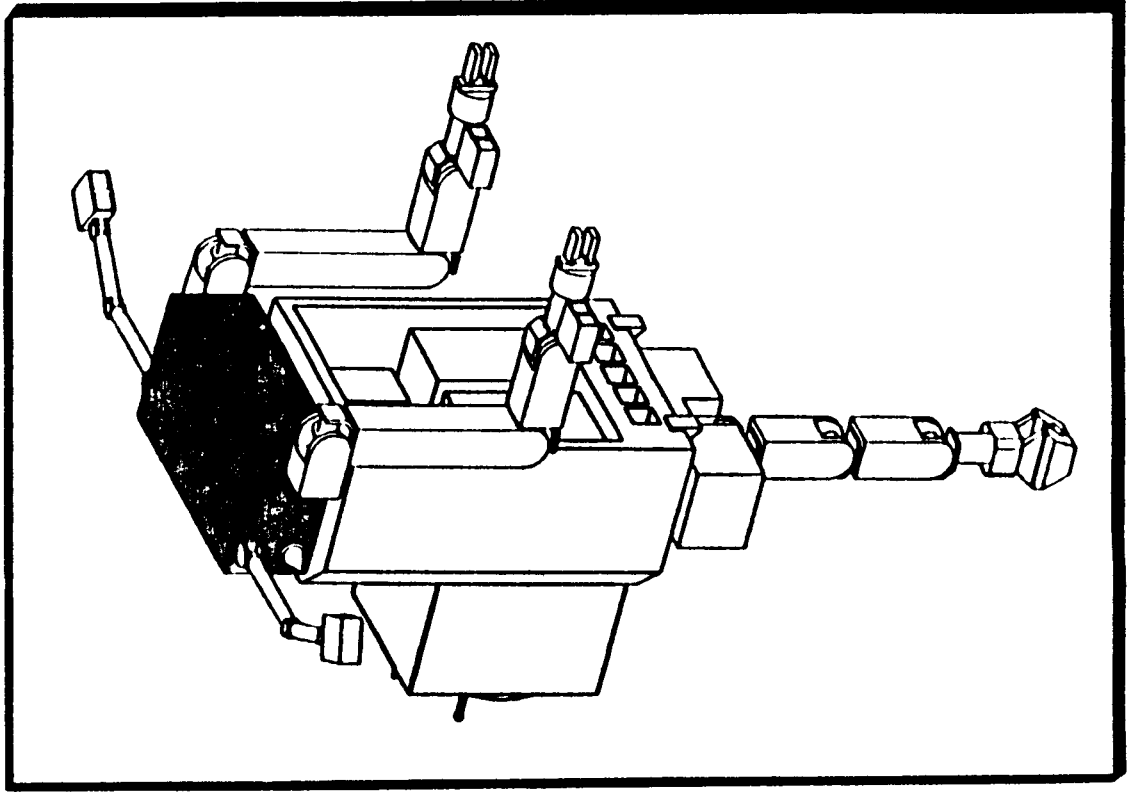
ILLUSTRATION OF FTS STRAWMAN CONCEPT

The FTS Program consists of the flight system, a demonstration test flight(s), and ground-based research development activities. Winning contractors for a nine-month preliminary design study of the FTS flight system were announced in December 1987. To facilitate the writing of the Request for Proposals for this study, a concentrated activity, called a "skunkworks," was conducted in the autumn of 1986. This activity developed requirements definitions, specifications, and performed feasibility analyses for the FTS project. Representatives from several other NASA Centers, the National Bureau of Standards, and the Oak Ridge National Laboratories participated in the multi-week effort. A major product of this activity was the development of an FTS strawman concept. This concept is illustrated below and is described in the following pages and in Hinkal, et al (ref. 1).

FTS STRAWMAN CONCEPT



Rear View



Front View

FTS STRAWMAN CONCEPT

The FTS strawman concept for the telerobot included manipulators, the body, and cameras. Two manipulators for operation on the workpiece and one for worksite attachment were chosen, with each manipulator having seven degrees of freedom. These manipulators would have standard mechanical, power, and data interfaces which would also be compatible with both the Space Station and Shuttle. On the ends of the manipulators would be end effectors which would use standard tools.

The body would consist of three segments: the shoulder, center body, and hips. There would be points of rotation at the hips and at the shoulders. The body would contain the computer, power converters, data management, and communications equipment. Tool storage slots would be also on the body along with a removable battery pack and grapple fixture. There would be two cameras and lights on articulated booms and a camera and light on each wrist.

FTS STRAWMAN CONCEPT

- **Manipulators**
 - **Two for operation on workpiece and one for worksite attachment**
 - **7 degrees-of-freedom for each**
 - **Standard mechanical, power, and data interface**
 - **End effectors, standard tools**

- **Body**
 - **Three segments, rotate at hips and shoulders**
 - **Contains computer, power converters, data management, and communications equipment**
 - **Tool storage slots**
 - **Removable battery pack with grapple fixture**

- **Cameras**
 - **Two on articulated booms, two on wrists**

FTS WORKSTATION

The Space Station will be able to support six crewmembers on a permanent basis after about the fifth assembly flight. The Station is to be designed to promote high productivity, so that it is essential that anything to do with the crew be designed properly, following human factors principles. Accordingly, the FTS must contribute to the productivity of the Station and also be designed for optimum interaction with the crew.

In terms of crew interaction with the FTS, it is the FTS workstation that is of interest. The workstation will be the point of control for the FTS telerobot. It will require only a single operator. It will allow both autonomous and teleoperated modes of telerobot control. It will allow the operator to have visibility of telerobotic operations. And it will coordinate with other FTS related operational components, such as other workstations, payload control, as well as the FTS systems.

There will be two physical configurations of the FTS workstation; one for the Space Station and one for the Shuttle. Even though there are two versions, they must be operationally compatible for minimal additional training and transfer errors. The Space Station version will be based on a common control station and will be located in the cupola. The Shuttle version will be portable requiring minimum modifications to the Shuttle and probably used in the aft-flight deck.

FTS WORKSTATION

- **Point of control for FTS telerobot**
 - **Single operator**
 - **Autonomous and teleoperated modes**
 - **Operator visibility of telerobotic operations**
 - **Coordination with other FTS related operational components**

- **Two physical configurations: Space Station, Shuttle**
 - **Operationally compatible for minimal additional training and transfer errors**
 - **Space Station version based on common control station and located in cupola**
 - **Shuttle version portable for aft-flight deck**

FTS WORKSTATION FUNCTIONS

Some specific FTS workstation functions are listed below. The workstation will process telerobot/operator commands, status, and housekeeping telemetry data from data management. It will alert the operator for the occurrence of faults, failures, and out-of-limit conditions. It will also indicate failure trends and unreliable telerobot operations. The workstation will also be capable of automated fault isolation and diagnosis while allowing the operator access to raw and partially processed telerobot parameters. The workstation will be able to support on-board training, a new idea for NASA. The astronaut, who will be on the station for a minimum of 90 days, will not be able to train on earth for every task. Therefore, the workstation must be able to aid in on-board training of FTS tasks through the display of simulated telerobot activity, status, sensor data, and command responses.

FTS WORKSTATION FUNCTIONS

- **Process telerobot/operator commands, status, and housekeeping telemetry data from data management**
- **Alert operator**
 - **Occurrence of faults, failures, out-of-limits**
 - **Failure trends, unreliable telerobot operations**
- **Automated fault isolation and diagnosis**
 - **Operator access to raw and partially processed telerobot parameters**
- **Support training**
 - **Display simulated telerobot activity, status, sensor data, and command responses**

FTS WORKSTATION WORKING GROUP

An FTS workstation working group has been formed to do preliminary development of the workstation. As of August 1987, the following had been achieved by the group: (1) A Human-FTS interface requirements document had been drafted which addresses the FTS status/feedback to the operator, the task information to the operator, the operator input to the FTS, and the workstation design requirements, which were extracted from the Space Station Man-Systems Integration Standards (ref. 2); (2) A database of documents and studies relating to teleoperators, robotics; and (3) a study plan has been devised to address the key human-FTS interface issues.

FTS WORKSTATION WORKING GROUP

- **Human-FTS interface requirements document**
 - **FTS status/feedback to operator**
 - **Task information to operator**
 - **Operator input to FTS**
 - **Workstation design requirements**
- **Database of documents on teleoperators, robotics, and human factors**
- **Study plan to address key human-FTS interface issues**

FTS CONSTRAINTS AND CHALLENGES

The FTS requirements and functions will pose many environmental and behavioral constraints and challenges on the crew interface. The environmental constraints include lighting extremes as the Station orbits through day and night, zero-gravity effects, a small and confined operational area, and limited direct viewing. The behavioral constraints include considerations associated with the combination of teleoperated and autonomous modes, heavy information workload potential, decision making which involves task allocation and task analysis. The latter means determining the steps of the task and who or which, the astronaut or the FTS, does each step. The command format and procedures will be important considerations in communications between the astronaut and FTS. Safety considerations involve error control and correction for the FTS operations, as well as accident prevention for itself and to other hardware and the crew.

FTS CONSTRAINTS AND CHALLENGES

ON CREW INTERFACE

- **Environmental**
 - **Lighting extremes**
 - **Zero-gravity effects**
 - **Small, confined operational area**
 - **Limited direct viewing**

- **Behavioral**
 - **Combination of teleoperated and autonomous modes**
 - **Heavy information workload potential**
 - **Decision making : task allocation, task analysis**
 - **Safety : error control and correction, accident risks**
 - **Command format/procedures**

HUMAN-FTS INTERFACE ISSUES

Although the FTS strawman concept is only a reference, there are some specific issues which were identified in the concept which address the challenges and constraints listed below. These issues are presented here and still require study and evaluation: (1) The type and configuration of telerobot controllers for the manipulator arms and camera controls; (2) Many factors of the displays, such as the camera configuration, camera and monitor parameters of color versus black and white, mono versus stereo vision, lighting parameters, other sensory feedback, and graphics; (3) The workstation design for panel layout, anthropometrics, biomechanics, and crew restraints; (4) FTS/Shuttle RMS coordinated simultaneous action requirements for the displays and controls when the FTS must depend upon the RMS for its mobility; (5) Task analysis impacts for all system and core testing to insure the flexibility of performance.

HUMAN-FTS INTERFACE ISSUES

- **Controls**
 - **Type and configuration of controller(s) for manipulator arms**
 - **Camera controls**
- **Displays**
 - **Camera configuration**
 - **Camera and monitor parameters**
 - **Lighting parameters**
 - **Other sensory feedback**
 - **Graphics displays**
- **Workstation Design**
 - **Panel layout**
 - **Anthropometrics**
 - **Biomechanics**
 - **Crew restraints**
- **FTS/RMS Coordinated Simultaneous Actions**
 - **Displays and controls**
- **Task Analysis**
 - **Impacts all testing**
 - **Insures flexibility of performance**

NASA/NBS STANDARD REFERENCE MODEL (NASREM)

A reference control system architecture was chosen for the FTS strawman concept based upon a model designed by the National Bureau of Standards (NBS), called the NASA/NBS Standard Reference Model or NASREM (ref. 3). This model provides generic hierarchical structured functional definitions for the system and a common reference during system definition studies. It also allows comparison of various proposed control architectures and defines potential interface points for hardware and software modularization. Finally, and very importantly, the model allows for enhancement and growth.

NASA/NBS STANDARD REFERENCE MODEL (NASREM) FTS CONTROL SYSTEM ARCHITECTURE

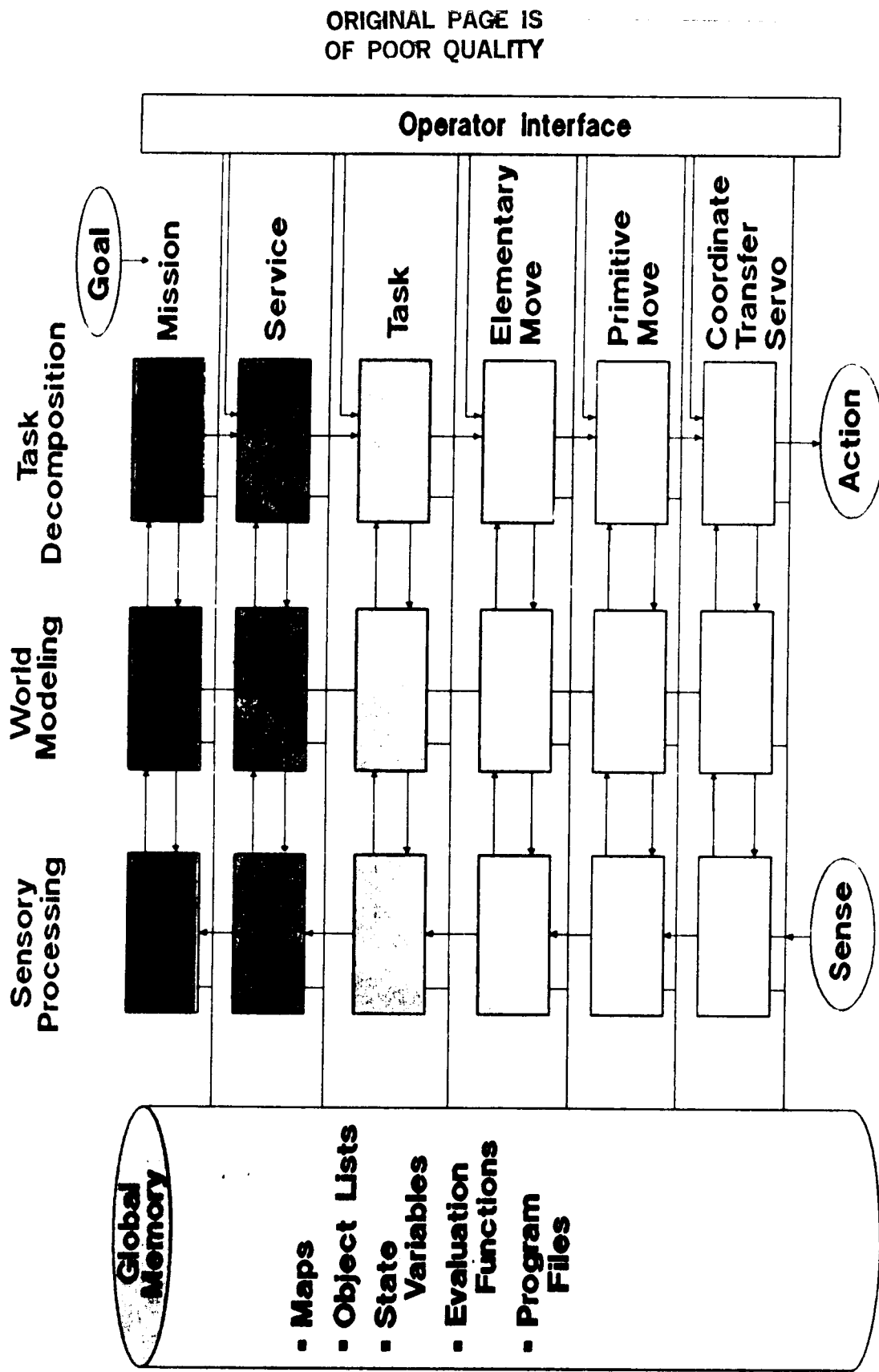
- Provides generic hierarchical structured functional definitions for the system**
- Provides common reference during system definition studies**
- Allows for comparison of various proposed control architectures**
- Defines potential interface points for hardware and software modularization**
- Allows for enhancement and growth**

NASREM ARCHITECTURE

As described by Albus, et al (ref. 3), the NASREM telerobot control system architecture is structured hierarchically into multiple horizontal layers in terms of different fundamental mathematical transformations. Complexity is increased with each level. At the lowest layer, level one, coordinates are transformed and the outputs are sent to servos. Level two computes mechanical dynamics into primitive moves. Obstacles are sensed and avoided as elementary moves in level three. Task end effector movements are the results of transformations of tasks on objects in level four. Tasks on groups of objects are sequenced and scheduled as a form of service in level five. And at level six, parts and tools are routed and scheduled between worksites which are involved in a mission.

Vertically, there are three layers: sensory processing, world modeling, and task decomposition. Sensory processing involves signal processing; pattern detection; recognition of features, objects, and relationships; and correlation between observed and expected values. World modeling includes computer-aided-design models of objects, maps of areas and volumes, object lists of features and attributes, and state variable tables which provide information on both the system and the environment. Task decomposition incorporates task planning and monitoring, value driven decisions, servo control, and operator interfaces. All of the layers depend on the system's global memory for information about the objects and the environment.

NASREM ARCHITECTURE



ROUSE INTELLIGENT INTERFACE ARCHITECTURE

The Rouse Intelligent Interface Architecture (ref. 4) is an example of a model for the actual interface between the computer/workstation and the human. It addresses various components that need to be considered and indicates the degree to which FTS will need to use expert system technology. There are four major components in the model, each with a corresponding function and subtasks/components. The interface monitor manages the flow of messages and requests (M/R) for effective operator interface. Its subtasks include M/R prioritization, M/R scheduling, M/R modality selection, and M/R formatting. The error monitor decreases the frequency of operator errors and avoids unacceptable consequences. This requires error identification, classification, and remediation. The adaptive monitor provides to the operator help which adapts to current needs and capabilities. Involved in this are the task queue, method selection, and M/R formulation. The operator model estimates current and predicted operator states and involves what Rouse calls the "intent model," the "resource model," and the "performance model."

ROUSE INTELLIGENT INTERFACE

ARCHITECTURE

<u>Component</u>	<u>Function</u>	<u>Subtasks/Components</u>
Interface Manager	Manage flow of messages and requests (M/R) for effective operator interface	M/R Prioritization M/R Scheduling M/R Modality Selection M/R Formatting
Error Monitor	Decreases frequency of operator errors Avoids unacceptable consequences	Error Identification Error Classification Error Remediation
Adaptive Aiding	Provide to operator help which adapts to current needs and capabilities	Task queue Method Selection M/R Formulation
Operator Model	Estimate current and predicted operator states	Intent Model Resource Model Performance Model

SPINOFFS

There will be several benefits or spinoffs of the FTS workstation development. From this development, an approach for configurations of data systems and complex operator interfaces will be defined and will include provisions for performance status and multiple sensory data. Techniques for cooperative human-machine control and monitoring will be identified which will allow control to be easily switched between them or controlled simultaneously by them. A method for efficiently handling emergency and failure conditions will be developed as a safety system.

SPINOFFS

- **Approach for configurations of data systems and complex operator interfaces**
 - **Performance status**
 - **Multiple sensory data**
- **Techniques for cooperative human-machine control and monitoring**
- **Method for efficiently handling emergency and failure conditions**

SUMMARY

In summary, this paper has discussed the FTS with particular attention to the FTS-human/computer interaction. The FTS will require a complex but highly constrained human-computer intelligent interface. A broad range of technical disciplines are required for development of the FTS workstation. The human-computer interactions issues identified require additional study. However, the final result will be that the FTS will merge manual and computer control techniques for intelligent human-machine systems.

SUMMARY

- FTS will require complex but constrained human-computer intelligent interface**
- Broad range of technical disciplines required for development of FTS workstation**
- Human-computer interaction issues require additional study**
- FTS will merge manual and computer control techniques for intelligent human-machine systems**

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