p. 464

NASA Conference Publication 10083

Beyond the Baseline 1991

Proceedings of the Space Station Evolution Symposium

Volume 2: Space Station Freedom

Part 2

Proceedings of a conference held at South Shore Harbour Resort and Conference Center League City, Texas August 6-8, 1991

NASA

(NASA-CP-10083-Vol-2-Pt-2) BEYOND THE BASELINE 1991: PROCEEDINGS OF THE SPACE STATION EVOLUTION SYMPOSIUM. VOLUME 2: SPACE STATION FREEDOM, PART 2 (NASA) 464 p
CSCL 22B G3/18
N92-17348 --THRU-- N92-17362
Unclas 0062419

NASA Conference Publication 10083

Beyond the Baseline 1991

Proceedings of the Space Station Evolution Symposium

Volume 2: Space Station Freedom

Part 2

Proceedings of a conference held at South Shore Harbour Resort and Conference Center League City, Texas

National Aeronautics and Space Administration

Scientific and Technical Information Branch

1991

Preface

This publication is a compilation of papers presented at the Second Space Station Evolution Symposium: "Beyond the Baseline 1991" from August 6 - 8, 1991. The symposium was structured as a forum to discuss the current status and future plans for Space Station Freedom (SSF). The primary purpose of the gathering was to review the plans and progress in ensuring a baseline design with the flexibility to accommodate a broad range of potential utilization demands and to effectively incorporate technology advances over the lifetime of the facility. The timing of the conference was chosen at the critical juncture between completion of the Delta Preliminary Design Reviews and the Program Critical Design Reviews.

The plenary papers describe the current status of the restructured Space Station Freedom design, the plans of the international partners, and future utilization of the facility. Related programs in advanced technology and space transportation are also discussed.

The technical sessions represent the results of tasks funded by Level I Space Station Engineering in Advanced Studies and Advanced Development. The charts presented are amplified here by facing page text. The work was accomplished in fiscal years 1990 and 1991 and was presented by those in government and industry who performed the tasks.

The results of SSF Advanced Studies provide a road map for the evolution of Freedom in terms of user requirements, utilization and operations concepts, and growth options for distributed systems. Regarding these specific systems, special attention is given to: highlighting changes made during restructuring; description of growth paths through the follow-on and evolution phases; identification of minimum-impact provisions to allow flexibility in the baseline, and identification of enhancing and enabling technologies.

The activities under Advanced Development and Engineering Prototype Development (EPD) are targeted to improve the functionality and performance of baseline systems, thus providing options to the program which reduce schedule and technical risks. These applications have the potential to improve flight and ground system productivity, reduce power consumption and weight, and prevent technological obsolescence. Products of these tasks include: "Engineering" fidelity demonstrations and evaluations of advanced technology; detailed requirements, performance specifications, and design accommodations for insertion of advanced technology, and mature technology, tools, and applications for SSF flight, ground, and information systems.

Dr. Earle K. Huckins, III
Director, Space Station Engineering
Office of Space Flight
NASA Headquarters

Listed below are the persons who made this symposium possible.

COMMITTEE MEMBERS

Conference Chair:

- Earle K. Huckins III
  NASA Headquarters

Program Planning Committee Technical Chairs:

- Stephen Cook
  NASA Headquarters
- Gregg Swietek
  NASA Headquarters
- Mark Gersh
  NASA Headquarters
- Peter Ahlf
  NASA Headquarters
- Alan Fernquist
  NASA Headquarters

Session Chairs:

- Lewis Peach
  NASA Headquarters
- John-David Bartoe
  NASA Headquarters
- W. Ray Hook
  NASA Langley Research Center
- Karen Brender
  NASA Langley Research Center
- Edward Chevers
  NASA Ames Research Center
- Gregg Swietek
  NASA Headquarters
- Mark Gersh
  NASA Headquarters
- Alan Fernquist
  NASA Headquarters

Administrative Co-Chairs:

- Glenn Freedman
  UH-Clear Lake
- Carla Armstrong
  Barrios Technology, Inc.

CONTENTS – Volume 2

Title	Page

SESSION VII: TELEROBOTIC SYSTEMS
SESSION CHAIR: MR. ALAN FERNQUIST, NASA HEADQUARTERS

Time	Topic	Presenter

Tuesday August 6, 1991

8:30 - 12:00	PLENARY SESSION 1 – OUTLOOK FOR SPACE STATION FREEDOM Session Chair: Dr. Earle K. Huckins III *NASA Headquarters*	
8:30	Welcoming Remarks	Dr. Aaron Cohen *Director, NASA Johnson Space Center*
8:45	Space Station Freedom: An Investment In The Future	Dr. William B. Lenoir *Associate Administrator. NASA Office of Space Flight*
9:45	Space Station Freedom Program Status	Dr. John Cox *Deputy Manager for Operations* *Space Station Freedom* *Program and Operations*
10:15	Break	
10:30	Columbus Programme	Mr. Derek Dell *ESA Representative* *Space Station Freedom Program and Operations*
11:00	Japanese Experiment Module	Mr. Kazuhiko Yoneyama *Director, Space Station Group* *Space Station Program Department NASDA*
11:30	Canadian Space Station Program	Mr. Karl Doetsch *Director General, Space Station Program* *Canadian Space Agency*
12:00 - 1:30	Lunch	
1:30 - 5:30	PLENARY SESSION 2 – FUTURE SPACE PROGRAMS AND PLANS Session Chair: Mr. Lewis L. Peach *NASA Headquarters*	
1:30	Space Station Freedom Evolution	Dr. Earle K. Huckins III *Director, Space Station Engineering* *NASA, Office of Space Flight*
2:00	SEI: An Update	Mr. Lewis Peach Assistant *Director for Space Exploration,* *NASA Office of Aeronautics, Exploration and Technology*
2:30	Advanced Space Transportation Systems	Mr. Robert Davies *Chief, Advanced Transportation Planning* *NASA, Office of Space Flight*
3:15	National Aero-space Plane	Dr. H. Lee Beach, Jr. *Director for National Aero-Space Plane,* *NASA Office of Aeronautics, Exploration and Technology*
3:45	Break	

Time	Topic	Presenter

Tuesday August 6, 1991 *(continued)*

PLENARY SESSION 3 — FUTURE UTILIZATION OF SPACE STATION FREEDOM
Session Chair: Dr. John-David Bartoe
NASA Headquarters

4:00	Commercial Opportunities During Space Station Freedom Evolution	Mr. Richard Ott *Director, Commercial Development Division* *Office of Commercial Programs*
4:30	Technology Development on the Evolution Space Station	Dr. Judith Ambrus *Assistant Director for Large Space Systems* *NASA Office of Aeronautics, Exploration and Technology*
5:00	Expanded Research and Development on Space Station Freedom	Dr. Edmond M. Reeves *Deputy Director, Flight Systems Division* *NASA Office of Space Science and Applications*

Wednesday August 7, 1991

8:00 - 11:45

STRATEGIES FOR EVOLUTION
Session Chair: Mr. W. Ray Hook
NASA Langley Research Center

8:00	A Historical Perspective on Space Station	Mr. W. Ray Hook *Director for Space,* *NASA Langley Research Center*
8:30	MIR: A Case Study for Evolution	Dr. B. J. Bluth *Technical Assistant to the Deputy Director, Space Station Freedom Program and Operations*
9:30	Break	
9:45	Space Station Advanced Studies	Mr. Peter Ahlf *Manager, Advanced Studies,* *NASA Space Station Engineering* *NASA, Office of Space Flight*
10:15	Space Station Advanced Development	Mr. Alan Fernquist *Manager, Advanced Development* *NASA Space Station Engineering* *NASA, Office of Space Flight*
10:45	Commercial Aspects of Space Station Freedom	Mr. Kevin Barquinero *External Programs Manager,* *NASA Space Station Engineering* *NASA, Office of Space Flight*

Time	Topic	Presenter
Thursday	**August 8, 1991** *(continued)*	
9:30	Software Life Cycle Methodologies & Environments	Mr. Ernie Fridge *NASA Johnson Space Center*
10:30	Break	
10:45	Intelligent Computer-Aided Training	Mr. Bowen Loftin *NASA Johnson Space Center*
11:15	Knowledge Based Systems Scheduler Re-Host	Ms. Lynne Cooper *NASA Jet Propulsion Laboratory*
11:45	Lunch	
1:00 - 3:00	PARALLEL SESSION: DISTRIBUTED SYSTEMS Session Chair: Mr. Gregory Swietek *NASA Headquarters*	
1:00	EMU System Evolution	Mr. Michael Rouen *NASA Johnson Space Center*
1:30	ECLSS Evolution Analysis	Mr. Sandy Montgomery *NASA Marshall Space Flight Center*
2:00	Environmental Control and Life Support System Automation	Mr. Brandon Dewberry *NASA Marshall Space Flight Center*
2:30	Environmental Control and Life Support System Predictive Monitoring	Dr. Richard Doyle *NASA Jet Propulsion Laboratory*
1:00 - 3:00	PARALLEL SESSION: TELEROBOTIC SYSTEMS Session Chair: Mr. Alan Fernquist *NASA Headquarters*	
1:00	Telerobotic System Technology	Mr. Wayne Zimmerman, Mr. Paul Backes *NASA Jet Propulsion Laboratory*
1:30	Telerobotics Ground Remote Operation	Mr. Wayne Zimmerman, Mr. Bruce Bon *NASA Jet Propulsion Laboratory*
2:00	Collision Avoidance Sensor Skin	Mr. John Vranish *NASA Goddard Space Flight Center*
2:30	Mars Aerobrake Assembly	Mr. John Garvey *McDonnell Douglas Space Systems Co. Advanced Product Development and Technology Division*

Time	Topic	Presenter

Wednesday August 7, 1991 *(continued)*

4:00	Real-Time Data Systems	Mr. Troy Heindel *NASA Johnson Space Center*
4:30	Computer System Evolution Requirements for Autonomous Checkout of Exploration Vehicles	Mr. Mike Sklar *McDonnell Douglas Space Systems Company* *Kennedy Space Division*

Thursday August 8, 1991

8:00 - 11:45 PARALLEL SESSION: DISTRIBUTED SYSTEMS
Session Chair: Mr. Gregory Swietek
NASA Headquarters

8:00	Advanced Photovoltaic Power Generation	Mr. Edward Fisher *Boeing Defense and Space Group* *Huntsville, Alabama*
8:25	Advanced Solar Dynamic Power Systems	Mr. Michael Zernic *NASA Lewis Research Center*
8:45	Power Management and Distribution Evolution	Mr. Michael Zernic *NASA Lewis Research Center*
9:05	Solar Alpha Rotary Joint Capability Enhancement	Mr. David Snyder *Lockheed Missiles and Space Company*
9:30	Power Management and Control Automation	Mr. James Dolce *NASA Lewis Research Center*
10:00	Power Management and Distribution Automation	Mr. Louis Lollar *NASA Marshall Space Flight Center*
10:30	Break	
10:45	Active Thermal Control System Evolution	Ms. Patricia Petete *NASA Johnson Space Center*
11:15	Thermal Control System Automation	Mr. Roger Boyer *McDonnell Douglas Space Systems Company*
11:45	Lunch	

8:30 - 11:45 PARALLEL SESSION: ENGINEERING TOOLS AND TECHNIQUES
Session Chair: Mr. Mark Gersh
NASA Headquarters

8:30	Failure Environment Analysis Tool	Mr. Dennis Lawler *NASA Johnson Space Center*
9:00	Space Station Freedom Software Reconfiguration	Mr. Larry Grissom and Bryan Porcher *NASA Johnson Space Center*

Time	Topic	Presenter
Wednesday	**August 7, 1991** *(continued)*	
11:15	Evolution Design Requirements and Design Strategy	Mr. Donald Monell *Space Station Freedom Office.* *NASA Langley Research Center*
11:45	Lunch	
1:30 - 4:45	PARALLEL SESSION: EVOLUTION CONCEPTS AND OPERATIONS Session Chair: Ms. Karen Brender *NASA Langley Research Center*	
1:30	Baseline Operations Concept	Mr. Granville Paules *Space Station Operations and Utilization* *NASA, Office of Space Flight*
2:00	Astronaut Scientific Associate	Mr. Silvano Colombano and Michael Compton *NASA Ames Research Center*
2:30	Growth User Requirements for Space Station Evolution	Mr. Kevin Leath *McDonnell Douglas Space Systems Co.,* *Washington SE & I*
3:00	Break	
3:15	SSF Growth Concepts & Configurations	Mr. William Cirillo *Space Station Freedom Office,* *NASA Langley Research Center*
3:45	STV Fueling Options	Mr. Kenneth Flemming *McDonnell Douglas Space Systems Co.,* *Kennedy Space Division*
4:15	A Safety Analysis of Cryogenic Propellant Handling on SSF	Mr. Sam Dominick *Martin Marietta* *Astronautics Group*
1:30 - 4:30	PARALLEL SESSION: SPACE STATION DATA SYSTEMS Session Chair: Mr. Edward Chevers *NASA Ames Research Center*	
1:30	Advanced DMS Architectures	Mr. Ed Chevers *NASA Ames Research Center*
2:15	Optical Protocols for Advanced Spacecraft Networks	Dr. Larry Bergman *NASA Jet Propulsion Laboratory*
2:45	Break	
3:00	Advanced Portable Crew Support Computer	Ms. Debra Muratore *NASA Johnson Space Center*
3:30	ISE Advanced Technology	Mr. Barry R. Fox *NASA Johnson Space Center*

Johnson Space Center-Houston, Texas

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

ENGINEERING PROTOTYPE DEVELOPMENT

Failure Environment Analysis Tool (FEAT)

D. G. Lawler, ER22
Section Head
Advanced Automation Section
August 8, 1991

N92-17349

PRECEDING PAGE BLANK NOT FILMED

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

DEVELOPMENT BACKGROUND

SPACE SYSTEMS FAILURE ANALYSIS:

- Several approaches used by NASA SRM&QA, e.g.:
  - Failure Modes and Effects Analysis/Critical Items List
  - Integrated Hazards Analysis
- Digraph Modeling:
  - Developed in late 60's for nuclear power systems
  - Supports existing analysis methods
  - Supports Fault Tolerance and Redundancy Mngt Analysis

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

NOTES FOR PAGE I OF: DEVELOPMENT BACKGROUND

- Detailed understanding of the nature and extent of failures within an engineered system is absolutely vital for the successful deployment of such systems.
- Current NASA practice employs a number of different analysis techniques to determine the probability of system failures, the nature of these failures, the effect of these failures on other system components and the ultimate consequence of these failures on safety and overall mission effectiveness.
- Typical of these analyses are the Failure Modes and Effects Analysis/Critical Items List and the Integrated Hazards Analysis.
- In response to the need for a detailed understanding of system failures and their effects, a technique called Digraph Matrix Analysis was developed from work done at Lawrence Livermore National Laboratories on nuclear reactor safety analysis.
- This technique utilizes a directed graph modeling technique extended with the use of simple boolean -and- gates to model the propagation of failures throughout a system; both working from initial failure to final consequence as well as the reverse case.
- Such a technique is very useful in determining the effectiveness of the fault tolerance and redundancy management in the system's design.

DEVELOPMENT BACKGROUND (cont'd)

FEAT PROJECT HISTORY:

- Shuttle use of digraphs began in 1988
- FEAT development began in 1989
  - Early general release in 1990
  - FEAT version 3.3. currently available
- SSFP directive for digraph use issued 7/91

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

NOTES FOR PAGE 2 OF: DEVELOPMENT BACKGROUND

- Use of the digraph technique for modeling STS systems began in 1988 under the STS integration contract with Rockwell.
- Modelers soon realized the need for software to ease the burden associated with both modeling and the analysis of the model.
- FEAT development began in 1989, sponsored by C. Vaughan, Chief of the NASA - JSC Propulsion and Power Division.
- FEAT operates on an Apple Macintosh II computer and displays in color the effects of user selected failures. It also displays the possible initial failures for user selected conditions. Selection and display can be on either the digraph or a system schematic.
- FEAT has the capability to handle very large, orbiter size models. It includes the capability to reconfigure the digraph and schematic by preselecting numerous failures as having occurred, and then observing the causes and effects of additional failures.
- Sponsorship of FEAT was shifted to Automation & Robotics in the fall of 1990, with funding from the SSFP.
- The Digraph Editor was released in the spring of 1991 to assist in building models.
- In July 1991, R. Moorehead (director of SSFP/Level II) directed that Digraph modeling methods be utilized for support of Integrated Failure Modes and Effects Analysis, Integrated Hazards Analysis and Fault Tolerance and Redundancy Management Analysis. He also directed that FEAT be used for this support.

DEVELOPMENT BACKGROUND (cont'd)

OBJECTIVE:

- To demonstrate advanced modeling and analysis techniques to better understand and capture the flow of failures within and between elements of SSF and other large complex systems

TECHNICAL CHALLENGE:

- Provide efficient modeling and analysis capabilities
- Capture system failure knowledge for use throughout program lifecycle
  - Integrate into other applications and environments

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

NOTES FOR PAGE 3&4 OF: DEVELOPMENT BACKGROUND

- This project is being pursued to enable SSFP managers to capture the flow of failure effects from within each element out to other elements, including those of the international partners.
- Successful completion of this project will provide a capability to quickly and efficiently predict effects from multiple failures in different station elements. It will also permit determination of the set of potential failures which are the most likely to have caused a given set of observed effects.
- FEAT will provide a means to demonstrate compliance with fault tolerance and redundancy requirements in a highly efficient manner. Also, design decisions can be affected by information available through FEAT and presented during design reviews.
- The model in FEAT will provide Engineering, Safety, Reliability, Supportability, Training, and Mission Operations support personnel with equal capability to determine the answers to "What if . . . ?" questions. When discussing issues, all of these organizations will be utilizing the same data set for these analyses.

DEVELOPMENT BACKGROUND (cont'd)

BENEFITS/APPLICATIONS:

- Support for SRM&QA analyses of large complex systems
  - Increase systems reliability and systems safety
  - Enables the comprehensive analysis of large complex systems
- Capture of system failure knowledge
  - Support for engineering design (e.g. system evolution) training, operations, etc.
  - Cost savings from maintenance of single data source

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

TECHNICAL APPROACH

OVERVIEW:

- Develop base capabilities on Macintosh
  - FEAT & Digraph Editor
- Port identical capability to Unix and X-Windows environments
  - Integrate into TMIS environment
- Support modeling activities
  - STS (e.g. MMU) & SSFP systems
- Support additional digraph applications

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

NOTES FOR PAGE 1 OF: TECHNICAL APPROACH

- Macintosh versions of FEAT are being produced first. The code is then ported to Unix operating system computers supporting the X Window interface environment, including the SSFP TMIS standard Intergraph CIE workstation. All coding is in the K&R C programming language. There is no PC version in development or planned at this time.
- All machines running the same version of FEAT will have the same look and feel to the user.
- At the end of August 1991 FEAT 3.3 and the Digraph Editor 3.0 will be released and forwarded to COSMIC. This will provide the basic functionality required to begin modeling Freedom and to analyze the resultant models.
- Model development is currently being funded separately from the software enhancement effort.

SSFP BASELINE INTEGRATION

GENERAL SUPPORT:

- Level III funding near term analysis support needs
- Level I funding advanced development efforts

SSFP LEVEL II:

- Digraphs and FEAT have been adopted for supporting Integrated FMEA, Integrated Hazards Analysis, etc.
- Support for MTC Phase Review and CDR

SSFP OPERATIONS:

- Support for SSCC Fault Detection and Management function (under consideration, decision by 1/92)
- Support for SSFP & STS training script development (under consideration)

NOTES FOR PAGE 1 OF: SSFP BASELINE INTEGRATION

- FEAT project funds are provided are by SSFP Levels I and II. - Level II, through level III Engineering at JSC, is funding the features needed in the near future to support Program decision points.
  - Level I is funding capability development to support needs required later in the Program.
- New versions of FEAT will support FMEA development and be integrated with the SSF TMIS.
- Initial Freedom modeling will focus on areas with the greatest payback in design evaluation at the MTC CDR.
- Digraphs and schematics in FEAT will support needs of at a minimum the following organizations:
  - Program Engineering (including design engineering integration, safety, reliability, and supportability)
  - Mission Operations (including training and mission support)

Engineering Prototype Development: Failure Environment Analysis Tool (FEAT)	Automation and Robotics Division	
	D.G. Lawler/ER22	8/8/91

GROWTH AND EVOLUTION

FEAT ENHANCEMENTS:

- Integration of FEAT with other SRM&QA tools
- Digraph Editor enhancements
- Large model processing

ADVANCED DEVELOPMENT:

- Smart Digraph Editor will provide automated support to model development
- Advanced modeling support
  - e.g. - Temporal modeling and analysis

NOTES FOR PAGE 1 OF: GROWTH AND EVOLUTION

- Enhancements to FEAT are being pursued by SSFP Levels I and II. - Level II, through level III Engineering at JSC, is funding the features needed in the near future to support Program decision points.
  - Level I is funding capability development to support needs required later in the Program.
  - This includes support of the Space Station Control Center Fault Detection and Management capability, as well as a Smart Digraph Editor to reduce the manpower intensity of digraph modeling.
  - Large model analysis is very expensive computationally. Parallel processing capability is being developed to significantly reduce the turn-around time required for transitive closure calculations.

SUMMARY

- FEAT is available now and in use by SSFP
- Robust, ongoing, development program
- Many significant potential applications
  - Significant cost avoidance/savings anticipated through use of common models

NOTES FOR PAGE 1 OF: SUMMARY

- FEAT is available now to support various types of engineering applications and is undergoing continuous improvement. It will be used to assist in the analysis of failure effects across Freedom, but the broad application of advanced modeling techniques is only now becoming understood within the NASA community. Significant cost savings is anticipated through the use of common models over a broad range of applications.

N92-17350

RECONFIGURATION MANAGEMENT DIVISION

SPACE STATION RECONFIGURATION OFFICE

Advanced Flight Software Reconfiguration

DP4/Bryan Porcher

8 August1991

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

WHAT IS RECONFIGURATION?

- Identifying Mission and Configuration Specific Requirements
- Controlling Mission and Configuration Specific Data
- Binding this Information to the Flight Software Code to Perform Specific Missions
- Release and Distribution of the Flight Software

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

WHAT IS THE PROBLEM?

- Space Station Freedom (SSF) Flight Software is Capable of Supporting Many Different Missions with Different Hardware Configurations and Payloads

- Mission Requirements, Payloads and Hardware Configurations will Change with Time

- Flight Software should be Designed to Incorporate Modifications while Minimizing Recoding

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

TO ACCOMPLISH THIS GOAL

- Specific Data about Missions, Payloads and Hardware Configuration will be Isolated from the Flight Software Code

- Details of the Missions and the Mission-Specific Configurations will be Contained in a Runtime Object Database (RODB), Telemetry Object Lists (TOLs) and Display Definition Files (DDFs)

- SSF Flight Software is being Developed using the Software Support Environment (SSE) to Provide Flexible and Cost-Effective Software Development in Addition to Configuration Control

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

OBJECTIVES

- Develop, Demonstrate and Validate Advanced Software Reconfiguration Tools and Techniques

- Demonstrate Reconfiguration Approaches on SSF Onboard Systems Displays

- Interactively Test Onboard System Displays, Flight Software and Flight Data

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

OBJECTIVES (continued)

- Develop New Tools and Procedures for Developing and Testing Displays, Flight Software and Flight Data
- Validate SSE Tools for their Usefulness as Reconfiguration Tools
- Validate Existing Space Shuttle Reconfiguration Procedures for use with SSF

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

BENEFITS

- Avoids the "Pitfall" of the "If we can Build it Once, it will be Easier the Second Time" Mentality Which has Proven to be VERY Expensive

- Effectively Trains a Space Station Reconfiguration Team

- Increase in Software Quality and System Safety Due to the Development of More Effective Procedures

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

BENEFITS (continued)

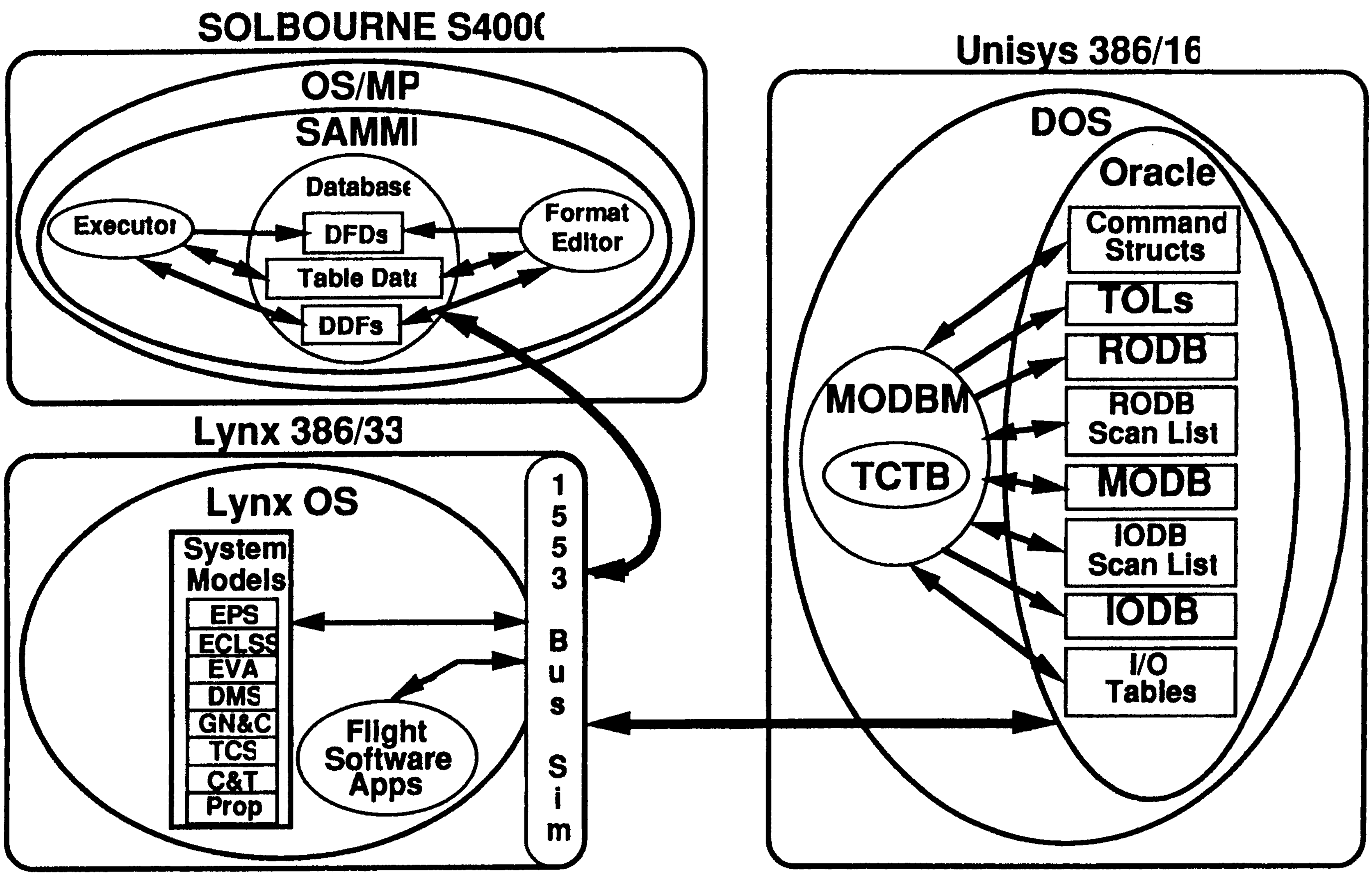
- Possible Increase in Effectiveness of Space Shuttle Reconfiguration Due to the Adaptation of New SSF Reconfiguration Procedures
- Benefits All Users of Reconfigurable Products By Providing More Intensive Testing Before Product Release
- Potential Cost Avoidance of Existing Reconfiguration Infrastructure

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

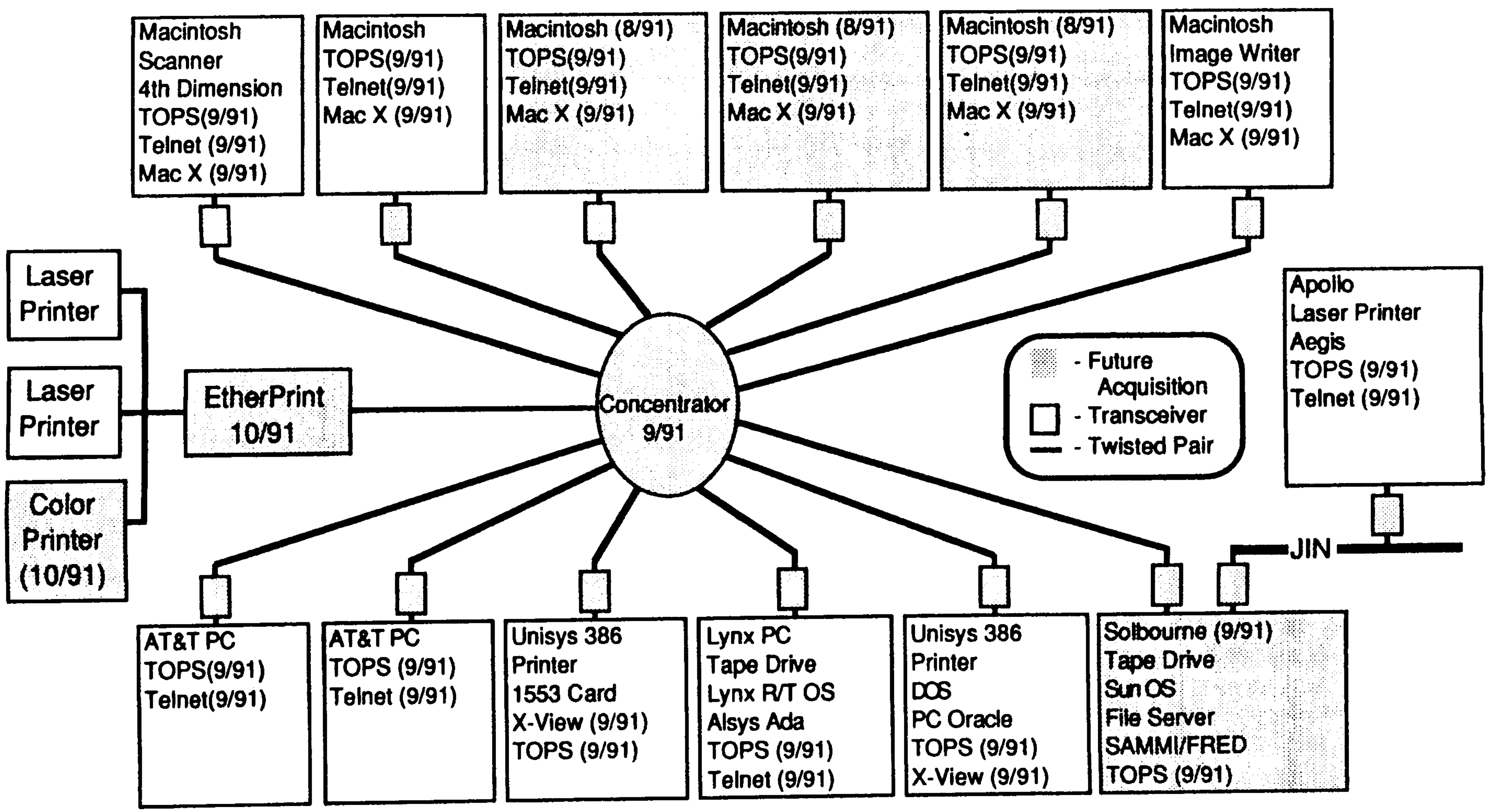
TECHNICAL APPROACH

- Build a Small Test Environment
- Lynx 386/33 Mhz System Hosts the Simulated Onboard Data Management System (DMS)
- Solbourne S4000 System Hosts the Ground System Simulation
- Unisys 386SX/16 MHz System Simulates the Master Object Database (MODB), RODBs, Input/Output Databases (IODBs), TOLs

ADVANCED FLIGHT SOFTWARE RECONFIGURATION



ADVANCED FLIGHT SOFTWARE RECONFIGURATION



ADVANCED FLIGHT SOFTWARE RECONFIGURATION

BASELINE INTEGRATION

- Data Management System (DMS) Upgrades are Available as Government Furnished Equipment (GFE) from Work Package 2 (WP-2)

- Software Developed by the Avionics Integration Environment (AIE) Project may be Reused

- Tools and Procedures Adapted for Space Shuttle Reconfiguration will be Integrated into the SPF on an Item-by-Item Basis

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

BASELINE INTEGRATION (continued)

- The Advanced Flight Software Reconfiguration Network is Planned to be Connected to the SPF by July 1993

- Tools and Procedures Developed Under this Project will be Integrated into the Reconfiguration Software Production Facility (SPF) for SSF Support in January 1994

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

GROWTH AND EVOLUTION

- Automated Mission Requirements, Flight Software and Display Product Generation

- Automated Product Verification and Validation

ADVANCED FLIGHT SOFTWARE RECONFIGURATION

SUMMARY

- Allows Reconfiguration to be Designed into the SSF System

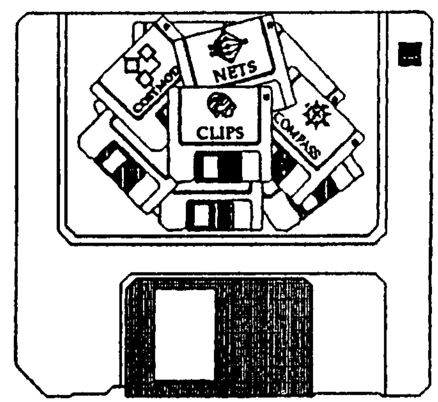
- Provides Valuable Hands-on Experience to the Space Station Reconfiguration Team

- Increases the Quality and Safety of the Space Station Freedom Program (SSFP) Due to the Development of More Effective Tools and Procedures

N92-17351

NASA Johnson Space Center
Information Systems Directorate
Information Technology Division

SOFTWARE LIFE CYCLE METHODOLOGIES AND ENVIRONMENTS



Ernest Fridge, Deputy Chief
Software Technology Branch
Mail Code: PT4
Johnson Space Center
Houston, Texas, 77058

August 8, 1991

SOFTWARE LIFE CYCLE METHODOLOGIES AND ENVIRONMENTS

The software (S/W) development process will be one of the most critical elements of all phases of the Space Station Freedom Program (SSFP), from early design through long-term operations. Improvements in the S/W development process will have significant benefits: reducing both short-term and long-term costs, improving reliability and safety, and improving the functionality and usability of all elements of the Space Station Freedom. This process, though complex, can be improved through the application of a variety of advanced S/W technologies. These new technologies, in the form of methodologies, tool, and environments will benefit both specific Space Station Freedom applications, as well as general Space Station Freedom development practices.

The approach to this activity is to:

- Identify bottlenecks and inefficiencies in existing NASA S/W development practices.
- Evaluate a wide variety of advanced technology approaches for improving the current practices.
- Provide requirements for inserting these new technologies into the SSFP.
- Develop, test, and deploy specific tools, methodologies and environments for use in appropriate places in Space Station Freedom Program.
- Provide assistance in the technology insertion process

The products of this activity will significantly improve the quality and productivity of Space Station software processes by reducing development and maintenance costs, improving software reliability and safety, and broadening the range of problems that can be solved with computational solutions.

OUTLINE/SPEAKERS

Background/Objectives/Benefits - Ernest Fridge

Environments

- CASE - Ernest Fridge
- CLIPS/CLIPS Ada - Gary Riley

Methodologies

- Cooperating Expert Systems - Jorge Rufat-Latre
- Fuzzy Logic - Dr. Robert Lea

Summary - Ernest Fridge

BACKGROUND

The dramatic growth in software in recent years is producing what many writers call the software crisis. More software is required to be produced than the predicted workforce can build. NASA's software projections indicate that they will feel the effect of the crisis unless higher productivity and higher quality can be achieved. NASA's software requirements are increasing drastically with each new program. NASA's systems are extremely large and are both mission and safety critical. In addition, these large systems will last for many years and will be around after the original developers have left the task and after the original technology has become obsolete.

BACKGROUND

- The amount of software to be developed and maintained by NASA is dramatically increasing with each new program
- Very large scale (millions of lines of code) mission critical software systems are to be developed and maintained for many years
- The software development and maintenance process will be one of the most critical elements of all phases of the Space Station Freedom Program (SSFP), from early design through long term operations
- The Shuttle program already faces a staggering software maintenance problem which will be inherited by the SSFP

BACKGROUND (CONT')

The Software Technology Branch (STB) is chartered to develop technologies to combat this crisis. R&D has been underway for several years and techniques to support both conventional and Knowledge Based System (KBS) software have been developed . Coordination with DOD, academia, and commercial tool vendors is being pursued vigorously. The projects discussed in this paper are the ones supported by the SSFP as engineering prototype development, but they leverage the other work done in the STB.

BACKGROUND (CONT')

- The project discussed in this presentation builds upon a base of several years of research into using Knowledge Based Systems approaches to supporting the development and maintenance of both conventional software and knowledge based systems
- The project leverages USAF methodology and environment development research
- The project is part of a larger CASE activity tracking DOD, COTS, NIST standards, and CASE trends plus the development of specific CASE tools

BRANCH SOFTWARE TECHNOLOGY PROJECTS

The STB has many advanced software development projects. The projects that are part of the SSFP's engineering prototype development are indicated by an "*". The STB coordinates the effort between these tasks and leverages capabilities as much as possible.This results in individual projects receiving more benefit that would be available from the funding available for each individual task.

BRANCH SOFTWARE TECHNOLOGY PROJECTS

ADVANCED SOFTWARE TOOLS AND ENVIRONMENTS

• Mission and Safety Critical Systems Software Support
• Software Design Recovery and Reuse
• Software Cost Models
* Engineering Script Languages
* Advanced Software Development Workstation
* CASE Tool Consultation/Evaluation/Selection Process
• Knowledge-Based Systems tools
* Knowledge Acquisition Tools
* Planning and Scheduling
* Intelligent Computer-Aided training
• Computational Neural Systems
• Genetic Algorithms
• X-Window tools

("*"- SSFP engineering prototype development)

BRANCH SOFTWARE TECHNOLOGY PROJECTS

BRANCH SOFTWARE TECHNOLOGY PROJECTS (CONT')

ADVANCED METHODOLOGIES

* Fuzzy Logic
* Distributed Cooperating Expert Systems

- Verification and Validation
- Machine Vision
- Multi Media
- Formal Methods

("*"- SSFP engineering prototype development)

OBJECTIVES

High level objectives are to improve the quality and productivity of the large NASA software development and maintenance projects. Any tool, process, or methodology that improves the software life cycle is a candidate for consideration by the STB. The objectives of this project consider some of the most promising knowledge based systems approaches to support CASE, methodologies, and processes for software reuse, software development, and software maintenance.

OBJECTIVES

- Improve quality and productivity of large software development and maintenance projects through a variety of software technologies such as:
  - Computer Aided Software Engineering (CASE)
  - Methodologies and Processes for Conventional and Knowledge Based Systems development
  - Software Reuse
  - Engineering level software application development

BENEFITS

Processes , including software reuse processes, and tools that support and automate those processes seem to be two of the key factors in avoiding unnecessary software costs and in producing higher quality, more reliable, and safer software. The processes, methodologies, and tools being researched and developed within this project effect software across its lifetime. Both conventional and knowledge based systems are addressed. The software lifetime includes the maintenance phase. It also includes the operations phase since the software development process must also include those products such as user guide information required to efficiently operate the software. The size of the NASA systems is also be considered since many processes and tools cannot scale up to support software systems of this large size.

BENEFITS

- Cost avoidance through better processes and the use of better tools
- Improve reliability and safety
- Improve functionality and usability of software elements of SSFP
- Improve software development and maintenance practices
- Provide maintenance and reengineering support to the millions of lines of existing code. Current support is very labor intensive
- Improve the efficiency in operating the complex ground software applications of SSFP

TECHNICAL APPROACH

The STB's charter has goals that include researching and developing methodologies and tools to support improving software engineering of both conventional and knowledge based systems development, operations, and maintenance. The branch's Computer Aided Software Engineering (CASE) outlook insures that the whole software lifecycle gets considered. When the technology is sufficiently mature as shown through proof of concept or other means, it is applied in pilot projects to SSFP elements. The usual activities are the following:

- Identify bottlenecks and inefficiencies in existing NASA software development practices and environments. This requires the STB to keep aware of existing problems and needs within the NASA projects
- Evaluate a wide variety of advanced technology approaches for improving the current practices
- Provide requirements for inserting these new technologies into the SSFP. This is usually done in conjunction with personnel from the application areas
- Develop, test, and deploy specific tools, methodologies and environments for use in appropriate places in SSFP

TECHNICAL APPROACH

Branch charter's goals include researching and developing methodology and tools to support improving software engineering of both conventional and Knowledge Based Systems development, operations, and maintenance.

Technology insertion is provided by applying this technology in SSFP projects

Specific activities include:

- Identify bottlenecks and inefficiencies in existing NASA software development practices and environments
- Evaluate a wide variety of advanced technology approaches for improving the current practices
- Provide requirements for inserting these new technologies into the SSFP
- Develop, test, and deploy specific tools, methodologies and environments for use in appropriate places in SSFP

ENVIRONMENTS

ADVANCED SOFTWARE DEVELOPMENT WORKSTATION (ASDW)

The STB's analysis of CASE product status and direction indicates that a number of good tools are available, but there are some important capabilities and tools that still require further research and development. The Advanced Software Development Workstation (ASDW) project is researching and developing specific types of advanced technology and tools that an advanced workstation for software development should provide. One of these tools is a Parts Composition System (PCS) for developing applications from reusable software parts, using knowledge-based technology. This PCS will have an Engineering Script Language (ESL) as a graphical user interface. This will allow engineers who are not also programmers to generate engineering applications. Another tool being developed is the Intelligent User Interface development Tool (INTUIT). A third tool, a Configurable Control Panel (CCP) for an integrated CASE environment, is being developed under the Framework Programmable Platform (FPP) subtask of the ASDW project. The CCP will be a horizontal tool for managing and enforcing a (locally configurable) model of the software development process.

ADVANCED SOFTWARE DEVELOPMENT WORKSTATION (ASDW)

The ASDW project has been studying ways to apply knowledge based technology to support software engineering. Currently the system has three major components

- The Parts Composition System/Engineering Script Language: Permits an engineer to define an application via a graphical logic diagram. The system contains a library of software parts and the knowledge to support the engineer in populating the graphical diagram with the parts.
- The Framework Programmable Platform: Provides software development process description and work flow control. It follows the Zachman framework concepts and uses the IDEF3 language developed in a joint effort with the USAF.
- The Intelligent User Interface: Provides the support in operating the developed applications. It contains the knowledge of the users guide and advises the user as well as doing constraint testing. Some JSC applications require thousands of inputs and require expert users several weeks to set up and debug.

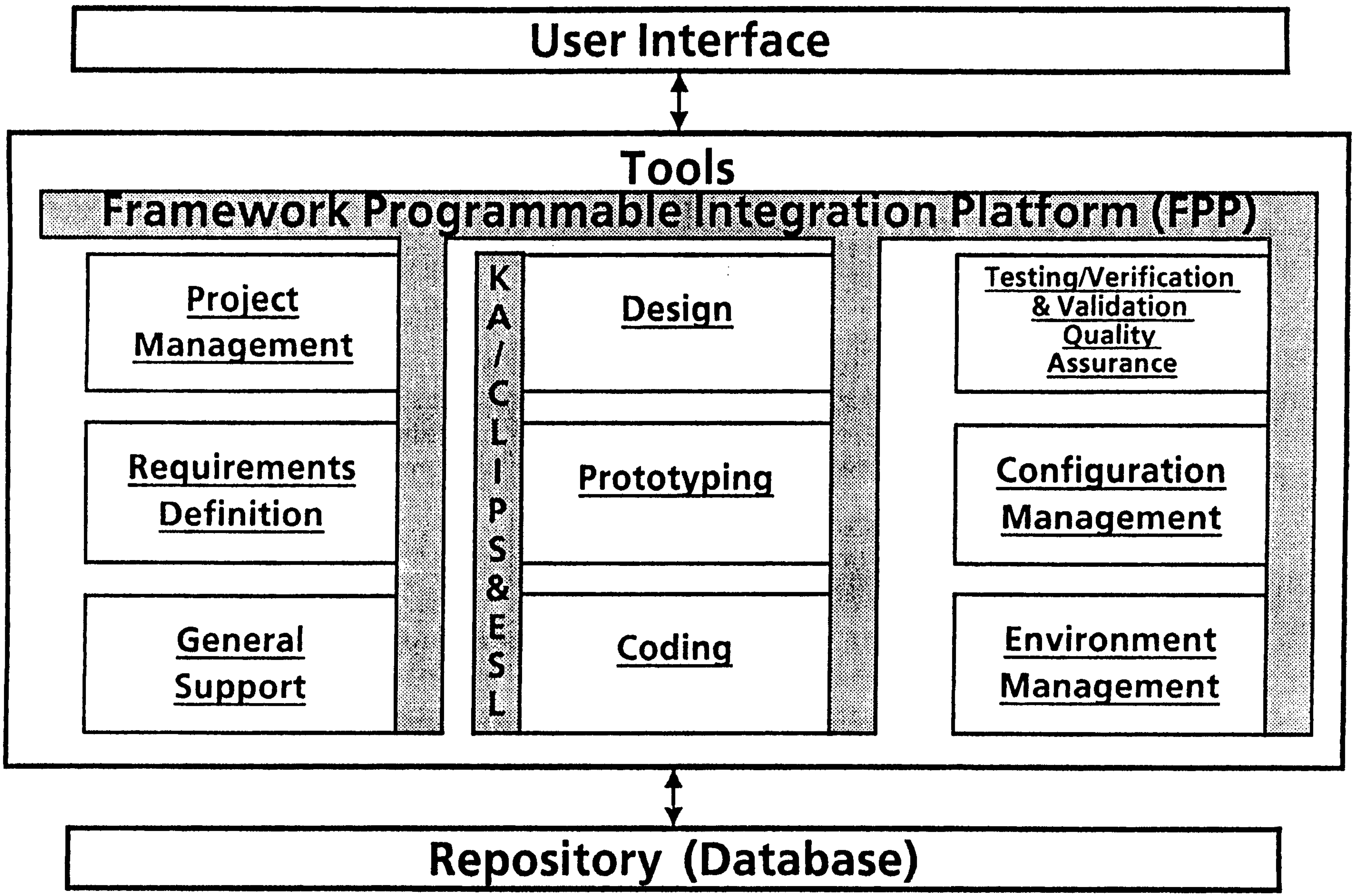
INTELLIGENT INTEGRATED CASE

This chart illustrates the role of the software life cycle methodologies and environments task. It illustrates the long term goal of fully integrating all phases of the software lifecycle via the Framework Programmable Platform (FPP) being performed in the Advanced Software Development Workstation subtask. This slide also contains other tools supported by the Software Technology Branch.

The FPP subtask of the ASDW project is researching some of the issues involved in building an integrated CASE environment. The current focus of the FPP is the management and control of the software development and maintenance processes -- crucial factors in the success or failure of any large software system. Specifically, the FPP subtask is developing a horizontal tool, called a Configurable Control Panel (CCP), for specifying, managing, and enforcing a model of the software development process.

The chart also illustrates the near term goal of integrating design, prototyping, and coding via the Intelligent Computer Aided Training (ICAT) work that is merging knowledge acquisition tools with CLIPS to automatically generate expert systems and the use of an Engineering Script Language (ESL) to perform the same function for conventional code.

INTELLIGENT INTEGRATED CASE (CONCEPTUAL OVERVIEW)

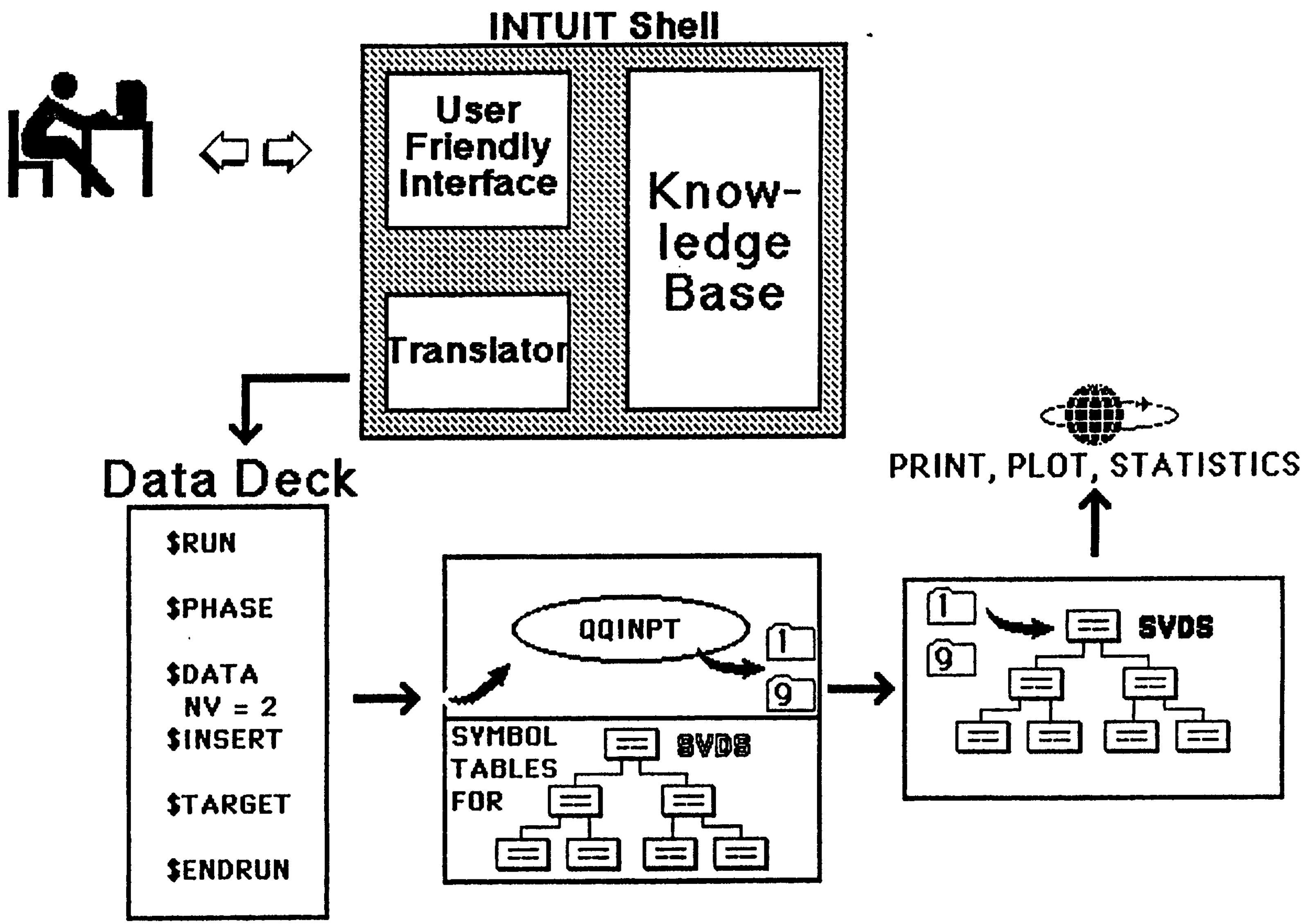


INTELLIGENT USER INTERFACE

A good user interface is critical to the successful use of a complex scientific application such as a space flight simulation, which typically involves very large sets of input data. Even an expert user may expend substantial effort to introduce the right data in the right manner. An Intelligent User Interface (IUI) uses knowledge-based technology to provide the user with the capability to easily prepare the input data without requiring prior extensive knowledge of the underlying software. An IUI is also commonly called a Knowledge-Based Front-End (KBFE). INTUIT (INTelligent User Interface development Tool) is a generic IUI shell that a knowledge engineer configures for a specific application by adding a knowledge base that includes input variable names which are immediately understandable by the users, the range of permissible data values, the structure and format of the data sets, and rules for error and consistency checking. The current knowledge representation scheme used within an INTUIT knowledge base is fully described in. Many of the same subsystems required by a PCS are also required by INTUIT, which may therefore be considered to be a "PCS for input data sets." In fact, INTUIT is a PCS subshell.

The INTUIT shell was used to develop a KBFE for Space Vehicle Dynamics Simulation (SVDS), a computer program currently used at JSC for designing the trajectory and flight plans for Space Shuttle missions. The SVDS application called Ground Simulation (GNDSIM) was selected for KBFE development, and an INTUIT knowledge base was built for it. Flight planners use GNDSIM to verify and refine the sequence of maneuvers required to accomplish a rendezvous. KBFE for GNDSIM can be summarized as follows. All the users who participated in the tests were very satisfied with the KBFE. Building an input data stream with the KBFE proved to require from one-half to one-fifth the time needed using the current interface. As a result of these tests, specific enhancements to INTUIT are planned. The development of KBFEs for other tools used by the flight designers is also being considered.

INTELLIGENT USER INTERFACE FOR SVDS



ASDW POTENTIAL

Most of the activity in the ASDW project is done in a rapid prototyping mode with the future users involved. Field studies with the Shuttle's Flight Analysis and Design System (FADS) in particular has been pursued. The SSFP plans to inherit this software. Personnel from other SSFP ground systems are currently reviewing the three primary ASDW elements.

The ESL/PCS is being field tested to check its applicability to the FADS project on software that could migrate to the SSFP. It has good growth potential since engineering application development from graphical specifications was identified in a JSC survey as a key requirement for future ground and flight applications.

The IUI has been evaluated by FADS personnel. The concepts were proved in the FADS project to increase user productivity and were adopted. Growth potential exists since more extensive knowledge based support for constraint testing is being pursued. Even expert users cannot keep in mind the large numbers of constraints that can be violated in runstreams whose inputs number several thousand.

The FPP is still under prototype development but it is getting a lot of attention by possible users. It appears to have good growth potential since NASA is heavily process oriented for producing products of various types. All types of processes conducted by people can be described.

ASDW POTENTIAL

ESL/PCS

- Performing field testing to check its applicability to the FADS project on software that could migrate to the SSFP

  GROWTH: Engineering application development from graphical specifications was identified in a JSC survey as a key requirement for future ground and flight applications

IUI

- Concepts were proved in the FADS project to increase user productivity and were adopted.

  GROWTH: More extensive knowledge based support for constraint testing is being pursued

FPP

GROWTH: NASA is heavily process oriented for producing products of various types. All types of processes conducted by people can be described.

SLCSE INVESTIGATIVE TASK

The Software Life Cycle Support Environment (SLCSE) was developed for the United States Air Force Rome Laboratory as an advanced development prototype. Its contract was awarded in 1986. It was created to incorporate existing and advanced software engineering technology and was intended to generate documents as a by-product of the software activity. Its framework supports the life cycle phases (requirements, design, etc.), activities (requirements analysis, document production, etc.), roles (project manager, software designer, etc.); and products (software requirements specification , code, etc.)

SLCSE provides an evolutionary foundation for incorporating advances in software engineering technology and tools to support extensibility, tailorability, and scalability. This concept is based upon the unifying life cycle database; formal compilable framework data model that may be tailored; and the CASE tool integration platform to support toolset evolution.

A distinguishing feature of the SLCSE is its underlying entity-attribute/relationship-attribute (EA/RA) model which provides a flexible model capable of supporting a wide range of life cycle phases, activities roles, and products; It facilitates the automated production of documentation allowing capture of necessary information during the course of the project and provides traceability and consistency by storing only one copy of each piece of information and maintaining relationships among entities in order to create life cycle products.

SLCSE INVESTIGATIVE TASK

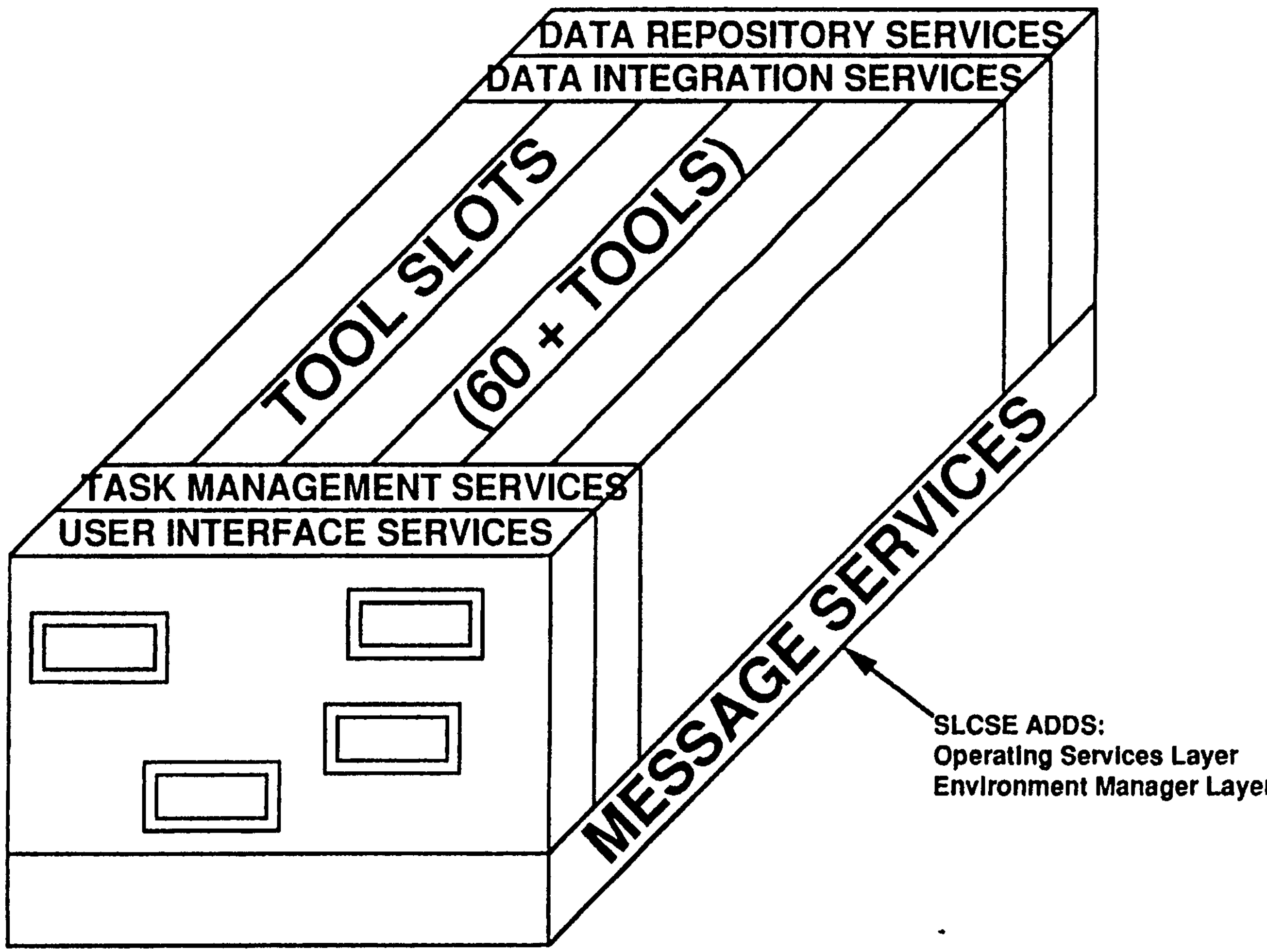
- Evaluated the framework to see if the concepts could be used to add requirements to current JSC environments
- SLCSE Framework supports:
  - Life cycle phases
  - Activities
  - Roles
  - Products
- Findings and recommendations were provided to the USAF's Rome Laboratory for incorporation into SLCSE enhancements
- Still investigating the information model for its potential on some JSC application developments
- Developed a framework evaluation capability used to evaluate CASE environments. SLCSE contributed significantly to the semantics requirements

SLCSE/NIST REFERENCE MODEL MAPPING

One of the biggest thrusts in software engineering technology today is the push to develop an open, fully-integrated CASE environment -- i.e., a CASE environment wherein different vendors' hardware and software components can work together effectively. Many of the world's largest computer companies (such as IBM and DEC) and software vendors, the U.S. Department of Defense (DOD), and others are investing great sums in research and development to produce a framework to support an open, fully-integrated CASE environment. A reference model for CASE environment frameworks has been developed by the European Computer Manufacturers' Association (ECMA), and it has been submitted as a proposed standard to the National Institute of Standards and Technology (NIST). This model will be referred to as the NIST Reference Model but it is often informally called the "toaster model" because of its general appearance.

This model is being used by STB so that a consistent metric can be applied to all CASE framework evaluations and recommendations. The SLCSE framework has been mapped to the NIST model and it matches fairly closely. Two additional layers were identified as shown on the chart. The mapping was done by the SLCSE developers.

SLCSE/NIST RM MAPPING



SLCSE POTENTIAL

The current version of SLCSE is a prototype. The concepts are excellent and can be used to evaluate framework products and CASE environment. It maps very well with the NIST reference model for CASE environments. The information model is useful as it stands. STB plans to investigate the use of the current prototype more and to follow the development of the commercial product.

SLCSE POTENTIAL

- The information model of the DOD's 2167 software development process is perhaps the best available
- SLCSE is consistent with the NIST reference model for CASE framework
- The current planned enhancements are intended to turn the current prototype model into a robust framework for supporting mission critical software development

CASE TECHNOLOGY SELECTION AND INSERTION PROCESS

Technology transfer of emerging CASE technology to NASA is the primary objective of all of the STB's CASE projects. Technology transfer can occur in many different ways, including the direct use of tools developed by the STB, the adoption of new methods and technology identified by the STB (such as repository technology when it matures), and the purchase of appropriate commercial off-the-shelf (COTS) tools.

The STB set a goal of collecting information about existing CASE products and characterizing those products in order to provide a CASE tool consulting service for the JSC community. The motivation for establishing such a service was the complex nature of CASE and the confusing status of the CASE tool market. The sheer number of available CASE tools and the rapid rate of change of the CASE market, coupled with unrealistic consumer expectations of what CASE tools can do, have led to some exaggerated claims about CASE and, consequently, to some disappointed consumers.

Rather quickly, the scope of this CASE consulting service was expanded to a software engineering consulting service. CASE tools can only assist in the software engineering process. A software development organization must have a well-managed, repeatable, and explicit software development process. If a disciplined software engineering process does not exist within an organization, then that organization must adopt one, and this will likely imply a change in its way of doing business.

Technology insertion, in particular, seems to be successful only when key people within the organization (called change agents) actively participate. Change agents tend to be knowledgeable persons in middle management, recognized for their abilities and credibility by both upper and lower management.

CASE TECHNOLOGY SELECTION AND INSERTION PROCESS

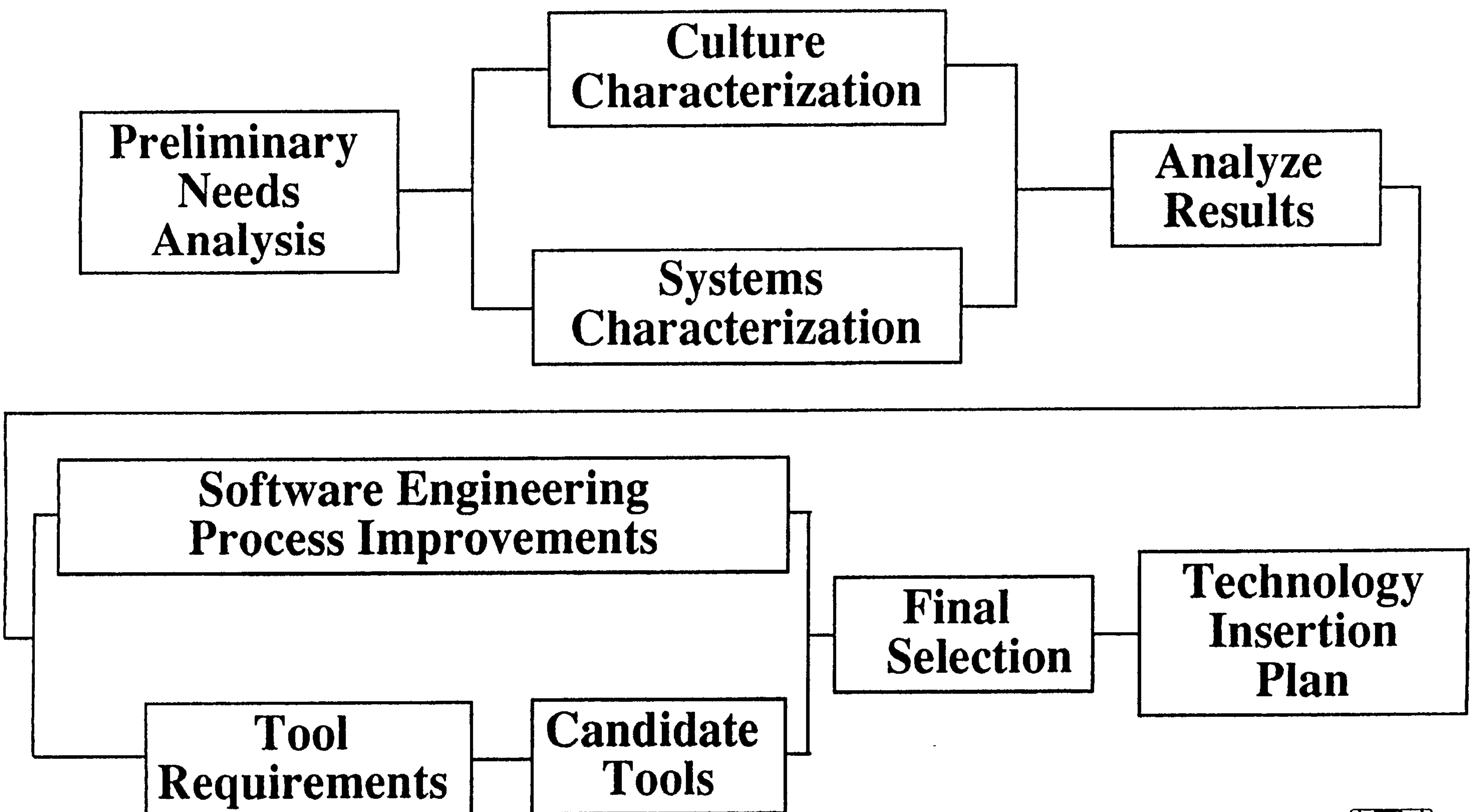
- CASE environments are complex in nature
  - No single vendor will assume total investment risk
- Hundreds of CASE vendors are marketing tools and the tool market is rapidly changing
- Tools and environments will change the development and maintenance culture and drastic changes will result in the tools not being used
- A process is required before tools are selected
- The tool environment should support the culture and the process
- A CASE technology insertion process has been developed to help organizations utilize CASE

CASE TECHNOLOGY SELECTION AND INSERTION PROCESS

In order to make sound CASE recommendations and to improve the chances of achieving CASE technology insertion, there are five basic activities that occur during the process: characterize the organization's culture; characterize the software systems produced; identify improvements to the organization's software engineering process; identify candidate tools and environments; and develop a technology insertion plan. The process is somewhat iterative as most software processes are. Some activities can proceed in parallel as shown on the chart.

NASA Johnson Space Center
Information Systems Directorate
Information Technology Division

Technology Selection and Insertion Process



Software Technology Branch

CASE PROCESS POTENTIAL

This task has produced considerable interest at JSC. It is being used for the first time to help the Information Systems Directorate select CASE tools and environments for JSC's institutional information systems. This work will certify the process. Another task has just been initiated to help the Mission Operations Directorate select CASE tools for both the SSFP ground support systems and the Shuttle maintenance system. The system will also be used with the Strategic Avionics Technology Working Group (SATWG)'s effort to determine the CASE requirements to support future generic avionics software development.

CASE PROCESS POTENTIAL

CURRENT

- Process is being certified by applying it to JSC institutional information systems
- Process is being initiated to apply it to the ground operations and flight planning systems for SSFP as a pilot project

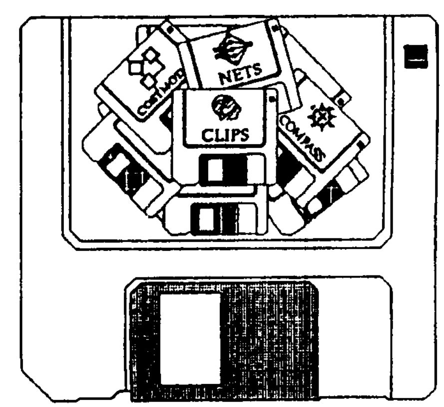
GROWTH

- The process will be used by the SATWG software subcommittee to determine the CASE requirements for supporting future SSFP maintenance and the exploration program

CLIPS and CLIPS/Ada

Task Managers: Chris Culbert and Gary Riley
NASA/Johnson Space Center
Software Technology Branch

Presented by: Gary Riley



CLIPS and CLIPS/Ada

Expert systems are computer programs which emulate human expertise in well defined problem domains. The potential payoff from expert systems is high: valuable expertise can be captured and preserved, repetitive and/or mundane tasks requiring human expertise can be automated, and uniformity can be applied in decision making processes.

The C Language Integrated Production System (CLIPS) is an expert system building tool, developed by the Software Technology Branch at the Johnson Space Center, which provides a complete environment for the development and delivery of expert systems. CLIPS was specifically designed to provide a low cost option for developing and deploying expert system applications across a wide range of hardware platforms. The use of CLIPS has many benefits: CLIPS runs on conventional hardware systems and is completely portable to a wide range of computers; CLIPS can be integrated with and embedded within conventional software systems; CLIPS source code is free to all government agencies.; CLIPS can be easily extended and modified; CLIPS can be used with environment specific interfaces for PC compatible, Macintosh, and X Window environments; CLIPS comes with extensive documentation; and CLIPS users can receive support from either a help desk or an electronic bulletin board.

An version of CLIPS developed entirely in Ada, CLIPS/Ada, is also available for use.

CLIPS and CLIPS/Ada

- Expert systems are computer programs which emulate human expertise in well defined problem areas.
- The C Language Integrated Production System (CLIPS) is a programming language environment used for the creation of expert system applications.
- CLIPS was specifically designed to provide a low cost option for developing and delivering expert system applications across a wide range of hardware platforms.
- CLIPS/Ada is a version of CLIPS developed entirely in Ada.

Approach

The current release of CLIPS, version 5.0, provides support for rule-based, object-oriented, and procedural programming. Rule-based programming allows knowledge to be represented as heuristics which specify a set of actions to be performed for a given situation. Object-oriented programming allows complex systems to be modeled as modular components (which can be easily reused to model other systems or to create new components). Procedural programming allows a set of instructions to be grouped together in a procedure which examines or manipulates data.

The current release of CLIPS/Ada, version 4.3, provides support for rule-based programming and is fully syntax compatible with version 4.3 of CLIPS. The next planned release of CLIPS/Ada, version 4.4, is scheduled for September 1991 and will support rule-based and procedural programming.

Approach

- The current release of CLIPS, version 5.0, provides support for rule-based, object-oriented, and procedural programming.
- The current release of CLIPS/Ada, version 4.3, provides support for rule-based programming and is fully syntax compatible with version 4.3 of CLIPS.
- The next planned release of CLIPS/Ada, version 4.4, is scheduled for September 1991 and will support rule-based and procedural programming.

SSFP Integration

Baseline Program

Space Station Freedom applications will require deep integration of expert system technology with applications developed in conventional languages, specifically Ada. Since SSF has a requirement that all SSF software be developed in Ada, Ada based expert system tools may be required to allow the use of expert systems in SSF applications.The ability to apply automation to SSF functions could be greatly enhanced by widespread availability of state-of-the-art expert system tools based on Ada. At a minimum, Ada based tools will ease integration issues for expert systems used in SSF applications. Although there have been some efforts to examine the use of Ada for expert system applications, there are few existing products which provide state-of-the-art capabilities in an Ada tool. The development of CLIPS/Ada version 4.3 has been completed and this version is ready to meet SSFP Ada requirements. Both CLIPS and CLIPS/Ada are being distributed by the SSE.

Growth & Evolution

The continued growth and evolution of the Space Station will require extensive automation to reduce operational costs and manpower requirements as well as enhance safety and reliability. The use of expert systems will provide an effective means for developing the high levels of automation required. Several SSFP contractors are already using CLIPS to evaluate advanced automation concepts for SSFP evolution.

SSFP Integration

Baseline Program

- CLIPS/Ada is developed and ready to meet SSFP Ada requirements.
- CLIPS and CLIPS/Ada are being distributed by the SSE.

Growth & Evolution

- The continued growth and evolution of the Space Station will require extensive automation to reduce operational costs and manpower requirements as well as enhance safety and reliability.
- Several SSFP contractors are already using CLIPS to evaluate advanced automation concepts for SSFP evolution.

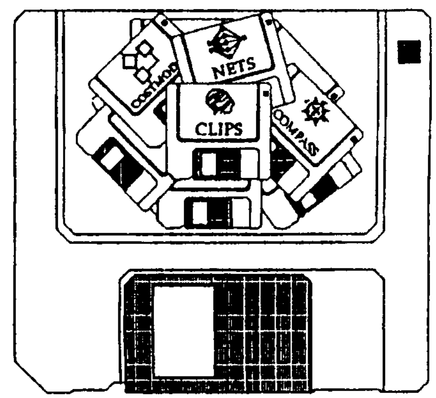
METHODOLOGY

Distributed Intelligent Systems

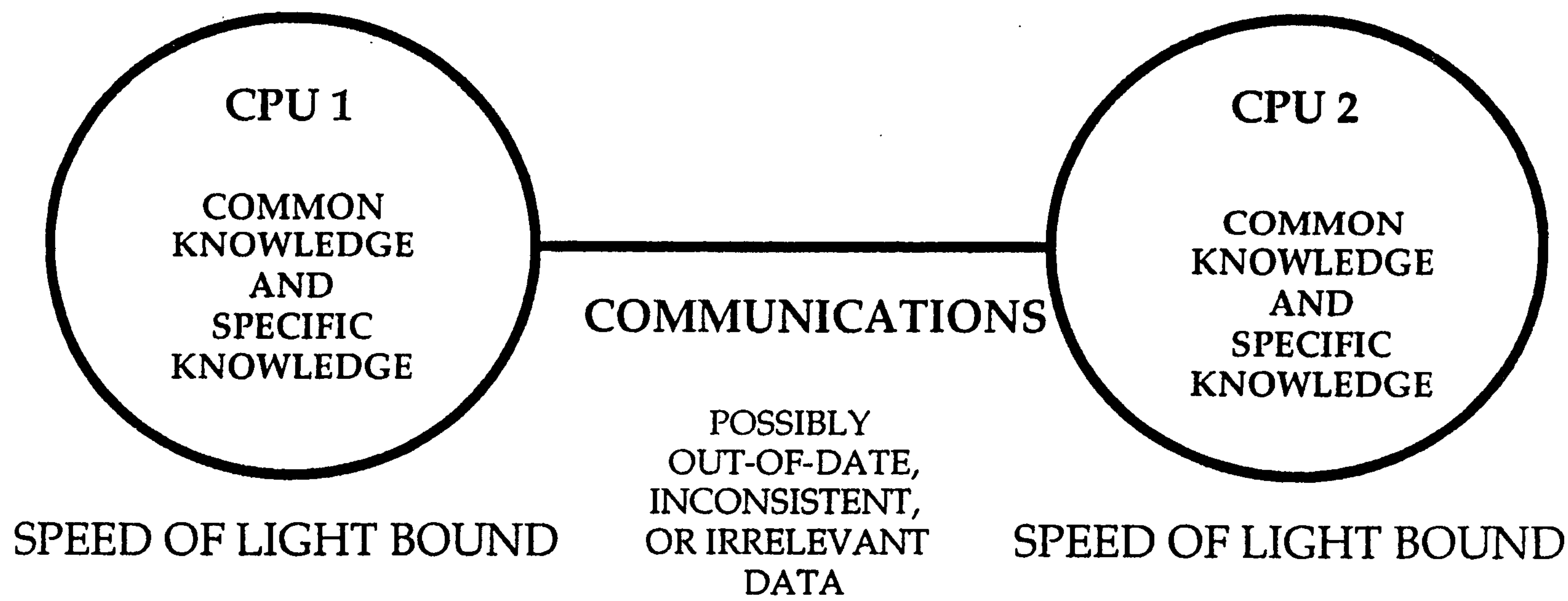
Task Manager: Chris Culbert
NASA/Johnson Space Center
Software Technology Branch

Task Support: Jorge Rufat-Latre (MDSSC)
Grayum Watts (MDSSC)
Paul Vu (MDSSC)
Brooks Slaughter (MDSSC)

Presented by: Jorge Rufat-Latre (task lead)



The need for Cooperation



COOPERATION BETWEEN LOOSELY COUPLED AGENTS IS AN EFFECTIVE MECHANISM TO OVERCOME PHYSICAL BOUNDS ON COMPUTING POWER

Distributed, Intelligent Systems Objectives

Requirement

- As computer applications expand in complexity and scope, it becomes increasingly important to take full advantage of all available processing resources. Improvements in processing speed, drastic reductions in workstation prices, and the spread of local area networks have allowed mission control center applications to move from mainframes environments to widely distributed workstation environments. Similiar improvements in space qualified hardware systems will eventually lead to distributed computer systems in spacecraft also. However, to take full advantage of these enviroments requires the development of mechanisms for sharing and coordinating distributed information.

Solution

- Intelligent data distribution and distributed scheduling are two examples of new capabilities achieved by applying these state-of-the-art technologies. Peer-to-peer intelligent agent cooperation and negotiation schemes coupled with rigorous performance studies open new areas of opportunity. Properly designed and implemented systems which can work cooperatively in distributed processing environments can significantly improve system reliability by improving fault tolerance. They can also provide significant performance enhancements and improve design flexibility. Finally, they provide an effective environment for solving more complex problems than those which can be addressed by non-distributed systems.

Distributed, Intelligent Systems Approach

The basic approach for this task is to:

- Develop techniques for using distributed, cooperative, intelligent systems to support management of ground or on-board systems. Demonstrate these capabilities in appropriate applications.
- Integrate multiple intelligent systems in a distributed processing testbed and demonstrate different approaches to distribution and cooperation.
- Analyze the various trade-offs and design decisions associated with varying levels of cooperation and intelligence in on-board or ground systems.

Distributed, Intelligent Systems
SSFP Integration

Baseline Integration

The Real Time Data System (RTDS) is currently used in the Mission Control Center to support Shuttle missions. This system has proven invaluable for allowing the development and use of advanced systems to support ongoing Shuttle operations. One of the objectives of this task, to be performed under the direction of Troy Heindel, is to provide significant improvements in RTDS functionality by making RTDS data available to numerous application workstations across a LAN. Another goal is to improve the performance and fault tolerance of the RTDS by appropriately designing and developing distributed communications capabilities. Short term plans will include the development of appropriate communications protocols and communications managers for distributing RTDS data to multiple workstations. Long term plans will evaluate approachs to long-term communications and cooperation needs, including looking at multicast or broacast options, negotiation based managers, and other approaches to providing large amounts of RTDS data to multiple applications in real-time. These will be required to allow use of RTDS in Space Station Freedom applications.

Growth and Evolution

As the Space Station Freedom matures, it will become increasingly important to share and manipulate information residing in multiple locations. Ongoing work at NASA/LeRC has develoepd approaches to this problem based on price/cost models for scheduling of activities. This approach is similar to the negotiation approaches to cooperation. Their current approach is heiracrchically structured and not very distributed. During FY92, we will work with NASA/Lewis to define peer-to-peer approaches to negotiation based cooperation (a more robust, fault tolerant technique than pure heirarchies) as well as developing better ways of using these techniques in a distributed environment. Finally, we will try to apply these techniques to distributed versions of COMPASS (a NASA scheduling tool), and possibly to future (long term) versions of RTDS.

Distributed, Intelligent Systems SSFP Integration

Baseline Program

- Support the development of distributed processing tools for the current RTDS in Mission Control Center. Evaluating advanced approaches to distributed, cooperative systems for use in evolution of RTDS for Space Station support. These extensions will improve the efficiency and fault tolerance of RTDS when used in the high data volume environments typical for Space Station Freedom.

Growth & Evolution

- In conjunction with ongoing work at NASA/Lewis, develop approaches to distributed processing which support advanced applications such as distributed scheduling. Such systems will become increasinly important as SSF evolves and require use of advanced algorithms for effective use of SSF computing resources.

Fuzzy Control Applications for Space Station

Task Manager: Robert N. Lea
NASA / Johnson Space Center
Software Technology Branch

Task Support: Jack Aldridge (MDSSC)
Jonathan Weiss (MDSSC)
Yashvanti Jani (LinCom)
James Villarreal (NASA - PT4)

Presented by: Robert N. Lea

Fuzzy Logic

Fuzzy logic is a logic based on Lotfi Zadeh's theory of fuzzy sets. Fuzzy sets can be used to represent ambiguous, vague, or imprecise conditions. They are defined by continuous functions from the universal set to the unit interval thus generalizing the notion of a characteristic function of a set. This concept permits evaluation of the degree to which a statement or condition is satisfied. Thus Zadeh's logic is concerned with the formal principals of approximate reasoning, the logic that allows one to infer approximate answers to questions whose premises and conclusions are conditions that may change continuously from true to false, rather than abruptly, and therefore may sometimes be only partially true.

The type of uncertainty that fuzzy logic deals with is different from the uncertainty dealt with by probabilistic based methods. The probability that a random sample will belong to a set is different from the degree to which the sample belongs to the set. For example, if a person walks into a room an evaluation can be made as to how well the person fits the condition of being tall. This is fuzzy uncertainty since the set of tall people is not Boolean. On the other hand if people are labeled as tall or not tall this is not a fuzzy or probability problem since the person is there and the conclusion is known. The underlying premise is that fuzzy logic is not a competing method with probabilistic methods for handling uncertainty, but a method of handling uncertainty of a different type. Specifically, fuzzy logic deals with evaluations of degrees to which certain conditions have occurred as opposed to predictions as to whether or not they will occur.

Fuzzy logic is therefore a natural concept to apply to expert systems development for modelling the rules of the expert that invariably are stated in natural language which is inherently full of fuzzy terms.

Fuzzy Logic

FUZZY LOGIC IS A LOGIC OF COMMON SENSE REASONING THAT

- ALLOWS FOR PARTIAL TRUTHS OF CONDITIONS, e.g. *LOW* TEMPERATURES, *SMALL* RESIDUALS
- PROVIDES A METHOD FOR SOLVING ILL-DEFINED AND COMPLEX NON-LINEAR CONTROL PROBLEMS BASED ON DECISION MAKING AND SENSOR EVALUATION LOGIC LEARNED FROM HUMANS
- INCREASES THE EFFECTIVENESS OF RULE BASED EXPERT SYSTEMS IN MODELING NATURAL LANGUAGE STATEMENTS OF RULES, e.g., IF TEMP IS *HIGH* AND RPM IS *FAST* THEN PRESSURE SHOULD BE *REDUCED.*

- PROVIDES A METHODOLOGY FOR EVALUATING THE UNCERTAINTY OF VAGUENESS OF NATURAL LANGUAGE EXPRESSION AS OPPOSED TO PREDICTING THE PROBABILITY OF CORRECTNESS

MOTIVATION FOR SPACE STATION APPLICATIONS

Our decision to pursue fuzzy logic for space station applications has been motivated to a large extent by early successes at the JSC in the development of fuzzy logic methodologies for vehicle and process control and decision making. However, one of the strong driving forces has been the outstanding successes of the Japanese in the commercial development of fuzzy logic applications over the last three or four years. These include applications in high technology areas such as train control systems, camera stabilization and autofocusing systems, automotive applications to automatic transmission and braking systems, air conditioning control systems, television auto contrast and brightness control, and control of nuclear reactors as well as commercially successful applications to household products such as washing machines and vaccuum cleaners.

MOTIVATION FOR SPACE STATION APPLICATIONS

DECISION TO PURSUE FUZZY LOGIC APPLICATIONS FOR SPACE STATION APPLICATIONS HAS BEEN BASED ON

- MANY SUCCESSES OF FUZZY LOGIC APPLICATIONS IN JAPAN
  - SENDAI SUBWAY SYSTEM
  - CAMERA STABILIZATION AND AUTOFOCUSING
  - AIR CONDITIONING CONTROL SYSTEMS
  - AUTO TRANSMISSION AND BRAKING CONTROL
  - TELEVISION AUTO CONTRAST AND BRIGHTNESS CONTROL
- JSC SUCCESSES IN SIMULATED SPACE VEHICLE CONTROL, PROCESS CONTROL, TETHER CONTROL, AND OTHER APPLICATIONS

Selection of Applications

NASA HQ Level I co-sponsored (with McDonnell Douglas Space Systems) a Workshop in Fuzzy Logic Control for Space Station Applications. The purpose of the conference was to identify potential applications of Fuzzy Logic and to determine the validity of those applications. Attendees included internationally recognized experts in Fuzzy Logic (Kosko, Yen, Togai, Xu, Sugeno, Lea, Ma, Berenji, Jani), NASA managers (Gersh, Fernquist, Lea, Lawler), and MDSSC managers and engineers with knowledge of the potential Space Station applications. While all problems were judged to be appropriate applications of Fuzzy Logic, some were selected for immediate efforts based on considerations of timing, NASA priorities, and potential spin-off opportunities.

Selection of Applications

- 11 Candidate applications identified at November 1990 Huntington Beach Workshop
  - problems described by engineers
  - initial responses from noted fuzzy experts
  - initial screening based on technical merit, NASA need, and timing factors
- Final candidates selected based on
  - probability of baseline application
  - immediate NASA benefit
  - committed ownership by user
  - potential for multiple applications
  - low risk and cost

Applications - Blowdown Thruster

Space Station reboost will be accomplished using blowdown thrusters (engines whose thrust comes from gas pressure which decreases with usage). Guidance, Navigation, and Control needs to predict accurately the level of thrust available at different points throughout the maneuver, but this is complicated because the same engines provide thrust for attitude control, resulting in rapid fluctuations in the actual usage curves.

Fuzzy Logic can be used to develop a rule-based time series model that fits blowdown performance better than a polynomial approximation. Even more value may be achieved if a fuzzy control model can be developed to measure and improve the efficiency of attitude controls during the maneuver (e.g. by timing x-direction thrusts to minimize the need for y- and z-corrections).

Applications

- <u>Blowdown Thruster</u> - difficult to predict thrust levels as engine blows down due to unknown rate of attitude control thrusting
- Current status - work order started 7/22/91; have identified two promising fuzzy approaches and met with GN&C experts to validate approach

Applications - RFMD Pump

The Rotary Fluid Management Device Pump may flood due to heat load changes on the evaporators in the Thermal System. When this happens, current controls react with large transient power corrections. These in turn place unnecessarily high loads on electrical components and may use power inefficiently.

By using Fuzzy Logic Control instead of proportional control, we may be able to spread a more gradual response over a longer period of time, thus reducing power transients and potential overshoots. A fuzzy rule-based control system incorporate timing and safety constraints while producing this smoother response and utilize power more efficiently.

Applications

- <u>RFMD Pump</u> - pump may flood due to heat load changes on evaporators; constant frequency control leads to excessive power excursions; by matching pump RPM to thermal load, may be able to minimize power usage
- Current status - work order started 7/22/91; initial approach to flooding problem developed

SUMMARY

The software methods and environments being researched and developed within the STB will make CASE technology available for both conventional and knowledge based systems The support extends across the development, operational, and maintenance phases of the life cycle. This will significantly improve both the quality and productivity of SSFP software and will avoid cost resulting from poor quality software and poor processes. The reliability and safety of the software will be improved. Tasks are directed towards the environment and tools and towards methodologies for providing advanced software solutions.

SUMMARY

- Products of this project will significantly improve the quality and productivity of SSFP software processes by:
  - Improving software reliability and safety
  - Broadening the range of problems that can be solved with computational solutions
- Project brings in CASE technology for:
  - Environments
    - ESL/PCS application generator
    - Intelligent User Interface for cost avoidance in setting up operational computer runs
    - Framework programmable platform for defining process and software development work flow control
    - Process for bringing CASE technology into an organization's culture
    - CLIPS/CLIPS Ada language for developing expert systems

SUMMARY (CONT')

- Methodologies
  - Method for developing fault tolerant, distributed systems
  - Method for developing systems for common sense reasoning and for solving expert systems problems when only approximate truths are known

INTELLIGENT COMPUTER-AIDED TRAINING (ICAT)

AUGUST 8, 1991

ROBERT T. SAVELY
NASA/JSC
713-483-8105
FTS 525-8105
NASAMAIL: RSAVELY

DR. R. BOWEN LOFTIN
UNIVERSITY OF HOUSTON
AND NASA/JSC
713-483-8070/FTS 525-8070
NASAMAIL: BLOFTIN

INTELLIGENT COMPUTER-AIDED TRAINING

Since 1985 the Software Technology Branch at NASA/Johnson Space Center has been applying artificial intelligence technology to the development of autonomous, workstation-based training systems for use by astronauts, flight controllers, and other ground-support personnel. This activity has been under the management of Robert T. Savely (Chief, Software Technology Branch) and under the technical direction of Dr. R. Bowen Loftin (Professor, University of Houston-Downtown). A talented team of civil servants, contractors, and students has been assembled to support both the short and long range projects described herein.

1106

INTELLIGENT COMPUTER-AIDED TRAINING

BACKGROUND:

- TRAINING IS A MAJOR EFFORT AT ALL NASA CENTERS; DIRECT TRAINING COSTS ARE IN THE $100M RANGE WHILE INDIRECT COSTS ARE FAR GREATER
- TRAINING TIME HAS A DIRECT IMPACT ON SCHEDULES
- LACK OF ADEQUATE TRAINING IN ALL PHASES OF SSF MISSION OPERATIONS CAN BE DETRIMENTAL TO SAFETY AND THE ACHIEVEMENT OF MISSION OBJECTIVES

INTELLIGENT COMPUTER-AIDED TRAINING

Historically, NASA has devoted extensive resources to training—especially the training of astronauts. Training costs represent a significant faction of the budgets of operational centers, such as the Johnson Space Center. For example, the Shuttle Mission Simulator costs approximately $30,000 per hour to operate. One unfortunately result of the high cost of sophisticated training is its scarcity. Astronauts receive far more training than most, if not all, ground-support personnel. The delivery of the best training via complex simulators severely restricts the time and quality of training received by novices.

Since training is an essential ingredient for a successful mission, the need to schedule adequate training has a direct impact on the scheduling of missions. Moreover, when the same resources (e.g., the Mission Control Center) are used for both training and mission operations, the impact of training on operations is obvious.

Crew performance is inevitably linked to training. Not only is adequate training preceding a mission necessary, but also training on-orbit may be needed, especially for infrequently-performed operations that are mission critical. In general, there is no such thing as too much training for personnel that support missions.

INTELLIGENT COMPUTER-AIDED TRAINING

BACKGROUND (continued):

- CURRENT TRAINING METHODS THAT RELY ON LARGE-SCALE SIMULATORS MAY NOT BE COST EFFECTIVE VEHICLES FOR DELIVERING TRAINING TO ALL SSF MISSION OPERATIONS PERSONNEL
- SSF MISSION CONTROL CENTER WILL BE IN CONTINUOUS USE FOR OPERATIONS
- CURRENT TRAINING METHODS ARE NOT APPLICABLE TO THE SSF ON-ORBIT ENVIRONMENT

INTELLIGENT COMPUTER-AIDED TRAINING

Large-scale simulators are both expensive to build and expensive to maintain. The great expense of such simulation training environments clearly limits their numbers and, consequently, limits the training that can be delivered by such means. Intelligent Computer-Aided Training technology can, in some cases, replace and, in other cases, augment and make more effective such simulators. As a result more training can be delivered to more personnel in less time and with less expense.

Training for Apollo and Shuttle missions has been supported by use of the Mission Control Center for integrated simulations. With the advent of the Space Station Freedom and the eventual 24-hour utilization of the Space Station Control Center, such exclusive devotion of the facility to training will be eliminated.

Current simulators rely on physical mockups of the systems for which training is required in addition to significant computer resources and large numbers of training personnel. On-orbit training, deemed essential for Space Station Freedom, cannot be delivered in such a manner. The workstation-based nature of the ICAT technology permits the delivery of training systems for on-orbit use that can approach or match the efficacy of ground-based simulators.

INTELLIGENT COMPUTER-AIDED TRAINING

OBJECTIVES:

THE APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGY TO THE DEVELOPMENT OF AUTONOMOUS SYSTEMS FOR TRAINING PERSONNEL IN THE PERFORMANCE OF COMPLEX, PROCEDURAL TASKS ASSOCIATED WITH BOTH THE GROUND BASED AND ON-ORBIT OPERATIONS OF SPACE STATION FREEDOM

- DESIGN, DEVELOPMENT AND TESTING OF A GENERAL ARCHITECTURE FOR ICAT SYSTEMS THROUGH THE BUILDING OF SPECIFIC APPLICATIONS
- PRODUCTION OF A SOFTWARE DEVELOPMENT ENVIRONMENT FOR BUILDING ICAT SYSTEMS

INTELLIGENT COMPUTER-AIDED TRAINING

Recognizing that no one approach can successfully solve all training problems, ICAT technology has been specifically shaped to address training in complex, procedural tasks. Such tasks are common to the NASA environment and constitute the bulk of training requirements for mission operations personnel. This narrow focus has permitted the creation of a general architecture for ICAT systems that has been proven to be adaptable to a wide variety of training tasks.

In order for ICAT technology to become an essential element in the NASA training environment, two criteria must be met. First, substantial code reuse must be possible in order to reduce the time necessary to develop new ICAT applications. Secondly, software tools must be available that empower the training community to build new ICAT applications without, in large measure, the intervention of those in the software development community. The first of these criteria has been met through the development and refinement of the general ICAT architecture. The second criteria is being met through the development of an integrated set of workstation-based software tools, built for use by those lacking extensive programming experience.

INTELLIGENT COMPUTER-AIDED TRAINING

BENEFITS:

- ICAT SYSTEMS MAGNIFY THE EFFORTS OF TRAINERS TO DELIVER TRAINING, SERVE TO CAPTURE PERISHABLE TRAINING EXPERTISE, AND ENHANCE THE MAINTAINABILITY OF TRAINING SYSTEMS
- ICAT SYSTEMS PROVIDE UNIFORM AND VERIFIABLE TRAINING, ENHANCING SAFETY AND THE PROBABILITY OF MISSION SUCCESS
- ICAT SYSTEMS CAN SIGNIFICANTLY REDUCE THE TIME REQUIRED FOR TRAINEES TO ACHIEVE GIVEN LEVELS OF PROFICIENCY IN A TASK

INTELLIGENT COMPUTER-AIDED TRAINING

The very best trainers are always in short supply and often can personally serve only a fraction of those who are to be trained. An ICAT system can "capture" much of what makes an excellent trainer and deliver this to unlimited numbers of trainees, independent of schedule or location. High turnover rates among training personnel make it difficult to preserve corporate knowledge. Since an ICAT system captures the valuable knowledge and experience of one or more trainers, it can become a repository for much expertise that may be lost due to transfers or retirements. Most NASA training environments are dynamic. Both the systems for which personnel are being trained and the procedures appropriate to those systems may change frequently. ICAT technology provides both the structure (a general architecture) and the means (software tools) to rapidly evolve training systems to keep pace with the operational environment.

When many personnel are involved in the delivery of training it is inevitable that the training will be uniform to a greater or lesser extent. Moreover, it is difficult to effectively verify that training delivered by more than one trainer is correct and has met all training objectives.

As the data provided below shows, the one-on-one nature of the ICAT system's interaction with trainees and its inherent ability to provide optimal training experiences for trainees with diverse skills and backgrounds lead to extraordinary performance gains.

INTELLIGENT COMPUTER-AIDED TRAINING

BENEFITS (continued):

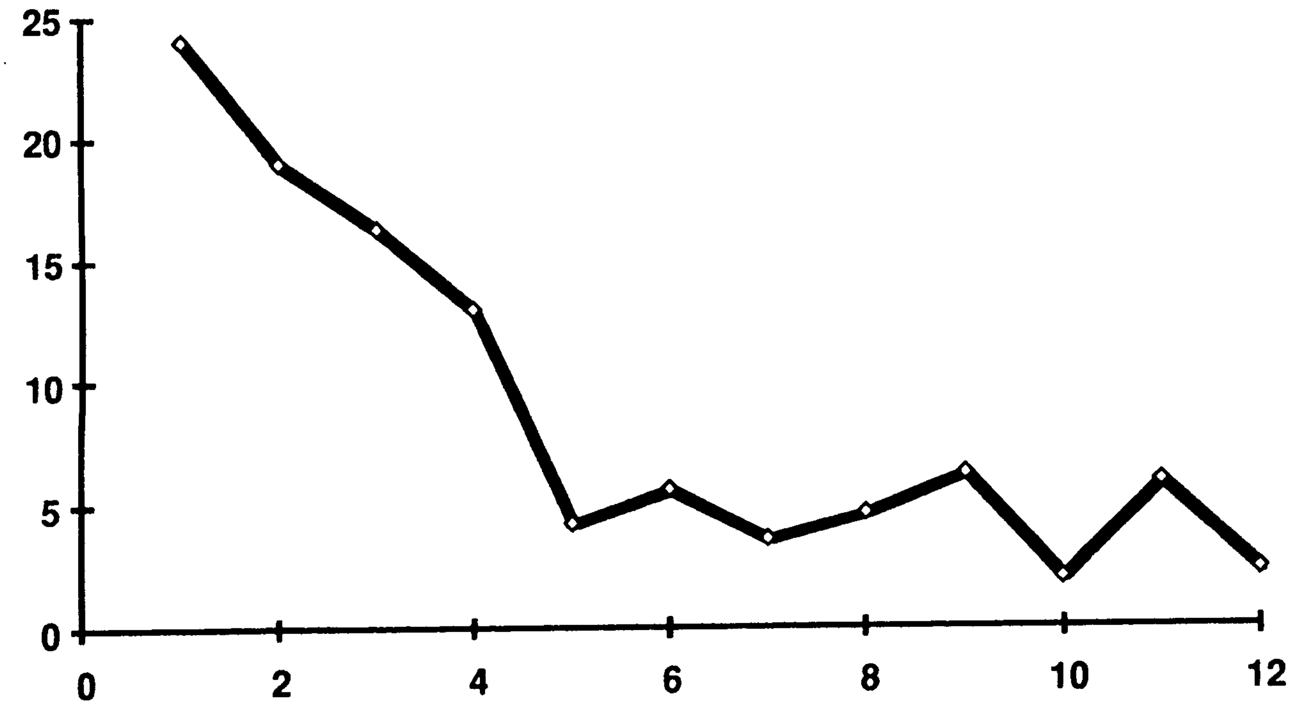
- ICAT SYSTEMS CAN BE USED FOR ON-ORBIT "REFRESHER" TRAINING, THEREBY REDUCING TIME REQUIRED FOR COMPLEX IVA AND EVA SSF ACTIVITIES
- ICAT SYSTEMS CAN BE DELIVERED IN BOTH GROUND-BASED AND ON-ORBIT ENVIRONMENT AND CAN AUGMENT SIMULATION-BASED TRAINING FACILITIES
- ICAT SYSTEMS HAVE APPLICABILITY THROUGHOUT NASA OPERATIONAL CENTERS, ALL GOVERNMENT AGENCIES, INDUSTRY, AND EDUCATIONAL INSTITUTIONS

INTELLIGENT COMPUTER-AIDED TRAINING

Astronauts have placed a high priority on the availability of on-orbit training, especially for mission critical tasks that are infrequently performed. Since Space Station Freedom will demand both lengthy periods of on-orbit duty and provide a extraordinary range of complex tasks for the crew to master, the availability of sophisticated workstation-based training systems in the on-orbit environment is essential for safety and mission success. ICAT technology provides a cost-effective way of delivery such on-orbit training.

INTELLIGENT COMPUTER-AIDED TRAINING

AVERAGE NUMBER OF TOTAL ERRORS FOR TRAINEE GROUP USING PD/ICAT



INTELLIGENT COMPUTER-AIDED TRAINING

The data shown in this graph was obtained from three novice Flight Dynamics Officers with very different backgrounds and prior knowledge of the task to be trained. The were each assigned to use the Payload-Assist-Module Deploys (PD)/ICAT system as often as they wished in order to master the nominal deployment task. The data clearly shows that they rapidly approached a low "error" rate. It is important to note that the error rate reported here is a "total" error rate. Those residual errors remaining after about the sixth training session were of a noncritical nature and generally involved failure to verify (manually) that correct parameters had been entered by "support personnel." The total time required for a given trainee to experience twelve sessions was approximately fifteen hours spread over three to five days. In order to experience a comparable number of deployments in the integrated simulation environment might have required as much as two years due to the limited availability of the Mission Control Center for non-Mission-specific training.

INTELLIGENT COMPUTER-AIDED TRAINING

AVERAGE TASK COMPLETION TIME FOR TRAINEE GROUP USING PD/ICAT

INTELLIGENT COMPUTER-AIDED TRAINING

The data shown in this graph was obtained from three novice Flight Dynamics Officers with very different backgrounds and prior knowledge of the task to be trained. The were each assigned to use the Payload-Assist-Module Deploys (PD)/ICAT system as often as they wished in order to master the nominal deployment task. The data clearly shows that the trainees were able to reach a reasonable performance time in about five sessions. The total time required for a given trainee to experience twelve sessions was approximately fifteen hours spread over three to five days. In order to experience a comparable number of deployments in the integrated simulation environment might have required as much as two years due to the limited availability of the Mission Control Center for non-Mission-specific training.

ICAT ARCHITECTURE:

THE ICAT ARCHITECTURE PROVIDES THE TRAINEE WITH A SIMULATION OF THE TASK ENVIRONMENT, REAL-TIME COACHING, AND TRAINING EXERCISES THAT EVOLVE IN DIFFICULTY TOWARD THAT OF THE MOST COMPLEX TASK SCENARIO. THE ARCHITECTURE'S MAJOR COMPONENTS INCLUDE:

- EXPERT SYSTEMS THAT INCORPORATE SUCCESSFUL TRAINING METHODS AND THE TRAINING DOMAIN KNOWLEDGE
- HIGH FIDELITY USER INTERFACE

INTELLIGENT COMPUTER-AIDED TRAINING

The user of an ICAT application is presented with an interface that duplicates, to the extent possible, the task environment for which he or she is being prepared. The system examines the prior interactions, if any, of the trainee with the ICAT system (as embodied in a trainee model) and designs an appropriate training scenario for the session. As the scenario unfolds, the trainee's actions are monitored and compared to those of expert in the same context. When discrepancies between the expert's behavior and that of the trainee are detected, the ICAT system uses the trainee model of determine an appropriate response. The ICAT system can also provide context-sensitive help and hints in response to the trainee's request for such aid. At the conclusion of a training session, the trainee is provided with a trace of his or her actions that emphasizes those points where those actions differed from those of the expert. The next training session repeats this process and provides a new training scenario that will move the trainee closer to the ultimate training goals while testing the trainee's success in overcoming previously-identified weaknesses.

As will be more thoroughly explored below, the ICAT architecture includes rule-based expert systems that incorporate knowledge of the system and procedures to be trained, knowledge of how to train, and knowledge of how to structure new and ever more challenging training experiences.

The interface of an ICAT system consists of a "shell" of menus and text windows that provide for communication between the system and the. Other elements are usually unique to the system to be trained and may consist of formatted data displays, keyboards, keypads, control panels, indicators, and other elements.

ICAT ARCHITECTURE (continued):

- MODELS OF TRAINEES THAT CONTAIN A KNOWLEDGE OF THEIR GENERAL BACKGROUNDS AND THEIR PREVIOUS INTERACTIONS WITH THE ICAT SYSTEM
- A TRAINING SCENARIO GENERATOR CAPABLE OF PRODUCING USEFUL AND REALISTIC TRAINING EXERCISES APPROPRIATE FOR A TRAINEE'S CURRENT LEVEL OF ACCOMPLISHMENT
- PRESENTATION OF PERFORMANCE DATA TO THE TRAINEE AND TRAINING PERSONNEL
- INTEGRATION OF THESE ELEMENTS, WHEN APPROPRIATE, WITH QUALITATIVE OR MATHEMATICAL SIMULATIONS

INTELLIGENT COMPUTER-AIDED TRAINING

The trainee model is, at its most fundamental level, a compact trace of all that a trainee has done during the present and past interactions with the ICAT system. This basic data is organized in a hierarchical manner to facilitate its use in categorizing the trainee's demonstrated strengths and weaknesses. This model provides necessary input for the design of new training scenarios as well as for the handling of trainee errors during a training session.

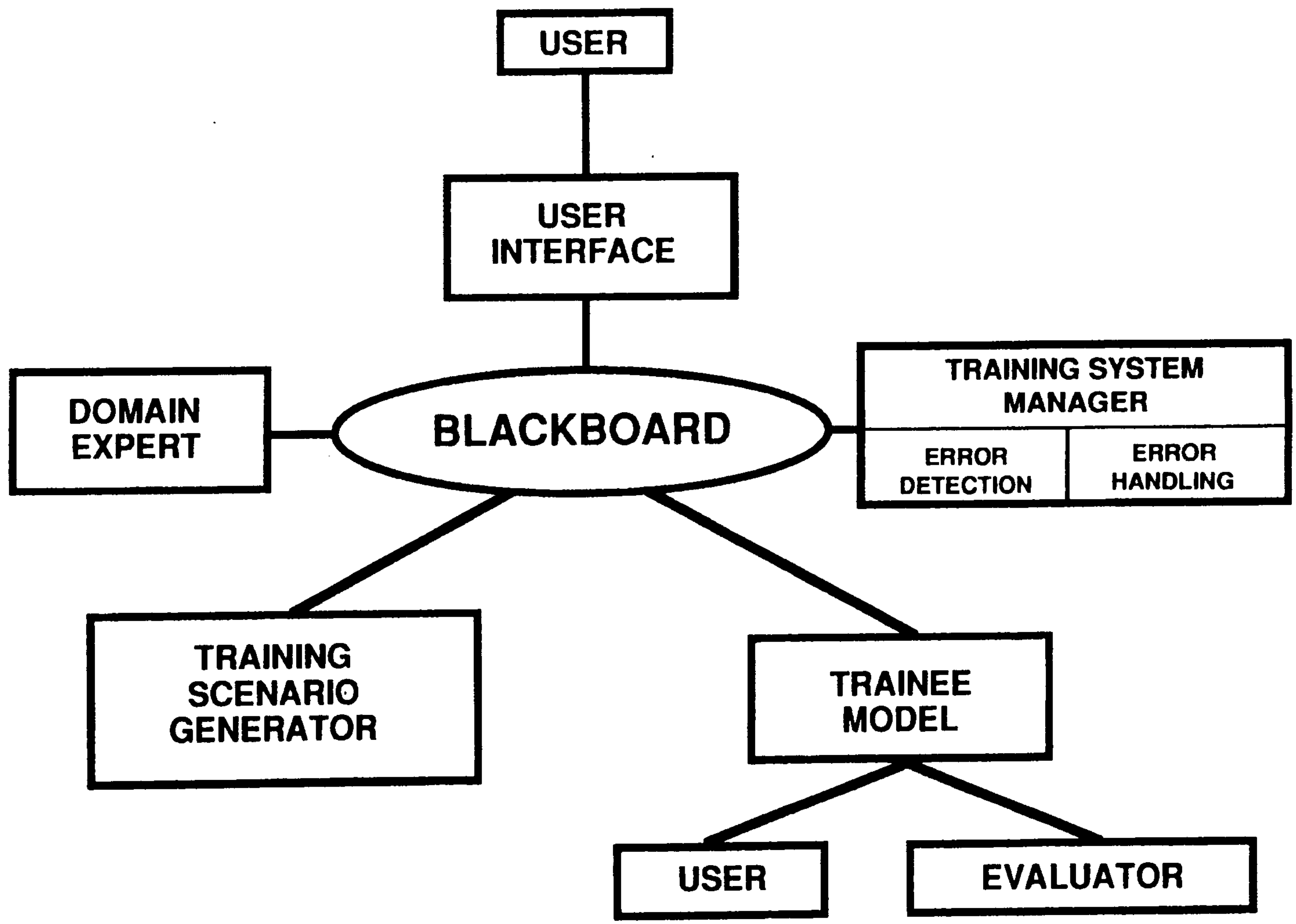
The training scenario generator is a hybrid expert system that utilizes a knowledge base (in rules) and an object-oriented database to design and assemble unique training scenarios appropriate to a specific trainee's current needs.

At the conclusion of each training session the trainee is provided with a formatted trace of his or her actions during the sessions. Where those actions were not optimal or even correct, the action and that recommended by the expert are emphasized. In addition the trace notes instances when help was requested or provided. A training supervisor can, moreover, examine a trainee's record or can access summary data for a specific group of trainees.

Finally, many ICAT applications must also contain a quantitative or qualitative simulation that provides the actual scenario presented during the training session. In some cases theses simulations may be created especially for the ICAT application while, in other cases, the ICAT application may make use of an existing simulation.

INTELLIGENT COMPUTER-AIDED TRAINING

ICAT ARCHITECTURE SCHEMATIC



INTELLIGENT COMPUTER-AIDED TRAINING

In order to provide a robust and flexible architecture for the development of ICAT applications, domain-independent elements have been segregated from domain-dependent elements. The domain expert is a conventional rule-based expert system. The Training Session Manager consists of two rule-based expert systems—one for error detection and a second for error handling. The Training Scenario Generator is a hybrid system that uses a rule-base to decide on the general design of anew training scenario and then draws on an object-oriented database to provide the details of that scenario. The Trainee Model is a complex data structure that stores the history of each trainee's interaction with the ICAT application and organizes that data in a hierarchical manner to facilitate its use in identifying the strengths and weaknesses of the trainee. Both the trainee and a training supervisor can examine a trainee's model.

All elements of the ICAT architecture communicate via a blackboard approach. In this instance the blackboard is a common"factbase" that contains facts describing the current training environment as wells as actions taken by the trainee and those that would be taken by an expert.

INTELLIGENT COMPUTER-AIDED TRAINING

SPACE STATION APPLICATIONS:

- JOINTLY WITH SPACE STATION TRAINING OFFICE
- ACTIVE THERMAL CONTROL SYSTEM (ATCS) ICAT
  - TRAINS CREW AND FLIGHT CONTROLLERS IN OPERATION OF THE SSF ACTIVE THERMAL CONTROL SYSTEM
  - UNDER DEVELOPMENT BY MCDONNELL DOUGLAS USING IR&D FUNDS
  - DEVELOPED USING COMPLETE ICAT ARCHITECTURE ON THE MACINTOSH
  - SPANS TRAINING IN BOTH NOMINAL AND NONNOMINAL OPERATIONS

INTELLIGENT COMPUTER-AIDED TRAINING

A cooperative effort between the Software Technology Branch, the Space Station Training Office, and McDonnell Douglas Space Systems Company is directed at the development of an ICAT application for the Space Station Active Thermal Control System (ATCS). The ATCS/ICAT system is designed to train both crew members and ground-based flight controllers in the operation of the ATCS. The system will provide training in both the nominal operations of the ATCS and in anticipated nonnominal operations.

The ATCS/ICAT system utilizes the complete ICAT architecture as previously described. Its development is proceeding on a Macintosh platform with eventual goal of its delivery on the Macintosh, under Windows on PC platforms, and under X-Windows on unix platforms.

INTELLIGENT COMPUTER-AIDED TRAINING

SPACE STATION APPLICATIONS (continued):

- VIRTUAL ENVIRONMENTS FOR ICAT SYSTEMS
  - EVALUATE VIRTUAL ENVIRONMENT TECHNOLOGY FOR SPACE STATION TRAINING
  - INTEGRATE VIRTUAL ENVIRONMENT AND ICAT TECHNOLOGY

INTELLIGENT COMPUTER-AIDED TRAINING

Another activity pursued jointly by the Software Technology Branch and the Space Station Training Office is directed at exploring virtual environment (or reality or worlds) technology for Space Station training. In one instance virtual environment technology will b compared to dome and pancake window approaches to delivery graphically-generated sciences to trainees. In a second effort a virtual environment interface will be developed for an ICAT application directed at a Space Station training task.

INTELLIGENT COMPUTER-AIDED TRAINING

ICAT APPLICATION PROJECTS:

- PAYLOAD-ASSIST MODULE DEPLOY ICAT SYSTEM (PD/ICAT)
- VACUUM VENT LINE ICAT SYSTEM (VVL/ICAT)
- MAIN ENGINE PROPULSION SYSTEM ICAT SYSTEM (MPP/ICAT)
- INSTRUMENT POINTING SYSTEM ICAT SYSTEM (IPS/ICAT)

INTELLIGENT COMPUTER-AIDED TRAINING

PD/ICAT is a comprehensive intelligent computer-aided training system used by Flight Dynamics Officers in learning to deploy PAM (Payload-Assist Module) satellites from the Space Shuttle. This system was the first developed in the effort described in this paper and has served as a testbed for the development of a general architecture for ICAT systems. PD/ICAT is intended to train NASA flight controllers in performing the computations and other operations necessary to determine the time and proper Space Shuttle orientation for a satellite deployment.13-16

VVL/ICAT is a limited, PC-based intelligent computer-aided training system for use by mission and payload specialists in learning to perform fault detection, isolation, and reconfiguration (FDIR) on the Spacelab VVL system. This system does not contain the full complement of student modelling, scenario generation, and trainee session management that is a part of the other systems described in this section.

MPP/ICAT is comprehensive intelligent computer-aided training system for use by test engineers at NASA/Kennedy Space Center in learning to perform testing of the Space Shuttle Main Propulsion Pneumatics system. This system utilizes the complete general ICAT architecture as found in PD/ICAT. The Firing Room console environment is duplicated in the MPP/ICAT interface, and training is provided in carrying out the Operations and Maintenance Instruction pertinent to the 750psi Helium pneumatics system that controls the Space Shuttle Main Propulsion System. In addition to training engineers in nominal test procedures, MPP/ICAT is ultimately intended to address the development and implementation of test procedures employed when faults are detected.

IPS/ICAT is intended for use by payload and mission specialists at NASA/Johnson Space Center and Marshall Space Flight Center in learning to utilize the IPS on Spacelab missions. The IPS is a platform used for mounting and pointing astronomical telescopes during the Astro series of Spacelab missions. The system provides a graphical representation of the Space Shuttle aft flight deck, from which one can access interactive, digitized images of relevant control panels as well as the displays used in operating the IPS. IPS/ICAT is designed to trainee astronauts in the activation, deactivation, and initial pointing of the IPS as well as in the final pointing of one of the instruments mounted on the IPS (the Hopkins Ultraviolet Telescope). The system uses the general ICAT architecture as found in PD/ICAT and MPP/ICAT.

INTELLIGENT COMPUTER-AIDED TRAINING

ICAT APPLICATION PROJECTS (continued):

- CENTER INFORMATION SYSTEM COMPUTER OPERATIONS ICAT SYSTEM (CISCO/ICAT)
- SHUTTLE REMOTE MANIPULATOR ARM ICAT SYSTEM
- PROPULSION CONSOLE TRAINER
- SATELLITE OPERATIONS CONTROL LANGUAGE ICAT SYSTEM (GSFC)

INTELLIGENT COMPUTER-AIDED TRAINING

CISCO/ICAT addresses the training of mainframe computer operators within the context of the Johnson Space Center's Center Information System. Operators are provided, in a PC and Windows environment, with a console operator display as well as a "map" of the hardware locations. Utilizing these displays, trainees are instructed in standard operations, including power-up, power-down, and initial process load. Both console operations as well as physical interaction with devices are a part of the training regimen. CISCO/ICAT also uses the same ICAT architecture that is found in PD/ICAT, MPP/ICAT, and IPS/ICAT.

Through an SBIR (Phases I and II) project with Global Information Systems an ICAT system has been "married" to an existing kinematic simulation of the Shuttle Remote Manipulator System (RMS). The ICAT component of this system significantly enhances the utility of the simulation by providing appropriate goals, help/hints, and performance evaluation.

The U.S. Air strong laboratory has funded the development, by Southwest Research Institute, of an ICAT system for training flight controls in the operation of the propulsion console (Mission Control Center). The system specifically targets the development of automaticity on the part of the trainees.

Goddard Space Flight Center has utilized a portion of the general ICAT architecture in developing an ICAT system for training personnel in satellite control operations.

INTELLIGENT COMPUTER-AIDED TRAINING

ICAT ANCILLARY PROJECTS:

- CLIPS INTELLIGENT TUTORING SYSTEM (CLIPSITS)
- INTELLIGENT PHYSICS TUTOR
- INTELLIGENT LITERACY TUTOR

INTELLIGENT COMPUTER-AIDED TRAINING

A PC-based intelligent tutoring system for the CLIPS language was developed and distributed with version 4.2 of CLIPS. This system, due to its delivery platform, has very limited student modeling capabilities but is capable of assisting students in acquiring a working knowledge of CLIPS syntax and proper programming style.

The ICAT project has also stimulated the development of an intelligent tutoring system (ITS) for use in a high school or introductory college physics course. The goal of this ITS is not the conveyance of facts and concepts but rather the transfer of problem solving skills to the student. Ultimately, this project will not only produce a useful teaching aid for students enrolled in high school or introductory college physics courses, but will also provide a development structure suitable for building additional intelligent tutors for other academic subjects which require the application of problem solving skills (e.g., mathematics, chemistry, and engineering). The tutor is in its final stages of development and will be licensed for commercial distribution in the near future.

The latest "spinoff" of ICAT technology is an intelligent tutoring system designed to aid adults in mastering literacy skills. The tutor uses the core of the intelligent physics tutor as well as extensive video, speech recognition, and speech generation facilities.

ICAT DEVELOPMENT ENVIRONMENT:

A SUITE OF SOFTWARE TOOLS TO AID TRAINING PERSONNEL IN APPLYING THE ICAT ARCHITECTURE TO SPECIFIC TRAINING TASKS.

- EVALUATION OF EXISTING TOOLS AND REQUIREMENTS DEVELOPMENT
  - KNOWLEDGE ACQUISITION, KNOWLEDGE BASE EDITING, AND DATABASE DEVELOPMENT
  - USER INTERFACE DEVELOPMENT
  - TRAINEE MODELING

INTELLIGENT COMPUTER-AIDED TRAINING

In order to facilitate the rapid production and efficient maintenance of ICAT applications, a suite of software tools is under development. These software tools will aid both experienced programmers and those not proficient in computer programming in adapting the general ICAT architecture for specific applications and in modifying existing applications to address the evolution of the systems and procedures for which they were developed.

The approach followed has been (1) the identification of those areas for which tools should be available, (2) the evaluation of existing tools that address those areas, (3) the development of requirements for the tools needed, and (4) the development and/or adaptation of the needed tools.

The most serious "bottleneck" to the development of knowledge-based systems is the acquisition and maintenance of expert knowledge. The highest priority element of this project is the provision of a tool or tools for knowledge acquisition and the "editing" of existing knowledge bases. The building of databases to support training scenario generation has also been addressed in this manner.

The next most significant barrier to the efficient production of ICAT applications lies in the development of the user interface component.

Finally, the use of the ICAT architecture for widely diverse training tasks requires the ability to make some alterations in the trainee model element of the architecture.

ICAT DEVELOPMENT ENVIRONMENT (continued):

- THE PRODUCTION, ADAPTATION, AND TESTING OF SPECIFIC TOOLS
- TOOL INTEGRATION INTO A COMPREHENSIVE DEVELOPMENT ENVIRONMENT ENVIRONMENT
- FULL-SCALE TESTING BY OPERATIONAL CENTERS
- INTEGRATION INTO SSF BASELINE

INTELLIGENT COMPUTER-AIDED TRAINING

Upon completion of an extensive evaluation and requirements development effort in the areas of knowledge acquisition and interface building, work began on the actual production of tools for these two areas.

Beta testing of these elements is now underway and their integration into a general purpose development environment (GPDE) will proceed following the testing phase. Finally, the integrated GPDE will be utilized at NASA operational centers for ICAT application development.

Through interaction with the Space Station Training Office and McDonnell Douglas Space Systems Company, progress is being made to demonstrate the applicability of ICAT technology for Space Station training and to encourage its incorporation, for both ground-based and on-orbit training, into the Space Station Freedom baseline.

ICAT DEVELOPMENT ENVIRONMENT (continued):

- KNOWLEDGE ACQUISITION TOOLS:
  - TWENTY-TWO KNOWLEDGE ACQUISITION TOOLS WERE EVALUATED
  - US NAVY VISTA PRODUCT SELECTED AS FUNCTIONAL PROTOTYPE
  - DEVELOPMENT OF TASK ANALYSIS AND RULE GENERATION TOOL (TARGET) BEGAN 1/91
  - CURRENT DEVELOPMENT IS BASED ON PC PLATFORM AND WINDOWS 3.0

INTELLIGENT COMPUTER-AIDED TRAINING

Following the evaluation of twenty-two existing tools for knowledge acquisition, a tool developed by the U.S. Navy Training Systems Center was selected for extensive use in the ICAT activity. The Visual Interactive System for Task Analysis (VISTA) was used as a vehicle to investigate knowledge acquisition modes specifically adapted to procedural knowledge. After extensive use of the VISTA tool a product, sharing some of its "look and feel" was designed. The Task Analysis and Rule Generation Tool (TARGET) permits an expert to visually describe complex procedural tasks and, from that description, automatically produces a task analysis and, upon completion, CLIPS rules representing the knowledge of how to perform the task. The version of TARGET now under development is based on the PC (386) and Microsoft Windows 3.0.

ICAT DEVELOPMENT ENVIRONMENT (continued):

- TARGET SUPPORTS KNOWLEDGE ACQUISITION, KNOWLEDGE REFINEMENT, KNOWLEDGE VALIDATION AND VERIFICATION, AND TRANSLATION OF KNOWLEDGE FROM A GRAPHIC TO A CLIPS REPRESENTATION
- TARGET V0.3 WAS RELEASED 6/91
- AUTOMATED GENERATION OF CLIPS PROCEDURAL CODE DEMONSTRATED 7/91; AUTOMATED RULE GENERATION PLANNED FOR 10/91
- FUTURE PLATFORMS INCLUDE MACINTOSH AND UNIX
- EXTENSION TO PASSIVE KNOWLEDGE ACQUISITION UNDERWAY

INTELLIGENT COMPUTER-AIDED TRAINING

TARGET provides an integrated environment in which complex procedural tasks can be represented in a a three-dimensional graphical form. From this representation a standard task analysis chart can be generated. Ultimately, TARGET will also generate CLIPS rules or CLIPS procedural code from this representation. Editing any one of the three representations will automatically result in appropriate alterations of the other two representations. TARGET will ultimately be implemented in the Macintosh and unix environments also.

The use of TARGET will greatly facilitate the acquisition of knowledge from experts, the generation of expert consensus, the automatic creation of the domain-dependent knowledge bases required for ICAT applications, and the maintenance of ICAT knowledge bases.

In addition to its specific application to ICAT system development TARGET promises to be a versatile and robust tool for the creation of expert systems in general.

ICAT DEVELOPMENT ENVIRONMENT (continued):

- USER INTERFACE BUILDING TOOL:
  - USER INTERFACE BUILDING TOOL ELEMENTS
    - ICAT INTERACTION SHELL
    - FORMATTED DATA DISPLAYS
    - TEXT WINDOWS
    - INTERACTIVE DIGITIZED IMAGES
    - KEYBOARDS/KEYPADS AND INDICATORS

INTELLIGENT COMPUTER-AIDED TRAINING

Since the creation of an appropriate user interface for an ICAT system can require a significant fraction of the total system development time, an interface building tool for ICAT applications is also under development. The interface builder addresses the creation and/or customization of the general ICAT interface shell (menus and text windows), formatted data displays, special text windows, interactive digitized images of hardware elements, and graphical representations of many commonly found input/output devices (for example, keyboards, keypads, gauges, switches, and a number of types of indicators).

INTELLIGENT COMPUTER-AIDED TRAINING

ICAT DEVELOPMENT ENVIRONMENT (continued):

- X-WINDOWS CURRENTLY SERVES AS THE BASIS FOR THE ICAT USER INTERFACE
- FORMATTED DATA DISPLAYS, TEXT WINDOWS, AND INTERACTIVE DIGITIZED IMAGES ELEMENTS HAVE BEEN DEMONSTRATED
- INTEGRATION OF DIGITAL VIDEO INTERACTIVE TECHNOLOGY

- TOOL FOR TRAINEE MODEL ADAPTATION PLANNED
- DATABASE DEVELOPMENT TOOL PLANNED

INTELLIGENT COMPUTER-AIDED TRAINING

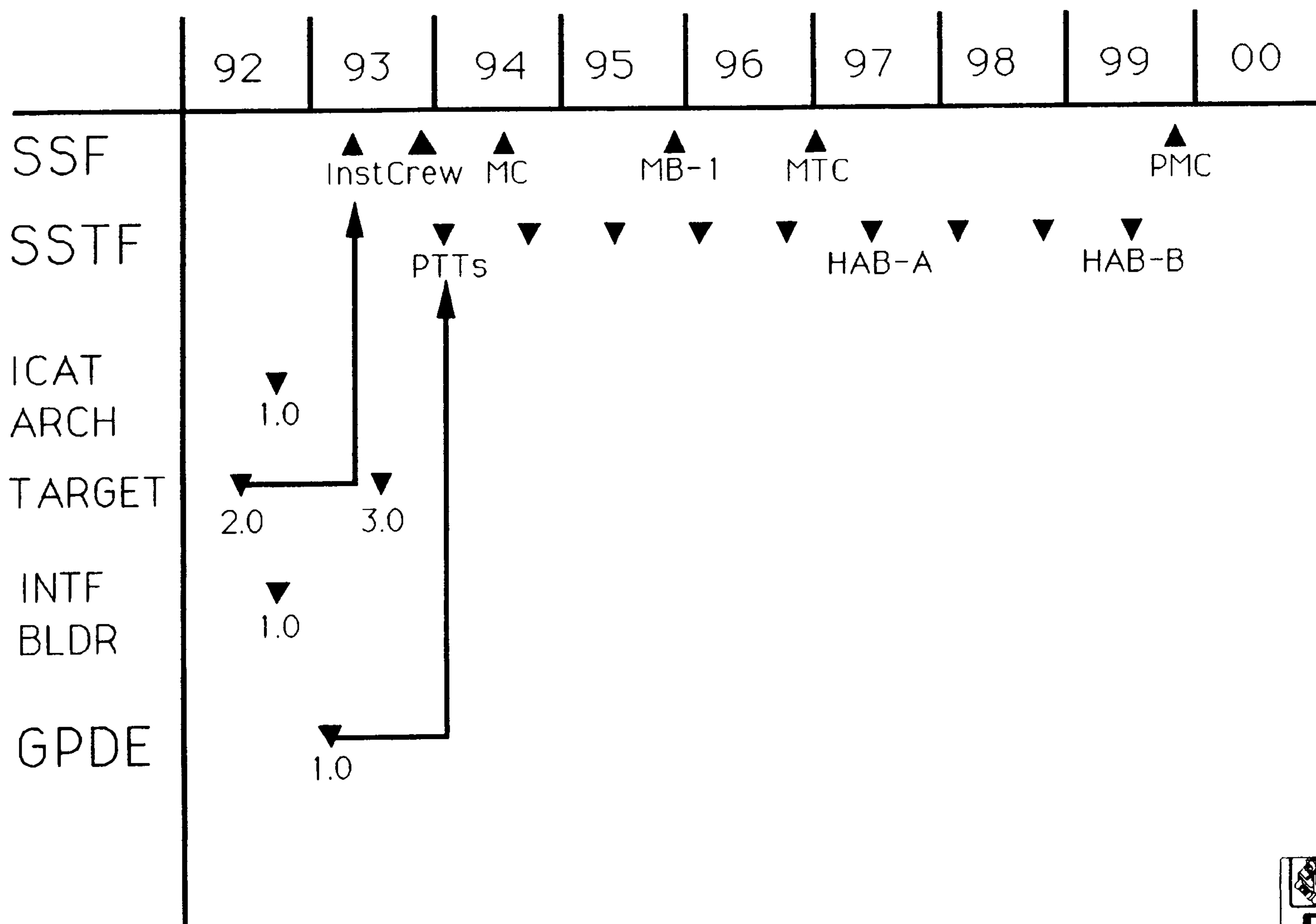
The ICAT interface builder is currently under development in an X-Windows environment; it will ultimately be available for the Macintosh and Microsoft Windows as well.

Through an SBIR (Phase I) project with Betac Corporation the integration of Intel's Digital Video Interactive technology is also underway.

Two additional elements of a software tool suite for ICAT application development are also planned. The way in which basic trainee action can be organized and used to identify both skill/knowledge mastery and misconceptions/lack-of-knowledge can vary among task environments. A tool to facilitate the adaptation of the trainee model structure for specific task environments will greatly aid trainers in "molding" the trainee model to give a more detailed representation of trainee performance, thus enhancing the overall ability of an ICAT system to provide an optimal learning experience for the trainee. The object-oriented database used by the Training Scenario Generator to assemble a specific training scenario would also benefit from a tool designed to facilitate the entry of appropriate domain-specific data.

INTELLIGENT COMPUTER-AIDED TRAINING

Project Schedule:



INTELLIGENT COMPUTER-AIDED TRAINING

The development of the general ICAT architecture and the General Purpose Development Environment for ICAT systems has been planned to coincide with milestones in the Space Station Freedom program. As the schedule shows, the general ICAT architecture and elements of the ICAT GPDE will be available for assessment and application development in advance of the assembly and training of instructor teams. The availability of TARGET can provide significant support to the Space Station Training Office in its analysis and development of procedures. The GPDE will be available for use in development part-task trainers and systems trainers.

SUMMARY:

- EFFECTIVE AUTONOMOUS ICAT SYSTEMS HAVE BEEN BUILT AND DELIVERED IN A WORKSTATION ENVIRONMENT
- A GENERAL ICAT ARCHITECTURE FOR PROCEDURAL TASKS HAS BEEN DEVELOPED AND USED TO CREATE SPECIFIC APPLICATIONS
- A SUITE OF SOFTWARE TOOLS THAT FACILITATE THE BUILDING OF SPECIFIC ICAT SYSTEMS FROM THE GENERAL ICAT ARCHITECTURE IS UNDER DEVELOPMENT

INTELLIGENT COMPUTER-AIDED TRAINING

The Software Technology Branch has developed and demonstrated a number of Intelligent Computer-Aided Training Systems for a variety of complex procedural tasks in the NASA operational environment. A general ICAT architecture has been developed and shown to be adaptable across this spectrum of tasks. Currently underway is the assembly of a suite of software tools that will permit the training community to rapidly develop and deploy ICAT systems for a variety of Space Station training tasks.

INTELLIGENT COMPUTER-AIDED TRAINING

SUMMARY (continued):

- THE COST OF DEVELOPING, DELIVERING, AND MAINTAINING TRAINING SYSTEMS CAN BE SIGNIFICANTLY REDUCED
- AUTONOMOUS TRAINING SYSTEMS CAN BE DELIVERED FOR BOTH GROUND-BASED AND ON-ORBIT USE; SUCH SYSTEMS COULD SIGNIFICANTLY REDUCE EVA TIME AND CAN REFRESH PERSONNEL PRIOR TO PERFORMING INFREQUENT OPERATIONS
- TRAINING EFFICIENCY, UNIFORMITY, AND VERIFIABILITY CAN BE ENHANCED—INCREASING SAFETY AND THE PROBABILITY OF MISSION SUCCESS

INTELLIGENT COMPUTER-AIDED TRAINING

The use of ICAT technology for selected training applications within the Space Station Freedom program can significantly reduce the costs of training system development. Once developed ICAT systems can be more readily and efficiently evolved and maintained that many conventional training systems.

ICAT systems can be delivered for both ground-based and on-orbit training. The availability of sophisticated on-orbit training will serve to reduce EVA time and can be especially useful in preparing crew for the performance on infrequent, mission-critical tasks.

ICAT systems can deliver uniform but individualized training to large numbers of personnel in a workstation environment. Such training does not impact the use of operational systems and is subject to detailed verification. These features demonstrate that ICAT systems can enhance safety and increase the probability that mission goals are met in an optimal manner.

N92-17353

JPL

OPERATIONS MISSION PLANNER

Beyond the Baseline

Eric Biefeld
(818) 354-4634

Presented by:
Lynne Cooper

Jet Propulsion Laboratory
California Institute of Technology

August 8, 1991

Operations Mission Planner

Eric Biefeld
Jet Propulsion Laboratory

Abstract

The scheduling of Space Station Freedom must satisfy four major requirements. It must ensure efficient housekeeping operations, maximize the collection of science, respond to changes in tasking and available resources, and accommodate the above changes in a manner that minimizes disruption of the ongoing operations of the station. While meeting these requirements the scheduler must cope with the complexity, scope, and flexibility of Space Station Freedom operations. This requires the scheduler to deal with an astronomical number of possible schedules.

JPL has been researching advanced software scheduling systems for several years (DEVISER, SWITCH, PLAN-IT, RALPH, PLANNER, and OMP). Our current research, the Operations Mission Planner (OMP), is centered around minimally disruptive (non-nervous) replanning and the use of heuristics limit search in scheduling. OMP has already demonstrated several new AI-based scheduling techniques such as Interleaved Iterative Refinement and Bottleneck Identification using Process Chronologies.

We are currently delivering these techniques to JSC for integration into the COMPASS scheduling tool. The first test case will by the Shuttle Systems Engineering Simulator (SES)

JPL

BACKGROUND

- Space Station Requires Advance Scheduling Techniques
  - Large Complex Ongoing Operations
  - Non-Nervous Replanning
  - Maximize Science Collection
- Leverages off of Current Research at JPL
  - DEVISER, SWITCH, PLAN-IT, RALPH, and OMP

Background

The scheduling of Space Station Freedom must satisfy four major requirements. It must ensure efficient housekeeping operations, maximize the collection of science, respond to changes in tasking and available resources, and accommodate the above changes in a manner that minimizes disruption of the ongoing operations of the station. While meeting these requirements the scheduler must cope with the complexity, scope, and flexibility of Space Station Freedom operations. This requires the scheduler to deal with an astronomical number of possible schedules.

JPL has been researching advanced software scheduling systems for several years (DEVISER, SWITCH, PLAN-IT, RALPH, PLANNER, and OMP). Our current research, the Operations Mission Planner (OMP), is centered around minimally disruptive (non-nervous) replanning and the use of heuristics limit search in scheduling. OMP has already demonstrated several new AI-based scheduling techniques such as Interleaved Iterative Refinement and Bottleneck Identification using Process Chronologies.

Concurrently, JSC and McDonnell-Douglas (MDAC) are performing work on developing interactive scheduling tools for use by ground personnel and astronauts on the Space Shuttle and for Space Station Freedom (SSF). This task is led by Dr. Barry Fox of MDAC, Houston and is sponsored by NASA Codes M and ST and contracted from the Software Technology Branch under Robert Savely at JSC.

These two efforts complement one another. The usefulness of interactive tools for scheduling will be enhanced by removing some of the burden from ground-based and astronaut users by automating aspects of the scheduling process.

JPL

OBJECTIVE

- Develop and Demonstrate Advanced Automated Scheduling Techniques Suitable for Space Station Freedom

Operations Mission Planner

BBL 8/91-3

Objective

Deliver software implementing functional capabilities for automated scheduling from JPL to Mr. Savely's and Dr. Fox's effort at JSC/MDAC to support SSF scheduling needs.

JPL

WHY?

Scheduling problem is intractable

Existing NASA scheduling is manually intensive

SSF will require continuous scheduling over extended lifetime

→

SSF Cannot afford the cost or non-responsiveness of existing scheduling philosophies

Operations Mission Planner

BBL 8/91-4

Why?

Scheduling and resource allocation needs for NASA are manifold: Maximizing science data collection, ensuring efficient routine operations, minimal disruption of ongoing activities during timely responses to unexpected events like transient science opportunities and resource disruptions. Currently most flight projects' schedules are largely built and maintained manually.

Future flight projects like SSF, EOS, or CRAF/Cassini, will demand a higher level of complex scheduling extended over large continuous periods of time. These flight projects may also require distribution of the scheduling task through out the various science communities. This will place exorbitant demands on the current style of highly manual scheduling. Emerging AI-based technology can provide automated assistance in the form of human/machine cooperative scheduling tools.

JSC with McDonnell-Douglas (MDSSC) is performing work on developing interactive scheduling tools (COMPASS) for the Space Shuttle and for Space Station Freedom (SSF). This task is led by Dr. Barry Fox of MDSSC, Houston, is sponsored by NASA Code MD. Our work on OMP complements the COMPASS work. The usefulness of interactive tools for scheduling will be enhanced by removing some of the burden from users by automating aspects of the scheduling process. A Code MT funded task exists to transfer OMP automated scheduling techniques to COMPASS.

JPL

BENEFITS

- Increase Mission Operations Productivity
  - Less Manual Effort in Producing and Maintaining Schedules
- Increase Station Utilization
  - Optimization of Schedule
- Increase Station Responsiveness
  - Reduce Time to Modify Schedule

Operations Mission Planner

BBL 8/91-5

Benefits

OMP will reduce the time and effort necessary in both generating and maintaining a mission plan.

Performance Enhancement:

OMP will allow the schedulers to spend more of their time in optimizing the schedule. This will lead to an increase in the science return of a mission. Also since the time to modify a schedule can be reduced it will become feasible to change the science request in response to earlier science observations.

Cost Reduction:

Automated scheduling will enable the creation of schedules in significantly less time and with substantially less human involvement. This can lead to a direct reduction in the size and numbers of the scheduling teams.

It will be faster, less expensive, and less disruptive to modify a schedule. The OMP approach, allows modification of an executing schedule while also maximizing the return received from that schedule and minimizing disruption.

The subsequent costs of using the schedule will be reduced because changes in the schedule will be automatically tracked. The use of a standardized, computer-based medium for schedule representation will enable the automated use of the schedule as input to other processes.

JPL

APPROACH

- Automated Scheduling
  - Iterative Refinement
  - Chronology
  - Search Paradigms
- Common Graphics Substrate
  - Support Multiple Styles
  - Portable
- OMP - COMPASS Integration
  - Initial data exchange
  - OMP as a COMPASS Button
  - Recode OMP Modules in ADA for COMPASS

Operations Mission Planner

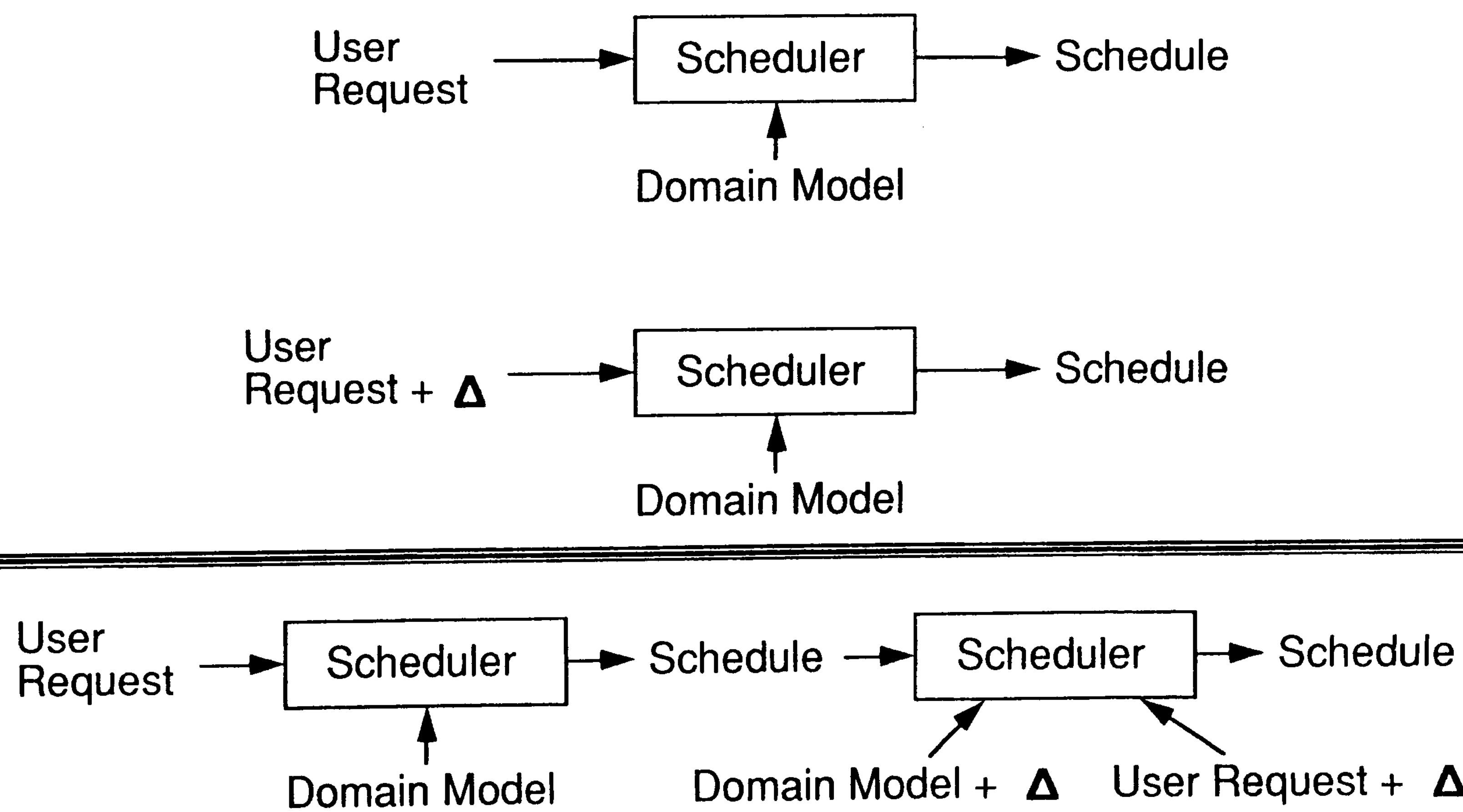
BBL 8/91-6

Approach

The approach to automated scheduling developed in OMP is based on the process used by expert human schedulers in planning the use of scientific instruments for Voyager planetary encounters This approach highlights several new AI-based scheduling techniques. The major innovation is the incorporation of multi-pass scheduling -- Interleaved Iterative Refinement -- where the scheduling system builds and refines a schedule over a series of passes. During the passes OMP constructs chronologies to assess progress and effort expended during the evolution of a schedule. The chronologies are used to identify schedule bottlenecks and focus the search process. This approach allows the same system to be used for both schedule construction and dynamic replanning. Details are in "Operations Mission Planner Final Report", JPL Publication 89-48, by E. Biefeld and L. Cooper.

JPL

REACTIVE SCHEDULING



Operations Mission Planner

BBL 8/91-7

Reactive Scheduling

Since the world is not a static place, replanning is a functional requirement for scheduling. Events in the real world change the assumptions upon which a plan is based. These events can be spectacular. For example, the first pictures returned by Voyager of Jupiter's moon, Io, showed a volcanic eruption. The mission scientists immediately requested changes in Voyager's schedule to obtain more information on this totally unexpected event. Most events are, however, more mundane and happen well in advance of the encounter.

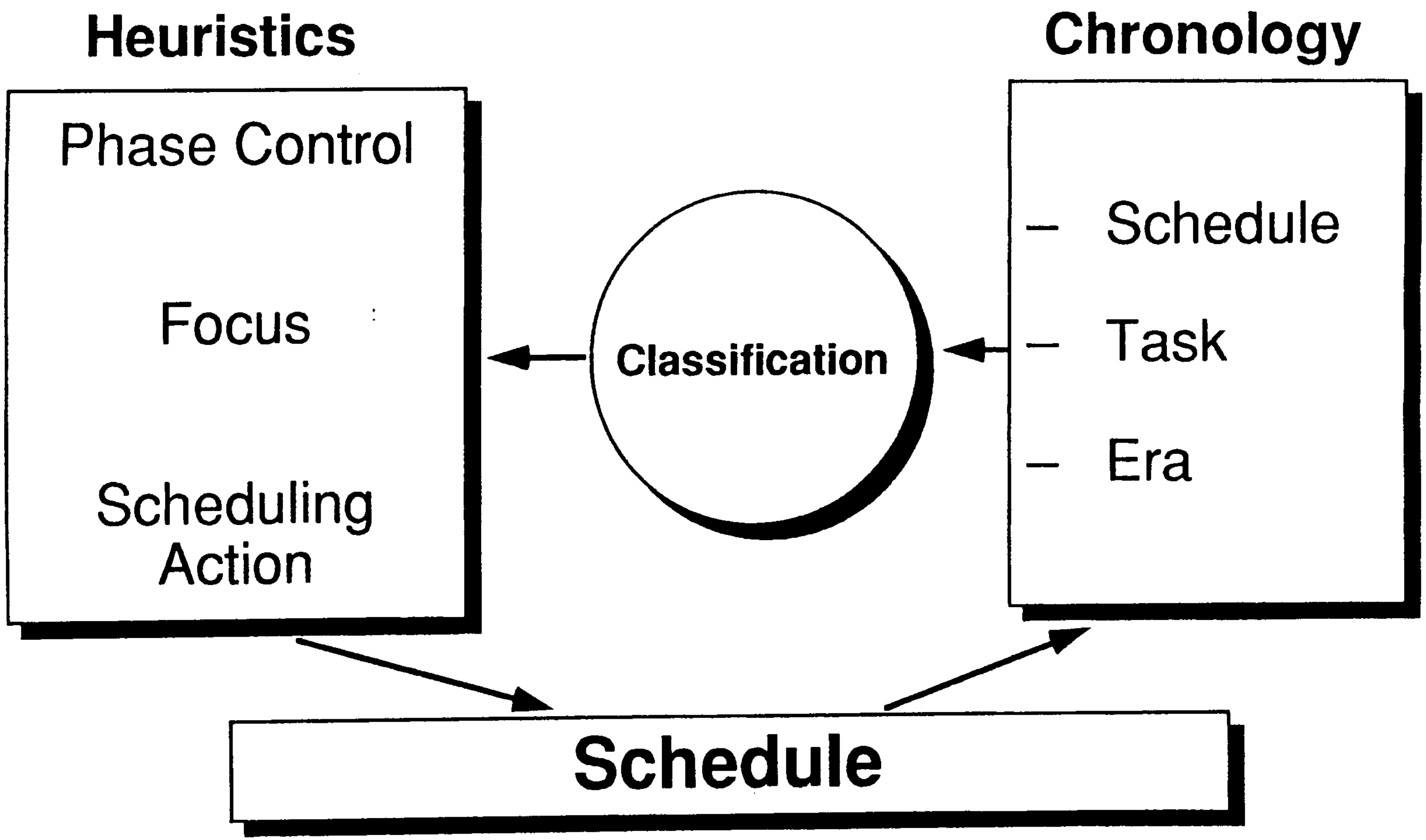
A currently popular approach to automated replanning is to simply plan again. The knowledge base and input tasks are updated and the software scheduler is rerun. The software scheduler then produces a new schedule which accomplishes the new tasks using the modified resources. Each time the scheduler runs, however, a radically new schedule is produced.

This approach leads to nervous replanning. This nervous behavior arises due to the underconstrained nature of the scheduling problem. For any mission scheduling-type problem, there exist many acceptable solutions that are radically different. Any change, however slight, in the planner's inputs may cause the planner to explore an entirely different section of the solution space. This change in the search will, most likely, lead to a schedule radically different from the original schedule. Mission planning is known to be extremely input-sensitive.

For a scheduler to survive in an operational environment it must be capable of making small changes to an existing schedule. If the inference engine must do extensive backtracking in order to change a task, then the scheduler is destined to exhibit nervous replanning. The old schedule must therefore be an input to the scheduler. The scheduler knowledge base must include the operational cost of making a change to the existing schedule, and the scheduling inference engine must accommodate this operational requirement for non-nervous replanning.

JPL

AUTOMATED SCHEDULING



Operations Mission Planner

BBL 8/91-8

Automated Scheduling

The scheduling problem devolves into controlling the search through a very large and complicated problem space. Brute-force search mechanisms are incapable of supporting automated scheduling with realistic and acceptable response times. Instead, heuristics are used to determine how to conduct the search.

Heuristics are simply rules of thumb which guide the performance of a given activity. Research at JPL has characterized three types of heuristics: (1) assessment heuristics, which assess the state of the schedule and provide information on how well the scheduler is performing; (2) dispatch heuristics, which perform the actual scheduling actions; and (3) control heuristics, which set and change the focus of attention of the scheduling process . The heuristics are the "brain" of the scheduling system. They determine what areas of the schedule to concentrate on; what types of changes to make; and, based on how well the scheduler is doing, when to change approaches.

In order to control the search, the scheduler must know about the difficulties arising in the particular schedule. The scheduler must identify the problem contention areas, called bottlenecks. Once this information is available, the scheduler can then use that information to direct the search process. This type of use of heuristics has been used in Ralph , a scheduler for the NASA Deep Space Network, and OPT and OPIS for factory scheduling.

JPL

ITERATIVE REFINEMENT

- After Each Pass
  - More is Known About the Schedule
  - Willing to Perform Deep Search on a Few Items
  - Not Willing to Perform Search on Many Items
- Five Phases
  - Initial Load
    - Resource Centered
      - Bottleneck Centered
        - Optimization
          - Event Handling

Operations Mission Planner

BBL 8/91-9

Iterative Refinement

Iterative planning consists of a series of scheduling phases. Each phase is responsible for a different aspect of the overall planning process. The first of these techniques roughs out the plan and identifies areas of high resource conflicts. The later techniques use the knowledge of the resource conflicts to refine the plan and solve many of the scheduling problems. The final techniques try to solve the last of the conflicts and add a few more tasks. Once the schedule is executing, changes are accomplished by reverting to the appropriate planning phase and making use of the information available on the schedule up to that point. During each phase, the scheduler cycles through its scheduling activities until it determines that a change in phase is appropriate.

By specializing the planning techniques associated with each phase, the techniques can be made more efficient. For example, the first techniques use shallow searches over a broad spectrum of tasks. Later techniques will use deeper searches which are applied to only a limited number of tasks. They will use knowledge about the particular schedule (i.e., the current resource conflicts, which tasks have changed most often in the scheduling process) to constrain the search space. The techniques will employ either a shallow and broad search or a deep and narrow search. If a planner must perform a broad and deep search, it will not be able to generate a schedule in any reasonable time. However, if the planner is always restricted to a shallow search, it will generate a severely suboptimal schedule.

JPL

CHRONOLOGY

- Limited History of the Scheduling Process
  - Actions Recorded Depend on Focus State
- Used to Guide Search Process
  - Provide Assessment of Scheduling Process
  - Identifies Bottlenecks

Operations Mission Planner

BBL 8/91-10

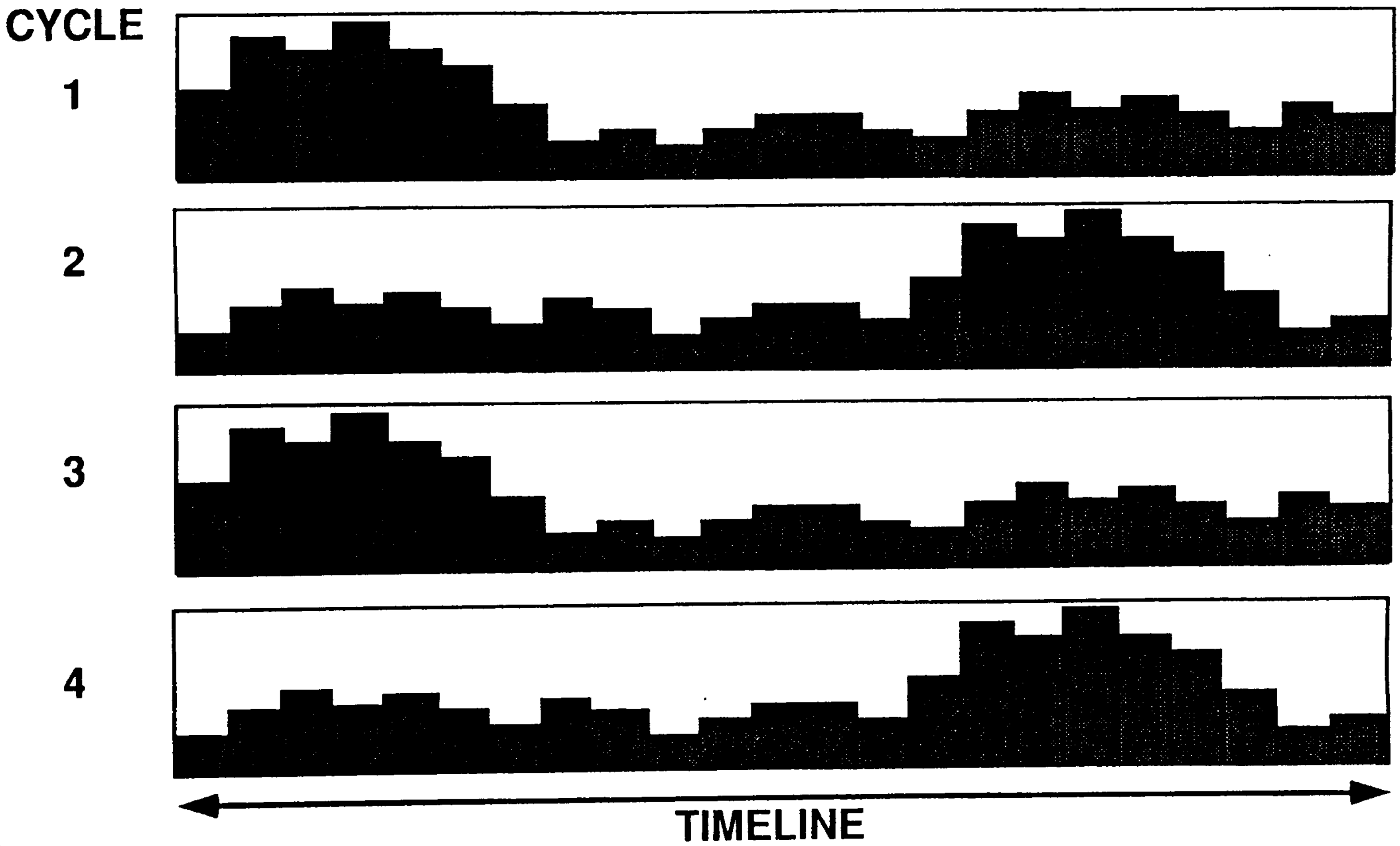
Chronology

A chronology is a limited history of the scheduling activity that has taken place. The chronology does not keep a complete snapshot of the changes taking place during the scheduling process. Rather, it focuses on characteristics which can provide information useful in directing subsequent searches. The chronology is used to identify interactions between time regions across several resources, detect the termination condition of a scheduling phase, and identify tasks that cause problems for the scheduler. Because we use an iterative approach to planning in which the scheduler focuses on either resources or tasks, the chronology keeps either resource or task information, depending upon the phase.

There are two activities associated with the chronology system: (1) collecting the information and (2) analyzing this information to characterize the schedule. During the multiple passes of each scheduling phase, information is collected to help the scheduler identify when the goals for that phase have been accomplished. For example, during the resource-centered phase, the goal is to identify the bottlenecks. Information which enables the scheduler to determine the boundaries of the bottlenecks is collected and analyzed. Once the bottleneck areas have been identified, that phase is complete and the scheduler changes its focus to perform bottleneck-centered scheduling.

JPL

BOTTLENECK IDENTIFICATION



Operations Mission Planner

BBL 8/91-11

Bottleneck Identification

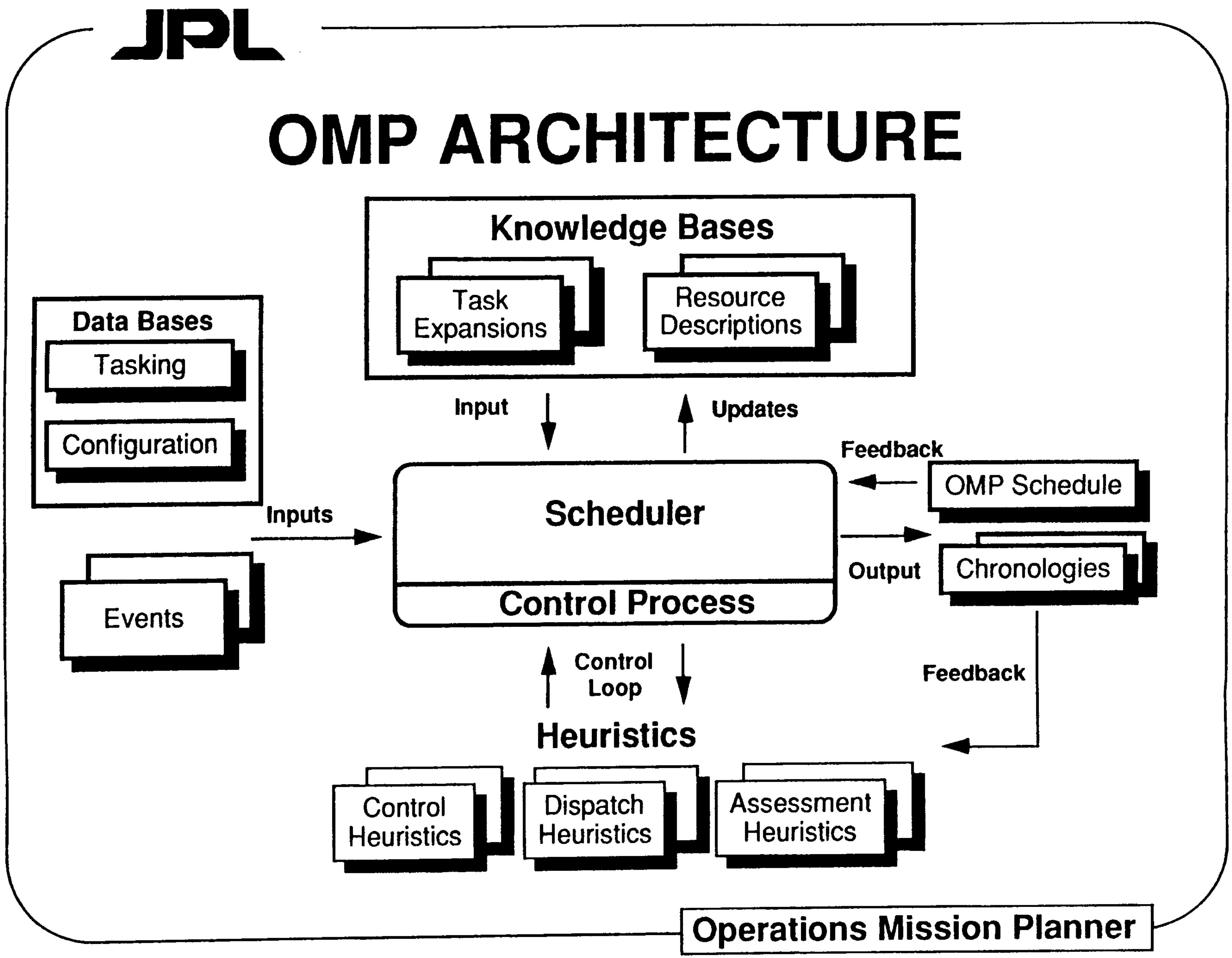
The identification of bottlenecks is an important and necessary step for effective scheduling. The exact location and extent of the bottlenecks are highly context-dependent. Since the scheduler cannot anticipate where the bottlenecks will be located, the basic approach is to perform a simple exploration of the schedule space and use the information gathered to identify the bottlenecks.

After performing the initial expansion of the tasks into activities, the scheduler focuses on the area in the schedule with the most conflicts The scheduler performs a shallow search, which lowers the number of conflicts in this area. Only the activities that are involved in the conflict are modified. The chronology module records the impact of these modifications on the resources.

While the search tries to avoid creating new conflicts, it will create them if necessary. The magnitude of these new conflicts may be larger than the magnitude of the original conflict that initiated the search. The scheduler will eventually focus on one of the new conflict areas. Solving this area may, in turn, cause other conflicts and so on, until the original conflict spot is once again in conflict. As the search progresses through the oversubscribed resources, the level of conflict in these and other areas oscillates. The conflict areas that continually oscillate in this manner are classified as potential bottlenecks.

As the scheduler focuses on a single conflict area, several other areas will be affected by the subsequent search. Since the conflict level for all these affected areas is modified during the same *focus state*, these areas and the conflict changes are all associated in the system's chronology. This chronological association of the oscillating resource areas allows the chronology module to group these areas into bottleneck regions.

OMP ARCHITECTURE



BBL 8/91-12

OMP Architecture

One of the major benefits of the use of AI in automated planning is the decoupling of the schedule model from the scheduling engine. This allows the addition of different types of tasks and resources without requiring changes to the scheduler. A generalized view of an intelligent scheduling system is given in the opposing view graph. The major components of the system are the knowledge bases, the data bases, the heuristics, and the schedule itself. The information in these distinct areas are integrated by the scheduling engine which produces the actual schedule.

JPL

SEARCH PARADIGMS

- **Hill Climbers**
  - **Quickly Finds a "Good" Schedule**
  - **Not Complete**
  - **Approaches to Local Maximum Problem**
    - Classical: Add Randomness
      Simulated Annealing
      Boltzman Machines (Neural Networks)
      Genetic Algorithms
    - Innovative: Varying Strategies
      Iterative Refinement
      Chronologies

Operations Mission Planner

BBL 8/91-13

Search Paradigms

At its highest level of control, OMP is a "Hill Climber." Hill climbing is a search strategy where neighboring nodes are evaluated to identify the best next step to take to improve the schedule. Hill climbers are fast and generally find a "good" schedule, but they don't provide a complete search. The major flaw with hill climbers is that they get caught at local maximums.

The classical approach to solving the local maximum problem is to add randomness to the evaluation function (simulated annealing), thereby allowing the scheduler to move beyond the local maximum.

OMP's approach is to vary search strategies based a characterization of the problem area. Essentially, OMP changes the evaluation functions over the local regions in order to search using the most appropriate strategy.

JPL

SEARCH PARADIGMS CONT

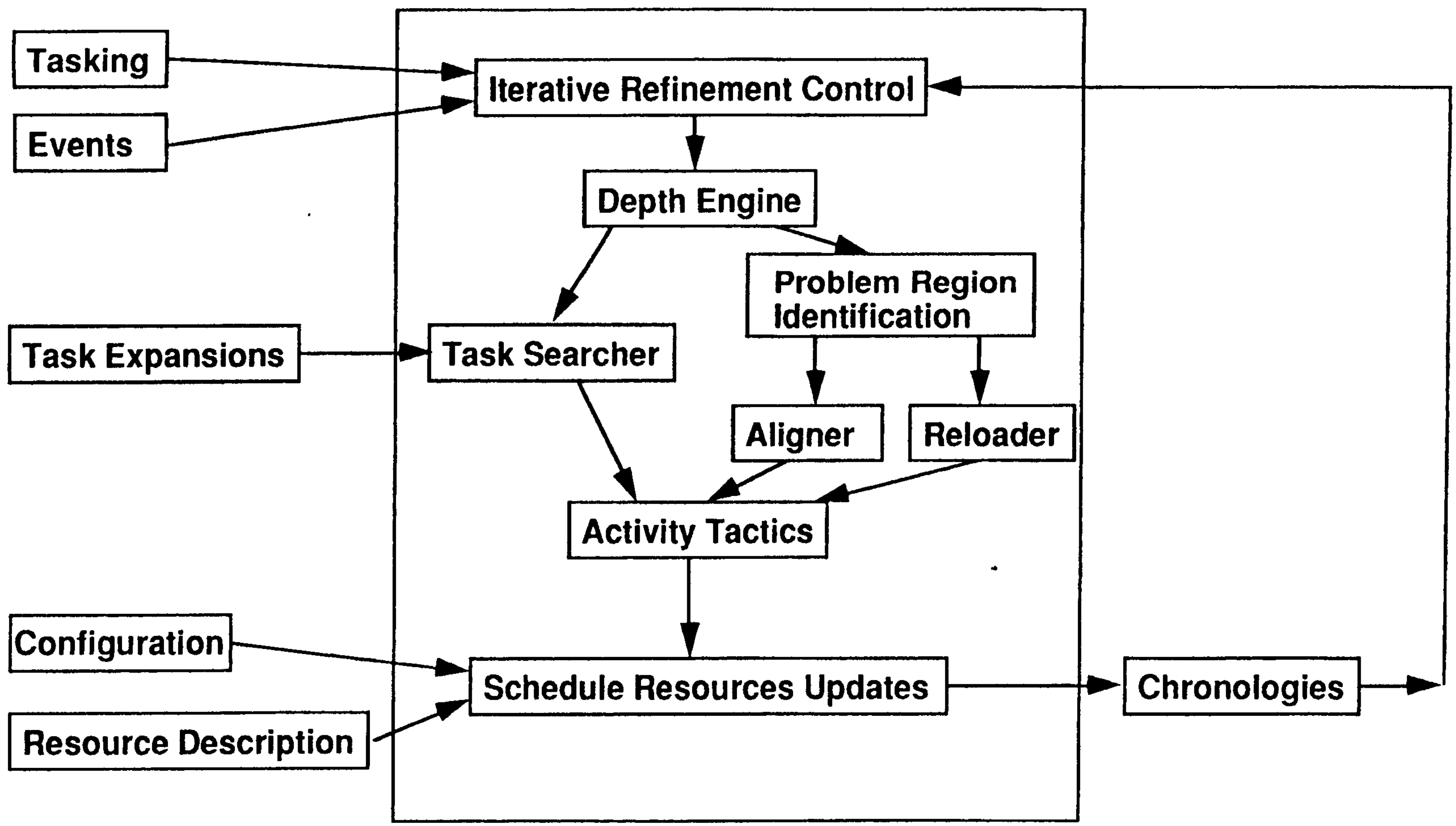
- Hill Climber With Seven League Boots
  - Keep Speed of Hill Climber
  - Use to Find Non-Shallow Task Interleaving
  - Address Local Maximum Problem
  - Provide Depth Cutoff

Operations Mission Planner

BBL 8/91-14

JPL

OMP ARCHITECTURE - 2



Operations Mission Planner

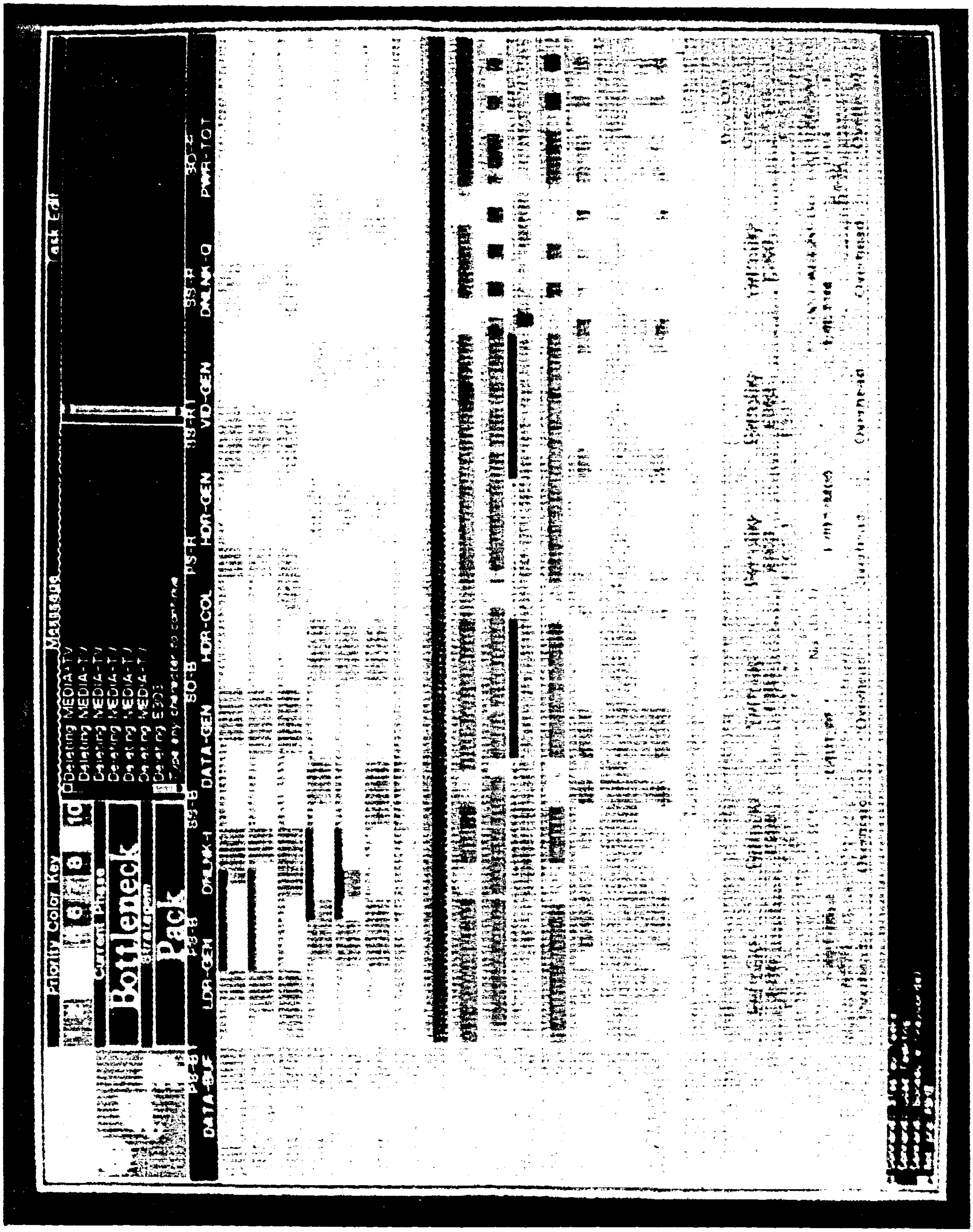
BBL 8/91-15

OMP Architecture - 2

There exist many different scheduling heuristics that focus the search on a particular aspect of the schedule. While these techniques exhibit excellent performance in some cases, they are not universally applicable. Therefore, the scheduler must identify when a particular scheduling heuristic may be appropriate. The iterative refinement approach is based on making the most effective use of the various scheduling heuristics.

In using the search, there is a trade-off between power and time; the deeper the search, the longer the time required. The use of a deep search over the entire schedule is infeasible and unnecessary, but limiting the deep search to limited segments where a less powerful search is ineffective is productive without incurring unreasonable costs.

The chronology system provides the necessary information for the control heuristics to determine which scheduling heuristics to use and where. This provides the scheduler with the flexibility necessary to approach the variety of scheduling problems encountered in the generation of a single schedule. This, in turn, enables the scheduler to expend a greater amount of effort on tightly focused areas, thus producing a more effective schedule.



ORIGINAL PAGE IS
OF POOR QUALITY

JPL

COMMON GRAPHICS SUBSTRATE

- Designed to Support Variety of Graphical Styles and Future Enhancements.
  - PLAN-IT
  - COMPASS
  - OMP
  - RALPH
- Portable (C++ & ADA)
  - X-Window
  - Macintosh
  - Microsoft Windows
  - PostScript
- Separates Graphics from Scheduling Engine

Common Graphics Substrate

During the past year a group of individuals from various NASA scheduling projects formed an informal working group to address issues in building portable scheduling graphics. The members of this group have built scheduling graphics in support of their research (PLAN-IT, COMPASS, OMP, and RALPH). While on the surface these graphical interfaces are not identical there is much commonality in their components. The results of this working group is an outline of a Scheduling Graphic Substrate. This substrate would support a verity of GUE features and be applicable for all of our different scheduling engines. It would also modularize the windowing system specific code to allow easier porting of the system from platform to platform.

JPL

OMP - COMPASS INTEGRATION
Long Term Plan

- COMPASS Produces Request, OMP Generates Schedule, COMPASS Displays Results
  - Standardized I/O Data Representation
- Integrate OMP as COMPASS Button
  - OMP is Background Process of COMPASS
- Recode Selected Modules of OMP and Integrate Code into COMPASS
  - Ada
  - Standardized Internal Data Structures

Operations Mission Planner

BBL 8/91-18

OMP - COMPASS Integration

There are three stages to the OMP - COMPASS integration. In the first stage COMPASS builds a file of the schedule and the changes that need to be made in the schedule. OMP can then read this standardized file and modify the schedule. OMP will then produce a standardized file continuing the new schedule that COMPASS will then read in and display. The advantage of this approach is that it will be easy for other systems other than OMP to use the same techniques to preform joint test and demonstration with COMPASS.

In the second stage both OMP and COMPASS will be closely coupled. COMPASS will invoke the OMP module and pass it the schedule information. OMP will then represent the schedule in its own internal format, modify the schedule and return the results to COMPASS. COMPASS will once again display the results. In this stage OMP will be directly called by COMPASS (as a button or buttons on COMPASS display) and the data transfer will be by directly function call and return.

In the third stage selected modules of OMP are recoded into Ada. This code will directly use the COMPASS internal data structures and will become part of the COMPASS program.

JPL

INITIAL COMPASS - OMP

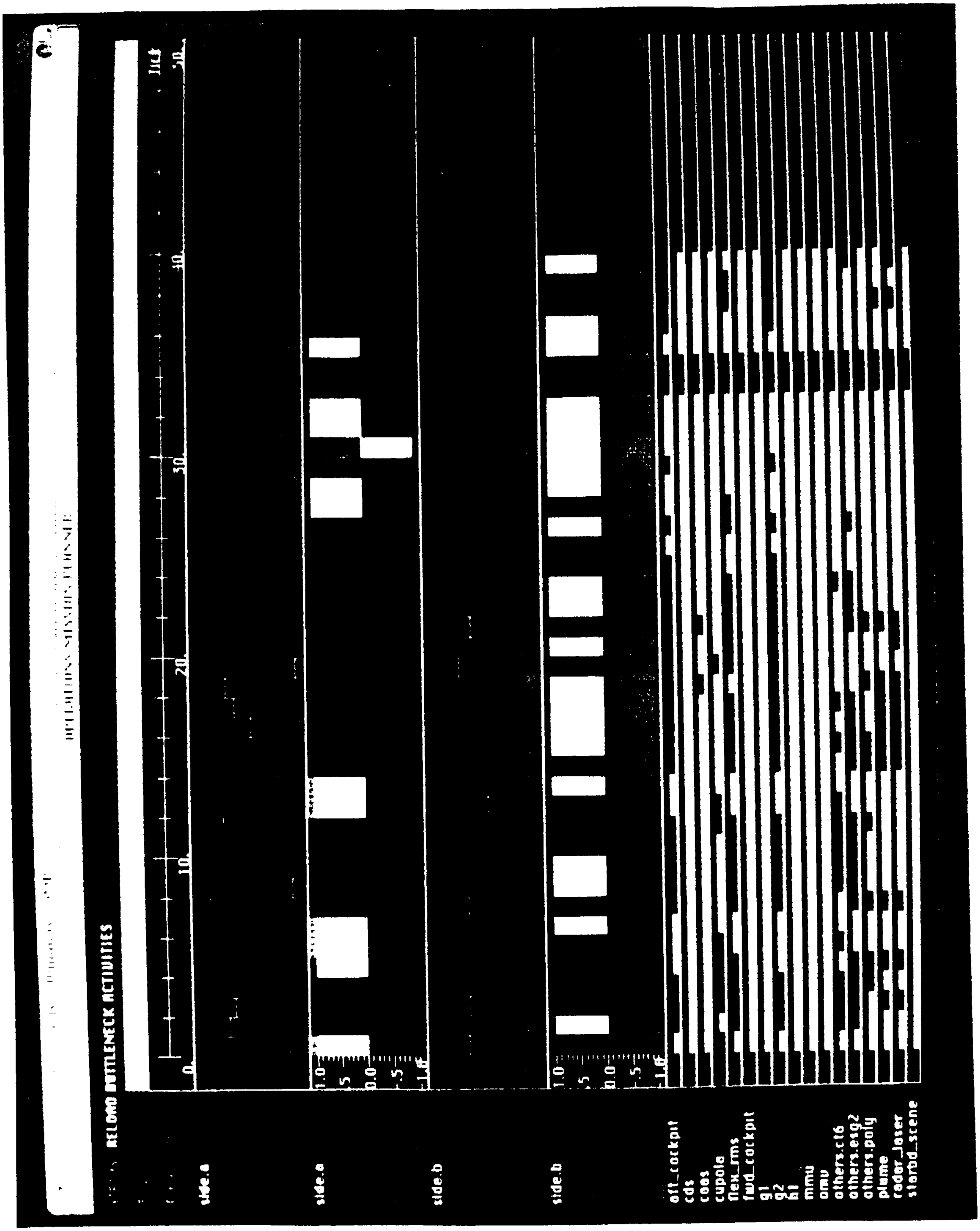
- Schedule Data in COMPASS Format
  - Data Sent Electronically to OMP
  - COMPASS to OMP Translator
  - Resulting Schedule Displayed by COMPASS
- Initial Test Case
  - Space Shuttle Simulator
  - One Week Schedule
  - 55 to 75 Request in a Week
  - About 20 Resources
  - Running Time 7 Minutes

Operations Mission Planner

BBL 8/91-19

Initial OMP - COMPASS

We have already sent a file continuing COMPASS output to OMP. OMP reads in this data and produces a modified schedule. The output will then be sent in a file back to COMPASS for redisplay.



ORIGINAL PAGE IS
OF POOR QUALITY

JPL

ACCOMPLISHMENTS (FY91)

- Demonstrated New AI-based Scheduling Techniques
  - Interleaved Interative Refinement
  - Bottleneck Identification using Process Chronologies
- Developed MacOMP
  - Received and parsed data from COMPASS
  - Ported OMP to Macintosh
- Integrated OR Strategies into OMP
  - Enhanced Chronology System
  - Strategies Produce Better Results then OMP I or II

Operations Mission Planner

BBL 8/91-21

Accomplishments (FY91)

In FY91 we have finished demonstrating the concepts of interleaved interative refinement and bottleneck identification using process chronologies. These concepts form the core of OMP architecture.

The newest concept demonstrated is the integration of Operation Research techniques with the chronology system. This will become the basis for out future work.

The new hardware platforms (SUN SPARC and Macintosh) have been procured and installed. The basic schedule representations are being ported to Common LISP and are being revised to support the newly designed scheduling engine. A set of graphical scheduling animation primitives have been implemented on the SUN SPARC and on the Macintosh workstations.

JPL

PLANS (FY92)

- Implement Generic Scheduling Interface Architecture
  - X-Windows/Sum MacToolBox/Macintosh
- Integrate Optimize Phase with OMP Chronology System
  - Next Generation OMP
- Demonstrate OMP III with COMPASS

Operations Mission Planner

BBL 8/91-22

Plans (FY92)

During FY91 we will complete the implementation of OMP on a SUN SPARC and Macintosh workstations. The new implementation of OMP will prototype the Load and Optimize phases of the general OMP scheduling theory. The basic representation of OMP will be expanded to include several new constraints (Renewable-Consumables, States) and will feature an extended version of its current goal planning capability

This new version of OMP will be transferred to Code MT by way of JSC's COMPASS scheduling system. A COMPASS generated schedule and a new unscheduled activity will be sent electronically to OMP where the schedule is modified to include the new activity. The resulting schedule is then sent to COMPASS to be displayed.

Other goals for this year include implementing the generic scheduling graphics substrate in both X-Windows.and the MacToolBox.

JPL

SUMMARY

- Extended State of the Art in AI-based Scheduling
  - Advanced Control of Search Process
  - Minimally Disruptive Replanning Demonstrated
- Established Interface with COMPASS
- Demonstrated OMP Techniques on SSF-relevant Domains

Operations Mission Planner

BBL 8/91-23

Summary

The demonstration of multiple classes of scheduling knowledge, the use of chronologies to identify scheduling bottlenecks, the classification of these bottlenecks in determining which type of scheduling heuristic to use, and the interleaving of finding and solving bottlenecks, were all major research objectives demonstrated in the OMP prototype. This prototype was tested using COMPASS supplied data from a real world scheduling problem. The purpose of developing these techniques is to show the feasibility of an automatic scheduler which can use the knowledge gained in trying to construct a schedule and which operates by continually modifying an existing schedule. These techniques allow the construction of automatic schedulers which will be able to quickly and optimally construct large and complex schedules. The same systems will also be able to maintain the schedule in a minimally disruptive manner.

EMU EVOLUTION

EVOLUTION SYMPOSIUM
SOUTH SHORE HARBOUR
CONFERENCE CENTER
LEAGUE CITY, TX

8 AUGUST, 1991

PRESENTER: M. Rouen / NASA JSC / EC6

ABSTRACT

Evolution of Extravehicular Mobility Unit (EMU) technology is necessary to support the Extravehicular Activity (EVA) requirements of the Space Station Freedom Program and those of the Space Exploration Initiative (SEI). Key qualities supporting long-duration missions include technologies that are highly reliable, durable, minimize logistics requirements, and are in-flight maintainable and serviceable. While these qualities are common to SSF and SEI EVA, development paths will differ where specific mission requirements impose different constraints.

Development of reusable, regenerative technologies is necessary to minimize the logistics penalties. Increased battery discharge/recharge cycle life and useable wet life, compact high current density fuel cells, reusable CO_2 absorbing media, and thermal radiation coupled with venting heat rejection technologies are just some methods of reducing consumables. Development must strive for durable, reliable systems that are in-flight serviceable and maintainable, which are vital for missions where logistics capabilities are extremely constrained. Key areas include suit components (e.g. gloves, boots, and cooling garments), and life support hardware such as fans, pumps, instrumentation, and emergency O_2 systems.

Higher pressure suits will reduce EVA prebreathe requirements and pre-EVA operations overall. Many challenges of higher pressure suits have been addressed by on-going development. Emphasis on glove development is necessary to provide low fatigue, dexterous glove mobility at higher suit pressures.

Minimum impact hooks and scars which support an advanced SSF EMU have been identified. These accommodations permit upgrades that support servicing of low volume, high pressure oxygen systems, and hydrogen technologies such as fuel cell, and venting hydrogen heat rejection systems.

AGENDA

- Development Trends
  - History through STS EMU
  - Requirements vs Implementation
- SSF Baseline Requirements
  - Shuttle EMU enhancements to meet baseline
- SSF EVA Evolution Requirements & Implementation Paths
- SSF Evolution Hooks & Scars for Advanced EMU
- SEI EVA Concepts/Requirements
  - Common development paths (SSF & SEI)

DEVELOPMENT TRENDS

CATEGORY	REQUIREMENTS	IMPLEMENTATION
EVA Translation & Vehicle Proximity	EVA near vehicle (Gemini, Skylab)	Umbilical life support, venting
	No proximity restrictions (Apollo, Shuttle)	Independent, portable life support, closed-loop systems, compact packaging, increased complexity, maximum capacity for wt & vol
Equipment Service Life	Single Mission (Gemini, Skylab, Apollo)	Custom size suits, non-maintainable construction, limited life requirements, ground maintenance & servicing
	Multiple Missions, long shelf life (Shuttle)	Standard sized suit components, maintainable modular construction, highly durable materials, more on-orbit servicing & maintenance
Crew Cabin Environment	3 - 5 psia (100% O2) (Gemini - Apollo)	Similar suit pressures, prebreathe completed prior to launch
	10.2 - 14.7 psia, O2, N2 mixture (Shuttle)	Increased: suit pressure, prebreathe protocol, suit & glove mobility

DEVELOPMENT TRENDS - TEXT

It is clear from the development of EVA capability in the U.S. Space Programs that the major shifts in the Extravehicular Mobility Unit (EMU) space suit and life support system design and implementation are driven by significant changes in the nature of the EVA mission and, to some extent, the nature of the specific program life and funding.

Early EVA missions of the Gemini program were conducted specifically to develop EVA requirements and techniques for future programs. As the character of EVA operations became better understood, the role of EVA shifted from that of 'flight experiment' to 'mission resource'. As EVA shifted to that of a mission resource, the EMU hardware life cycle shifted to fit not only the mission requirements, but the program life requirements as well.

The EVA missions of the Gemini, Skylab, and Trans-Earth Apollo required no extensive excursions far from the space vehicle. These systems tended to use open-loop, umbilically supported life support systems except when flight testing EVA equipment for different mission requirements. The Apollo-Lunar and the Shuttle program EVA mission requirements called for independent, portable life support systems. The Apollo-Lunar EVA requirements necessitated total independence from the vehicle in order to make EVA an effective resource for Lunar exploration and research. The Shuttle EVA missions, although generally conducted within the vehicle payload bay, are more broad in scope (such as satellite retrieval) and also require independent, portable life support. These systems had to be closed-loop, and tightly packaged to meet size, weight, and mobility requirements.

As program requirements shifted from single mission to continuing operations, the life cycle requirements and the construction of the EVA equipment shifted dramatically. The suits for Gemini through Apollo were custom made for each crewmember to optimize fit. The size and dynamic nature of the crew cadre for long-term programs such as Shuttle required smaller inventories of standard sized suit components and sizing elements to keep program costs low. Life support construction also shifted from low maintainable in-line construction to more maintainable modular construction to facilitate equipment processing with low inventory and enhance on-orbit maintenance and servicing.

SSF EMU BASELINE

- SSF program selected the STS EMU to reduce program cost
- STS EMU life support technologies

Primary Oxygen	900 psia compressed O_2
Emergency Oxygen	6000 psia O_2, not rechargeable on-orbit
Heat Rejection	Water sublimation to space, venting
CO_2 Control	Chemical absorption (LiOH), not regenerable
Humidity Control	Condensing heat exchanger with water separator
Power	Ag-Zn battery, 135 day wet life, 8 charge/discharge cycles

- Current certification
  - 7 hour maximum EVA @ 1000 Btu/hr
  - 30 minute emergency life support from high pressure O_2 system
  - On-orbit rechargeable primary life support consumables
  - Bends protection satisfied with 4.3 psia suit pressure and prebreathe protocol
  - 3 EVAs between ground checkouts

SSF EMU BASELINE - TEXT

The SSF program, as part of a program redefinition activity, selected the STS EMU as the baseline space suit and life support system to conduct SSF extravehicular activity. The decision was seen as a cost savings alternative to the program developing an advanced EMU specifically for SSF. The STS EMU system configuration, interfaces, and capabilities were designed specifically for Shuttle Orbiter interfaces, and Shuttle EVA mission criteria. Effort is underway to integrate the STS EMU into the baseline SSF EVA System.

The primary life support system provides 1.217 lbs of useful oxygen for metabolic consumption and other suit requirements. The primary oxygen is stored at 900 psia in the EMU portable life support system (PLSS) and is serviced from the Shuttle Orbiter Cryogenic oxygen system. The STS EMU ventilation loop is closed. A non-regenerable contamination control cartridge is used to scrub carbon dioxide from the vent loop by chemical absorption. Humidity is removed with a condensing heat exchanger. A centrifugal water separator pumps the condensate to the EMU water tanks for later use in heat rejection. A pressure-regulated water-fed sublimator provides the major heat rejection and heat exchanger sink temperature for the STS EMU during EVA. Each EMU holds a minimum of 9.8 lbs of water for EVA heat rejection. An eight (8) charge/discharge cycle, silver-zinc battery provides the electrical power during EVA. The battery has a wet-life of 135 days after chemical activation.

The STS EMU can support a maximum EVA duration of 7 hours. If the average metabolic rate is at 1000 Btu/hr or less, the battery tends to be the limiting consumable. The nominal suit operating condition is at 4.3 psia with 100% oxygen concentration. Since the orbiter cabin condition is a mixture of oxygen and nitrogen at 10.2 psia to 14.7 psia, protection against decompression sickness is satisfied with an appropriate prebreathe protocol for the cabin condition. All of the EMU primary life support consumables are on-orbit serviceable. The EMU oxygen and water are serviced with ECLSS fluids via the EMU servicing subsystem. The batteries can either be charged in the EMU, or replaced with fresh batteries prior to the next EVA. The contaminant control cartridge is replaced prior to each EVA.

A 30 minute emergency open-loop life support capability is provided by a regulated 6000 psia oxygen package. This unit is not rechargeable on-orbit.

The STS EMU is currently certified for 3 EVAs per Shuttle mission between ground checkout cycles. Some limited life components currently constrain the maximum time between uses to 60 days.

SSF EMU BASELINE

- SSF EVA requirements exceed present STS EMU certification
  - 22 EVAs maximum between resupply periods assuming skip cycle
    — Consistent with requirement of 52 EVAs per year
  - Approximately 200 days between ground refurbishment
- STS EMU enhancements underway to meet EVA demand and extended refurbishment interval
  - Recertification of current life support system and suit
  - Redesign and certification of some system filters
  - Increased maintenance interval on suit bearings and connectors

Other STS EMU enhancements planned to streamline STS processing and on-orbit use

- Captive fasteners on many life limited components
- Improved suit resizing capability
- Metal hard upper torso

SSF EMU BASELINE - TEXT

The SSF program baseline requirements call for the EVA System to support up to 52 EVAs per year at SSF permanent manned capability (PMC) phase. Three EMUs are on-board SSF at any given time (two prime units, and one backup). The EVA System and SSF must support up to 44 EMU recharges (equivalent to 22 two-man EVAs) between orbiter resupplies. This enables a moderate EVA capability should the SSF encounter a skip in the nominal orbiter resupply period as defined by the NASA Mission Operations Directorate.

	Period (Days)	SSF Operations Mode	EVAs per Period
Nominal Resupply	90	Nominal	13
Skip Cycle	45 (first)	Nominal	6
	45 (last)	Contingency	3
Totals	180		22

Assuming additional time for ground transportation and handling, the total time between EMU ground checkout could be 200 days. Also, the EMUs that are replaced will probably need to be able to support an orbiter contingency EVA raising the total requirement to 23 EVAs in 200 days. Since these requirements exceed current STS EMU capabilities, enhancements and testing are underway to extend the STS EMU in-flight service limits.

The majority of the STS EMU service life extension can be achieved by testing and recertification of current configuration space suit and life support hardware. This activity is in work. Some system filters require redesign and recertification to achieve desired service life goals.

Additional STS EMU design enhancements are planned to streamline processing of STS EMU equipment. Limited life system filters that significantly impact EMU performance will be identified by testing and those filters will be redesigned with increased capacity. Captive fasteners to speed replacement will be incorporated into this redesign. Suit sizing elements will be redesign for rapid resizing of lower arms, and upper and lower leg suit segments. In addition, the space suit hard upper torso will be redesigned with aluminum to extend component service life.

SSF EVA EVOLUTION

- High EVA demand is forecast for SSF evolution scenarios
  - Impacts on logistics, crew time, EVA crew task data handling
- Development Goals

GOAL	IMPLEMENTATION PATHS
Minimize logistics	• Employ low venting, regenerative technologies • Maximize on-orbit service life of life support and space suit equipment • Employ low weight system configurations
Minimize crew time	• Maximize equipment service life between maintenance intervals • Automate maintenance, servicing, and checkout functions • Electronic access of crew data • Decrease suit maintenance and resizing time
Minimize crew fatigue	• Reduce/eliminate prebreathe time • Improve suit and glove mobility

SSF EVA EVOLUTION - TEXT

Both the Fisher - Price External Maintenance Task team and the Solutions team final reports forecast high EVA demand for maintenance on-board Space Station Freedom. In addition, SSF evolutionary scenarios, including vehicle processing for SEI, will dramatically increase EVA processing requirements. In order to effectively and efficiently meet these challenges, EVA impacts to logistics requirements, crew time, and EVA crew task data handling must be minimized.

The minimization of EVA related logistics penalties is critical to the success of any long duration space missions where on-board resources are at a premium. By developing and employing low venting and regenerable technologies to future space suit/EMU designs, precious on-board consumables are kept to a minimum. Other logistics penalties may be reduced by maximizing the on-orbit service life of both the life support and space suit equipment. By reducing equipment failure modes and extending system life, fewer on-orbit spares are required to maintain an EVA capability. Other systems concerns are reduced when low weight system configurations are employed, this not only reduced resupply weight but also reduces overall station weight as well.

Crew support prior, during and post EVA must be kept to a minimum to facilitate the efficient operation of other crew related activities. Crew time, as with all other limited on-board resources, must be optimized and used efficiently. By maximizing equipment service life between maintenance intervals and providing equipment with automated maintenance, servicing and checkout functions, crew maintenance task time can be significantly reduced. Another method of increasing EVA crew effectiveness is to provide electronic access to crew operations data. This would eliminate reliance on manually updated/printed cuff checklists, reduce data retrieval time, and enable access to the latest information and newly generated data that address unanticipated EVA problems. Suit maintenance and resizing is a time consuming event with todays EMU and new technologies and design principles must be employed to future designs to facilitate suit maintenance and resizing.

A significant problem with today's EMU is crew prebreathe requirements and suit and glove mobility both of which contribute to crew fatigue. By minimizing crew fatigue, more efficient and productive EVAs can be expected.

ADVANCED THERMAL CONTROL SYSTEMS

- NON-VENTING
  - VAPOR COMPRESSION RNTS
  - ICE PACKS
  - THERMAL ELECTRIC/WAX/RADIATOR (RNTS II)
  - METAL HYDRIDE HEAT PUMP (MHHP)
- VENTING
  - VENTING METAL HYDRIDE HEAT PUMP (VMHHP) WITH AND WITHOUT RADIATOR
  - RADIATOR/VENTING LIQUID OXYGEN

THERMAL - TEXT

Original SSF requirements allowed only a non-venting EMU system due to expendables resupply and equipment contamination issues. The following thermal control options were studied, and as shown, the non-venting requirement resulted in large, heavy systems:

OPTION	VOLUME (ft3)	WEIGHT (lbm)	DURATION (hrs)
ICE PACK	2.0	160	8 (6 @ 1000 + 2 @ 500 Btu/hr)
TE/WAX/RAD	1.7	138	8 (6 @ 1000 + 2 @ 500 Btu/hr)
MHHP	0.7	196	4 @ 1000

(The Vapor Compression RNTS was found to be infeasible at this time, due to the current state of the art in compressors.) In 1989, the no-vent requirement was relaxed to allow consideration of smaller, lighter thermal control options. Because of this new consideration, the goal has shifted to development of a system which not only minimizes weight and volume, but also minimizes consumables.

OPTION	VOLUME (ft3)	WEIGHT (lbm)	DURATION (hrs)	LBM EXPENDABLES/EVA
VMHHP	0.2	70	4 @ 1000	0.7
RAD/LOX	0.2	29	8 (6 + 2)	6.1

For easy comparison with the current state of technology, the following is a list of STS-EMU characteristics:

OPTION	VOLUME (ft3)	WEIGHT (lbm)	DURATION (hrs)	LBM EXPENDABLES/EVA
SUBLIMATOR & WATER TANK	0.49	26	7 @ 1000	8.9

ADVANCED VENT LOOP COMPONENTS

- CO_2 AND H_2O REMOVER
  - MOLECULAR SIEVES
  - TE CONDENSING HEAT EXCHANGER
  - DESICCANTS
  - SOLID AMINE (HCCS)
  - ELECTROCHEMICAL (ERCA)
  - METAL OXIDE (MOCHR, MORES)
  - VENTING MEMBRANES
- PRIME MOVERS
  - AIR BEARING FAN

CO2 AND H2O - TEXT

The current STS-EMU utilizes non-regenerable Lithium Hydroxide (LiOH) for CO2 removal and a sublimator cold plate condenser for humidity control. In order to minimize logistics and resupply costs, the currently envisioned CO2 and H2O removal technologies should be regenerable at reasonably low temperatures and power levels. Some of these systems are able to perform both vent loop functions. The table below shows a weight and volume comparison of the systems under consideration for an Advanced EMU life support system:

OPTION	VOL (in3)	WT (lbm)	POWER (W)	CO2	H2O
TE CHX	100	8.0	20	NO	YES
DESICCANT	525	17.5	0	NO	YES
METAL OXIDE (MORES)	334	20.7	0	YES	NO
MOLE SIEVE	375	24.3	1	YES	YES
SOLID AMINE	2419	98.5	0	YES	YES
ELECTROCHEMICAL	1037	66.0	0.5	YES	YES
METAL OXIDE (MOCHR)	622	28.0	0	YES	YES
VENTING MEMBRANE	350	25.0	0	YES	YES

In addition to these CO2 and H2O removal components, development is underway for a low volume, and low power air bearing fan with variable speed control having potentially lower maintenance requirements than the current fan/pump/water separator assembly.

ADVANCED OXYGEN STORAGE AND SUPPLY

- HIGH PRESSURE OXYGEN
  - 3000-5000 psia
- SUBCRITICAL LIQUID OXYGEN
- SOLID OXYGEN
  - Metal Oxides

ADVANCED POWER SYSTEMS

- HIGH POWER DENSITY/CYCLE LIFE BATTERIES
- FUEL CELLS (FCESS)

O2 and Power - Text

The current STS-EMU uses high pressure gaseous oxygen for suit pressurization and metabolic O_2 supply. The primary oxygen bottles have a pressure of 900 psia, while the Secondary Oxygen Pack (SOP) is at 6000 psia. The goal for advanced life support oxygen supply is to increase the storage density of the oxygen in order to decrease the weight and volume of the existing system. There are three ways in which to meet this goal.

The first way is to store the gaseous oxygen at very high pressures, i.e. 5000 psia. This will significantly decrease primary O_2 storage volume from 852 in3 to 527 in3. However, due to the increased pressure, the system weight is expected to increase from 12.6 lbm to 22.4 lbm due to thicker walls of the pressure vessel. This option has inherent problems as well as benefits, not the least of which is the concern for safety while operating at such high pressures.

A second way in which to increase the oxygen storage density is to use a liquid oxygen system. Liquid oxygen can be stored in roughly one-third the volume of an equivalent high pressure oxygen system, while greatly increasing the overall system safety. As a result of low pressure operation a comparable LOX system would be only 150 in3, and have an operating pressure of approximately 150 psia. The problems encountered with using a LOX storage and supply are due to the difficulty of working with liquids in a zero gravity environment, namely, system recharge and quantity gaging.

A third option for decreasing the oxygen system weight and volume is to store the oxygen in a solid form. An example of this solid storage would be regenerable metal oxide oxygen storage. System weight and volume for this candidate has not yet been determined.

Another area in which technology development is on-going is in power systems. Due the greater power requirements envisioned for an advanced EMU, and again the need to reduce logistics and resupply costs, more efficient power supplies must be created. More specifically, batteries must emerge which have a higher current storage density and a greater charge/discharge cycle life than those currently used on Shuttle missions. In addition to battery development, fuel cells must be investigated for their high energy storage levels and ease of recharge.

Each of the advanced system options discussed here have both a number of benefits, as well as associated problems. Each system must be studied and the advantages and disadvantages weighed before a final system choice can be made.

ADVANCED CONTROLS, INSTRUMENTATION, AND INFORMATION DISPLAYS

- HELMET MOUNTED DISPLAY (HMD)
- ELECTRONIC CUFF CHECKLIST (ECC)
- VOICE RECOGNITION SYSTEM (VRS)
- AUTOMATIC COOLING CONTROL (ACC)
- FAST RESPONSE CO2 SENSOR (FRCS)

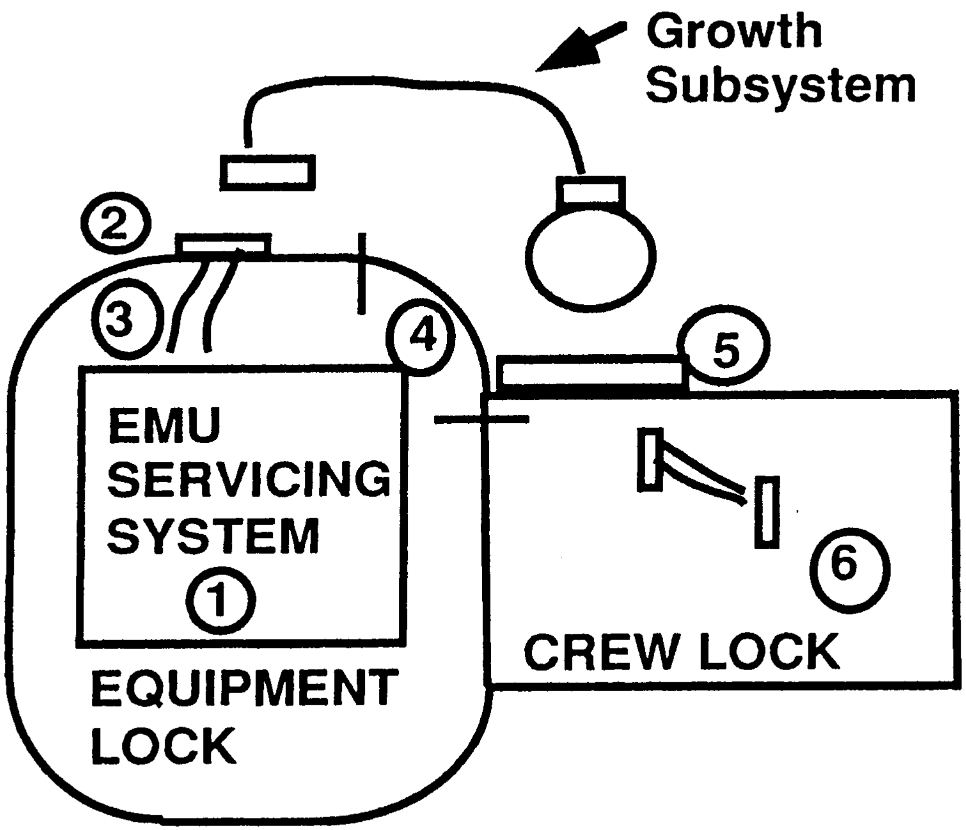
Displays and Controls - Text

The increased number of Extravehicular Activities (EVA) envisioned for the evolution of SS Freedom will dictate a need to increase crewman productivity and EVA efficiency overall. This increase can be accomplished through the faster dissemination of information to the EVA crew by means of an Electronic Cuff Checklist (ECC) or a Helmet Mounted Display (HMD). The ECC will allow for the storage of greater amounts of information than that currently available with the "paper" cuff checklist. Furthermore, the information display can be more easily accessed and updated than can the current system. Similarly, the HMD can allow a crewman access to even more information, which can be updated real-time from a ground- or space-based operation. Furthermore, when used in conjunction with a voice recognition system, the HMD can allow the crewman to access the needed information in a totally hands-free mode.

Another way in which to increase EVA efficiency is to incorporate an Automatic Cooling Control into the suit. This is a device which will sense the astronaut's metabolic activity level and operating environment and will adjust the amount of cooling through the Liquid Cooling Garment (LCG) accordingly. This automatic control has several benefits: 1) the crewmember does not need to interrupt important activities in order to adjust the cooling, 2) the crewmember is not distracted by the discomfort of becoming too hot or too cold, and 3) the thermal control system for the EMU will be smaller and lighter due to the more efficient use of the limited resources available.

In addition to these display and control methods, EVA productivity can also be increased through the use of more efficient EMU sensing systems. An example is the Fast Response CO2 Sensor (FRCS). This system can sense a change in the CO2 level of suit within seconds, and can be constantly updating the readings which allows CO2 level to be used as another indication of metabolic rate. In addition, development of this new sensor has become a necessity for Space Shuttle because the current CO2 sensor manufacturer is no longer making these sensors.

EVAS/AIRLOCK SCARS FOR ADVANCED EMU



Airlock has growth capability inherent in baseline design

1. Upgrade of EMU servicing system in EL at rack level
2. Few additional shell penetrations required
3. On-orbit plumbing additions possible
4. Growth capacity in shell and bulkhead power/avionics penetrations
5. Available mounting space for external growth subsystems
6. Upgrade of CL umbilical interface assembly

HOOKS AND SCARS FOR ADVANCED EMU - TEXT

The advanced EMU system configuration and technologies have many growth paths and the NASA has not selected any particular configuration. Sufficient hooks and scars should be incorporated into the baseline that complement inherent baseline growth capability to ensure that promising growth paths are not precluded.

Studies to date indicate that the airlock has growth capability inherent in the baseline design. Upgrade of the EVA System and airlock to support an advanced EMU can be accomplished with few additional hooks and scars. The most significant scar requirements accommodate external growth subsystems that service an advanced EMU with high pressure oxygen (3000 psia), and hydrogen. A high pressure oxygen compressor makes EMU primary and emergency O_2 on-orbit serviceable, and provides life support system packaging benefits. A hydrogen servicing subsystem would support promising advanced EMU technologies such as an EMU fuel cell and EMU cooling schemes that incorporate metal hydrides. A few additional airlock shell fluid penetrations are necessary to support the external growth subsystems. Existing power and avionics penetrations in the shell and bulkheads have adequate capacity to support growth scenarios. However, cabling must be added to the baseline to make full use of the growth capacity.

Upgrade of the EMU servicing system equipment located in the equipment lock (EL) can be done at the rack level. Preliminary evaluations show that rack weight and volume constraints can be met even with other distributed system equipment embedded in the racks. Rack level upgrade would require that other embedded equipment be duplicated in the growth racks.

Internal plumbing line additions to support new fluid services to the EMU servicing system can be made on-orbit for most fluids using a swage process that has been baselined for plumbing maintenance and repair. Leakage estimates for lines at 3000 psia using this swaging process range from 1xe-5 to 1xe-6 scc/s He. For installations of external subsystems, it is recommended that the utility scar design account for EVA access and operations with a pressurized glove. Judicious routing of utility lines and cables from shell penetrations to umbilical style interfaces will avoid EVA intensive on-orbit external plumbing and cabling.

Currently, mounting space that could be utilized by external growth equipment exists in the airlock baseline design. If the available space proved to be inadequate, scars to accommodate additional mounting grids would be a minor impact.

HOOK FOR COMMUNICATIONS WITH ADVANCED EMU

- NASA implementing digital UHF for dual use on SSF and STS
  - Allocations for current frequencies going away
  - Digital method more efficient use of frequency bandwidth
  - Time Division Multi-Access (TDMA) method selected
    - — One frequency, multiple users (time slots)
    - — Time slot allocations on-orbit selectable
    - — This technique supports growth with proper hook
- Current implementation of digital UHF supports forward link audio communications with 4 EMUs
- SSF UHF operational modes resident in firmware
  - Mode 1: SSF-to-Orbiter
  - Mode 2: SSF-to-ACRV1 and ACRV2
  - Mode 3: SSF-to-4 EMUs, MSC, MTFF
- Baseline operational modes preclude access by EVA astronauts to electronic data that support EVA operations
- Recommend hook that incorporates forward link data communications with advanced EMU
  - Mode n+1: SSF-to-4 EMUs including forward link(FL) data
    - — Recommend further evaluation to define all growth modes
  - Less cost than hardware upgrade later in program

HOOKS AND SCARS FOR ADVANCED EMU - TEXT

Another growth capability that should not be overlooked with an advanced EMU is the ability to provide the EVA astronaut access to electronic data. This would include access to the latest EVA operations datafiles, as well as custom generated data that would address unforeseen EVA circumstances. Many of the EVAs to date were to fix problems, some of which required on-orbit mission planning. An ability to update or generate specific EVA operations data by ground and on-orbit personnel with subsequent transmission to EVA crewmembers will enhance the likelihood of mission success.

Currently, the EVA crewmember carries a printed cuff checklist. This method is not desirable for SSF operations because cuff checklists are not easily revised, require special materials and printing processes for vacuum compatibility, and would require crew time to replace cuff checklist pages.

NASA is implementing a digital ultra high frequency (UHF) communications system for dual use on SSF and the Shuttle orbiter for a variety of reasons including frequency allocation. A Time Division Multi-Access (TDMA) method was selected to implement the digital UHF communications. This method, with the proper hooks, supports growth scenarios. The TDMA approach time-shares many users (one user per time slot) on one frequency. Which users, and what data types (audio, or telemetry) are supported can be changed by selecting any one of a few pre-determined operational modes. Proper definition and baseline inclusion of the evolution operational modes will allow communication modes for evolution without further hardware changes.

The baseline digital UHF system includes modes that support 1) audio communications between SSF and STS Orbiter, 2) audio and data communications between SSF and the Assured Crew Return Vehicles (ACRVs), 3) audio communications with EMUs and data communications with the Mobile Service Center (MSC), and a Man-Tended Free Flyer (MTFF), etc. These mode configurations will be resident in firmware which is not on-orbit reconfigurable.

In order to support an evolution capability of providing EVA crewmembers access to electronic data, it is recommended that an additional operating mode be included in the baseline modes definition that supports audio communications and forward link data communications with the EMUs. This kind of change made in the baseline will be significantly cheaper than future on-orbit upgrades which require hardware changeouts.

SPACE EXPLORATION INITIATIVE

REQUIREMENTS	IMPLEMENTATION PATHS
EVA in Partial Gravity	Light weight system configurations, improved suit mobility for surface locomotion
EVA Translation & Vehicle Proximity	Independent, portable life support, closed-loop systems, compact packaging
Dust / Contamination	Environmental seals, suit cleaning, protective over-garments
Minimize Logistics	Employ low venting, regenerative technologies, Maximize on-orbit service life of life support and space suit equipment, Employ low weight system configurations
Crew Cabin Environment probably < 10.2 psia	Prebreathe with current suit pressures may be minimal or nonexistent
Equipment Service Life	Standard sized suit components, maintainable modular construction, highly durable materials, on-orbit servicing & maintenance compatible with mission requirements

SPACE EXPLORATION INITIATIVE-TEXT

EVA mission requirements for the Space Exploration Initiative (SEI) (i.e. Lunar base and manned Mars missions) will bring about additional changes in EMU technology development. While the development of an SSF EMU is the first step to the development of an SEI EMU, additional technologies are required for EVA in partial gravity and partial atmospheres.

EVA in partial gravity will require EMUs that are light weight and extremely mobile to enhance surface locomotion and to minimize crew fatigue. Surface exploration will place the crew member at a significant distance from main transportation vehicle requiring EMUs that maintain independent, portable life support, are closed-loop for maximum performance, and are compact and mobile.

Another problem arising from surface exploration is dust and contamination. EMUs will require environment seals to eliminate internal contamination. New suit cleaning procedures will have to be developed. A possible path to minimizing suit contamination is to develop a disposable EMU protective over-garment.

Due to the distance and duration of SEI missions, EMU logistics penalties must be kept at a minimum. One method of obtaining this goal it to employ low venting, regenerative technologies and to maximize on-orbit (or surface) service life of both life support and space suit equipment. In addition, all systems must be of low weight configurations to increase payload capabilities.

Prebreathe penalties with current suit pressures may be minimal or nonexistent, if the crew cabin pressures for SEI are maintained at 10.2 psia or below, which increases EVA readiness and minimizes some aspects of crew fatigue.

Equipment service requirements for SEI could be different for Lunar and Mars programs. Lunar EVA could be similar to the STS program where small inventories of equipment supports a dynamic EVA cadre and a high number of EVA sorties. Early Mars missions are more likely to be characterized by smaller EVA cadres, but extremely long mission durations. Design goals for these missions will strive to maximize equipment stay time at Lunar/Mars bases. These requirements call for EMUs that are of maintainable modular construction, are of standard sized/ rapidly resizeable suit components, are constructed of highly durable materials and have on-orbit servicing and maintenance compatible with mission requirements

COMMON SEI AND SSF EVA TECHNOLOGY PATHS

Life Support System

Primary & Secondary Oxygen	• High pressure storage • Solid O2 storage • Subcritical LOx
Heat Rejection	• Radiator/Venting LOx • Radiator/Venting Metal Hydrides
CO2 & Humidity Control	• Venting membranes (vacuum application) • Light-weight, regenerable sorbents
Power	• Long life, high cycle battery • EMU Fuel Cell
Crew Data	• Electronic Cuff Checklist • HMD
Instrumentation	• Fast response, long-life, self-correcting sensors for CO2, O2, humidity, flow, and contamination

Space Suit

Mobility	• Improved glove mobility at any pressure • Reduced torque elbows and knees
Suit Sizing	• In-situ, rapid suit resizing

COMMON SEI AND SSF EVA TECHNOLOGY PATHS - TEXT

Common implementation paths were indicated in some areas to meet both SSF and SEI requirements. Common implementation point to common technology paths when compatible with other constraints specific to either SSF or SEI missions.

The common technology paths indicated for the portable life support system areas of primary & secondary oxygen, heat rejection, CO_2 & humidity control, and power support the often conflicting goals of reducing logistics penalties, and providing a fully serviceable light-weight, low-volume EMU. The oxygen technologies are compact with the subcritical LOx being the lightest technology approach. The heat rejection can be accomplished with radiators coupled with venting technologies for supplemental cooling. Venting membranes for CO_2 and humidity control also reduce system heat rejection penalties often associated with closed-loop methods of heat rejection. If logistics constraints demand closed-loop solutions, light-weight regenerable sorbents must be developed to minimize system weight. Long life, high charge/discharge cycle batteries and fuel cell technology will both reduce the logistics penalties for EVA.

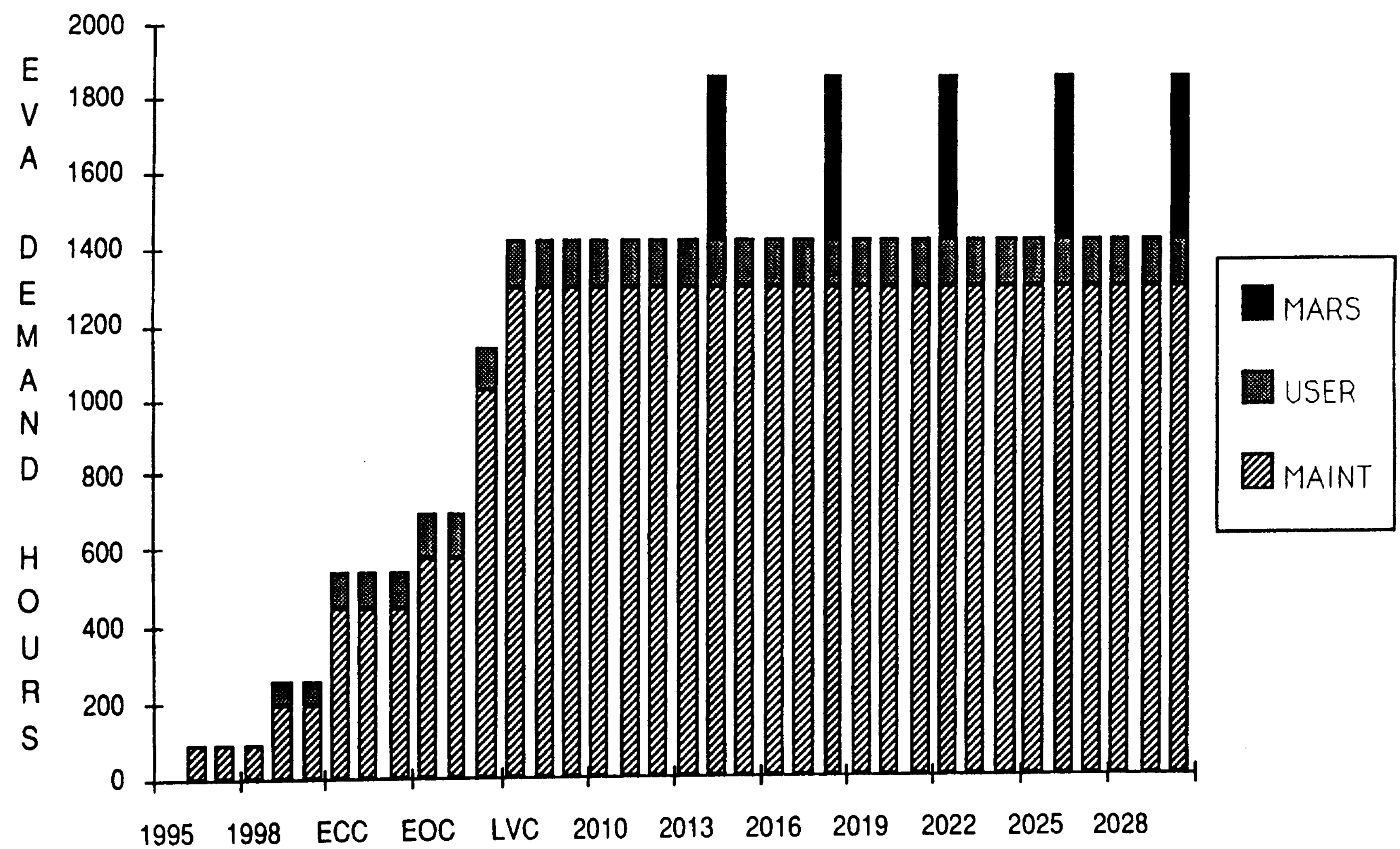
Technology paths such as an electronic cuff checklist, and helmet mounted displays, that support access and display of crew data, will enhance overall EVA operations while increasing the likelihood of mission success.

Highly reliable, self-correcting or calibrating instruments are critical to minimizing logistics penalties and crew time associated with life support system maintenance. Oxygen pressure sensors are often embedded in high pressure or LOx systems. Embedded sensors can drive the refurbishment cycle of larger subsystems. Fast response sensors enhance overall system caution and warning response to system malfunctions, as well as, provide data that supports automatic system control.

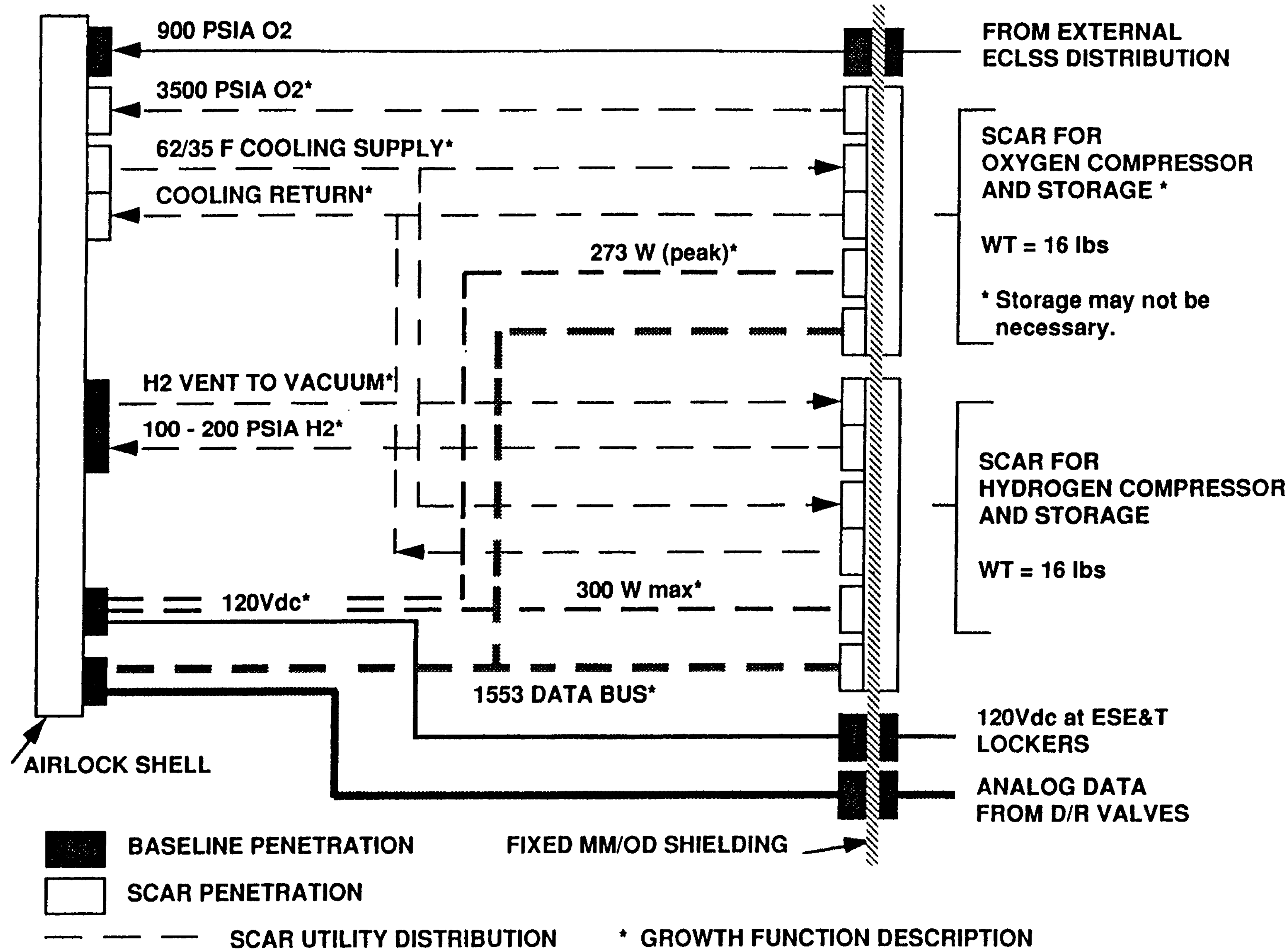
Common suit development paths for SSF and SEI will continue to increase suit and glove mobility to enhance EVA crewmember effectiveness. In-situ, rapid suit resizing capability will also reduce logistics and crew time penalties associated with the resupply of EVA crew and equipment.

BACKUP CHARTS

POTENTIAL EVOLUTION SSF EVA DEMAND



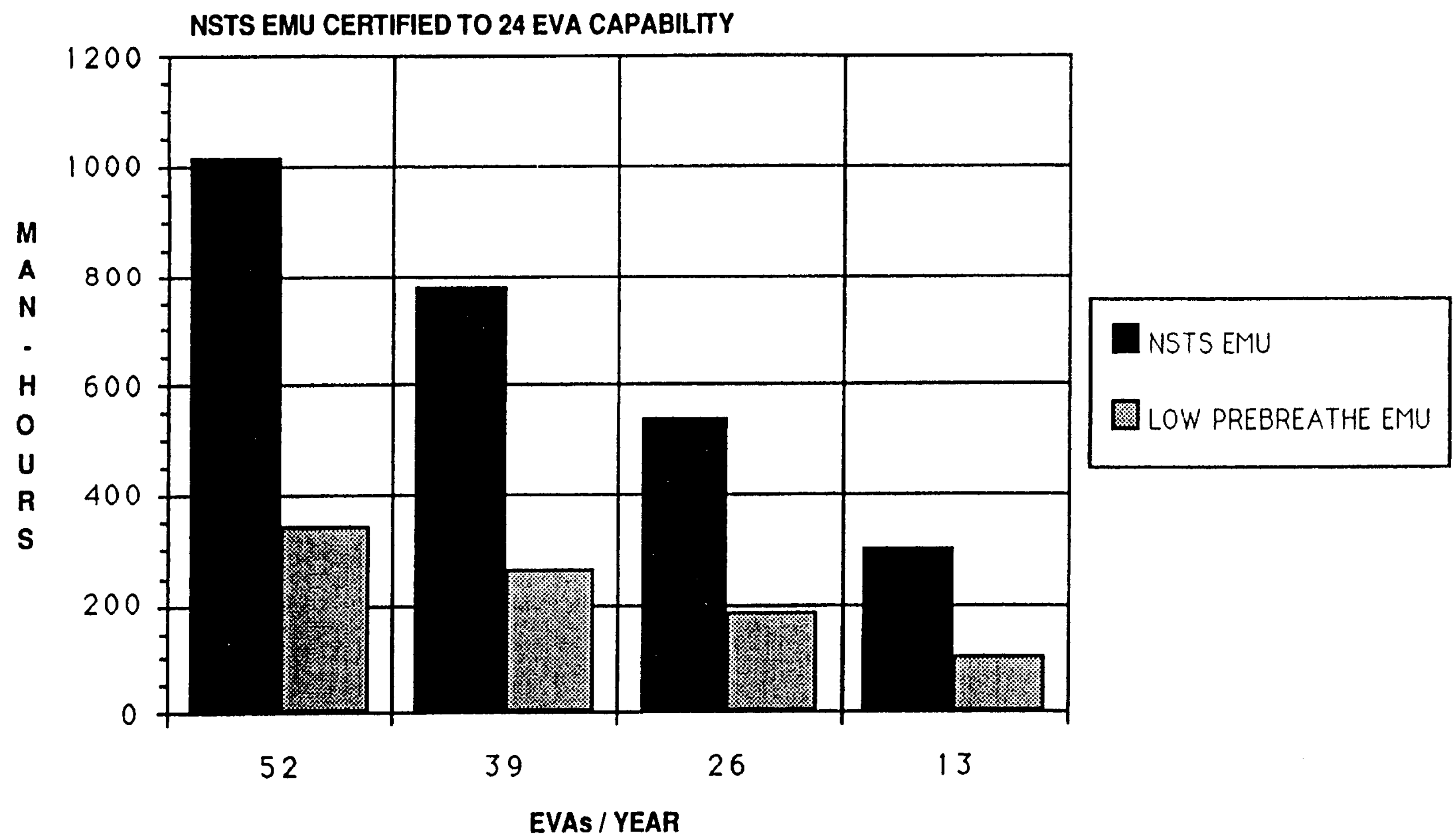
EXTERNAL AIRLOCK SCARS FOR ADVANCED EMU - FUNCTIONAL DIAGRAM



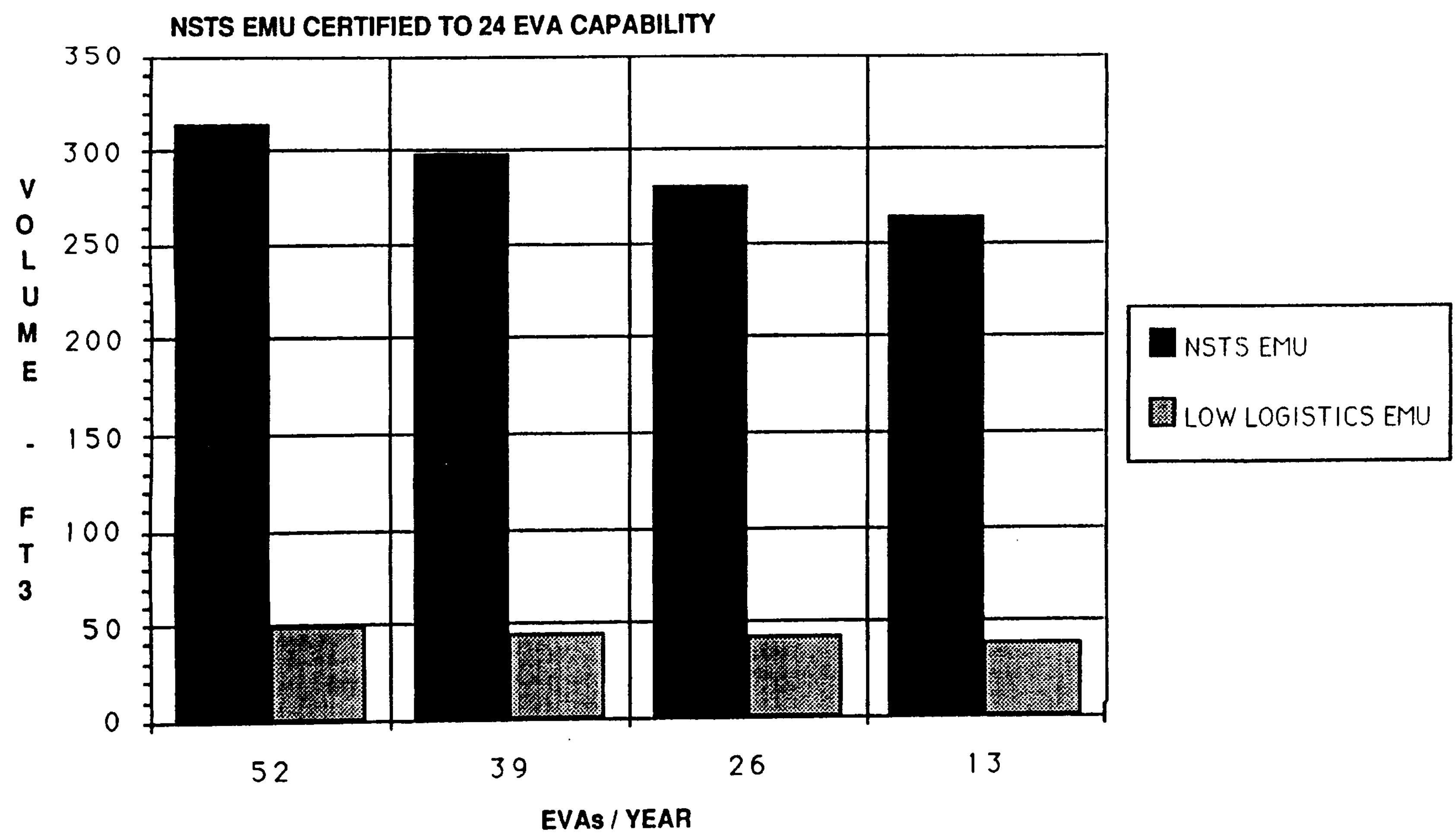
INTERNAL AIRLOCK INTERFACES FOR ADVANCED EMU

- On-orbit plumbing upgrades to support advanced EMU servicing system possible using swage process baselined for fluid line maintenance and repair
  - 3500 psia O_2
  - Internal Temperature Control System lines for external subsystems
  - 100 - 200 psia H_2
- Existing Equipment Lock (EL) to Crew Lock (CL) penetrations support advanced EMU except digital data communications with servicing system
  - Spare pins in existing avionics penetrations to CL able to support growth for digital data communications
    - Adequate cabling/pigtails from spare pins required to support growth
- On-orbit upgrade of advanced EMU servicing system equipment in the EL is possible at the rack level
  - Upgrade volume and weight estimates consistent with baseline constraints
    - Assumes worst case impacts to servicing system
- On-orbit upgrade of CL umbilical equipment also required

ANNUAL IV CREW TIME REQUIREMENT COMPARISON

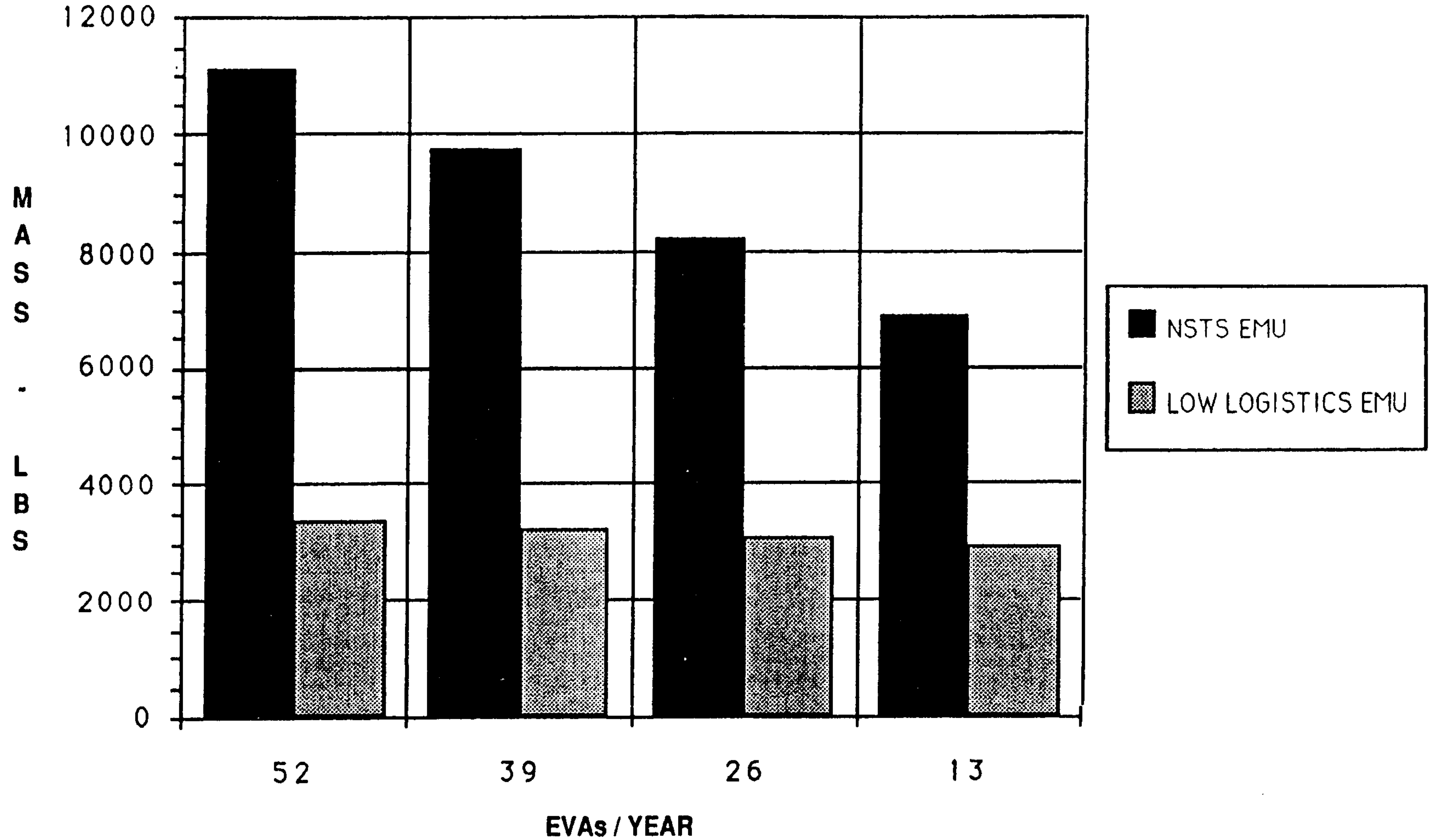


ANNUAL LAUNCH VOLUME COMPARISON



ANNUAL LAUNCH MASS COMPARISON

NSTS EMU CERTIFIED TO 24 EVA CAPABILITY



NASA
National Aeronautics and
Space Administration

Space Station Evolution:
Beyond the Baseline

FREEDOM

N92-17355

Environmental Control and Life Support System Evolution Analysis

Paul Wieland
Environmental Control and Life Support Branch/ED62
Marshall Space Flight Center
(205)544-7215

Presented by
Sandy Montgomery
Orbital Systems Support Group/PS04
Marshall Space Flight Center

August 8, 1991
League City, Texas

PRECEDING PAGE BLANK NOT FILMED

PAGE 1236 INTENTIONALLY BLANK

Space Station *Freedom* ECLSS Evolution

I. Introduction: Space Station *Freedom* Evolution Impact on the ECLSS and Technology Development Needs

The Space Station *Freedom* Environmental Control and Life Support System (ECLSS) will have to accommodate the changes made to *Freedom* as it evolves over 30 years or more. Requirements will change as pressurized modules are added, crew numbers increase, and as the tasks to be performed change. This evolution will result in different demands on the ECLSS which will have to adapt to these changes. Technologies other than the baselined ones may be better able to perform the various ECLSS functions and technological advances will result in improved life support hardware better able to meet the new requirements.

Some requirements such as resupply limitations are not as stringent for *Freedom*, which is in low Earth orbit, compared to more distant missions such as returning to the Moon and venturing to Mars. But resupply is still expensive and reductions are highly desirable. For the Lunar and Mars missions resupply is essentially impossible and this aspect determines many of the requirements which differ from *Freedom's*. Since one role for *Freedom* will be to serve as a test facility for the ECLSS for Lunar and Mars missions the advances necessary for these missions can also benefit *Freedom*. Other requirements for these missions also will be more stringent in significant ways, such as reliability and autonomy of operation.

It is necessary to identify the areas where present technology is inadequate to meet the more stringent requirements in order to focus research and development efforts. This will ensure that the required technological capabilities are available when needed. Several areas where technology development is needed have been identified and this presentation will focus on these.

Space Station *Freedom* ECLSS Evolution

Baseline ECLSS Design ⇨

- Changes in roles for SSF over 30 years
- Technology advances
- Test bed for Lunar/Mars mission hardware

⇨ Design Requirements for evolved ECLSS

- To prepare for these changes it is necessary to identify where technology development is needed.
- Several areas have been identified and are discussed below.

II. ECLSS Evolution Requirements

It is necessary to understand the ways in which the initial ECLSS will not meet the future requirements. By then comparing these future requirements with the technological capabilities now available, the areas where technology development is needed can be identified.

The questions to be answered are: What requirements of future missions will not be met by the initial ECLSS on *Freedom*?
What technology development is needed to ensure that these requirements will be met?

Aspects of Space Station ECLSS evolution which are important and which are being evaluated, include the fluid, power, and thermal requirements of alternative technologies; the impacts of adding modules in various locations with regard to the intermodule ventilation system and maintaining acceptable concentrations of CO_2 and trace contaminants; and evaluating the evolution scenarios as more detail becomes available to determine the ECLSS requirements more specifically. This presentation will focus on the ECLSS technology development needs for Space Station *Freedom* evolution and related Lunar/Mars missions.

ECLSS Evolution Requirements

- What ECLSS requirements of future missions will <u>not</u> be met by the initial ECLSS on *Freedom*?
- What technology development is needed to ensure that these requirements will be met?
- Aspects of ECLSS evolution such as fluid, thermal, and power requirements of alternative technologies and the impacts of adding modules, are important and are being evaluated.
- This presentation will focus on technology development needs for Space Station *Freedom* evolution and related Lunar/Mars missions.

III. Space Station *Freedom* Assembly Phases

Freedom will become operational in a phased manner. The first operational phase is the MTC (Man-Tended Capability) which includes the "Lab A" module, one node, and a mini-pressurized logistics module (mini-PLM). The Shuttle is relied upon for life support functions.

The next phase is PMC (Permanently-Manned Capability) which will include the Japanese and European modules, the "Hab A" and "Lab A" modules, a second node, a full-sized PLM, and one Assured Crew Return Vehicle (ACRV). Some ECLSS functions are provided including water recovery and CO_2 removal.

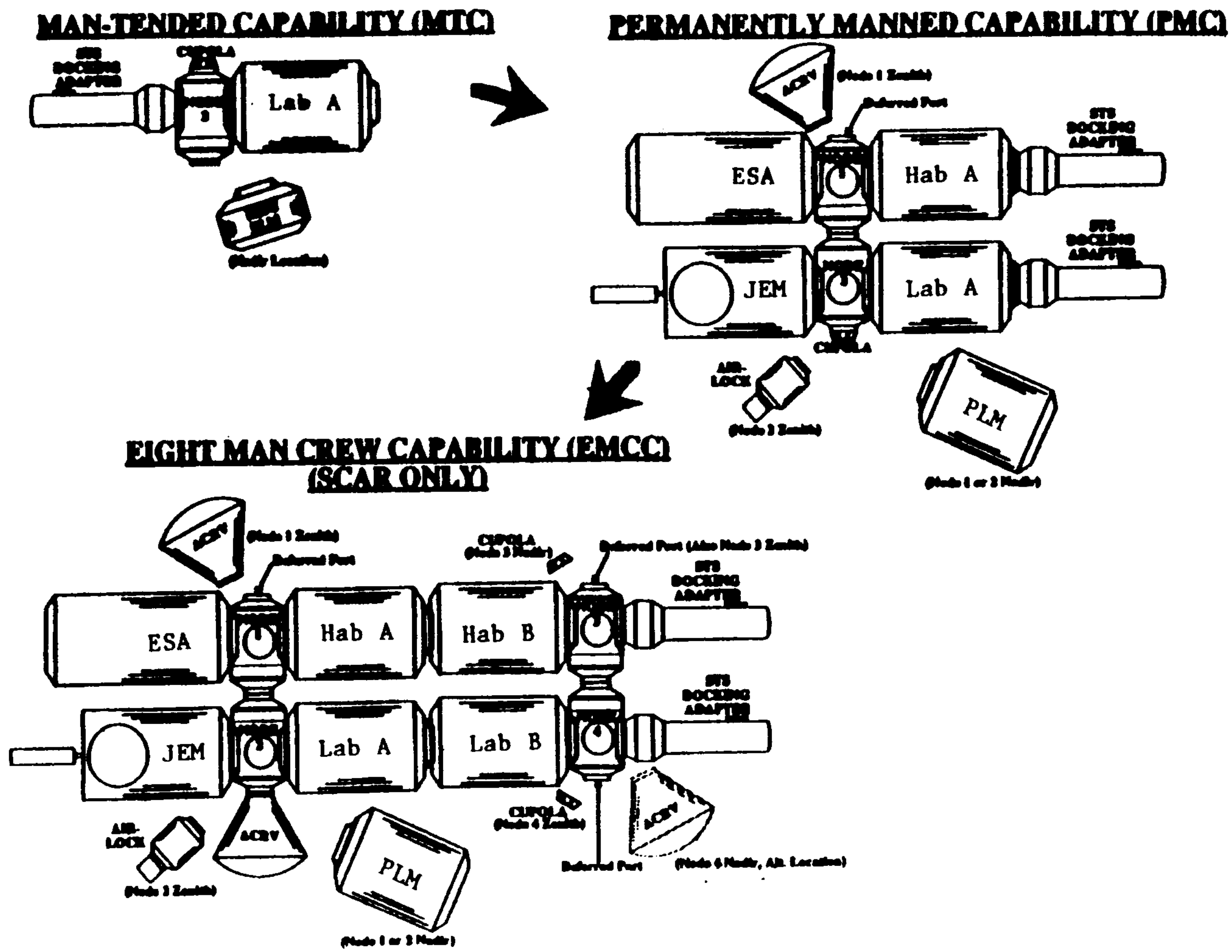
At EMCC (Eight-Man Crew Capability) the "Hab B" and "Lab B" modules will be added and two additional nodes to complete a "racetrack" configuration. The O_2 loop will also be closed when the "B" modules are added.

National Aeronautics and
Space Administration

Space Station Evolution:
Beyond the Baseline

FREEDOM

Space Station *Freedom* Assembly Phases



IV. Space Station *Freedom* ECLSS Features

At the Permanently Manned Configuration (PMC) the water loop will be closed with the potable and hygiene water loops combined. Potable quality water will come from the Orbiter fuel cells to makeup for inefficiencies in the recycling process. The oxygen loop will be open with only CO_2 removal being performed (by a Four-Bed Molecular Sieve). The concentrated CO_2 will either be vented overboard or will be used by the propulsion system. Oxygen will be supplied from cryogenic storage tanks which will be resupplied every 90 days. All solid waste will be stored and returned to Earth. For this phase the module configuration requires the intermodule ventilation flow to be parallel into and out of each pressurized element.

For the Eight-Man Crew Configuration (EMCC) the water loop will be closed as for PMC. In addition, the O_2 loop will also be closed with CO_2 reduction by a Sabatier Subsystem and O_2 generation by a Static Feed Water Electrolysis Subsystem. In order to minimize the amount of "scarring" required to close the O_2 loop, the closed loop hardware will be contained in the "B" modules and the 4BMS in the "A" modules will become backups. As during PMC all solid waste will be stored and returned to Earth. With the addition of two more nodes connecting the "B" modules to make a "racetrack" the intermodule ventilation flow can be in series, which has some advantages, for this configuration, over parallel flow.

Space Station *Freedom* ECLSS Features

Permanently Manned Capability (PMC)

- Closed Water Loop with combined potable and hygiene water reclamation (makeup water will be obtained from the Orbiter fuel cells)
- CO_2 Removal will be performed by Four–Bed Molecular Sieves with the concentrated CO_2 vented or sent to the propulsion system
- O_2 will be supplied from cryogenic storage tanks
- All solid waste will be returned
- Open module pattern

Eight–Man Crew Capability (EMCC)

- Closed Water Loop with combined potable and hygiene water reclamation (makeup water will be obtained from the Orbiter fuel cells)
- CO_2 Removal will be performed by Four–Bed Molecular Sieves with the concentrated CO_2 delivered to a CO_2 reduction subsystem (Sabatier) for O_2 recovery
- O_2 will be generated by electrolyzing water (Static Feed Water Electrolysis Subsystem)
- Scarring will be minimized by having the closed O_2–loop hardware in the "B" modules, the 4BMS in the "A" modules will then become backup
- All solid waste will be returned
- Racetrack module pattern

V. Impacts on the ECLSS of Evolution Beyond EMCC

The distinctions and impacts on the ECLSS can be identified by evaluating two representative evolution scenarios: research facility and transportation node. The research facility is dedicated to scientific and commercial development research, with experiments inside the lab modules, mounted externally, and assembled externally as free flyers or for transfer to deep space. The transportation node is oriented toward assembly, maintenance, and repair of transfer vehicles for Lunar and Mars missions, with less research occurring.

Common factors of these evolution scenarios include an increase in the number of people with up to 30 for some scenarios, an increase in the number of EVA's performed to 52 to 250 per year of 8 hours each, additional modules and pressurized volume for laboratory or habitat space and logistics modules, increased power production to operate experiments or vehicle maintenance facilities, and safe haven considerations.

The details of these factors differ for each scenario, but the overall effects on the ECLSS are similar and can be summed up as: increased capability to process higher rates of mass, improved performance to operate more efficiently, and added functions to perform additional tasks such as solid waste processing.

Specific impacts on the ECLSS include: reducing the need for expendables such as reagents or filters, increasing the reliability of the hardware such as by eliminating rotating components, optimizing recovery of mass such as by eliminating venting or brine waste, and increasing autonomy of operation so the crew can use their time more productively.

Impacts on the ECLSS of Evolution Beyond EMCC

Common factors of the evolution scenarios

- Increased number of people (15 to 30 depending upon the scenario)
- Increased EVA (52 to 250 per year)
- Additional modules and pressurized volume (short modules plus nodes, logistics modules, "pocket" labs, etc.)
- Power availability (depends upon user requirements and production capacity)
- Safe haven considerations

Overall effects on the ECLSS requirements

- Increased capability
- Improved performance
- Added functions

Impacts on ECLSS design

- Reducing the need for expendables
- Increasing reliability of hardware
- Optimizing recovery of mass
- Increasing autonomy of operation

VI. Technology Development Needs

In several areas the ECLSS requirements for the growth scenarios exceed the capabilities of present ECLS technologies and additional development will be needed in order to ensure that future ECLSS requirements can be met.

Based on the experience with developing the ECLSS for *Freedom* and on evaluations of scenarios for future missions, ECLSS technology requirements for the evolving *Freedom* and future missions are being identified at MSFC.

The technology development needs that have been identified at this time fall into five areas:

Sensors and Instrumentation
Water Recovery
Waste Processing
Atmosphere Revitalization
Closed Environment Systems

These needs have been prioritized and recommendations have been made for inclusion in the Office of Space Flight Technology Requirements Document.

The high and medium priority technology development needs are described below.

Technology Development Needs

Experience with ECLSS for *Freedom*

Evaluation of future missions for ECLSS needs

Technology Development Needs
Sensors and Instrumentation
Water Recovery
Waste Processing
Atmosphere Revitalization
Closed Environment System

- These needs have been prioritized and technologies recommended for inclusion in the Office of Space Flight Technology Requirements Document.
- The high and medium priority technology development needs are described below.

VI. Technology Development Needs (cont.)

Sensors and Instrumentation

Ensuring acceptable quality of recycled water is a major challenge for Space Station *Freedom* and will be an even greater challenge for Lunar/Mars missions. Great strides have been made at MSFC with the recent water recovery testing. Fifteen volunteers, who literally contributed their sweat, drank the purified water in a blind taste test which also included municipal water. Most thought the recycled water tasted better. Continued testing is expected to demonstrate that the water can be recycled repeatedly. Before the volunteers drank the water, however, numerous laboratory analyses were performed to ensure acceptable purity. On a long duration mission, especially to the Moon or Mars, we won't have the benefit of a laboratory full of analysis equipment. Nor will we want to wait a day or two to find out if the water is acceptable. For these reasons, on-line real-time instruments are needed to monitor microorganisms and chemicals. Two specific technology needs are described below.

Technology Development Needs (cont.)
Sensors and Instrumentation

Technology Need: On–Line Real–Time Microorganism and Chemical Monitor

Present Status: Present methods of microorganism monitoring are labor intensive, require large sample volumes, require large volumes of sterile reagents and nutrient solutions, generate biologically active wastes, and require 48 hours or more to confirm results. Chemical monitoring methods also.are typically labor intensive and must be calibrated for specific compounds.

Technical Goal: A rapid, automated method which does not require large amounts of expendables is needed.

Technology Need: On–Line Monitor of Total Organic Carbon·and Specific Organic Constituents in Water

Present Status: Total Organic Carbon (TOC) content is a significant parameter to determine the quality water. Present methods are limited in sensitivity and are not able to detect, identify, or quantify the constituents which contribute to the TOC content.

Technical Goal: An analyzer is required which can detect, identify, and quantify the constituents contributing to the TOC content. Of the 500 μg/l TOC allowable in potable water, at least 80% must be quantified to fully assess the medical acceptability of the water.

VI. Technology Development Needs (cont.)

Sensors and Instrumentation (cont.)

Monitoring of atmosphere quality, both major constituents and trace contaminants, is essential, but present methods require about 90 minutes to identify and quantify trace contaminants. A rapid method (10 minutes or less) with better resolution, range, and size than the present GC/MS is needed. Also the ability to monitor low mass compounds and identify O_2, CO_2, CH_4, and H_2 is needed. One method which may be able to meet the requirements is the ion trap MS/MS.

Technology Development Needs (cont.)
Sensors and Instrumentation

Technology Need: Improved Monitoring of Major Constituents and Trace Contaminants

Present Status: The present state–of–the–art method is the gas chromatograph/mass spectrometer method which requires about 90 minutes to analyze a sample and has limited resolution.

Technical Goal: Rapid (10 minutes or less) analysis of atmosphere samples with better resolution, range, and size than a GC/MS is needed. The capability of monitoring low mass compounds is necessary, as well as identifying O_2, CO_2, CH_4, and H_2. One method which can potentially meet these goals is the ion trap MS/MS.

VI. Technology Development Needs (cont.)

Water Recovery

In addition to water quality monitoring, improvements are also needed in processing waste water. Specifically, higher recovery efficiencies and reduction in expendables are needed. Two methods which are recommended for further development are the Air Evaporation System and Reverse Osmosis. The potential benefits of these methods are described below.

Technology Development Needs (cont.)

Water Recovery

Technology Need: Improved Water Recovery from Urine

Present Status: The baseline method of processing urine on *Freedom* is the Vapor Compression Distillation (VCD) subsystem which has an efficiency of 85 to 90%. The VCD contains precise, rotating components and flexible peristaltic pump tubing which are potential weaknesses with regard to long–term reliability.

Technical Goal: A higher rate of water recovery is needed to reduce resupply and storage penalties. The Air Evaporation System (AES) method has a recovery rate approaching 100% and has an inherently higher reliability than the VCD because of fewer moving parts. Improvements in the AES are needed with regard to power consumption and wick changeout.

This page is intentionally blank.

Technology Development Needs (cont.)

Water Recovery (cont.)

Technology Need: Improved Water Recovery from Waste Potable and Hygiene Water

Present Status: The baseline method of processing waste potable and hygiene water on *Freedom* is multifiltration which requires the use of expendable "unibeds." The recovery rate is 100%, but the expendables weigh 1 to 2% of the water processed.

Technical Goal: A method which requires no expendables is needed to reduce resupply and storage penalties. The Reverse Osmosis (RO) method has the potential to achieve a high recovery rate without requiring expendables. Improvements in the RO membrane are needed in order to:
(1) Improve fouling resistance to obtain water recovery efficiencies approaching 100% (the present efficiency is about 95%),
(2) Remove low molecular weight organic molecules, and
(3) Increase the high temperature tolerance to allow sterilization in place in the event of microorganism contamination.

VI. Technology Development Needs (cont.)

Waste Processing

Any mass (gas, liquid, solid, or heterogeneous) that is vented or stored is a liability by increasing the amount of mass that must be resupplied or stored from the beginning of a mission. Methods of processing these wastes to convert them into useable forms are required.

Technology Development Needs (cont.)

Waste Processing

Technology Need: Processing of Wastes to Recover Mass

Present Status: Gaseous wastes will be vented from *Freedom*. Solid wastes and hazardous liquid wastes will be stored for return to Earth. These methods result in loss of recoverable mass and require crew involvement in storing and transporting waste materials.

Technical Goal: Advanced methods of processing waste gases, liquids, and solids and heterogeneous wastes are required to recover water and gases. This would also reduce the amount of storage and resupply required.

VI. Technology Development Needs (cont.)

Atmosphere Revitalization

Controlling the level of trace contaminants to maintain low concentrations is very important for long duration missions, due to potential hazards of long term exposure to even small concentrations of some contaminants. The present method relies on adsorption on activated charcoal, catalytic oxidation, and absorption on LiOH. The power and resupply penalties of this method make it unsuitable for Lunar and Mars missions, and very expensive for *Freedom*. Smoke control presently relies on containing the smoke in a single module and venting the atmosphere after a major smoke event. This is acceptable on *Freedom* where the crew can return to Earth if the contingency atmosphere is used up, but for a Lunar or Mars mission this approach could be disastrous. A regenerable method of removing trace contaminants, including smoke, quickly and reliably is needed.

Technology Development Needs (cont.)

Atmosphere Revitalization

Technology Need: Trace Contaminant Removal and Smoke Control

Present Status: The present trace contaminant removal method is activated charcoal, catalytic oxidation, and LiOH pre– and post–sorbent beds. This approach, while effective, requires high temperatures and, for long duration missions, large quantities of LiOH and charcoal sorbent materials. This method has only limited capabilities with regard to cleanup after a fire or spill of hazardous substances. Presently, smoke control relies on containing the smoke in a single module and venting the atmosphere after a major smoke event.

Technical Goal: Regenerable sorbents for trace contaminant control and smoke removal with improved abilities to desorb to space vacuum are needed.

VI. Technology Development Needs (cont.)

Atmosphere Revitalization (cont.)

At EMCC *Freedom* will have a closed O_2 loop, but with the Sabatier reactor for CO_2 reduction mass will be lost as CH_4. The Bosch reactor and the Carbon Formation Reactor are two methods by which the hydrogen can be recovered (as water) leaving only solid carbon. Even though solid waste remains, this is a step toward complete recovery of mass. Additional development is required in order to perfect the Bosch and CFR reactors.

The efficiency of the Bosch and CFR reactions is adversely affected by inert gases (N_2) in the concentrated CO_2 supply. The present 4BMS product CO_2 contains about 2% N_2. A method of reducing this level to less than 1% is needed to increase the performance of the CO_2 reduction subsystem.

Technology Development Needs (cont.)

Atmosphere Revitalization (cont.)

Technology Need: Improved Recovery of O_2 From CO_2

Present Status: The baseline AR for *Freedom* in the PMC is the Four–Bed Molecular Sieve for CO_2 removal only, and venting of the CO_2 to space. For the EMCC a Sabatier CO_2 reduction subsystem will produce methane (to be vented or used for propulsion) and water (to be electrolyzed or added to the potable water supply). The mass loss due to venting methane can be substantial and requires resupply of water to make up the hydrogen loss.

Technical Goal: Closure of the O_2 loop requires recovering O_2 from CO_2 and hydrogen from the CO_2 reduction process. The Bosch and Carbon Formation Reactor are two methods of doing this which leave only solid carbon as a residue. Further work is needed to perfect them including researching reactor kinetics to better understand the reaction processes.

Technology Need: Improved Separation of Inert Gases From CO_2

Present Status: Presently the concentrated CO_2 produced by the Four–Bed Molecular Sieve contains about 2% inert gases (primarily N_2) which reduce the efficiency of the CO_2 reduction subsystems.

Technical Goal: Removal of inert gases to levels below 1% by membrane separation or other methods is needed to allow optimum performance of the CO_2 reduction subsystem.

VI. Technology Development Needs (cont.)

Closed Environment System

Some technology needs apply to the closed environment system as a whole.

The ECLSS for *Freedom* contains many rotating components: pumps, blowers, rotating drums, etc. which generate noise. Long duration missions such as *Freedom* and Lunar/Mars missions will have lower allowable noise levels than previous missions due to physiological effects of exposure to continuous noise. Insulation can reduce the amount of noise transmitted but reducing the amount of noise generated would reduce the need for insulation and simplify packaging and maintenance procedures. Noise also indicates inefficiencies and energy losses.

Technology Development Needs (cont.)
Closed Environment System

Technology Need: Component Noise Reduction

Present Status: Presently, sound insulation material is used to minimize noise from pumps, fans, compressors, and other rotating equipment. Long duration missions such as *Freedom* and Lunar/Mars missions will have lower allowable noise levels than previous missions due to physiological effects of exposure to continuous noise. Noise also indicates inefficiencies and energy losses.

Technical Goal: Rotary equipment which generates little noise and requires little or no sound insulation.

VI. Technology Development Needs (cont.)

Closed Environment System (cont.)

Minimization of leakage is very important on long duration missions and allowable leakage limits will decrease. The capability of detecting leaks ranging from 0.05 to 1.0 lb/day is needed. Also the ability to identify the location of a leak is needed.

Particulate contaminants can also be a significant problem and improvements are needed over the present time-consuming microscopic examination process. On *Freedom* the process will be partly automated but additional improvements are needed to monitor specific size ranges of particles (0.5 to 10 microns, 10 to 100 microns, etc.), the mass density, and the total count.

Technology Development Needs (cont.)
Closed Environment System (cont.)

Technology Need: Leak Detection

Present Status: Current leak detection methods for the Space Shuttle Orbiter are a dP/dT sensor on orbit and a pressure decay test during preflight checkout. For *Freedom* the mass loss will be calculated from the total pressure and temperature. Identification of the location of a leak is not automatically performed.

Technical Goal: An advanced leak detection system capable of detecting leakage ranging from 0.05 to 1.0 lb/day is needed. The capability of identifying the location of a leak is also needed.

Technology Need: Particulate Contamination Monitor

Present Status: Present methods used on the Shuttle rely on crew detection by microscopic examination, which is a time consuming process. On *Freedom* a light scattering diode laser will measure the total count in the 0.5 to 100.0 micron range on a continuous basis and microscopic examination will be done periodically (e.g., weekly).

Technical Goal: A particulate monitor is needed which can monitor specific size ranges of particles (e.g., 0.5 to 10 microns and 10 to 100 microns), the mass density, and the total count.

VII. Technology Development Priorities

The technology development needs reviewed here are the ones which have been identified as "high" or "medium" priority.

The "high" priority development needs are:

- On-Line Real-Time Microorganism and Chemical Monitor
- Processing of Wastes to Recover Mass
- Trace Contaminant Removal and Smoke Control
- Component Noise Reduction

The "medium" priority development needs are:

- On-Line Monitor of Total Organic Carbon and Specific Organic Constituents in Water
- Improved Monitor of Major Constituents and Trace Contaminants
- Improved Water Recovery from Urine: Air Evaporation Subsystem
- Improved Water Recovery from Waste Potable and Hygiene Water: Advanced Reverse Osmosis
- Improved Recovery of O_2 from CO_2
- Improved Separation of Inert Gases from CO_2
- Leak Detection
- Particulate Contamination Monitor

It is recommended that development efforts be focused on these, especially the "high" priority ones, to meet the requirements of *Freedom* as it evolves over its thirty-year lifetime.

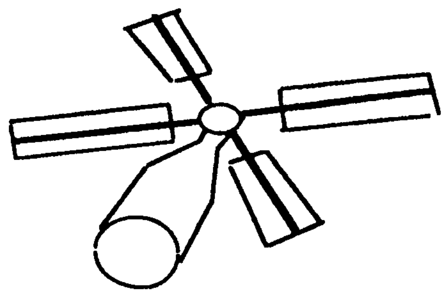
Technology Development Priorities

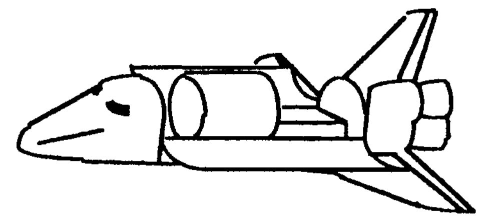
Priority	Technology Development Need
	Sensors and Instrumentation
High	On–Line Real–Time Microorganism and Chemical Monitor
Medium	On–Line Monitor of Total Organic Carbon and Specific Organic Constituents in Water
Medium	Improved Monitor of Major Constituents and Trace Contaminants
	Water Recovery
Medium	Improved Water Recovery from Urine: Air Evaporation Subsystem
Medium	Improved Water Recovery from Waste Potable and Hygiene Water: Advanced Reverse Osmosis
	Waste Processing
High	Processing of Wastes to Recover Mass
	Atmosphere Revitalization
High	Trace Contaminant Removal and Smoke Control
Medium	Improved Recovery of O_2 from CO_2
Medium	Improved Separation of Inert Gases from CO_2
	Closed Environment System
High	Component Noise Reduction
Medium	Leak Detection
Medium	Particulate Contamination Monitor

The Environmental Control and Life Support System Advanced Automation Project

Brandon S. Dewberry
NASA / George C. Marshall Space Flight Center
System Software Branch / EB42
Marshall Space Flight Center, AL 35812
(205) 544-4247
NASAMail : BDEWBERRY
email : brandon@deputy.msfc.nasa.gov

Environmental Control System History





SkyLab

Systems:

- air conditioning
- trace contaminant control
- carbon dioxide removal
- long duration consumables supported by ground resupply

Controls:

- embedded analog circuitry with ground supervision
- open-loop (scheduled) control

Shuttle / SpaceLab

Systems:

- air conditioning
- trace contaminant control
- carbon dioxide removal
- some oxygen generation
- short duration consumables

Controls:

- embedded analog circuitry with some flight software supervision
- firmware controllers introduced into subsystems
- scheduled control

Space Station Freedom ECLSS Description

The Space Station Freedom ECLSS can be divided into 2 parts: Environmental Control, which is the air conditioning part, and Life Support, which is the regenerative part that supplies air and water to the crew.

Environmental Control contains trace contaminant control, the temperature and humidity control, and atmospheric pressure control subsystems.

Life Support contains air revitalization which is carbon dioxide removal, carbon dioxide reduction, and oxygen generation, as well as water recovery management which recycles waste water after use.

The interaction of these reclamation subsystems (air and water) is minimized by gas and water tankage in between the subsystems. This minimizes the control complexity similiar to using a large amount of fuel in the carberator to minimize dependency on fine tuned parameters.

Hardly any controls are RLC (Analog circuits). Embedded firmware (software which has been made permanent in controller) is extensively allocated to each subsystem, with some flight software supervision on-board to manage system change-over and interaction.

The system is still controlled basically open-loop, meaning that chemical and gaseous constituents are not used overall to change system setpoints - but mostly checked occasionally to verify the health of the system.

The system is heavily monitored and timed, scheduled control is used.

Space Station Freedom ECLSS

FREEDOM

Systems:

- air conditioning (environmental control)
- trace contaminant control
- air revitalization also includes carbon dioxide removal, carbon dioxide reduction, and oxygen generation
- waste water is recycled after use
- reclamation subsystem interaction minimized by tankage
- long duration resupply minimized by recycling air and water

Controls:

- embedded firmware with some flight software supervision
- still basically open-loop, heavily monitored, scheduled control

Restructured Regenerative ECLSS Description

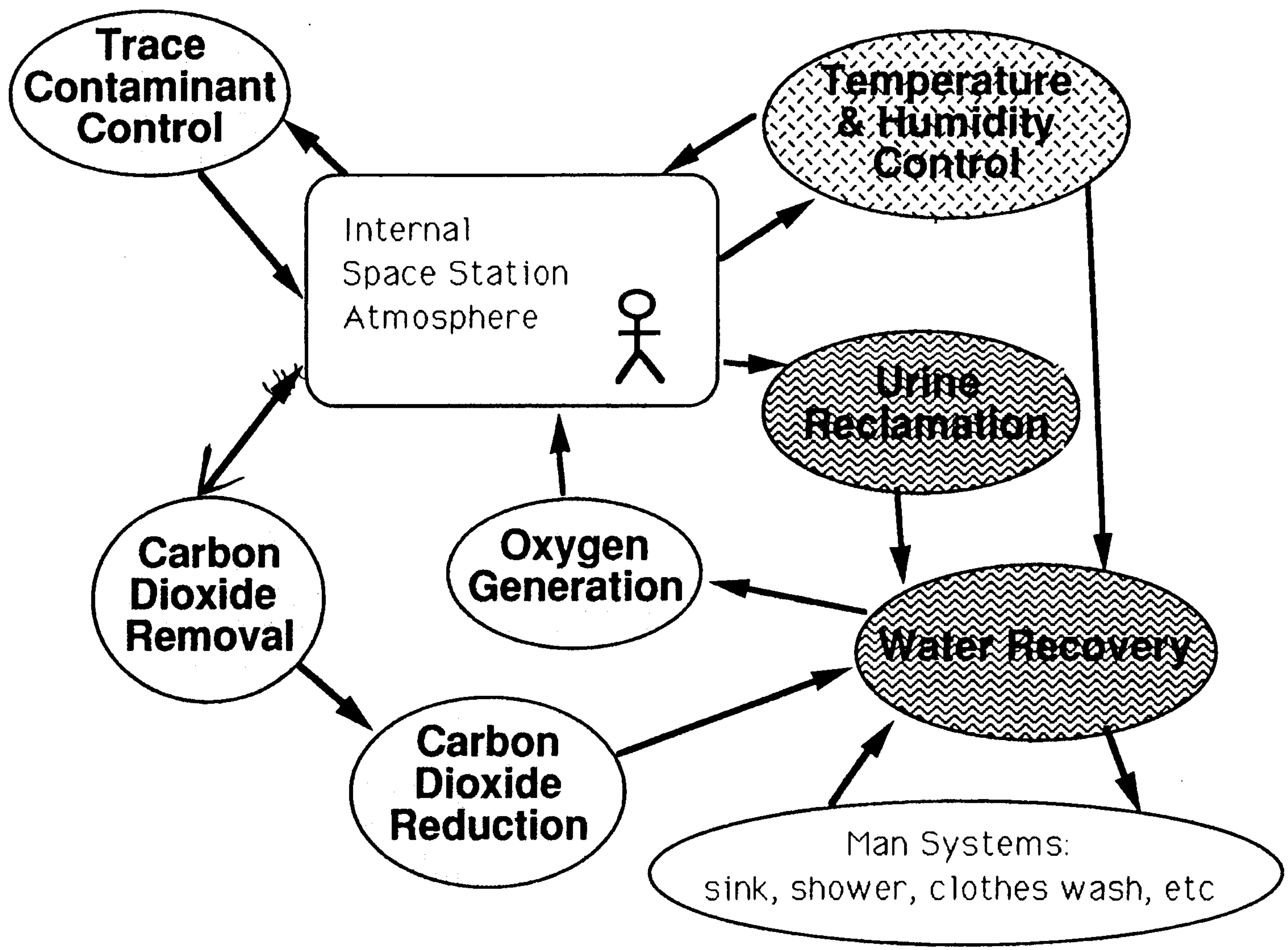
This is a picture of the regenerative ECLSS subsystems after restructure removed the separate hygiene recovery loop. Air Revitalization (AR) subsystems are lightly shaded, Water Reclamation (WR) subsystems have dark waves, and the Temperature and Humidity Control (THC) subsystem is shaded with alternating dashes.

The Space Station Freedom ECLSS supplies air and water to the crew by regenerating oxygen from the overabundance of water, and reclaiming waste water and condensate.

These complex interacting subsystems will be developed and integrated in parts - the temperature and humidity control, trace contaminant control, and carbon dioxide removal subsystems will be the extent of the initial ECLSS subsystems during Man-Tended Operations. Water Recovery will be gradually integrated and operational at the Permanently Manned Configuration (PMC). The oxygen used by four crew members in 90 days does not present a logistics barrier, so Air Revitalization Components CO2 Reduction and Oxygen Generation, do not come online until Eight Man Crew Operations.

Notice that the Water Recovery System is the end of the line for contaminants in the air and water - where the buck stops - and chemical and microbial faults would propagate to this reservoir.

Restructured Regenerative ECLSS



Software Architecture

This is a cartoon of the ECLSS software architecture. Flight software is shown on the left inside node and lab module boxes. Ground software is shown at right in the ECLSS sustaining engineering facility.

During scrub activity in FY90 and restructure activity in FY91 all sensors and software which were not required for "real-time" control and fault detection was moved to the ground.

On board the software can be divided into hard real-time and soft real-time. Hard real-time is control code in which a delay in response can cause a failure. Soft real-time is supervisory code in which a delay in response will cause a degradation of performance, but not a failure.

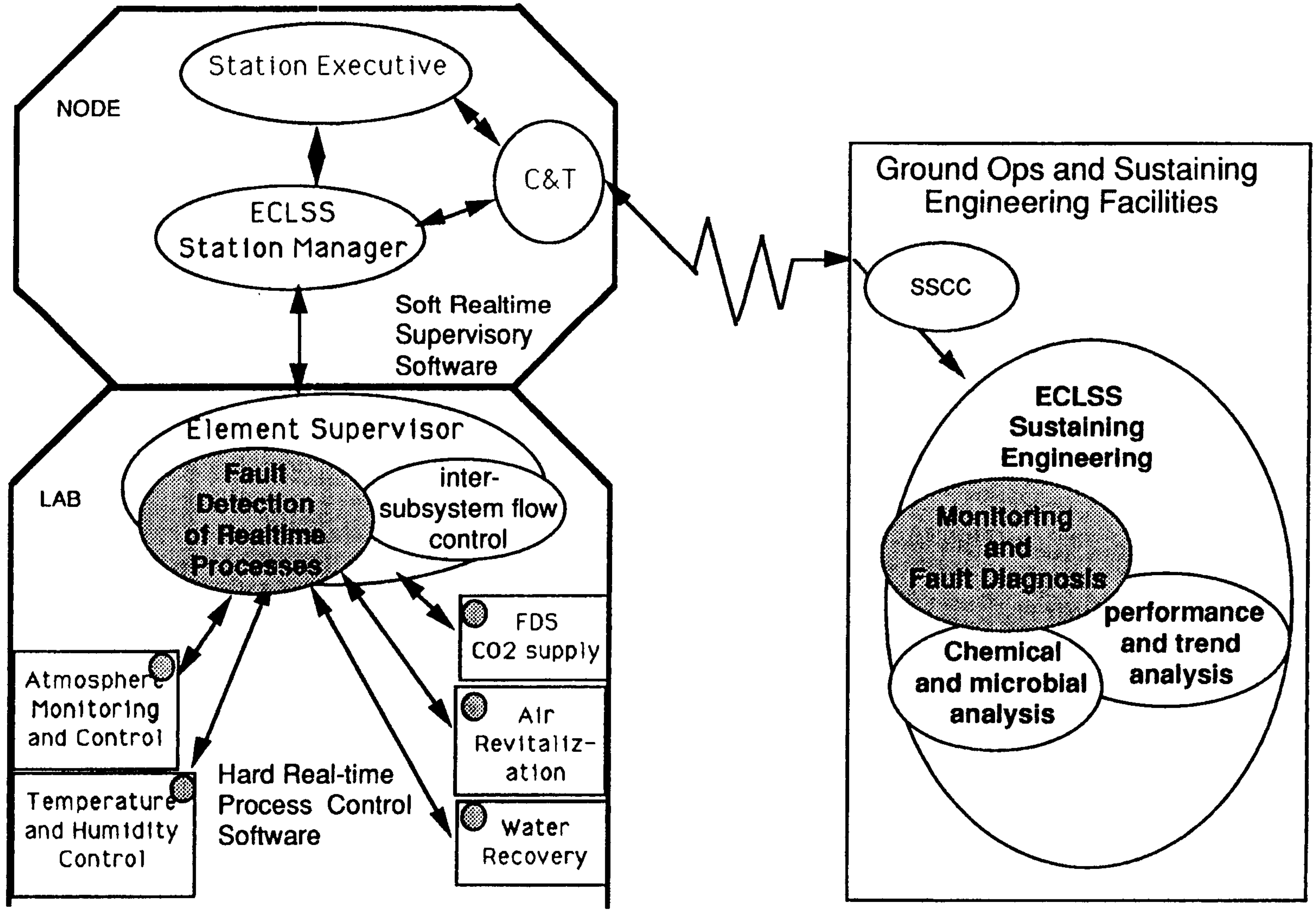
On-board fault detection of realtime processes is contained in both hard real-time and soft-realtime software.

All ground software is a combination of soft real-time or non-real-time software.

Fault detection is finding that a fault has occurred. Fault diagnosis is discovering which component of the subsystem caused the fault and how it occurred.

The ECLSS Advanced Automation Project

Software Architecture



The ECLSS Advanced Automation Project

Objectives Description

The objectives of the ECLSS Advanced Automation project include reduction of the risk of associated with the integration of new, beneficial software techniques. Our prime contractor has a certain conservative attitude toward advanced software - or non-advanced software for that matter.

In order to alleviate MSFC and Prime Contractors' concerns over development of diagnostic and control systems which maximize ECLSS operational functionality while meeting development constraints.

Demonstrations of this software to baseline engineering and test personell will show the benefits of these techniques. The advanced software will be integrated into ground testing and ground support facilities, familiarizing its usage by key personell.

Objectives

Reduce the risk of integration of new, beneficial software techniques.

Develop diagnostic and control systems which maximize ECLSS operational functionality while meeting development constraints.

Demonstrate to baseline engineering the benefits of these techniques by integrating them into ground testing and ground support.

Benefits Description

Reduced Instrumentation without decreasing functionality can be achieved by using models of the system to diagnose faults rather than dedicate sensors for fault diagnosis.

Reduced Crew IVA to trace and fix faults in the system is achieved by isolating the fault to a component which can be replaced. Testing for isolation should be minimized.

Currently, large Orbital Replaceable Units (ORU's) are being designed, for instance, the Condensing Heat Exchanger, the main component of the Temperature and Humidity Control subsystem, is approximately a 3x3x3 box which is an ORU. The consequences are that faults are isolated only to this large black box and a spare box this large must be available to fix a fault in this system.

Inhanced Safety by persistent, consistent monitoring. The software proposed is not artificially intelligent. It simply automatically monitors the subsystems for faults and reports it, then helps the operator to isolate that fault to a component. It performs the monitoring day and night, presenting the operator with consistent results of its analysis.

Increased Productivity by presenting information rather than data. The operators first job looking at the sensor values of a system being monitored is to form a mental model of the system. This software will assist the operator to perform this function.

Benefits

Reduced Instrumentation without decreasing functionality.

Reduced Crew IVA to trace and fix faults in the system.

Inhanced Safety by persistent, consistent monitoring.

Increased Productivity by presenting information rather than data.

Technical Approach Description

This is basically an outline of the Technical Approach section which is the main portion of this presentation. This section is divided into:

Model-Based Fault Detection and Diagnosis - a brief overview and example of the technology,

Graphical User Interfaces which we've developed to increase operator productivity while showing the performance of the system,

Predictive Monitoring of Complex Systems will be discussed somewhat by Dr. Richard Doyle of JPL, and will not be addressed in this presentation. It will be mentioned on the distributed computing environment slide.

Distributed Computing Environment overhead will show in general how these tools fit together into a concise whole.

Specific Implementation outlines the hardware and software tools for development and delivery of this software.

Technical Approach

Model-Based Fault Detection and Diagnosis

Innovative Graphical User Interfaces

Predictive Monitoring of Complex Systems

Distributed Computing Environments

Specific Implementation

Model-Based Diagnosis Description

Model Based Fault Detection and Diagnosis are two processes which rely on the same structural and behavioral model of the system.

Nominal behavior - defined by the computer model - is compared with the behavior of the system. The computer has access to command changes and resulting sensor value changes.

Fault detection is reporting to the operator when a descrepancy exists between nominal and system behavior. The model is run in parallel with the system and modeled sensor values are compared with system sensor values.

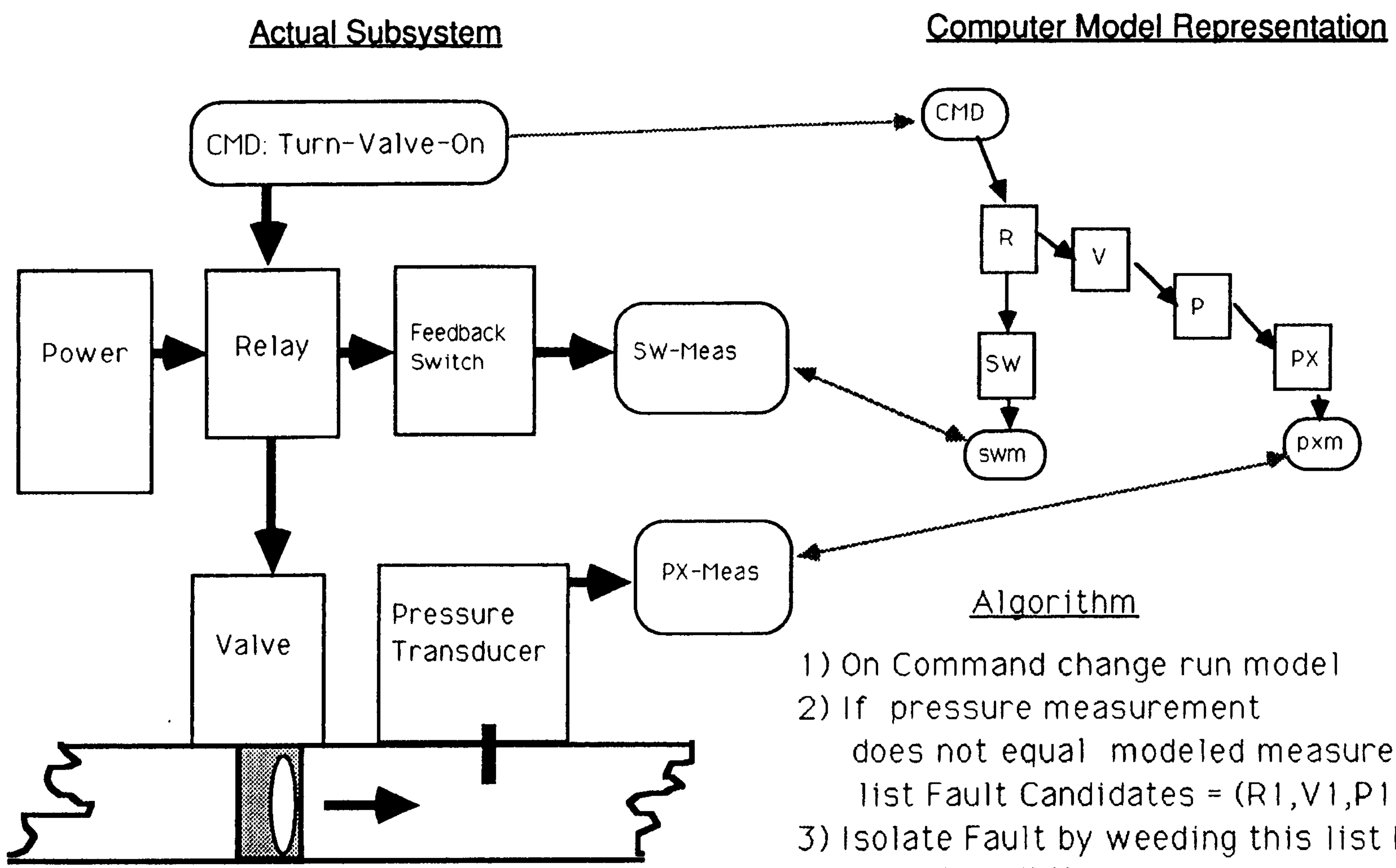
Fault detection is the act of finding out which specific component caused the failure. This is achieved by comparing sibling sensor values of the faulty sensor and by inverting the component transfer functions to determine the possibility of the upstream component causing the fault.

Two things separate this technique from traditional associational approaches:

1) sensors are part of the component model, and diagnosis of sensor faults is as easy as diagnosis of other component faults (not so in associational fault diagnosis).

2)any off nominal behavior is considered a fault, an exhaustive list of all fault possibilities is not required (as in associational fault diagnosis).

Model-Based Diagnosis



Algorithm

1) On Command change run model
2) If pressure measurement does not equal modeled measurement list Fault Candidates = (R1,V1,P1,PX)
3) Isolate Fault by weeding this list by checking sibling sensors and back propogation of the discrepancy

Results from Reverse Osmosis Analysis Description

We have developed Model Based Fault Detection of the Reverse Osmosis Hygiene Water Recovery Subsystem. Reverse Osmosis was a competing technology for water recovery. Its complexity provided a good proof of concept at the time.

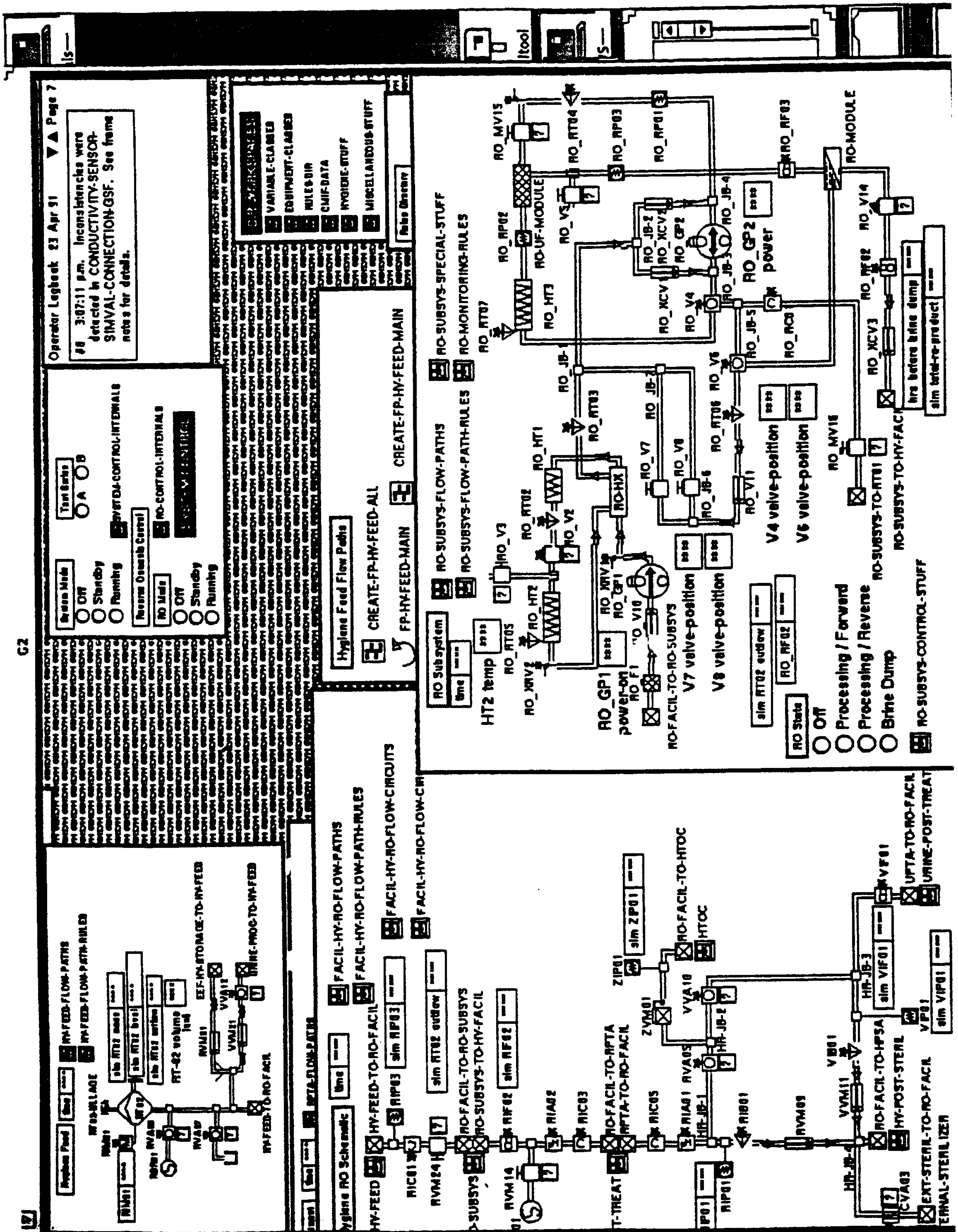
Subsequently, this subsystem was pulled from the baseline in favor of Multifiltration (MF). Apparently, the complexity of the system was more detrimental than the MF's resupply of unibed penalty.

Even though we lost some work in that we possibly could have had the prototype developed and integrated this year, 3 things were learned from this study:

1) component models are still valid - pumps, valves, and tanks have very similar models in any system,

2) a multiaspect equation solver is needed to model these complex flow systems,

3) the commercial tool, G2, is a fine tool for model-based fault detection, but not suited for Model-Based Diagnosis. The reason is the difficulty in answering questions about the model in software - reasoning about the model components themselves.



ORIGINAL PAGE IS
OF POOR QUALITY

Environmental Control System History Description

SkyLab

The Skylab system was mostly an elaborate air conditioning system. It was not called a life support system but simply an environmental control system. Resupply from the ground, in general, implies the system is an environmental control system and not a life support system.

This basic air conditioning system is augmented by Trace contaminant control (TCC) and CO2 removal capabilities. TCC filters the air of small (trace) amounts of unwanted constituents, usually by activated carbon beds. Carbon dioxide removal lowers the amount of CO2 in the air.

Long duration consumables supported by ground resupply, no recycling of crew wastes to minimize resupply. At this time NASA knew recycling the wastes was the way to go for a permanent space station, but at the time the process and computer technology could not support it.

The skylab subsystems were controlled with embedded analog circuitry, (RLC circuits), with ground supervision. Subsystems, such as heat exchangers, operated continuously based on a built-in setpoint, or had scheduled mode changes.

Shuttle / SpaceLab

Similar to skylab, the Space Shuttle and Spacelab systems were basically elaborate, augmented air conditioning systems. TCCS and CO2 removal were improved over Skylab, while some oxygen generation by electrolysis of water has been experimented with in preparation for a long duration space station.

The controls used are mostly embedded analog circuitry with some flight software supervision. For instance the partial pressures of oxygen and nitrogen are controlled by a ppO2 sensor tied to an O2/N2 flapper valve. This method would not work in a large area with pockets of air. Complete, instantaneous mixing is assumed.

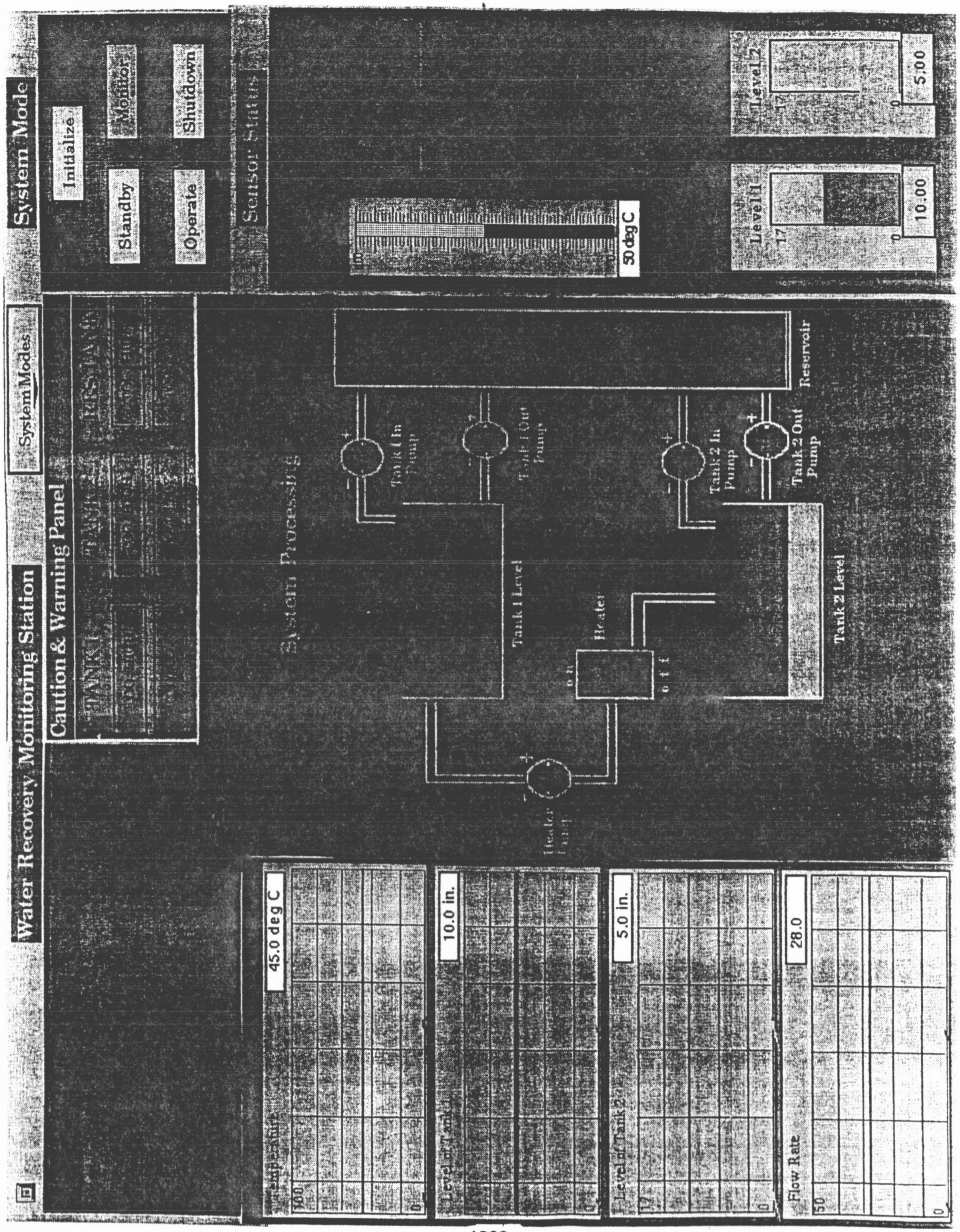
The control software contains firmware controllers (eg. GCMS control), and scheduled, open-loop, test-it-on-the-ground-and-hardwire-the-parameters is still the norm.

Graphical User Interface Description

This is a screen dump of a graphical user interface for a prototype water recovery subsystem.

Extraneous devices, such as multiple input tanks, are not shown on the interface so that it may have more room to deliver the information which the operator needs. Strip charts are included because the operators interviewed insisted that this would be the most valuable feature.

This is a first cut - duplication of sensor data has been avoided in the next version and the central drawing made bigger.


Water Recovery Monitoring Station
System Modes
Caution & Warning Panel
System Mode
Initialize
Standby
Monitor
Operate
Shutdown
Sensor Status
50 deg C
Level 1
Level 2
10.00
5.00
System Processing
Tank 1 In Pump
Tank 2 In Pump
Tank 2 Out Pump
Reservoir
Tank 1 Level
Heater
Tank 2 Level
45.0 deg C
10.0 in.
5.0 in.
28.0
Flow Rate

Distributed Computing Environment Description

This is a cartoon of the overall architecture of the system. The integrated system is fed by a model of the structure and behavior of the system, as well as time-tagged data of system operation in the testbed.

The processing is divided into 3 separate processes:

1) KATE, the Kennedy Automated Test Engineer process, is our development system for Model-Based Fault Detection and Diagnosis.

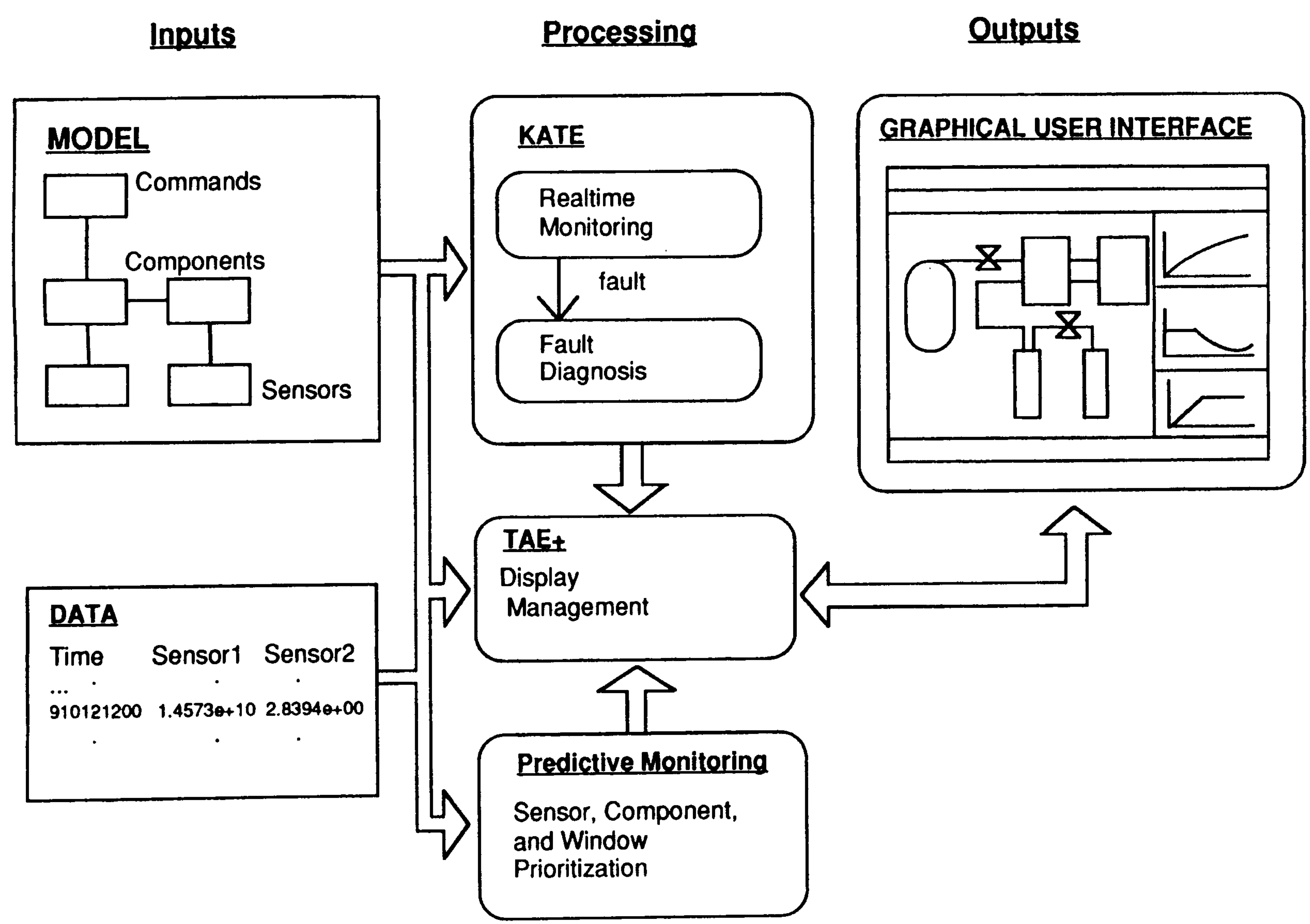
2) TAE+, which uses the X Windowing System, is a software tool from GSFC which allows easy prototyping of graphical user interfaces. It is being used to display the system state as well as the performance of the KATE system.

3) Predictive Monitoring is a place-holder for the system from JPL which will allow us to determine dynamic sensor, component, and window prioritization for complex system monitoring.

KATE and the TAE+ system run on separate computers.

The common model is the glue which is the basis for each process and allows separate development and delivery with integrated performance.

Distributed Computing Environment



Implementation and Tools Description

Model Based Diagnosis currently being developed using KATE on a Symbolics. This is an antiquated environment, but suitable for functional proof of concept.

Future plans are to port this functionality to a UNIX environment. Sun Sparcstations are being used, but any high-performance UNIX-based workstation should work for delivery.

Graphical User Interface development uses the X Window System with TAE+. This supports a portable GUI, which is one of the holdups of the KATE system.

ECLSS Predictive Monitoring development is compatible. Although Dr. Doyle's presentation which follows concerns selective rather than predictive monitoring, the basics are the same and software from the effort is compatible.

Implementation and Tools

Model Based Diagnosis currently being developed using KATE on a Symbolics.

Future plans are to port this functionality to a UNIX environment.

Graphical User Interface development uses the X Window System with TAE+.

ECLSS Predictive Monitoring development is compatible.

Baseline Integration Description

After RO was dropped from the baseline we had to go looking for another subsystem to begin with, proving out concept. The CDRA was picked for 2 reasons:

1) the complexity of the component interaction was viewed as an asset, as the test engineers stated, "if you can automatically diagnose this system, I'll be convinced that you can automatically diagnose any in Water Recovery."

2)the testing of this system in 92 supported our demonstration schedule.

A viewgraph of this subsystem and how we fit into the test schedule is coming up.

The Boeing AI Center is involved with ECLSS testing by developing Oracle database interfacing software. This is another foot in the testbed door which doesn't hurt.

Direct interface for monitoring the prototype CDRA subsystem (four bed molecular sieve) has been agreed upon. An RS232 line directly from the subsystem will be used to start with, bypassing the main data aquisistion computer. As the Fault Diagnosis system gains more subsystem functionality, the data aquisition computer will be used.

Already allocated a spot in the testbed area to develop software and unobtrusively monitor tests. This was a harder problem than it seems. Each square foot of space in the testbed area is allocated. It is proof of Test Lab support that we have a spot.

"Testing support Equipment is Ground Support Equipment" is a quote from restructure. This implies that since we are helping to develop test equipment, then by default, we are developing ground support equipment because the same equipment is designated to migrate to the ground support facility.

Baseline Integration

We began development and integration of the Carbon Dioxide Removal Assembly (CDRA) Advanced Monitoring application for the ECLSS Preliminary Operational Systems Testbed (POST).

Our group is already configuring the sensor database for baseline testing, and will be involved in other ECLSS testbed software development activities.

Direct interface for monitoring the prototype CDRA subsystem (four bed molecular sieve).

Already allocated a spot in the testbed area to develop software and unobtrusively monitor tests.

"Testing support Equipment is Ground Support Equipment"

The ECLSS Advanced Automation Project

CDRA Viewgraph Description

This is the Carbon Dioxide Removal Assembly. This is the system we plan to develop prototype model-based detection and diagnosis software for.

It uses the Molecular Sieve Technology to remove CO2 from the air.

It operates using scheduled control, air blows one way for a while removing CO2, then the oposite way to push the CO2 absorbed out of the system for venting or reduction.

ECLSS Testbed Description

This is the outside of the ECLSS Core Module Simulator Testbed.

BLDG 4755 MSFC

Control Room Viewgraph Description

This is the control room for the core module simulator testbed.

The main displays have operators watching text numbers on VT240 terminals.

There are plans to use more advanced monitoring techniques in the POST, BOST and MOST ECLSS Testbeds, but not much more advanced.

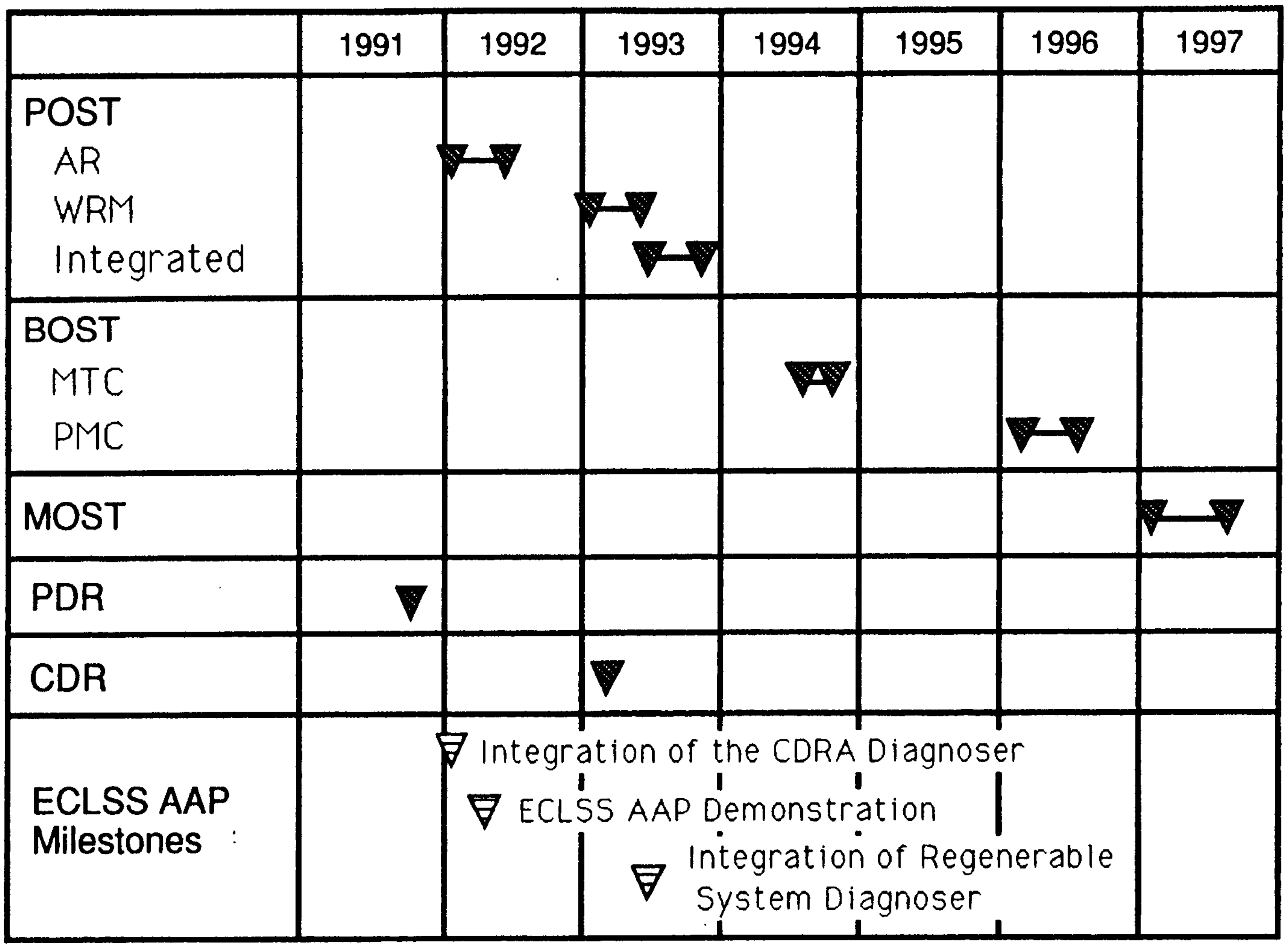
Integrated Schedule Description

As this schedule indicates, our first big demonstration will be before the ECLSS CDR.

Follow-on work will include more systems in the integrated tests.

The ECLSS Advanced Automation Project

Integrated Schedule



Growth and Evolution Options Description

Flight option on portable computer which plugs into front of ECLSS racks. The design has a data interface plug on the front of each double rack. This plug can be used when the subsystem inside is broken for bringing a more cabable diagnostic machine online to concentrate on diagnosing the system failure.

New modules (beyond EMCC) with new Standard Data Processor loads could carry this type of fault detection and diagnosis, the computers used should have more capability and the fault detection algorithm could be model based rather than associational.

Inclusion of chemical and biological in the fault detection and diagnosis system. The overall goal of the ECLSS, for practical and political reasons, is to keep itself operating nominally. Any instrumentation in the ECLSS (eg GCMS) is there to check that the system outputs meet required specifications - not to make sure the crew is safe.

With regeneration of air and water, the crew and bacteria are integrated parts of the overall system. The next viewgraph shows how MBD can be used to integrate the diagnosis job.

Growth and Evolution Options

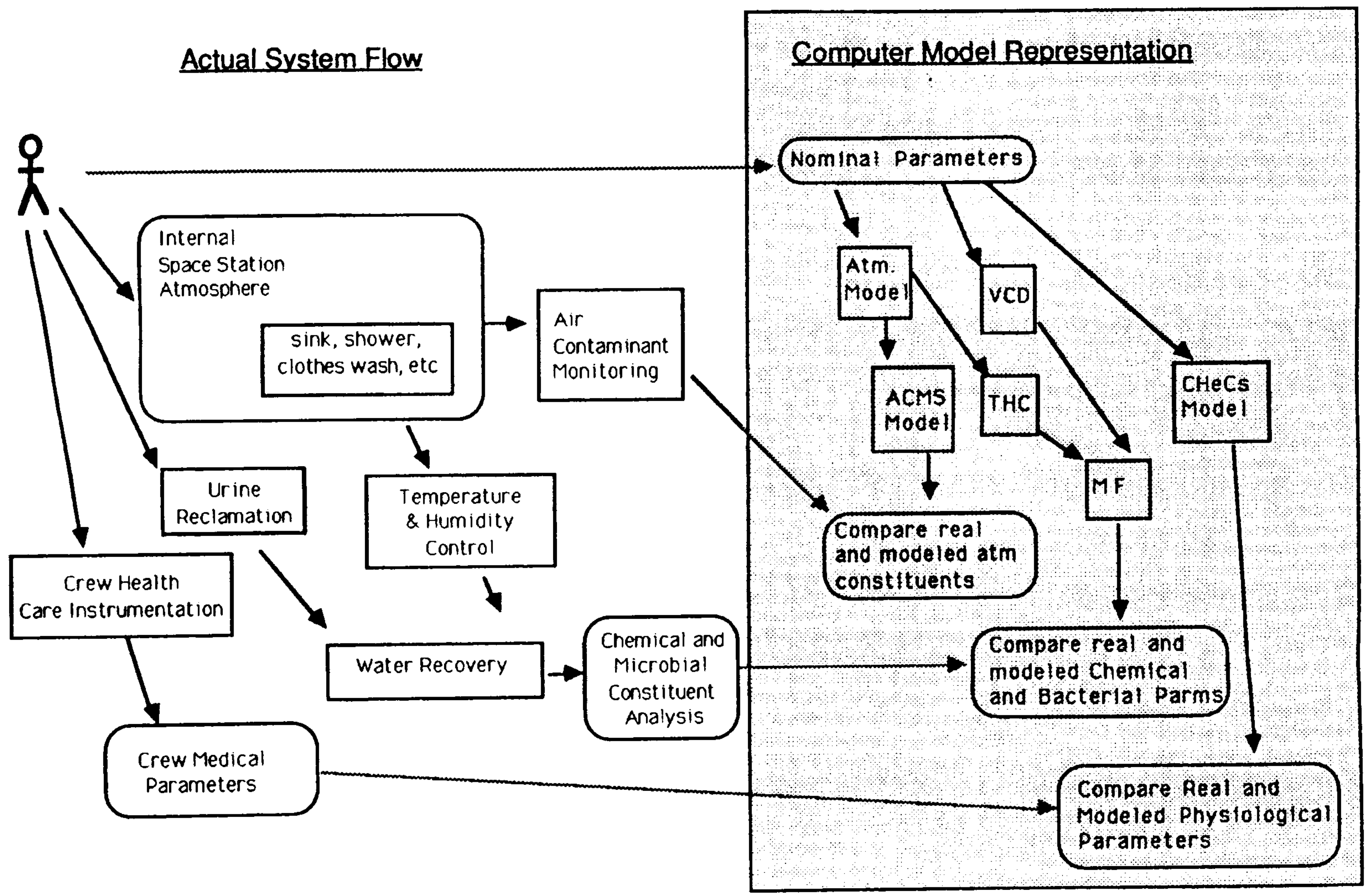
Flight option on portable computer which plugs into front of ECLSS racks.

New modules (beyond EMCC) with new SDP loads could carry this type of fault detection and diagnosis.

Inclusion of chemical and biological [Models] in the fault detection and diagnosis system. The purpose of a life support system, after all, is to keep the crew healthy, not just to keep itself healthy.

The ECLSS Advanced Automation Project

Chemical and Biological Model-Based Fault Detection and Diagnosis



Chemical and Biological Model-Based Fault Detection and Diagnosis Description

In a manner similar to the model based diagnosis of the valve system shown previously, chemical, physiological, and bacterial faults can be diagnosed using models of the system and instrumentations' structure and behavior.

The CHeCS monitors the medical aspects - blood, detailed urine, etc - while the Life Support system can pick up alternate fault causes.

Long duration trend analysis of chemical and microbial faults in the lines, filters, and crew members may be isolated in this manner.

Related Work

Dr. Richard Doyle / JPL is applying their sensor placement and analysis algorithm to the ECLSS.

In-house work concentrates on Automatic Generation of real-time software from control block diagrams, and Graphical User Interfaces for Payload Monitoring.

Small Business Inovative Research Project applying Neural Networks to the ECLSS Trace Contaminant Analysis and Fire Detection Systems.

Summary

ECLSS is a complex system which can be automated using advanced software technology.

The subsystem we began with was restructured out of the program, but all was not lost.

Although we originally planned on integrating advanced algorithms in the flight system, we now are refocused on ground test and support.

In the testing and ground support areas, we can make the most immediate beneficial impact, while positioning for flight integration.

Future implementations of life support systems will be more autonomous due to this project.

N92-17357

FREEDOM

Advanced Development Program

UPN 476-14

ECLSS Predictive Monitoring

Dr. Richard J. Doyle
Dr. Steve A. Chien

Artificial Intelligence Group
Advanced Information Systems Section
Jet Propulsion Laboratory
California Institute of Technology

Space Station Evolution:
Beyond the Baseline
League City, Texas
August 8, 1991

JPL

PRECEDING PAGE BLANK NOT FILMED

PAGE 1310 INTENTIONALLY BLANK

TITLE

ECLSS Predictive Monitoring: Automated Evaluation of Sensor Placements

Dr. Richard J. Doyle
Dr. Steve A. Chien

Artificial Intelligence Group
Advanced Information Systems Section
Jet Propulsion Laboratory, M/S 301-490
California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099

presented at
Space Station Evolution:
Beyond the Baseline
League City, Texas
August 8, 1991

The trend for many years as space platforms have become more complex has been to oversense these systems, to anticipate unforeseen fault modes and sensor failures. However, this strategy becomes untenable when the amount of sensor data becomes too great for operators to assimilate and interpret, and when the cost, launch weight, and power consumption of too many sensors becomes unacceptable.

On Space Station Freedom (SSF), design iterations have made clear the need to keep the sensor complement small. Along with the unprecedented duration of the mission, it is imperative that decisions regarding placement of sensors be carefully examined and justified during the design phase.

In the ECLSS Predictive Monitoring task, we are developing AI-based software to enable design engineers to evaluate alternate sensor configurations. Based on techniques from model-based reasoning and information theory, the software tool makes explicit the quantitative tradeoffs among competing sensor placements, and helps designers explore and justify placement decisions. This work is being applied to the Environmental Control and Life Support System (ECLSS) testbed at MSFC to assist design personnel in placing sensors for test purposes to evaluate baseline configurations and ultimately to select advanced life support system technologies for evolutionary SSF.

BACKGROUND

JPL is conducting research on advanced monitoring systems which maximize feedback of engineering information from complex, dynamic space systems where human and computational resources are constrained. This work has impact upon both real-time monitoring (sensor selection) and system design (sensor placement).

MSFC and Boeing contractors are working on fault detection, isolation, and recovery (FDIR) for SSF ECLSS and are performing tests on and evaluating designs for SSF ECLSS hardware.

The ECLSS Predictive Monitoring task will transfer results on real-time monitoring capabilities and sensor placement guidance from work on the SELMON system at JPL to MSFC to support ECLSS testbed activities addressing SSF baseline and evolutionary requirements.

BACKGROUND

JPL:
research on monitoring and monitorability of complex, dynamic space systems

MSFC and Boeing:
FDIR and design evaluation for SSF ECLSS

ECLSS Predictive Monitoring task
sensor placement guidance during system design and sensor selection for real-time monitoring

PROBLEM

Sensor placement is the task of determining a set of sensors which allows the most accurate, safe, and reliable determination of the overall state of a monitored system while minimizing sensor power consumption, cost, computing power requirements, and weight. Reducing these quantities is particularly important in space-borne systems due to power and payload restrictions. In complex systems, this minimization task can be quite difficult.

PROBLEM

Sensor placement is the task of determining a set of sensors which allows an accurate determination of the overall state of the system while minimizing:

- power consumption
- cost ($$)
- computing power requirements
- launch weight

for space-borne systems (SSF), minimization is crucial

in complex systems (SSF ECLSS), minimization is difficult

OBJECTIVE

The objective of this project is twofold: Current work is aimed at providing ECLSS design engineers with software tools for evaluating alternative baseline SSF sensor placements. More specifically, to assist ECLSS designers in verifying that proposed baseline sensor configurations ensure safe, reliable monitoring while minimizing power, weight, computing requirements, and monetary cost. For evolutionary SSF, automated sensor placement will facilitate the utilization of advanced life support technologies (e.g. closed-loop regenerative life support) with more complex monitoring requirements which were unacceptable for baseline ECLSS because the monitoring requirements could not be easily met with available techniques.

OBJECTIVE

Baseline: Facilitate minimization of sensors while maintaining safe, reliable monitoring

Evolutionary: Enable utilization of more advanced technologies while maintaining monitorability

BENEFITS

Our approach uses a model-based simulation capability to evaluate how each sensor rates with respect to several monitorability measures over the behavior space of the monitored system. These scores can then be used to evaluate a proposed sensor configuration.

This sensor placement evaluation capability provides a number of benefits. First, this evaluation capability will aid designers in the sensor placement task by facilitating evaluation of alternative sensor placements. In particular, this capability would provide a quantitative measure of tradeoffs in sensor placements which previously have been viewed only subjectively. A second benefit is that quantification of sensor placement measures will aid in design documentation by allowing quantitative justification for sensor placements. Third, the automated evaluation capability will facilitate assessment of the impact of system design changes upon sensor placements. Finally, as a fourth benefit, this sensor placement evaluation capability can be used to aid in sensor power planning. When the utility of a sensor depends greatly upon the operating mode of the monitored device, it may be possible to reduce overall sensor power consumption by powering certain sensor suites only in limited operating modes. Because our approach measures the utility of sensors in each system operating mode, it can assist in sensor power planning.

BENEFITS

- Facilitates evaluation of alternative sensor placements.
- Provides a quantitative measure of tradeoffs.
- Supports design documentation.
- Facilitates assessment of impact of design changes.
- Facilitates sensor power planning.

MODEL-BASED APPROACH

Our approach to sensor placement can be described generally as follows:

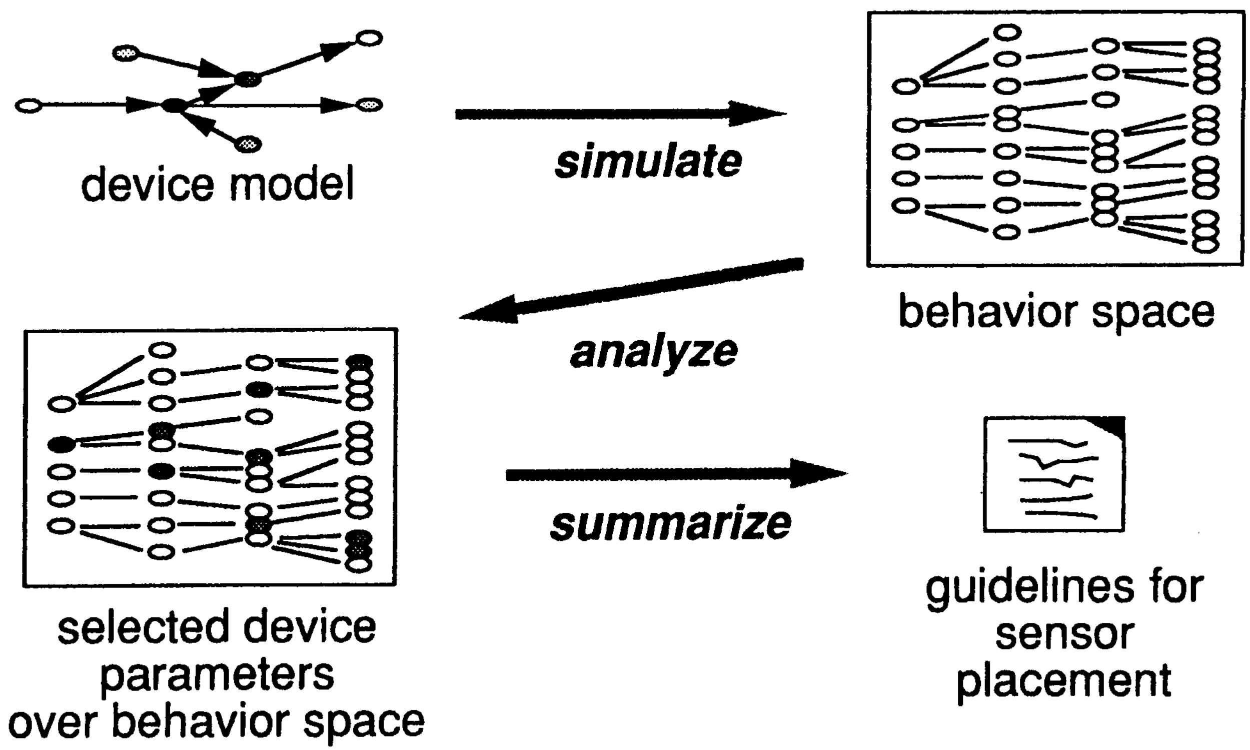
1. Given nominal behavioral models of the system and a causal simulation capability, generate a behavior space for the system.

2. Apply monitorability measures for sensitivity, cascading alarms, and potential damage to simulated system operation over these operating modes.

3. Compute teleological analysis scores.

4. Compute sensor placement recommendations as those with highest scores from the analyses.

MODEL-BASED APPROACH



MONITORABILITY MEASURES

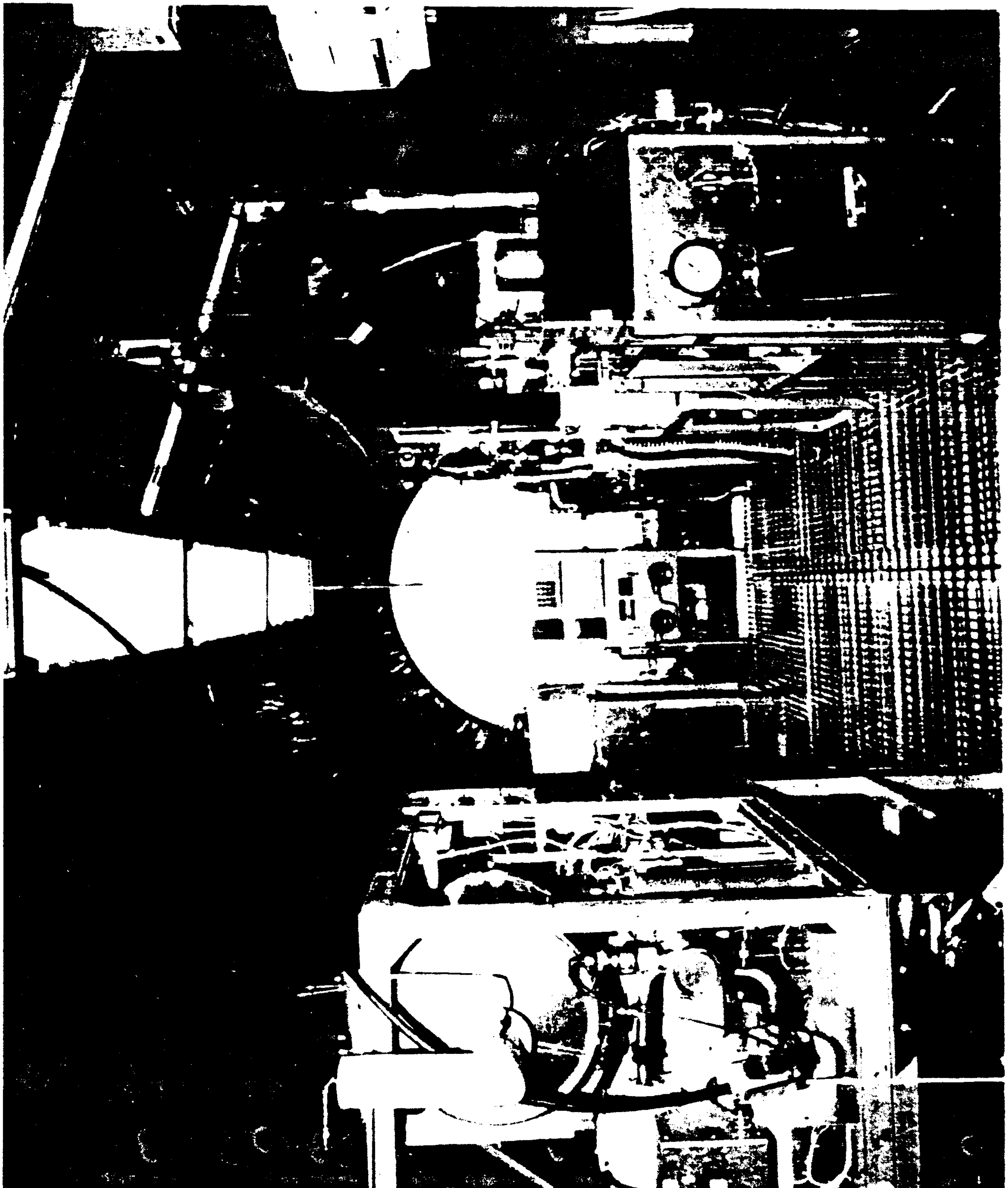
Our model-based reasoning approach to evaluating sensor placements uses four monitorability measures. *Sensitivity Analysis* suggests sensor placements which measure quantities which have the greatest impact upon the overall state of the system. *Cascading Alarm Analysis* suggests sensor placements which measure quantities whose changes have the potential to generate many alarms. *Potential Damage Analysis* suggests those sensor placements which measure quantities which are likely to cause permanent damage to devices in the system being monitored. *Teleological Analysis* suggests sensor placements which monitor quantities relevant to specified operational goals of the system. Our approach uses a model-based simulation capability to evaluate how each sensor rates with respect to each of these measures over the behavioral space of the monitored system. These scores can then be used to generate a proposed sensor set.

MONITORABILITY MEASURES

- Sensitivity analysis
- Cascading Alarms analysis
- Potential Damage analysis
- Teleological analysis

THE SSF ECLSS TESTBED AT MSFC

Our sensor placement approach is being tested upon the water reclamation subsystem of the Environmental Control and Life Support System (ECLSS) for Space Station Freedom. A model describing the behavior of the multifiltration (MF) subsystem in terms of fluid flow and heat transfer has been constructed. This model was developed via a combination of study of design documentation (i.e. schematics, etc.) and consultation with domain experts (e.g. the operators of the testbed). This model has been validated by comparison against actual data from the subsystem testbed undergoing evaluation at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. We are in the process of extending our model to cover more of the ECLSS subsystems, including the air recycling subsystem.



THE MULTIFILTRATION SUBSYSTEM

The ECLSS multifiltration (MF) subsystem consists of two parts -- the sterilization loop and the unibed assembly. In this subsystem, the water first passes through a pump at the inlet to the system. Next, the water passes through a coarse filter before entering the sterilization loop. In the sterilization loop the water is heated in the regenerative heat exchanger and then by the in-line heater. The in-line heater has only a coarse temperature control and thus the water temperature here may differ by as much as 10° F from the goal of 250° F. Within the sterilizer reservoir, the temperature of the water is maintained more accurately at 250°F for about 9 minutes. In the second portion of the subsystem, the water passes through a set of unibed filters designed to remove particulate contaminants from the water. Possible sensor types are flow rate, water pressure, and temperature. Possible sensor locations are indicated in by ovals.

Specified operational goals are:

1. maintain processed water at 250°F in sterilizer reservoir for 9 minutes; and
2. maintain water flow through the unibed of at least 15 mL/minute.

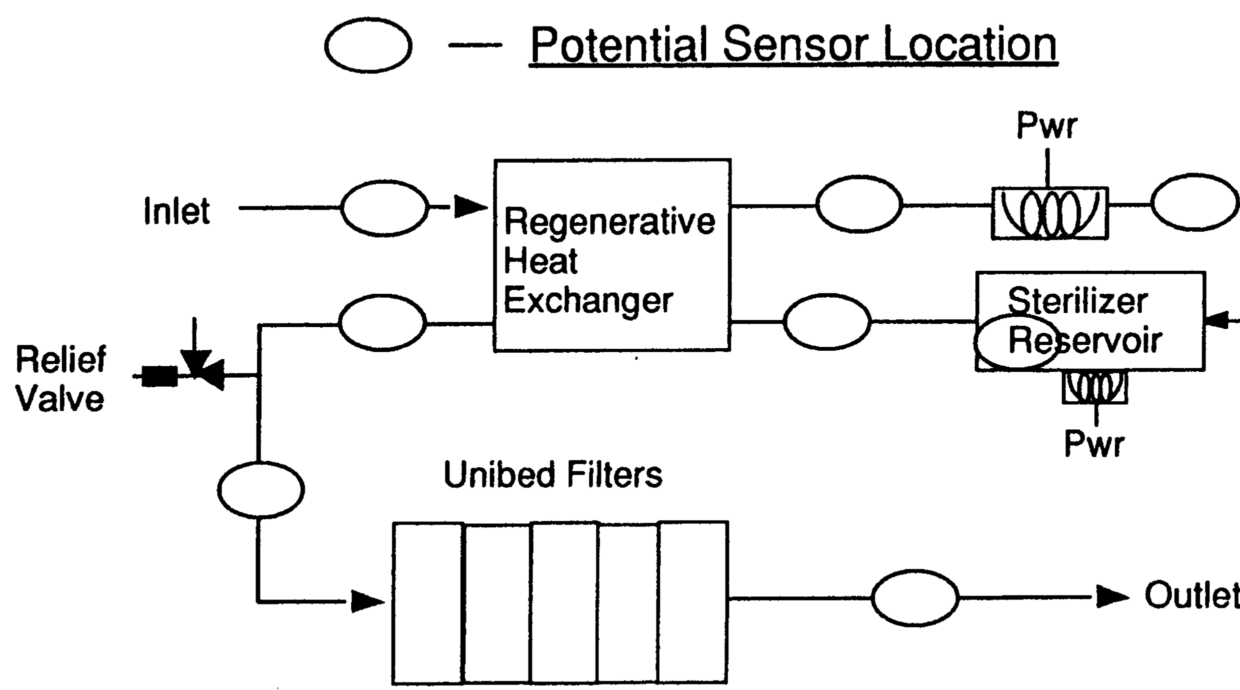
JPL

Advanced Development Program

ECLSS Predictive Monitoring

FREEDOM

MULTIFILTRATION SUBSYSTEM



SENSITIVITY ANALYSIS

Sensitivity Analysis measures the sensitivity of other quantities in the monitored system to changes in a given quantity. This measure depends upon information about "normal" magnitudes of change for the devices in question. For each normal operating mode of the system, the following procedure is followed. For each quantity $Q \in$ MonitorableQuantities (the set of all monitorable quantities in the model), determine nominal operating values and alarm ranges. Next compute a normalized change increase $\Delta Q+$ and decrease $\Delta Q-$ as the average amount of change between updates for that operating mode. Next, for each quantity Q, beginning with an initial state where all devices/sensors are at nominal operating values, simulate a change ΔQ in Q, propagating this change to other quantities in AllQuantities (the set of all quantities in the model), as dictated by the model. For each such changed quantity Q' $\in$ AllQuantities, for each time the quantity changes during the simulation, collect a sensitivity score proportional to the amount of change in Q' from its normal value $Q'_{nominal}$ relative to alarm thresholds but also modified by a decreasing function of time[1]. This calculation captures the notion that delayed and less direct effects are more likely to be controllable and less likely to occur. Thus, a change which affects a quantity Q' but occurs slowly is considered less important. This simulation proceeds for a preset amount of simulated time. Then, for each changed quantity Q', take the maximum of the collected change score for that quantity. The sensitivity score for Q is the sum of these maximums for all the Q's. Thus, for each quantity Q, a simulated change produces a set of changescores for other quantities in the model. The sensitivity score for Q is the sum of the respective maximums of each of these sets[2]. The computation of the sensitivity scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default).

For each change to a quantity Q' occurring at time T_{change}, compute a change score as follows.

let Q'_{new} be the new value for Q'

$$\text{changescore}(Q') = \frac{|Q'_{new} - Q'_{nominal}|}{|Q'_{alarm} - Q'_{nominal}|} \cdot \frac{(\Delta T - T_{change})}{\Delta T}$$

add this changescore to the set of collected changescores for Q'

let MaxChangeScore(Q') = the maximum of the set of collected changescores for Q'

$$\text{let sensitivity}(Q) = \sum_{Q' \in \text{AllQuantities}} \text{MaxChangeScore}(Q')$$

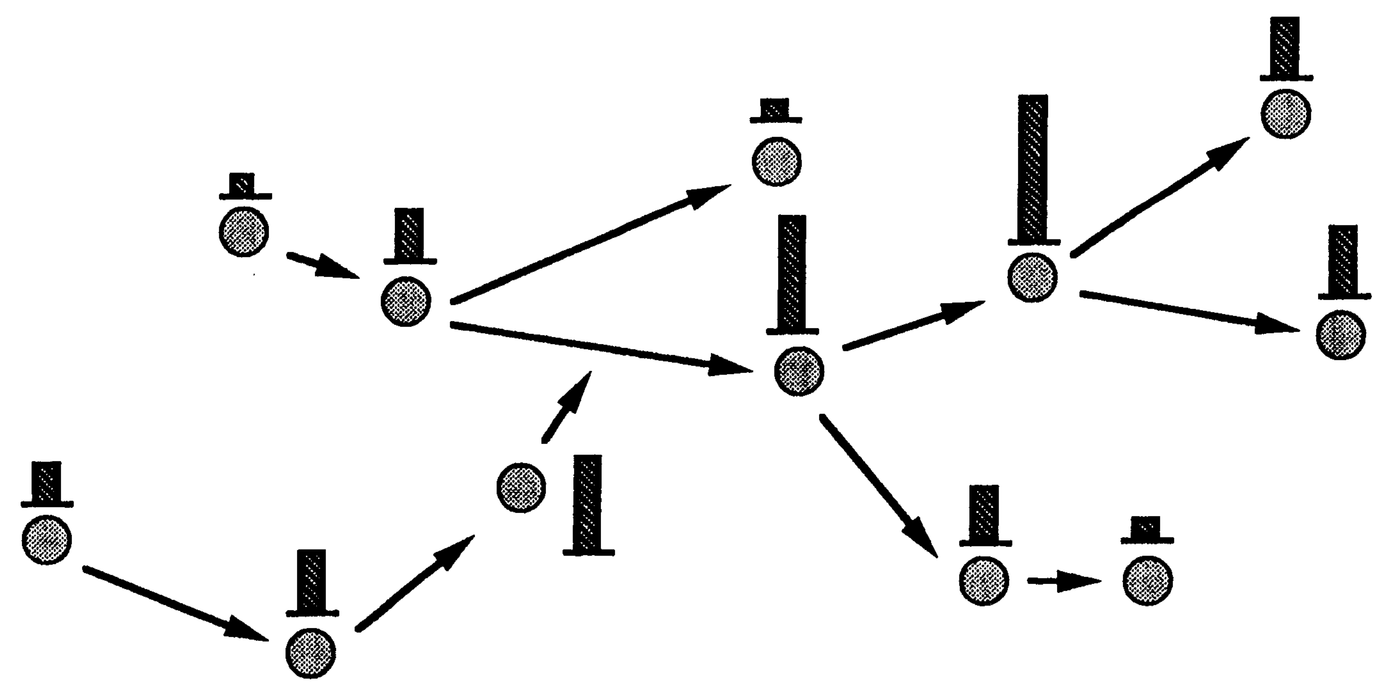
The overall sensitivity score for Q is then computed by summing the sensitivity scores for $\Delta Q+$ and $\Delta Q-$ weighted by relative frequency of increase vs. decrease for Q.

---

[1]This can be viewed as an average $\partial Q'/\partial Q$ modified by a decreasing function of time elapsed and normalized for the alarm threshold for Q'.

[2]Quantities which do not change when Q is changed produce an empty set of changescores. We define the maximum of this empty set as 0 for the purpose of the sensitivity summation.

SENSITIVITY ANALYSIS

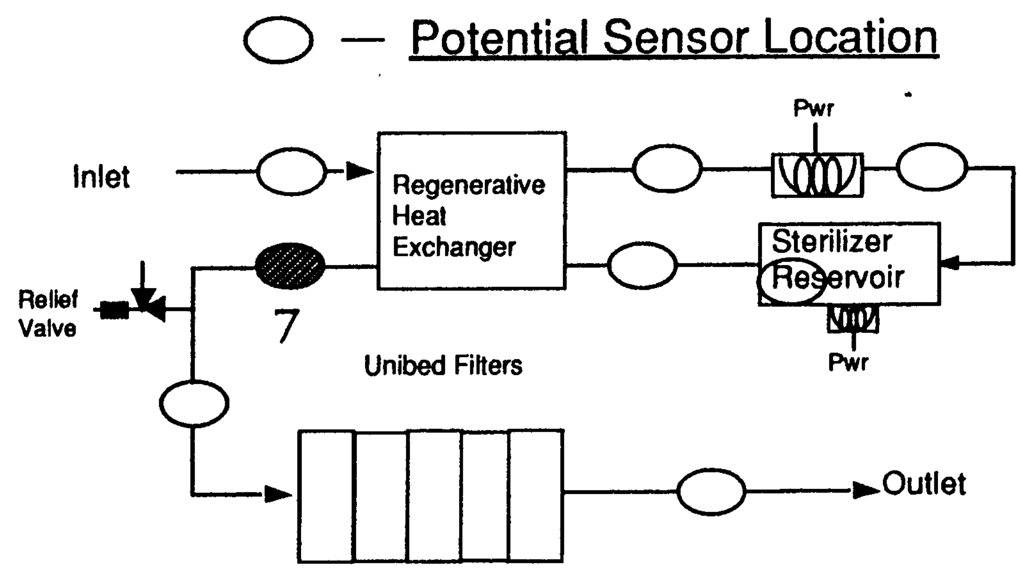


identify those sensors which, when undergoing change, result in the greatest global change within the system

SENSITIVITY RECOMMENDATIONS

Sensitivity Analysis suggests the specific placement of a pressure sensor near the relief valve at point 7. This is because the relief valve is pressure controlled; if the pressure at point 7 is above 40 psig, the relief valve will open and drastically change the system behavior. The opening of the relief valve would cause an immediate significant pressure loss, as well as significantly affecting flow in the MF subsystem.

SENSITIVITY RECOMMENDATIONS



recommend pressure sensor at point 7 because pressure there affects the operation of the relief valve, which significantly affects overall system operation

CASCADING ALARMS ANALYSIS

Cascading alarms analysis measures the potential for change in a single quantity to cause a large number of alarm states to occur, thus causing information overload and confusion for operators. As with sensitivity analysis, cascading alarms analysis is performed for each operating mode of the monitored system. For a standardized amount of increase and decrease for each monitorable quantity Q, the effects of such a change are propagated throughout the system and the number of triggered alarms is counted. This standardized amount of change is different from the measure used in the sensitivity analysis as normal changes are not likely to produce cascading alarm patterns. The alarm count is then normalized for the total number of possible alarms. The weight of each alarm state triggered is also decreased as a function of the time delay from the initial change event to the alarm. This has the effect of focusing this measure on quickly developing cascading alarm sequences which are the most difficult to interpret and diagnose. The computation of cascading alarms scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default) where $\Delta Q+$ and $\Delta Q-$ are functions of the distance between the nominal value for Q and the alarm value for Q in the increasing and decreasing directions respectively

$$\text{let CascadingAlarm}(Q) = \frac{\sum_{Q' \in \text{all quantities}} \text{InAlarm}(Q')}{\text{number of quantities } Q'}$$

where $\text{InAlarm}(Q') = (\Delta T - T_{alarm})/\Delta T$

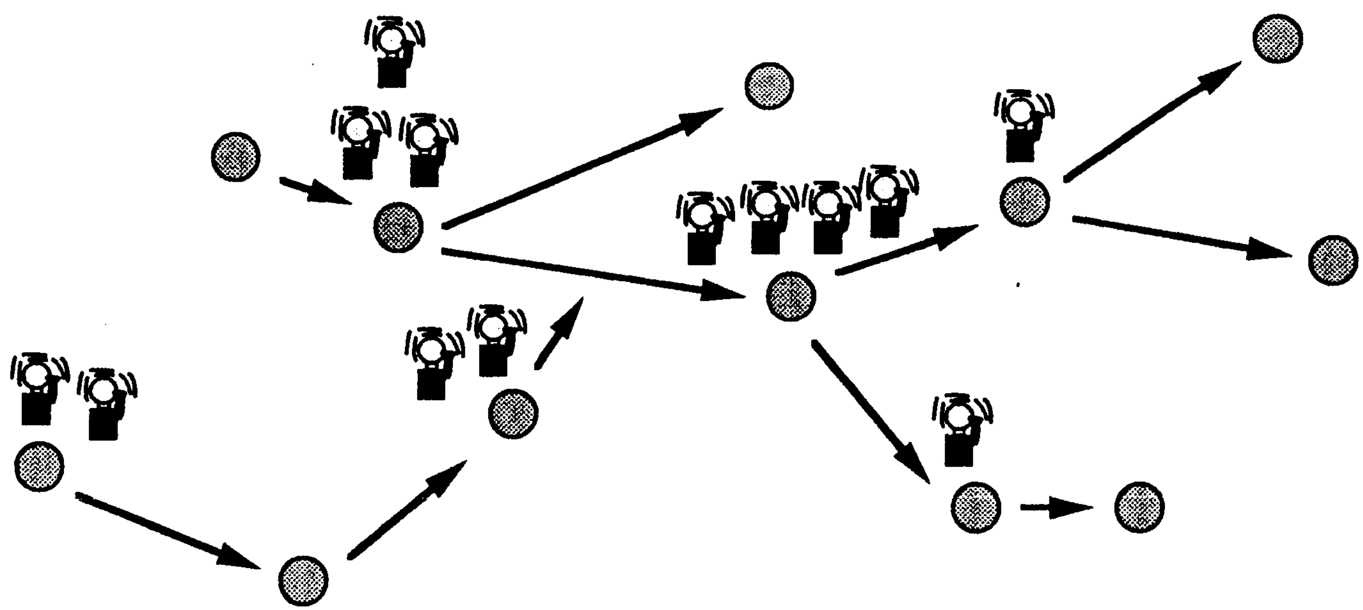
if Q' entered an alarm range during the simulation
and T_{alarm} is the earliest time Q' was in an alarm range

and

$\text{InAlarm}(Q') = 0$

if Q' did not enter an alarm range during the simulation.

CASCADING ALARMS ANALYSIS

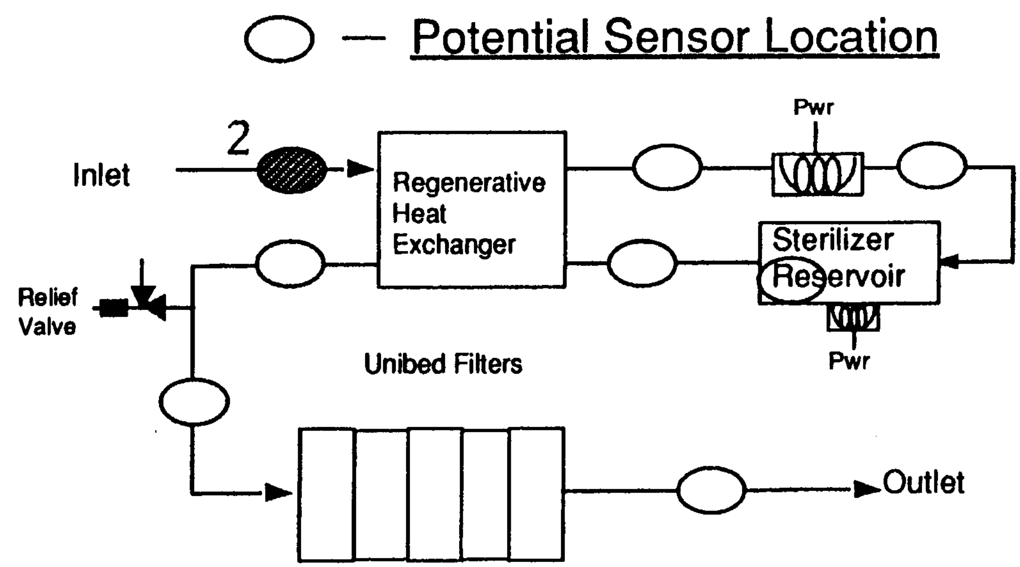


identify those sensors which, when in alarm, have the greatest potential to create alarm states elsewhere in the system

CASCADING ALARMS RECOMMENDATIONS

Cascading alarms analysis suggests placement of flow rate sensors because significant perturbations in flow rate can cause cascading temperature and pressure alarms.

CASCADE RECOMMENDATIONS



recommend flow sensor at point 2 because anomalous flow can cause cascading pressure and temperature alarms

POTENTIAL DAMAGE ANALYSIS

Another measure is potential damage analysis, which is computed in two parts -- predictive potential damage and potential damage detection. Predictive potential damage measures the capability of a sensor to predict damage to devices in the system. For each device and quantity associated with that device, there is an associated operating range which is judged to be harmful to the device. Predictive potential damage analysis is performed by simulating a change in each monitorable quantity Q and scoring upon the basis of how many devices will enter harmful ranges due to the change in Q. Predictive potential damage analysis scores are moderated by the number of control points which may interdict the damage. For the causal path leading to the damaged device, for each mechanism (arc in the causal graph) which can be influenced by a controllable parameter, the potential damage score is reduced. The potential damage measure depends more critically upon domain-specific information beyond the schematic, as many of the potential damage scenarios involve device or subsystem interactions. The computation of potential damage scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default).

let $\text{PotentialDamagePredict}(Q) = \sum_{Q' \in \text{all quantities}} \text{Damaged?}(Q')$

where

$$\text{Damaged?}(Q') = \frac{(\Delta T - T_{alarm})}{\Delta T \times (\text{control} + 1)}$$

if Q' entered a damaging range during the simulation where T_{alarm} is the earliest time Q' was in a damage range and control is the number of control points in the causal chain leading to the damaging quantity value and

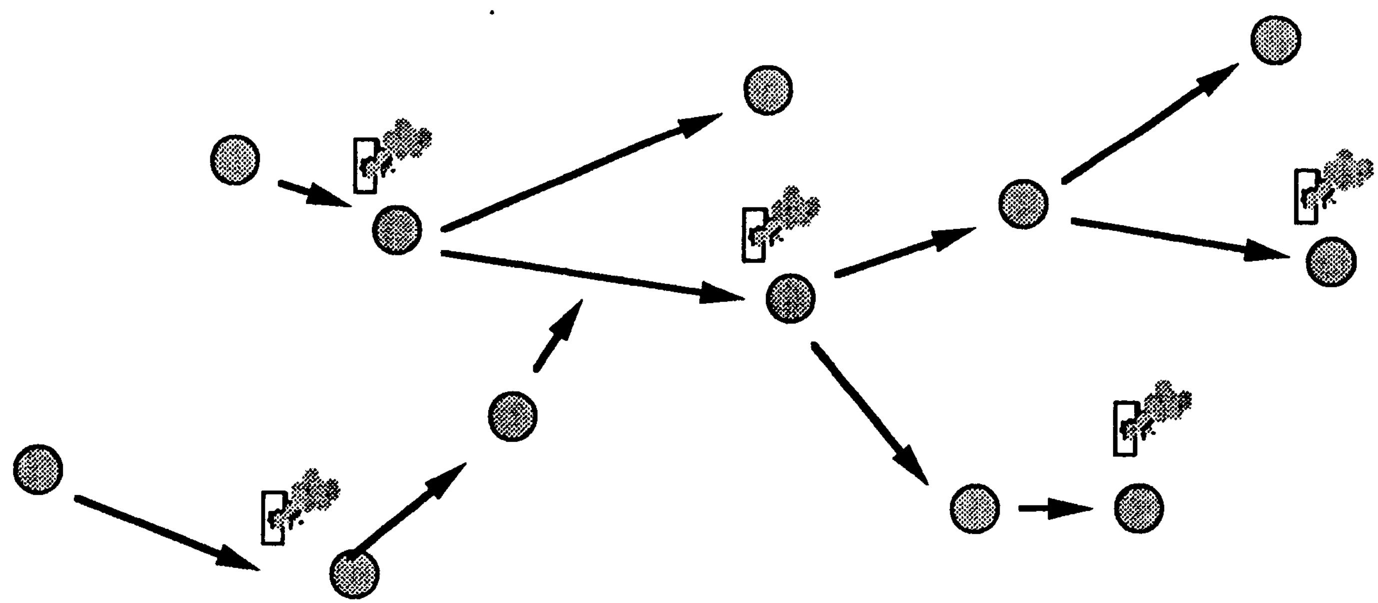
$\text{Damaged?}(Q') = 0$

if Q' did not enter a damage range during the simulation.

The second part of potential damage analysis is damage detection. In this measure, the model is used to simulate devices in the system entering damaging operating modes, and potential sensors are scored upon the basis of how much they change (in the same manner as the sensitivity analysis). Damage detection analysis is performed by propagating a change resulting in a device entering a damaging range, and measuring the resulting change in other sensors as in sensitivity analysis. Those sensors which change more significantly to indicate the damaging device state are scored higher by the damage detection analysis. Let $\Delta Q'+$ or $\Delta Q'-$ be changes sufficient to cause Q' to enter a device damaging range. Simulate a change $\Delta Q'+$ or $\Delta Q'-$ to Q' beginning at time 0 and continuing to time ΔT (a user-supplied default).

let $\text{PotentialDamageDetect}(Q) = \sum_{Q' \in \text{all quantities}} \text{Changescore}(Q)$

POTENTIAL DAMAGE ANALYSIS



identify those sensors which predict or inform of permanent damage to the system

POTENTIAL DAMAGE RECOMMENDATIONS

Potential Damage Detection Analysis suggests placing a temperature sensor at point 4. If the in-line heater overheats, it could cause the water flowing through to be raised to an unacceptably higher temperature than normal.

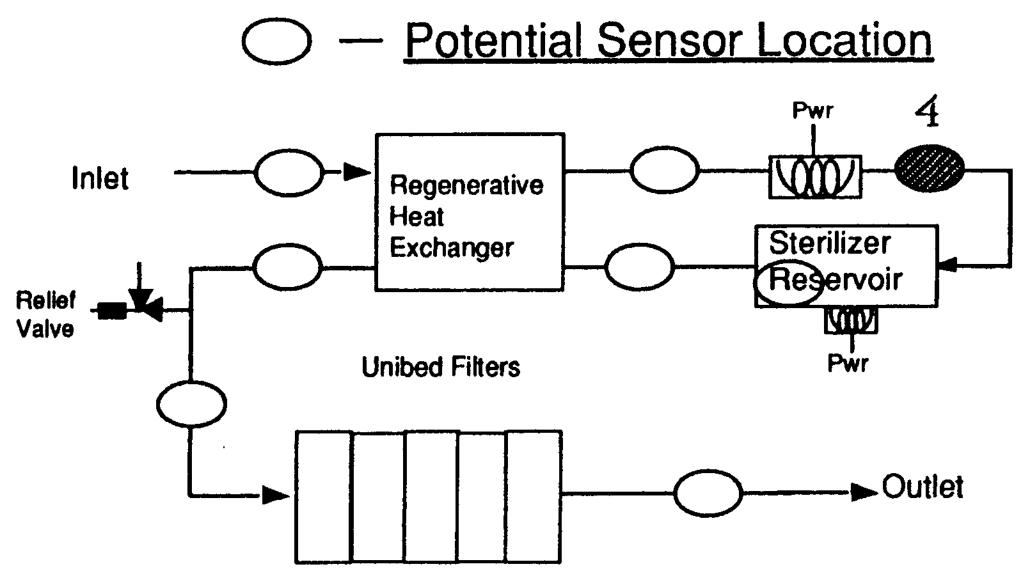
JPL

Advanced Development Program

ECLSS Predictive Monitoring

FREEDOM

DAMAGE RECOMMENDATIONS



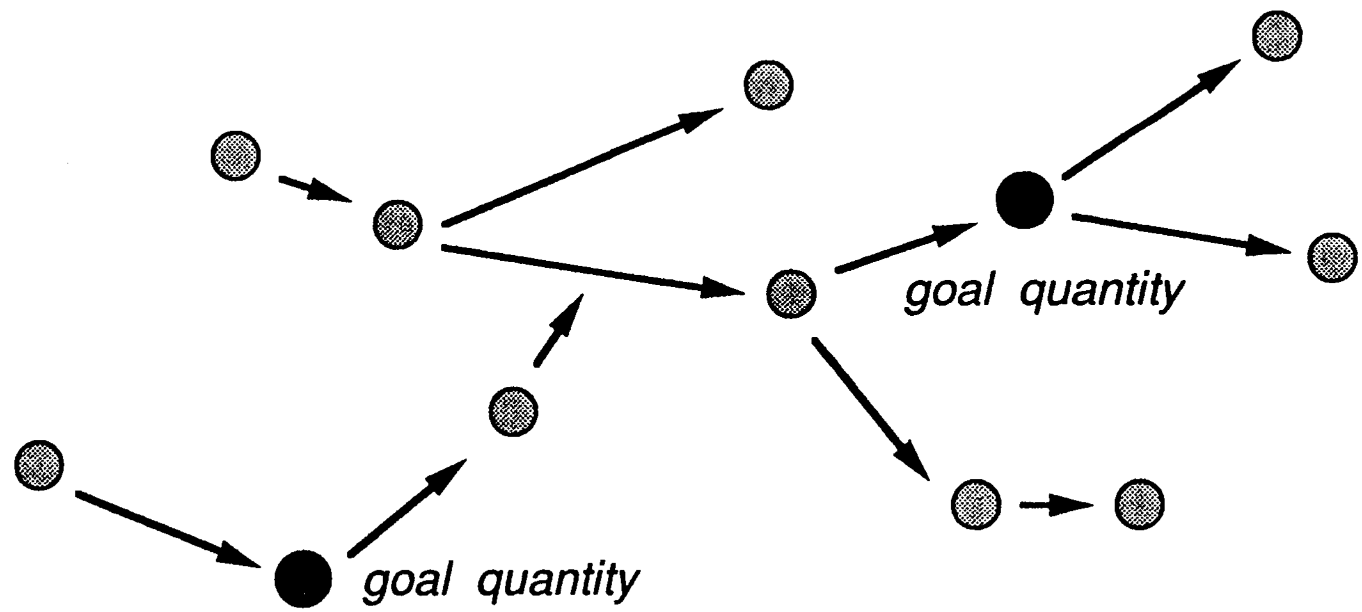
recommends temperature sensor at point 4 to detect a damaging overheating of the in-line heater immediately upstream

TELEOLOGICAL ANALYSIS

The final measure is teleological analysis, which does not use the model-based simulation capability. Instead, teleological analysis directly examines mechanism dependencies in the causal graph to produce a sensor placement score.

Teleological analysis suggests measurements of quantities which provide the most direct feedback on operational goals of the system being monitored. In this measure, those quantities directly mentioned in the operational specifications of the system are scored highest, those quantities directly influencing these quantities are scored next highest, etc. The exact computation of the teleological measure involves backtracing the causal graph. Directly monitorable quantities appearing in the goal description receive a score of 1. For each mechanism affecting the goal quantity, a teleology score inversely proportional to the number of such mechanisms is divided equally among the inputs to the mechanism. Thus, if there are m mechanisms affecting a goal quantity, and one of these mechanisms has n inputs, each such input receives a score $1/mn$. Note that multiple independent causal influence paths combine additively. While this process proceeds recursively for mechanisms potentially influencing the inputs to the given mechanism, each level is multiplied by $1/d$ where d is the number of mechanisms (arcs in the causal graph) distant from the goal quantity.

TELEOLOGICAL ANALYSIS

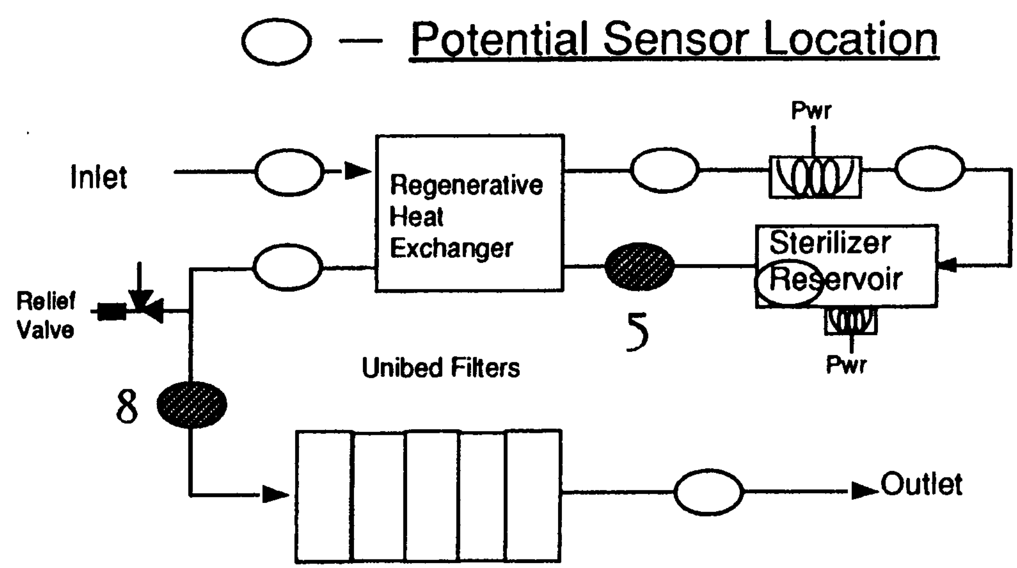


identify those sensors which correspond to quantities most directly related to operational goals of the system

TELEOLOGICAL RECOMMENDATIONS

Teleological Analysis suggests placing flow rate sensors at point 8 to verify the flow of water through the unibeds as the flow rate is directly mentioned in the operational goal specification. Teleological Analysis also scores highly a flow rate sensor in the sterilizer reservoir (point 5), as this quantity determines the time spent by the water in the sterilizer reservoir. Finally, Teleological Analysis suggests placement of a temperature sensor for the sterilizer reservoir (point 5), as this quantity appears in the operational goal specification of the system.

TELEOLOGICAL RECOMMENDATIONS



recommends temperature and flow sensor at point 5 because of the temperature and time goals of the sterilizer reservoir; recommends a flow sensor at point 8 because of the unibed flow goal

COLLABORATION

JPL and MSFC personnel are collaborating in the ECLSS Predictive Monitoring Task. JPL personnel are developing information quantification and model-based reasoning techniques applicable to both sensor placement for monitorability and sensor selection in monitoring. In support of these goals, MSFC personnel are assisting by providing technical expertise to support the construction of models of ECLSS subsystems. Additionally, MSFC personnel are providing ECLSS testbed data to be used in testing the sensor placement and sensor selection software being developed at JPL. As results from this testing become available, they are made available to MSFC personnel who provide feedback on the value and accuracy of sensor placement and sensor selection recommendations. This feedback is used to refine the methods and software being developed at JPL.

JPL/MSFC COLLABORATION

JPL

MSFC

sensor placement capability to support ECLSS design

sensor selection capability to support ECLSS monitoring

ECLSS test data to drive research

feedback from domain experts on sensor recommendations for ECLSS

SCHEDULE

The first users of the sensor placement evaluation and generation capabilities developed in this task will be the MSFC ECLSS design team led by Environmental Control and Life Support Branch Chief K. Mitchell.

FY91: The design for the sensor placement evaluation tool based on four monitorability measures has been completed. A proof-of-concept[3] demonstration will be completed for the SSF ECLSS MF subsystem. Causal modelling efforts have been targeted for the water reclamation subsystem of ECLSS.

FY92: The proof-of-concept sensor placement tool based on monitorability measures will be extended to a functional prototype system. This full-capability system will be available for evaluating proposed baseline ECLSS sensor configurations. Although the delivery date for this system will miss the POST milestone for the air side of ECLSS, it will precede the POST milestone for the water side of ECLSS by 6 months, the POST milestone for integrated ECLSS subsystems by 12 months, and the first BOST deadline for ECLSS (air side) by ~18 months. Also, in FY92, a design and proof-of-concept demonstration for a sensor placement evaluation tool based on diagnosability measures will be completed. Causal modelling efforts on the water reclamation subsystem of ECLSS will be completed and modelling efforts on the air recycling subsystem will be initiated. A design for a sensor placement generation tool also will be developed.

FY93: The functional prototype sensor placement tool based on monitorability measures will be extended to a pilot system. The proof-of-concept sensor placement tool based on diagnosability measures will be extended to a functional prototype system. This full-capability system will be available for evaluating proposed baseline ECLSS sensor configurations. Although the delivery date for this system will miss the POST milestone for the air side of ECLSS and coincide with the POST milestone for the water side of ECLSS, it will precede the POST milestone for integrated ECLSS subsystems by 6 months, and the first BOST deadline for ECLSS (air side) by ~12 months. Also in FY93, causal modelling efforts on the air recycling subsystem will be completed. A proof-of-concept demonstration for a sensor placement generation tool will be completed.

FY94 & FY95: The functional prototype sensor placement tool based on diagnosability measures will be extended to a pilot system. Both pilot sensor placement evaluation tools will be available for evaluating monitoring and diagnosis requirements for advanced life support technologies for evolutionary SSF. The proof-of-concept system for a sensor placement generation tool will be extended to a functional prototype system. Sensor configurations obtained with this software tool will be available for evaluation. In FY95, the functional prototype system for a sensor placement generation tool will be extended to a pilot system.

---

[3] A proof-of-concept (POC) system is one which works correctly on a specific example or set of examples but is not designed to be robust and extendable. A functional prototype system is one which provides full capability, is robust and extendable, and is delivered both for actual use and for rigorous testing and evaluation in a real setting. A pilot system is one which has been refined through feedback provided on the functional prototype system and is delivered for general use with stated and frozen design specifications.

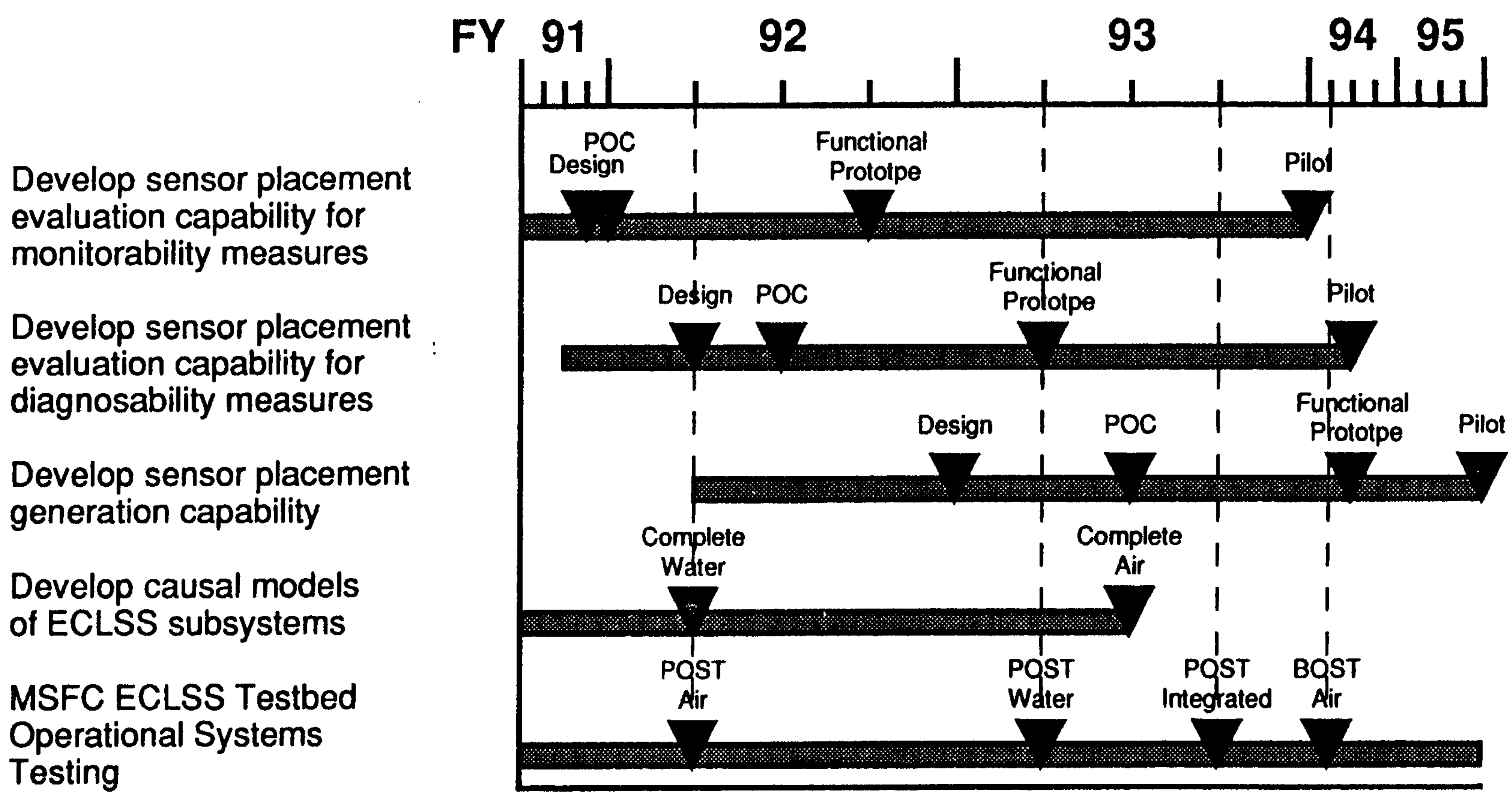
JPL

Advanced Development Program

ECLSS Predictive Monitoring

FREEDOM

SCHEDULE



SUMMARY

The trend for many years as space platforms have become more complex has been to oversense these systems, to anticipate unforeseen fault modes and sensor failures. However, this strategy becomes untenable when the amount of sensor data becomes too great for operators to assimilate and interpret, and when the cost, launch weight, and power consumption of too many sensors becomes unacceptable.

On Space Station Freedom (SSF), design iterations have made clear the need to keep the sensor complement small. Along with the unprecedented duration of the mission, it is imperative that decisions regarding placement of sensors be carefully examined and justified during the design phase.

In the ECLSS Predictive Monitoring task, we are developing AI-based software to enable design engineers to evaluate alternate sensor configurations. Based on techniques from model-based reasoning and information theory, the software tool makes explicit the quantitative tradeoffs among competing sensor placements, and helps designers explore and justify placement decisions. This work is being applied to the Environmental Control and Life Support System (ECLSS) testbed at MSFC to assist design personnel in placing sensors for test purposes to evaluate baseline configurations and ultimately to select advanced life support system technologies for evolutionary SSF.

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

We would like to thank Jay Wyatt of Marshall Space Flight Center for innumerable discussions regarding the operation of the ECLSS water reclamation subsystem.

For further information see:

S. A. Chien, R. J. Doyle, and L. S. Homem de Mello, "A Model-based Reasoning Approach to Sensor Placement for Monitorability," *Space Operations, Applications, and Research Symposium*, Houston, July 1991. Also appears in the *Proceedings of the Workshop on Model-Based Reasoning, 9th National Conference on Artificial Intelligence*, Anaheim, July 1991.

R. J. Doyle, U. M. Fayyad, D. Berleant, L. K. Charest, L. S. Homem de Mello, H.J. Porta, and M.D. Wiesmeyer," Sensor Selection in Complex Systems Monitoring Using Information Quantification and Causal Reasoning" in *Recent Advances in Qualitative Physics*, B. Faltings and P. Struss (eds.), MIT Press, 1991.

R. J. Doyle, S. M. Sellers, and D. J. Atkinson, "A Focused, Context-Sensitive Approach to Monitoring," *11th International Joint Conference on Artificial Intelligence*, Detroit, August 1989.

R. J. Doyle, D. J. Atkinson, and R. S. Doshi, "Generating Perception Requests and Expectations to Verify the Execution of Plans," *5th National Conference on Artificial Intelligence*, Philadelphia, August 1986.

JPL

Advanced Development Program

ECLSS Predictive Monitoring

FREEDOM

SUMMARY

- Trend has been to oversense systems to be monitored.

- SSF sensor complement must be small.
- Constrained by cost($$), launch weight, power consumption, computing requirements.
- Must maintain safe, reliable monitoring.

- JPL is developing an AI-based tool to assist design engineers in evaluating alternative sensor placements.
- Being applied to evaluation of alternate baseline SSF ECLSS sensor configurations.
- Will be applied to ensure monitorability of advanced life support technologies for evolutionary SSF.

NASA JPL

JPL SPACE STATION TELEROBOTIC ENGINEERING PROTOTYPE DEVELOPMENT

ADVANCED TELEROBOTICS SYSTEM TECHNOLOGY

August 6-8, 1991

Paul G. Backes
Technical Task Manager
Jet Propulsion Laboratory
Pasadena, California

NASA JPL

ADVANCED TELEROBOTICS SYSTEM TECHNOLOGY

Scope:

The Scope of the Advanced Telerobotics System Technology Task is to develop/prototype advanced telerobotics supervisory and shared control to enhance IVA teleoperation on Space Station. The technology provides enhanced telerobotics capabilities while operating within the expected constraints of computation limitations, time delay, and bus bandwidth. A local site operator interface has also been developed for specifying teleoperation and shared control modes as well as supervised autonomous macros for execution at the remote site. The primary objective of the task is to transfer the advanced technology to appropriate flight centers to enhance the baseline Station capabilities.

NASA
JPL

ADVANCED TELEROBOTICS SYSTEM TECHNOLOGY

Scope:

- Remote Site Telerobotic System Development
  - Shared Control
  - Supervised Autonomous Control
  - Minimal Computational Requirements
- Local Site Operator Interactive Task Specification
  - UMI User Macro Interface
- Technology Transfer

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

TECHNOLOGY TRANSFER

Two technology transfer deliveries to GSFC were successfully achieved. A document specifying the desired process for technology transfer was written with GSFC and its process was followed. The technologies transferred were Generalized Compliant Motion With Shared Control and the UMI User Macro Interface.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

TECHNOLOGY TRANSFER

Transferred to GSFC:

- Generalized Compliant Motion With Shared Control
- UMI User Macro Interface

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

UMI USER MACRO INTERFACE

The UMI User Macro Interface was developed to provide local site interactive operator specification of the desired remote site robot execution. This included local site macro and task building, mode selection for shared control, supervised autonomous task sequencing, and task simulation on a 3 D simulator.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

UMI USER MACRO INTERFACE

Developed/Demonstrated Robust:

- Local Site Interactive Macro/Task Building
- Mode Selection for Shared Control
- Supervised Autonomous Task Sequencing
- Task Simulation

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

SHARED AND SUPERVISORY CONTROL

Robust supervisory and shared control were developed and demonstrated in the laboratory. Shared control included the real-time merging of operator teleoperation inputs with autonomous force control. Three modes of shared control were provided: World, Tool, and Camera. There was also the option for partitioning the task degrees of freedom into operator and autonomous controlled degrees of freedom. Supervised autonomous control included the development of remote site task execution primitives including Generalized Compliant Motion.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

SHARED AND SUPERVISORY CONTROL

- Developed/Demonstrated Robust Shared Control
  - Real-Time Merging of Operator Inputs with Autonomous Control
  - World, Tool, Camera Modes
- Developed/Demonstrated Robust Supervised Autonomous Control
  - Remote Site Autonomous Control Primitives
  - Generalized Compliant Motion

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

DUAL-ARM COOPERATIVE CONTROL
(Two Robots Manipulating One Common Object)

The supervisory and shared control capabilities developed for a single robot arm were expanded for dual-arm control. Two robots hold one common object. The operator moves one hand controller to specify the desired motion of the common object and the two robots move in concert with the object. Move-squeeze decomposition is used to decompose the forces sensed at the wrists of the two robots into squeeze forces which cause internal forces in the object and move forces that move the object or cause contact forces between the object and its environment. The Generalized Compliant Motion With Shared Control primitive was generalized to dual-arm control capability.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

DUAL-ARM COOPERATIVE CONTROL
(Two Robots Manipulating One Common Object)

- Demonstrated Shared Control
  - One Hand Controller, Cooperating Robots
- Demonstrated Supervisory Control
  - Dual-Arm Generalized Compliant Motion
- Demonstrated Move-Squeeze Decomposition of Dual Robot Forces

NASA
JPL

FY91 STATUS/ACCOMPLISHMENTS

LABORATORY EXPERIMENTS

Various laboratory experiments were performed to validate the technology. A videotape showing some of the experiments was made.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

LABORATORY EXPERIMENTS

- Single-Arm Control: Compliant Grasp, Bolt Seating and Turning, Electronics Card Insertion/Removal, Door Opening, Electrical Connector Insertion/Removal
- Single and Dual-Arm Control: Pin Insertion, Contour Following, ORU Manipulation
- Dual-Arm Control: Satellite Capture, Fluid Coupler Insertion/Removal

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

OPERATOR PERFORMANCE STUDY

An operator performance study was designed and data collection is presently underway. The study is comparing three modes of teleoperation: force reflecting teleoperation, shared control, and feedforward position only. Nine operators are performing three tasks: electrical connector removal/insertion, ORU removal/insertion, and electronics card removal/insertion. Additionally, a multiple bolt seating/turning task is being done by a subset group of the operators. The results will indicate various results including time of task execution, force buildup, and various operator observations and preferences.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

OPERATOR PERFORMANCE STUDY

Performance Assessment Design (Data Collection and Analysis In-Process)

- Nine Operators
- Three Teleoperation Modes
  - Force Reflecting Teleoperation
  - Shared Control
  - Feedforward Position Only
- Four Tasks:
  - Electrical Connector Removal/Insertion
  - ORU Removal/Insertion
  - Electronics Card Removal/Insertion
  - Multiple Bolt Seating/Turning

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

DESIGN OF NEW REMOTE SITE SYSTEM
MOTES: A MODULAR TELEROBOT TASK EXECUTION SYSTEM

To be more valuable to the flight community, the supervisory and shared control system is being rewritten in the Ada programming language (it was in C). The new system, Modular Telerobot Task Execution System (MOTES), maintains the capabilities of the previous system but requires less computation capability and is more modular in design.

NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

DESIGN OF NEW REMOTE SITE SYSTEM
MOTES: A MODULAR TELEROBOT TASK EXECUTION SYSTEM

Maintains Supervisory and Shared Control Capability While Minimizing Remote Site Computational Requirements

- Written in Ada Programming Language
- Communication With Local Site System
- Shared Control
- Supervised Autonomy
- Multi-Sensor Integration
- Fusion of Multi-Sensor Control
- Parameter Driven Task Execution

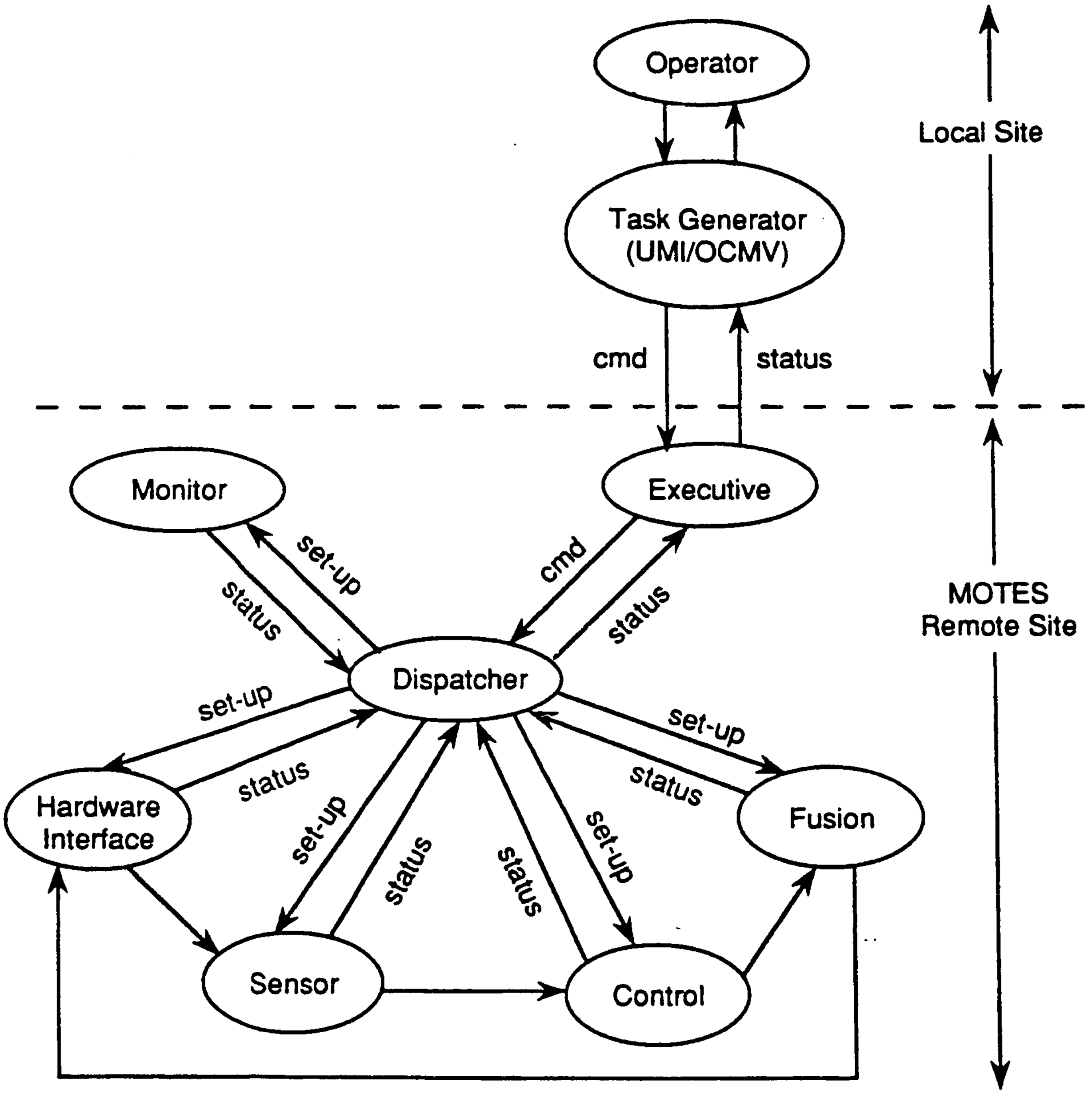
NASA JPL

FY91 STATUS/ACCOMPLISHMENTS

MOTES
MODULAR TELEROBOT TASK EXECUTION SYSTEM

The MOTES data flow diagram indicates the modularity of the system design. The Monitor, Hardware Interface, Sensor, and Control modules may each actually be multiple modules associated with different equivalent level functionalities, e.g., Sensor could include modules for force-torque sensing, proximity sensing, and trajectory generation.

MOTES
MODULAR TELEROBOT TASK EXECUTION SYSTEM



MOTES Data Flow Diagram

NASA JPL

FY91 ON-GOING WORK

REDUNDANT ARM CONTROL

Also, to better match the flight systems, the new MOTES system includes control of a 7 degree of freedom redundant manipulator. Besides the previous supervisory and shared control capability, the new system will provide redundant arm kinematics, efficient redundancy utilization, and simulation of the 7 DOF arm.

NASA JPL

FY91 ON-GOING WORK

REDUNDANT ARM CONTROL

Developing Supervisory and Shared Control for 7 Degree of Freedom Manipulator

- Redundant Arm Kinematics
- Efficient Redundancy Utilization
- Simulation of 7 DOF Arm

JPL SPACE STATION TELEROBOTIC ENGINEERING PROTOTYPE DEVELOPMENT
FY 91 STATUS/ACHIEVEMENTS
AUGUST 6-8, 1991

WAYNE ZIMMERMAN
PROJECT MANAGER
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

In this brief overview, it is important to provide the context in which the current engineering prototyping activity is being conducted. The primary operation activities through the addition of shared control and local-remote control; and, the enhancing of Space Station utilization during periods when the crew is not present in the man-tended phase, again, through the use of the local-remote control architecture. Both of these contextual areas were derived from earlier workload and tasking studies such as the Fisher-Price study. The two protoyping tasks that support these problem areas are 1) Telerobotics Ground Remote Operations (TGRO),and 2) Advanced Telerobotics System Technology (Shared Control).

INTRODUCTION/BACKGROUND

- PROBLEM AREAS ADDRESSED THROUGH CURRENT ACTIVITY
  - STREAMLINING IVA TELEOPERATION ACTIVITIES ON SPACE STATION
  - ENHANCING SPACE STATION UTILIZATION DURING MAN-TENDED PHASE

- CURRENT PROJECT ELEMENTS
  - TELEROBOTIC GROUND REMOTE OPERATIONS (TGRO)
  - ADVANCED TELEROBOTICS SYSTEM TECHNOLOGY (SHARED CONTROL)

MAJOR FY 91 DEVELOPMENTS/ACHIEVEMENTS

- COMPLETED DUAL ARM COORDINATED CONTROL
- PERFORMED/DOCUMENTED TELEOPERATOR PERFORMANCE
  - POSITION/RATE CONTROL
  - FORCE REFLECTION
  - SHARED CONTROL
- DEVELOPED/IMPLEMENTED A SOUND TECH TRANSFER MECHANISM BETWEEN A RESEARCH FACILITY (JPL) AND A USER FACILITY (FTS/GSFC)
- MOVED PREVIOUS 6DOF ROBOT SHARED CONTROL SYSTEM TO A 7DOF ROBOTICS RESEARCH ARM CONTROL ENVIRONMENT
- MOVED S/W CONTROL ENVIRONMENT TO ADA FOR BETTER COMPATIBILITY WITH IMPLEMENTATION/USER COMMUNITY
- REDESIGNED CURRENT LOCAL-REMOTE ROBOT CONTROL ARCHITECTURE IN RECOGNITION OF
  - NEED TO KEEP CONTROL SYSTEM AS SIMPLE/STREAMLINED AS POSSIBLE
  - HIGHLY CONSTRAINED ON-BOARD COMPUTATIONAL RESOURCES (BOTH SSF AND SSRMS/SPDM/FTS)
  - DESIRE TO MOVE ENGINEERING PROTOTYPING S/W PRODUCTS INTO NEXT PHASE OF DEVELOPMENT IN ACTUAL USER/FLIGHT ENVIRONMENT (I.E., BETTER MODULARITY TO ACCOMMODATE GROWTH/TECH TRANSER)
- PARTIAL IMPLEMENTATION OF OPERATOR-GRAPHICS USER INTERFACE ON IRIS
  - OBJECT MODEL KB
  - X-WINDOWS GRAPHICAL USER INTERFACE
  - VIDEO DISPLAY ON IRIS

The major FY91 accomplishments to date are as follows:

-Dual arm coordinated control; this capability was developed to allow the manipulator arms to be controlled by one hand controller under equal status meaning that the arms individually monitor forces and torques about a center reference point and move so as to zero any external or internal buildup of forces.

-Performance/documentation of operator performance; three major modes of control (position/rate, force reflection, and shared control) were assessed using 10 trained teleoperators to establish which of the three modes appears best relative to total elapsed task time, force buildup, and operator errors.

-Technology transfer; a joint technology transfer specification was drawn up by JPL and GSFC to insure the transfer of new technology is done properly JPL successfully transferred the User Macro Interface (UMI) and Shared Control technologies to the GSFC telerobotics laboratory.

-7DOF Robot Control; to stay current with proposed flight like manipulator designs, the JPL Engineering Prototyping lab initiated the move of its current 6DOF shared con trol software to a Robotic Research Arm environment additionally, the software environment has now been shifted to ADA to also stay current with the SSF software environment. Local-Remote Control Architecture Implementation; the FY90 robot control architecture design has been moved towards a more streamlined version concentrating on the primary local components (operator interface, sensing interface, task building, and handcontrollers), and remote components (servo/primitive control component, sensor monitoring, and teleop/autonomous control fusion) this change has been driven by the desire to be sensitive to projected on board computing constraints of both the station and robots.

The above accomplishments and task descriptions have been driven by domumented quirements derived via workload and tasking studies done over the last three years.These studies suggest that the ability to offload some tasks (that exceed the operator's bandwidth or are highly repetitive) to the remote autonomous system, or, perform some tasks from the ground, provides substantial potential to enhance station utilization and reliability. Further, the technology is developing at a rate which will allow it to have an impact on post FEL baseline operations. The requirement for this technology has been reasonably endorsed by station management, and the Level II Robotics Working Group.

CAPABILITY IS ESSENTIAL TO SSF PROGRAM

- HAS THE POTENTIAL TO INCREASE SSF UTILIZATION/RELIABILITY DURING MAN-TENDED PHASE.
- TECHNOLOGY CURRENTLY DEVELOPING AT RATE WHICH WILL ALLOW IT TO HAVE IMPACT ON BASELINE OPERATIONS.
- SUPERVISED AUTONOMY (A COMPONENT OF THE SHARED CONTROL CAPABILITY) AND GROUND CONTROL ARE TWO OF THE SEVEN ROBOTIC TECHNOLOGIES CURRENTLY ON LIST OF CODE M TECHNOLOGY PRIORITIES; LIST OF TECHNOLOGIES TRANSMITTED TO A. ALDRIDCH IN W. LENOIR LETTER OF APRIL 26, 1991.
- REQUIREMENT FOR SHARED CONTROL TECHNOLOGY ENDORSED BY SSF LEVEL II ROBOTICS WORKING GROUP (MAY 1991).
- SSF LEVEL II ROBOTICS WORKING GROUP FORMED SPLINTER WORKING GROUP ON GROUND CONTROL (MAY 1991).
- TECHNOLOGIES INCLUDED IN LIST OF RECOMMENDATIONS IN FISHER-PRICE STUDY

Within the two engineering prototyping tasks described in the preceding viewgraphs,there exist several areas of focus:

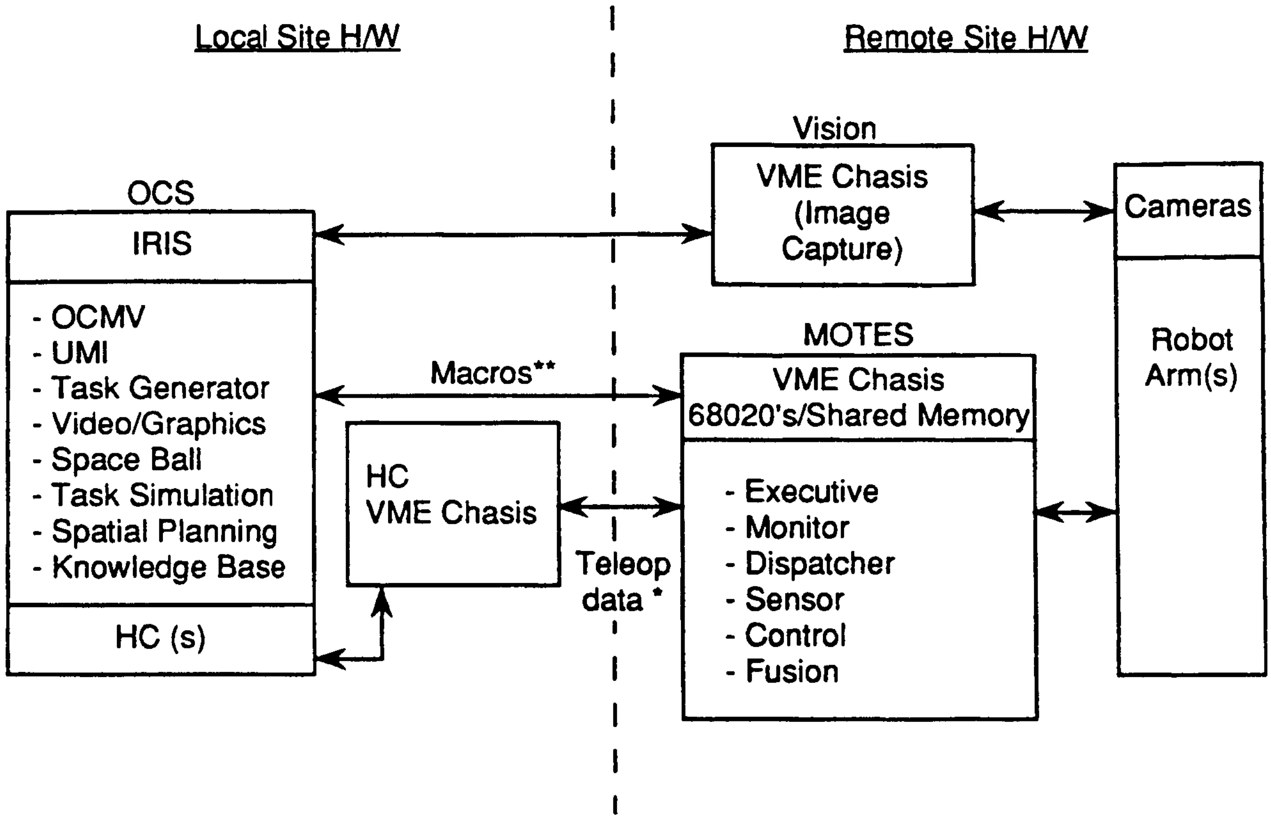
- Development of a robust local-remote control architecture which enables robot control in the presence of time delays such as bus latencies or ground remote operations via TDRSS.
- Development of robust single and dual arm shared control that provides the operator with multiple options in parsing/performing tasks under teleoperation or supervised autonomy.
- Development of extremely robust supervised autonomous control architectures and control macros; this development also includes the construction of error recovery schemes.
- Development of a rich User Interface; the current implementation of this interface the User Macro Interface (UMI) which was developed to provide the operator with a flexible means of building task sequences and simulating that sequence before actually executing the control sequence at the remote robot site.
- Development of Operator Coached Machine Vision; as part of the above user interface, it is important to allow the operator to accommodate changes or errors in the task environment this capability is a step in that direction.
- Operator performance assessment; this component of the current work is considered essential to understanding limitations of the existing technology.
- Technology Transfer; the JPL activity considers the transfer of technology to development testbeds at user flight centers entremely important if indeed the technology is to ever be employed.

CURRENT AREAS OF A/D FOCUS

- CONTROL ARCHITECTURE DESIGN ENABLING REMOTE ROBOT CONTROL WITH TIME DELAY.
- SHARED CONTROL (FLEXIBLE/FLUID CONCURRENT ROBOT CONTROL BY BOTH OPERATOR AND AUTONOMOUS SYSTEMS).
    - ABILITY TO PERFORM TELEOP FUNCTIONS IN CONJUNCTION WITH AUTONOMOUS FUNCTIONS.
    - ABILITY TO DOWNLOAD REAL TIME CLOSED LOOP CONTROL PARAMETERS COMPLETELY TO REMOTE AUTONOMOUS CONTROL SYSTEM.
- SUPERVISED AUTONOMY.
- USER MACRO INTERFACE (ABILITY TO DEVELOP LARGE ARRAY OF TASKS USING KERNEL OF ROBOT PRIMITIVES WITH A SPECIFIC INPUT PARAMETER SET [CALLED MACROS]).
- OPERATOR COACHED MACHINE VISION (INTERACTIVE OBJECT MODELING/WORLD MODEL UPDATE AND CORRECTION).
- OPERATOR PERFORMANCE ASSESSMENT.
- TECHNOLOGY TRANSFER TO DEVELOPMENT TESTBEDS.

The previous viewgraphs discussed the importance of the local-remote architecture in relation to allowing robust robot control in the presence of either bus latency induced time delays, or the desire to perform ground-remote robot control during the man-tended phase. As an introduction to the current work being done to stream-line the old version of the local-remote control architecture, the enclosed figure shows the high level hardware implementation and data flow. The operator coached machine vision (OCMV) and UMI will represent the primary operator interfaces residing on a Silicon Graphics Workstation (IRIS) at the local site. At a more detailed level, the UMI task macro generator will also be a software module on the IRIS. The video/ graphics modules will support the OCMV system on the IRIS, and in conjunction with UMI, will also have supporting knowledge bases of object model/robot control parameters. The spaceball allows the operator to manipulate the various graphics elements. It is planned to eventually incorporate the spatial planning capability into the task simulator. Also, the complete IRIS workstation will eventually replace a large portion of the current operator control station. In the near term, the IRIS will be ported to the prototyping laboratory to be in proximity to the handcontrollers and alternate camera views of the work cell. At the remote site the control architecture will contain two VME chasis- one chasis to capture video images for transmission to the videoport on the IRIS; and, the second chasis to perform all robot control/monitoring functions. The Modular Telerobotic Execution System (MOTES) runs in the second VME chasis and contains several functional software control modules which not only enable robot control, but are also designed to allow for growth. Both the local site design and remote site design are described in greater detail in the following viewgraphs.

Streamlined Local-Remote Telerobot Control Architecture



Note: * This implementation is for real-time teleoperation.

** This implementation will allow macro parameters to be sent to the remote site VME chasis; but, in the future, HC data will also be sent across this communication link.

NASA
JPL

TELEROBOTIC GROUND-REMOTE OPERATIONS

Bruce Bon

Technical Task Manager

Wayne Zimmerman

Code MT Technical Project Manager

August 8, 1991

NASA
JPL

TELEROBOTIC GROUND-REMOTE OPERATIONS

The Telerobotic Ground-Remote Operations task consists of development of a demonstration local-site operator control station that includes a graphical user interface (GUI) for control of a remote robot, and development of operator-assisted perception algorithms and software that will provide flexible and accurate world modeling capabilities.

TGRO-1s

Bruce Bon 8/8/91

NASA JPL

TELEROBOTIC GROUND-REMOTE OPERATIONS

- Local Site Development
- Operator-Assisted Perception

TGRO-1

Bruce Bon 8/8/91

NASA
JPL

LOCAL SITE DEVELOPMENT CONFIGURATION

The local-site hardware consists of a Silicon Graphics Incorporated (SGI) workstation with advanced graphics capabilities. It includes hardware for stereo display using special viewing glasses, video input displayable in stereo, and a "spaceball" for 6-axis control of object poses and graphics viewpoint. The cpu is a MIPS 3000 providing approximately 50 times the raw processing power of a MicroVAX II. Ethernet with TCP/IP is used for communications with the remote site.

NASA JPL

LOCAL SITE DEVELOPMENT CONFIGURATION

SGI Workstation with:

- Advanced graphics capabilities
- Stereo display for depth perception
- Video input, displayable in stereo
- Spaceball -- 6 axis operator input
- MIPS cpu for mini-supercomputer machine vision performance
- Ethernet/TCP/IP for communications

NASA JPL

SYSTEM DESIGN

Implementation Decisions:

- SGI Graphics Library -- chosen for speed, power and support; also has some measure of portability
- X window system, Motif, Widget Creation Library for graphical user interface -- chosen for capabilities for rapid prototyping of a powerful graphical user interface and for portability to other platforms
- Communications via Distributed Communication System (DCS) -- chosen for compatibility with other systems being developed at JPL (code sharing, etc.), and for ease of use and a good match with our requirements

NASA JPL

SYSTEM DESIGN

Implementation Decisions:

- SGI Graphics Library
- X window system, Motif, Widget Creation Library for graphical user interface (GUI)
- Communications via Distributed Communication System

NASA JPL

SYSTEM DESIGN

The main program is an infinite loop that calls other modules to check for and service events. There are modules for network communications, operator interface, knowledge base, video/graphics, operator-assisted graphics and operator-assisted manipulation.

The Graphical User Interface (GUI) Module presents a high-level, easy-to-use interface to the operator and responds to window/mouse-generated events.

The Operator-Assisted Perception Module interacts with the operator, the knowledge base module and the video/graphics module to provide the system with information on the poses and geometries of objects. Machine vision, embedded within this module, refines objects poses and geometries for increased accuracy.

The Operator-Supervised Manipulation Module interacts with the operator and the Knowledge Base Module to control remote manipulation activities.

The Video/Graphics Module controls all video and graphics display activities, as well as the spaceball. There is a single stereo window in which all video and graphics are displayed.

The Network Communications Module uses DCS to receive and process incoming messages. Outgoing messages do not generate events and originate with the appropriate other module.

The Knowledge Base Module contains data structures for object models, the world model tree, camera models, etc., and provides functions for easily accessing all information.

NASA JPL

SYSTEM DESIGN

Major modules:

- Main program: infinite loop, calls other modules to service events
- Graphical User Interface: X windows, Mac-like GUI
- Operator-Assisted Perception
- Operator-Supervised Manipulation
- Video/Graphics Module: all display of video images and graphics overlays, spaceball handling
- Network Communications: receive data from remote site
- Knowledge Base: object models, world model, camera models, etc.

NASA
JPL

OPERATOR CONTROL STATION (I.E. LOCAL SITE)

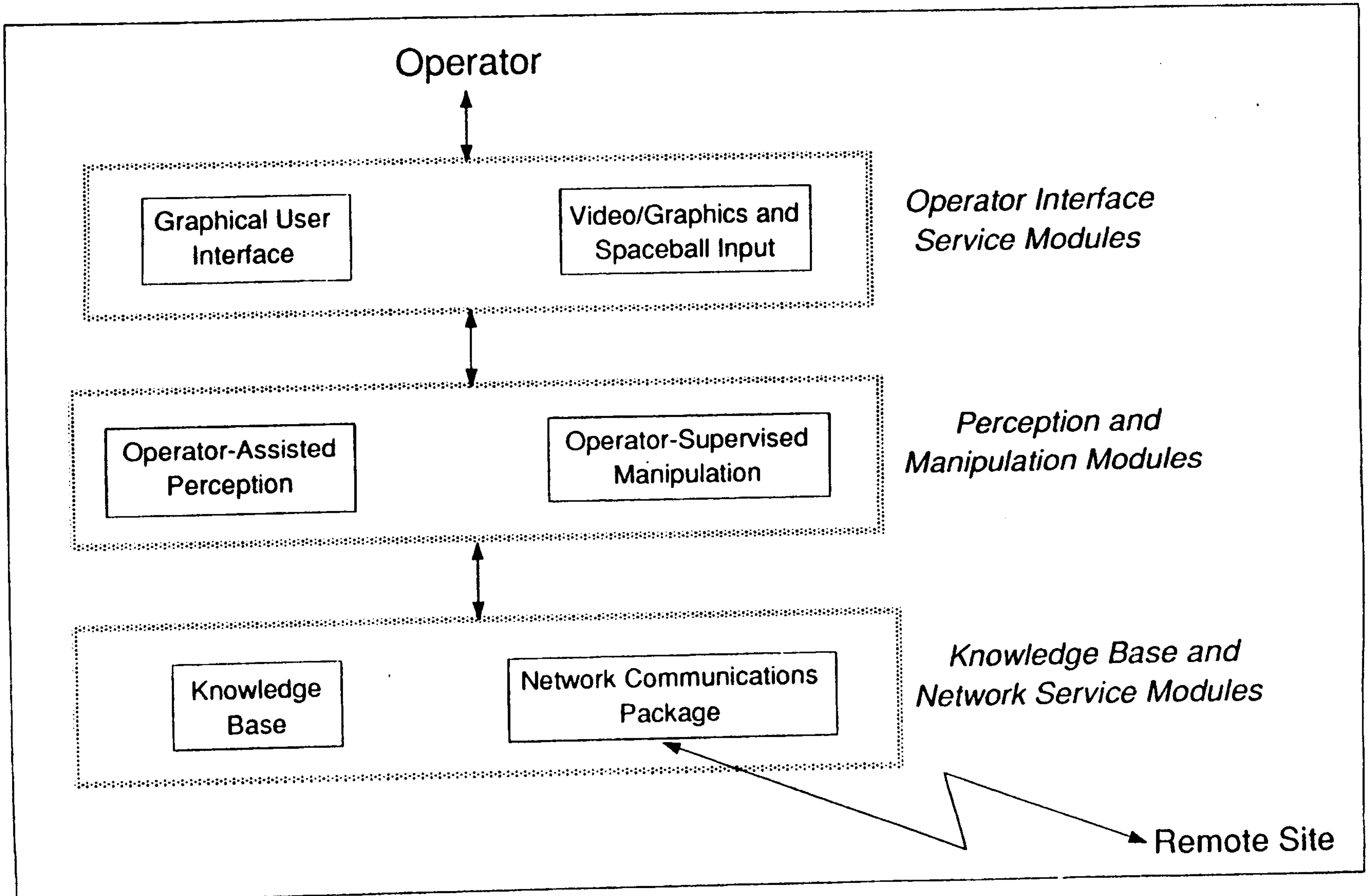
SOFTWARE BLOCK DIAGRAM

TGRO-5s

Bruce Bon 8/8/91

TELEROBOTIC GROUND-REMOTE OPERATIONS

Operator Control Station Software Block Diagram



TGRO-5

Bruce Bon 8/8/91

NASA JPL

OPERATOR-ASSISTED PERCEPTION

The fundamental principal of operator-assisted perception is to utilize computer power for precision measurement where computational requirements are heavy, and to utilize the capabilities of the operator for recognition, scene segmentation, etc., where reliable and efficient computer algorithms are not available.

To aid human perception, the system provides views from multiple video cameras, as well as graphics-only display from arbitrary viewpoints. Stereo displays allow the operator to use binocular stereo cues for depth perception.

Graphics-overlay models of objects are easily movable by the operator using the spaceball to command both translations and rotations.

Once the operator has achieved reasonable registration of an object model overlay with video images of the object, machine vision can measure its position and orientation accurately.

NASA JPL

OPERATOR-ASSISTED PERCEPTION

Principals:

- Human provides intelligence for recognition, segmentation, etc.
- Computer provides computational power
- System provides multiple views including stereo for depth perception
- Graphics models of objects, movable using spaceball, allow natural data input by operator
- Machine vision for precision geometry measurement

Bruce Bon 8/8/91

NASA JPL

OPERATOR-ASSISTED PERCEPTION

Operations available:

- Object localization: Computer determines pose (position and orientation) of known objects using a priori pose provided by operator positioning of graphic model overlaid on video images, with machine vision for precision pose estimation using image edge measurements.

- Object creation and editting: Allows operator to designate the positions and relationships of object features in order to create a model of an unknown object, followed by machine vision to determine accurate geometry and pose. May also be used to edit existing object models in order to account for inaccuracies or changes in objects represented.

- Changing world view: Allows operator to select cameras for video image display, stereo pair or monocular views from wing cameras, optionally with graphics overlays representing known objects; or to select arbitrary viewpoints for graphics viewing without video.

TGRO-7s *Bruce Bon 8/8/91*

NASA JPL

OPERATOR-ASSISTED PERCEPTION

Operations:

- Object localization: determining position and orientation of known objects using operator a priori plus machine vision
- Object creation and editting: allowing operator to create models of unknown objects and to edit existing models, augmented by machine vision to determine accurate geometry and pose
- Changing world view: selecting cameras for video images, optionally with graphics overlays; selecting arbitrary viewpoint for graphics viewing without video

Bruce Bon 8/8/91

NASA JPL

STATUS

The main program is essentially complete. File input for initialization is complete, and stubs are used for initialization and event servicing of yet-to-be-implemented modules.

The top-level of the GUI, displaying the background window and menu bar, is complete. Most menu items are non-functional, and the GUI is not yet integrated with the main program. The Operator-Assisted Perception Module has not been implemented except for a machine vision algorithm for estimating object geometry from operator and edge-detector measurements. (This algorithm was implemented before SGI development began, in portable C, on a MicroVAX.) The Operator-Supervised Manipulation Module has not been implemented on the SGI workstation. An earlier version was implemented on a Sun workstation and will be ported to the SGI. The Video/Graphics Module is the current focus of development. The framework is in place and stereo display of video images from files is currently available. Graphics overlays are under development, and graphics-only display with operator-controlled viewpoint is planned.

The Network Communications Module consists of a router that performs actual message transmission plus routines to handle incoming messages. The router is complete. Implementation of message handling routines awaits definition of network interfaces.

The core of the Knowledge Base Module, data structures for representing the various forms of knowledge plus routines to read and write files from these data structures, is complete. Routines to access knowledge base data have been defined but not implemented.

NASA JPL

STATUS

- Main program: complete except for minor details
- Graphical User Interface: top-level complete
- Operator-Assisted Perception: machine vision model-fitting complete
- Operator-Supervised Manipulation: not yet ported to SGI
- Video/Graphics Module: stereo video from files displayed, graphics under development
- Network communications: skeleton complete, interface details TBD
- Knowledge Base: file reading/writing and internal data structures complete, most access calls designed but not implemented

Bruce Bon 8/8/91

COLLISION AVOIDANCE SENSOR SKIN

SSF Evolution Conference

Houston, TX

August 6,7,8 1991

Collision avoidance is a prime safety concern for space operations as cited several times in the Fischer-Price report. Computer modelling, augmented by cameras, is currently the preferred robot collision avoidance technique. Because of the several obvious problems inherent with computer modelling listed on the slide, there are many who would prefer a sensor-based system. But what sensor system? Vision systems have problems associated with lighting, blind spots and lack of precision in determining precisely where an object is. Also, they require a lot of computer power, especially when machine vision is involved. Lasers are outstanding for determining range and edges and they are not bothered by lighting conditions or the sun but, they have serious blind spots and, when scanning is used (as frequently it must be), they become complex and computationally intensive. An array is perhaps the best solution in terms of totally eliminating blind spots. But, these are inherently range limited (particularly capacitive and inductive), are computationally intensive , have too many I/O lines (if the pixel sizes are small) and, since they cover the entire surface of the robot arm, disturb the form factor of the system. They tend to upset the thermal system, bulk up the arm and emit omni-directional EMI. Electro-optical arrays tend to be blinded by the sun and inductive arrays are sensitive to the conductivity and/or magnetic properties of the materials they are encountering. The ideal solution would be an array, to eliminate blind spots, range on the order of one (1) foot, minimal pixel numbers (no imaging), ability to locate an object (precision sufficient for collision avoidance), and no disturbance to the robot form factor. For most of these requirements save range and edge determination, a capacitive system coupled with a vision camera is best. Is it possible to develop a capacitive array with relatively long range (on the order of one (1) foot) which can determine edges (sufficient for collision avoidance) and which does not require imaging and a large number of pixels?

BACKGROUND AND HISTORY

- Collision Avoidance A Prime Safety Concern in Space (Cited Several Times in Fischer-Price)

- Sensory - Driven And Computer Modelling Two Main Approaches

- Computer Modelling Disadvantages
  - Omissions
  - Location Uncertainties
  - Data Intensive And Inefficient
  - Unexpected Event Difficulties

- Vision/Laser Disadvantages
  - Field of View Blind Spots
  - Lighting Conditions (Visions)
  - Scanning Requirements (Laser)
  - Computer Requirements (Imaging Only)

- Array Disadvantages
  - Range Limitations (Capacitive, Inductive)
  - Form Factor Problems (EO)
  - Computer Requirements (Imaging Only)
  - I/O's (Imaging Only)
  - Material-Sensing (Inductive)
  - Sensing To Sun (EO)

What If A Capacitive Array Could be Found With Sufficient Range and Did Not Require Imaging?

The objective of this project started out to be an ambitious one. It soon got even more ambitious. We wanted to totally eliminate the possibility of a robot (or any mechanism for that matter) inducing a collision in space operations. We were particularly concerned that human beings were safe under all circumstances. It appears this has been accomplished. As will be shown during this presentation, GSFC has a system that is ready for space qualification and flight. But, it soon became apparent that much more could be accomplished with this technology. Payloads could be made invulnerable to collision avoidance and the blind spots behind them eliminated. This could be accomplished by a simple, non-imaging set of "Capaciflector" sensors on each payload. It also is evident that this system could be used to align and dock the system with a wide margin of safety. Throughout, lighting problems could be ignored, and unexpected events and modelling errors taken in stride. At the same time, computational requirements would be reduced. And, this can be done in a simple, rugged, reliable manner that will not disturb the form factor of space systems. It will be practical for space applications. The lab experiments indicate we are well on the way to accomplishing this. Still, the research trail goes deeper. It now appears that the sensors can be extended to End Effectors to provide precontact information and make robot docking (or any docking connection) very smooth, with minimal loads impacted back into the mating structures. This type of ability would be a major step forward in basic controls techniques inspace. There are , however, baseline and restructuring issues to be tackled. The payloads must get power and signals to them from the robot or from the Astronaut servicing tool. This requires a standard electromechanical interface. Any of several could be used. The GSFC prototype shown in this presentation is a good one. And, sensors with their attendant electronics must be added to the payloads, End Effectors and robot arms and integrated into the system.

OBJECTIVES

- Why Are We Doing This Project?
  - Eliminate The Danger of Robot (Mechanism)
  - Induced Collisions

- What Benefits Can Be Expected From This Applications?
  - Collision Avoidance Risk Near Zero
  - Less Force Impact While Docking, Controls Much Smoother
  - Unexpected Events, Model Errors Less Dangerous
  - Lighting Problems Significantly Reduced
  - Computational Requirements Reduced

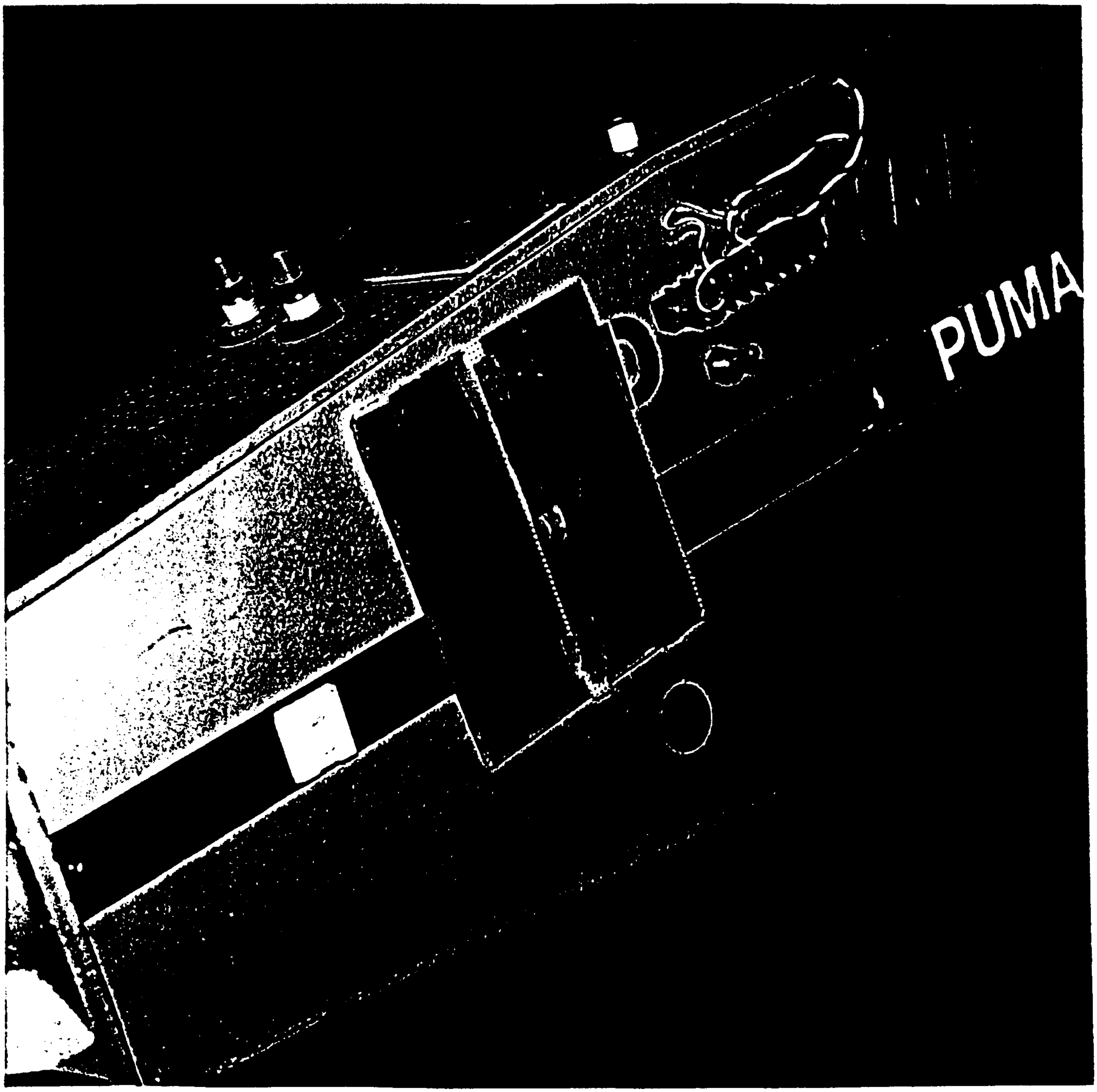
- What Baseline And Restructuring Issues Are Tackled?
  - Sensors Electronics, Standard Interfaces Added To Payload And Robot

The approach used in the GSFC collision avoidance project is described to include several demonstrations and experimental highlights which are illustrated on video. The "Capaciflector" sensor is central to the collision avoidance system and its suitability for use in space is described in detail. It will be shown that this sensing system is outstanding for space use and ,indeed, has already gone through most of the space qualification criterion. It will also be shown that sensory-based controls employing the "Capaciflector" sensor has potential that is significant and far reaching for robotics in general; much more so than has generally been recognized.

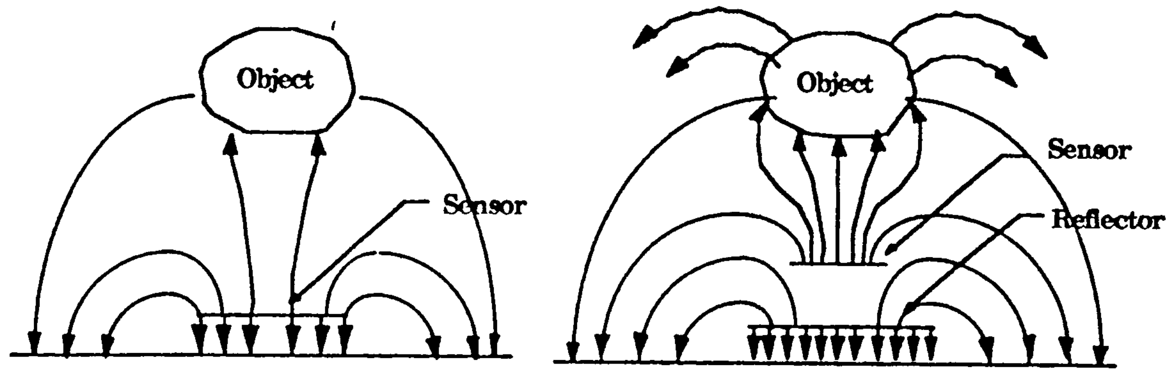
APPROACH

- Project Approach/Results to Date (Work done in-house at GSFC)
- Efforts Towards Ensuring Space Suitability
- Potential Of Technology

This photo shows a single element "Capaciflector" sensor mounted on a Puma robot arm. It performed computer-controlled collision avoidance at ranges in excess of one foot. The photo shows the simplicity of the device. The sensor is the thin strip of copper tape (1/4 in. wide) between the two black screws. The "Capaciflector" driven shield is the (4 in. X 4 in.) rectangle of copper tape behind the sensor. The electronics is mounted behind the sensor inside the robot arm. But, the Puma arm is grounded, and it is common knowledge that the range of a capacitive-type sensor is only about one (1) in. when it is near a ground plane. How, then, does the GSFC sensor achieve ranges in excess of one (1) foot?


PUMA

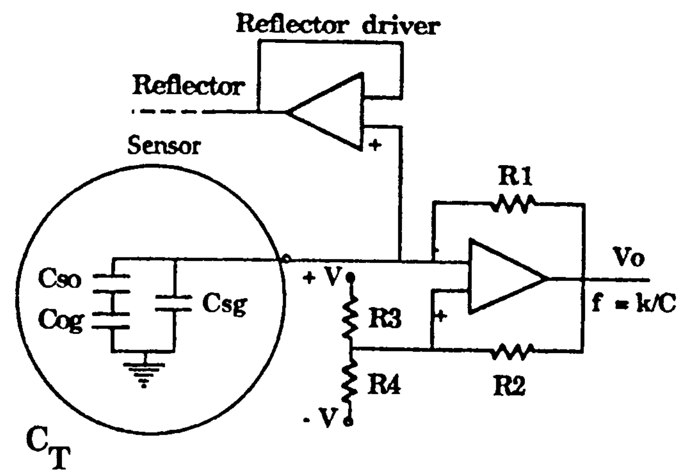
This pair of diagrams explains the "Capaciflector" principle. The diagram on the left shows a normal capacitive sensor in the presence of a ground plane. Most of the electrical field lines couple into the ground plane with only a few projecting outwards to sense the object (and then complete the circuit back to ground). This results in a very poor signal-to-noise ratio and reduced range and sensitivity. This is normally improved by "standing the sensor off" from the ground plane (and adding to robot bulk in the process). The diagram on the right shows the "capaciflector" approach. A reflective shield is inserted between the sensor and the ground plane. This shield is driven at the same frequency and at the same potential as the sensor. Hence the electric field lines from the sensor must travel around the shield in order to reach ground. In the process, more of them are "reflected" towards ther object, significantly improving range and sensitivity at no penalty in "stand-off". The shield acts as a capacitive reflector, hence the descriptor "Capaciflector".



(a) without reflector

(b) with reflector

This diagram illustrates the simplicity of the electronics circuitry. It also shows how the driven shield is integrated into the circuit. It should be noted that the shield is electrically isolated from the sensor. It does not "see" an object even though it is at the same potential and frequency as the sensor and even though it follows the sensor as the oscillator changes frequency.


Reflector driver
Reflector
Sensor
R1
Vo
f = k/C
Cso
Cog
Csg
+ V
R3
R4
R2
- V
C_T

This photo shows a four (4) element array mounted on the Puma robot arm, each of which is identical to the single element example. These sensors are equally spaced across the robot arm. It is almost impossible to see the sensors. They are covered with Kemglaze A276 flight paint and are made of flight-qualified materials throughout. Even the stickers are flight-qualified and the electronics is mil spec. This array has been examined for EMI, thermal conductivity, safety and power consumption. It could be qualified for flight now. The "Capaciflector" performs right through the paint and stickers as if hey were not there. Computer-controlled collision avoidance with ranges in excess of one (1) foot is routinely performed with this device.


NASA
Goddard Space Flight Center

Capacitance sensing operates exceptionally well in a vacuum, even better than in air. Also, the lack of humidity changes in space is an advantage. This sensor senses any thing that either conducts electricity or has a significant dielectric constant. And, that turns out in practice to be nearly every thing (paper, wood, styrofoam, plastic). It sees humans, graphite, aluminum (and other metals) extremely well. There is virtually nothing we know of on orbit that it will not see or that is not in the vicinity of something it can sense. It is immune to all but deliberate EMI jamming and a study proves that it will easily meet Shuttle (and Space Station) requrements for EMI emmisions-it is low power and low frequency (approx. 30 khz). It is thermally conductive and thermal paints can be applied right over it so from a thermal stand point it isn't present. Also, it doesn't appear to be bothered by temperature changes. New phase-correcting circuitry and a crystal-controlled oscillator will permit it to operate indefinitely with minimal drift. Also, it is indifferent to lighting condition difficulties.

SPACE SUITABILITY

- Outstanding performance in vacuum
- Senses every expected obstacle in orbit
- Outstanding for humans, structural members, thermal blankets
- Independant of lighting conditions
- Outstanding characteristics in EMI, thermal conductivity, temperature tolerance
- Minimal electrical and compute power requirements.
- Minimal wires, leads, I/O's
- Outstanding form factor
- Simple, rugged, reliable, proven technology
- Indefinite operation w/minimal drift

ARM COLLISION AVOIDANCE

ARRAY

IS READY TO QUALIFY AND BE

PUT IN USE NOW

The payload is the most vulnerable region in collision avoidance. It is the object that sticks out the furthest and it is also the region that the camera cannot see behind. It has blind spots. An array of "Capciflectors" can easily be added to each Orbital Replacement Unit (ORU) and eliminate these blind spots. Our calculations and lab experiments indicate that not many sensors would be needed (typically 4 to 8) and power, leads , circuitry and compute power would not be burdensome. With these sensors, one could practically ensure that the ORU would not collide with anything no matter what the circumstances. That is, even if the computer model is in error, an unexpected event occurs, the operator is inattentive, lighting conditions are misleading or blind spots are encountered , the ORU will still not experience a collision. Clearly with the enormous emphasis on safety and the value of the ORU payloads, this sensing protection will be essential. The only question is whether power and signals can be sent between the robot and the payload. As will be shown in the next slide they certainly must and can. It also turns out, that our lab experiments have shown that payload collision avoidance can be extended to include docking; even in a cluttered environment in which several payloads are placed close together. The docking accuracy of the "Capaciflector" to a simple coded passive element in the attachment region is surprisingly good; several times better than what is required for docking. And, it seems apparent that the same techniques in collision avoidance and docking should be extended to the End Effectors themselves. GSFC has also begun this research starting with the robot attachment mechanism (foot). This slide shows a photo of the GSFC robot foot. Conceived, designed and developed in-house at GSFC, this device has been incorporated into the Flight Telerobotic Servicer (FTS) End Item Specification and can attach the (FTS) to the Space Station structure with sufficient repeatability and strength to meet all requirements. Also, it can make all necessary electrical power and electronics and fiber optics signal connections. A miniaturized version of this (approximately the size of a cofee cup) is in fabrication to serve

FURTHER POTENTIAL APPLICATIONS

- Payloads(including Orbital Replacement Units)

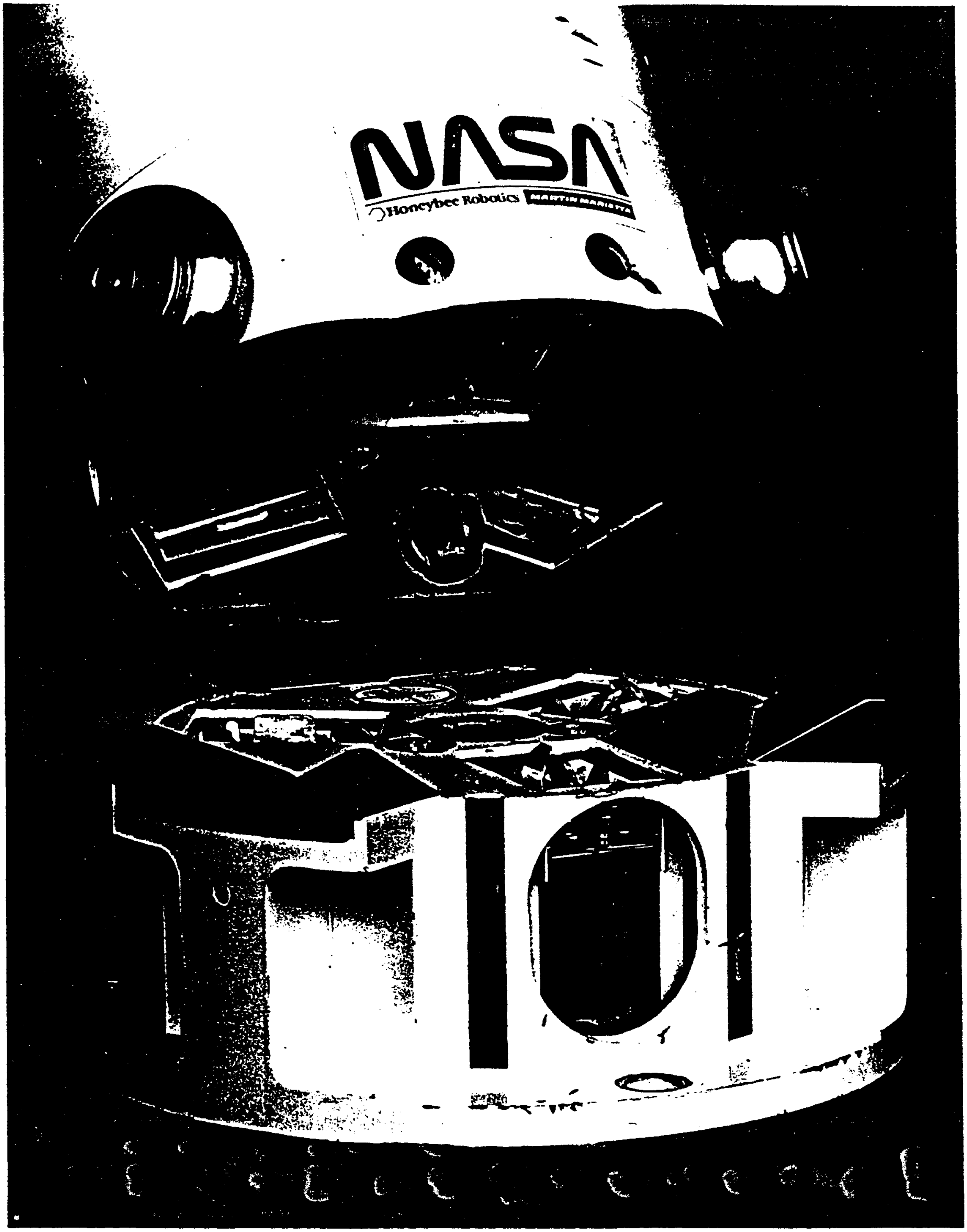
  Collision avoidance

  Blind spot elimination

  Safe, simple docking

- End Effector collision avoidance and docking

This slide shows a photo of the GSFC robot foot. Conceived, designed and developed in-house at GSFC, this device has been incorporated into the Flight Telerobotic Servicer (FTS) End Item Specification and can attach the (FTS) to the Space Station structure with sufficient repeatability and strength to meet all requirements. Also, it can make all necessary electrical power and electronics and fiber optics signal connections. A miniaturized version of this (approximately the size of a coffee cup) is in fabrication to serve as the End Effector for the up-coming group of experiments on ORU collision avoidance and docking. The central point is that getting power and signals to and from a payload is not particularly difficult.



ORIGINAL PAGE IS
OF POOR QUALITY

Capacitance sensing operates exceptionally well in a vacuum, even better than in air. Also, the lack of humidity changes in space is an advantage. This sensor senses any thing that either conducts electricity or has a significant dielectric constant. And, that turns out in practice to be nearly every thing (paper, wood, styrofoam, plastic). It sees humans, graphite, aluminum (and other metals) extremely well. There is virtually nothing we know of on orbit that it will not see or that is not in the vicinity of something it can sense. It is immune to all but deliberate EMI jamming and a study proves that it will easily meet Shuttle (and Space Station) requrements for EMI emmisions-it is low power and low frequency (approx. 30 khz). It is thermally conductive and thermal paints can be applied right over it so from a thermal stand point it isn't present. Also, it doesn't appear to be bothered by temperature changes. New phase-correcting circuitry and a crystal-controlled oscillator will permit it to operate indefinitely with minimal drift. Also, it is indifferent to lighting condition difficulties.

DIRECTIONS IN SENSOR DEVELOPMENT

- Flight applications and prototype testing (in cooperation with JSC and Astronauts)
- Phase-correcting circuits

    Cross-talk rejection

    Improved performance

    Indefinite operation in space

    Simpler, more compact circuits

- VLSI electronics/flexible PC sensors and arrays
- Imaging arrays (in cooperation w/ARC)
- Commercial sensors (in cooperation w/Industry)

In exploring the sensory-based collision avoidance problem it soon became clear that this technology kept going deeper; first arm collision avoidance, then payload collision avoidance, then payload docking, then End Effector collision avoidance and docking. Apparently a missing key in the hierarchy of sensors has been found. We now have vision, collision avoidance, precontact forces and contact (tactile) forces. In the past, collision avoidance and precontact forces have been missing. In the animal world we see an example of this in the whiskers on a cat which enables it to go through small holes in the dark. The "Capaciflector" system provides electric field whiskers for robots and payloads. This has very significant and fundamental implications for robot control strategies. Adaptive control techniques are much improved resulting in smoother, safer, more precise and efficient performance. We have much more information where and when we need it so computer modelling will yield somewhat to local sensory-based information. At the same time, computer modelling information will be combined with local path planning strategies and enable the robot to perform limited search routines to verify the environment before it begins docking. The operator can be involved as needed. For example, if the model and the sensor disagree, the robot can back up and signal the operator to take a look and resolve the disagreement. And, the operator will now be able to "feel" precontact/proximity forces. But, even though we will have more information at the local site where we need it, the total required information can be reduced.

GSFC

POTENTIAL FOR FUNDAMENTAL ADVANCES

- Hierarchical sensory-based strategy
- Smoother, safer, more precise performance
- Emphasis toward sensor-based system from computer modelling
- Docking strategies based on computer modelling combined with local path planning reinforced by sensor in formation
- Less computer power required
- Modelling errors and unexpected event dangers reduced
- Teleoperators "feel" precontact forces

SUMMARY

- Collision avoidance skin for robot arms ready for integration into space system (work done in-house at GSFC)
- Work progressing on payload collision avoidance, docking and commercial sensor (work done in-house at GSFC)
- Fundamental advances in robot controls, path planning and operational strategies are now possible (perhaps inevitable)

N92-17362

MARS AEROBRAKE ASSEMBLY DEMONSTRATION

John M.Garvey
McDonnell Douglas Space System Co.

SSF Evolution - Beyond theBaseline
Houston, Texas

8 August 1991

PROBLEM

MDSSC

NASA has identified aerobraking as a potentially critical technology for SEI. The size of Mars aerobrakes may be beyond the capabilities of future launch vehicles to place them into orbit in one launch. On-orbit assembly using facilities and operations developed under the SSF program represent one approach for realizing such large structures. The results of early testing in this subject can help influence the future evolution of Space Station Freedom.

J. GARVEY
8/8/91

OBJECTIVES

MDSSC

- Generate empirical data on operational procedures for on-orbit assembly of a large Mars aerobrake
- Develop aerobrake design concepts
- Identify critical issues and requirements associated with SSF utilization
- Stimulate student participation in the Space Exploration Initiative

J GARVEY
8/8/91

SSF FACILITY REQUIREMENTS

MDSSC

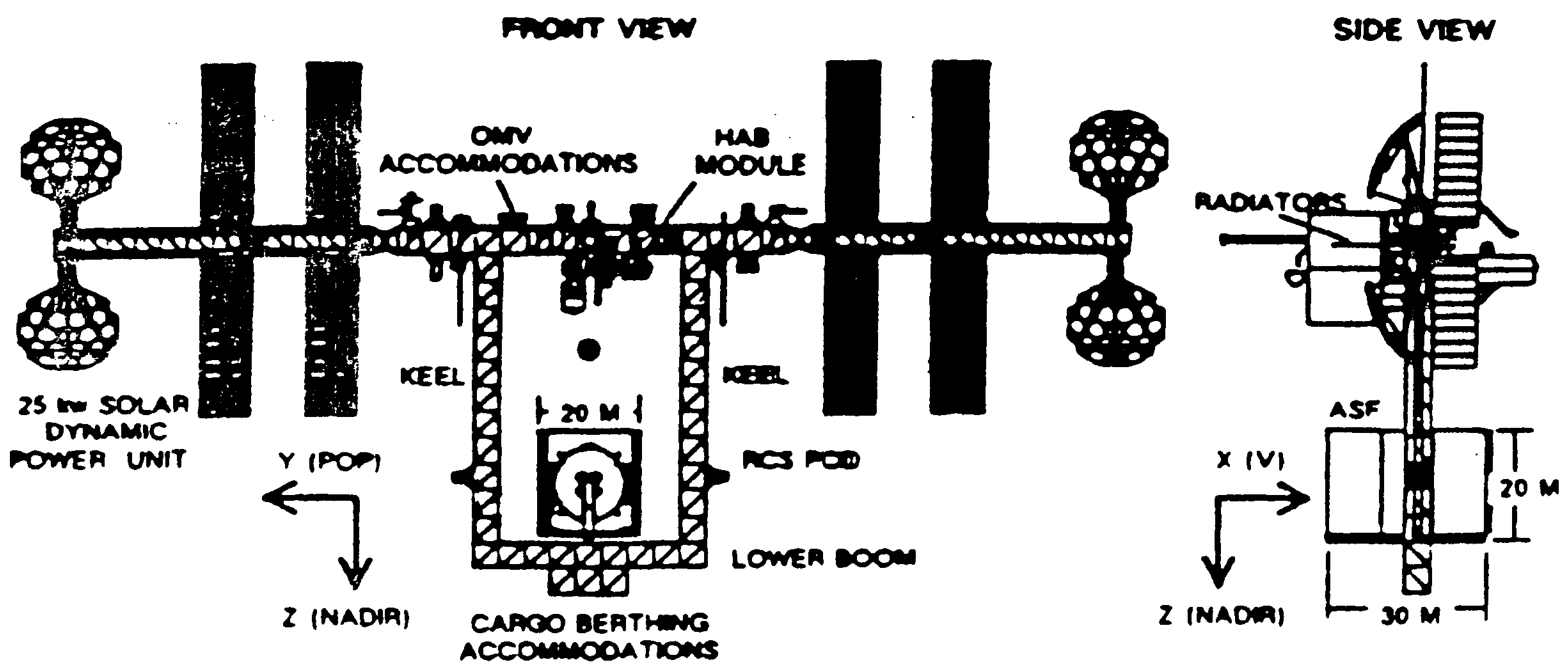
Earlier Space Station Freedom designs incorporated the potential for evolving into an on-orbit assembly facility. This is one such example, where a lower boom has been added to allow the integration of an aerobrake-equipped space transfer vehicle

J GARVEY
8/8/91

SPACE STATION FREEDOM FACILITY REQUIREMENTS

VJY894

MDSSC-SSD



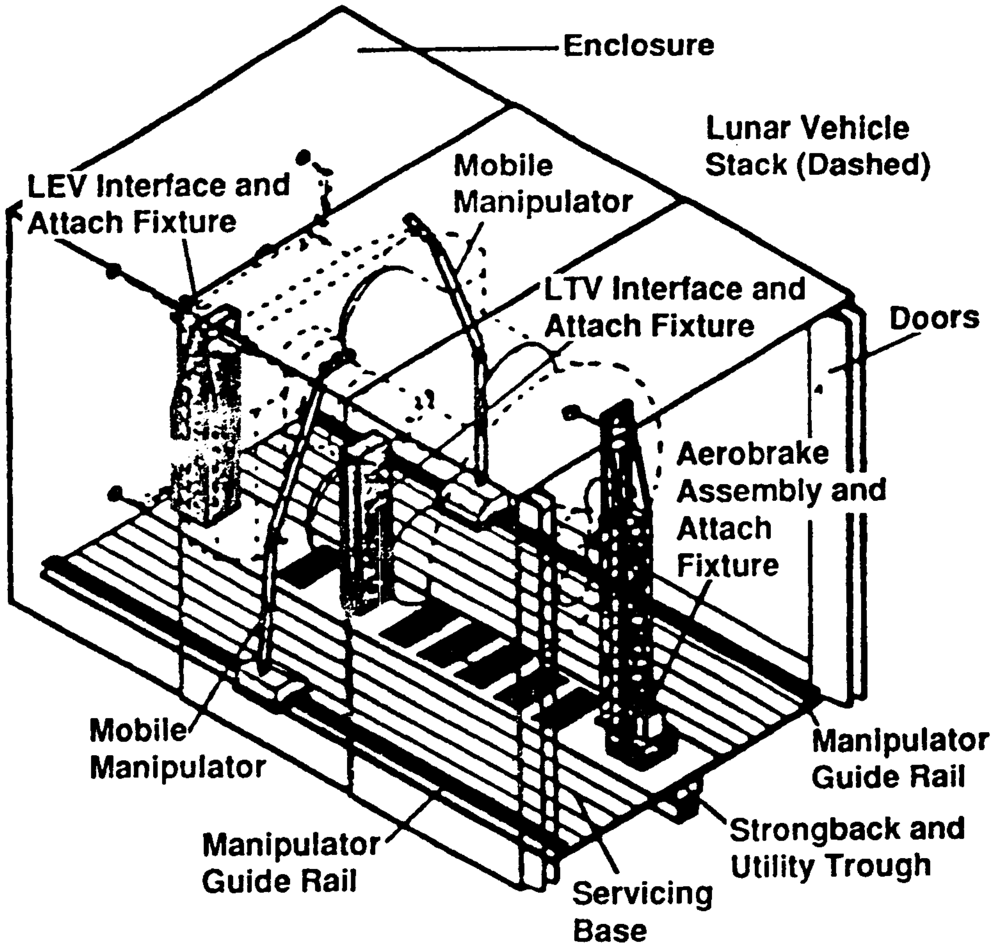
ORIGINAL PAGE IS OF POOR QUALITY

ASSEMBLY & SERVICING FACILITY

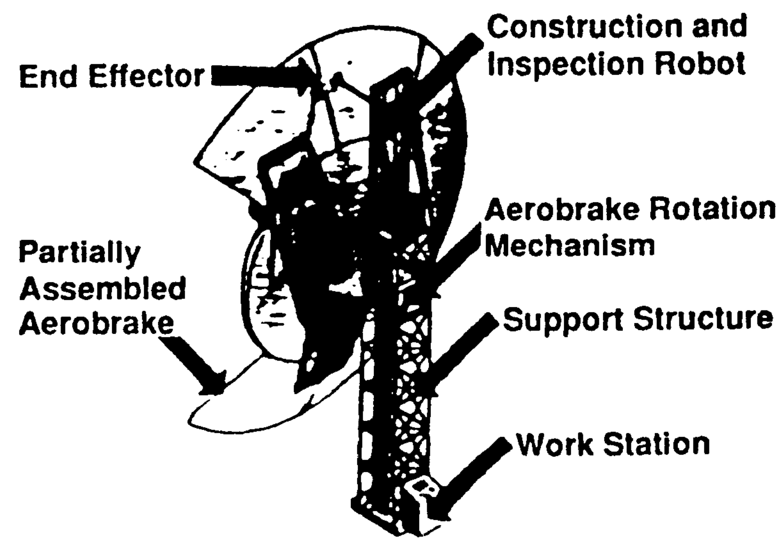
MDSSC

This is a more detailed drawing of a candidate Assembly & Servicing Facility (ASF) that would accomodate large space transfer vehicles. In this NASA-Langley concept, the aerobrake is assembled on a rotating "lazy susan" fixture. Our tests followed a similar approach.

J GARVEY
8/8/91



ASF Configuration and Components



Aerobrake Assembly and Attach Fixture

AEROBRAKE ASSEMBLY TEST PROJECT ORGANIZATION

MDSSC

This is the team that we pulled together to conduct this project. Two parallel IRAD efforts at McDonnell Douglas provided direction and implemented the actual tests, while the Mars Mission Research Center (MMRC) supported mockup design activities, fabricated the mockup and also participated in the neutral boyancy tests. MMRC is a NASA-sponsored Space Engineering Research Center co-located at North Carolina State University and North Carolina Agricultural and Technical State University.

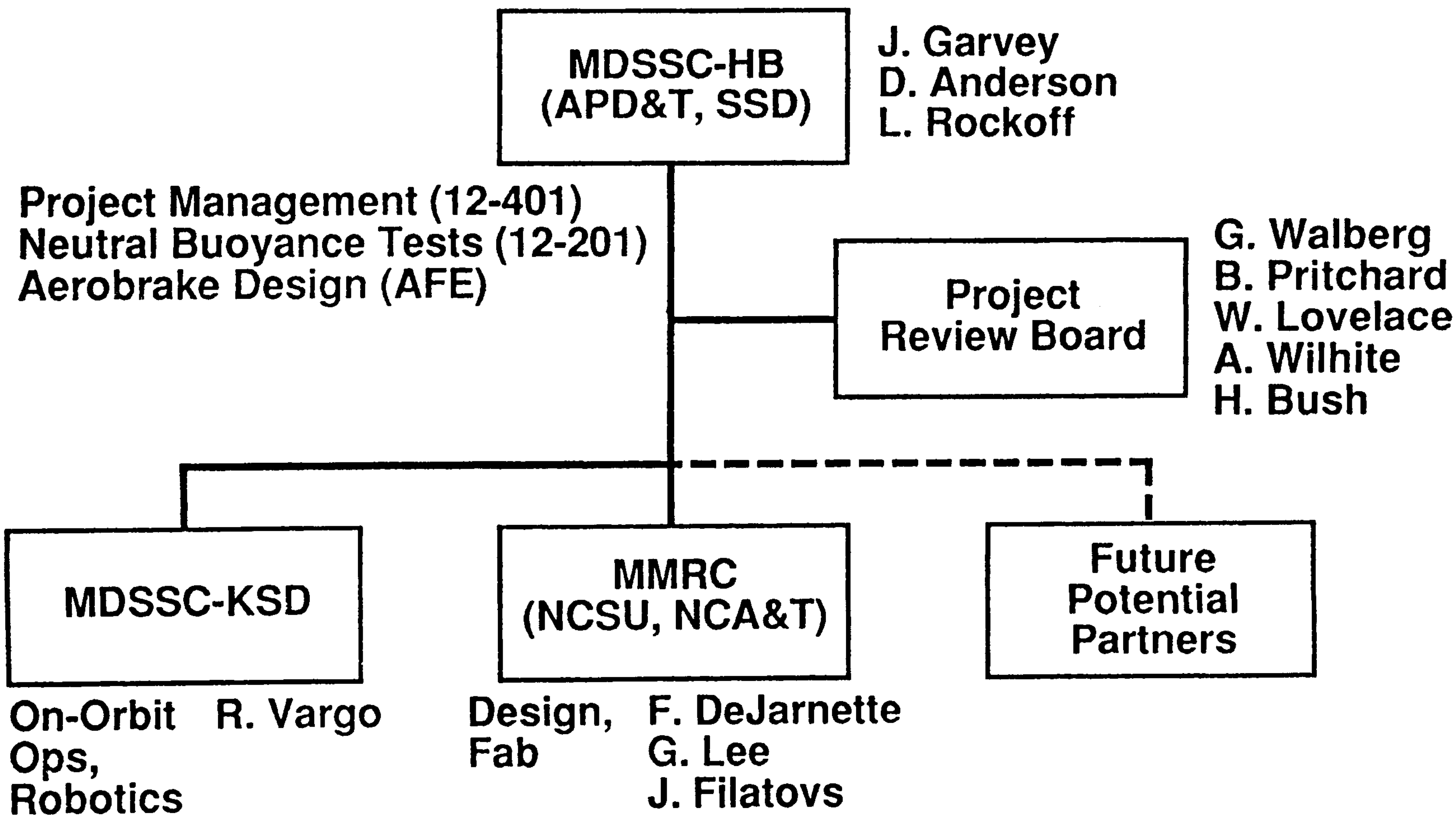
Additional inputs were received from our MDSSC group at KSC, and Langley representatives who provided guidance to MMRC (Langley is the monitoring NASA facility for the MMRC).

J GARVEY
8/8/91

AEROBRAKE ASSEMBLY TEST PROJECT ORGANIZATION

VJZ243.1 M9BH

MDSSC/MMRC



SCHEDULE

MDSSC

We began discussions with the MMRC in 1988, shortly after it was created by NASA. By mid-1989, soon after the President's SEI speech, the support was sufficient to start this project. MDSSC gave the MMRC a small contract to initiate student studies in the fall, during which the reference aerobrake was defined. A mockup design and fabrication contract followed in 1990, and six months later the initial swim-through tests using only scuba and surface-supplied-air took place. Using feedback from this initial check-out, full-scale testing with an EVA suit and telerobotic device then occurred in October.

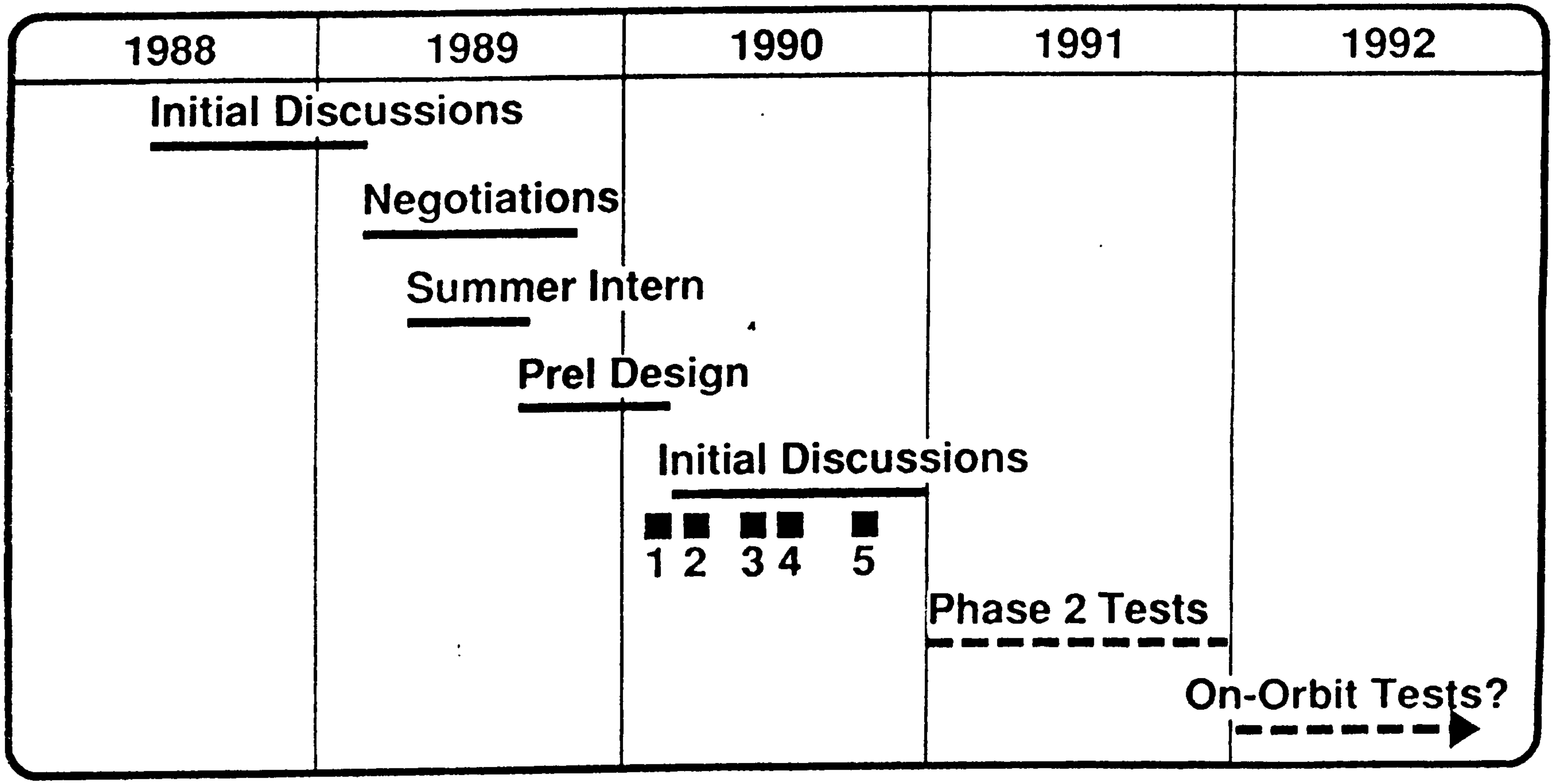
A number of follow-on tasks have been identified, but funding constraints have pushed them to the right.

J. GARVEY
8/8/91

MDSSC/MMRC AEROBRAKE ASSEMBLY PROJECT – SCHEDULE

VJZ254.1 M9BH

MDSSC/MMRC



1 PDR
2 CDR
3 Mockup shipment
4 UWTF Tests – scuba swim-through
5 UWTF Test – EVA suited subjects and telerobotic arm

MDSSC

REFERENCE MARS AEROBRAKE DESIGN

This is the reference Mars aerobrake. It is derived from the AFE design and consists of three main sections - a central monolithic core that is launched in one piece, a symmetrical ring of eight panels or petals around this core, and then an outer, unsymmetrical ring that results in a raked ellipse configuration that can achieve an L/D of 0.3. It is worthwhile to note that the core and inner ring have a high correlation with a candidate lunar STV aerobrake. Thus, such a device and associated facilities could be implemented and tested during the lunar phase of SEI, and then evolved up to this Mars vehicle aerobrake

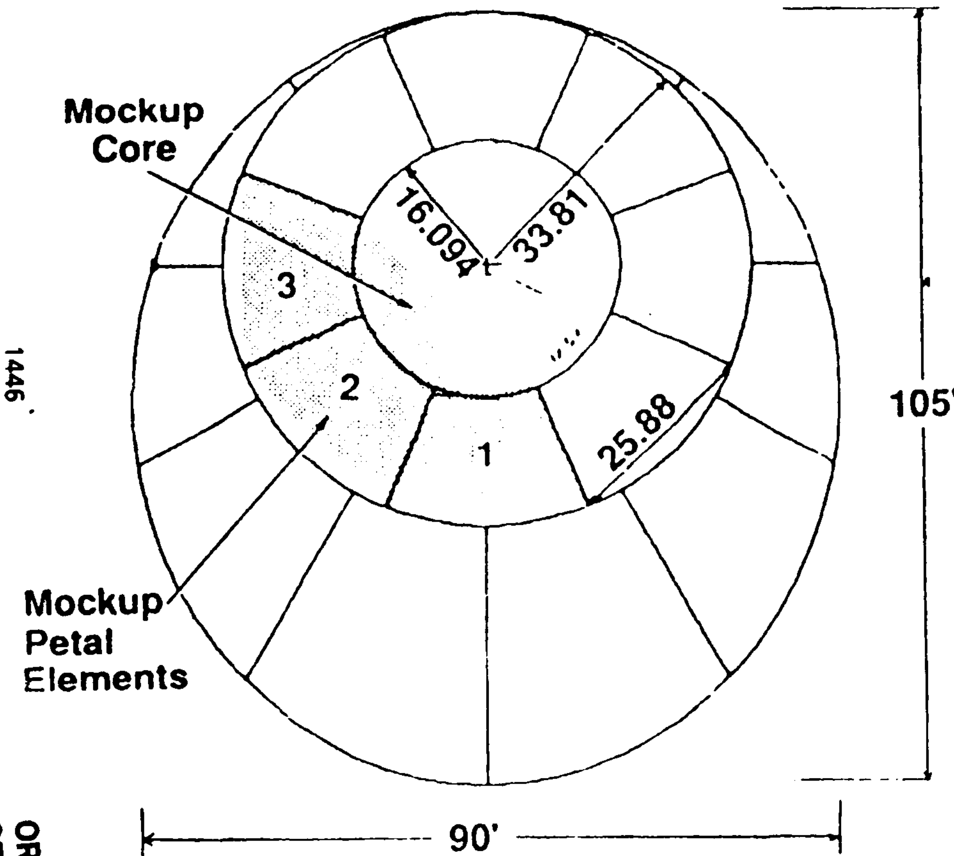
Because the longest dimension is 105 feet and the MDSSC Underwater Test Facility is only 70 feet wide, we were constrained to only testing several representative components, which are indicated by the shaded areas.

J GARVEY
8/8/91

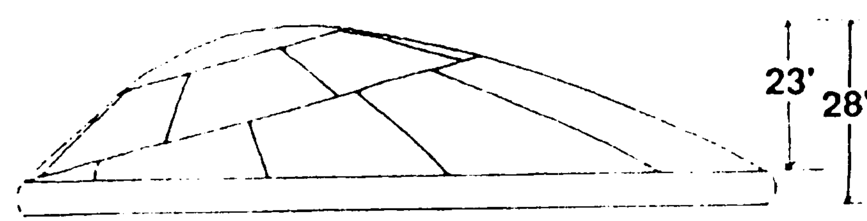
REFERENCE MARS AEROBRAKE DESIGN

VJY897 2 M3DN

MDSSC/MMRC



Top View



Side View

ORIGINAL PAGE IS
OF POOR QUALITY

MOCK-UP DESIGN

MDSSC

This is the final configuration drawing for the aerobrake mockup. As will become clearer in later drawings, it consists of three petals and part of the central core. A series of struts were incorporated to enable some study of EVA/telerobotic interaction, however, this truss is not intended to represent a load-carrying structure and requires much more refinement.

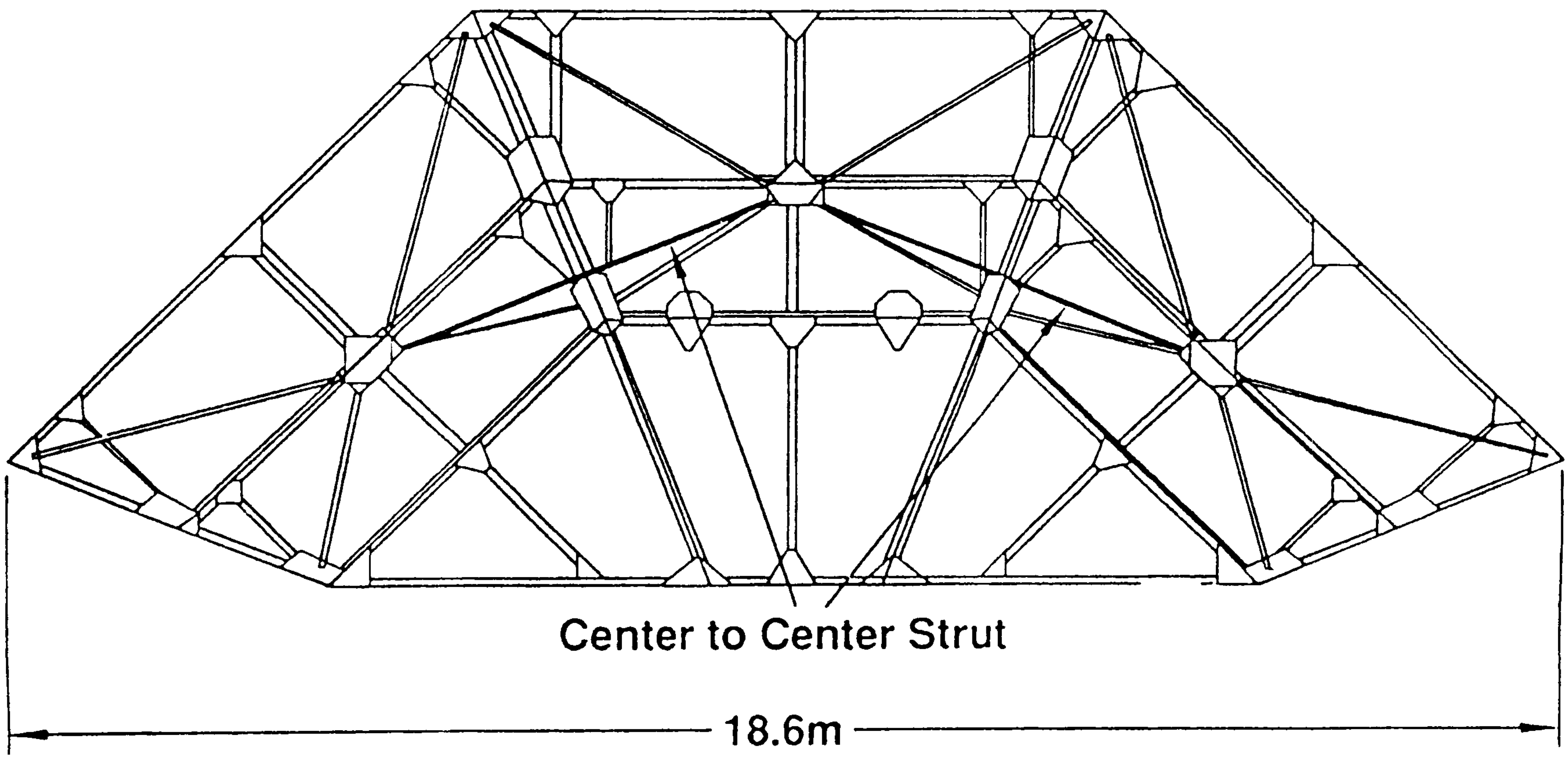
Straight elements were used to construct this mockup instead of curved ones in order to keep material costs down. Such approximation was deemed acceptable for initial assembly tests, but future iterations should eventually incorporate higher fidelity components.

J. GARVEY
8/8/91

MOCK-UP DESIGN

VJZ632 M10CM

MDSSC



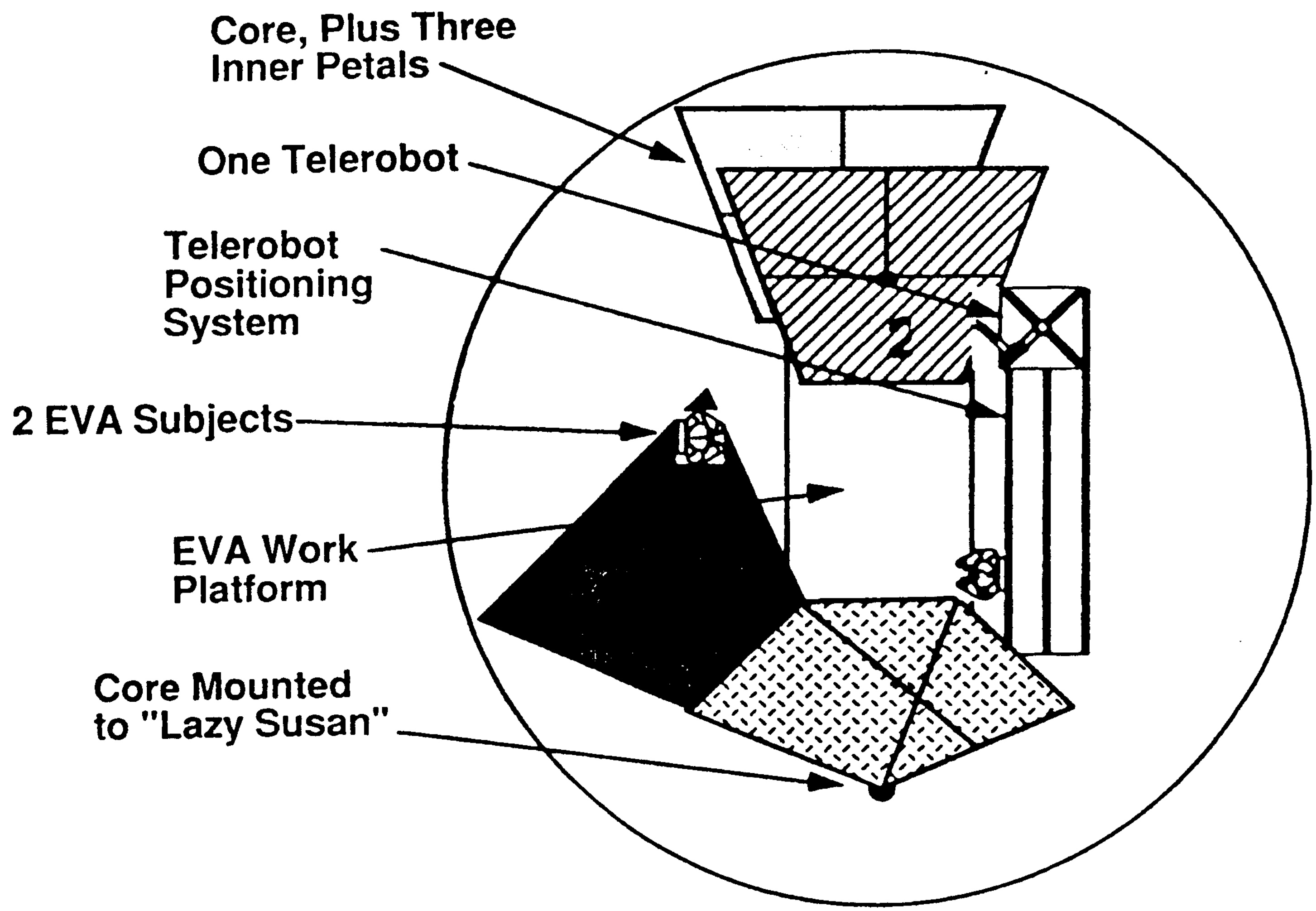
- 3 petals will be used to simulate 3 operations
  - Attachment of the first petal (petal 1)
  - Attachment of additional petals (petals 1 and 2)
  - Attachment of the last petal (petal 2 inserted between 1 and 3)

- The telerobotic arm will translate a petal to its docking station, where the two EVA suited subjects will then complete soft docking and close the hard-dock latch mechanisms

CONFIGURATION IN UWTF

VJY900

MDSSC-SSD



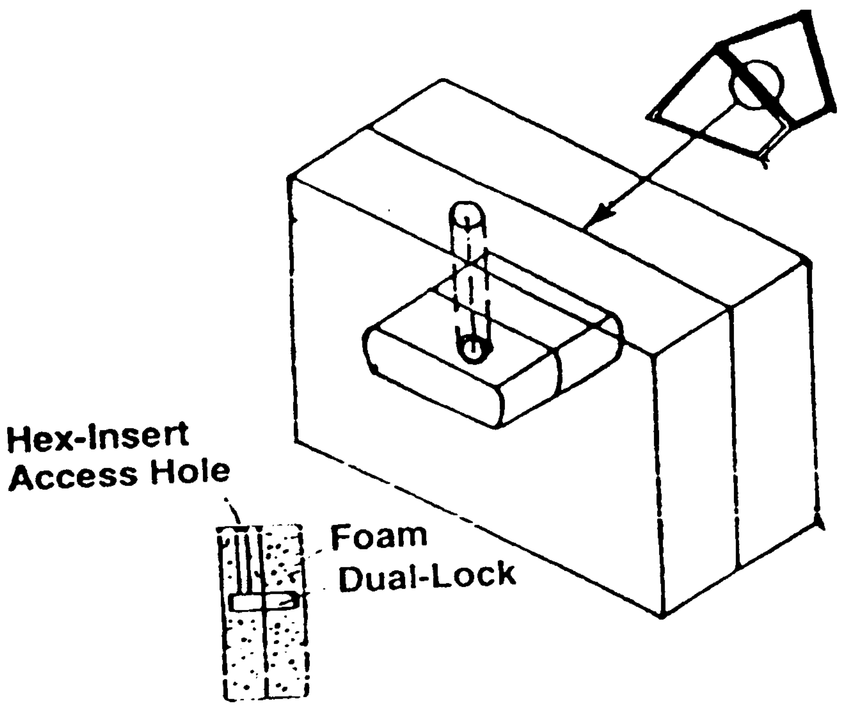
- An integrated latching mechanism was utilized to eliminate loose items (i.e. – bolts, washers). A single tool activates it.

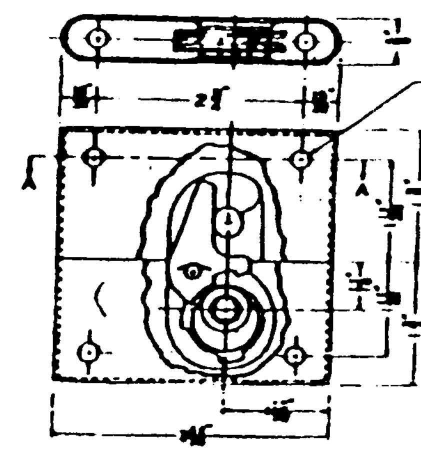
- To minimize cost a $4/unit latch from the housing industry was used. Such a latch was designed to minimize labor requirements for homebuilders. An alternative activation approach is under consideration. By reorienting the latches and connecting them by a drive element, it may be possible to eliminate EVA intervention entirely

HARD-DOCK LATCH REDUCES EVA REQUIREMENTS

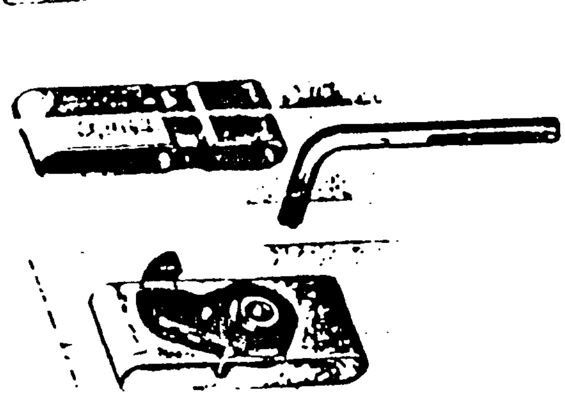
VJY902 M3DN

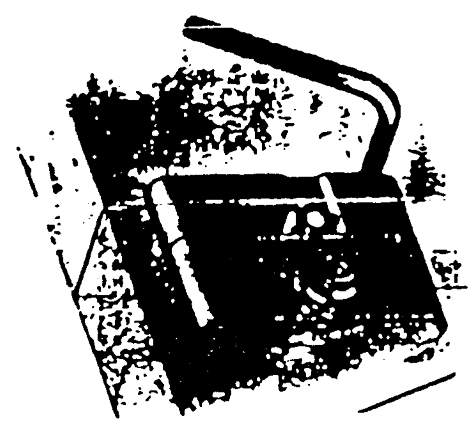
MDSSC/MMRC





GJF





ORIGINAL PAGE IS
OF POOR QUALITY

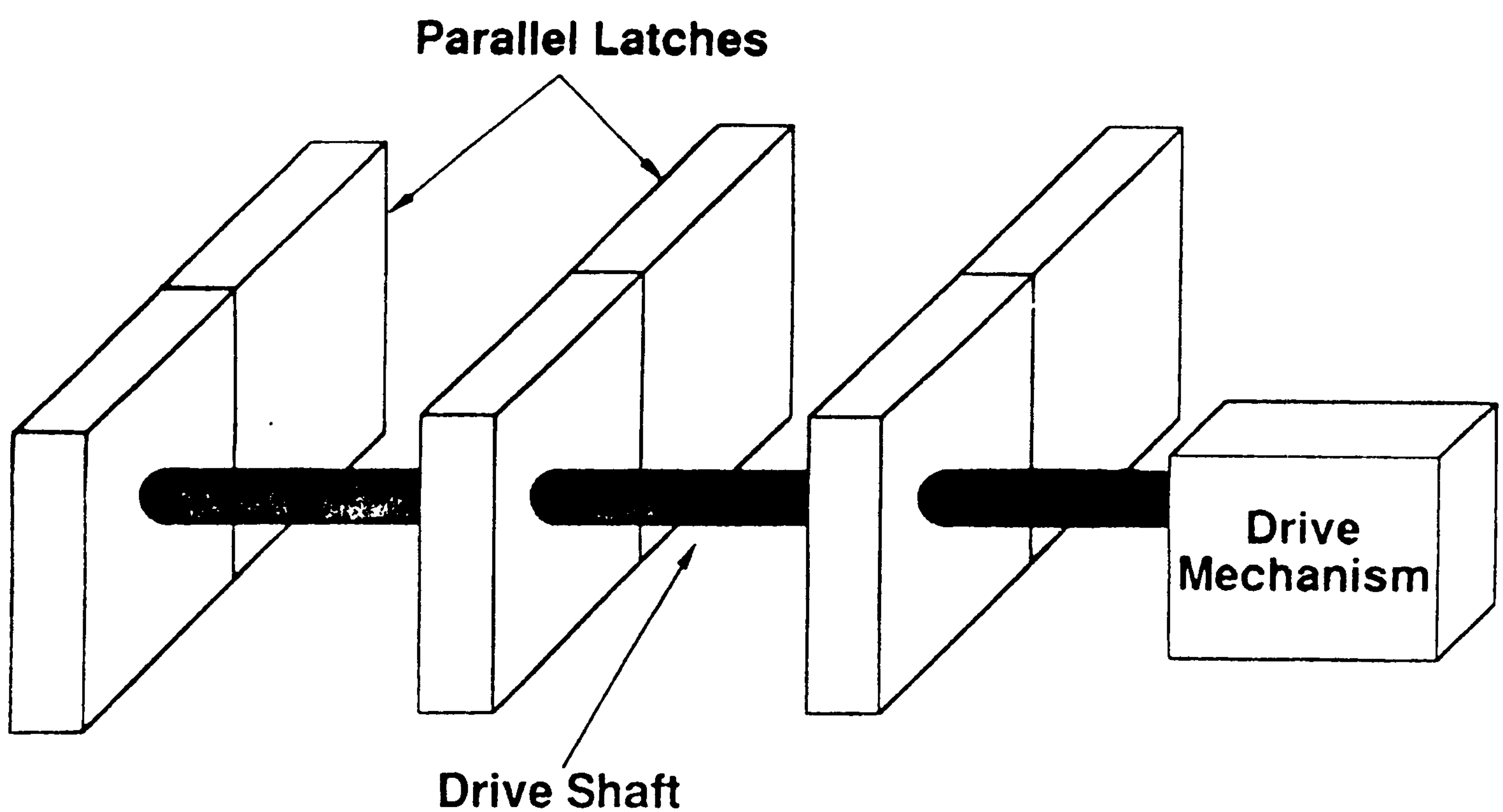
ALTERNATIVE LATCHING ARRANGEMENT

If it is determined that closing such latches requires excessive EVA and/or telerobotic support, an alternative arrangement as shown here can greatly reduce such requirements. In this case, the latches are lined up in parallel and closed by a single drive mechanism. This approach is similar to that employed on cargo doors for large aircraft. One of the issues that needs to be considered is the impact if one or more of the latches do not fully close.

J. GARVEY
8/8/91

ALTERNATIVE LATCHING ARRANGEMENT

MDSSC VJZ619 M9BL



TPS INTERFACE OPTIONS

MDSSC

One other area that requires further attention is the TPS close-out between adjacent petals. For these tests, we selected an approach similar to that used on the Shuttle, where a separate panel is placed over the bulkhead structure interface.

During testing, inserting and fastening these TPS close-out panels proved to be the most difficult operations, and the results overall were unsatisfactory.

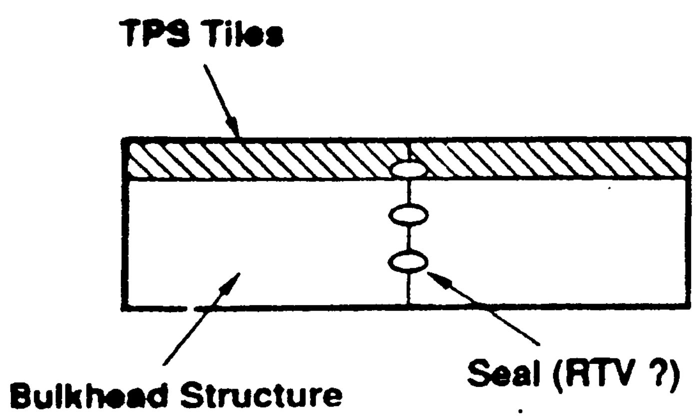
J GARVEY
8/8/91

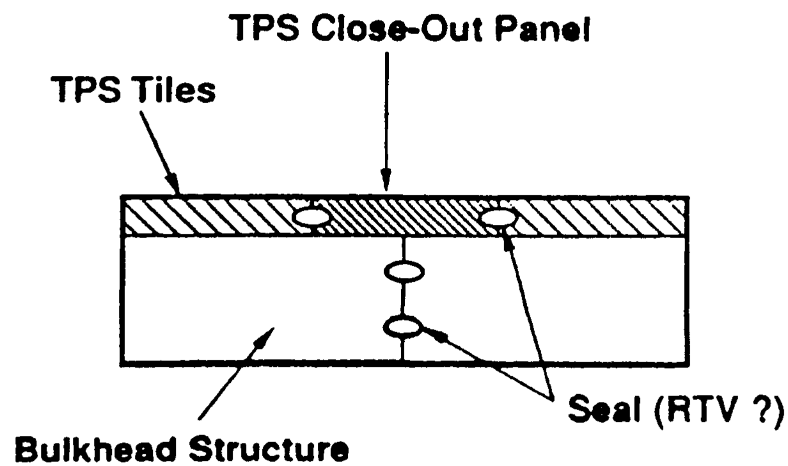
CANDIDATE TPS INTERFACE OPTIONS

VJZ620.1 M9BL

MDSSC

Leading Edge Surface





Trailing Edge

A) Direct Interface **B) Close-out Panel**

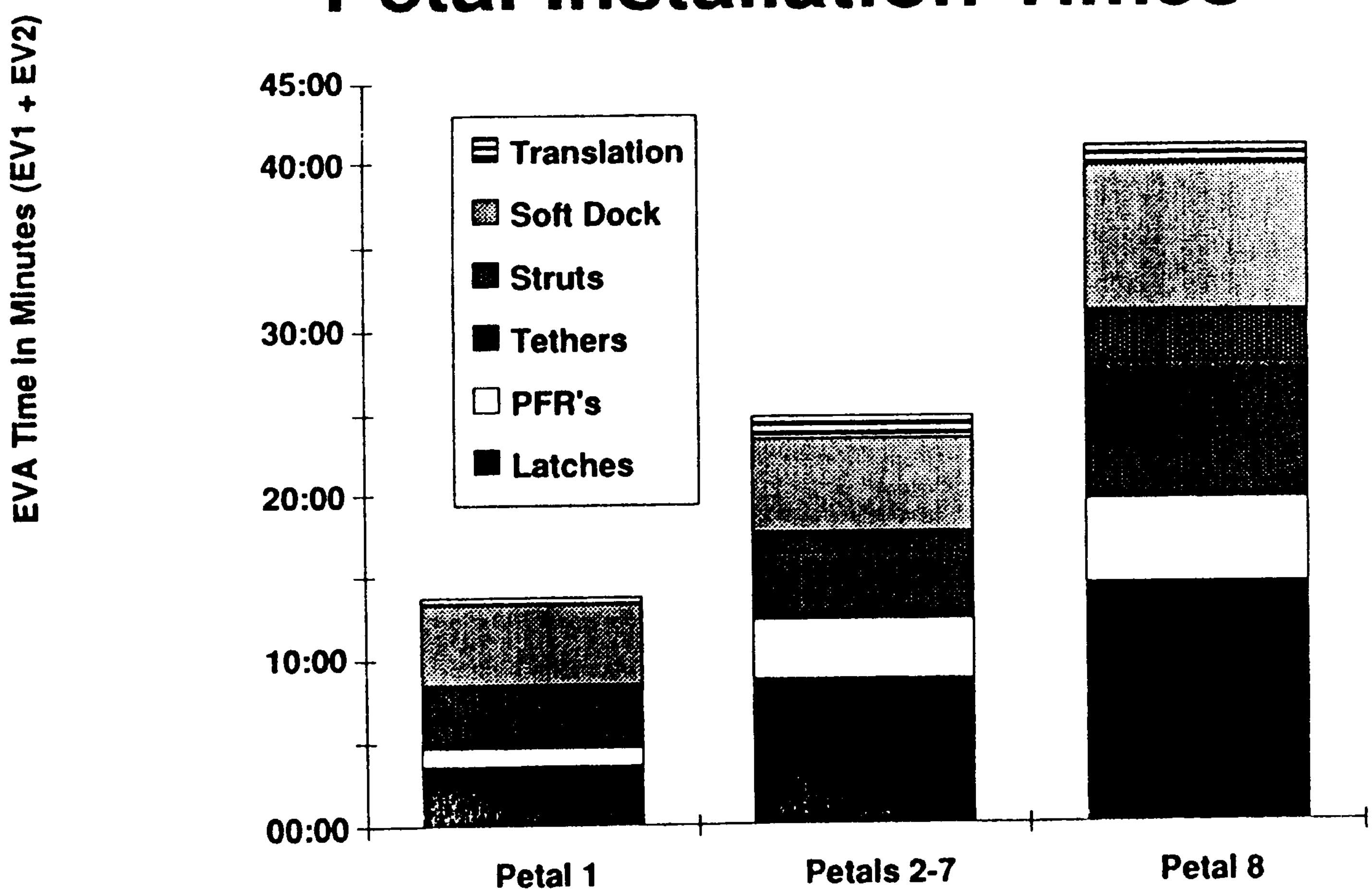
PETAL INSTALLATION TIMES

MDSSC

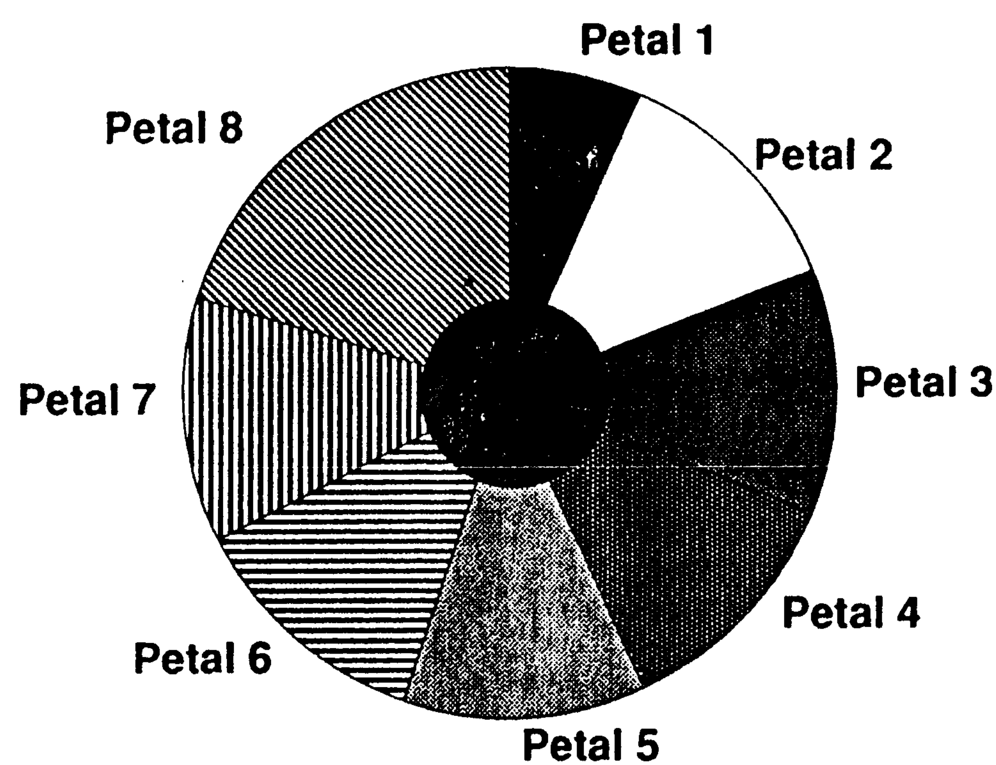
Dave Anderson, co-PI on this project, developed this EVA time break down. It is worthwhile to note that at least three of these time allocations - soft docking, tethers and latches, can be reduced if a greater degree of automation and robotics is available. For example, a "smart" alignment system would significantly reduce the operational complexity of soft docking a petal, while an Astronaut Positioning System (APS) would eliminate much of the tethering activity.

J GARVEY
8/8/91

Petal Installation Times



Full Aerobrake Assembly Time



Total 3:23:40 Hours

— Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed

David E. Anderson 4/17/91-000-3 AB Presentation

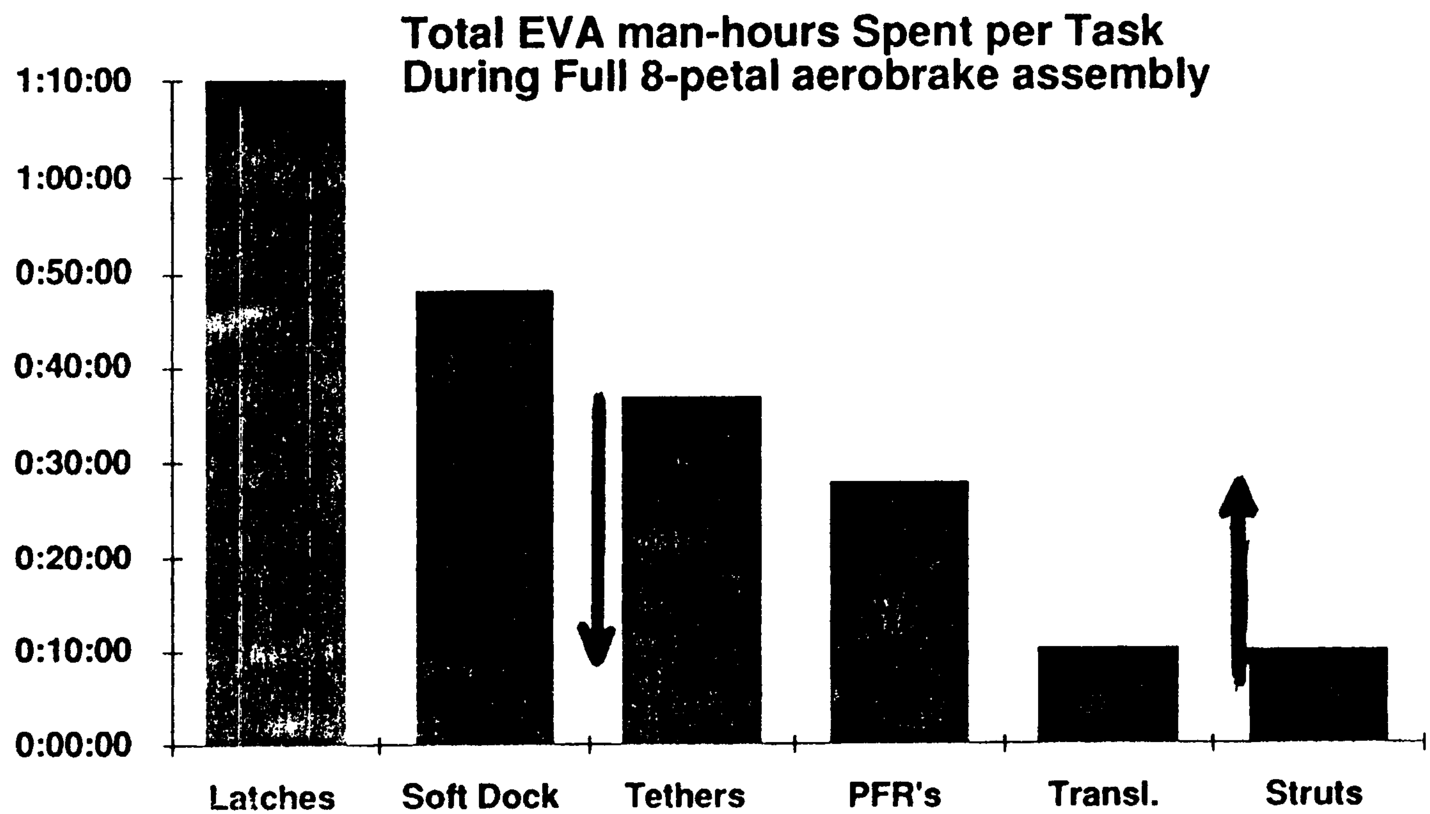
AEROBRAKE TIMELINE COMPONENTS

MDSSC

This chart is a breakdown of the task times to assembly the aerobrake from the previous chart. As indicated previously, one could expect some change in at least the struts, tethers and probably soft dock.

J GARVEY
8/8/91

Aerobrake Timeline Components



FOLLOW-ON ACTIVITIES

MDSSC

We originally planned to fabricate a new, full-scale mockup aerobrake for a Lunar Transfer Vehicle, but a variety of obstacles have delayed that effort indefinately.

Another series of aerobrake assembly tests involving the same basic mockup, with two functional APS mockups and the Ames AX-5 hard suit is now planned for January, 1992.

Work is under way with NASA Langley to test the assembly of their Precision Segmented Reflector mockup this fall.

Attention is also focusing on conducting neutral buoyancy simulation of assemblying and servicing a Nuclear Thermal Rocket mockup in 1992

J. GARVEY
8/8/91

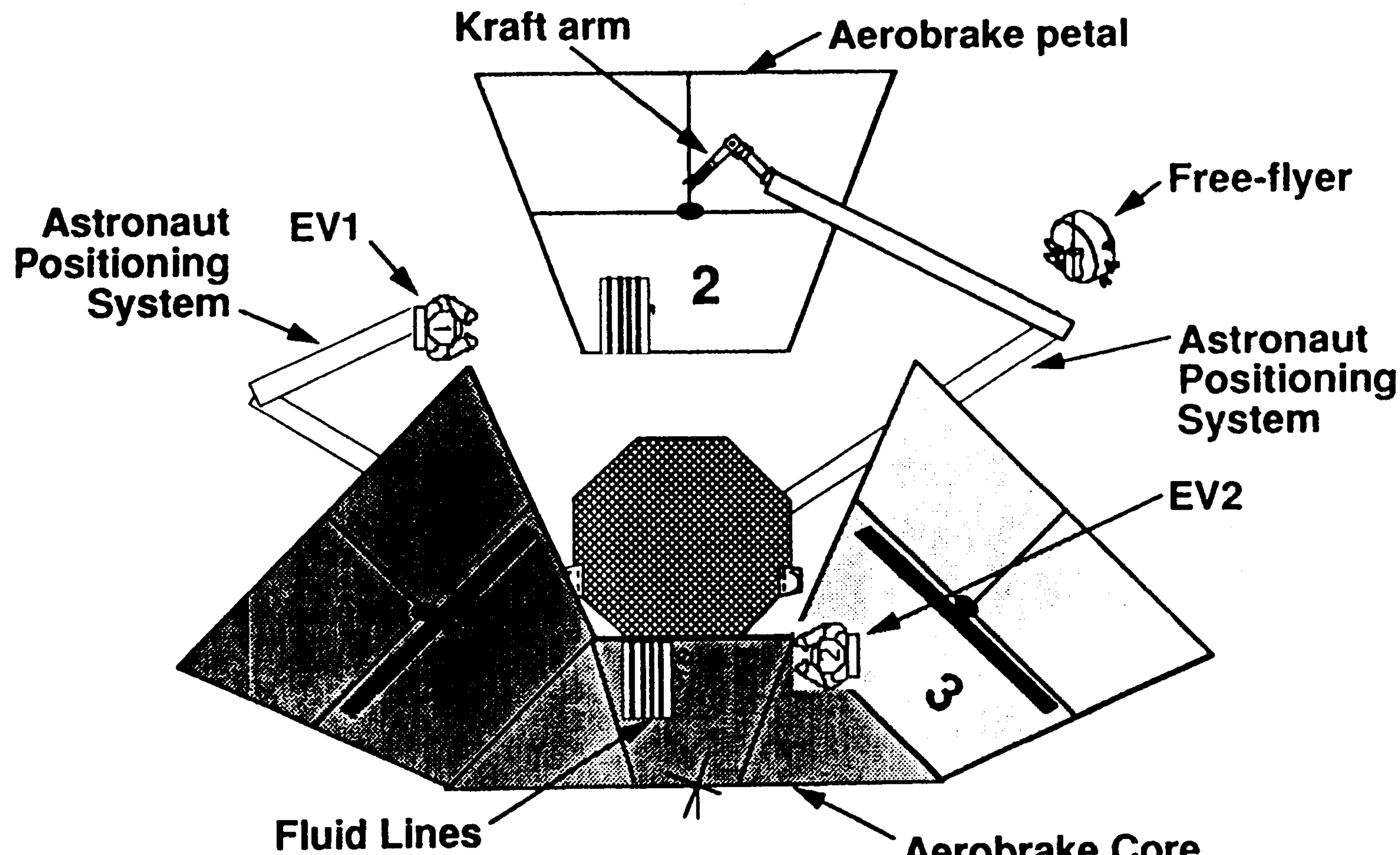
1991 AEROBRAKE TEST SET-UP

MDSSC

The next aerobrake assembly will utilize the same mockup, with two APS arms from the SSF program, a standard EVA suit, and the prototype AX-5 hardsuit that Ames is developing. Such a suit operates at 8 p.s.i. and is intended to improve EVA performance.

J. GARVEY
8/8/91

1991 Aerobrake Test Set-up



— Space Station Freedom — McDonnell Douglas • GE • Honeywell • IBM • Lockheed

David E. Anderson 4/17/91-000-5 AB Presentation

LTV AEROBRAKE MOCKUP

MDSSC

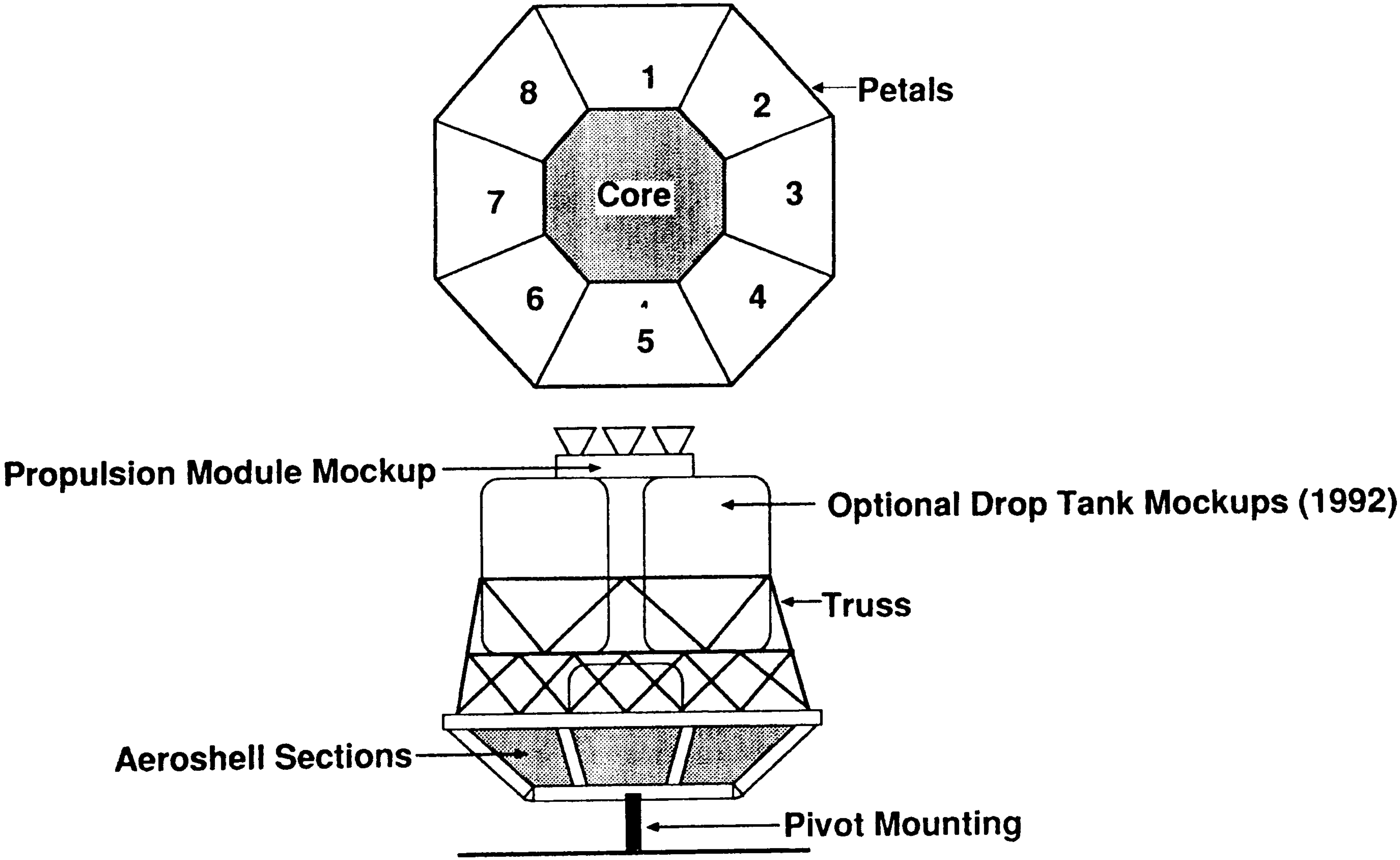
A mockup aerobrake for a Lunar Transfer Vehicle would incorporate several improvements over the initial Mars aerobrake mockup, such as better latch placement and interfaces and a higher fidelity truss structure. It would also be capable of integration with modules that would represent the other components of the LTV.

Because the LTV mockup is small enough to fit in the UWTF, it would be possible to study a larger number of on-orbit assembly and servicing issues. Such research could take place in an evolutionary fashion.

J. GARVEY
8/8/91

THE NEXT AEROBRAKE MOCKUP WILL GIVE US THE ABILITY TO ASSESS DESIGN AND ASSEMBLY ISSUES ASSOCIATED WITH AN ENTIRE LTV

131.3 12-401



PSR ASSEMBLY

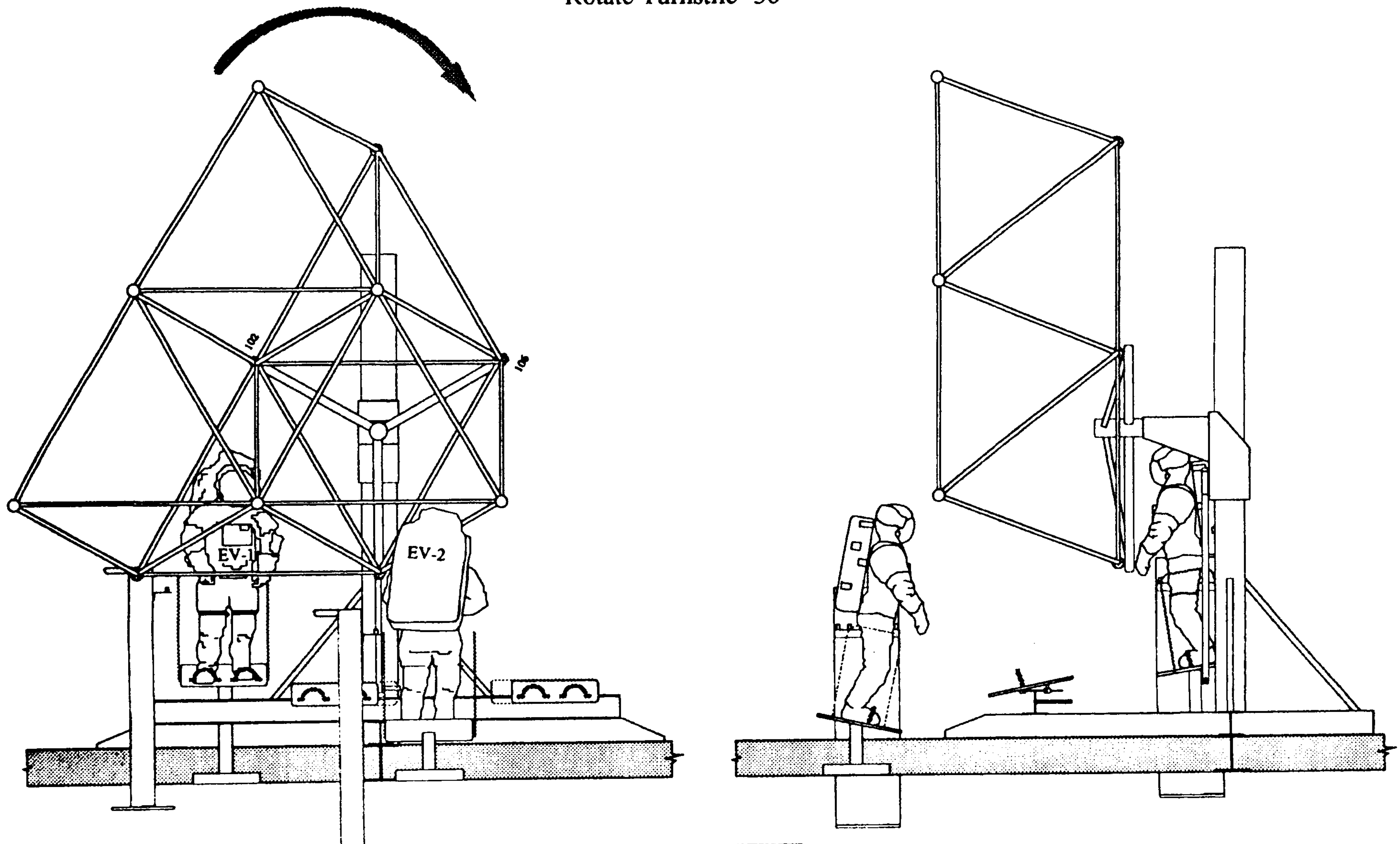
MDSSC

NASA is developing the technology to construct the Precision Segmented Reflector, which would follow the Great Observatory series of orbiting astronomical platforms. The truss structure will share assembly issues common to aerobrakes and other large space structures.

This test will utilize a Langley mockup for initial neutral buoyancy simulations in the UWTF this fall.

J GARVEY
8/8/91

Rotate Turnstile -30°



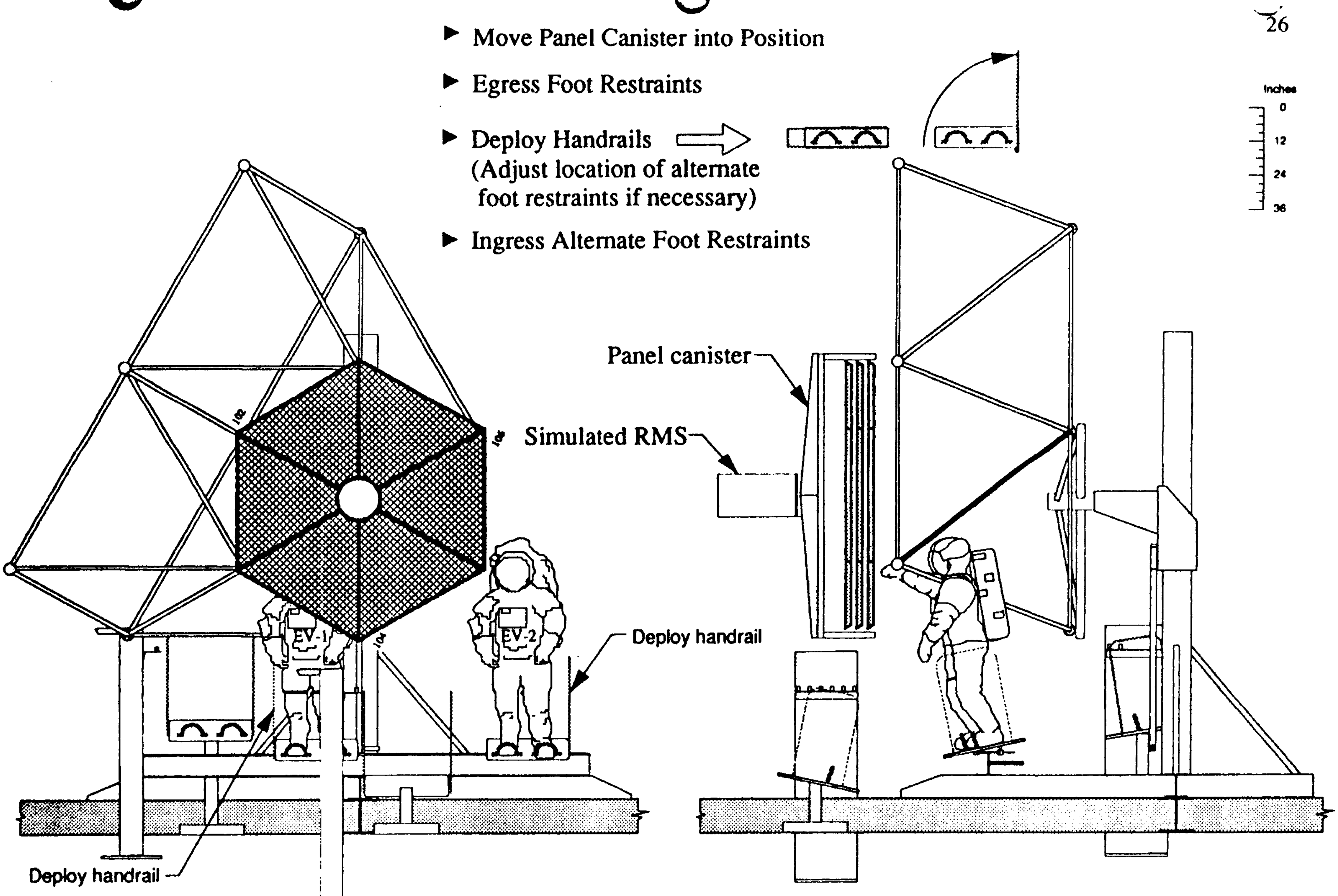
ELAPSED TIME
00:29:40

UWTF Ass'y Proc

NASA-Langley

26

- Move Panel Canister into Position
- Egress Foot Restraints
- Deploy Handrails (Adjust location of alternate foot restraints if necessary)
- Ingress Alternate Foot Restraints



ELAPSED TIME
00:33:40

UWTP Ass'y Proc

NASA-Langley

SUMMARY

MDSSC

This initial aerobrake assembly demonstration indicates that such an operation could be feasible.

No "show-stoppers" were identified, but much more work is still needed on the supporting truss structure, TPS close-out panels, and associated role of SSF support facilities.

Automation and robotics can play important roles in soft-docking, latch alignment and closing, and astronaut translation.

J. GARVEY
8/8/91

AUTHOR INDEX