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Systems Autonomy Technology: Executive Summary and Program Plan

Ames Research Center

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Systems Autonomy Technology: Executive Summary and Program Plan

Ames Research Center
Goddard Space Flight Center
Jet Propulsion Laboratory
Johnson Space Center
Kennedy Space Center
Langley Research Center
Lewis Research Center
Marshall Space Flight Center

December 1987

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

PREFACE

This document was originally prepared and written as a Program Plan without the normal publication standards of a NASA Technical Memorandum.

Because of its significance as an Agency Plan, and to make it a more retrievable document, it is being reproduced in its original form as a NASA TM.

EXECUTIVE SUMMARY

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SYSTEMS AUTONOMY TECHNOLOGY EXECUTIVE SUMMARY

TABLE OF CONTENTS

SYSTEMS AUTONOMY TECHNOLOGY PROGRAM PLAN
EXECUTIVE SUMMARY

GOAL AND OBJECTIVES

Program Goal

The Systems Autonomy Technology Program (SATP) is an aggressive new program with the overall Program Goal to develop, integrate, and demonstrate the technology to enable **Intelligent Autonomous Systems** for future NASA missions. Some of the more important space missions which will require this technology are those future national space challenges recommended by the Report of the Presidential Commission on Space: (1) establishment of a permanent presence in space through the Space Station, (2) establishment of a lunar outpost by 2005 to serve as a base for future exploration of the solar system, and (3) establishment of a Mars outpost by 2015 for further manned and robotic exploration of Mars.

Program Objectives

Program Objectives to achieve this Goal are:
(1) **Significantly advance** the technologies for cooperating intelligent systems;
(2) **Demonstate, evaluate, and validate** technologies in operational environments;
(3) **Transfer the technology** for user implementation.

PROGRAMMATIC AND TECHNICAL JUSTIFICATION

Programmatic Justification

To preserve the nation's leadership position in space, it is necessary that NASA provide a research and development focus for development and application of intelligent autonomous systems technology. This technology is crucial to successful accomplishment of the national space challenges, and to remain ahead of international competition.

The NASA Office of Aeronautics and Space Technology (OAST) has initiated the Systems Autonomy Technology Program (SATP) to provide this focus on Intelligent Autonomous Systems technology, and to provide the required technology for successfully accomplishing the National Space Challenges.

Technical Justification

For NASA to be successful in these future space programs it is imperative that space operations be more efficient and less costly. For example, inadequate automation on Space Station will mean that astronaut flight crews will spend more time on "house-keeping" chores and less time on scientific research. With inadequate automation, ground support operations and ground mission operations will become larger and costlier to support a permanent presence in space. With inadequate automation, mission success rate will be low due to impact of unanticipated anomalies.

State-of-the-Art: Current intelligent knowledge-based systems in operational use are generally small standalone systems which are slow and static. That is, they are not integrated with other systems, are too slow for critical real-time performance, and have no capability to improve or expand their knowledge autonomously.

Knowledge-based systems currently are also "fragile". That is, they begin to fail rapidly when used at the limits of their knowledge. Another serious limitation is the lack of insight in how to validate knowledge-based systems. Current validation methodologies have not had to deal with scenarios which include unanticipated environments.

Technical Challenges - Technical challenges to achieve program objectives include:
(1) **Real-time** Knowledge-based Systems.
    Diagnosis and planning decisions in milliseconds.
(2) **Dynamic** Knowledge Acquisition.
    Automated knowledge base expansion in real time (learning).
(3) **Robust** Planning and Reasoning.
    Reliable decisions in unanticipated environments.
(4) **Cooperating** Knowledge-based Systems.
    Mutual resource planning decisions between intelligent systems.
(5) **Validation** Methodologies.
    Evaluation criteria for decision quality based on fundamental theory.

Payoffs - Automation through Intelligent Autonomous Systems will provide significant payoffs in the following areas:
(1) Reduced mission operations costs through automation of labor intensive operations (Reduce manpower);
(2) Increased mission productivity through automation of routine onboard housekeeping functions (Offload astronaut time);
(3) Increased mission success probability through automation of real-time contingency replanning (Save experiments or possibly entire missions).

PROGRAM CONTENT

The program objectives will be accomplished by a Core Technology research program closely coupled with several major Demonstration Projects. The Demonstration Projects provide a means to evaluate and validate concepts developed through scientific and engineering research in the Core Technology.

Technology transfer will occur through design criteria from Demonstrations and functional criteria from Core being transferred to user organizations for operational implementation.

Demonstrations

1. Space Station Demonstrations (SADP).

   a. Thermal Control Systems (TCS). This joint effort between ARC and JSC will demonstrate technologies in 1988 for autonomous thermal control system operation on the Space Station. This demonstration is significant in that it will be one of the first knowledge-based systems to control a large complex system in real-time and with real operational hardware. Key technology capabilities to be demonstrated include fault diagnosis and correction advice of anticipated faults, incipient failure prevention through trend analysis, and explanation displays. Key technology thrusts include causal modeling of a complex electrical/mechanical system, and combined causal models and heuristic rules for more intelligent reasoning, trend analysis heuristic rules, and validation methodologies.

b. Thermal/Power Control System. This joint effort between ARC, LeRC, MSFC, and JSC will demonstrate technologies in 1990 for autonomous control of the thermal and power system operation on Space Station. This demonstration is significant in that it will show coordinated simultaneous control of two large complex systems. There is great potential for significant operation cost reduction through the use of a mature autonomous power system due to its unique role among the onboard systems. Specific technology capabilities to be demonstrated include fault detection/classification and isolation methodologies, system restoration strategies, replanning in the face of uncertainty, and operator training methodologies. Key technology thrusts include causal modeling of complex electrical/mechanical systems, cooperation of two knowledge-based systems, and validation methodolgies.

c. Hierarchical Knowledge-Based Systems. In this SADP 1993 demonstration, the key technology thrust will be to evaluate and validate methodologies for expert system control of more than two Space Station subsytems through hierarchical architectural strategies.

d. Distributed Knowledge-Based Systems. In this SADP 1996 demonstration, the key technology thrust will be to evaluate and validate methodologies for expert system control of multiple Space Station subsystems through distributed architectural strategies.

2. Operations Demonstrations.

A set of specific Domain Demonstrations has been planned to facilitate technology transfer to domains other that Space Station and to insure that generic technology developed on Space Station testbeds is practical for many NASA applications.

a. Shuttle Flight Control Room Operations. A rule-based integrated communications officer (INCO) online expert system will be developed and demonstrated in 1988, and advanced powerful graphics capabilities will be incorporated in 1989. This demonstration is significant in that it will be the first NASA knowledge-based system to be implemented into a real-time operational environment. The expert system will aid Flight Control operations at JSC with minimal backroom support during STS missions, thus reducing manpower requirements for flight controllers who support Space Shuttle system operations.

b. Launch Operations. The demonstrations at KSC will include systems software and hardware for autonomous diagnostics and control of interactive complex electro/mechanical launch processing systems that will perform better than system engineers. Key technology capabilities demonstrated will include goal-directed control/reconfiguration, fault recognition/warning/diagnosis, systems scheduling/rescheduling, automated trend failure analysis, and intelligent user interfaces. Key technology thrusts include model-based simulation, CAD/CAM knowledge-base capture, explanation displays, limited uncertainty management, and validation techniques.

c. Mission Operations Ground Data Systems. Demonstrations will develop and demonstrate technologies which will enable and enhance the multi-mission monitoring and diagnosis of ground data systems for unmanned spacecraft by emphasizing tools commonly applicable to the automated monitoring of spacecraft telemetry and space flight operations ground data systems. The technology demonstrations at JPL include a multi-mission telemetry monitoring workstation for spacecraft engineering telemetry in 1988, automated monitoring of Voyager/Neptune encounter in 1989/90, automatic command verification and monitoring for spacecraft in 1992/93, and dynamically configurable and teachable ground data system controller in 1994/95.

Core Technology

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4. Planning and Reasoning.

4.1 Reasoning Under Uncertainty - The ability to make sensible judgements and carry out reasonable actions when world knowledge is imprecise or incomplete, or heuristics and models have built-in uncertainty, or actions have uncertain effects.

Ongoing internal research will focus on probabilistic methods for uncertainty management. External collaborations will include research on fuzzy logic and integration of decision theoretic and heuristic methods. Work will also be sponsored in developing methodologies and tools for combining classical methods with AI methods.

4.2 Learning - The ability to alter and improve all functionalities as conditions change and knowledge is added over time. Learning may occur manually by being taught or automatically by experimentation, generalization, or discovery.

Internal work will be in the areas of learning by discovery and explanation based generalization. External collaborations with Carnegie-Mellon on learning by experimentation, and with the University of Michigan on learning by search will continue. Major milestones include an initial demonstration of learning by experimentation in a robotic environment during 1989 and self-improving knowledge bases as part of the 1990 Systems Autonomy Demonstration Project. During 1991-1992 discovery-based learning by introspection will be demonstrated on a large database of sensor-based information on a testbed for Space Station such as the Data Management System.

4.3 Causal Modeling - The ability to utilize structural and functional information about a device, along with the physical laws that govern the device, to simulate and reason about the device.

Internally, the 1988 SADP Space Station Thermal System will be used as a test domain for the combination of heuristic and model-based methods in diagnosing flaws in complex systems. Externally the University of Arizona will be funded in integration of knowledge-based and traditional simulation methods and Stanford University in logical representations of structure and function. A major milestone is the successful demonstration of these methods during the 1988 SADP Thermal System demonstration. More sophisticated methods will be employed in work on the Hubble Space Telescope and other projects that involve modeling complex devices.

4.4 Knowledge Acquisition - The ability to preserve the "corporate memory", i.e. to ensure that all the facts, heuristics, and other information gained during the design, construction, and testing of a device are available in a practical and usable form during the operational life of the device.

Internal work will be focused on studying the Hubble Space Telescope (HST) and the Space Infrared Telescope Facility (SIRTF) as test domains for three research areas: integration of knowledge acquisition into the design, construction, and testing process, acquisition of knowledge from large numbers of experts, and large knowledge base technology. MSFC, in collaboration with ARC and Stanford, will concentrate on the latter two topics in the HST domain, while ARC will utilize SIRTF for explorations in the first area. It will be shown how the products of traditional engineering activities supporting design and testing in major products can be utilized in knowledge acquisition during 1988 and 1989. A very large knowledge base system will be demonstrated during 1991. Methodologies for the combination of expertise from at least a dozen experts will be presented during 1990.

4.5 Advanced Planning Methods - The ability to take a set of goals, design a plan to utilize existing and potential resources to achieve those goals, monitor the execution of that plan, and dynamically alter the plan when initial assumptions prove incorrect.

Behavioral net architectures will be investigated at LaRC for application to the problem of planning and scheduling, and for the develoment of a prototype domain-independent planning and scheduling tool. At ARC, internal work will proceed on testing the limits of current AI-based scheduling methodologies applied to NASA problems, particularly in space science. Work on dynamic replanning will continue and research will be initiated on the application of skeletal planning and plan refinement to NASA domains. Externally there will be collaboration with work at JPL in sensor-based planning, with industry in the development of a Truth Maintenance System-based planner, and at USC-ISI in the application of DARPA-sponsored methods to NASA problems. Current methodologies for heuristic scheduling will be demonstrated in a Pioneer-Venus experiment for automated "orbit building". The JPL work has milestones in a sensor-rich subsystem of Space Station during 1988 and 1989. That work and other internal and external efforts will be demonstrated as part of scheduling the power subsystem of Space Station during the 1990 SADP demonstration.

4.6 Cooperating Knowledge Based Systems - The ability to provide for synergistic cooperation among several significant knowledge-based systems in a complex environment.

Internal research focus will be on the 1990 SADP demonstration; a demonstration of coordinated control of thermal and power subsystems. The use of the Hubble Space Telescope will be considered as a second domain for cooperative systems. Externally work will be supported at the Stanford Knowledge Systems Laboratory in blackboard architectures for distributed control of knowledge-based systems, at the University of Maryland in potential hierarchical control methods, and MIT in languages for command of multiple systems. In addition, a major new effort, jointly sponsored with DARPA, will begin at Stanford, SRI, and Rockwell in methodologies for interacting intelligent agents in the domain of Space Station Construction. Blackboard architectures will be demonstrated in NASA domains during 1988.

4.7 Validation Methodologies - The ability to validate the correctness of the facts, heuristics, and models used by a knowledge-based system and to verify that the knowledge has been correctly represensented within the system.

Reliability and performance validation methods for life-critical knowledge-based systems will be investigated at LaRC. Proposed techniques and prototype tools will be applied to knowledge-based systems underdevelopment at LaRC such as rule-based systems for fault prediction and trend analysis, and model-based systems for fault diagnosis and recovery planning. Activities at ARC include a NASA/Industrial workshop which was held in 1987 to begin to understanding the practical issues of knowledge-based system validation in NASA domains with a particular focus on Space Station. The result of that workshop will be a detailed report to appear in early fiscal 1988. The first major milestone will be the development of an accepted validation methodology for the 1988 SADP Thermal System demonstration. Validation work will also occur as part of the work described above on multiple-expert knowledge acquisition and large knowledge base technology. This will produce results in parallel with those milestones in 1989 and 1990.

5. Control Execution - The possibility of developing a mathematical theory will be explored that enables the design of symbolic controllers for dynamic systems. The approach through in-house research and university grants will be to build up predicate calculus to include time and dynamics concepts within the syntax. Specific research products include (1) ways for translating sentences of the command sequences into arithmetic functions of time, (2) ways for representing estimated states and time histories symbolically, and (3) means for expressing global system properties such as stability, robustness, and disturbance rejection.

6. Operator Interface - Human machine interfaces will be developed that enable communication with intelligent, autonomous systems in space in a manner natural to the human operator. Emphasis will be placed on "intelligent" systems which satisfy human factors requirements, and where the distribution of the workload between human and machine is optimized. Specific research products include (1) design decision aids and rapid prototyping tools, (2) more natural human-computer dialog systems, (3) advanced display/control concepts, and (4) computer aided interface design system.

7. Systems Architecture and Integration - ARC objective is to develop systems concepts required for the implementation of robust knowledge-based systems in spaceborne applications. Specific tasks include (1) design and development of the spaceborne integrated symbolic/numeric multiprocessor computer; (2) definition and development of the network interfaces and data transmission protocol for a vendor independent environment; (3) development of the software protocol and management for large, distributed knowledge-based data systems; (4) development of software compilers and translators for use in development and operational environments; (5) and design and development of verification and validation methodologies for fault-tolerant reconfigurable multiprocessor architectures. Milestones for the spaceborne processor include conceptual design by mid FY-88, detailed design by mid FY-90, with development and qualification by FY-94. Complementary to the ARC effort, GSFC will develop knowledge-base management technologies needed for automated control center operations through use of distributed expert systems.

COLLABORATION WITH OTHER AGENCIES/INDUSTRY

Significant collaborative efforts have been established with DARPA in the area of cooperating intelligent systems, with the Air Force in the demonstration and evaluation of automated systems for ground mission control and operation of multiple satellites, and with DARPA and DOD in the development of spaceborne processors. Significant collaborative efforts have also been established with industry to transfer the automation technologies for use in highly automated commercial spaceborne payloads such as the Industrial Space Facility and Space Habitat.

SCHEDULE

SYSTEMS AUTONOMY PROGRAM SCHEDULE

FY	88	89	90	91	92	Requirements/Goals
Demonstrations						
1. Spa. Sta. Demos (SADP)	1		2		3	Eval. & Valid. of coop. K-B Sys.
2. Operations Demonstrations	4 5		6	78		Alternate domain benchmark sys.
Core Technology						
3. Intentionally Blank						
4. Planning and Reasoning						
4.1 Reas. under Uncert.		1	2			Decision robustness.
4.2 Learning		3		4		Automated K-B expansion.
4.3 Causal Modeling/Sim.	5			6		High qualilty decisions.
4.4 Knowledge Acquisition		7		8		Dynamic K-B Acq.
4.5 Adv. Planning Meth.			9	10	11	Real-time contingency plans
4.6 Coop. K-B Systems		12	13		14	Interactive coop. planning.
4.7 Validation Meth.	15		16	17	18	Methodology based fund. theory.
5. Control Execution						
5.1 Symbolic Control		1		2		Symbolic-algorith. cont. interface.
6. Operator Interface						
6.1 Human Int. Design		1	2	3	4	Comp. aided inter. design tool.
7. Systems Arch./Integ.						
7.1 Symbolic Processor	1		2 3			Real-time performance.
7.2 Dist. K-B Mgmt		4		5		Large K-B software to applic. engg.

SYSTEMS AUTONOMY PROGRAM SCHEDULE MILESTONES

Demonstrations

1. Space Station Demonstrations (SADP)
    1. Control of single subsystem (Thermal).
    2. Control of two subsystems. (Thermal/Power).
    3. Demo plan for hierarchical control of multiple subsystems.
2. Operations Demonstrations
    4. Shuttle flight control room automation (INCO).
    5. Shuttle launch ops diagnostics/control automation (ECS).
    6. Space Station ground multi-system diag./cont. auto. (PFCU).
    7. Space Station ground hier./dist. diag./cont. auto. (GDMS).
    8. Planetary mission ops. automation (Ground Data Systems).

Core Technology

3. Intentionally Blank
4. Planning and Reasoning.
    - 4.1 Reasoning under Uncertainty.
        1. Major review document of current methdologies.
        2. Demonstration of uncertainty management in 1990 SADP Demo.
    - 4.2 Learning.
        3. Demonstration of learning by experiment.
        4. Demonstration of learning by discovery.
    - 4.3 Causal Modeling/Simulation.
        5. Demo of combined causal models & heuristics in 1988 SADP Demo.
        6. Demo of complex modeling of Hubble Space Telescope.
    - 4.4 Knowledge Acquisition.
        7. Demo of design and testing tools.
        8. Demo of combined expertise from over ten experts.
    - 4.5 Adv. Planning Methodologies.
        9. Demo of scheduling in 1990 SADP Demo.
        10. Demo of behavioral network architectures.
        11. Integration of learning with planning methodologies.
    - 4.6 Cooperating Knowledge-Based Systems.
        12. Demo of blackboard architectures.
        13. Demo of two cooperating subsystems in 1990 SADP Demo.
        14. Hierarchical methodologies for control of multiple subsystems.
    - 4.7 Validation Methodologies.
        15. Report of Validation Workshop.
        16. Validation methodology for single subsystems.
        17. Validation methodology for multiple subsystem.
        18. Establishment of fundamental validation theory.
5. Control Execution.
    - 5.1 Symbolic Control.
        1. Algorithmic supervisors of arithmetric controllers.
        2. Demo of global sys. prop. of symbolic/algorithmic interfaces.
6. Operator Interface.
    - 6.1 Human Interface Design.
        1. Design decision aids and rapid prototyping tools.
        2. Natural human-computer dialog systems.
        3. Advanced display/control concepts.
        4. Computer aided interface design (CAID) system.
7. Systems Architecture and Integration.
    - 7.1 Symbolic Processor.
        1. Complete conceptual design.
        2. Complete detailed design.
        3. Initiate development, testing, and qualification.
    - 7.2 Distributed K-B Management.
        4. Large distributed knowledge base models.
        5. Large K-B management development tools.

FUNDING ($K)

SYSTEMS AUTONOMY PROGRAM FUNDING SUMMARY

FY	88	89	90	91	92	Total
DEMONSTRATIONS	4763	4700	4280	4300	3850	21893
1. Space Station Demos	3399	3500	3500	3500	3500	17399
o Thermal	1905	500	0	0	0	2405
o Thermal/Power	1125	2300	2500	700	0	6625
o Hierarchical	369	700	1000	2700	3100	7869
o Distributed	0	0	0	100	400	500
2. Operations Demos	1364	1200	780	800	350	4494
o STS Flt Cont Room Ops	620	350	0	0	0	970
o Launch Operations	397	500	430	450	0	1777
o Ground Data Systems	347	350	350	350	350	1747
CORE TECHNOLOGY	6366	6948	7643	7900	8583	37390
3. Intentionally Blank						
4. Planning and Reasoning	3701	4050	4090	4250	4583	20674
4.1 Uncertainty Mgmt.	140	200	240	300	400	1280
4.2 Learning	500	500	500	500	600	2600
4.3 Causal Modeling	250	300	300	300	300	1450
4.4 Knowledge Acq.	971	1000	1000	1000	1000	4971
4.5 Adv. Planning Meth.	647	650	650	700	700	3347
4.6 Coop. K-B Systems	753	800	800	750	783	3886
4.7 Validation Meth.	440	600	600	700	800	3140
5. Control Execution						
5.1 Symbolic Control	96	150	200	200	200	846
6. Operator Interface						
6.1 H-M Inter. Design	385	400	403	500	500	2188
7. Systems Arch./Integ.	2184	2348	2950	2950	3250	13682
7.1 Symbolic-Num. Arch.	1986	2000	2500	2500	2750	11736
7.2 Dist. K-B Mgmt.	198	348	450	450	500	1946
	=====	=====	=====	=====	=====	=====
Total (Net)	11129	11648	11923	12200	12383	59283
Program Support	1195	973	994	1014	1028	5204
HQ Unique Requirements	0	179	183	186	189	737
Total (Gross)	12324	12800	13100	13400	13600	65224

FUNDING ($K)

SYSTEMS AUTONOMY PROGRAM FUNDING SUMMARY
(Element Funding by Center)

	88	89	90	91	92	Total
DEMONSTRATIONS	4763	4700	4280	4300	3850	21893
1. Spa. Sta. Demos (ARC)	3399	3500	3500	3500	3500	17399
o Thermal	1905	500	0	0	0	2405
ARC	1305	300	0	0	0	1605
JSC	600	200	0	0	0	800
o Thermal/Power	1125	2300	2500	700	0	6625
ARC	575	1250	1400	400	0	3625
JSC	0	300	300	100	0	700
LeRC/MSFC	550	750	800	200	0	2300
o Hierarchical						
ARC	369	700	1000	2700	3100	7869
o Distributed						
ARC	0	0	0	100	400	500
2. Operations Demos	1364	1200	780	800	350	7869
o STS Flt Cont Room (INCO)						
JSC	620	350	0	0	0	970
o Launch Operations						
KSC	397	500	430	450	0	1777
o Miss Cont Gnd Data Sys						
JPL	347	350	350	350	350	1747
CORE TECHNOLOGY	6366	6948	7643	7900	8533	37390
3. Intentionally Blank						
4. Planning and Reasoning	3701	4050	4090	4250	4583	20674
ARC	2883	3000	3050	3150	3483	15556
LaRC	347	550	550	600	600	2647
MSFC	471	500	500	500	500	2471
5. Control Execution						
ARC	96	150	200	200	200	846
6. Operator Interface						
ARC	385	400	403	500	500	2188
7. Systems Arch/Integ	2184	2348	2900	2950	3250	13682
ARC	1986	2000	2500	2500	2750	11736
GSFC	198	348	400	450	500	1946
	=====	=====	=====	=====	=====	=====
Total (Net)	11129	11648	11923	12200	12383	59283

MANPOWER (my)

SYSTEMS AUTONOMY PROGRAM MANPOWER SUMMARY
(Element Civl Service Manpower by Center)

	88	89	90	91	92	Total
DEMONSTRATIONS	39	41	43	38	17	178
1. Space Station Demonstrations	24	24	25	21	14	108
o Thermal	12	9	3	1	0	25
ARC	8	7	3	1	0	19
JSC	4	2	0	0	0	6
o Thermal/Power	11	14	21	16	1	63
ARC	1	4	9	9	0	23
JSC	0	0	2	1	1	4
LeRC	10	10	10	6	0	36
o Hierarchical						
ARC	1	1	1	4	9	16
o Distributed						
ARC	0	0	0	0	4	4
2. Operations Demonstrations	15	17	18	17	3	70
o STS Flt Cont Room (INCO)						
JSC	2	2	0	0	0	4
o Launch Operations						
KSC	10	12	15	14	0	51
o Miss Cont Gnd Data Sys						
JPL	3	3	3	3	3	15
CORE TECHNOLOGY	26	32	38	39	40	175
3. Intentionally Blank						
4. Planning and Reasoning	15	20	25	27	29	116
ARC	8	12	16	18	20	74
LaRC	3	4	5	5	5	22
MSFC	4	4	4	4	4	20
5. Control Execution						
ARC	2	2	2	2	2	10
6. Operator Interface						
ARC	2	2	2	3	3	12
7. Systems Arch/Integ	7	8	8	7	6	36
ARC	5	5	5	4	3	22
GSFC	2	3	3	3	3	14
	=====	=====	=====	=====	=====	=====
Systems Autonomy Total (MY)	65	73	81	77	57	353

PROGRAM PLAN

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SYSTEMS AUTONOMY TECHNOLOGY PROGRAM (SATP)
PLAN

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035
December 1987

AMES RESEARCH CENTER
GODDARD SPACE FLIGHT CENTER
JET PROPULSION LABORATORY
JOHNSON SPACE CENTER
KENNEDY SPACE CENTER
LANGLEY RESEARCH CENTER
LEWIS RESEARCH CENTER
MARSHALL SPACE FLIGHT CENTER

SYSTEM AUTONOMY TECHNOLOGY PROGRAM PLAN

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FOREWORD

The National Space Strategy approved by the President and Congress in 1984 sets for NASA a major goal of conducting effective and productive space applications and technology programs which contribute materially toward U.S. leadership and security. To contribute to this goal OAST has the responsibility within NASA to support the Nations' civil and defense space programs and overall economic growth. OAST objectives are to ensure timely provision of new concepts and advanced technologies, to support both the development of NASA missions in space and the space activities of industry and other organizations, to utilize the strengths of universities in conducting the NASA space research and technology program, and to maintain NASA's centers in positions of strength in critical space technology areas.

In line with these objectives, the National Aeronautics and Space Administration has established an ambitious new program in space automation and robotics. This program will result in the development and transfer of advanced automation technology to increase the capabilities, productivity, and safety of future NASA space programs including the Space Station, automated space platforms, lunar bases, Mars missions, and other deep space ventures.

The NASA/OAST Automation and Robotics program is currently subdivided into two roughly equal parts. The Ames Research Center has the lead role for that portion of the program that seeks to develop and demonstrate System Autonomy capabilities for space systems that need to make their own decisions and do their own planning. The Jet Propulsion Laboratory has the lead research, development, and demonstration role for Telerobotics, i.e., that portion of the program that has a strong human operator component in the control loop and some remote handling requirement in space.

This Program Plan is intended to be a working document for NASA Headquarters, Program Offices, and implementing Project Management. It is thus a living document that should be reviewed and updated at least once every year.

This Program Plan has been prepared with contributions from all participating NASA Centers. The final version of the document has been reviewed and concurred with by each NASA Center as indicated on the signature page.

SYSTEMS AUTONOMY TECHNOLOGY PROGRAM PLAN

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY

AI	Artificial Intelligence
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CPM	Critical Path Method
DARPA	Defence Advanced Research Projects Agency
DOD	Department of Defence
FCR	Flight Control Room
FY	Fiscal Year
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KB	Knowledge Base
KSC	Kennedy Space Center
LaRC	Langley Research Center
LeRC	Lewis Research Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
SADP	System Autonomy Demonstration Program
SAIWG	System Autonomy Intercenter Working Group
SATP	System Autonomy Technology Program
STS	Space Transportation System

PROGRAM ABSTRACT

NASA's Office of Aeronautics and Space Technology has implemented through its Ames Research Center a System Autonomy Technology Program that will sponsor and pursue the required research, developments, and technology demonstrations for integration of Intelligent Autonomous Systems into space systems. This document is the System Autonomy Technology Program Plan with a horizon of approximately ten years starting in 1988. The general goal to establish and maintain NASA as a world leader in intelligent, autonomous systems for space applications will be achieved by significantly advancing the required technologies, by validating these technologies in operational environments, and by developing and maintaining world-class technical expertise, facilities and tools within the NASA organization.

Autonomous systems are generally characterized by sensing and perception units, databases, control computers, actuators, and an operator interface for human intervention, if required. They are operationally characterized by their ability to communicate at high levels with humans and with other intelligent machines. They are able to recognize and resolve human-induced errors that would inadvertently endanger the system or its performance. They can operate autonomously for extended periods of time by virtue of knowledged-based systems which have capabilities of acquiring and understanding dynamic world knowledge, of learning, and of deducing reliable decisions in uncertain environments.

More than any other project, the Space Station will be a driver of system autonomy in the near future. The importance of system autonomy will increase for the success of future complex space missions, such as unmanned lunar bases or Mars sample return missions. To satisfy more mundane requirements, system autonomy will also become pervasive in less conspicuous areas of the space program, as for example, in design, testing, launch and mission operations, and in-space servicing and construction.

To maintain general validity, the critical technologies for research and development are identified on the basis of a paradigm of intelligent autonomous systems. The core technology areas for research, development, and demonstration are: (1) task planning and reasoning (with subareas: reasoning under uncertainty, learning, causal modeling, knowledge acquisition, advanced planning methods, cooperating knowledge base systems, and validation methodologies) (2) control execution, (3) operator interface, and (5) system architecture and integration. These core technologies will be developed in research laboratories to the point of breadboard integration and testing at component and subsystem levels.

At suitable time intervals, the core technologies will be aggregated and integrated into meaningful technology demonstration projects. Prototype subsystems and systems will be tested in the context of realistic application scenarios. The implementation of

these demonstration projects will assure technology relevancy and maturity for space mission applications. Prototype test and demonstration projects currently under development are: (1) Space Station testbeds covering a broad spectrum of systems technology including a single thermal control system, a multiple thermal and power control system, a hierarchical system, and a distributed system; and (2) specific domain demonstrations including STS flight control room operations, launch operations, and mission operations ground data systems.

The demonstrations will be designed to validate intelligent control operations of single subsystems in 1988, intelligent, coordinated control of several subsystems in 1990, intelligent, hierarchical control in 1993, and intelligent control of several distributed subsystems in 1996. The prototype tests and demonstrations identified in the previous paragraph will exercise required technical capabilities in all technology areas and their elements, i.e., in task planning and reasoning, control execution, operator interface, and systems architecture and integration.

The System Autonomy Technology Program is managed by the Chief of the Information Sciences Division at ARC. He interfaces operationally directly with the Director of the Information Sciences and Human Factors Division at NASA/HQ. The Program Manager is Chairman of the Systems Autonomy Intercenter Working Group which has a representative from each NASA Center and advises on program plans and implementation.

The following table gives the funding resources for SATP.

SYSTEMS AUTONOMY PROGRAM FUNDING (NET $K)

	FISCAL YEAR				
	88	89	90	91	92
CORE TECHNOLOGY	6366	6948	7643	7900	8533
DEMONSTRATION PROJECTS	4763	4700	4280	4300	3850
SATP TOTAL	11129	11648	11923	12200	12383

1. INTRODUCTION

Striking changes have occurred in the way we monitor, control, and operate modern systems of all types. For example, aircraft and spacecraft once had a much higher human-to-machine functional ratio than exists today. In the past, individual subsystems were monitored and controlled by operators linked to a supervisor or operations director. Today, the decision speed and complexity of many systems calls for a new approach based on computer and software technology. Machines equipped with artificial intelligence will be developed to perform autonomously many of the functions previously done by human operators (Fig.1). Some people will still be in the loop, but their actions are oversight control and functional mode selection.

In recognition of the requirement for increased developments toward automated systems, and in particular intelligent autonomous systems, the National Aeronautics and Space Administration (NASA) has taken steps to provide the means and develop the necessary technologies for applications in space missions. NASA's Office of Aeronautics and Space Technology (OAST) has decided to implement through the Ames Research Center (ARC) a System Autonomy Technology Program that will sponsor and significantly advance the required technologies and in-house capabilities for transfer and integration into space system operations.

1.1. Document Purpose and Scope

The purpose of this document is to establish a framework and guidelines for the definition and implementation of specific research, development, and technology demonstration work at ARC and other NASA Centers in areas pertaining to system autonomy and autonomous systems. The specific objective is to present a NASA Systems Autonomy Technology Program (SATP) Plan with a horizon of approximately ten years, i.e., FY 1987 through FY 1996. As much as possible, the plan is based on the requirements of NASA missions projected to the end of this century and beyond. It also takes into account related technology programs for leverage, notably those sponsored by DOD.

The scope of this document covers broad policies and procedures for managing the System Autonomy Technology Program. It establishes a framework for resource deployments within NASA based on specific technical, management, procurement, and schedule considerations for basic research, technology developments, integrated technical demonstrations, and testing. Specifically, this SATP Plan:

a. Establishes program goals and objectives,
b. Describes the overall approach to implementation,
c. Establishes organizational relationships,
d. Identifies program resources by fiscal year,
e. Establishes major program milestones through 1996,
f. Defines the program-level management approach, and
g. Establishes program management control mechanisms.

HOW TIMES CHANGE

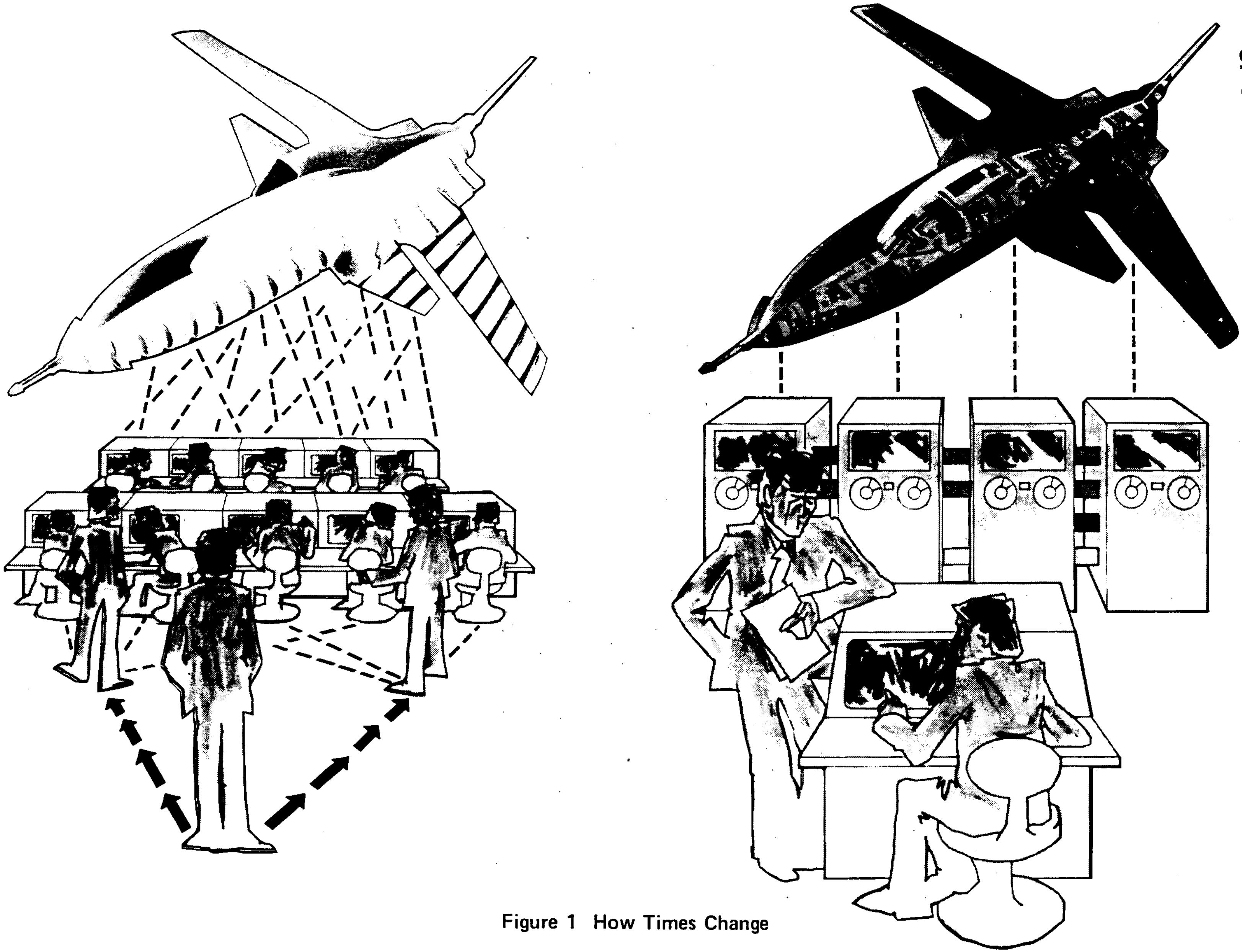

Figure 1 How Times Change

This SATP Plan also includes specific plans for the core research and demonstration projects which are implemented at various NASA Centers. These plans provide detailed visibility and traceability of accomplishments and resource expenditures.

1.2. Program Goal and Objectives

The overall goal of the SATP is the development of intelligent, autonomous system technologies that will enable the successful accomplishment of the national space challenges such as a permanent presence in space, a lunar outpost, and the exploration of Mars (Figs.2 and 3). The scope of this goal requires an Agency-wide effort involving all NASA Centers to establish and maintain NASA as a leader in intelligent autonomous systems for space applications . In the context of such NASA programs, intelligent autonomous systems will contribute to significant payoffs in terms of increasing mission effectiveness, productivity, and success probability, and of reducing mission operation costs.

The objectives of the SATP are: (1) significantly advance technologies for intelligent autonomous systems; (2) demonstrate, evaluate, and validate technologies in operational environments; and (3) develop and maintain NASA world-class in-house capability in technical expertise and facilities (Fig.4).

1.3. Program Approach and Elements

The SATP concept includes two major program elements, namely core technology research and system autonomy demonstration projects as depicted in Fig.5. The demonstration projects give focus to the technology developments. The products of the core technology research feed into the definition of the technology demonstration projects, where the developed techniques are tested and validated. The Program provides to NASA an in-house capability of technical expertise, facilities, and tools.

The technical scope of the SATP comprises systems autonomy at various hierachical levels including the automation of the corresponding supervisory systems, the interface systems, the man-machine interface technologies, and the behaviour of humans within man-machine systems. The Program is concerned with the system design and production phases, as well as with the system operation phases. The technology areas identified for research, development, and demonstration are the "core technologies" and are designated as <u>task planning and reasoning, operator interface, sensing and perception, control execution, and system architecture and integration.</u> The core technologies feed into two demonstration programs, namely <u>system autonomy</u> and <u>telerobotics</u> which in turn enable a broad spectrum of target capabilities germain to a wide variety of applications in space systems. Peripheral technologies, such as power, propulsion, materials, structures, etc., are here of concern only to the degree to which they influence the automation and autonomy characteristics of the operational systems.

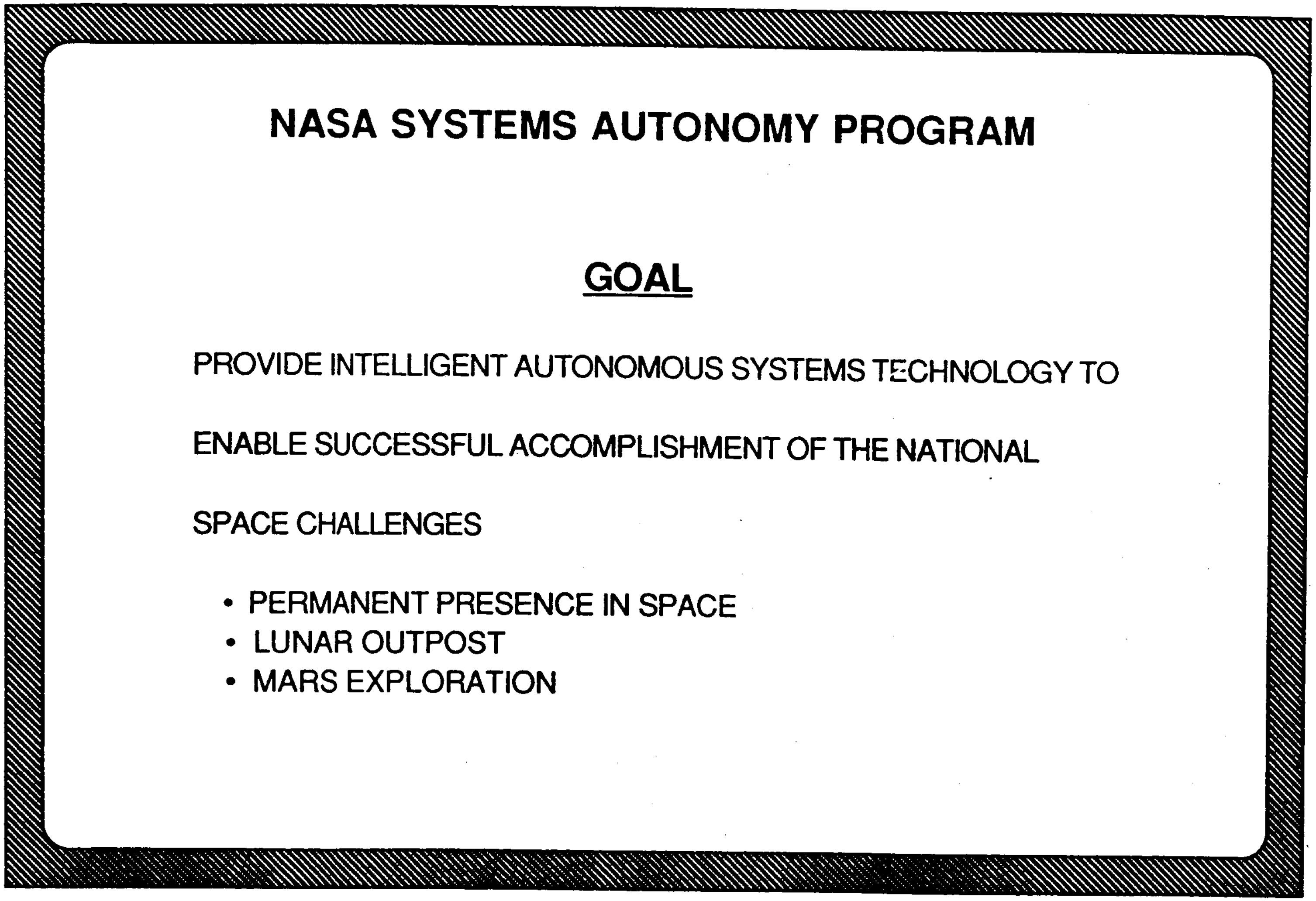

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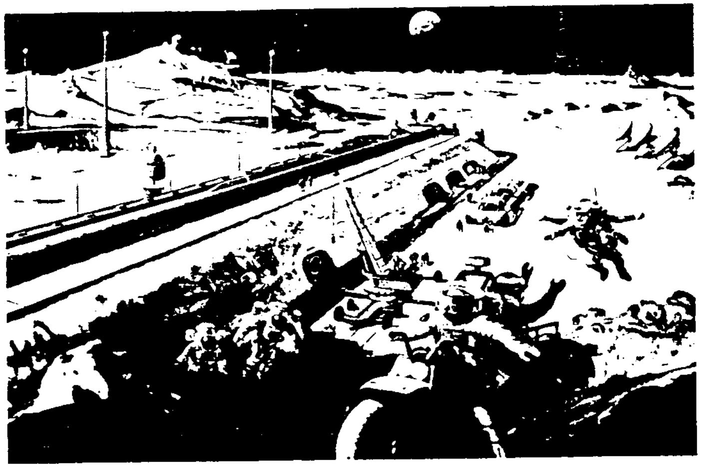
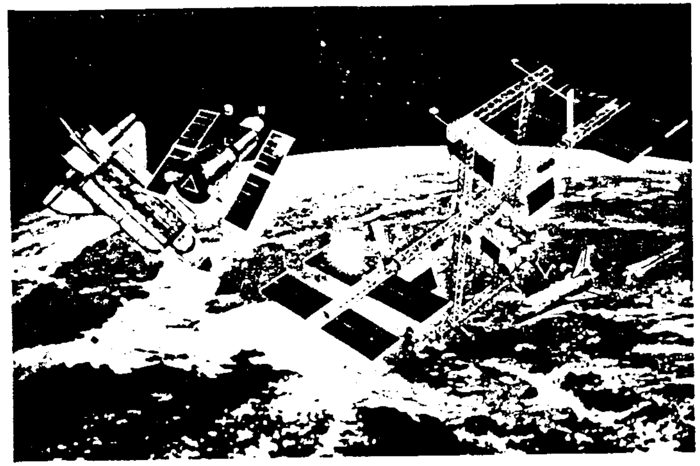
Figure 2 - Systems Autonomy Program Goal.

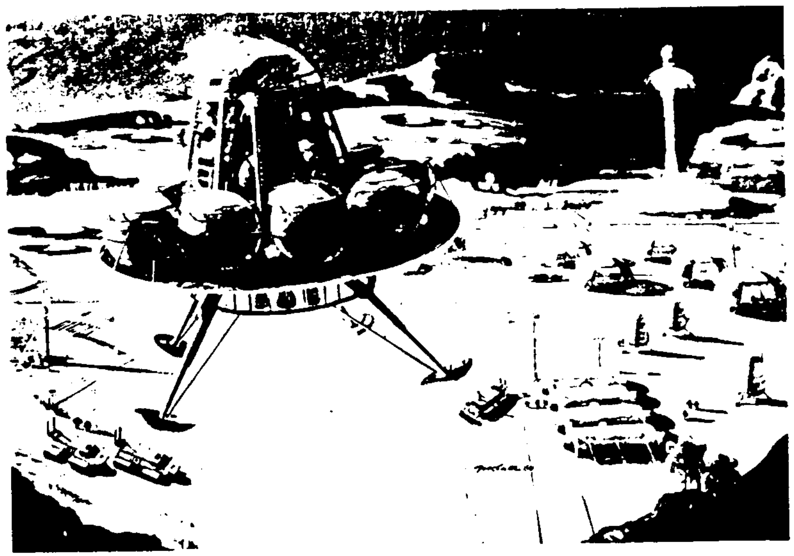
THE NATIONAL SPACE CHALLENGES



LUNAR OUTPOST



PERMANENT PRESENCE IN SPACE



MARS EXPLORATION

Figure 3 - National Space Challenges.

SYSTEMS AUTONOMY PROGRAM

OBJECTIVES

- SIGNIFICANTLY ADVANCE TECHNOLOGIES FOR COOPERATING INTELLIGENT AUTONOMOUS SYSTEMS
- DEMONSTRATE, EVALUATE, AND VALIDATE TECHNOLOGIES IN OPERATIONAL ENVIRONMENTS
- DEVELOP AND MAINTAIN NASA WORLD-CLASS IN-HOUSE CAPABILITY
  - TECHNICAL EXPERTISE
  - FACILITIES AND "TOOLS"

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Figure 4 - Systems Autonomy Program Objectives

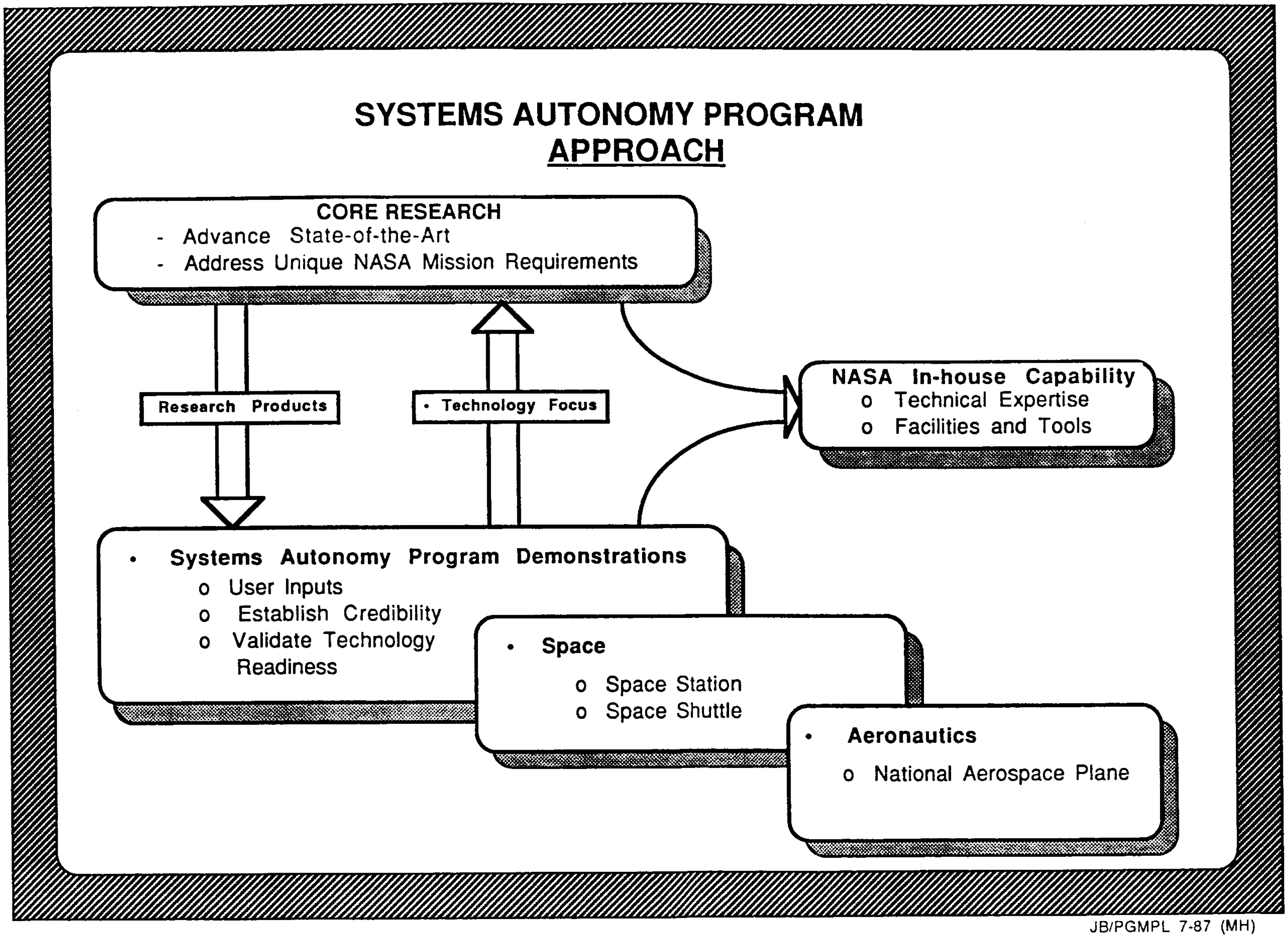

Figure 5 - Systems Autonomy Program Approach

This SATP Plan is primarily concerned with system autonomy demonstrations and the corresponding supporting core technologies managed by the NASA Ames Research Center. The telerobotics demonstrations and related core technologies managed by the Jet Propulsion Laboratory are not part of this Plan. Nevertheless, in view of an anticipated (necessary) merger of these two programs in the future, the discussions on autonomous system characteristics, space applications, and target capabilities in the following two chapters take an integrated point of view.

1.4. Program Background and Need

System autonomy research and development at NASA/OAST are the result of several years of study, planning, and advocacy. This resulted in a number of related technical study reports, e.g. Refs. 1 and 2, which concluded that the adoption of automation technology can, to an appreciable degree, increase the effectiveness and productivity of the development and operation of NASA-sponsored systems and missions. The potential benefits in terms of increased capability, reliability, efficiency, and cost savings for operational systems in space or on the ground gave impetus to a research and development program for related technologies. Recently, however additional strong motivations were stimulated by the report and recommendations to Congress of the Advanced Technology Advisory Committee (ATAC) which stated: "The development of the Space Station offers a chance both to advance the technology of automation and robotics as proposed by Congress and to put that technology to use. The use of advanced automation and robotics technology in the Space Station would greatly enhance its capabilities. And the Space Station would thereby provide a logical driving force for a new generation of machine intelligence, robotics, computer science, and microelectronics" (Ref.3). Of course, NASA's needs for automation and robotics are not limited to Space Station applications. They extend to the space program as a whole, and the recommendations by ATAC are here considered applicable to the entire space program.

For example, needs for system autonomy became especially evident for deep space exploration missions with long communication distances. The signal delay times, ranging between seconds to the moon and hours to the outer planets, require that the spacecraft be capable of managing its affairs autonomously at least for the signal's round-trip time. At the existing state of technology, this requires that the spacecraft be preprogrammed in advance for all its actions. In the space program, it has only recently become practically possible to cope with some unforeseen situations in which the spacecraft had to make limited autonomous diagnostic decisions on its own. This was feasible through the application of advanced automation technologies including artificial intelligence techniques (Ref.4).

The ATAC also recommended that the various versions of the Space Station should incorporate, to the degree permitted by time and resources, significant elements of automation and robotics technology through designs which allow for expansion and evolution. The verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for space use. Satellites and their payloads accessible from the Space Station should be designed, as far as possible, to be serviced and repaired by robots. Maximum use should be made of technology developed for industry and Government, and a vigorous program of technology transfer to U.S. industries and development communities should be pursued.

2. AUTONOMOUS SYSTEM CHARACTERISTICS

2.1. Operational Characteristics

The effect of introducing system autonomy through AI is to remove entirely or partially the human element from the control loops of the system, thus achieving autonomous or semiautonomous operations, respectively. The state of current technology in AI is such that it might be possible to delegate complete autonomy to relatively simple, well-defined subsystems, but not to systems of appreciable complexity. One expects therefore, for the foreseeable future, to be faced with the design, development and operation of systems which function in a man-machine symbiotic, semiautonomous mode. In this mode, humans will make the high-level decisions and will, at times, also be able to engage in low-level control processes, if required. The computer, on the other hand, will evolve by virtue of new developments to higher levels of intelligent capabilities, Fig.6. It will take over those decision and control functions which will be enabled by available and validated AI technology. These systems are then operated in the so-called supervisory mode.

The concept of system autonomy as used here implies independence from the outside world in terms of problem solving and decision making, i.e., perception, planning, diagnosis, activation, etc. The systems under consideration are autonomous with respect to detailed human information input, but not necessarily with respect to information output and energy or material exchanges. For example, a space station, with or without astronauts on board, is in an autonomous state while there is no communication to the space station, although communication from the space station may occur at any time. The same holds for unmanned spacecraft. Similarly, a subsystem on the Space Station is autonomous, if it does not receive messages from the astronauts or other subsystems, although it sends messages out. At lower levels in the system hierarchy, a component system is autonomous, if it does not receive messages from other components or subsystems, although it sends messages out. Current technology does not allow the construction of completely autonomous systems; and in most cases, it would for various economic or complexity reasons not even be desirable. The concern here is therefore primarily with semiautonomous systems which receive at least some control information from humans or other systems. The degree of systems autonomy is thus a function of the characteristics of the required control inputs - their information content, their frequency, etc.

Hence, autonomous systems, as envisioned in this Program Plan, are artificially created operational systems which are able for extended periods of time to govern themselves and make their own decisions in accomplishing given objectives. These capabilities derive from their ability to reason based on information acquired from other systems and/or sensory inputs, make reliable decisions in uncertain environments, learn from experience, and resolve human induced errors (Fig.7). In accomplishing the given objectives, the systems manage their resources and maintain their

THE EVOLUTION OF MACHINES THAT THINK

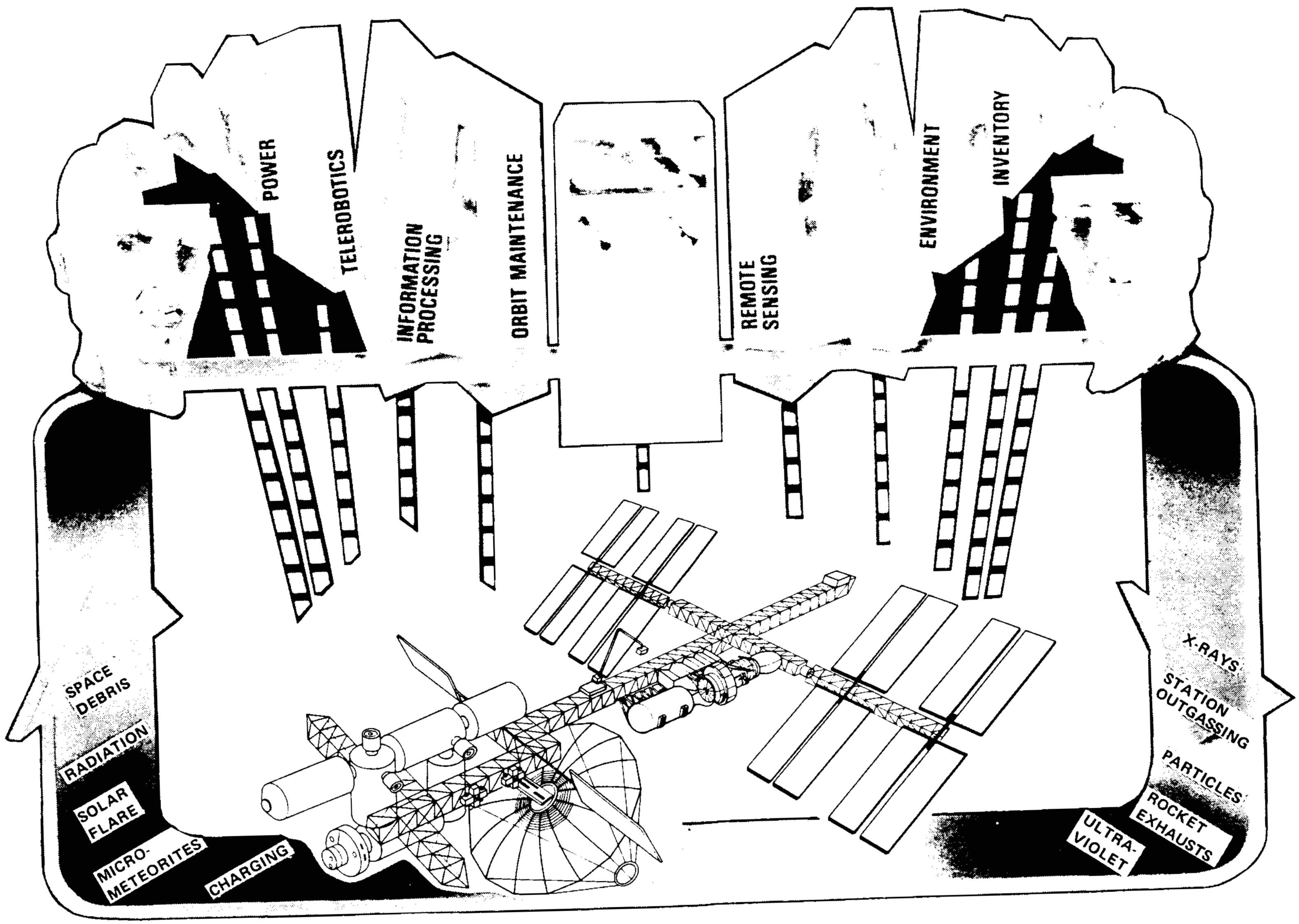

Figure 6 The Evolution of Machines That Think

CHARACTERISTICS OF INTELLIGENT AUTONOMOUS SYSTEMS

- ***KNOWLEDGE-BASED SYSTEMS***
  - o DYNAMIC WORLD KNOWLEDGE ACQUISITION AND UNDERSTANDING
  - o RELIABLE DECISIONS IN UNCERTAIN ENVIRONMENTS
  - o LEARNING CAPABILITY
- ***COMMUNICATE AT HIGH LEVELS***
  - o WITH HUMANS
  - o WITH OTHER INTELLIGENT MACHINES
- ***RECOGNIZE AND RESOLVE HUMAN-INDUCED ERRORS***
- ***OPERATE AUTONOMOUSLY FOR EXTENDED PERIODS OF TIME***

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Figure 7 - Characteristics of Intelligent Autonomous Systems

integrity. At the highest level of abstraction, an operating autonomous system consists of four elements:

(1) Sensing and Perception System - The sensor system acquires data and information about the internal state of the autonomous system, about its environment, and about its relationship to its environment. The data and information are packaged into symbolic descriptions or their constituent parts.

(2) Database System - The database of the autonomous system includes all data, information and knowledge necessary to plan system actions, perform diagnoses, and simulate system performance. The database contains factual and heuristic information such as CAD/CAM data, system configuration data, dynamic environmental data from sensory inputs, heuristic rules, and general declarative and procedural knowledge.

(3) Control Computer System - Based on newly acquired data through sensory inputs and/or database and knowledge base search, the control computer system assesses the current state of the autonomous system with respect to the desired goal state, continuously updates the database and existing plans, and performs a planning process which results in a set of decisions for immediate and/or future actions, for control, and for recovery from errors and faults.

(4) Actuator System - The implementation of the decisions prepared by the control computer system is carried out by the actuator system, resulting in sensible and measurable effects within prescribed and controlled operational limits.

The ultimate setting of goals for, and supervision of, autonomous systems is done by humans. For simple systems this may be done directly by setting a switch or the like. For complex systems, such as an autonomous robot vehicle, the goal setting and supervision may be done by a team of operators with the help of an off-line or integrated computer system. The human operator(s), together with the supporting computer system and other peripheral equipment, are collectively referred to as the "supervisory system". In general, one is dealing with a hierarchy of autonomous systems, where the higher level (echelon) elements are the supervisors of collections of elements at the next lower level. By extension, at the highest level in the hierarchy is (are) the human operator(s). If there are many human operators, as is the case, for example, in ground-based mission operations, they too will be organized into a suitable hierarchical organization, where the lowest level, the operator level, is usually at the machine interface.

2.2. System Functional Architecture

System autonomy for space systems is additive in the sense that as the technology advances, more autonomous capabilities can be incorporated into the system, provided the system has been designed accordingly. This implies a possible evolutionary development for the space system, where a manually operated system evolves into a highly autonomous system in time. The modular architecture postulated below will support such evolutionary developments, because of the built-in capability to exchange functional modules at any level and at any time. An example of such intelligent autonomous systems may be the Space Station including auxiliary subsystems, or it may be a free flying service robot with manipulators and propulsion units. It may also be an intelligent controller for a specific subsystem or a collection of subsystems, or it may be an expert system that advises human operators on the ground or astronauts in space about decisions of planning, diagnosis and other functions.

In order to establish a coherent framework that aids in the identification and definition of the technical areas, it is convenient to use a system architecture which displays the major subsystem functional blocks and their interrelations. To conduct a generally valid discussion, a paradigm of a functional architecture is used that shows subsystem modules and information flows and captures general, but essentially characteristic, aspects of a representative intelligent, autonomous system as shown in Fig.8. Note that while the system excludes the human operator and the outside world, both are, nevertheless, a major consideration in determining technology requirements and system capabilities.

At this level of abstraction, it is possible to depict a hierarchical system architecture and integration scheme of parallel information processing subsystems which work concurrently and asynchronously on different aspects of the overall task assigned to the intelligent autonomous system. These subsystems communicate the appropriate results, at the appropriate time, to those subsystems which are in need of these data to perform their functions. Note that at this level the human operator is part of the control loop and represents the decision making element at the highest level. There are provisions envisioned (not shown in Fig.8) for the operator to have direct access through the operator interface to all subsystems at lower levels in the hierarchy in task planning and reasoning, in control execution and in sensing and perception. This enables the operator to work directly with each individual subsystem, or groups of subsystems, to perform local manual control, diagnosis, debugging, and the like.

During system operations, the operator obtains and maintains, by virtue of displayed perceptor and modeling information and his own a priori knowledge, a more or less representative model of the external and internal world in his head. When the need arises, he decides in broad terms what tasks should be accomplished, and what "intelligent autonomous system" has the appropriate capabilities. The operator then formulates a high-level implementation strategy taking into account overall system capabilities, resources and time constraints. Using a high-level language, the strategy will be transmitted to the controls module and will then be automatically converted into a task description for the planner. Calling upon the knowledge base, for detailed planning data (world state data), the planner prepares a detailed implementation plan for the system. Before execution, the plan is usually sent to the simulator for checkout and validation by the operator via displays. In this process, the simulator uses world state information from, and may make corrective changes to, the knowledge base. After validation, the plan is sent to the executor, where detailed command sequences are prepared and sent to control execution. The actuators then perform the planned actions on the system itself or on the outside world. The perceptor subsystem consisting of various different sensors and associated data interpretation computers, observes the task implementation process and sends the appropriate state observables to the monitor subsystem. Here, the actual observables are selected and sent via the simulator to the displays, and actual world states are identified and sent to the knowledge base for updating. Also, the monitor makes a comparison with the expected states from the simulator. For minor performance deviations due to drifts, uncertainties, etc., the monitor will send vernier control information to the executor for corrective action. Information on faulty behaviour, on the other hand, will be sent to the diagnoser, where the anomalies and their causes will be deduced and corrective task descriptions will be prepared, both with the help of data from the knowledge base. The resulting world states will be used to update the knowledge base, and the corrective task descriptions will be sent to the planning subsystem, thus initiating a new process cycle.

As has been indicated above, the content of the knowledge base is subject to continuous change due to various updates before and during system operation. This ensures that at all times current data and the correct representations about the physical, environmental and operational characteristics of the system are in the knowledge base. It follows that the development of a reliable, updatable knowledge base is crucial for intelligent autonomous systems.

During operation of the system, the most important information for the knowledge base update comes from the ever changing environment via the sensing and perception subsystem. The perceptor subsystem receives inputs from a real and fuzzy external environment and from a relatively well-structured internal world, namely the system itself. The word 'perceptor' is to be viewed here in a broad sense, i.e., it includes all sensors required to operate the system effectively. The main task for the perceptor is to package the sensory information into prototype images or simple symbolic descriptions of such images or their constituent parts and send them to the monitor. Again, by image we mean a representation based on any one or several sensory modalities. An important feature of this architecture is that the perceptor passes on information to the knowledge base and the operator, and the knowledge base and/or operator can also control the perceptor by recognizing a need and by initiating the corresponding effector action through the planner and executor. A typical example is when the system's knowledge base recognizes that a greater resolution of the image is necessary and effects a readjustment of the focusing mechanism.

Another source of knowledge base update is the diagnoser. After a fault has been diagnosed, the system must be restored to an operating state which will preserve/protect its output to the best extent possible with the least deleterious effect on its integrity, reliability, and operating lifetime. Otherwise, the system will work at a degraded condition which requires a corresponding update of the knowledge base by sensed and/or inferred information. A third source for knowledge base update is the simulator, which may cause corrections to the information as a result of the validation process. And finally, the operator is able to make knowledge base changes as required by high-level strategic decisions.

The system architecture in Fig.8, does not take into consideration that for space missions, one often deals with two systems separated by a communication link. First, there is the proximal control system or ground-based operations center which usually includes the human operator(s), the operator interfaces, the operations simulator and perhaps a portion of the knowledge base. Second, there is the remote system in space including everything else. In many cases it does not matter, from an information handling point of view, whether the task planning and reasoning abilities reside in the proximal or in the remote system, or are distributed in both. It seems that when the communication delay time is small compared to the allowable time for action at the remote site, most of the intelligence, at least the higher-level intelligence, may be kept in the proximal system. How the system's intelligence should be distributed in such subdivided systems is still an open and vexing research question. Its solution is expected to have considerable influence on approaches to system architecture and integration. For example, it might prove appropriate to duplicate certain units, such as the knowledge base, at both ends of the overall control loop. It is expected that future technology demonstrations will shed light on some of these questions.

At the next and lower levels of abstraction within each subsystem of the intelligent autonomous system shown in Fig.8, the architectures may be combinations of parallel and hierarchical structures. Presently, it is envisioned that the modules within the subsystems are a reflection of the major operational functions of the space system, such as navigation, position control, power management, etc., and that these modules will be able to communicate with one another and with a coordination and decision making element (e.g., subsystem executive) at the next higher level in the hierarchy.

INTELLIGENT AUTONOMOUS SYSTEM ARCHITECTURE

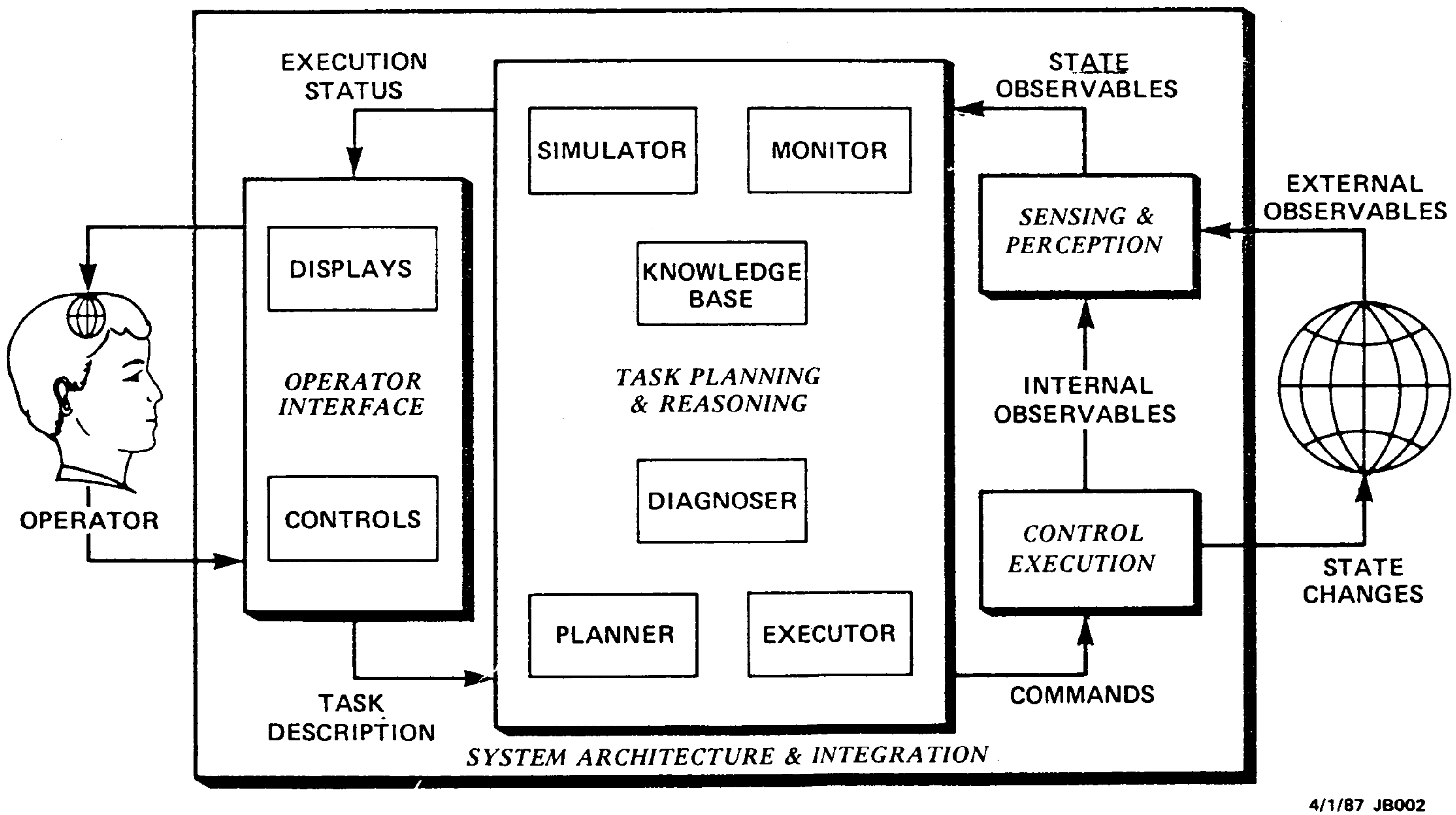

Figure 8 - Intelligent, Autonomous System Architecture.

3. SPACE APPLICATIONS AND TARGET CAPABILITIES

The effective development and demonstration of technology for autonomous systems are profoundly dependent on the context of the prospective applications. For example, system autonomy may be, and already is extensively being, incorporated by industry in CAD/CAM/CAE facilities to provide intelligent aides in the form of expert systems. These developments support not only the commercial sector, but also contribute directly to the design, manufacture, and test capabilities for space systems. These application contexts will therefore not be of primary concern in the definition of this SATP. The emphasis in this program is on the operational aspects of space systems and missions, where intelligent aides in the form of expert diagnosers, planners, simulators, etc., will be used by human operators, or where such, or similarly intelligent, systems will be used as parts of an intelligent autonomous system, such as an autonomous free-flying robot, an autonomous space platform, or a major autonomous subsystem of the Space Station. Below, brief statements for major potential application areas are given for orientation.

3.1. Ground-Based Applications

Major mission developmental and operational applications of autonomous systems on the ground are expected to be in the form of expert planning, monitoring, diagnostic, control and simulation systems in support of ground based responsibilities such as:

(1) Launch operations at KSC,
(2) Space Station and STS operations at JSC,
(3) Command/Control at GSFC for Earth orbital spacecraft,
(4) Mission control at JPL for deep space missions,
(5) Propulsion systems testing and space laboratory systems at MSFC.

3.2. Space-Based Applications

Autonomous systems in space may be auxiliary subsystems of major system complexes, or they may function as the major constituent of an autonomous robot, such as in:

(1) Space Shuttle applications as knowledge-based systems support for astronauts in the control of the Shuttle, the Shuttle manipulator, and other operational equipment.

(2) Space Station applications as knowledge-based systems support for astronauts in the control of the Space Station, associated IVA equipment, and auxiliary EVA space vehicles.

(3) Autonomous robot applications, including sensors, actuators, and control computers as orbiting maneuvering vehicles and other free flyers for in-orbit operations.

(4) Deep Space applications of autonomous robots functioning as planetary fly-bys, orbiters, planetary surface explorers, and the like.

Some specific benefits expected from applying intelligent autonomous systems in the space program are summarized in the following statements. Intelligent autonomous systems will contribute to:

(1) Reduce the work load for users and operators of ground-based systems (e.g., documentation, maintenance, management);

(2) Limit the amount of required communication with remote systems (e.g., because of planetary occultation, two-way light time, chance of detection);

(3) Compensate for technical limitations of communications with remote systems (e.g., limited bandwidth, error rate, response time of equipment);

(4) Sustain reliable performance of ground-based and remote systems (e.g., fault tolerance, self maintenance).

These benefits include both technical and economical components. The primarily technical components aim at system or mission enablement, while the primarily economical components focus on cost effectiveness.

3.3. Broader Opportunities

The technologies developed for autonomous systems will have potential applications in the automation of manufacturing processes, nuclear plant operations, underground mining, and undersea work. In addition, autonomous systems will find extensive applications in a variety of military operations.

3.4. Required Target Capabilities

In reviewing a comprehensive set of goals and mission objectives in the space program, one can identify a spectrum of functions that require, or may benefit from, system autonomy and, hence, from artificial intelligence technology. The assumption here is that before such technologies are available, these functions will either not be performed because of their difficulty, or they will be accomplished in a manual mode to the degree possible with only little or no assistance from system autonomy. It is further assumed that by virtue of developing technologies during the planning period of this Plan, the corresponding functional arrangements will be able to evolve from such initial circumstances into intelligent autonomous systems.

The projected applications of autonomous systems require a dedicated effort of technology development and a well-implemented plan for technology testing and demonstrating. The technology developments and demonstrations are planned to achieve certain target capabilities which are necessary to insure that progressively more capable space systems can be designed. The following target capabilities are representative of the major technology drivers in this program. The corresponding technologies are expected to be available within the current planning horizon of about ten years, and the plan outline for their development is presented in Chapters 5 and 6 of this document.

3.4.1. Goal-Oriented Behavior

Intelligent autonomous systems operating in space or on the ground are able to arrange their activities and allocate their resources in order to achieve prescribed goals. The goals are communicated to the systems at correspondingly high levels by human operators or by other systems that are placed higher in the control hierarchy. In turn, the systems communicate back at compatible levels to these agents about their states and operations. In striving toward the given goals, the systems must cope with new and unanticipated situations. They must be able to accept dynamically changing data from sensors and perceptors and accordingly develop new operation plans; they must replan existing strategies automatically to accommodate new objectives and uncertain environmental changes.

3.4.2. Self Maintenance

Intelligent autonomous systems operating in space and on the ground must be able to maintain themselves in working condition, so that their stated goals can be achieved. A primary attribute of these systems is their ability to recognize and resolve human-induced errors, faulty commands, unrealistic goal statements, etc. In addition, intelligent autonomous systems monitor themselves, detect and identify faults to the subsystem and component levels, and diagnose the faulty state with respect to the mission objectives. The corresponding status monitoring data is collected routinely for telemetry and crew display. Maintenance actions and periodic calibration of subsystems and components are done routinely. Faults at the system and subsystem levels are diagnosed from available sensor data, and relevant details are displayed to the human operators. Strategies for self recovery and/or self repair are then planned automatically or by the human operators with the help of associated expert systems.

3.4.3. Information Extraction and Interpretation

Services and science missions require a tremendous capability to handle and interpret sensory data. Autonomous systems based on artificial intelligence techniques must be able to perform automatic scene analysis and recognition, pattern recognition and identification, and contextual data interpretation. Data from several sensory modalities must be integrated and interpreted in the context of overall system functions and packaged for diagnostic and operations planning purposes.

3.4.4. Servicing and Repair

Servicing and repair of satellites, spacecraft, and space stations require remotely operated or autonomous robots to accomplish the required tasks. Such robots require autonomous handling and manipulative capabilities to perform module exchanges, test operations, and act with the required dexterity. For these autonomous operations, the target capabilities under 3.4.1. to 3.4.3. are a prerequisite.

3.4.5. In-space Assembly

The in-space assembly of large space systems, such as space stations or large antennas, generally requires multiple robots working in a coordinated and cooperative process to accomplish necessary construction. This requires advanced artificial intelligence and systems integration techniques which build on the target capabilities identified in 3.4.1. to 3.4.4.

3.5. Technological Challenges

The target capabilities of greatest and most urgent concern in the SATP Plan are goal-oriented behaviour and self maintenance. These capabilities are extensions (although, in some cases large extensions) of current knowledge-based systems. The technologies of knowledge-based systems provide the foundation for future intelligent autonomous systems which also include sensor and perceptor units and control execution units as implied by the target capabilities identified in 3.4.4. to 3.4.5.

The development of systems with capabilities of goal-oriented behaviour and self maintenance represents considerable technological challenges. These are primarily in artificial intelligence related areas and include such items as real-time knowledge-based systems, dynamic knowledge acquisition, robust planning and reasoning, cooperating knowledge-based systems, and validation methodologies. Fig.9 summarizes for each of these areas some indicators of the current state of technology and of anticipated future achievements.

It must be noted that the level of competency on the part of the intelligent, autonomous system to perform the above target capabilities or to meet any or all of the more detailed challenges in Fig.9 has not been specified. All that has been given are general technical goal and trend statements in more or less overlapping areas based on heuristic judgements by experts in the field. It is difficult if not impossible to establish, at this time, criteria that would provide a general yardstick for measuring the degree of proficiency at which a target function can be executed by autonomous capabilities. The development of such measures is strongly dependent on the application contexts. It is part of each specific research area and must be derived in conjunction with postulated and verified technology capabilities during laboratory testing and technology demonstrations.

SYSTEMS AUTONOMY PROGRAM
WHERE WE ARE TODAY

REAL-TIME KNOWLEDGE-BASED SYSTEMS

- NO PARALLEL SYMBOLIC-NUMERIC PROCESSORS
- SLOW SPECIAL PURPOSE HARDWARE (1 GBYTE MEM, 5 MIPS)
- PROTOTYPING SW SHELLS (ART, KEE, KNOWLEDGECRAFT)
- DIAGNOSIS AND PLANNING DECISIONS IN 1-10 MINUTES

DYNAMIC KNOWLEDGE-ACQUISITION

- NO AUTOMATED EXPANSION OF K-B
- SMALL STATIC PRE-PROGRAMMED K-B
- DEC "XCON" LARGEST (5000 RULES, 2000 COMPONENTS)

ROBUST PLANNING AND REASONING

- HEURISTIC RULES ONLY, SHALLOW CAUSAL MODELS
- PRE-MISSION PLANNING (NO REAL-TIME REPLANNING)
- DIAGNOSIS OF ONLY ANTICIPATED SINGLE FAULTS
- "FRAGILE" NARROW DOMAINS (RAPID BREAKDOWN AT K-B LIMITS)
- EXAMPLES: WESTINGHOUSE "ISIS" FACTORY RESOURCE ALLOCATION AND JPL "DIVISOR" SPACECRAFT PROCEDURE SEQUENCER

COOPERATING KNOWLEDGE-BASED SYSTEMS

- SINGLE STANDALONE DOMAIN SPECIFIC SYSTEMS
- HUMAN INTERACTION ONLY, NO INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES

- CONVENTIONAL TECHNIQUES FOR ALGORITHMIC SYSTEMS

Figure 9a - Technology Challenges, Where We Are Today.

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SYSTEMS AUTONOMY PROGRAM

WHERE WE NEED TO GO

REAL-TIME KNOWLEDGE-BASED SYSTEMS

- PARALLEL SYMBOLIC-NUMERIC PROCESSORS (100 GBYTES, 500 MIPS)
- NEURAL NETWORKS (BRAIN CELL EMULATION)
- LAYERED TRANSPARENT SW
- DIAGNOSIS AND PLANNING IN MILLISECONDS

DYNAMIC KNOWLEDGE ACQUISITION

- AUTOMATED K-B EXPANSION IN REAL-TIME (LEARNING)
- LARGE DYNAMIC DISTRIBUTED K-B

ROBUST PLANNING AND REASONING

- COMBINED HEURISTIC RULES AND CAUSAL MODELS
- REAL-TIME CONTINGENCY REPLANNING
- DIAGNOSIS OF UNANTICIPATED FAULTS
- SPECIFIC DOMAINS ON BROAD GENERIC K-B (GRACEFUL DEGRADATION)

COOPERATING KNOWLEDGE-BASED SYSTEMS

- HIERARCHICAL AND DISTRIBUTED SYSTEMS
- HUMAN AND INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES

- METHODOLOGY FOR EVALUATING DECISION QUALITY
- FORMAL THEORETICAL FOUNDATION

JB/SAP 5-87 (MH)

Figure 9b - Technology Challenges, Where We Need To Go.

4. TECHNOLOGY AREAS

Research and developments in critical technology areas will achieve the target capabilities and meet the technology challenges identified in the previous chapter. Some of these areas are already part of the existing NASA Program and others will be initiated. The critical technologies identified and described in this chapter take into account the present state of technology, the projected needs in space missions, currently available talents in research and development, organizational factors and system architectural considerations.

4.1. Critical Technologies

Technologies for system autonomy, funded by NASA during the last decade, have not yet led to generally applicable capabilities. In this subsection, a high-level description of the most critical system autonomy technologies is given, portraying a functional point of view and identifying the state of these and related techniques in the context of technology developments, demonstrations, and space mission applications. The technology developments and demonstrations focus initially on the target capabilities of goal-oriented behaviour and self maintenance, where first knowledge-based systems for planning and diagnosis in various application contexts are considered. Later, sensory information extraction and interpretation will gradually be incorporated to arrive eventually at an autonomous capability for servicing, repair, and assembly.

Accordingly, it is envisioned that space system autonomy will evolve from relatively simple to advanced capabilities in several technology development steps, and that the associated system architectures will be designed to accommodate a stepwise progression of ever more capable autonomous systems. The general architecture described in Chapter 2 and the technology challenges in Chapter 3 imply the development of a broad spectrum of required technical advances in artificial intelligence that are not within immediate reach. Considering existing limitations on related technology development resources, one must make choices regarding those technical areas with the highest priority to accomplish most significant overall progress toward space system autonomy. These requirements have implications not only at the system and subsystem level, but also at lower levels and at all interfaces.

4.1.1. Task Planning and Reasoning

The critical technologies in the task planning and reasoning area are primarily related to four subsystems in Fig.8, namely the planner, the simulator, the diagnoser and the system knowledge base. The technologies for the monitor and executor subsystems appear to be sufficiently well in-hand to satisfy space system requirements. The research and developments in planning and reasoning concentrate primarily on issues of artificial intelligence.

4.1.1.1. Reasoning under Uncertainty

Unreliable data or knowledge in the systems knowledge base has numerous origins. In building the knowledge base originally, all of the data may not be available, some may be suspect, and some of the knowledge for interpreting the data may be unreliable. Inputs from human operators during operation may contain errors, and sensory inputs and their interpretations about the environment and/or about the state of the system itself may be inaccurate, spotty, and fragmentary. The problem of reasoning with and drawing inferences from uncertain or incomplete data has led to a variety of technical approaches to its solution. For example, one of the simplest approaches has been used in MYCIN by using so-called certainty factors to indicate the strength of a heuristic rule. MYCIN, an expert system for selecting antibiotic therapy for bacteremia, is probably the most elaborate and most advanced of the existing knowledge-based systems. Other more elaborate approaches are based on Bayes' Rule, fuzzy logic, belief-revision systems, data correction rules, etc. Little agreement exists today on the utility of any of these approaches for intelligent autonomous systems in the space arena. Much of the future work will necessarily be exploratory research to determine which technique or combination of techniques proves most appropriate.

4.1.1.2. Learning

To develop computer systems that could learn has been a goal since the early beginnings of AI research. Perhaps the best definition of learning in the context of intelligent autonomous systems has been stated by Herbert Simon as "any process by which a system improves its performance." This definition includes such notions as the acquisition of explicit knowledge, the acquisition of skills, theory formation, hypothesis formation, and inductive inference. Today, a prevailing view about learning is that a system can only be expected to learn high-level concepts, and thus autonomously improve its performance, if it has at least some knowledge about the domain of discourse, i.e., a knowledge base forms the basis for discovering high-level concepts. Hence, for the system knowledge base, the initial content and the associated representational forms are particularly important design considerations which aim at expressiveness, ease of inference, modifiability, and extendability. The initial content of the knowledge base will be improved and extended in the learning process, when the system interacts with human operators and/or with the environment. The quality of information input has a major effect on the difficulty of the learning process. Similarly, the level, or the degree of generality, of the information provided by the environment and/or the human operators determines the kinds of hypotheses that the system must generate. Since all the related technical areas are still basic research topics at university laboratories, it is not expected that a practically applicable learning system will soon be available.

4.1.1.3. Causal Modeling

The operation of a complex autonomous system in space, (for example a Mars rover, a free-flyer robot, etc.) will occasionally be subject to major redirection of its planned activities. Before making a commitment and sending the commands for such changes in plans, the control station should simulate the causal process and determine the effects of such redirection. This provides the possibility of experimenting with the causal model in order to assure the best and most reliable outcome.

The causal model in the simulator processes key planning elements in conjunction with the appropriate information in the knowledge base and displays the simulated results to the operator. The operator is then able to make high-level control corrections and do replanning before the plan is executed by the system. This process entails close interaction between the operator and the operator interface. When the plan has been checked out and is sent to the executor for execution, the simulator will also receive it. Together with the required information in the knowledge base, the simulator comes up with a profile of the expected system behavior due to plan execution. This will then be used by the monitor subsystem for comparison with the actual system behavior.

While, in principle, many causal modeling and simulation techniques are available, to date none have been researched and developed that would satisfy the performance requirements for such intelligent autonomous systems as envisioned here. In addition to modeling and representing a complex dynamic process involving different operational data handling requirements, here the simulator must do this ultimately in real-time or, at least, in near real-time. Also, the simulation process puts an extraordinarily heavy burden on the architecture and information content of the knowledge base. For example, a realistic simulation of a dynamic process to be executed by the system in an uncertain environment requires a dynamically changing world model based on sensory information inputs. This type of technology is as yet not available, nor is it presently under development. In this context, the first steps in this research and development work will have to deal with utilizing structural and functional information about devices and processes together with the governing physical laws and establishing generally valid reasoning procedures.

4.1.1.4. Knowledge Acquisition

The development of the system knowledge base is the central, most critical technology development area, because it interacts with the most important subsystems and influences the operation of all aspects of intelligent autonomous systems. Knowledge base development for dynamic large-scale systems, especially for space systems such as the Space Station, still requires comprehensive definition and planning work. For application domains with existing operational human expertise, it is usually the most difficult development area to accomplish satisfactorily. For the Space Station, presently without such expertise, it is the most important and urgent research and development area that requires careful planning far into the future. This process must start during the design phase, where the final design represents a first baseline set of factual information from which factual knowledge for the system knowledge base can be extracted. The knowledge base can be completed with heuristic knowledge obtained in the usual manner by a question and answer process from humans at a later time. Of immediate concern, therefore, is the development of a mechanism for capturing and storing relevant design information in machine readable format and the development of techniques for extracting operational knowledge for the system knowledge base from this design information.

Equally important for dynamic systems, such as the Space Station, is the development of a perceptor-driven dynamic world model that can change its information content based on sensory information. The knowledge base should also be designed to allow for dynamic changes of the CAD/CAM data, the system configuration and perhaps the heuristic information. In addition to maintaining current knowledge base content, this will provide the ability to preserve relevant past experience and knowledge of previous situations. As it becomes possible to develop and incorporate learning algorithms, the system will be able to recognize task descriptions in the context of similar situations handled previously. Based on this past experience, the system will have learned and will be able to plan more effective task strategies. In time, it will become robust for handling uncertain data and unknown or unanticipated events with confidence.

Since the system's knowledge base is the hub on which everything else depends, it and its development are the driving elements for technological developments. Given that the knowledge base is appropriately designed, other subsystems, such as planners, simulators, diagnosers, etc., can also be developed in parallel with, or at almost any time after the knowledge base. Thus, by adding and properly interfacing progressively more advanced subsystem modules, the system will evolve over time into an intelligent autonomous system. In addition, it will be possible to develop and use dedicated expert systems as intelligent aides which are not elements of the intelligent autonomous system, but nevertheless may use part or all of the system's knowledge base.

At least a major portion of the information for the knowledge base will be created during the design process, long before the intelligent autonomous system starts operation. This implies that certain information should be captured at the latest during the final design stage and should be kept current with subsequent test, manufacturing, and operational data as required. Hence, an approach to design information capture and subsequent knowledge base design is required. In fact, one can express the strong belief that the success of intelligent autonomous systems in connection with space systems is critically dependent on how reliably the related design information can be captured and updated.

The final design information is the first baseline description of the system. It is important that attention be given to its organization as early as possible, so that it can be augmented by subsequent changes and can be modified to accommodate new situations. For most space systems, this is complicated by the fact that the design efforts are distributed over many organizations, each with different design responsibilities, and each likely to use different design tools and techniques. These problems require not only technical, but also organizational, solutions in the areas of standardizations, networkings, etc., related to distributed databases.

The distributed database must have capabilities which go beyond those of traditional, relational data models (Ref.6). These capabilities include representations of relationships, mappings, dependencies (time, spacial, attribute, etc.), constraints, classes, inheritances, procedures, system operations, and the like. In addition, it is necessary to support data types that include matrices, graphics, pictorial images, text, CAD/CAM data, voice, etc. Such extended data models are currently not available, but are being researched, and should be incorporated into the distributed database as they become available. Also, a combined relational and hierarchic data model should be considered for development, since in the future, such a model may more effectively satisfy the needs of future space systems.

4.1.1.5. Advanced Planning Methods

The planning system accepts task description inputs in terms of goals and scheduled events at the system level. Together with the information in the knowledge base, the planning system then develops a partially ordered network of actions and events similar to the critical path method (CPM) in project scheduling. At the simplest level, without considering resource constraints, CPM software requires explicit specification of the precedent relations to develop the corresponding partially ordered network plan. The AI-based methods, on the other hand, deduce the precedent information from the knowledge in the knowledge base. In general, not only precedent relations but also various resource and system constraints must be satisfied. Because these problems tend to explode exponentially with the number of variables or subgoals involved, their solution process usually entails the application of search procedures based on suitable context dependent heuristic criteria and, therefore, does not necessarily result in an optimum but a possible solution. The effectiveness of AI-based planning methods in generating acceptable plans is critically dependent on the design of the knowledge base.

Within the context of space program applications, some work for AI-based planners has been performed by NASA. However, beyond the inherent problem of search control, this work still has severe limitations. It requires that complete, perfect, and deterministic information be given. This is typical and usually satisfactory for deep space probe activity planning, but is probably inadequate for planning complex operations associated with the Space Station. Future planning systems should be able to cope with uncertain, incomplete and spacial information, and they should evolve to include also learning capabilities. Efforts in various directions for developing such technologies seem to encounter no fundamental limitations and are in fact the subject of ongoing research at major AI laboratories.

4.1.1.6. Cooperating Knowledge Base Systems

Knowledge-based systems will initially be designed to serve a limited number of functions performed by a particular subsystem. The coordination between two or more knowledge-based systems will be done by human operators. In the course of evolving technological capabilities and as operational and system complexities increase, the coordination functions also will be subject to automation. The knowledge-based systems and the interfaces will be designed and configured to facilitate both coordination and cooperation in serving the functions of more than one subsystem. Communication with the human operator(s) will then occur at a correspondingly higher level. The system architecture issues include hierarchical structures, distributed structures, connectivity of system elements, and architectural alternatives. Operational issues include coordination of processes, real-time operations, cooperative processing, dynamic connectivity of processes, and communication protocols among processes. Characteristic problems in connection with cooperating knowledge-based systems are knowledge replication, segmentation, fusion, synthesis, and consistency. The subject of cooperating knowledge-based systems is a new area of research with little specific technical and development background.

4.1.1.7. Validation Methodologies

Unlike many conventional programs, knowledge-based systems usually do not deal with problems with a clearly right or wrong answer, such as sorting a list or inverting a matrix. It is therefore often difficult to demonstrate in a straightforward manner that the resultant answers are correct and then can be used to solve other dependent problems. The evaluation and validation of new knowledge-based systems requires some kind of standard with which the results of the new methodology can be compared. In general, there are currently two views of how to define the standard for a knowledge-based systems' task domain. First, there is what eventually turns out to be the correct answer for a problem in some objective sense, and second, there is what a human expert, or group of them, presented with the same information available to the program, say is the correct answer. In the context of space systems the first view turns out to be not as important for the evaluation and validation process. The second view requires that domain experts themselves be subjected to rigorous evaluations of their decisions. Such assessments of human expertise provides a useful set of benchmarks against which to measure the expertise of a knowledge-based system. However, in the space arena there are many situations for which human expertise is not available, e.g., the operation of the Space Station or a Mars rover. The development of validation methodologies for knowledge-based systems that are to be applied in space missions must take this circumstance into account when evaluating and validating the facts, heuristics, and models in the knowledge base as well as the operational processes of the system.

4.1.2. Control Execution

Actuators of some sort will perform the handling functions necessary for assembly, construction, repair, and the like. These devices will move on rails or will be attached to free flying robot vehicles. Common characteristics of all of them are probably that they are relatively light and flexible and will require control strategies and techniques which still must be developed. A number of broader issues also need to be resolved and the corresponding autonomy technologies developed, such as autonomous navigation, proximity operations, cooperating manipulator control, cooperating robots, etc. This requires that strategic command issues related to symbolic controllers be investigated. Autonomous space vehicles require the ability to carry out tasks at a high conceptual level. Their manipulation activities will involve cooperation between multiple arms and multiple robots. This requires not only accurate force and position control, but also the strategic guidance necessary to plan and carry out tasks involving more than one device. The communication of manipulative strategies, whether they originate from human or artificial intelligence, is not well understood.

4.1.3. Operator Interface

In line with an evolutionary system, the operator interface evolves from continuous supervisory control with goal and causal explanation displays to interrupted supervisory control by the addition of operator aids for unanticipated failures, task-oriented dialog capabilities and human error tolerance capabilities, to sparse supervision using a goal driven natural language interface. The critical technologies for the operator interface are primarily in the areas of human factor designed displays for complex data streams and the reliable recognition and interpretation of natural language inputs.

The displays present necessary information for high-level (and, if necessary, also low-level) decision-making to the operator. This information includes alphanumeric data, geometrical representations, simulator-computed trend extrapolations of system behaviour, etc. The controls, on the other hand, will parse and package the operator's high-level inputs into task descriptions for the automatic planner. To provide operational flexibility, it is assumed that the operator will also be able to operate, with direct access, the planner, the simulator, and the diagnoser as tools in the form of expert systems. The knowledge for these expert system tools may be embedded in the system's knowledge base or in other, compatible knowledge bases with similar content.

4.1.4. Systems Architecture and Integration

A primary requirement for systems architecture and integration is to provide the posssibility for evolutionary, modular growth from current stand-alone knowledge-based systems to coordinated multiple systems followed by hierarchical and distributed systems. Systems under development today are not suitable for such large, real-time knowledge-based systems projected for the Space Station and subsequent space projects; and the unique NASA requirements in this area will not be addressed by research in industry and/or academia without related funding. Some indicative capabilities required by future systems are allocation and deallocation of large memory stacks, integration of numeric and sysmbolic processing in both cooperative and autonomous handling of data functions, management of multiprocessor architectures in a fault-tolerant environment, and management of large knowledge bases in excess of one gigabyte.

The implementation of robust knowledge-based systems for spaceborne applications requires the development of new conceptual approaches to integrated numeric/symbolic multiprocessor computers, network interfaces and data transmission protocols, and software protocol and management for large distributed databases. Advanced software compilers and translators need to be developed for both developmental and operational environments. Unprecedented verification and validation methodologies are required for fault-tolerant reconfigurable multiprocessor architectures.

4.2. Technology Breakdown Structure

The development of the critical core technologies leading to their demonstrations and space mission applications is schematically illustrated in Fig.5.

4.2.1. Technology Demonstrations

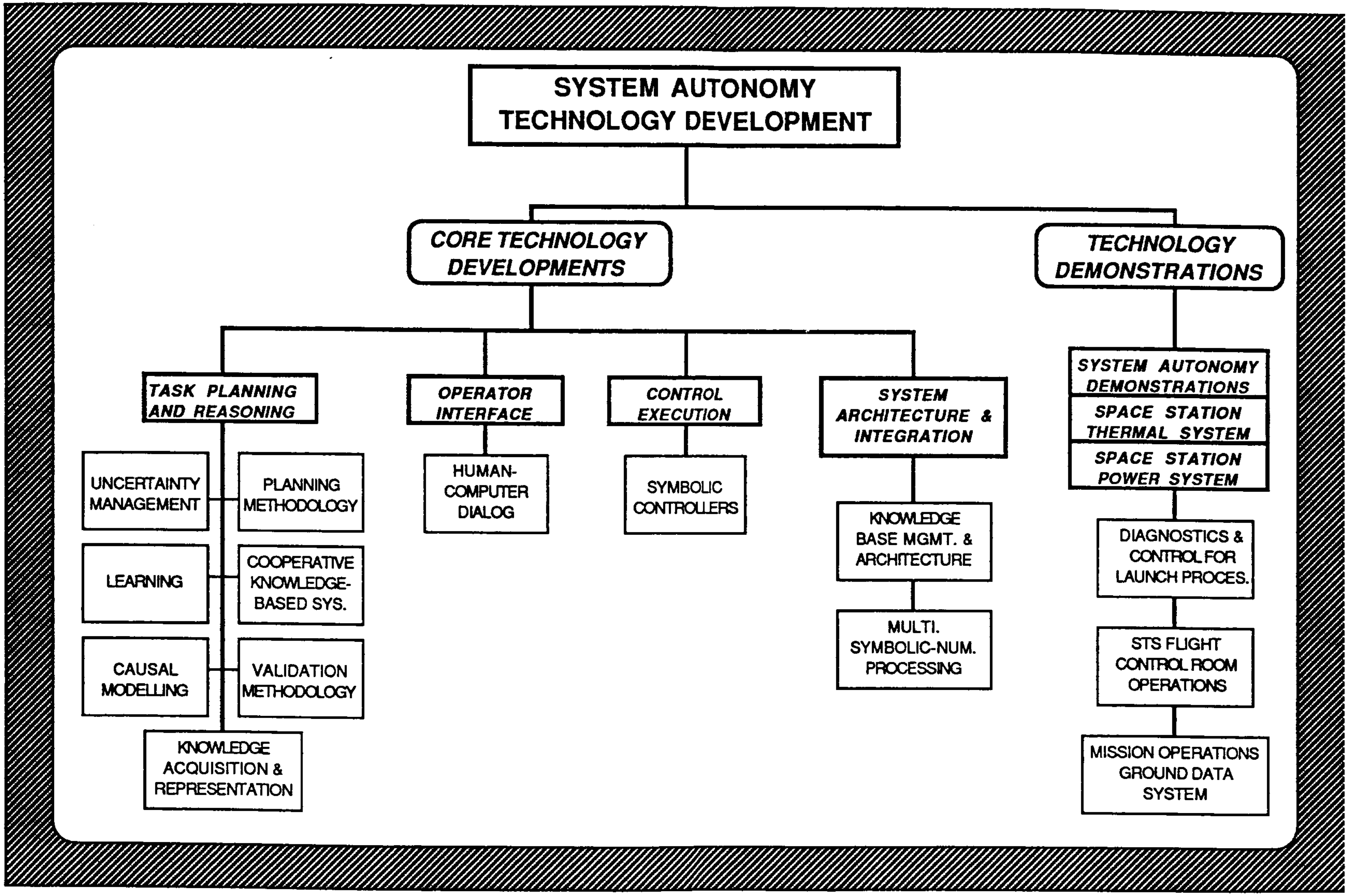
Key technologies and operational capabilities will be demonstrated and validated through a series of progressively more complex and demanding system demonstrations, before the technlogies will be applied to actual missions, or before it will be integrated into flight experiment demonstrations. The System Autonomy Demonstrations concentrate on test and verification of software and hardware technologies leading to artificial intelligence based systems which will find application in ground-based mission operations, in ground-based information management systems, in spacecraft system autonomy, in space station system autonomy, in space-based autonomous robots, in intelligent human-machine interface systems, and the like. There are two types of demonstration projects: (1) Space Station testbeds for a thermal control subsystem, a thermal/power control multiple subsystem, a hierarchically structured system, and a system with distributed architecture; and (2) Specific domain demonstrations including STS flight control room operations at JSC, launch operations at KSC, and mission operations ground data systems at JPL.

4.2.2. Core Technology Developments

A broad spectrum of basic core technologies contributes to the successful implementation of autonomous space systems. Many of these technologies have been under development through NASA/OAST and other funding agencies in the country (e.g.DARPA), while others must be newly initiated. Some of these technologies have reached a level of maturity enabling their integration into a first-level demonstration project in 1988. However, all core technologies must be readied to be compatible with the demonstration system integration requirements and must be further developed for later, more demanding demonstrations. The primary areas of required core technology are reasoning under uncertainty, learning, causal modeling, knowledge acquisition, advanced planning methods, cooperative knowledge-based systems, validation methodologies, control execution, operator interface, and system architecture and integration.

4.2.3. SATP Technology Breakdown Structure

The two major SATP activities, core technology developments and technology demonstration projects, and their subdivisions are shown in Fig.10.



JB/PGMPL 7-87 (MH)

Figure 10 - Systems Autonomy Technology Development

5. TECHNOLOGY DEVELOPMENT PLAN

It is clear that autonomous systems technology will play an important role in the development and operation of future space systems. Hence, within the broad goal and objectives of the Systems Autonomy Technology Program (SATP) stated in Section 1.2., programmatic and technology development efforts will be initiated and implemented to enable future difficult space missions, to make future missions affordable and cost effective, to maintain a competent and vigorous R&D capability in related technical disciplines, and to ensure the transfer of technology to space mission applications.

5.1. Programmatic Efforts

To ensure that the stated general goal and objectives can be accomplished, the SATP will pursue and sustain the following programmatic efforts:

(1) Fundamental research efforts will be sustained at the appropriate level to satisfy future demands and needs in system autonomy technologies, such as task planning and reasoning, control execution, operator interface, and systems architecture and integration.

(2) Collaborative and contracted efforts in the above areas will be established and sustained with academic and industrial institutions to train and engage the best available talents of the country in this Program.

(3) Efforts will be sustained to understand programmatic and technological needs in autonomous system technologies for NASA and to develop new approaches to capture, retain, and apply to future projects the expertise gained within the Agency.

(4) Programmatic and technical initiatives will be undertaken to develop techniques at the component, subsystem and system levels for the effective utilization of system autonomy and to establish a systems autonomy technology base that will permit the implementation of new and more reliable and cost effective space missions.

(5) Efforts will be made to ensure that the developed technologies for autonomous systems will be tested, validated and made available in a timely manner for space mission applications.

5.2. Technical Goals and Objectives

The development of technologies for space missions can be roughly subdivided into enabling and enhancing technologies. Without enabling technology, the corresponding mission, operation, process, etc. would not be feasible. This type of technology is therefore highly mission-dependent. Once identified, it usually receives the highest priority, since it must be ready for integration about three to four years before mission start. Enhancing technology and/or cost reducing technology, on the other hand, has generally less stringent readiness dates. There is usually a way of doing a project differently, although it may not be affordable, or the attainable performance may not be totally satisfactory. Most technologies related to systems autonomy fall into this latter category.

For this SATP Plan, future NASA missions and their requirements have been examined. Individual mission dates and their requirements often change radically, while the broad spectrum of technology requirements remains relatively constant. Thus, a phased research and development program is envisioned, that is derived from projected broad space system capabilities (not specific enabling capabilities) to be achieved by the end of the 1990's. Specific enabling capabilities will be identified and developed with the appropriate priority through periodic reexamination of changing space mission requirements.

Hence, the broad, long-term technical goals of this plan are to develop, within the next decade, the required technology for intelligent, autonomous space systems which will have capabilities to validate instructions from system supervisors and reject those that would inadvertently endanger the system or its performance. Such autonomous systems will also be able to maintain acceptable operation through self diagnosis and repair and perform task planning to select satisfactory or optimal strategies for achieving high-level system goals, particularly in the presence of large environmental or system variations.

The long-term technical goals will be accomplished by several thrusts of core technology developments which will be implemented at NASA Centers, universities and industrial institutions. These efforts will be at the laboratory breadboard integration level and will be carried to the point where they can be transferred to technology demonstration projects. Hence, systematically selected, representative demonstration projects will serve as foci and gauges for core development progress. The implementation of the demonstration projects will ensure technology relevency and maturity for space mission applications.

5.3. Demonstration Projects

Based on technology assessments, a typical sequence of progressively more complex technology demonstration levels has been identified. These demonstration levels serve as indicators for the kind of technology capabilities that are necessary to perform integrated operations which exemplify intelligent, autonomous systems. The demonstration level indicators correspond roughly to the intelligent control and operation of single subsystems in 1988, of multiple subsystems in 1990, of hierarchical multiple subsystems in 1993, and of distributed multiple subsystems in 1996.

The core technology capabilities identified in Fig.11 are indicative of what can be demonstrated in realistic operational settings at the indicated date. Hence, these technology capabilities serve as guides to determine the objectives and as gauges to measure the accomplishments of core research and developments. They also serve as guides to establish expected results of specific demonstration projects which will appropriately exercise and validate new technologies for system autonomy. The first demonstration level, to be reached in 1988, is based on technologies which are now ready for integration. The technology capabilities for the second demonstration level, to be reached in 1990, need about one year of additional developments and then two years for integration. The technology capabilities for the demonstration levels to be accomplished in 1993 and 1996 still need, respectively, an estimated four and seven years of core technology research and development and about two additional years for integration.

Specific technology demonstration projects have been selected and will be implemented at various NASA Centers with contracted support from industry and universities. These demonstrations are planned to show in realistic application settings that the respective technology capabilities, as identified in Fig.11, have been advanced to levels of capabilities enabling integration into space missions.

Future technology demonstration projects will be screened and selected, from time to time, based on need, available resources, and suitability of demonstration objectives. One measure of the suitability of a demonstration objective is the degree to which core technology capabilities with respect to the demonstration levels in Fig.11 will be exercized, demonstrated, and validated.

Currently, the following technical areas and their corresponding demonstration objectives are being pursued as prototype demonstration projects.

5.3.1. Space Station Testbeds

The Space Station is at the forefront of new projects under development, and its initial version is scheduled to become operational by the middle of the 1990s. System autonomy technology for the Space Station therefore has a high priority to be tested for possible applications.

5.3.1.1. Thermal Control System

This joint effort between ARC and JSC will demonstrate technologies in 1988 for autonomous thermal control system operations on the Space Station. This demonstration is significant in that it will be one of the first NASA knowledge-based system to control a large complex system in real-time and with real operational hardware. Key technology capabilities to be demonstrated include advice on diagnosis and correction of anticipated faults, incipient failure prevention through trend analysis, and explanation displays. Key technology thrusts include causal modeling of a complex electrical/mechanical system, and combined causal models and heuristic rules for intelligent reasoning, trend analysis, and validation methodologies.

5.3.1.2. Thermal and Power Control System

This joint effort between ARC, LeRC, MSFC, and JSC will demonstrate technologies in 1990 for autonomous control of the thermal and power system operation on Space Station. This demonstration is significant in that it will show coordinated simultaneous control of two large complex systems. The power system, because of its unique role among the onboard systems, has great potential for significant operational cost reductions through mature autonomous power systems. Specific technology capabilities to be demonstrated include fault detection/classification and isolation methodologies, system restoration strategies, replanning in the face of uncertainty, and operator training methodologies. Key technology thrusts include causal modeling of complex electrical/mechanical systems, cooperation of knowledge-based systems, and validation methodolgies.

5.3.1.3. Hierarchical Knowledge-Based Systems

This is a 1993 demonstration in which the key technology thrust is to evaluate and validate methodologies for expert system controls of more than two Space Station subsytems through hierarchical architectural strategies.

5.3.1.4. Distributed Knowledge-Based Systems

This is a 1996 demonstration in which the key technology thrust is to evaluate and validate methodologies for expert system controls of multiple Space Station subsystems through distributed architectural strategies.

5.3.2. Specific Domain Demonstrations.

A set of specific Domain Demonstrations has been planned to facilitate technology transfer to domains other than Space Station and to insure that generic technology demonstrated on Space Station testbeds is applicable in all NASA missions.

5.3.2.1. STS Flight Control Room Operations

A rule-based integrated communications officer (INCO) on-line expert system will be developed and demonstrated in 1988. Advanced powerful graphics capabilities will be incorporated in 1989. This demonstration is significant in that it will be the first NASA knowledge-based system to be implemented into a real-time operational environment. The expert system will aid Flight Control operations at JSC with minimal backroom support during STS missions, thus reducing manpower requirements for flight controllers who support Space Shuttle system opertions.

5.3.2.2. Launch Operations

The demonstrations at KSC will include system software and hardware for autonomous diagnostics and control of interactive complex electromechanical launch processing systems that will perform better than system engineers. Key technology capabilities demonstrated will include goal-directed control/reconfiguration, fault recognition/warning/diagnosis, systems scheduling/rescheduling, automated trend failure analysis, and intelligent user interfaces. Key technology thrusts include model-based simulation, CAD/CAM knowledge-base capture, explanation displays, limited uncertainty management, and validation techniques.

5.3.2.3. Mission Operations Ground Data Systems.

This demonstration project will develop and demonstrate technologies which will enable and enhance the multi-mission monitoring and diagnosis of unmanned spacecraft by emphasizing tools commonly applicable to the automated monitoring of spacecraft telemetry and space flight operations ground data systems. The technology demonstrations at JPL include a multi-mission telemetry monitoring workstation for spacecraft engineering telemetry in 1988, automated monitoring of Voyager/Neptune encounter in 1989/90, automatic command verification and monitoring for spacecraft in 1992/93, and dynamically configurable and teachable ground data system controllers in 1994/95.

5.4. Core Technology Developments

Taking into account the core technology capabilities in Fig.11 and the outline in previous chapters, the following core technology goals and objectives are established. In each case, the work includes basic research and development of hardware and software technologies to the breadboard level of integration and testing in the laboratory. This work thus provides new techniques and components which can be integrated into systems at the prototype level for the technology demonstration projects discussed above.

5.4.1. Task Planning and Reasoning

The general objectives of task planning and reasoning are to develop those technologies necessary to structure and build knowledge-based hardware/software systems which will enable intelligent autonomous systems to accept and retain uncertain and incomplete information from sensory and/or operator inputs. Furthermore, this information and previously retained information will be used to perform diagnostic searches, do simulations for performance assessments, and formulate reliable action strategies and plans which, when executed, will affect the space system itself and/or its environment in a desired manner. The knowledge-based systems have learning capabilities which provide over time improving performance to the intelligent autonomous system. Specific objectives are described in the following.

5.4.1.1. Reasoning Under Uncertainty

The objectives are to develop the ability to make sensible judgements and carry out reasonable actions when world knowledge is imprecise or incomplete, or heuristics and models have built-in uncertainty, or actions have uncertain effects.

Ongoing internal research will focus on probabilistic methods for uncertainty management. External collaborations will include work on fuzzy logic and research on integration of decision theoretic and heuristic methods. Work will also be sponsored in developing methodologies and tools for combining classical methods with AI methods.

5.4.1.2. Learning

The objectives are to develop the ability to alter and improve all functionalities as conditions change and knowledge is added over time. Learning may occur manually by being taught or automatically by experimentation, generalization, or discovery.

Internal work will be in the areas of learning by discovery and explanation based generalization. External collaborations with Carnegie-Mellon on learning by experimentation and with the University of Michigan on learning as search will continue. Major milestones include an initial demonstration of learning by experimentation in a robotic environment during 1989 and self-improving knowledge bases as part of the 1990 Systems Autonomy Demonstration Project. During 1991-1992 discovery-based learning by introspection will be demonstrated on a large database of sensor-based information on a type of data management system testbed for Space Station.

5.4.1.3. Causal Modeling

The objectives are to develop the ability to utilize structural and functional information about a device, along with the physical laws that govern the device, to simulate and reason about the device.

Internally, the 1988 Thermal Control System testbed will be used as a test domain for the combination of heuristic and model-based methods in diagnosing flaws in complex systems. Externally the University of Arizona will be funded in integration of knowledge-based and traditional simulation methods and Stanford University in logical representations of structure and function. A major milestone is the successful demonstration of these methods during the 1988 Thermal Control System demonstration. More sophisticated methods will be employed in work on the Hubble Space Telescope and other projects that involve modeling complex devices.

5.4.1.4. Knowledge Acquisition

The objectives are to develop the ability to preserve the "corporate memory", i.e. to ensure that all the facts, heuristics, and other information gained during the design, construction, and testing of a device are available in a practically usable form during the operational life of the device.

Internal work will be focused on studying the Hubble Space Telescope as a test domain for three research areas: (1) integration of knowledge acquisition into the design, construction, and testing process, (2) acquisition of knowledge from large numbers of experts, and (3) large knowledge base technology. Internal to NASA, MSFC will manage the knowledge engineering for this project in accordance with technical guidance supplied by ARC with regard to appropriate tools and methods. The large Hubble Space Telescope knowledge base developed by MSFC will serve as the "testbed" for this research as well as provide direct benefits to the Hubble Space Telescope. Externally, there will be collaboration with Stanford on the latter two topics and with Carnegie-Mellon on the first topic. It will be shown how the product of traditional engineering activities supporting design and testing in major projects can be utilized in knowledge acquisition during 1988 and 1989. A very large knowledge base system will be demonstrated during 1991. Methodologies for the combination of expertise from at least a dozen experts will be presented during 1990.

5.4.1.5. Advanced Planning Methods

The objectives are to develop the ability to take a set of goals, design a plan to utilize existing and potential resources to achieve those goals, monitor the execution of that plan, and dynamically alter the plan when initial assumptions prove incorrect.

Behavioral net architectures will be investigated at LaRC for application to the problem of planning and scheduling and for the development of a prototype domain-independent planning and scheduling tool. At ARC, internal work will proceed on testing the limits of current AI-based scheduling methodologies applied to NASA problems, particularly in space science. Work on dynamic replanning will continue and research will be initiated on the application of skeletal planning and plan refinement to NASA domains. Externally there will be collaboration with work at JPL in sensor-based planning, with industry in the development of a Truth Maintenance System-based planner, and at USC-ISI in the application of DARPA-sponsored methods to NASA problems. Current methodologies for heuristic scheduling will be demonstrated in Pioneer Venus experiments during 1987. The JPL work has milestones in a sensor-rich subsystem of the Space Station during 1988 and 1989. That work and other internal and external efforts will be demonstrated as part of scheduling the power subsystem of the Space Station during the 1990 Thermal and Power Control System tests.

5.4.1.6. Cooperating Knowledge-Based Systems

The objectives are to develop the ability to provide for synergistic cooperation among several significant knowledge-based systems in a complex environment.

Internal research focus will be on the 1990 Thermal and Power Control System demonstrations. The use of the Hubble Space Telescope will be considered as a second domain for cooperative systems. External work will be supported at the Stanford Knowledge Systems Laboratory in blackboard architectures for distributed control of knowledge-based systems, at the University of Maryland in potential hierarchical control methods, and at MIT in languages for commanding multiple systems. In addition, a major new effort, jointly sponsored with DARPA, will begin at Stanford, SRI, and Rockwell in methodologies for interacting intelligent agents in the domain of Space Station Construction. Blackboard architectures will be demonstrated in NASA domains during 1988. A plan for the development of the technology required for coordinated construction of the Space Station by human and robotic entities will be presented during 1989. This plan will utilize the results of small-scale demonstrations in a robotic test environment at SRI during 1988 and 1989.

5.4.1.7. Validation Methodologies

The objectives are to develop the ability to validate the correctness of the facts, heuristics, and models used by a knowledge-based system and to verify that the knowledge has been correctly represented within the system.

During 1987 a NASA/Industrial workshop was held to begin understanding the practical issues of knowledge-based system validation in NASA domains with a particular focus on Space Station. The result of that workshop will be a detailed report to appear in early fiscal 1988. The first major milestone will be the development of an accepted validation methodology for the 1988 Thermal Control System demonstrations. Validation work will also occur as part of the work described above on multiple-expert knowledge acquisition and large knowledge base technology. This will produce results in parallel with those milestones in 1989 and 1990.

5.4.2. Control Execution

The objectives are to explore the possibility of developing a mathematical theory to enable the design of symbolic controllers for dynamic systems. The approach will use in-house research and university grants to build a predicate calculus with time and dynamics concepts within the syntax. Specific research products include: (1) ways for translating sentences of the command sequences into arithmetic functions of time, (2) ways for representing estimated states and time histories symbolically, and (3) means for expressing global system properties such as stability, robustness, and disturbance rejection.

5.4.3. Operator Interface

The objectives are to develop human machine interfaces that enable communication with intelligent autonomous systems in space in a manner natural to the human operator. Emphasis will be placed on "intelligent" systems which satisfy human factors requirements, and where the distribution of the workload between human and machine is optimized. Specific research products include: (1) design decision aids and rapid prototyping tools, (2) more natural human-computer dialog systems, (3) advanced display and/or control concepts, and (4) computer aided interface design systems.

5.4.4. Systems Architecture and Integration

The objectives are to develop system concepts required for the implementation of robust knowledge-based systems in spaceborne applications. Specific tasks include: (1) design and development of the spaceborne integrated symbolic/numeric multiprocessor computer; (2) definition and development of the network interfaces and data transmission protocols for a vendor-independent environment; (3) development of the software protocols and management for large, distributed knowledge-based data systems; (4) development of software compilers and translators for use in development and operational environments; and (5) design and development of verification and validation methodologies for fault-tolerant reconfigurable multiprocessor architectures. Milestones for the spaceborne processor include conceptual design by mid FY-88, detailed design by mid FY-90, with development and qualification by FY-94.

5.5. Traceability of Technology Developments and Demonstrations

The technical goals and objectives set forth in Subsections 5.2., 5.3., and 5.4. including Fig.11, represent current NASA thinking with regard to the technologies necessary to satisfy NASA's system autonomy requirements for the next decade. The technology capabilities identified in Fig.11 are aggregations of technology elements which will be the subject of more detailed planning documentation in subsequent sections of this plan.

The technology development objectives address the whole spectrum of required technology capabilities indicated in Fig.11. Since the technology capabilities serve as measures of accomplishments for core technology developments, they are equally useful for measuring and judging the effectiveness of technology demonstration projects to advance, exercise, and validate system autonomy. These technology capabilities establish the tracing links between technology developments and technology demonstrations.

There is some overlap among the demonstration projects in terms of technology capabilities to be demonstrated. Since the overlapping items are demonstrated in different application contexts, they will be tested under different conditions and will,

EVOLUTIONARY DEVELOPMENT OF CORE TECHNOLOGY CAPABILITIES IN SUPPORT OF INCREASING TECHNOLOGY DEMONSTRATION LEVELS

CORE TECHNOLOGY		1988 CONTROL OF SINGLE SUBSYSTEM	1990 CONTROL OF TWO SUBSYSTEMS	1993 HIERARCHICAL CONTROL OF MULTIPLE SUBSYSTEMS	1996 DISTRIBUTED CONTROL OF MULTIPLE SUBSYSTEMS
TASK PLANNING AND REASONING	UNCERTAINTY MANAGEMENT	• PROBABILISTIC METHODS	• EVIDENTIAL REASONING	• INTEG. OF PROBABILISITC, EVIDENTIAL, & FUZZY LOGIC	• INTEGRATION WITH LEARNING SYSTEMS
	LEARNING	• PROBABILISTIC CLASS IDENTIFICATION	• EXPLANATION-BASED GENERALIZATION	• DISCOVERY AND EXPERIMENTATION METHOD.	• INTEGRATION INTO TOTAL SYSTEMS
	CAUSAL MODELLING	• RULE-BASED SIMULATION	• MODEL-BASED SIMULATION	• INTEGRATION OF CAD/CAM KNOWLEDGE BASE	• INTEGRATION OF MULTIPLE CAD/CAM K-BASES
	PLANNING/SCHED.	• SCHEDULING/RESCHEDULING	• PLANNING/REPLANNING	• PLANNING UNDER UNCERT.	• REAL-TIME PLANNING/REPLANNING
	KNOW.ACQUISITION/ REPRESENTATION	• KNOWLEDGE REPRESENTATION-GENERIC "SHELLS"	• KNOWLEDGE ACQUISITION-SEMI AUTOMATIC	• KNOWLEDGE ACQUISITION-AUTOMATIC	• AUTOMATIC KNOWLEDGE ACQUISITION FROM CAD/CAM DATA
	COOPERATIVE K-B SYSTEMS	• COORDINATION OF TWO SINGLE SUBSYSTEMS	• TWO COOPERATING SUBSYSTEMS	• HIERARCHICAL MULTIPLE SUBSYSTEMS	• DISTRIBUTED MULTIPLE SUBSYSTEMS
	VALIDATION METHODOLOGIES	• STANDARDS FOR PROGRAM'S ENVIRONMENT	• STANDARDIZED VALIDATION TECHNIQUES	• ADV. VALIDATION TECHNIQUES BASED ON NEW THEORY	• EXPANDED VALIDATION TECHNIQUES
CONTROL EXECUTION	SYMBOLIC CONTROL	• SYNTAX TIME AND DYNAMIC CONCEPTS	• DYNAMIC SITUATION SYMBOLIC REPRESENTATION	• SUPERVISORY COMMAND ARITHMETIC REPRESENTATION	• SYMBOLIC CONTROL MATHEMATICAL THEORY
OPERATOR INTERFACE	HUMAN COMPUTER DIALOG	• GOAL AND CAUSAL EXPLANATION DISPLAYS	• OPERATOR AIDS FOR UNANTICIPATED FAILURES	• TASK ORIENTED DIALOGUE, HUMAN ERROR TOLERANCE	• GOAL DRIVEN NATURAL LANGUAGE INTERFACE
SYSTEM ARCHITECTURE AND INTEGRATION	SYM-NUM PROC.	• GROUND-BASED VLSI PROTOTYPE MULTIPROCESSOR	• GROUND-BASED VHSIC PROTOTYPE MULTIPROCESSOR	• SPACE-BORNE VHSIC SYMBOLIC PROCESSOR	• SEVERAL VHSIC SYMBOLIC PROCESSORS
	DISTRIBUTED K-B MANAGEMENT	• INTERFACE STANDARDS	• MEMORY MANAGEMENT FOR COOP. K-B SYSTEMS	• NETWORK PROTOCOLS FOR HIERARCHICAL SYSTEMS	• NETWORK PROTOCOLS FOR DISTRIBUTED SYSTEMS

JB/PGMPL 7-87 (MH)

Figure 11 - Evolutionary Development of Core Technology Capabilities

accordingly, become the more robust elements of the technology. These elements will serve as the more reliable building blocks in subsequent demonstrations and will be the most suitable ones for transfer to space mission applications. Hence, such overlaps are not considered duplications, but a necessary and desirable byproduct in the evolutionary process.

6. PROGRAM MANAGEMENT

This Section describes the overall program management structure. It explains how special committees and advisory groups support the SATP, and how significant interfaces with other participating organizations function. It delineates the process of program reviews and outlines the interface and control strategies.

Overall direction and evaluation of the SATP is the responsibility of the Associate Administrator of the Office of Aeronautics and Space Technology. He assigned NASA Headquarters responsibility for this Program to the Director of the Information Sciences and Human Factors Division, and NASA Center responsibility to the Director of the NASA Ames Research Center.

The ARC has coordination and management responsibility for the implementation of the Systems Autonomy Technology Program. The Director of ARC assigned this responsibility to the Information Sciences Division at ARC.

6.1. Organization

The SATP is managed by the Manager of the Information Sciences Division at ARC. The Manager of the Information Sciences Division interfaces directly with the Director of the Information Sciences and Human Factors Division at NASA Headquarters, who receives NASA-wide management advice from the NASA Automation and Robotics Management Committee. The SATP Organization, together with the major organizational interfaces, is shown in Fig.12.

6.1.1. SATP Office at ARC

The SATP Office at ARC is responsible for maintaining appropriate contacts and information exchanges with the respective program offices at NASA/HQ for funding, reporting, and reviews. The SATP Manager is responsible for staffing the SATP within the Information Sciences Division at ARC and for overall program planning, direction, organization, performance, and evaluation of all matters pertaining to the SATP. The SATP Office Manager is also responsible for coordinating, through the SAIWG, the timely development of the core technology and the implementation of the demonstration projects at the various NASA Centers.

6.1.2. Interfaces with Other NASA Centers

Several NASA Centers contribute to the development of core technology and to the preparation and conduct of technology demonstrations. These activities are coordinated through a Systems Autonomy Intercenter Working Group (SAIWG). The SAIWG includes one Center Representative from each NASA Center (ARC, GSFC, JPL, JSC, KSC, LaRC, LeRC, MSFC) and is chaired by the SATP Manager. The SAIWG reviews program plans and advises on the definition of, and broad guidelines for, the implementation of specific core technologies and demonstration projects.

SYSTEMS AUTONOMY PROGRAM ORGANIZATION

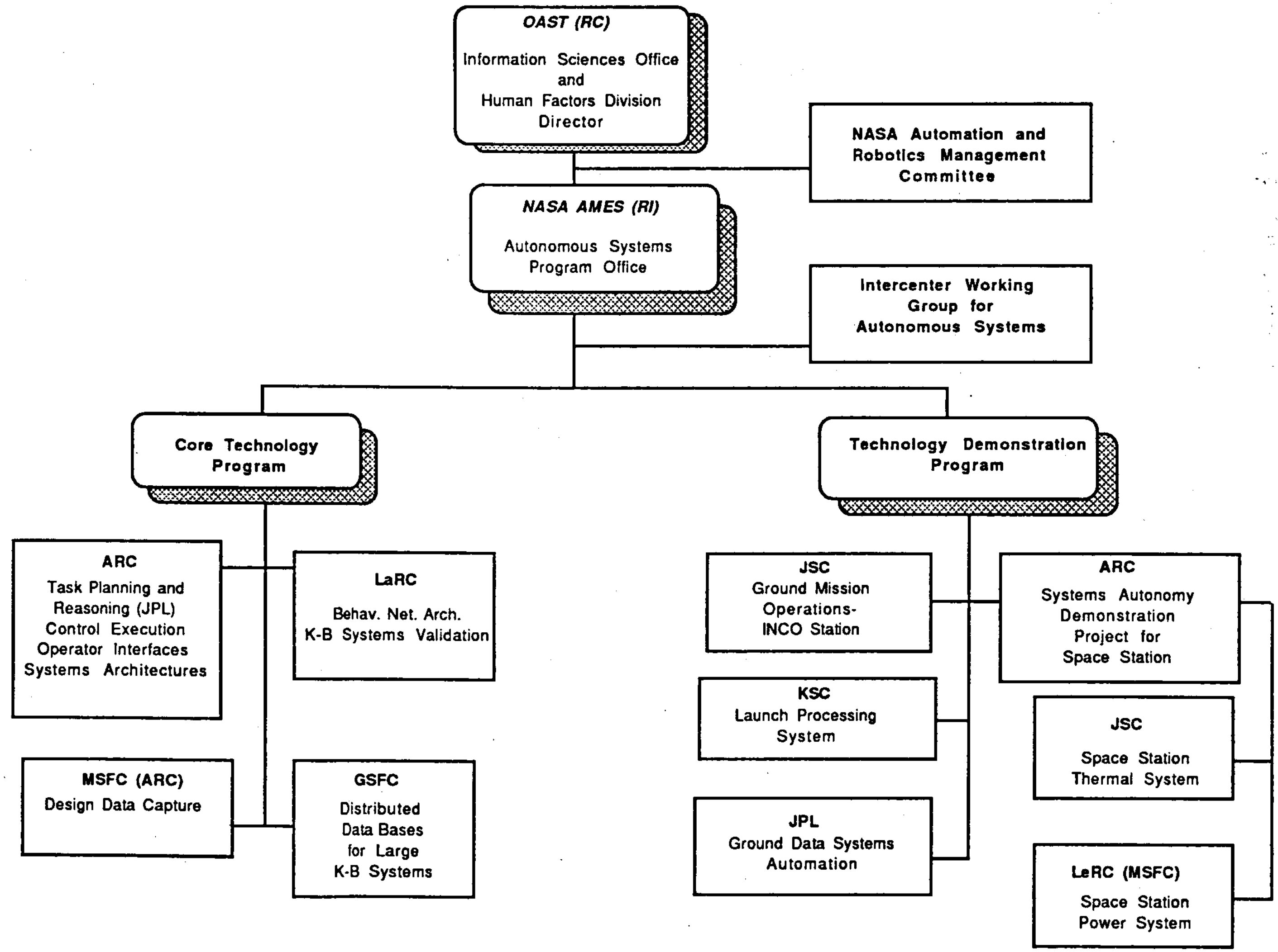


Figure 12 - Program Organization

JB/SAP 5/87 (MH)

6.1.3. Collaboration with Other Organizations

Significant collaborative efforts have been established with DARPA in the area of cooperating intelligent systems, with the Air Force in the demonstration and evaluation of automated systems for ground mission control and operation of multiple satellites, and with DARPA and DOD in the development of spaceborne processors. Collaborative efforts have also been established with industry to transfer the automation technologies for use in highly automated commercial spaceborne payloads such as the Industrial Space Facility and the Space Habitability Facility.

6.2. Milestones and Schedule

The successful completion of a demonstration project warrants the possible transfer of the demonstrated technology to space missions. The space mission requirements and associated flight dates are, in general, the drivers of technology developments, especially if the technology is mission enabling. The developed technologies must usually be demonstrated about three to four years before the launch date of the mission in which it is to be applied. The planned Space Station and its auxiliaries are currently the primary space systems that determine the contents and schedules of technology and demonstration developments for system autonomy.

6.2.1. Technology Demonstration Milestones

Technology demonstrations are planned and will be implemented covering a broad spectrum of potential application areas as shown in Fig.13. The milestones of the major planned demonstrations are clustered in 1988 and 1990. In agreement with the statements above, the demonstrations in 1988 are based on existing technology which still needs to be system integrated, while those after 1988 involve at least some technology that is still being developed. The success of each demonstration project depends not only on the availability of the technology at a particular point in time, but also on the compatibility of these technologies among themselves in terms of their levels of development. This requires a careful balance of the technology developments in different technical areas and at different geographical locations. At the appropriate time, about one to two years before the demonstration date, the necessary technologies and techniques will be garnered and integrated into the demonstration system for testing and validating.

SYSTEMS AUTONOMY PROGRAM
TECHNOLOGY DEMONSTRATIONS MILESTONES

TECHNOLOGY DEMONSTRATION PROJECTS	87	88	89	90	91	93	96
SYSTEM AUTONOMY DEMONSTRATION PROGRAM (SADP) • SPACE STATION THERMAL CONTROL • SPACE STATION POWER SYSTEM			DEMO. OF THERMAL CONTROL SYSTEM △ DEMO. OF POWER RESOURCE MGR.EXP.SYS. △	DEMO. OF COORDINATED THERMAL/POWER SYSTEMS △		DEMO. OF HIERARCHICAL CONTROL △	DEMO. OF DISTRIBUTED CONTROL △
LAUNCH OPERATIONS		DEMO. OF ENVIRONMENTAL CONTROL SYSTEM DIAGNOSTICS △		△ DEMO. OF MULTIPLE SYSTEM DIAG./CONTROL	DEMO. OF HIERARCHICAL/ DISTRIBUTED CONTROL △		
STS FLIGHT CONTROL ROOM OPERATIONS		DEMO. OF SHUTTLE MONITORING △	DEMO. OF ADVANCED GRAPHICS △				
MISSION OPERATIONS GROUND DATA SYSTEMS		DEMO. OF MULTIMISSION TELEMETRY WORKSTATION △		DEMO. OF VOYAGER/NEPTUNE ENCOUNTER MONITORING △	DEMO. OF S/C COM'D. VERIF. & MONITORING △	DEMO. OF DYNAMIC CONFIG'BLE & TEACHABLE GROUND CONTROLLER △	

Figure 13a - Technology Demonstration Milestones

JB/PGMPL 7-87 (MH)

SATP CORE TECHNOLOGY DEVELOPMENT - MILESTONES

CORE TECHNOLOGY DEVELOPMENTS	88	89	90	91	92
TASK PLANNING AND REASONING					
• REASONING UNDER UNCERTAINTY		DOCUMENT CURRENT METHODOLOGIES △	1990 SADP DEMO △		
• LEARNING		DEMON. BY EXPERIMENT △		DEMON. BY DISCOVERY △	
• CAUSAL MODELING & SIMULATION	△ DEMO COMBINED MODELS & HEURISTICS			DEMO HUBBLE SPACE TELESCOPE △	
• KNOWLEDGE ACQUISITION		DEMO DESIGN & TESTING TOOLS △		DEMO COMBINED EXPERTISE △	
• ADVANCED PLANNING METHODS			DEMO SCHEDULING IN 1990 SADP DEMO △	DEMO BEHAV. NETWORK ARCH. △	INTEG. OF LEARNING W/PLANNING △
• MULTIPLE K-B SYSTEMS		DEMO BLACKBOARD ARCHITECTURES △	DEMO TWO COOPERATING SUBSYSTEMS △		HIERARCHICAL METHODOLOGIES △
• VALIDATION METHODOLOGIES	△ VALIDATION WORKSHOP REPORT		VALID. METHOD. FOR SINGLE SUBSYSTEM △		FUNDAMENTAL VALIDATION THEORY △
CONTROL EXECUTION					
• SYMBOLIC CONTROLLER		ALGORITHMIC SUPERVISORS △		DEMO WITH INTELLIGENT ROBOTS △	
OPERATOR INTERFACE					
• HUMAN INTERFACE DESIGN	△ DECISION AIDS RAPID PROTOTYPING		NATURAL HUMAN-COMPUTER DIAGLOG SYSTEMS △		COMPUTER-AIDED INTERFACE DESIGN △
SYSTEM ARCH. & INTEGRATION					
• SPACEBORNE SYMBOLIC PROCESSOR	△ CONCEPTUAL DESIGN		DETAILED DESIGN △	DEVEL. & QUALIFICATION △	
• DISTRIBUTED K-B MANAGEMENT		LARGE DISTRIBUTED K-B MODELS △		LARGE K-B MANAGEMENT TOOLS △	

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Figure 13b - Core Technology Milestones.

6.2.2. Core Technology Schedule

The core technology research and development schedules are based on first-cut estimates of the time necessary to accomplish the identified tasks based on current funding guidelines. These schedules and milestones are most strongly guided by the requirement to accomplish the levels of core technology capabilities at the years indicated in Fig.11, i.e., coordinated system control of multiple systems in 1990, hierarchical system control in 1993, and distributed system cooperative control in 1996, each with the respective subareas of identified technology capabilities. The required technologies for the 1988 (and before) capability levels are essentially current state of the art. Hence, the schedules and milestones in Fig.14 show detailed core research and development tasks, which must be implemented to ensure that the increasing technology capabilities and demonstration levels will be achieved starting with 1990 as presented in Fig.11. These schedules and milestones assume that relevant technologies of other government and industrial programs, notably those of DOD, can be transferred to NASA and do not need to be developed as part of this program.

6.2.3 Reporting

The accomplished work under the SATP will be documented as required for management, archival, and technology transfer purposes. There will be a formal and an informal reporting process. Formal reporting consists of annual submissions of detailed task proposals from the implementing NASA Centers to the SAIWG for endorsement within the framework of this SATP Plan. These proposals include information generally required for OAST RTOPs, such as task descriptions, required staffing, requested funding, milestone schedules, facility requirements, etc. In addition, meetings and associated oral presentations will be held as necessary. The informal reporting consists primarily of publications in the open literature including books, refereed journals, conference proceedings, lectures, and technical reports.

Fig.14. SYSTEMS AUTONOMY PROGRAM SCHEDULE

FY	88	89	90	91	92	Requirements/Goals
Demonstrations						
1. Spa. Sta. Demos(SADP)	1		2		3	Eval. & Valid. of coop. K-B Sys.
2. Operations Demos.	4 5		6	7 8		Alternate domain benchmark sys.
Core Technology						
3. Intentionally Blank						
4. Plan. and Reasoning						
4.1. Reas. under Uncert.		1	2			Decision robustness.
4.2. Learning		3		4		Automated K-B expansion.
4.3. Causal Model./Sim.	5			6		High qual. decisions.
4.4. Knowl. Acquisition		7		8		Dynamic K-B Acq.
4.5. Adv. Plan. Meth.			9	10	11	Real-time contingency replanning.
4.6. Coop. K-B Systems		12	13		14	Interactive planning by intell. systems.
4.7. Validation Meth.	15		16	17	18	Methodology based on fundamental theory.
5. Control Execution						
5.1. Symbolic Control		1		2		Symbolic-algorithmic control interface.
6. Operator Interface						
6.1. Human Int. Design		1	2	3	4	Comp. aided inter. design tool.
7. Systems Arch./Integ.						
7.1. Symbolic Processor	1		2 3			Real-time performance.
7.2. Dist. K-B Mgmt		4		5		Large K-B software to applic. engg.

SYSTEMS AUTONOMY PROGRAM SCHEDULE
MILESTONE NUMBERS AND TITLES

Demonstrations

1. Space Station Demos (SADP)
    1. Control of single subsystem (Thermal)
    2. Control of two subsystems. (Thermal/Power)
    3. Plans for hierarch. cntl. of mult. subsyst. (cont. next page)

2. Operations Demonstrations
    4. Shuttle flight control room automation (INCO)
    5. Shuttle launch ops diagnostic/control automation (ECS)
    6. Space Stat. ground multi-sys. diag/control autom. (PPCU)
    7. Space Stat. ground hierarchical/distr. diag/control autom.(GDMS)
    8. Planetary mission ops. automation (Gnd data systems)

Core Technology
  3. Intentionally Blank
  4. Task Planning and Reasoning
   4.1. Reasoning under Uncertainty
      1. Major review document of current methdologies
      2. Demonstration of uncertainty management in 1990 SADP Demo
   4.2. Learning
      3. Demonstration of learning by experiment
      4. Demonstration of learning by discovery
   4.3. Causal Modeling/Simulation
      5. Demo of comb. causal models & heuristics in 1988 SADP Demo
      6. Demo of complex modeling of Hubble Space Telescope
   4.4. Knowledge Acquisition
      7. Demo of design and testing tools
      8. Demo of combined expertise from over ten experts
   4.5. Adv. Planning Methodologies
      9. Demo of scheduling in 1990 SADP Demo
      10. Demo of behavioral network architectures
      11. Integration of learning with planning methodologies
   4.6. Cooperating Knowledge-Based Systems
      12. Demo of blackboard architectures
      13. Demo of two cooperating subsystems in 1990 SADP Demo
      14. Hierarchical methodologies for control of mult. subsystems
   4.7. Validation Methodologies
      15. Report of Validation Workshop
      16. Validation methodology for single subsystems
      17. Validation methodology for multiple subsystem
      18. Establishment of fundamental validation theory
  5. Control Execution
   5.1. Symbolic Control
      1. Algorithmic supervisors of arithmetic controllers
      2. Demo of global system properties of symb.-algorithmic interf.
  6. Operator Interface
   6.1. Human Interface Design
      1. Design decision aids and rapid prototyping tools
      2. Natural human-computer dialog systems
      3. Advanced display/control concepts
      4. Computer aided interface design (CAID) system
  7. Systems Architecture and Integration
   7.1. Symbolic Processor
      1. Complete conceptual design
      2. Complete detailed design
      3. Initiate development, testing, and qualification
   7.2. Distributed K-B Management
      4. Large distributed Knowledge base models
      5. Large K-B management development tools

6.3. Resources

The following Fig.15 shows the SATP resources required to meet the projected core technology developments and to implement the planned technology demonstration projects for system autonomy.

Fig.15a. SYSTEMS AUTONOMY PROGRAM FUNDING SUMMARY
(Funding by Program Element)

FY	88	89	90	91	92	Total
Demonstrations	4766	4700	4280	4300	3850	21893
1. Spa. Sta. Demos (SADP)	3399	3500	3500	3500	3500	17399
o Thermal	1905	500	0	0	0	2405
o Thermal/Power	1125	2300	2500	700	0	6625
o Hierarchical	369	700	1000	2700	3100	7869
o Distributed	0	0	0	100	400	500
2. Operations Demos.	1364	1200	780	800	350	4494
o STS Flt Cont Room Ops	620	350	0	0	0	970
o Launch Operations	397	500	430	450	0	1777
o Ground Data Systems	347	350	350	350	350	1747
Core Technology	6366	6948	7643	7900	8533	37390
3. Intentionally Blank						
4. Planning and Reasoning	3701	4050	4090	4250	4583	20674
4.1. Uncertainty Mgmt.	140	200	240	300	400	1280
4.2. Learning	500	500	500	500	600	2600
4.3. Causal Modeling	250	300	300	300	300	1450
4.4. Knowledge Acquisition	971	1000	1000	1000	1000	4971
4.5. Adv. Planning Meth.	647	650	650	700	700	3347
4.6. Coop. K-B Systems	753	800	800	750	783	3886
4.7. Validation Meth.	440	600	600	700	800	3140
5. Control Execution	96	150	200	200	200	846
5.1. Symbolic Control	96	150	200	200	200	846
6. Operator Interface	385	400	403	500	500	2188
6.1. H-M Inter. Design	385	400	403	500	500	2188
7. Systems Arch./Integ.	2184	2348	2950	2950	3250	13682
7.1. Symbolic-Num. Arch.	1986	2000	2500	2500	2750	11736
7.2. Dist. K-B Mgmt.	198	348	450	450	500	1946
Systems Auton. Total (Net)	11129	11648	11923	12200	12383	59283
Program Support	1195	973	994	1014	1028	5204
Unique Requirements	0	179	183	186	189	737
Systems Auton. Tot. (Gross)	12324	12800	13100	13400	13600	65224

Fig.15b. SYSTEMS AUTONOMY PROGRAM FUNDING SUMMARY
(Element Funding by Center)

FY	88	89	90	91	92	Total
Demonstrations	4766	4700	4280	4300	3850	21893
1. Spa. Sta. Demos.(SADP)	3399	3500	3500	3500	3500	17399
o Thermal	1905	500	0	0	0	2405
ARC	1305	300	0	0	0	1605
JSC	600	200	0	0	0	800
o Thermal/Power	1125	2300	2500	700	0	6625
ARC	625	1250	1400	400	0	3675
JSC	0	300	300	100	0	700
LeRC/MSFC	550	750	800	200	0	2300
o Hierarchical						
ARC	369	700	1000	2700	3100	7869
o Distributed						
ARC	0	0	0	100	400	500
2. Operations Demos	1364	1200	780	800	350	4494
o STS Flt Cntl Room (INCO)						
JSC	620	350	0	0	0	970
o Launch Operations						
KSC	397	500	430	450	0	1777
o Mssn Cntl Gnd Data Sys						
JPL	347	350	350	350	350	1747
Core Technology	6366	6948	7593	7900	8533	37390
3. Intentionally Blank						
4. Planning and Reasoning	3701	4050	4090	4250	4583	20674
ARC	2883	3000	3050	3150	3483	15556
LaRC	347	550	550	600	600	2647
MSFC	471	500	500	500	500	2471
5. Control Execution	96	150	200	200	200	846
ARC	96	150	200	200	200	846
6. Operator Interface	385	400	403	500	500	2188
ARC	385	400	403	500	500	2188
7. Systems Arch/Integ	2184	2348	2900	2950	3250	13682
ARC	1986	2000	2500	2500	2750	11736
GSFC	198	348	400	450	500	1946
Systems Auton. Total (Net)	11129	11648	11923	12200	12383	59283

Fig. 15c. SYSTEMS AUTONOMY PROGRAM MANPOWER SUMMARY
(Element Manpower by Center)

FY	88	89	90	91	92	Total
Demonstrations	39	41	43	38	17	178
1. Spa. Sta. Demos. (SADP)	24	24	25	21	14	108
o Thermal	12	9	3	1	0	25
ARC	8	7	3	1	0	19
JSC	4	2	0	0	0	6
o Thermal/Power	11	14	21	16	1	63
ARC	1	4	9	9	0	23
JSC	0	0	2	1	1	4
LeRC/MSFC	10	10	10	6	0	36
o Hierarchical						
ARC	1	1	1	4	9	16
o Distributed						
ARC	0	0	0	0	4	4
2. Operations Demonstrations	15	17	18	17	3	70
o STS Flt Cntl Room (INCO)						
JSC	2	2	0	0	0	4
o Launch Operations						
KSC	10	12	15	14	0	51
o Mssn Cntl Gnd Data Sys						
JPL	3	3	3	3	3	15
Core Technology	26	32	38	39	40	175
3. Intentionally Blank						
4. Planning and Reasoning	15	20	25	27	29	116
ARC	8	12	16	18	20	74
LaRC	3	4	5	5	5	22
MSFC	4	4	4	4	4	20
5. Control Execution						
ARC	2	2	2	2	2	10
6. Operator Interface						
ARC	2	2	3	3	3	13
7. Systems Arch/Integ	7	8	8	7	6	36
ARC	5	5	5	4	3	22
GSFC	2	3	3	3	3	14
Systems Autonomy Total (MY)	65	73	81	77	57	353

6.4. Facilities

The implementation of the SATP requires existing and new research and demonstration facilities at the contributing NASA Centers. A description of available and newly required facility capabilities in terms of hardware and software is give in the Appendix for each NASA Center Work Package.

7. RELATED NASA AND DOD ACTIVITIES

Other ongoing activities in the area of system autonomy or closely related disciplines will be closely monitored, and applicable results will be incorporated in the SATP through technology transfer to NASA as appropriate. The Telerobotics Program, managed by JPL, is of particular interest in this respect. Coordination and technology transfer activities among the SATP and the Telerobotics Program will be sustained on a continuous basis to ensure the possibility of a program merger in the future should this become required. The following programs are dealing with similar generic technologies as the SATP, although the application contexts are substantially different. The summaries of the three programs below are intended to indicate potential areas of commonality with the SATP.

7.1. NASA Aircraft Automation Program

This program will seize upon the current opportunity for major improvements for aircraft systems through use of AI technology. AI offers the promise of higher-level automation. The program objective or strategic goal is to establish a national focus for research in automation of aeronautical flight and air traffic management systems. The technology will be developed for the design of intelligent flight path management systems which are goal driven and human error tolerant.

The term "goal-driven" implies a higher level of interaction between the pilot and his aircraft system than is currently available. Communications will be by intent rather than by having to select specific autopilot modes or insert specific waypoints by latitude/longitude coordinates. In helicopter automated NOE flight, the vision might be one of the horseman who controls the horse by simple commands and not high bandwidth/precise path control.

The program potential payoff is in the form of improved mission effectiveness, elimination of pilot-induced accidents, and reduced crew complement and training costs. These opportunities are available to high-performance aircraft, rotorcraft, and civil transports. Recognized mission requirements in these three vehicle classes provide the research focus.

7.2. Army-NASA Aircrew/ Aircraft Integration Program

This program is an Army-NASA exploratory development program with the purpose of developing a rational predictive methodology for helicopter cockpit system design, including mission requirements and training system implications, that integrates human factors engineering with other vehicle/design disciplines at an early state in the development process. The program will produce a Human Factors/Computer Aided Engineering workstation suite for use by design professionals. This interactive environment will include computational and expert systems for the analysis and estimation of the impact of cockpit design and mission specification on system performance by considering the performance consequences from the human component of the system. The technical approach is motivated by the high cost of training systems, including simulators, and the loss of mission effectiveness and possible loss of lives due to ill-conceived man-machine design. The methodology developed to achieve goals of this program might be generalized as a paradigm for the development and planning of a variety of complex human operated systems.

The program is jointly managed and executed by the Aeroflightdynamics Directorate of th US Army Aviation Research and Technology Activity (ARTA) and the NASA Ames Research Center Aerospace Human Factors Research Division.

7.3. DARPA Information Science Technology Office

The Defense Advanced Research Projects Agency (DARPA) has recently combined its basic AI research and technology demonstration projects within a single office called Information Science Technology Office (ISTO). ISTO and its predecessor, Information Processing Techniques Office (IPTO), are the largest single sources of funding for basic and applied AI research in the world. ISTO supports AI research efforts at universities such as Stanford, Carnegie-Mellon, and MIT (typically at $1M/yr). Funded projects include the areas of knowledge representation, knowledge acquisition, and advanced inference methods such as the blackboard system, and machine learning.

In addition, a major effort analogous to Systems Autonomy, called Strategic Computing, was started approximately two years ago. The purpose of Strategic Computing is to both build and demonstrate an applied AI technology base necessary for military users in the next several decades. Seven applied research programs are funded at places such as Intellicorp, Teknoledge, General Electric, Stanford University, and University of Massachusetts in areas of next-generation AI tool development and advanced hardware and software architectures for AI systems. Three major demonstrations, Pilot's Associate, Autonomous Land Vehicle, and Air-Land Battle Management are currently underway in multi-company teams.

Through various efforts, both formal and informal, demonstrations presented as part of the Systems Autonomy program will utilize and leverage upon DARPA developed technology. The ARC Information Sciences Office is currently finalizing a working arrangement with the DARPA ISTO.

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APPENDIX

TECHNICAL WORK PACKAGES FOR NASA CENTERS

A. TECHNICAL WORK PACKAGES FOR NASA CENTERS

The implementation of the SATP includes core technology developments and technology demonstrations. The core technology developments will be driven by requirements derived from the technology demonstration levels of Fig.11 and, if applicable, from the requirements of the demonstration projects. These technologies will be developed as parts of existing OAST RTOPs managed at the implementing NASA Centers. The core technology development tasks include basic research, fundamental developments, and laboratory testing of system autonomy tools and techniques. Plans for these tasks, tools, and techniques will be prepared and proposed by the respective NASA Centers to the SAIWG for endorsement and then to NASA Headquarters for funding.

The technology demonstration projects will be implemented under the OAST SATP RTOP which is managed by the SATP Office at ARC. The specific demonstration projects will be defined, planned, and proposed by the respective NASA Centers to the SAIWG for endorsement and then to the SATP Office for inclusion in the SATP RTOP and funding by NASA Headquarters. The demonstration development tasks include work necessary to prepare the system autonomy tools and techniques, which were tested in core research laboratories, for integration into the specific demonstration project scenario and testbed. These tasks will be defined and managed by the Prject Managers at the respective implementing NASA Centers.

Within the framework of this SATP Plan, each implementing NASA Center is pursuing the work outlined in the following pages.

APPENDIX

TABLE OF CONTENTS

A1. AMES RESEARCH CENTER.

A1.1 CORE RESEARCH AND TECHNOLOGY (Task Planning and Reasoning).

TITLE: Task Planning and Reasoning.

OBJECTIVES:

The program described in this section represents the bulk of the science and engineering research thrusts of the Artificial Intelligence Branch of the Ames Research Center. It has the following major objectives:

- o Conduct fundamental research on a limited, but significant number of topics in cognitive artificial intelligence that are of clear importance to the long-range technology development plans for NASA.
- o Sponsor external research collaborators in academia and industry to help us jointly meet ambitious goals in those research topics.
- o Develop significant in-house NASA expertise in the potential application of the technology being developed to practical NASA problems.
- o Participate in the study and planning of major future NASA missions to determine AI technology needs and provide a pathway for their acceptance.

The program will expand as senior in-house personnel are added and additional resouces are provided to it. Through fiscal 1988, the following seven topics form the foci of the program:

- o Reasoning under Uncertainty--the ability to make sensible judgments and carry out reasonable actions when world knowledge is imprecise or incomplete, heuristics or models have built-in uncertainty, or actions have uncertain effects.
- o Learning--the ability to alter and improve all functionalities as conditions change and knowledge is added over time. Learning may occur manually by being taught or automatically by experimentation, generalization, or discovery.
- o Causal Modeling and Simulation--the ability to utilize structural and functional information about a device, along with the physical laws that govern the device, to simulate and reason about the device.
- o Knowledge from Design through Operations--the ability to preserve the "corporate memory," i.e. to ensure that all the facts, heuristics and other information gained during the design, construction, and testing of a device are available in a practically usable form during the operational life of the device.

- o Advanced Planning Methods--the ability to take a set of goals, design a plan to utilize existing and potential resources to achieve those goals, monitor the execution of that plan, and dynamically alter the plan when initial assumptions prove incorrect.
- o Cooperation among Multiple Knowledge-Based Systems--the ability to provide for synergistic cooperation among several significant knowledge-based systems in a complex environment.
- o Validation Methodologies--the ability to validate the correctness of the facts, heuristics, and models used by a knowledge-based system and to verify the knowledge has been correctly represented within the system. Much of this work will involve practical considerations imposed by the potential end users of knowledge-based systems within NASA.

RATIONALE:

To achieve the ambitious goals for automation of major NASA projects like Space Station it is clear that a enormous amount of both short and long term research is necessary. Short-term work concentrates on generalizing and scaling up existing methodologies to meet NASA needs; this is engineering research. Long-term work involves fundamental scientific research aimed at exploring and developing new methodologies. While it is certainly true that other governmental programs and agencies are interested in solving problems in artificial intelligence common to NASA's, it is also true that simply relying on those programs to meet NASA's AI Technology needs would be naive and unrealistic. The work described in this section represents an attempt to build a strong internal research resource and develop a long-term collaborative team of the best the external world has to offer. Significant sponsorship of external research is necessary both because of limited personnel and other resources within NASA and because it leads to a steady stream of interested and skilled researchers to potentialy devote to NASA problems (and who, in the current form of graduate students, may eventually join the Agency).

APPROACH AND MILESTONES:

As stated above the work will be accomplished by a collaborative research team consisting of scientists and engineers from Ames, industry, and academia. No external work will be conducted as "hands-off" activities; there will always be a senior in-house researcher monitoring and sharing information with the activity. Limited budgetary resources will be leveraged by cooperation with other government-sponsored AI programs, particularly the DARPA Information Science Technologies Office (ISTO). Ames has developed a MOU with DARPA ISTO under which we agree to act as contracting agent and technical monitor for several contracts of mutual interest in exchange for significant influence on the conduct of the work (usually involving the substitution of NASA test domains for other military domains). In addition, we have the right to add funds to DARPA work sponsored through other agents and co-manage the technical directions of that work. In practical terms, this can mean up to a tenfold leveraging of our funds (see examples below).

We will now briefly describe, for each of the research areas described above, how the program will likely proceed in fiscal 1988. In addition, best-guess milestones will be provided for each area. It should be noted that since much of the work is basic science, that milestones beyond a year or two out will most likely undergo significant alteration as the real world dictates the course of such work.

o Reasoning under Uncertainty--We will continue our internal work, led by Peter Cheeseman, on probabilistic methods for uncertainty management. External collaborations will include Lotfi Zadeh's (UC-Berkeley) work on fuzzy logic and research by students in the Stanford Medical Computer Science Group on integration of decision theoretic and heuristic methods. We may also sponsor work by organizations like Advanced Decision Analysis and Advanced Decision Systems in developing methodologies and tools for combining classical methods with AI methods. A synthesis of current ideas will appear in the form of a major review or book during 1988. A practical demonstration of the ideas being developed will occur during the 1990 Systems Autonomy Demonstration Project.

o Learning--By the beginning of fiscal 1988, we hope to have as part of our staff three respected researchers in this area (one is already onboard). Internal work is likely in the areas of learning by discovery and explanation based generalization. External collaborations with Tom Mitchell and Jaime Carbonell at Carnegie-Mellon on learning by experimentation and with John Laird at the University of Michigan on learning as search will continue. Each of these projects has demonstration milestones in the 1988 to 1990 time frame; major milestones include an initial demonstration of learning by experimentation in a robotic environment during 1989 and self-improving knowledge bases as part of the 1990 Systems Autonomy Demonstration Project. During 1991-1992 we plan to demonstrate discovery-based learning by introspection on a large database of sensor-derived information, most likely either as part of a collaboration with SETI researchers or on a DMS-type testbed for Space Station. Truly robust methods will probably not be available until at least 1993-1994.

o Causal Modeling and Simulation--Internally we are using the 1988 SADP Space Station Thermal System as a test domain for the combination of heuristic and model-based methods in diagnosing flaws in complex systems. In addition, we hope that at least one of two candidates currently being pursued in this area come onboard and initiate new internal research programs. Externally we will fund Bernard Ziegler at the University of Arizona in integration of knowledge-based and traditional simulation methods and Michael Genesereth at Stanford University in logical representations of structure and function. A major milestone is the successful demonstration of these methods during the 1988 SADP Thermal System demonstration. More sophisticated methods will be employed in work on the Hubble Space Telescope and other projects that involve modeling complex devices.

o Knowledge from Design Through Operations--Internally we will focus our work on studying the Hubble Space Telescope as a test domain for three research areas: integration of knowledge acquisition into the design, construction, and testing process, acquisition of knowledge from large numbers of experts, and large knowledge base technology. Externally, the Knowledge Systems Laboratory at Stanford will collaborate with us on the latter two topics and Mark Fox at Carnegie-Mellon on the first topic. We will show how design and testing tools can be used for knowledge acquisition during 1988 and 1989. A very large knowledge base system will be demonstrated during 1990. Methodologies for the combination of expertise from at least a dozen experts will be presented during 1990.

o Advanced Planning Methods--Internal work will proceed on testing the limits of current AI-based scheduling methodologies applied to NASA problems, particularly in space science. Work on dynamic replanning will continue and we will initiate research on the application of skeletal planning and plan refinement to NASA domains. Externally we will support and collaborate with work at JPL in sensor-based planning, at IntelliCorp in the development of a Truth Maintenance System-based planner, and at USC-ISI in the application of DARPA-sponsored methods to NASA problems. Current methodologies for heuristic scheduling will be demonstrated in Pioneer Venus experiment scheduling during 1987. The JPL work has milestones in a sensor-rich subsystem of Space Station during 1988 and 1989. That work and other internal and external efforts will be demonstrated as part of scheduling the power subsystem of Space Station during the 1990 SADP demonstration. The TMS-based planner will be delivered to NASA during 1989 and applied to at least one significant problem during that year. Finally, we will integrate learning methods into planning systems during 1989-1990.

o Cooperation among Multiple Knowledge-Based Systems--Our internal research focus will be on the 1990 SADP demonstration; most likely a demonstration of coordinated control of thermal and power subsystems. We will use consider the use of the Hubble Space Telescope as a second domain for cooperative systems. Externally we will support work at the Stanford Knowledge Systems Laboratory in blackboard architectures for distributed control of knowledge-based systems, by Ron Larsen at the University of Maryland in potential hierarchical control methods, and by Tom Sheridan at MIT in languages for command of multiple systems. In addition, a major new effort, jointly sponsored with DARPA, will begin at Stanford, SRI, and Rockwell in methodologies for interacting intelligent agents in the domain of Space Station Construction. Blackboard architectures will be demonstrated in NASA domains during 1988. A plan for coordinated construction of Space Station by human and robotic entities will be presented during 1989 with small scale demonstrations in a robotic test environment at SRI during 1988 and 1989. A practical demonstration of cooperative control (somewhere in the spectrum of distributed to hierarchical) will occur in the 1990 SADP demonstration.

o Validation Methodolgies--During 1987 we will conduct a NASA/Industrial workshop to begin to come to grips with the practical issues of knowledge based system validation in NASA domains with a particular focus on Space Station. This will involve participation from other NASA centers, Boeing, Rockwell, Honeywell, Lockheed, MACDAC, and several others. The result of that workshop will be a detailed report to appear in early fiscal 1988. We are considering several externally-sponsored projects, particularly at Lockheed and Honeywell. The first major milestone will be the development of an accepted validation methodology for the 1988 SADP Thermal System demonstration. Validation work will also occur as part of the work described above on multiple-expert knowledge acquisition and large knowledge base technology. This will produce results in parallel with those milestones in 1989 and 1990.

PRODUCTS AND BENEFITS:

Since the focus is on research rather than development, the most important "products" of our work will be problem-solving methodologies as represented by "existence proofs" and publication in major, respected journals and conferences (in the field of Artificial Intelligence, approximately eight journals and three conferences fit that description). However, because even our long-term research will be conducted in the framework of a difficult NASA problem domain, it is certain that a stream of short-term applications to those domains will result. Our desire to use space science scheduling problems as a test domain for work in advanced planning methods will result in an automated scientific experiment scheduling product for Pioneer Venus during fiscal 1987, and more sophisticated resource management systems for more complex spacecraft in 1988 and later. The Hubble Space Telescope work, in collaboration with MSFC will produce an Orbital Verification system in fiscal 1989 and a full Ground Support system in 1990. A tool to link existing NASA databases to knowledge-based systems will be either built de novo or adapted from commerical products in 1989 or 1990. It has been our experience that the successful conduct of knowledge-based systems research involves long-term interactions with experts in the domains we use to test our ideas. Those experts will only retain their interest in our long-term goals if we provide such short-term benefits to them.

In addition, when existing commercial tools prove inadequate to conduct our research work, we will develop initial forms of new tools to enable our research progress. If those are promising, we will begin the generalization process and attempt to find a suitable, usually commercial mechanism for the "productization" of that work. Part of this may automatically occur in work we sponsor in industry. The areas of Planning and Knowledge from Design through Operations described above are those most likely to result in such generalizable tool developments.

BUDGET AND RESOURCES:

Budget in Fiscal 1987 is $985K. Expected budget in 1988 is $3.5M with a projected increase of $1M/year for the next three years. Of that budget, we expect roughly $1M/year will be spent internally on equipment and support service contractors (Sterling and RIACS mostly) and the remainder spent in sponsoring academic and industrial collaborators. Effective budget in 1988 and beyond, because of the DARPA agreement, will be greater; in 1988 we will be managing at least $2M of DARPA funds on at least two contracts/grants (Stanford/SRI/Rockwell, and USC-ISI) and contributing to at least two DARPA SCI contracts managed by other agents.

By the beginning of 1988, personnel will consist of approximately 8 civil servants and 7 support service contractors (who will be considered full NASA participants in the program). The number of civil servants devoted to research in this core technology area will increase by at least four per year for at least three years with an emphasis on researchers with a PhD in artificial intelligence. Contractors will increase at a considerably slower rate (approximately two per year), as several current contractors will be converted to civil servants upon availability of job slots and naturalization of certain foreign nationals.

TECHNOLOGY DELIVERABLES:

Work conducted under this element of the Systems Autonomy Program spans a range of activities from long-term scientific research to medium-term tool development to short-term applications demonstrations and products. All activities are conducted in the context of challenging NASA problems, and all will have spinoffs into those problem domains. The history of applied AI indicates that particular spinoffs are nearly impossible to predict in advance, particularly this early in an expanding research program. However, for each of the seven major areas of research within this core technology element, we indicate short (0-2 year), medium (2-5 year) and long (greater than 5 year) term goals as they now exist. Shorter term goals are more concrete than longer term ones and fall more into the category of "deliverable" products. In addition, we expect considerable sharing of ideas, tools, and research results with all other elements in the Systems Autonomy Program; in particular, this element will be providing expertise in scheduling and cooperative knowledge-based systems to the SADP element and conducting joint research activiities with the MSFC HSTDEK element.

Machine Learning - A short-term goal is to make the AUTOCLASS system into a useful tool for a wide-variety of data analysis tasks. Medium-term goals are to demonstrate utility of the learning by experimentation approach, and begin to integrate learning mechanisms into diagnosis and control systems useful for missions like Space Station. Longer-term goals include successful model-based discovery systems and full integration of robust learning methods into flight systems.

Planning and Scheduling - Short-term goals are to deliver heuristic scheduling systems to several relevant Agency missions and to demonstrate initial solutions to highly combinatoric science mission scheduling problems. For the medium term there are plans to provide a truth-maintenance-based planning tool for use in dynamic environments and to demonstrate reactive planning in such domains as Mars Rover science planning. A long-term goal is to provide full integration of planning, plan monitoring, and plan execution for complex tasks like Space Station resource scheduling.

Cooperating Knowledge-Based Systems - In the short-term, blackboard systems will be demonstrated as a potential solution to loosely-coupled control of multiple subsystems. Over the medium term, further mechanisms for coordinated control at various points along the distributed to hierarchical spectrum will be developed and applied to NASA problems, and detailed scenarios for interacting intelligent agents performing complex tasks (like construction tasks) will be published. A long-term goal is to demonstrate a system that illustrates full, robust communication of intents, beliefs, and goals among many disparate agents in a major problem domain.

Validation of Knowledge-Based Systems - A short-term goal is to provide a practical solution to the problem of SADP thermal system validation. A medium-term goal is to tightly couple the process of system specification with system implementation for knowledge-based systems so that changes in specification are accurately and automatically reflected in the operational program. A long-term goal is to provide validation solutions for AI systems which can learn and therefore are self-modifying (solutions which are more satisfying than simply revalidating the total system each time a modification is made).

Management of Uncertainty - In the short term, systems which illustrate probabilistic, fuzzy logic, and evidential control of uncertainty will be produced and demonstrated. A medium-term goal is to integrate two or more of these methods into a synergistic approach to the problem. A long-term goal is to combine machine learning with these static methods to achieve robust system behavior under wide varieties of changeable conditions.

Causal Modeling - Short-term goals will be reflected in a demonstrable system which illustrates causal modeling for the SADP thermal management system. Over the medium term, the ability to model interactions among related subsystems (i.e a total system view) will be shown. A long-term goal is to build a system that can model a complicated device at many different levels of detail (dependent on problem-solving needs).

Knowledge Acquisition and Large Knowledge Base Technology - A short-term goal is to illustrate the integration of knowledge acquisition with traditional CAD/CAM design tools. In the medium-term, methodologies for completeness and consistency management of knowledge bases built from multiple sources of expertise will be demonstrated. Over the long term, there will be nearly automatic knowledge acquisition during design, construction, and testing of a complex device, as well as usable, very large knowledge-based systems representing both experiential and functional knowledge about entities as complex as Space Station.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

TASK PLANNING AND REASONING

OBJECTIVES

CONDUCT FUNDAMENTAL RESEARCH IN KNOWLEDGE-BASED SYSTEMS FOR APPLICATION TO CURRENT AND FUTURE NASA AEROSPACE MISSIONS

- DEVELOP IN-HOUSE NASA EXPERTISE AND FACILITIES
- SPONSOR RESEARCH COLLABORATIONS WITH ACADEMIA, INDUSTRY, AND OTHER GOVERNMENT ORGANIZATIONS

PARTICIPANTS AND FACILITIES

PARTICIPANTS

- ARC ARTIFICIAL INTELLIGENCE RESEARCH BRANCH
- ARC SYSTEMS AUTONOMY DEMONSTRATION PROJECT
- JPL ARTIFICIAL INTELLIGENCE GROUP
- UNIVERSITIES: STANFORD, MIT, CARNEGIE-MELLON, MICHIGAN, UC BERKELEY, ARIZONA, USC
- INDUSTRY: SRI, ROCKWELL, LOCKHEED, TEKNOWLEDGE, INTELLICORP, EG & G, HONEYWELL

FACILITIES

- ARC INFORMATION SCIENCE DIVISION LABORATORIES
- COLLABORATORS LABORATORIES AND EQUIPMENT

SCHEDULE AND FUNDING

	88	89	90	91	92
- Reasoning under uncertainty	140	200	240	300	400
- Learning	500	500	500	500	600
- Causal modeling and simulation	250	300	300	300	300
- Knowledge Acquisition	500	500	500	500	500
- Advanced planning methods	450	400	350	400	400
- Cooperating K-B Systems	753	800	800	750	783
- Validation methodologies	330	300	350	400	500
Funding ($K)	**2883**	**3000**	**3050**	**3150**	**3483**
Civil Service MY	**8**	**12**	**16**	**18**	**20**
Support Contract MY	**8**	**10**	**12**	**14**	**16**

JB/PGMPL 7-87 (MH)

A1. AMES RESEARCH CENTER

A1.2 CORE RESEARCH AND TECHONOLOGY (Control Execution).

TITLE: Symbolic Controller.

OBJECTIVE: Develop and test a mathematical theory for the design of symbolic controllers which provide the required interface between the high-level AI planning/supervision levels and the realtime arithmetic levels where the commands are executed and system behavior measured.

RATIONALE: There is a symbolic/arithmetic interface inherent in all intelligent autonomous systems because strategies must first be generated by manipulating data at high levels symbolically by means of high-level languages and then automatically converted into detailed symbolic command sequences. The symbolic commands must then be converted into arithmetic functions of time to be used as guidance signals for the effectors. Similarly, the information gathered by the various sensors measuring the system behavior is initially arithmetic and it is processed arithmetically to obtain estimates of system state. The arithmetic functions of time expressing the system state estimates must then be converted into sentences in the high-level language used by the high levels of the system. Currently, there is a growing body of knowledge on how to design AI systems, and there is an effective methodology, strictly arithmetic, for the design of automatic systems, but there is no methodology for the design of the symbolic/arithmetic interfaces. Such a methodology must be developed.

In addition, since AI is concerned with heuristic reasoning about quasti-static processes, the AI methodology is not directly applicable to the design of dynamic systems. On the other hand, while dynamics is central to the conventional automatic control, design of reasoning algorithms is intractable with the arithmetic methodology in its current form. A method of expressing dynamics concepts symbolically must be found.

APPROACH: The subject research program will explore the possibility of developing a mathematical theory for the design of symbolic contollers for dynamic systems. The approach will be to build up predicate calculus to include time and dynamics concepts within the syntax; explore ways for representing estimated states and time histories symbolically; and explore ways for translating sentences of the command sequences into arithmetic functions of time. In addition, means for expressing global system properties such as stability, robustness, and disturbance rejection will be explored.

The research will be conducted both in-house, and through university grants, and NRC/IPA Research Associateships. The concepts and algorithms will be tested by means of realistic, ARC Symbolic Controller (Continued)

PRODUCTS: Methodology for the design of symbolic controllers.

BENEFITS: Symbolic controllers are essential components of intelligent autonomous systems.

SCHEDULING AND FUNDING:

	FY 88	89	90	91	92
Modal logic calculus for dynamic systems	50	50	75	75	75
State translator	46	50	50	50	50
Verifiable, algorithmic supervisors of arithmetic controllers		25	50	50	50
Tests and evaluation - NASP		25	25		
Tests and evaluation - Robotics				25	25
Totals ($K)	96	150	200	200	200
Civil Service MY	2	2	2	2	2
NRC/IPA		2	2	2	2

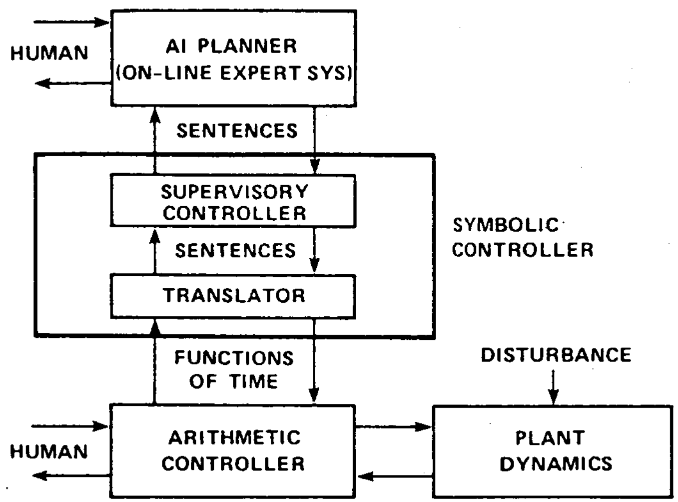
TECHNOLOGY DELIVERABLES:

- o Dynamic model of SADP/JSC Thermal Testbed — Oct 1988
- o Symbolic Control model problem developed — Oct 1989
- o Mathematical procedures for combining high level task planning with low level motion control — Oct 1990
- o Simulation tests of NASP autopilot — Oct 1990

C-2

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

CONTROL EXECUTION - SYMBOLIC CONTROLLER



OBJECTIVES

DEVELOP AND TEST A MATHEMATICAL THEORY FOR THE DESIGN OF SYMBOLIC CONTROLLERS

- BUILD UP PREDICATE CALCULUS TO INCLUDE TIME AND DYNAMICS CONCEPTS WITHIN SYNTAX
- SYMBOLIC REPRESENTATION OF DYNAMIC SITUATIONS
- ARITHMETIC REPRESENTATION OF SUPERVISORY COMMANDS

PARTICIPANTS AND FACILITIES

PARTICIPANTS

- AMES RESEARCH CENTER
- UNIVERSITIES: STANFORD, UC BERKELEY
- NRC AND IPA RESEARCH ASSOCIATES

FACILITIES

- AMES FLIGHT SIMULATORS
- AMES INTELLIGENT SYSTEMS LABORATORY

SCHEDULE AND FUNDING

	88	89	90	91	92
Formal dynamic logic	50	50	75	75	75
State translator	46	50	50	50	50
Command translator		25	50	50	50
Tests - NASP		25	25		
Tests - robot				25	25
Funding ($K)	**96**	**150**	**200**	**200**	**200**
Civil Service MY	**2**	**2**	**2**	**2**	**2**
NRC/IPA		**2**	**2**	**2**	**2**

JB/PGMPL 10-87 (LAH)

A1. AMES RESEARCH CENTER

A1.3 CORE R&T (Operator Interface)

TITLE: Human Interfaces to Automated Systems

OBJECTIVES: The objective of this program is to provide NASA with a capability and focused fundamental research program in human-machine interaction with highly automated systems. Efforts will be directed at three domain areas of interest to NASA's space effort, and the Systems Autonomy Program in particular:

(1) Systems Operation and Fault Diagnosis

(2) Planning and Reasoning

(3) Data Base Query and Access.

RATIONALE: Significant levels of automation are anticipated for many future space-borne systems, including Space Station. Experience with highly automated systems in transport aircraft has shown the need for improvements in the communication of operator intent and machine behavior. Moreover, a substantial proportion of development time is devoted to the human-machine interface. Significant advances in our understanding of human cognition and man-machine interaction are necessary to improve human-machine communication and develop design aids that will shorten development time.

APPROACH: The objectives will be met by developing the fundamental understanding and tools to develop advanced interfaces, and by developing focused applications of prototype interface technology, including very advanced graphics systems and the Virtual Workstation being developed under RTOP 506-47. Improved design aids and interface technologies will be developed in a collaborative NASA - university research program. Prototype applications will be developed using civil servants, in-house support service contractors, and visiting university researchers. Cooperation with other NASA, industry, and academic groups will range from informal sharing of results, sponsoring of joint workshops and symposia, to formal, funded projects. Facilities within ARC/FL will be extended to support in-house research and make it possible to provide appropriate resources to visiting scholars. Augmentations in civil servant research staff will be made to insure the breadth necessary to meet program goals.

PRODUCTS: The products include:

(1) Design Decision Aids and Rapid Prototyping Tools

(2) More Natural Human-Computer Dialog Systems

(3) Advanced Display/Control Concepts

Research and development efforts have been selected that will support the SADP and whose products will be incorporated in post-1988 demonstrations. A major goal of the research program is the development of a prototype Computer Assisted Interface Design (CAID) package that integrates the elements of the research into a single design tool. Specific products include:

DESIGN DECISION AIDS AND RAPID PROTOTYPING TOOLS: The refinement, application, and evaluation of existing formal task analysis models will be undertaken with the goal of improving accuracy and decreasing overhead in use. An in-house action-level model developed for use with the Orbital Refueling System will be extended to cover the Thermal Management System and implemented as a prototype software tool. Theoretical efforts directed at providing the necessary advances in our understanding of selected areas of human information processing will be documented.

MORE NATURAL HUMAN-COMPUTER DIAGLOG SYSTEMS: In-house capabilities in speech and natural language interfaces will be extended and applied to the Human Interface to TEXSYS. Evaluations will be documented and continued experimentation will lead to guidelines for the use of speech and natural language as dialog media. These efforts will be merged with the virtual workstation to produce a prototype virtual interface. Support will be supplied to universities for continuing advancement of natural language interfaces.

ADVANCED DISPLAY/CONTROL CONCEPTS: Research will focus on developing a set of rules, or guidelines, that would suggest how data graphs should be formatted, how schematics or other diagrams are best displayed, and how three-dimensional information should be presented on a two-dimensional screen. In addition to guidelines and reports, this effort will culminate in a prototype expert system for displaying graphic information. This work will be integrated with the virtual workstation.

COMPUTER AIDED INTERFACE DESIGN (CAID) SYSTEM: Individual research and development efforts will be integrated into a prototype computational design tool for interface development. A major emphasis will be on the development of methodologies for interface evaluation. A facility will be developed for iterative testing and refinement of CAID on large scale applications.

BENEFITS: The benefits from such a program would included software tools and guidelines that will facilitate the design and evaluation of human interfaces. The tools and guidelines will embody empirical and theoretical knowledge about human users that will guide the implementation of aids for unanticipated failures and goal directed natural language interfaces.

ARC Operator Interface (Continued)

SCHEDULE AND FUNDING:

	FY 88	89	90	91	92
Design Decision Aids and Rapid Prototyping Tools	200	200	150	150	150
More Natural Human-Computer Dialog	185	150	150	150	150
Advanced Display/Control Graphics		50	50	100	100
CAID Development			53	100	100
Totals ($K)	385	400	403	500	500
Civil Service MY	2	2	2	3	3

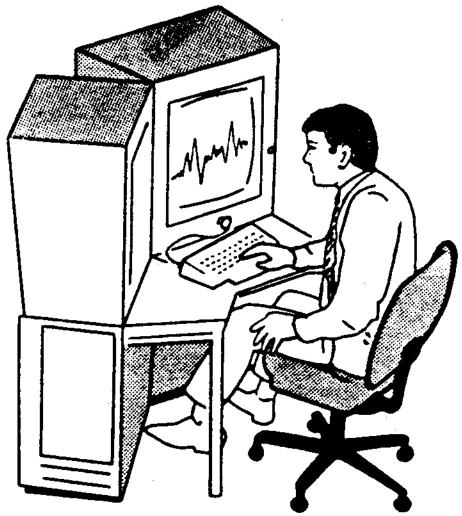
TECHNOLOGY DELIVERABLES: As the Systems Autonomy Program evolves an increasing capability in artificial intelligence and automation systems of increasing complexity will be supervised by fewer human operators. Current systems with high levels of automation have already been associated with a pattern of human error chacterized by a lack of situation awareness and a failure to generate appropriate system expectations. Human interface development and the integration of interfaces with automation and target "plants" is costly and time-consuming. An increased understanding of human cognition is required which focuses on the human operator's conceptual representation of situation, and addresses specific needs such as attention management, human error detection, information management, and communication of action and intent. Coupled with this is the need for tools that facilitate task analysis and the incorporation of task analytic and human performance data in the design of the human interface.

Consistent with these needs the 1988 Technology Deliverables from the Human Interface Core Research Program will center on the application, evaluation, and development of methods for task analysis and operator modeling. These will include: (1) A task model of the thermal control system; (2) A computerized task analysis tool derived, in part, from the application to the thermal control system: and, (3) An evaluation of three cognitive modeling methods. In addition, the 1988 deliverables will include efforts to improve the dialog between the human and an expert system by developing (1) a task-oriented natural language interface and example discourse system for the thermal control system, and (2) an operator-compatible qualitative model of a space-borne process control application designed to facilitate causal explanations. Finally, an Operator Interface Workshop will be held to foster an exhange of information of benefit to scientists, developers, and operators.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

OPERATOR INTERFACE

A MODEL OF THE OPERATOR INTERFACE DESIGN PROCESS



OBJECTIVES

CONDUCT FUNDAMENTAL RESEARCH TO SUPPORT DEVELOPMENT OF INTELLIGENT INTERFACES FOR ADVANCED AUTONOMOUS SYSTEMS. SUPPORT THE OUTYEAR DEMONSTRATION SEQUENCE FOR THE SYSTEMS AUTONOMY PROGRAM IN THE AREAS OF:

- SYSTEMS OPERATION AND FAULT DIAGNOSIS
- PLANNING AND REASONING
- DATABASE QUERY AND ACCESS

DEVELOP A COMPUTER AIDED INTERFACE DESIGN (CAID) TOOL INCORPORATING TECHNOLOGY FROM THREE CORE RESEARCH AREAS:

- DESIGN DECISION AIDS AND RAPID PROTOTYPING TOOLS
- MORE NATURAL HUMAN-COMPUTER DIALOG SYSTEMS
- ADVANCED DISPLAY/CONTROL CONCEPTS

PARTICIPANTS AND FACILITIES

PARTICIPANTS

- AMES RESEARCH CENTER
- UNIVERSITIES
  - GEORGIA INSTITUTE OF TECHNOLOGY
  - ECOLE POLYTECHNIQUE
  - UNIVERSITY OF OREGON
  - NEW MEXICO STATE UNIVERSITY

FACILITIES:

- HUMAN INTERFACE LABORATORY
- PROXIMITY OPERATIONS MOCK-UP FACILITY
- HUMAN RESOURCES LABORATORY

SCHEDULE AND FUNDING

	88	89	90	91	92
Design Decision Aids and Rapid Prototyping Tools	X	X	X	X	X
More Natural Human-Computer Dialog Systems	X	X	X	X	X
Advanced Display/Control Concepts		X	X	X	X
CAID Development		X	X	X	X
Funding ($K):	385	400	403	500	500
Civil Service MY:	2.0	2.0	2.0	3.0	3.0

JB/PGMPL 10-87 (LAH)

A1. AMES RESEARCH CENTER

A1.4 CORE R&T (Systems Integration and Architecture)

TITLE: Spaceborne VHSIC Multiprocessor System.

OBJECTIVE: Develop systems concepts required for the implementation of robust knowledge-based systems in spaceborne applications.

RATIONALE: Current systems under development today such as the 1750A architecture are not suitable for large real-time knowledge-based systems projected for the Space Station environment. Current limitations include the capability to allocate and deallocate large memory stacks vs. pages; the integration of numeric and symbolic processing for both cooperative and autonomous processing of data functions; the management of multiprocessing architecures in an automated, fault-tolerant environment; the management of large knowledge data bases in excess of 1 gigabyte; and, software compilers and translators to support both the development environment and the run-time operational environment. NASA has unique requirements in this area and cannot expect industry and/or academia to pursue this specialized area of research. As an example, Space Station will probably have the first large knolwedge-based system test case for use in a operational test bed environment (Thermal Control System followed by the Power System) which is driven by real-time fault-tolerant constraints placed on space systems.

APPROACH: Specific tasks include the design and development of the spaceborne integrated numeric/symbolic multiprocessor computer; definition and development of the network interfaces and data transmission protocols for an "open architecture" (vendor-independent environment); development of the software protocol and management for large, distributed knowledge-based data systems; development of software compilers and translators for use use in both a development and an operational environment; and, design and development of verification and validation methodologies for fault-tolerant reconfigurable multiprocessor architectures.

PLANNED ACCOMPLISHMENTS: Specific task elements to be accomplished under the System Architecture and Integration Task include the following:

o Processor Architecture

  2nd Qtr., FY-88: Complete the conceptual design of the spaceborne processor including identification of risks and design tradeoffs; delivery of computer models for simulation of the proposed architectures; projected system design configuration for a 6 to 8 processor configuration including weight, form factor, performance, fault tolerance methodologies, both software and hardware approaches, and radiation tolerance. Processor architectures being considered include a 32-bit numeric processor with a VAX instruction set and a 40-bit symbolic processor with a Common LISP instruction set. Current work is being done under a contract awarded to the Symbolics/TRW Team. Completion of this work is scheduled for February 1987.

3rd Qtr., FY-88: Initiate Phase Two of the development effort with contracts awarded to two competing efforts. Phase Two will be for 24 months and will include the detailed design of the multiprocessor architecture including both hardware and software environment and interfaces.

4th Qtr., FY-90: Initiate Phase Three of the effort with the contract awarded to the best of the two efforts from Phase Two above. Phase Three will be for 48 months and will include the development, test, and qualification of the spaceborne unit.

It is expected that Phases Two and Three will be jointed funded by Space Station and DARPA with possible participation by the Navy and Air Force. ARC will be the focal point for this activity.

o Software Environment

This effort focuses on the development of the software environment for the spaceborne multiprocessor. Activities include the development and validation of software compilers and translators for the software development environment and the operational run-time environment. Initially, Ada will be the target baseline language with compilers/translators being developed for compatibility with that language. Attention will be focused on Common LISP, Concurrent Common LISP, and Prolog. ARC will be the focal point for this activity. Other potential participants include Quintus, LaRC, and DoD. During FY-88, funding will either be via IR&D or in-house funding.

o Data Base Management

This effort focuses on the development of data base software methodologies for the control and management of large, distributed knowledge-based data systems including the maintenance and integrity of these large data bases under a dynamic, real-time operational environment. It is expected that these data bases will exceed 10 gigabytes. GSFC will be the focal point for this activity.

o Fault-Tolerant Systems

This effort focuses on the development of fault-tolerant methodologies, both hardware and software, for the management of real-time fault-tolerant reconfigurable multiprocessor architectures. Due to the complexity of these multiprocessor architectures, it is expected that a software approach to fault tolerance will be a significant factor in both processor fault tolerance and immunity to radiation including single event upsets. LaRC will be the focal point for this activity.

PRODUCTS: A Spaceborne VHSIC Symbolic/Numeric Processor capable of handling a minimum of 22,000 rules with an execution rate of 8,000 rules per second (equivalent to 8 mega-instructions per second). The processor will have an execution rate of 10-15 MIPS, 10 GBytes total memory, minimum of 100,000 rads radiation resistance, and a concurrent common LISP, Ada, Prolog, and C development environment.

BENEFITS: This research effort will produce the advanced computational architecture technology for future complex NASA aerospace missions which will require robust intelligent autonomous systems for increased capabilities, productivity, and safety while operating under adverse and hostile aerospace conditions.

SCHEDULE/RESOURCES:

FY	87	88	89	90	91	92	93	94
Concept Definition		====						
User Inputs/Evaluation		====	====	====	==			
Two Brassboards			====	====				
Flight Qualified Unit					====	====	====	===
Funding ($K)	1185	1986	2000	2500	2500	2750	3000	3000
Manpower (Civil Service)	5	5	5	5	4	3	2	2

TECHNOLOGY DELIVERABLES:

Several technology "products" will be derived during the development of the Spaceborne VHSIC Multiprocessor System (SVMS). Since the SVMS is being developed as a heterogeneous parallel computer system, the interim technology deliverables will be primarily software products which are required for the integration and operation of several specialized processors with architectures optimized for specific functions such as numerical processing, symbolic processing, data base management, etc. The SVMS will be fully compatible with the DoD-developed VHSIC line of modules and the 1750A processor. The projected hardware and software products are described below with the target delivery dates:

a. 1988

(1) Performance Metrics/Software "Traps" - A series of test cases representing large complex knowledge-based systems applications in both aeronautics and space domains will provide the reference baseline for the evaluation of the proposed SVMS architectures. The first of these test cases, the Thermal Control System (TCS) for Space Station application, will be available in mid-1988. Projected dates for the remaining test cases are as follows:

Late 1988: "MUSE", an aeronautics test case developed by the Royal Aircraft Establishment (RAE), for automated aircraft applications.

Mid-1990: TCS/Power Test Case, cooperating, intelligent systems for Space Station applications.

TBD: "Autocons", cooperating, intelligent agents for robotic construction of large space structures, a joint NASA/ARC and DARPA effort.

TBD: "Autosis", intelligent robot scientific explorer, a joint NASA/ARC and CMU effort.

(2) Interface standards/protocols - Draft set of guidelines/specifications will be developed to allow the evolution and integration of advanced computer architectures including data networks into the information systems architectures baselined for the Space Station. The concept for implementing the "hooks and scars" for evolutionary hardware and software will be evaluated during this process. The guidelines/specifications will be evaluated using the 1988 TCS Demonstration at NASA/JSC as the baseline system.

(3) Network protocols - The initial effort at defining and implementing the network protocols for multiprocessor systems including the dynamic management of large data bases in excess of 10 GBytes will be developed with delivery of the prototype software network management system. Final version of the software system will be delivered in late 1990.

b. 1989

(1) Performance measurements for multiprocessor systems - Using the test cases developed during the 1988 time period, several multiprocessor system architectures will be evaluated and their strengths and weaknesses identified and investigated. These results will be used in optimizing the system performance of the SVMS design and integrated with the 1990 SADP demonstration involving the automation of two cooperating intelligent systems (TCS and Power).

(2) Data Base Management System (DBMS) - The first version of the DBMS for multiprocessor systems associated with large data bases in excess of 10 GBytes will be delivered and tested. The results of the evaluation will be used in developing the final version of the DBMS targeted for delivery during late 1992.

c. 1990

(1) Automated load scheduler - An automated load scheduler for increasing the utilization of individual processors in a multiprocessor system will be delivered for evaluation. The load scheduler will be integrated into the operating system and will also include the software for fault diagnosis, identification, and correction. Final version is expected to be delivered in 1993.

(2) "Brassboard" SVMS - The brassboard Spaceborne VHSIC Multiprocessor System will be delivered complete with the software required to operate the system and its software development environment. The System will contain flight qualificable components and modules but will not be packaged in a flight configuration. Software capability for fault tolerant management will not be fully developed at this time.

d. 1992

(1) Reconfigurable, fault-tolerant software methodologies - Software for fault diagnosis, identification, and SVMS system reconfiguration using on-chip components for system reconfiguration and hardware fault recovery. Tolerance to single event upsets will also be included as part of the software package.

(2) Validated Cross-compilers and data translators - The initial version of the validated cross-compilers and data translators for the SVMS will be delivered in 1992. Emulations for the 1750A and VAX-780 instruction sets are expected to be included in this effort. The baseline run-time environment is ADA with Common LISP, Prolog, C, and ADA as part of the programming environment. Final version is expected during early 1995.

e. 1995

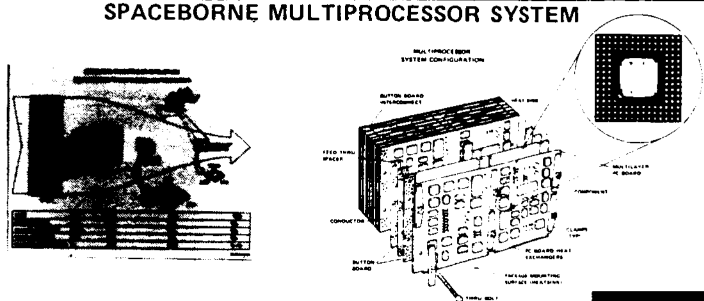
(1) Flight-qualified Spaceborne VHSIC Multiprocessor System, early CY-1995, 4 to 6 processors per system with supporting peripherals (networks, memory, etc.).

(2) Compatible line of VLSI/VHSIC library of hardware modules for specialized functions such as image processing, FFTs, symbolic processing, etc. These modules will constitute the supporting computational elements for the parallel heterogenous SVMS.

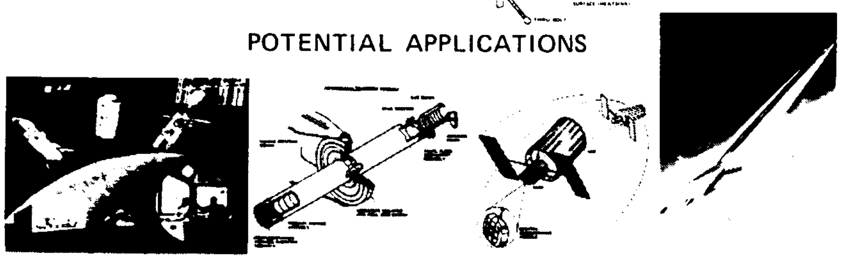
SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

ARCHITECTURE AND INTEGRATION - SPACEBORNE VHSIC MULTIPROCESSOR SYSTEM

SPACEBORNE MULTIPROCESSOR SYSTEM



POTENTIAL APPLICATIONS



OBJECTIVE

INTEGRATED PARALLEL PROCESSOR ARCHITECTURE FOR REAL-TIME KNOWLEDGE-BASED SYSTEMS APPLICATIONS, AERONAUTICS AND SPACE MISSIONS.

- SELF-TESTING, SELF-MAINTAINING, AUTOMATED RECONFIGURATION
- DATA ACCELERATORS FOR SPECIALIZED FUNCTIONS
- 32-BIT NUMERIC AND 40-BIT SYMBOLIC PROCESSORS
- OPTICAL INTERCONNECTS
- VLSI/VHSIC TECHNOLOGY/VHSIC MODULE "LIBRARY"
- CONCURRENT COMMON LISP, ADA, PROLOG, C LANGUAGES
- MINIMUM OF 10^5 RADS RADIATION RESISTANCE
- 10-15 MIPS SYSTEM EXECUTION RATE, 10 GBYTES MEMORY

PARTICIPANTS AND FACILITIES

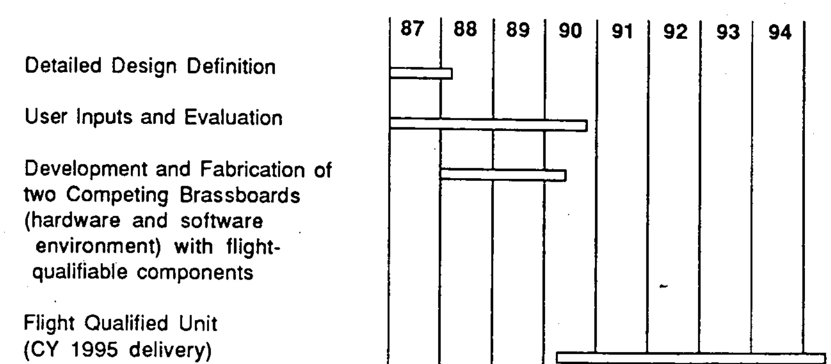
PARTICIPANTS

- AMES RESEARCH CENTER
- INDUSTRY: DEC, TI, CDC, SYMBOLICS, TRW, IBM
- ACADEMIA: STANFORD, UNIV. OF ILLINOIS,
- OTHER GOVERNMENT AGENCIES: DARPA, AIR FORCE
- ROYAL AERONAUTICAL ESTABLISHMENT (RAE), ENGLAND

FACILITIES

- ARC INTELLIGENT SYSTEMS LABORATORY

SCHEDULING AND FUNDING



	87	88	89	90	91	92	93	94
FUNDING ($M)	2.0	2.1	2.0	2.5	2.5	2.8	3.0	3.0
Civil Service MY	5	5	5	5	4	3	2	2

JB/PGMPL 10-87 (LAH)

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A1. AMES RESEARCH CENTER

A1.5 Technology Demonstrations.

TITLE: Systems Autonomy Demonstration Project (SADP).

OBJECTIVE: Demonstrate technology feasibility of intelligent autonomous systems for Space Station through testbed demonstrations.

RATIONALE: The Systems Autonomy Demonstration Project provides a technical focus for automation R&D in support of the agency's space programs, provides the means for validation and demonstration of the automation technology prior to transfer to the agency programs, and establishes credibility of automation technology and user confidence.

APPROACH: The Systems Autonomy Demonstration Project will be a joint effort between researach and operational centers, initially between ARC and JSC with the demonstration being conducted at JSC. It will be a phased knowledge engineering methodology consisting of identifying candidate systems/subsystems for automation (beneficial to agency's programs, demo in operational environment, availability of domain experts); protoype knowledge base development; and implementation in a realistic environment. Demonstrations will involve participation by both experts and novice personnel representing launch operations, mission operations and automated flight subsystems and automated sciences.

The planned 1988 demonstration will focus on automation of the Space Station Thermal Control System (TCS) Testbed at JSC. The automation involves the modeling and simulation of components and configurations of a complex electro-mechanical subsystem, and includes fault diagnosis of a majority of common problems, real-time fault correction for several problems, design and reconfiguration advice, intelligent interface to both novice and expert users, and training assistance.

PLANNED ACCOMPLISHMENTS:

- o Automated control of Space Station (SS) Thermal Control System - 1988
- o Automated control of Two SS subsystems (Thermal/Power) - 1990
- o Automated hierarchical control of multiple SS subsystems - 1993.
- o Automated distributed control of multiple SS subsystems - 1996.

SCHEDULE: FY	87	88	89	90	91	92
TCS Prototype Phase II	====					
TCS Knowledge Base Expansion	===					
TCS Integration into Thermal Testbed		====				
TCS Demonstration		==*				
TCS/Power Prototype		===				
TCS/Power Knowledge Base Expansion			====			
TCS/Power Demonstration				===*		
Demonstration Selection				==		
1993 Prototype Development					====	
1993 Knowledge Base Expansion						====

BENEFITS: The SADP will provide technology for minimizing crew monitoring of Space Station subsystems, increase crew safety through improved systems monitoring, provide design assistance, and training assistance. In addition, the SADP will promote strong working relationships between NASA Centers.

PRODUCTS: Products include verification and validation methodologies, automated systems immune to human-induced errors which allow efficient crew interactions with complex mission-critical systems, automated systems capable of self-monitoring and self-maintaing for extended periods in real-time, and intelligent systems capable of learning and rendering reliable decisions in new and uncertain environments.

	FY	87	88	89	90	91	92
FUNDING ($K)		3470	3399	3500	3500	3500	3500
MANPOWER (civil service)		9	10	12	13	14	14

TECHNOLOGY NEEDS:

The Systems Autonomy Demonstration Project has the following needs for new AI technology.

1988 TCS Demonstration - A method is needed for the Validation and Verification of Expert (Knowledge-based) Systems. If a method is not established for doing this, there will never be acceptance by the NASA user community of the AI technologies. The research will suffer as much as the demonstrations. It has been identified in the Core Technology research plan of ARC-RIA as a key research thrust. It is critical to have major emphasis on the solution to this problem and develop not only the concepts and methods for the 1988 Demo, but stay very focused, and develop actual software for an acceptable long-range NASA solution to the problem. A second technology need for the 1988 Demo is causal modeling and integration of such models with more traditional mathematical or algorithmic models.

1. SADP NEEDS: Validation and Verification Methodology

   CORE DELIVERABLES: Documentation describing acceptable concepts and methods for developing, testing, evaluating and approving expert systems for use on NASA missions.

   Software (as in usable products) to accomplish the above, i.e. computer assisted programming aids, etc.

2. SADP NEEDS: Causal Modeling and Integration of Causal Models with Traditional Mathematical or Algorithmic Models.

SADP DELIVERABLES: The immediate need of SADP for these methodologies necessitated SADP direct funding of the research and development needed for the solution. SADP has concepts, methodologies and actual software that can be contributed to other NASA centers to help with these problems.

1990 TCS/Power Demonstration - There is a need for a planning and scheduling solution for the Power System at Lewis Research Center. The domain experts for the Power System see a need for both reactive and predictive planning and scheduling for a dynamic, multiply constrained resource for Space Station. There is also a need for significant support in the area of cooperating expert systems and the mechanisms for communication, control, and interactive goal and task achievement.

1. SADP NEEDS: Planning and Scheduling System

CORE DELIVERABLES: Design, Development and Testing of a software solution to be integrated into the Power Expert System for the 1990 SADP Demo.

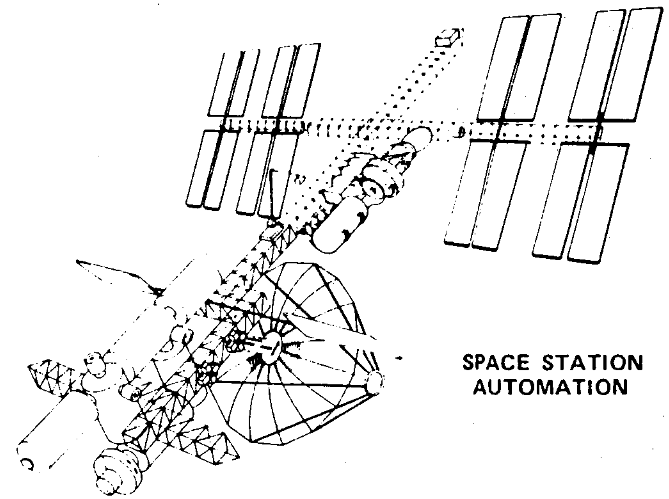
2. SADP NEEDS: Cooperating Knowledge Based Systems

CORE DELIVERABLES: Design, Development and Testing of a software solution to be used to couple the 1988 Thermal System with the 1990 Power System to Demonstrate Cooperating Expert Systems.

1993 and 1996 Demonstrations - The technology needs are for methods to handle multiple subsystem hierarchical or distributed cooperative control, fault recovery from unanticipated failures, planning under uncertainty, fault prediction and goal driven natural language interfaces. The SADP Office will need as deliverables from the Core Technology consulting, development of concepts and methods, and actual software and hardware to solve all of these long-range problems.

SYSTEMS AUTONOMY PROGRAM DEMONSTRATION

SYSTEMS AUTONOMY DEMONSTRATION PROJECT (SADP)



SPACE STATION AUTOMATION

OBJECTIVES

DEMONSTRATE TECHNOLOGY FEASIBILITY OF INTELLIGENT AUTONOMOUS SYSTEMS FOR SPACE STATION THROUGH TESTBED DEMONSTRATIONS

- 1988: SINGLE SUBSYSTEM (THERMAL)
- 1990: TWO COOPERATING SUBSYSTEMS (THERMAL/POWER)
- 1993: HIERARCHICAL CONTROL OF SEVERAL SUBSYSTEMS
- 1996: DISTRIBUTED CONTROL OF MULTIPLE SUBSYSTEMS

DEVELOP NASA IN-HOUSE EXPERTISE AND FACILITIES THROUGH TECHNOLOGY IMPLEMENTATIONS

PARTICIPANTS AND FACILITIES

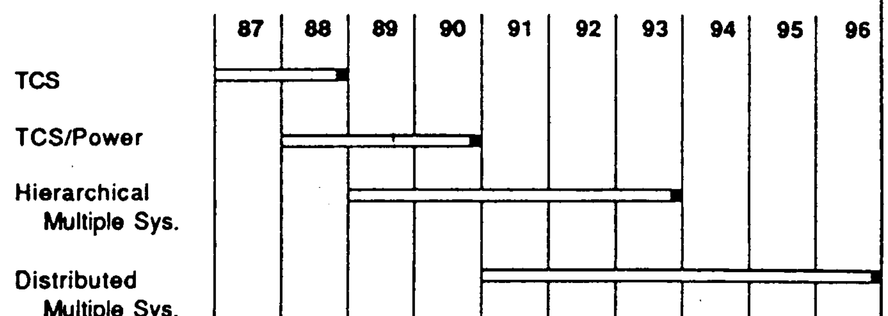
PARTICIPANTS

- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- INDUSTRY: LEMSCO, ROCKWELL INTERNATIONAL, GEOCONTROL SYSTEMS, STERLING SOFTWARE
- LEWIS RESEARCH CENTER

FACILITIES

- ARC INTELLIGENT SYSTEMS LABORATORY
- ISC INTELLIGENT SYSTEMS LABORATORY
- ISC THERMAL TEST BED
- LeRC POWER TEST BED

SCHEDULE AND FUNDING



	87	88	89	90	91	92	93	94	95	96
Funding ($M) (ARC)	3.4	3.5	3.5	3.5	3.5	3.5	3.6	3.8	3.9	4.0
Civil Service MY (ARC)	9	10	12	13	14	14	14	14	14	14

JB/PGMPL 10-87 (LAH)

A1.6 ARC FACILITIES

The implementation of the SATP at the ARC requires an augmentation of existing research facilities. Below is a brief statement about currently available equipment and a newly planned Automation Sciences Research Facility (ASRF). Additional information can be obtained from Refs. 7 and 8.

Existing Equipment for System Autonomy Research

Fig. A1 shows the existing network of computers and some of the hardware development activities which are examples of the kind of development that would be pursued in the ASRF. The ISO currently has the use of six specialized AI work stations and two other workstations, each of which supports only one or two individuals at a time. It also makes extensive use of time-shared DEC VAXes. These machines are located in laboratory space spread over three rooms and are used for software development, simulation, and testing of new algorithms, programs, and systems. The VAX also provides an electronic mail service that is heavily used for information transfer and as connections to other ARC computers, to external services such as the NASA Telemail service, and to the Milnet. Communication links exist from individual computers to terminals and some personal computers located at desks. Most of these terminal devices are directly connected to one of the major computer resources available to the ISO. A few are connected to a data switching system that provides access to multiple computers. Approximately one third of the staff have personal computers at their desk for software development, research, and word processing.

Automation Sciences Research Facility

Since in the coming years the existing facilities cannot support the projected research and development work for autonomous systems, a new ASRF is planned at the ARC. This facility will be in a 43,000 gross square feet building proposed for inclusion in the FY89 CofF budget. The ASRF will contain laboratories, training facilities, and offices to house and support the activities of the ISO. It will provide the space needed to support the organizational growth called for to meet programmatic needs. The facility will provide space and services for a focused program of research and development of automation technology, quick prototyping capabilities, integration validation, and demonstration of these technologies; and training and transfer of these technologies to NASA programs.

Human Performance Research Laboratory

Significant incorporation of AI technologies in Space Station and other future NASA aerospace missions will require fundamentally new rules for human-machine interaction. The Human Performance research Laboratory (HPRL) will provide necessary facilities for this critical integration of AI and Human Factors. The HPRL will provide laboratories and supporting areas required to develop crew interfaces with expert systems and techniques to verify and validate these new technologies. Construction of the HPRL will begin in FY88 and will be a 58,000 gross square foot building including offices and conference rooms. HPRL and ASRF will share a common high bay area containing mockups of portins of the Space Station. These will be used to support high fidelity simulations with the architecture and machinery of the Space Station.

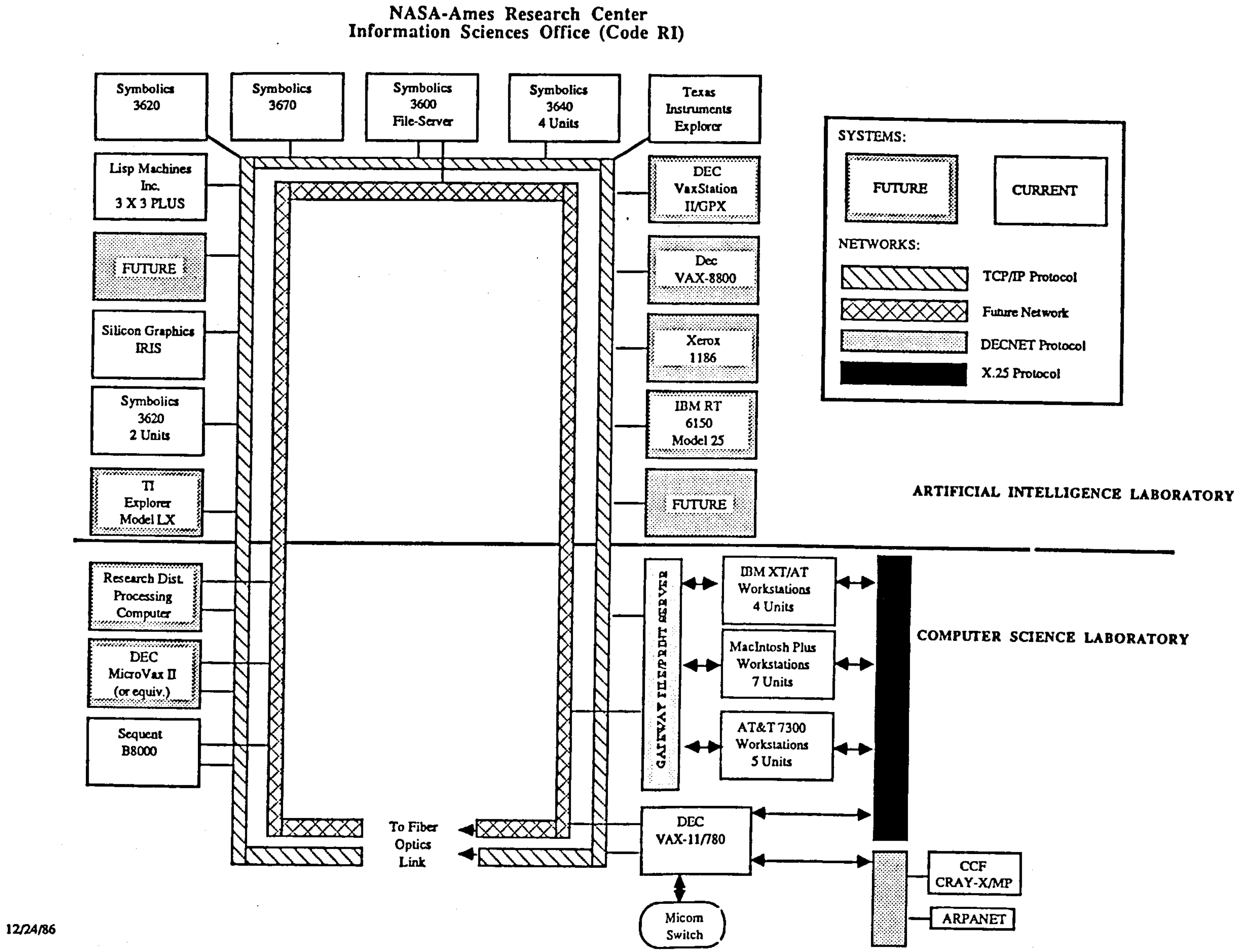


Figure A1 - Existing SATP Computer Facilities at Ames.

A2. GODDARD SPACE FLIGHT CENTER

A2.1. CORE R&T (Systems Integration and Architectures)

TITLE: Knowledge Base Management for Distributed Automated Systems.

OBJECTIVE:

This task will develop knowledge base management technologies needed for automated control center operations realized through the use of distributed cooperating expert systems. A major goal of this work will be to develop a methodology and framework to support the interconnection of discrete knowledge base systems, for cooperative action. Four major classes of technology issues will be studied and addressed under this task. These classes are: System Architecture, System Operations, Knowledge Base, and Human Factors. The system architecture issues include hierarchical structures, distributed structures, connectivity of system elements, architectural alternatives and models of system architectures. The system operations issues include coordination of processes, real-time operations, cooperative processing, dynamic connectivity of processes, and communication protocols among processes. The knowledge base issues include knowledge base development, knowledge representations, replication of knowledge at multiple sites, knowledge segmentation, fusion/synthesis of knowledge, incomplete knowledge, induction/reduction/abduction on knowledge bases, and consistency of distributed knowledge bases. The human factors issues will focus on interfaces/interactions between operators and knowledge base systems, and function allocation between humans and machines. A prime operational goal of this task will be to devise a distributed knowledge base architectural framework which will support high performance management of the knowledge bases. A supporting technology goal will be the prototyping and evaluation of Knowledge Base Management System engineering tools. Another significant goal is to develop in-house expertise in the theory and application of knowledge base management technologies.

RATIONALE:

Current spacecraft control ground/space systems depend on a highly synergistic mix of complex hardware/software systems and dedicated, highly trained operators functioning in a cooperative and collaborative manner to maintain effective and efficient operations. As these man/machine systems become more automated in response and reaction to increasing operational complexity more use will be made of knowledge-based system components. These will be configured and execute in a framework specifically designed to facilitate both coordination and cooperation in supporting operations, and high level interfaces/interactions with the system's human operators. This task helps provide the core technology developments in knowledge base management required to realize this type of automation.

APPROACH:

This research will be a collaborative activity involving Goddard's Data Systems Technology Division and other Goddard and NASA researchers along with researchers from academia and private industry. To ensure ready application, the identification by appropriate NASA centers of demonstration scenarios involving distributed knowledge base systems will be a major factor in establishing the proper focus and direction for this core technology development. The Goddard scenarios that will be used for the same purposes will be based on Space Telescope (ST) ground operations.

Various paradigms for realizing advanced knowledge base management systems operations including blackboard and object-oriented approaches will be formulated, analyzed, and evaluated within the contexts of automated ground systems and large space systems.

The research will address various technology issues associated with knowledge base management systems. These issues include those associated with the following:

- o Expert systems implemented within the framework of a "generic" expert system in such knowledge-based contexts as fault recognition/warning/diagnosis/recovery, planning and replanning, scheduling and rescheduling, fault prediction and trend analysis, and reasoning with uncertain and incomplete knowledge;

- o mechanisms needed for coordination/control of multiple knowledge-based systems;

- o protocols and communication mechanisms needed to support distributed, hierarchical, and heterarchical knowledge-based systems;

- o interactions between operators and knowledge-based systems including explanation aids, multiple levels of information presentation, task-oriented dialogs and error handling.

As the research matures and specific knowledge base techniques are identified and detailed the tools needed to instantiate and maintain operational versions of the knowledge base management systems will be designed, prototyped, and evaluated.

Facilities within the Data Systems Technology Lab along with resources provided by the Space Telescope Project will be used to support the in-house research.

PRODUCTS:

This task will develop:

- models for distributed knowledge-based systems
- model of "generic" expert system
- methodology for task decomposition
- prototypes of frameworks for interconnection of knowledge-based systems - prototypes and evaluations
- evaluation of alternative knowledge base management system architectures
- knowledge base management system development tools - prototypes and evaluations

BENEFITS:

Successful execution of this task will provide:

- proven approaches to knowledge base management applicable for use in demonstration and operational system
- tools to support the design, development and evaluation of knowledge base systems
- identification of knowledge base management techniques/technologies appropriate for Space Station
- development of in-house expertise in the knowledge base management system technologies

SCHEDULE/RESOURCES:

Item	FY	88	89	90	91	92	93
KBMS Model		X	X	X	X		
Generic ES Model		X	X	X	X		
Task Decomposition Methods		X	X	X	X		
Interconnection Frameworks		X		X		X	
Framework Prototypes And Evaluations			X	X	X	X	X
KBMS Tools Prototypes And Evaluation			X	X	X	X	X
Funding $K		198	348	400	450	500	500
Manpower In-House		2.5	2.5	3.0	3.0	3.0	3.0
Contractor		2.0	4.0	4.0	4.0	4.0	4.0

TECHNOLOGY DELIVERABLES:

The GSFC System Autonomy work will provide the following in support of demonstrations:

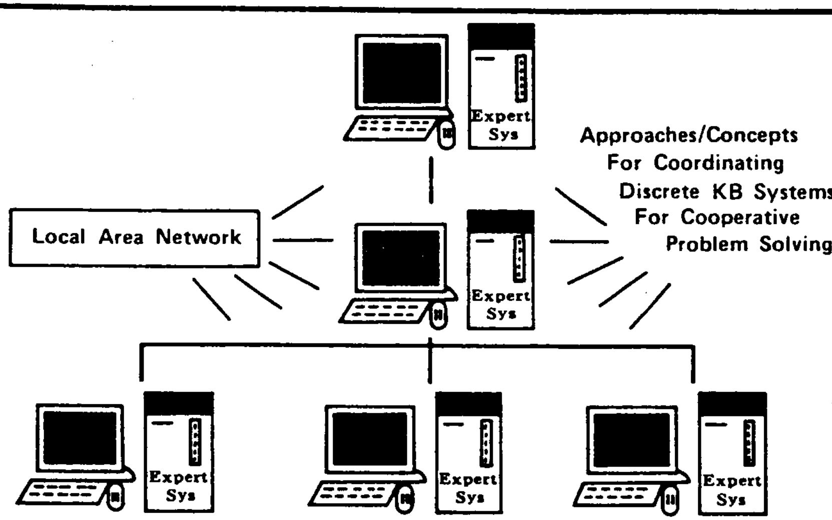
- o models of distributed knowledge-based systems
- o generic expert system model
- o task decomposition methods
- o prototypes and evaluations of frameworks for interconnection of distributed knowledge-based systems. ST and Cobe systems will be used to focus the prototypes and demonstrations.
- o evaluation of alternative KBMS architectures
- o KBMS development tools.

A2.2 GSFC FACILITIES

The prime facility to be used to support the GSFC Systems Autonomy work will be the Code 520 Data Systems Technology Lab. This facility provides Symbolics, Vax 785, Vax 8600, IBM PCs, IBM PSATs, and a Vax Station. Software support includes such components as ART, KEE, OPS5, LISP, MRS, C, NEXPERT, and CLIPS. It is planned that support for the demonstration of advanced technology in the Space Telescope environment will be provided by a network of ST MicroVAXs.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

ARCHITECTURE AND INTEGRATION - DISTRIBUTED KNOWLEDGE BASE MANAGEMENT



OBJECTIVES

DEVELOP METHODOLOGY AND FRAMEWORK TO SUPPORT THE INTERCONNECTION OF KNOWLEDGE-BASE SYSTEMS FOR COOPERATIVE ACTIVITY

- PROVIDE TECHNIQUES FOR HIGH PERFORMANCE KNOWLEDGE BASE MANAGEMENT SYSTEMS IN OPERATIONAL ENVIRONMENTS
- DEVELOP IN-HOUSE EXPERTISE IN THE THEORY AND APPLICATION OF KNOWLEDGE BASE MANAGEMENT TECHNIQUES
- PROVIDE KBMS TOOLS - PROTOTYPES

PARTICIPANTS AND FACILITIES

NASA PARTICIPANTS

- GSFC DATA SYSTEMS TECHNOLOGY DIVISION
- SPACE TELESCOPE PROJECT
- ST GROUND SUPPORT SYSTEMS OFFICE

CONTRACTOR SUPPORT

- INTELLITEK
- FORD
- LOCKHEED
- UNIVERSITY OF MARYLAND (PLANNED)

FACILITIES

- DATA SYSTEMS TECHNOLOGY LABORATORY
- SPACE TELESCOPE OPERATIONS CONTROL CENTER

SCHEDULE AND FUNDING

KBMS Model

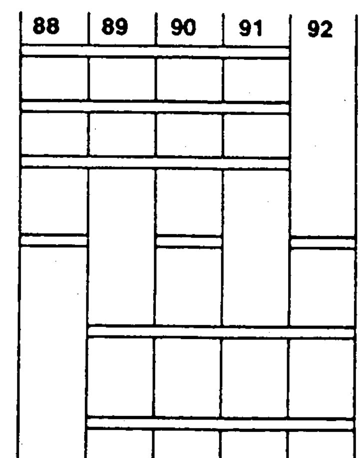
Generic ES Model

Task Decomposition Methods

Interconnections Framework Models

Framework Prototypes and Evaluations

KBMS Tools Prototypes and Evaluations



	88	89	90	91	92
Funding ($K)	198	348	400	450	500
Civil Service MY	2.5	2.5	3.0	3.0	3.0
Contractor	2.0	4.0	4.0	4.0	4.0

JB/PGMPL 10-87 (LAH)

A3. JET PROPULSION LABORATORY

A3.1 TECHNOLOGY DEMONSTRATION

WORK PACKAGE TITLE:
Automation For Mission Operations Ground Data Systems

OBJECTIVES:

The primary objective of this task is to develop and demonstrate technologies which enable and enhance the MULTI-MISSION monitoring and diagnosis capabilities of ground data systems for unmanned spacecraft. Effective detection, isolation, and recovery from anomalies requires consideration of both spacecraft and ground data systems. This task will develop tools commonly applicable to the automated monitoring of spacecraft telemetry and space flight operations ground data systems. Techniques will be developed for automated real-time monitoring of subsystem status, status trend analysis, trouble-shooting, and maintenance. In addition, technology for acquiring, modelling, and applying valuable human operator expertise in subsystem diagnosis and recovery will be developed. A phased series of demonstrations of increasing automated capability are planned. With the objective of a demonstration during the Voyager encounter of Neptune, initial work will focus on automated monitoring of spacecraft telemetry with subsequent extension to monitoring of ground data systems. The principle products of the task will be on-line software demonstrations of automated monitoring and diagnosis capability which are ready for installation in operational systems. The technology developed by this task will reduce human mission operator workload and improve ground operations productivity.

APPROACH:

1. Develop artificial intelligence techniques for monitoring, diagnosis, planning, error recovery, and human interface technology and integrate it into spaceflight operations. Moving this technology into operational environments will entail choosing and implementing the appropriate combinations of artificial intelligence and conventional computer science techniques.

2. Perform R&D necessary for centralized automated real-time monitoring of spacecraft telemetry, and monitoring and control of ground data subsystems. Currently these functions are distributed throughout the system.

3. Demonstrate the telemetry monitor and analysis capabilities for selected Voyager spacecraft subsystems during Neptune encounter.

A series of demonstrations of increasing autonomous capability are planned which are well correlated with the thrust of other System Autonomy Demonstration Programs and draw upon the technology developed for those demonstrations. The approach will be to develop new technology and to validate other technology developed in the System Autonomy program. Each demonstration makes available items of significant new technology which may be incorporated into operational ground data systems. Most of the demonstrations take place in actual mission operations facilities, including the JPL Space Flight Operations Center (SFOC) prototype, the existing Real Time Data System in the Space Flight Operations Facility (MCCC RTDS), and the (future) baseline SFOC facility.

BENEFITS:

This task will develop systems which will reduce workforce and improve productivity associated with the monitoring of spacecraft telemetry and the monitoring and control of ground data systems.

Currently the Flight Projects each have dedicated spacecraft teams consisting of real time and nonrealtime subsystem analysts. The real time subsystem analysts perform the functions of ensuring correct subsystem performance, identifying and characterizing subsystem anomalies, and identifying and initiating corrective actions. Real time analysts can be expected, depending on mission activity, to provide 24 hours a day, 7 days a week online support. This requires 1 to 3 persons for each subsystem per mission. With automated spacecraft subsystem monitoring tools, mission controllers may be able to perform these real time analyst functions. This has the potential of reducing a typical single project staffing by up to 21 real time personel.

The ground data system contains approximately 73 on-line CPUs which process spacecraft status and science data telemetry. Currently, approximately 23 displays are required to monitor ground data system status at 5 different locations. During spacecraft cruise flight stages, approximately 2 operators are needed at each of the five locations. This workforce is supplemented by additional personnel associated with individual flight projects coincident with encounter stages of flight.

This task will achieve the following productivity benifits:

1. Enable rapid detection and isolation of spacecraft and ground data subsystem faults, detection of failure trends, and recommendations for fault recovery. This will reduce the necessity for human monitoring of the spacecraft telemetry data, reduce ground data system downtime due to failures, and enable improved capture of scientific data. The workforce associated with spacecraft and ground data system trouble-shooting and recovery could be reduced, especially during encounter phases of flight.

2. Enable automated, on-line verification of uplink commands thru intelligent analysis of the downlink telemetry data to assist mission operators in the conduct of their mission. The workforce associated with spacecraft command verification could be reduced or freed to continue mission planning.

3. Enable rapid, automatic software and hardware reconfiguration in the ground data system in response to both scheduled spacecraft needs and to anomalies. This will result in improved system response with fewer resource conflicts and reduce the associated operator workforce.

4. Provide an automatic, uniform historical accounting of ground data system status and procedures in a representation suitable for computation. This would enable easy reference for training as well as real-time system control by operators or future automated systems.

PLANNED ACCOMPLISHMENTS:

1. MONITORING WORKSTATION
Development of a multi-mission telemetry monitoring workstation which provides a centralized monitoring capability for spacecraft engineering telemetry. The initial system will focus on support of the Voyager spacecraft. Developments for this demonstration will make use of monitoring and diagnosis techniques being developed for the JSC Thermal Management System demonstration and for the JSC INCO demonstration. System capabilities/features include:

On-line real-time monitoring of spacecraft subsystem engineering data.

Monitoring of spacecraft and limited ground factors which influence the data quality of spacecraft telemetry. This is a precursor to full monitoring of the ground data systems, and will include identification of additional sources of information necessary for a full monitoring capability. Examples of factors to be monitored include:

Antenna pointing residual.

Lock Status.

Frame Status.

S/N ratio.

Heuristic diagnosis of spacecraft subsystem anomalies. This capability will capture existing valuable expert knowledge on detection and isolation of anomalies. Reasoned correlations between anomalies on multiple spacecraft subsystems will be automatically generated. Upon isolation of a fault, any information about known, appropriate recovery procedures will be automatically presented to human operators for consideration.

Trend detection and monitoring of spacecraft subsystem status/health data.

Human factors based display, including graphical icons, menus, and improved command language.

Logging of data and significant events, including automatic report generation where standard formats are currently available.

2. AUTOMATED MONITORING FOR VOYAGER AT NEPTUNE
This effort will apply the Telemetry Monitor Workstation described in #1 above to the monitorins in support of the Neptune encounter as well as selected ground system factors. The workstation will be integrated with the MCCC Real-time Data System and be on-line for the encounter.

3. GROUND DATA SYSTEM MONITORING WORKSTATION
This effort will apply and extend the techniques developed in the automated Monitoring Workstation to the monitoring of additional ground data systems. This second, independent workstation will be integrated with the existing or developing SFOC Monitor and Control subsystem (SMC) and installed in the SFOC Prototype for evaluation.

4. INTEGRATED SPACECRAFT AND GROUND DATA SYSTEM MONITOR
Effective real-time detection and isolation of faults in either the spacecraft or ground data system requires close consideration of both spacecraft engineering telemetry and ground data system health and status. This effort will fully integrate the two workstations developed previously for monitoring and diagnosis of spacecraft telemetry and ground data systems. Techniques developed as part of the 1990 Space Station demonstration of coordination between thermal and power systems would be utilized. The system would be installed in the baseline SFOC for evaluation in support of on-going multi-mission operations.

5. EXTENDED GROUND DATA SYSTEM DIAGNOSIS AND MAINTENANCE
The objective of this effort would be to develop the capability to command ground data subsystems to run diagnostic tests and provide additional status data. The system would be installed in the SFOC prototype. In addition to all the capabilities provided by the Telemetry and Ground Data System Monitoring workstations, software hooks and hardware scars for subsequent hardware and software configuration planning and control in the ground data system would be included along with the following new capabilities:

Automatic running of preventive diagnostics on ground data subsystems, including peripherals such as tape drives and printers at remote locations.

Diagnosis and verification of network health and configuration by automatic sending of test data blocks. Automatic commanding of ground data subsystems to provide additional status or diagnostic information on demand. These will require reasoning about real-time resource conflicts with other tasks, e.g., to avoid taking systems off-line for troubleshooting when they are actively supporting operations.

Model-based diagnosis. This development will give the system the capability to reason about system failures using models and knowledge about the structure and function of subsystems in addition to the heuristic diagnosis capabilities developed in earlier tasks. This effort will provide additional automatic diagnostic capabilities to human troubleshooters which they do not now possess.

Implementation of software and hardware modifications necessary to support automated software and hardware configuration control in the ground data system. Subsequent tasks, as described below, will build on this capability.

Improved trend detection and evaluation of a greater number of subsystem health parameters.

Automated logging of all operator invoked diagnostics.

Real-time performance improvements, including multi-processing techniques for combining real-time monitoring, diagnosis, and commanding.

6. SPACECRAFT COMMAND VERIFICATION
The Telemetry Monitoring Workstation will be extended to utilize uplink spacecraft command sequences in the anticipation of spacecraft mode changes. This will enable automatic switching of format and alarm tables and thus reduce or eliminate this cause of data lossage. If appropriate spacecraft models are available, they will be used to generate predictions about engineering telemetry and thus further verify command completion. This development and installation will utilize the baseline SFOC.

7. DYNAMIC GROUND DATA SYSTEM CONFIGURATION CONTROLLER
The objective of this development is to extend the command and control ability of the ground data system monitoring workstation to dynamic hardware and software configuration control of ground data subsystems in the SFOC prototype. The task would extend SOE (Sequence of Events) planning to automatic generation of actual commands to accomplish the necessary changes. In addition to the capabilities provided by the earlier efforts, this development will include:

Automated planning and scheduling of hardware and software configuration changes, taking into account scheduled spacecraft needs, on-going maintenance, and other constraints on acceptable plans.

Automatic generation of extended configuration command sequences for the ground data system.

Supervised execution of dynamically generated ground data system configuration change sequences and autonomous verification of change command completion.

Full automation of simple recovery procedures e.g., those which respond to well known, or less critical anomalies.

Logging and internal representation of reconfiguration and other commands which are issued by operators in response to anomalies.

Automatic dynamic generation of alarm limits based on planned hardware and software configuration changes.

Diagnostic test selection in response to novel failures.

8. TEACHABLE GROUND DATA SYSTEM CONTROLLER
The objective of this development is to extend the control ability of the ground data system monitoring workstation to areas not covered by the earlier efforts and to automate the application of more sophisticated error recovery procedures. Importantly, the ability to acquire diagnostic and error recovery techniques directly from operators while the system is on-line is a new feature. The system would be developed and installed in the SFOC prototype. Capabilities include:

Fully automated configuration management.

Error recovery planning in response to novel failures in addition to application of standard recovery procedures.

Acquisition and ability to apply diagnosis and recovery procedures which are used by human system operators, including through a teaching mode as well as a "silent apprentice" mode where the system passively observes human procedures.

JPL Gnd. Data Sys. (Continued)

SCHEDULE:

ITEM/CY	88	89	90	91	92	93	94
1. Telemetry Monitoring workstation	---X						
2. Automated monitoring for Neptune Voyager		-------X					
3. Grnd Data Sys Monitor			--------X				
4. Integrated Telem/GDS monitor				-----X			
5. Extended GDS diagnosis/maintenance				-------X			
6. Spacecraft Command Verification					--------X		
7. Dynamic GDS Config. Controller						---------X	
8. Teachable GDS Controller							------X
Funding ($K)	347	350	350	350	350	350	350
JPL WORKFORCE	3	5	5	5	5	5	5

TECHNOLOGY NEEDS:

The Mission Operations Ground Data Systems demonstration task has needs for technology concepts and methodologies in several important areas. In the human interface area, the principle needs are for monitoring, diagnosis, planning, and control system display techniques. In the area of monitoring technology, methods for knowledge based signal to symbol transformation and situation assessment are needed. In the area of diagnosis technology, techniques are required for reasoning with uncertain or missing data, reasoning with deep knowledge, and hybrid technique diagnostic systems among others. Planning technology required for out-year demonstrations is required in the areas of maximizing resource utilization, dynamic replanning, and hybrid AI/Operations Research planning systems. Software validation and verification remain key methodological requirements, especially testing and verification procedures for knowledge based and hybrid systems. Finally, techniques are required which enable real-time processing in knowledge based systems. We expect most of this technology to be developed as part of the baseline core research program and the above mentioned requirements should not be considered hard levies on those tasks; instead, the requirements should be considered opportunities to utilize the advanced technology when it becomes available.

A3.2 JPL FACILITIES.

Artificial Intelligence Laboratory:

The Artificial Intelligence Laboratory currently includes six Symbolics LISP Machines, one of which is a color system. The site has over 1660 MBytes of hard media storage availabe, soon to be expanded. Three Sun 3/280C mini-computers will soon be added and will provide the basic development system for the demonstration. In addition, approximately three additional LISP Machines will be added in the coming year. Network connections to the USC campus provide the site with ARPANET access. The site is also connected locally to other JPL sites via the JPL local area network. The AI lab also has a complement of four Mac+ and one Mac SE for office automation. There are two Laserwriter printers and several other dot matrix and impact printers also available for general use.

Advanced Prototype Laboratory:

The demonstration will also make extensive use of the Advanced Prototype Laboratory at JPL. This site includes a wide variety of mainframe, mini, and micro-computers which are being evaluated for incorporation into the Space Flight Operations Center. The prototype lab's primary objectives are to test the key SOFC data system concepts and to model the required SFOC throughput and response time using real and simulated spacecraft telemetry. The Voyager telemetry monitoring demonstration during the Neptune encounter will take place in this facility. The facility will soon be connected via an ethernet to the Artificial Intelligence Laboratory.

Advanced Prototype Lab computers and support facilities include:

Sun computers (two 3/280, eight 3/50, one 3/160c)
VAX 11/750 running VMS
Microvax
Mascomp
Several IBM PC-AT
one Xerox 1108
one Symbolics 3640
one Apple Mac+, Mac II, and one Atari
Special hardware includes LAN analysers, graphics cameras, and a fiberoptics backbone using standard ethernet interfaces.
Additional shared facilities include a VAX 8600 running UNIX.

SYSTEMS AUTONOMY PROGRAM DEMONSTRATION

MISSION OPERATIONS GROUND DATA SYSTEM AUTOMATION

73 On-Line OPUs, 23 Displays, 5 Locations
Potential workforce savings >21 real time personnel per project

OBJECTIVES

AUTOMATION OF MONITORING AND CONTROL FUNCTIONS IN PLANETARY MISSION OPERATIONS

FUNCTIONAL CAPABILITIES:

- MONITORING WORKSTATION
- DIAGNOSIS AND MAINTENANCE
- DYNAMIC CONFIGURATION COMMANDER
- TEACHABLE GROUND DATA SYSTEM CONTROLLER

TECHNOLOGY THRUSTS:

- HEURISTIC AND MODEL-BASED DIAGNOSTICS
- MULTIPLE DATA SOURCE FUSION
- SYSTEM RESOURCE PLANNING AND SCHEDULING
- MODELS OF APPRENTICE LEARNING

PARTICIPANTS AND FACILITIES

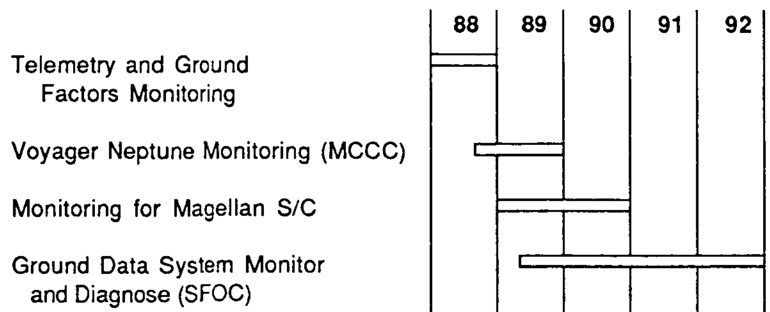
PARTICIPANTS

- JPL ARTIFICIAL INTELLIGENCE GROUP
- SPACE FLIGHT OPERATIONS SECTION
- CONTROL CENTER DATA SYSTEMS DEVELOPMENT
- PROJECT TEST AND OPERATIONS SECTION

FACILITIES

- JPL AI LABORATORY
- MCCC REAL TIME DATA SYSTEM
- SPACE FLIGHT OPERATIONS CENTER (SFOC)

SCHEDULE AND FUNDING



	88	89	90	91	92
Funding ($K)	**347**	**350**	**350**	**350**	**350**
JPL MY	**3**	**3**	**3**	**3**	**3**

JB/PGMPL 10-87 (LAH)

A4. JOHNSON SPACE CENTER

A4.1. TECHNOLOGY DEMONSTRATION.

Title: STS Flight Control Room Operations - INCO Expert System Operational Readiness Demonstration Prototype.

Objectives :

Develop an expert system for monitoring Space Shuttle communications and instrumentation systems which can be used to evaluate if expert system technology is sufficiently mature for use in decision making where human lives and major NASA vehicles are in jeopardy.

Connect this expert system to a real time Shuttletelemetry source and evaluate its performance during simulations. If simulation performance is acceptable, evaluate performance during actual Space Shuttle flight.

Evaluate the problems of developing, verifying, certifying an expert system for use in the shuttle Mission Control Center. Evaluate training requirements for operators.

Evaluate the use of laser disk technology and advanced graphics technology to replace paper products currently used by flight controllers.

Approach :

Taks Automation algorithms for fault detection of shuttle communications and instrumentation systems had previously been defined by Mission Operations Directorate personnel at JSC. Rules for an expert system to monitor Space Station communications systems had also been developed by these personnel. In this project the task automation algorithms will be coded on a UNIX workstation and combined with a rule based expert system built from a modified rule base from the earlier space station efforts. A standalone telemetry processor will be interfaced to the workstation and then integrated into the Shuttle Mission Control Center data system .

Evaluations will initially be performed in a laboratory environment utilizing shuttle telemetry tapes. After confidence is gained in the combined automation/expert system, it will be moved to the Flight Control Room in the Mission Control Center for use in integrated simulations. It will initially be used as a consultant to an experienced flight control team, then as a component of a "reduced" team with fewer operators to evaluate the use of the expert system to lower manpower requirements. After extensive testing , the system may be used as a consultant during actual shuttle flight if sufficient confidence can be gained in the system.

Laser Disk and advanced graphics technology will be integrated into the system after initial use in the MCC.

JSC INCO (Continued)

Planned Accomplishments:

Demonstration of use of microprocessor based telemetry processor supplying real time telemetry information to a rule based expert system.

Integration of task automation fault detection algorithm technology with a rule based expert system technology.

Use/Evaluation of task automation/expert system technology in a real operational environment.

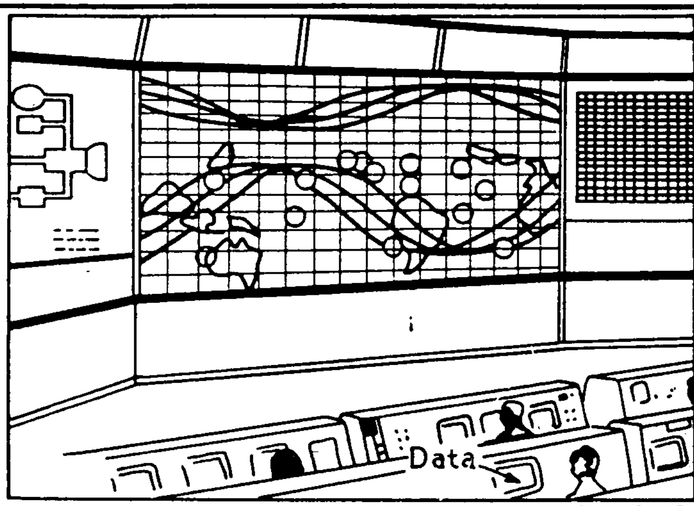
Use/Evaluation of Laser Disk Technology and advanced graphics to replace paper products used in the MCC by flight controllers.

Schedule:

Item	FY 87	88	89	90
Real Time Data Interface	May			
Task Automation/ Expert System Developed	Sept			
Simulation Demonstrations	Nov			
Use Inflight		Feb		
Revision 2 Expert System		Oct		
Integration of Laser Disk and Advanced Graphics		Nov		
Demonstration Of Revision 2 Inflight			Jun	
Funding	250K	620K	350K	
Manpower	1	2	2	

SYSTEMS AUTONOMY PROGRAM DEMONSTRATION

SHUTTLE FLIGHT CONTROL ROOM OPERATIONS



FLIGHT CONTROLLER

OBJECTIVES

DEVELOP AN ONLINE EXPERT SYSTEM TO RUN IN THE MISSION CONTROL ENVIRONMENT TO MONITOR AND MAKE RECOMMENDATIONS REGARDING MANAGEMENT OF SPACE SHUTTLE COMMUNICATIONS

FUNCTIONAL CAPABILITIES:

- LASER DISK STORAGE
- ADVANCED GRAPHICS INTELLIGENT INTERFACE ("PAPER FREE" CONSOLE)
- FAULT DETECTION ALGORITHMS
- FAULT CORRECTION ADVICE

TECHNOLOGY THRUSTS:

- HEURISTIC RULE KNOWLEDGE-BASE METHODOLOGY
- TECHNIQUES TO INTERFACE EXPERT SYSTEMS TO ANY TM SYSTEM
- ADVANCED GRAPHICS AND DATA STORAGE TECHNIQUES
- OPERATOR TRAINING TECHNIQUES
- VERIFICATION/VALIDATION TECHNIQUES

PARTICIPANTS AND FACILITIES

PARTICIPANTS

- LYNDON B. JOHNSON SPACE CENTER
  MISSION OPERATIONS DIRECTORATE
- AMES RESEARCH CENTER

FACILITIES

- JSC SYSTEMS OPERATIONS DEVELOPMENT LABORATORY
- JSC SHUTTLE MISSION CONTROL CENTER

SCHEDULE AND FUNDING

Initial Requirements/Design

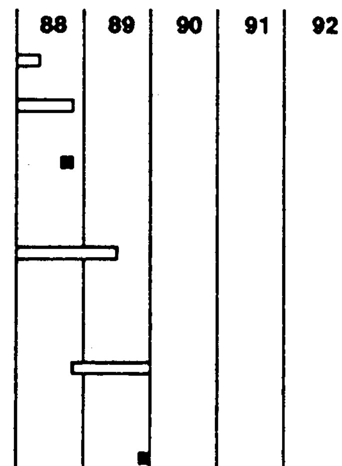
Prototype Code/Test

Demonstration in STS Simulation/ Evaluation in Flight

2nd Level Prototype Reqts/Design (Incorporate advanced graphics/ enhanced expert system)

Demo 2nd Level Prototype Evaluation in STS Flight

Evaluation Complete



	88	89	90	91	92
Funding ($K)	620	350			
Civil Service MY	2	2			

JB/PGMPL 10-87 (LAH)

A4. JOHNSON SPACE CENTER

A4.2. SADP TECHNOLOGY DEMONSTRATION.

TITLE:

Space Station Thermal Control Expert System (TEXSYS)

OBJECTIVE:

The major objective of the 1988 Demonstration, TEXSYS, is the implementation of AI technology in a real-time dynamic environment of a complex electrical- mechanical Space Station system-the Thermal Control System. Specific objectives include:

- o Real-time control
- o FDIR-fault detection and identification for all major faults, reconfiguration or isolation for a limited subset of faults.
- o Trend analysis for incipient failure prevention
- o Intelligent human interface
- o Causal modelling
- o Reasoning based on standard procedures
- o Qualitative and quantitative simulation
- o Integration with a real-time system
- o Validation and verification demonstration
- o Training and design assistance for Thermal engineers

RATIONALE:

The Thermal Control Expert System (TEXSYS) will demonstrate significant use of state-of-the-art AI technology in a real-world domain and will serve to "push" the state-of-the-art in several specific areas. The slow dynamics of thermal systems reduce certain technical risks, which allows concentration on technical issues which are currently of greatest interest to the SADP. The Thermal Test Bed is a bona-fide Space Station test bed, and as such, will facilitate the transfer of the technology to be demonstrated to the Space Station (and other) programs. Plans call for interfacing the Thermal Test Bed with other Space Station test beds. This will allow interfacing of TEXSYS with other test bed expert systems, thus providing a natural framework for supporting future goals of the SADP; i.e, demonstrations of cooperating, hierarchical, and distributed expert systems.

APPROACH:

The 1988 Demonstration is a ground-based demonstration of an expert system used to monitor, control, and diagnose faults for test article hardware within the Thermal Test Bed (TTB) at JSC. The TTB is an evolutionary program designed to develop a ground based system representative of the Space Station thermal control system, to verify the readiness of two-phase thermal technology and to provide system level evaluation of advanced thermal control technology for Space Station use. The Thermal Control Expert System (TEXSYS) will be fully integrated with the TTB and its conventional system and subsystem controllers.

TEXSYS will be developed jointly by Ames and JSC personnel with participation from industry contractors.

JSC TCS Demo (Continued)

PRODUCTS:

An expert system which:

- o Monitors, controls, and performs FDIR on a complex electrical-mechanical system operating in a real-time dynamic environment
- o Provides assistance to test bed engineers during test operations
- o Provides a flexible, intelligent human interface
- o Demonstrates incipient fault detection via trend analysis
- o Provides a facility for training and design assistance for thermal engineers

BENEFITS:

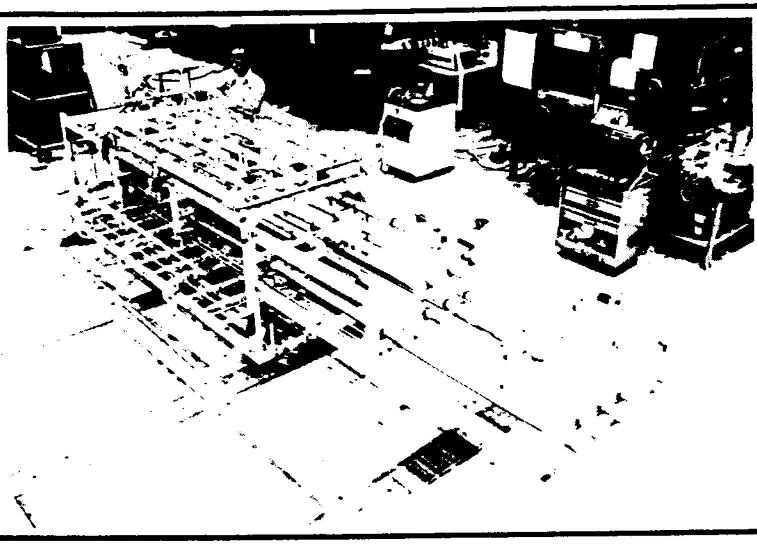
See RATIONALE

SCHEDULE:

FY	87	88	89	90	91
Development	====				
Requirements Definition	==				
Design Definition	==				
Integration into Testbed		===			
TCS Demonstration		*			
Power System Interfaces			====		
TCS/Power Demonstration				===*	
Analysis, Reporting					===
Funding ($K)	600	600	500	300	100
Civil Service MY	3	4	2	2	1

SYSTEMS AUTONOMY DEMONSTRATION PROJECT

SPACE STATION THERMAL CONTROL SYSTEM (TEXSYS)



OBJECTIVES

IMPLEMENTATION OF AI TECHNOLOGY INTO THE REAL-TIME DYNAMIC ENVIRONMENT OF A COMPLEX ELECTRICAL-MECHANICAL SPACE STATION SYSTEM - THE THERMAL CONTROL SYSTEM.

FUNCTIONAL CAPABILITIES:

- FAULT DIAGNOSIS OF MAJORITY OF FAILURE MODES
- REALTIME CONTROL AND RECONFIGURATION
- INCIPIENT FAILURE PREVENTION THROUGH TREND ANALYSIS
- INTELLIGENT INTERFACE TO BOTH NOVICE AND EXPERT USERS

TECHNOLOGY THRUSTS:

- KNOWLEDGE-BASED INTEGRATION INTO REALTIME ENVIRONMENT
- CAUSAL MODELING OF COMPLEX COMPONENTS AND ELEMENTS
- COMBINED MODEL-BASED AND EXPERIENTIAL RULE-BASED KNOWLEDGE
- VALIDATION METHODOLOGIES

PARTICIPANTS AND FACILITIES

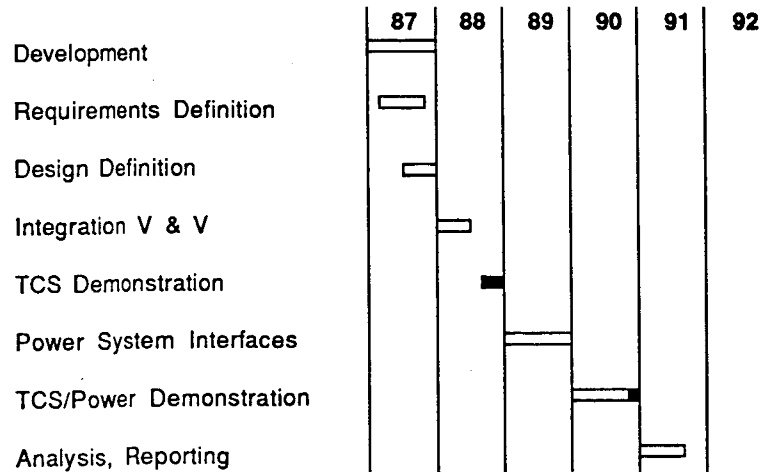
PARTICIPANTS

- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- INDUSTRY: LEMSCO, ROCKWELL INTERNATIONAL, GEOCONTROL SYSTEMS, STERLING SOFTWARE

FACILITIES

- ARC INTELLIGENT SYSTEMS LABORATORY
- JSC INTELLIGENT SYSTEMS LABORATORY
- JSC THERMAL TEST BED

SCHEDULE AND FUNDING



	87	88	89	90	91	92
Funding ($K)	600	600	500	300	100	
Civil Service MY	3	4	2	2	1	

JB/PGMPL 7-87 (MH)

A4.3 JSC FACILITIES.

JSC SADP TEXSYS FACILITIES:

The SADP TEXSYS facility will be located in Building 32 of the Johnson Space Center. This building is used by the Crew and Thermal Systems Division to perform vacuum and sea level testing of the prototype equipment for the Space Station thermal control system. The TEXSYS demonstration will use a prototype of the central thermal bus, supported by simulated heat sources and radiators, as its target system. The bus will have a MicroVAX II computer system as its data acquisition and control computer, using a commercial package called FLEXCON. In addition, a data archive system will be storing the real time data on a VAX 8650. The expert system will run on a Symbolics 3650 computer (using the KEE expert system shell) and a separate, undetermined computer will run the human interface software. All of these computers will be connected using DECNET protocols over an Ethernet.

JSC INCO FACILITIES:

INCO is an acronym for Instrumentation and Communications Officer. The INCO is the flight controller in the Space Shuttle Mission Control resposnible for monitoring and controlling the Space Shuttle instrumentation and communications systems. In the INCO Expert System Project, we are building a real time expert system to assist INCOs in monitoring Space Shuttle missions.

The goal of the INCO Expert System Project is to evaluate the performance of a real time expert system monitoring the Space Shuttle in a real operational environment. Two facilities are being used. The Systems Operations Development Laboratory (SODL) is being used as a development facility. When development is complete, the system will be moved into the Space Shuttle Mission Control Center (MCC) for use in simulated and real Space Shuttle missions.

The Systems Operations Development Laboratory is a single room located in the Flight Operations Suppport Facility (Building 4) at JSC. The SODL is currently hosting two projects in addition to the OAST (Code R) funded INCO project. One is currently sponsored by Space Station (Code S) and utilizes a Symbolics computer to prototype expert system based systems management concepts. A second project is hosted by Space Shuttle (Code M) and utilizes Optical Disk Technology and an IBM PC to store and retrieve data from the Shuttle Inflight Maintenance Database. The laboratory is approximately 300 square feet in size and has separate dedicated air conditioning and power connections. The door is protected by a Cipher Lock. The facility however is not cleared for classified work. A Local Area Network (LAN) server connects the SODL to the JSC Space Station Data Management System Testbed for Space Station project work.

The INCO project has placed several new pieces of equipment in the SODL which have significantly increased its capabilities. The INCO project has purchased a Honeywell 101E Portable Telemetry Tape Recorder. This recorder is used to playback tapes of unprocessed Space Shuttle telemetry into the INCO project telemetry processor.

The INCO project telemetry processor is a Loral Instrumentation Advanced Decom System (ADS-100) which processes the Shuttle telemetry and makes it available to other computers in the laboratory for use in expert system based monitoring prototypes. This telemetry processor is capable processing a 4 Megabit per second input data stream and extracting and calibrating over 4000 parameters a second.

The INCO project has currently interfaced this telemetry processor to a M68020 based UNIX workstation. This workstation was purchased from the JSC Mission Support Directorate and was originally built by C3 Corporation (C3 is an OEM utilizing Masscomp computers. The C3 has been selected by Mission Support Directorate as the standard Mission Control Center Workstation). This workstation is currently being used for development of a rule based expert system for monitoring real time Space Shuttle telemetry. The C3 workstation is also located in the laboratory. JSC Mission Operations Directorate has also loaned the INCO project the use of a second smaller Masscomp workstation for development. This device is also located in the laboratory.

When development is completed, the INCO project will start operations in the Space Shuttle Mission Control Center (MCC). The Mission Control Center is located at Building 30 at JSC and is the primary control center for all Space Shuttle flights. The INCO project is currently scheduled to start operations in the MCC in February 1988. The INCO project will be used duringr simulations prior to the next shuttle flight (STS-26) and be evaluated during the actual flight.

An ADS-100 Telemetry Processor and a C3 Workstation will be placed in Flight Control Room # 1 (FCR-1) which is the prime control room for STS-26. JSC Mission Operations Directorate is funding the installation of a data line in the Mission Control Center to connect the INCO telemetry processor with the real time telemetry from the mission. Data will be routed to the INCO project from all tracking stations and thê Tracking and Data Relay Satellite, as soon as the data is received at the MCC. The INCO project will not be connected to any data systems processing classified data. The INCO project will not be connected to any life or mission critical MCC equipment.

Display units from the C3 workstation are being installed at the INCO console and the Propulsion Officer console allow monitoring the performance of the INCO expert system in real time during the STS-26 mission. The INCO expert system will be evaluated during the STS-26 mission but will not be used to make any decisions affecting the conduct of the flight. The INCO project may be certified for operational use following the flight based on performance evaluation.

A5. KENNEDY SPACE CENTER

A5.1. TECHNOLOGY DEMONSTRATION.

TITLE: Diagnostics and Control for Launch Processing Systems

OBJECTIVES:

Develop and demonstrate the systems autonomy "core technology" software and hardware necessary to accomplish autonomous diagnostics and control of interactive complex electro/mechanical launch and cargo processing systems. The autonomous system will perform the duties of a systems engineer better than the best NASA systems engineer.

RATIONALE:

Parallel development of "core technology" diagnostics and control software: i.e. the ARC development using KEE on the Space Station Thermal Control System and Power System at JSC and LeRC; and the parallel KSC development efforts on ECS/PPCU/GDMS/CCMS II demonstrations against actual launch and cargo processing ground hardware, will provide assurance that the most robust software architecture is developed for use on Space Station, future ground processing systems, and mission control systems.

APPRAOCH:

During late 1987 and early 1988 existing KSC Knowledge-based Autonomous Test Engineer (KATE) diagnostics and control software and the Generic Model-Based Diagnostic System (GMODS) software, developed in previous years, will be merged into one autonomous diagnostics and control set of software and be demonstrated, showing single system diagnostics and control, using the new Shuttle Operational Maintenance & Refurbishment Facility (OMRF) Environmental Control System (ECS) in 1988. The KATE/GMODS software shell will then be modified to accomplish diagnostics and control of multiple systems within a shared complex network of Unix based equipment; this software structure will be called the Generic Control System (GCS). During 1989 the GCS software will be demonstrated against several real world electro/mechanical laboratory models. In 1990 the GCS shell will be modified to contain knowledge from the cargo Partial Payload Check-out Unit (PPCU) used to ground test Shuttle payloads; this PPCU shell will be tested against several payload hardware systems, operating simultaneously. In 1991 the GCS will be modified to contain the Space Station Ground Data Management System knowledge (GDMS- used for ground testing of the Space Station modules) which will represent hierarchical multiple expert systems running on a large (300 computers with 250,000 I/O points) distributed computer network. In the 1993-1995 time frame the GDMS shell will be modified to contain the knowledge of the Shuttle Launch Processing System which will constitute the advanced software structure for development of the new Launch Processing System (CCMS II).

PRODUCTS:

FY'87: Prototype software shell for accomplishing diagnostics and control on a single electro-mechanical system.

- -fault recognition/warning/diagnosis for all failures
- -symbolic/numeric processing integration
- -objects with state and feedback

FY'88: Operational software shell (OMRF/ECS) for accomplishing diagnostics and control on a single electro-mechanical system.

- -model based (causal modeling/first principles)
- -objects with state and feedback
- -multi-user Unix type operating system
- -goal directed control/reconfiguration
- -fault recovery from all failures

FY'89: Prototype software shell Generic Control System (GCS) for accomplishing simultaneous diagnostics and control on complex electro-mechanical systems.

- -complex models
- -multiple objects with state and feedback
- -model based control
- -design knowledge capture from CAD/CAM data base
- -complex expert system validation/verification techniques
- -advanced user interface function; voice, active graphics, etc.

FY'90: Operational software shell Partial Payload Check-out Unit (PPCU) accomplishing simultaneous diagnostics and control on complex electro-mechanical systems.

- -integrated LISP and Unix systems
- -parallel LISP processing
- -modest learning

FY'91: Operational software shell Ground Data Management System (GDMS) accomplishing simultaneous diagnostics and control within a very large network of control equipment (300 computers & 250,000 I/O points).

- -simultaneous control of distributed systems
- -high level user interface
- -planning and scheduling of multiple system integration
- -scenario based reasoning

BENEFITS:

Current ECS manpower levels in the operational system require two console personnel operating on a three shift basis when operating in the local control mode. Additionally, two system level engineers support on a two shift basis. With the implementation of the Autonomous Launch Processing System it is projected that the console operator level can drop to one operator per shift, for the total ECS operational manpower reduction of 37.5%. The manpower required for the ECS operations is typical of the some seventeen LPS systems and it is expected that this percentage reduction will be experienced throughout the operations when full systems autonomy is implemented within LPS. KSC currently has 7.9 million lines of software code which require 420 people to maintain on an annual basis. It is expected that the implementation of the proposed GDMS/CCMS II knowledge based type of software system, including the capability to directly modify code through CAD/CAM and other design capture techniques, will reduce the code maintenance requirement by as much as 80%. Therefore, the implementation of these techniques will greatly reduce the operational costs of Shuttle and Payload ground processing.

SCHEDULE:

Item:	FY:	87	88	89	90	91
Project Plan Development		-----				
Integration of KATE/GMODS			-----			
Develop OMRF/ECS Shell			----			
Demonstrate OMRF/ECS System			D			
HQ/ARC Project Review			P			
FY'88 Project Report			R			
Develop Generic Control System (GCS) Shell				-----		
Demo GCS Against Multi-systems Lab Models				D		
HQ/ARC Project Review				P		
FY'89 Project Report				R		
Develop PPCU Shell					-----	
Demonstrate PPCU System					D	
HQ/ARC Project Review					P	
FY'90 Project Report					R	
Develop GDMS Shell						-----
Demonstrate GDMS System						D
HQ/ARC Project Review						P
Final KSC SADP Report						R
Code R Funding (K$)		380	397	500	430	450
Other Funding(SS/M)(K$)		684	1006	1196	1300	1245
Contractor Manpower MY		4	8	14	12	11
Civil Service Manpower MY		8	10	12	15	14

Note:
- D: Demonstration
- P: Project Review
- R: Project Report

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TECHNOLOGY NEEDS AND DELIVERABLES

Core Technologies Needed

The following core technologies are required to complete the KSC Diagnostics and Control Demonstration:

1. A parsimonious, standard knowledge base representation.
   a. Based on a description of structure and function.
   b. Electrical, Fluid, and Mechanical circuits.
   c. Useable byb all NASA model based expert systems.
   d. Basis for deliverable documentation from vendors.

2. Improved and generialized functional relationship inverter
   a. Would replace existing limited INVERT function in KATE
   b. Usable in other diagnosers and controllers
   c. Similar to TK-Solver or Mathematica
   d. Finds possible input sets from output value(s)

3. A standard Flow Solver for expert systems
   a. Compressible and incompressible flow
   b. Assembles continuous flow models from description of structure and function
   c. Uses system commands to determine expected outputs
   d. Allows failure of components for diagnosis

4. A high performance parallel Lisp processor
   a. Vastly improves speed of diagnosis
   b. Parallel evaluation of failure possibilities
   c. 5 processor PC, 80386, 100 mega bytes
   d. Multiple Lisp Chip machine

Core Technologies Provided

The following Core Technologies will be provided by the KSC Diagnostics and Control Demonstration Project:

1. A complete expert system shell for all aspects of control and monitor.
   a. Driven by a changeable knowledge base
   b. Autonomous real-time model-based anomaly detection
   c. Autonomous real-time information display with manual control provision
   d. Autonomous component level control
   e. Very high level requirements interface to operator
   f. A real-time model-based diagnoser with explanation
   g. Off-line and on-line Single Point Failure Analysis
   h. Autonomous failure history retrieval, and design information
   i. Autonomous real-time plot generation
   j. Autonomous canera control
   k. Knowledge base validation tools

2. An intelligent CAD knowledge extraction system
   a. Builds structure and function knowledge bases from CAD files
   b. Uses Intergraph ICAD data base to creat KATE KB's
   c. Could use IGES version 3.0

A5.2 KSC FACILITIES.

Over the past four years KSC has developed three Artificial Intelligence Development Laboratories at the Center to support many AI application projects, thirteen as of FY'87. These laboratories are under a continuous process of development; the following capabilities list is the capability that will exist as of the completion of FY'87 procurements.

Design Engineering AI Laboratory:
This laboratory is used primarily for development of the KSC Systems Autonomy Demonstration Project. Another project being developed within this laboratory is the Thunderstorm Weather Forecasting System.

Symbolics 3601-1211
- 8Mb RAM
- 474 Mb Disk
- High resolution 19", 8 bit color system

Symbolics 3640-140
- 6Mb RAM
- 140Mb Disk
- 190Mb Disk

LGP 1 Laser Graphics Printer

Apple Laser Writter

2 ea IBM/AT
- Gold Hill Humming Boards
- Large Memory Gold Hill Common Lisp

5 ea IBM/AT
- Large Memory Gold Hill Common Lisp

Apple Mac II
- 3 Mb RAM
- 40Mb Disk

2 ea copies of Automated Reasoning Tool by Inference Corp.

Currently in procurement, specified as follows:
- Texas Instruments Explorer II/LX
  - 8Mb RAM
  - 500Mb Disk
  - Unix Co-processor
  - High Resolution Color
  - Ether Net

These computer systems are currently being integrated across an Ethernet.

Payload Operations AI Laboratory:
This AI laboratory is primarily involved in the development of the Smart Processing of Real Time Telemetry (SPORT) project which will provide real time intelligent analysis of Spacelab experiment data and will be a precursor for design of a ground checkout system for Space Station Payloads. The laboratory consists of the following equipment as procured through FY'87.

Symbolics 3670-1211
- 4Mb RAM
- 474 Mb Disk
- High Resolution 8 bit Color
- 9 track tape drive
- Floating point accelerator
- Frame grabber

Symbolics 3640-190
- 4Mb RAM
- 2 ea 190 Mb Disks

LPG 1 Laser Graphics Printer

Apple Laserwriter

14 ea IBM/XT/AT with various RAM/Disk configurations

Entire AI lab computer networked over Ethernet LAN using TCP/IP

Shuttle Operations AI Laboratory:
This laboratory is being used to develop AI systems for diagnostics of the Shuttle Launch Processing System software and hardware. The laboratory has been under development during FY'87 and the following description is what will be in place at the end of FY'87:

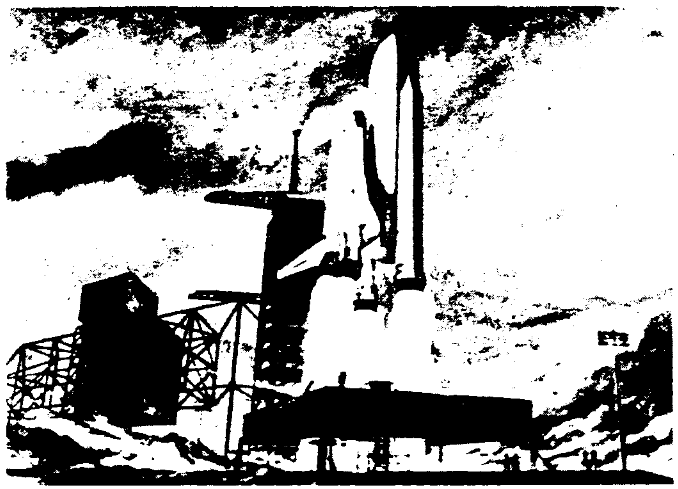
2ea Texas Instruments Explorer II
- 4Mb RAM
- 368Mb Disk

2ea copies of Knowledge Engineering Environment (KEE) by IntelliCorp

Other AI Development Capabilities:
During FY'87 KSC has been developing the capability of building small expert systems to support various Shuttle and Payload processing functions, four projects during FY'87 and an additional two for FY'88. To accomplish these tasks we are in the process of procuring Compaq 386 computers with 4 to 6 Mb RAM and 130 Mb Disks. The development of these systems is being accomplished using the Texas Instruments Personal Consultant Plus software, we have seven copies of this software including the Images software.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

DIAGNOSTICS AND CONTROL FOR LAUNCH PROCESSING SYSTEMS



OBJECTIVES

DEVELOP HARDWARE AND SOFTWARE FOR AUTONOMOUS DIAGNOSTICS AND CONTROL FOR THE KSC LAUNCH PROCESSING SYSTEMS

FUNCTIONAL CAPABILITIES:

- GOAL-DIRECTED CONTROL/RECONFIGURATION
- FAULT RECOGNITION/WARNING/DIAGNOSIS
- SYSTEMS SCHEDULING/RESCHEDULING
- AUTOMATED TREND FAILURE ANALYSIS
- INTELLIGENT USER INTERFACES

TECHNOLOGY THRUSTS:

- MODEL-BASED SIMULATION
- CAD/CAM KNOWLEDGE-BASE CAPTURE
- EXPLANATION DISPLAYS
- LIMITED REASONING UNDER UNCERTAINTY
- VALIDATION/VERIFICATION TECHNIQUES

PARTICIPANTS AND FACILITIES

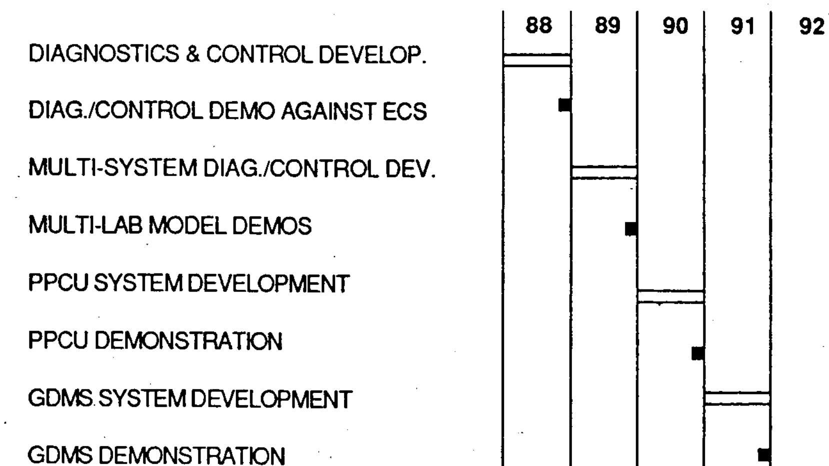
PARTICIPANTS

- KENNEDY SPACE CENTER: SHUTTLE DIRECTORATE, DESIGN DIRECTORATE
- INDUSTRY: TEXAS INSTRUMENTS, ELECTRIC POWER RESEARCH INSTITUTE
- CONSULTANTS: MITRE CORPORATION, UNIVERSITY OF CENTRAL FLORIDA, UNIVERSITY OF TENNESSEE

FACILITIES

- KSC AI DEVELOPMENT LABORATORY
- STS ENVIRONMENTAL CONTROL SYSTEM
- SS PARTIAL PAYLOAD CHECKOUT UNIT
- SS GROUND DATA MANAGEMENT SYSTEM
- STS LAUNCH PROCESSING SYSTEM - II

SCHEDULE AND FUNDING



	88	89	90	91	92
CODE R FUNDING ($K)	397	500	430	450	
OTHER FUNDING ($K)	1006	1196	1300	1245	
CONTRACTOR MY	7	14	12	11	
CIVIL SERVICE MY	10	12	15	14	

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A6. LANGLEY RESEARCH CENTER

A6.1. CORE R&T (Planning and Reseasoning).

TITLE: Application of Behavioral Net Architecture to Planning/Scheduling

OBJECTIVE:

To investigate the application of behavioral net architectures to the problem of planning and scheduling, and the development of a prototype domain-independent planning and scheduling tool.

RATIONALE:

Planning and scheduling problems are numerous throughout NASA, including telerobotic task planning, satellite fly-by scheduling, mission planning, crew activity planning and scheduling, job shop scheduling, and many more. Several tools have been developed in an attempt to automate these processes, but to date these tools have been extremely domain-specific. Furthermore, these tools are typically not capable of both static and dynamic planning and scheduling, are minimally interactive, and are non-real-time. The development of a "generic", domain-independent planning/scheduling tool has been deemed beyond the current state of the art.

Behavioral networks have recently shown promise in dynamic intelligent control execution for telerobotic systems. Behavioral nets are composed of multiple feedback control processes interconnected in a hierarchical lattice structure with weighted links. The structure of the network is determined by a hierarchy of resource requirements (including devices, space, and time), with the weights of the links determined by priorities and constraints within the system.

This architectural approach offers the potential for the development of a domain-independent tool for planning, scheduling, and resource allocation.

APPROACH:

As previous stated, many planning and scheduling domains and algorithms exist, and many approaches have been tried for individual domains. The initial task of this research effort would be the analysis of various domains, problems, and tools, in order to index techniques against application criteria. These criteria would include such things as the dynamic vs. static nature of the application environment, the extent of the resources available, the availablity of alterate resources, the different classes of potential contraints, etc. This survey will concentra on NASA-developed tools and application domains, but will not be limited to these.

Due to the inherent symmetry of the node and link structures in behavioral net architectures, a task specification language can be developed to allow a user to describe a planning/scheduling problem for initial plan resolution. This task specification language can also be used interactively to input modifications to the resource/constraint environment, which will cause a dynamic restructuring of the network to identify the optimum subsequent plan/schedule. Therefore, a second task in this research effort will be the specification of a behavioral net design language, and the implementation of a simple user interface for the use of this language in designing and manipulating a task-specific behavioral net. User displays will also be developed which show the current net state, i.e., the desired plan/schedule.

A behavioral network "engine" for planning and scheduling will be developed on an available sequential computer architecture (VAX). (This prototype will only be able to simulate the parallel computation inherent in the behavioral net concept. Thus the speed of execution will be proportional to the size of the net. Subsequent implementations will be on parallel distributed hardware, as additional funding becomes available.)

The prototype system will be used to develop plans and schedules for NASA-domain problems that have been encountered in operational situations. The choice of these problems will be based on interaction with personnel at other centers that have analyzed these problems and/or have developed tools for their solution, and who can provide specific resource/contraint information about the problems. This will require collaboration with other NASA personnel doing similar research.

The number of problems used to test the system will depend on the availablity of this information and time constraints. The results of the use of the prototype against these problems will be analyzed and compared with current tool performance, and will include ease of problem net design, ease of use, acceptability of solution, and relative speed of execution.

PRODUCTS:

8/88 Document surveying current applications and techniques in planning and scheduling, indexing techniques against specific domain criteria.

1/89 Document describing a task specification language for behavioral nets.

6/90 Document describing the use of behavioral nets to solve specific available planning and scheduling problems pertinent to NASA.

8/90 Prototype software implementation of a behavioral net "engine" for planning and scheduling, with a human interface using the task specification language, demonstrated and available for distribution.

LaRC Behavioral Nets (Continued)

SIGNIFICANT MILESTONES AND FUNDING REQUIREMENTS:

TASK	87	88	89	90
Domain/technique analysis and taxonomy	- - -------	---------*		
Task spec. language design	- - -	----------	---*	
Behavioral net "engine" for planning/scheduling	- - ------	----------	--------*	
User interface design and implementation		- - - ------	----------*	
Planning/sched. problem exp.		- - -	- - - - -	- ------*
Experiment results documented				-----*
Prototype demon. & avail.				*

	87	88	89	90
FUNDING:	(50)	197	300	300
MANPOWER:				
NASA in-house civil service	1	2	2	3
NASA in-house contractor programming support	.5	1.5	1.5	2.5
University grant support	3	7	2	2
TOTAL:	4.5	10.5	5.5	7.5

CORRELATION TO SADP CORE TECHNOLOGY NEEDS:

1990 - Planning/replanning
1993 - Planning under uncertainty
1996 - Real-time planning and replanning

Can provide a link between the Systems Autonomy and the Telerobotic Programs.

BENEFITS:

Provide an in-depth survey and analysis of planning and scheduling applications and techniques, particularly those applicable to NASA.

Extend the state-of-the-art to provide a domain-independent "shell" for planning and scheduling problems.

Provide documantation of the application of this technique to several planning/scheduling problems pertinent to NASA's mission needs.

Provide a common means of planning and scheduling between the System Autonomy Program and the Telerobotics Program, for eventual interaction between the two programs.

LaRC Behavioral Nets (Continued)

TECHNOLOGY DELIVERABLES:

8/88 - Document surveying current planning/scheduling systems compared to specific NASA requirements. This is pertinent to any planning/scheduling problem within NASA, including demonstrations of the 1990-phase and beyond.

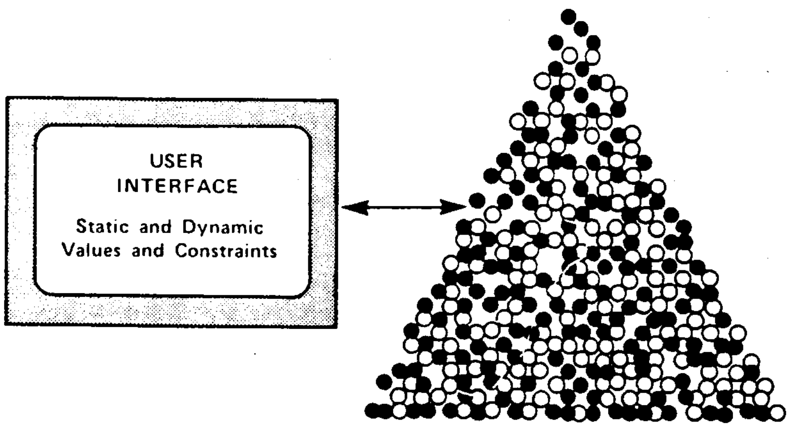
1/89 - Document describing a task specification language for behavioral nets -- possibly a formal generalized methodology for task decomposition. This is pertinent to researchers in any planning domain, including robotics, including both Systems Autonomy and Telerobotics demonstrations of the 1993-phase and beyond.

8/90 - Software with documentation of behavioral nets solving a variety of planning and scheduling problems, demonstrated and available for distribution. Pertinent to any planning/scheduling problem in NASA, including robotics, including both Systems Autonomy and Telerobotics demonstrations of the 1993-phase and beyond.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

PLANNING AND REASONING - BEHAVIORAL NET ARCHITECTURES FOR PLANNING

APPLICATION OF BEHAVIORAL NET ARCHITECTURE TO PLANNING/SCHEDULING



OBJECTIVES

DEVELOP A PROTOTYPE DOMAIN-INDEPENDENT PLANNING AND SCHEDULING TOOL BASED ON BEHAVIORAL NET ARCHITECTURES

- BEHAVIORAL NET TASK SPECIFICATION LANGUAGE
- BEHAVIORAL NET SOFTWARE PROTOTYPE DEMONSTRATED AND AVAILABLE FOR SPECIFIC NASA PLANNING APPLICATIONS

PARTICIPANTS AND FACILITIES

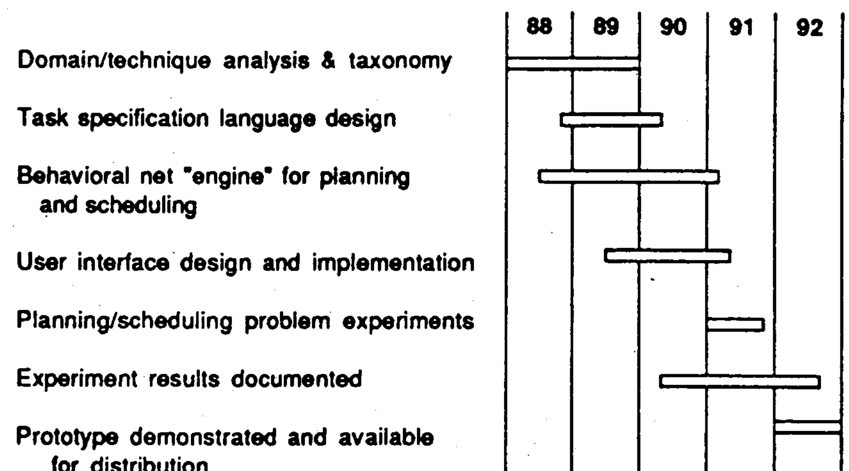
PARTICIPANTS

- LANGLEY AUTOMATION TECHNOLOGY BRANCH
- OLD DOMINION UNIVERSITY
- NORTH CAROLINA A & T STATE UNIVERSITY
- COLLEGE OF WILLIAM AND MARY

FACILITIES

- INTELLIGENT SYSTEMS RESEARCH LAB SUPERMINIS AND GRAPHICS CAPABILITIES

SCHEDULE AND FUNDING



	88	89	90	91	92
Funding ($K)	197	300	300	300	300
Civil Service MY	2	2	3	3	3

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A6. LANGLEY RESEARCH CENTER

A6.2 CORE RESEARCH AND TECHNOLOGY (Validation Methodology).

TITLE: Validation of Knowledge-Based Systems with High-Reliability Requirements.

OBJECTIVE:

To define reliability and performance validation methods for life-critical knowledge-based systems.

RATIONALE:

On-board systems for space application must be reliable and validatable. Many NASA space operations are life-critical. Even when astronaut personnel are not involved, the loss of equipment and/or experiments can be prohibitively expensive. Crew availablity is limited for the performance of routine or excessively time-consuming functions, and intelligent autonomous systems which are designed to perform these functions must be thoroughly validated.

Exhaustive testing of such complex systems as the knowledge-based systems proposed for space applications is insufficient to validate a man-rated system.

APPROACH:

The initial task will be to define quantitative parameters for characterizing the effects of an embedded knowledge-based system on the total system reliability. No such criteria currently exist. Performance and non-determinism are major reliability factors of a real-time knowledge-based system, in addition to the correctness of the rules. Therefore, the parameters will be measures of correctness and structure of the knowledge base, the performance and reliability of the hardware architecture, and the algorithm and implementation of the inference engine. Once the parameters to be measured are identified, analytical error models and/or simulative techniques will be developed for measuring the parameters. Proposed analysis techniques include graphical analysis of rule structures, graphical simulation of the dynamic behavior, and sensitivity analysis of critical rules. Once these techniques are in hand, it is possible to develop guidelines for designing validatable knowledge-based systems, and to develop a methodology and tools for quantifying the reliability of these systems.

The proposed techniques and prototype tools will be applied to knowledge-based systems being developed at NASA Langley, including rule-based systems for fault prediction and trend analysis and the CSDL Electronic Flight Engineer, and model-based systems for fault diagnosis and recovery planning and for automated reliability modelling.

LaRC Validation Methodology (Continued)

PRODUCTS:

5/89 Document defining the unique characteristics of knowledge-based systems and the applicability of current validation techniques to these systems.

8/91 Guidelines for building a validatable knowledge-based system.

8/92 Development and documentation of methodologies for validating knowledge-based systems.

SIGNIFICANT MILESTONES AND FUNDING REQUIREMENTS:

TASK	87	88	89	90	91	92
KNOWLEDGE-BASED SYSTEM VALIDATION						
Define qualitative measures	- - -	------	---*			
Develop evaluation methods		------	------	------	------	------*
ARCHITECTURES AND INFERENCE ENGINE DESIGNS						
Develop fault-tolerant model programming model		------	------	------	---*	
Evaluation and analysis				------	------	------*
FUNDING:						
KNOWLEDGE-BASED SYSTEM VALIDATION		100	150	150	200	200
ARCHITECTURES AND INFERENCE ENGINE DESIGNS		50	100	100	100	100
TOTAL FUNDING:		150	250	250	300	300
MANPOWER:		1.0	2.0	2.0	2.0	2.0

CORRELATION TO SADP CORE TECHNOLOGY NEEDS:

1993 - advanced validation techniques based on new theory
1996 - expanded validation techniques

BENEFITS:

Provide design guidelines and a validation methodology for building and validating a knowledge-based system with high-reliability requirements.

LaRC Validation Methodology (Continued)

TECHNOLOGY DELIVERABLES:

5/89 - Document defining the unique characteristics of knowledge-based systems and the applicability of current validation techniques to these systems. This is pertinent to any knowledge-based system development, including demonstrations of the 1990-phase and beyond.

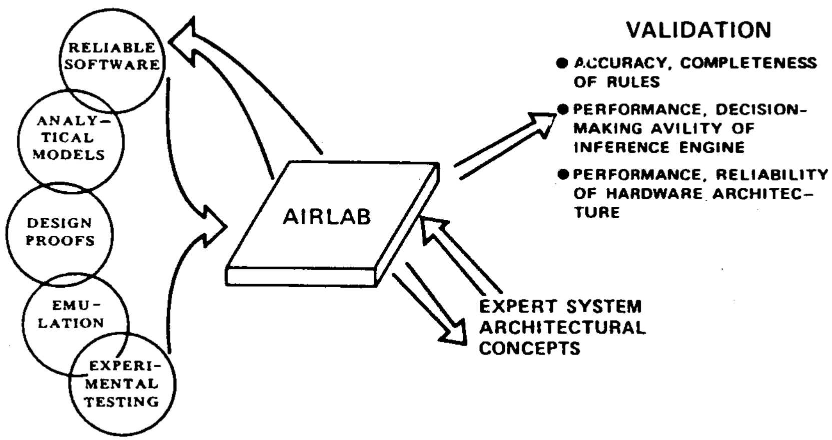
8/91 - Guidelines for building validatable knowledge-based systems. This is pertinent to any knowledge-based system development, including demonstrations of the 1993-phase and beyond.

8/92 - Development and documentation of methodologies for validating knowledge-based systems. This is pertinent to any knowledge- based system assessment, including demonstrations of the 1993-phase and beyond.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

PLANNING AND REASONING - VALIDATION METHODOLOGIES

Validation of Knowledge-Based Systems
with High Reliability Requirements



OBJECTIVES

DEFINE METHODOLOGIES FOR VALIDATION OF LIFE-CRITICAL KNOWLEDGE-BASED SYSTEMS

- PROVIDE MEANS FOR ANALYZING K-B SYSTEM PERFORMANCE
- PROVIDE TOOLS FOR INCREASING K-B SYSTEM RELIABILITY
- PROVIDE PROGRAMMING METHODOLOGY FOR INCREASING K-B SYSTEM VERIFIABILITY

PARTICIPANTS AND FACILITIES

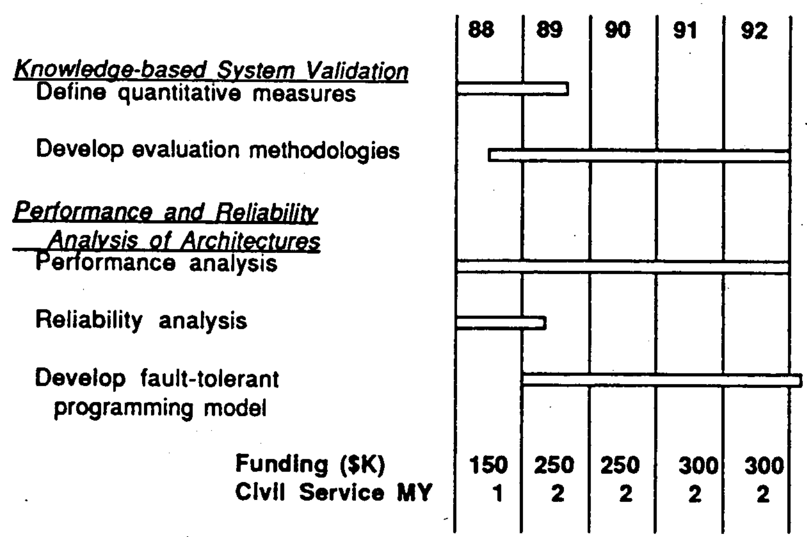
PARTICIPANTS

- LANGLEY SYSTEM VALIDATION METHODS BRANCH
- CHARLES STARK DRAPER LABORATORY

FACILITIES

- SYMBOLICS 3650
- DEC AI WORKSTATION WITH LUCID SOFTWARE
- ACCESSIBILITY OF SEVERAL KNOWLEDGE-BASED SYSTEMS USING DIFFERENT PARADIGMS

SCHEDULE AND FUNDING



JB/PGMPL 7-87 (MH)

A6. LANGLEY RESEARCH CENTER

A6.3 LaRC FACILITIES.

NASA Langley is the home of research activity in many aerospace disciplines. Research in Systems Automation and AI is conducted in the context of specific application areas. Therefore, Langley has chosen to provide AI research facilities in a manner that is cost/time efficient and consistent, yet gives maximum flexibility to the individual researcher.

Flexibility is provided by promoting the acquisition of AI research facilities by the individual research branches. Many branches have general-purpose computers, such as VAXes and IBM-PCs, and use AI-oriented software on these to provide an introduction to AI techniques. Other branches with mature AI research efforts are purchasing symbolic processors of their own that can be tailored to suit specific research objectives.

Efficiency and consistency result from a high degree of centralized support to AI researchers at Langley. A top-of-the-line symbolic processor was purchased with central funds and is centrally supported, both as a research tool for mature projects, and as an introductory machine for individual researchers considering the purchase of their own machine. An active and close-knit special interest group in AI disseminates AI-related information, hosts AI speakers, and forms a united voice for AI at Langley. AI-oriented software, such as CLIPS and GEST, is centrally disseminated, and the costs for expensive resources, such as KEE, are shared. Procurement of central support for distributed system maintenance and new-user tutoring has been initiated. Center support for individual branch ownership of symbolic processors is also being considered, especially in providing for continuing maintenance costs. This central support allows branches to acquire expensive AI research facilities even when AI activity is a small part of a branch's overall program.

BEHAVIORAL NETWORK ARCHITECTURES FOR PLANNING AND SCHEDULING:

This research activity is being conducted in the Automation Technology Branch (ATB). This branch houses sophisticated computing equipment for telerobotics research, including 5 VAXes, 7 PDP 11/73's, VS11 and GTI POLY 2000 graphics capabilities. This activity will use a Symbolics 3675 that is DECNETed to an ATB microVAX, and a DEC VAX AI Color Workstation that has been ordered by the branch, with the necessary auxilliary support peripherals.

VALIDATION OF K-B SYSTEMS WITH HIGH RELIABILITY REQUIREMENTS:

This research activity is being conducted in the Systems Validation Methods Branch (SVMB). This branch houses the AIRLAB facility, a network of 11 VAXes and a number of special-purpose fault-tolerant research processors. This activity will use a Symbolics 3650 and a DEC VAX AI Workstation with LUCID software, that are also supported by SVMB. In addition, SVMB researchers will have access to knowledge-based systems developed at Langley, for validation measurements.

A7. LEWIS RESEARCH CENTER.

A7.1. Technology Demonstrations.

TITLE: Space Station Power System Autonomy Demonstration.

OBJECTIVE:

To appy, evaluate, and demonstrate Autonomy Technologies for the operation of the Space Station Power System. Also, to participate in the 1990 demonstration of two systems - the Space Station Power System and the Thermal Control System - operating together in a coordinated mode with expert system controllers.

RATIONALE:

The space power system operating in a cooperative mode with other on-board systems has a special relationship with those other on-board systems. It supplies the resource, power/energy, upon which all of the other systems/ experiments will rely for their propoer functioning. It will place special requirements and have a unique interface with the executive controller. The power system, because of its unique role among the the space station systems has great potential for increased reliability and significant o operational cost reductions from the application of the "Autonomy Technologies. Development, application, and demonstration of these technologies for space power systems will represent a major contribution to the goals of the OAST Automation and Robotics Program.

APPROACH:

The 1990 Power Systems Autonomy Demonstration Program is a joint effort between the Lewis Research Center and the Marshall Space Flight Center working in conjunction with the Ames Research Center and the Johnson Space Flight Center. At the Lewis Rsearch Center, the program will entail participation by the Power Technology Division, (prime participant), and the Space Station Systems Directorate, (which is responsible for the development of the Space Station Power System. The program will entail:

- Use of the existing Space Station 25 KW PV/PMAD Test Bed.
- Develop and interface high speed data buss and microprocessor control with the test bed.
- Use the existing applicable power systems facilities and software developed by the Marshall Space Flight Center.
- Demonstrate autonomous control of selected subsystems:
  - Fault detection/classification/isolation.
  - Component operation/fault restoration.
  - Component health/trend monitoring.
- Aquire and assemble reqisie knowledge base.
- Aquire/develop resource manager/scheduler.
- Develop training procedures for power system operators.
- Demonstrate stand alone power system operation.
- Participate in combined systems test with the Thermal Control System.

LeRC Power Demonstration (Continued)

PLANNED ACCOMPLISHMENTS:

System test bed operational, 2nd Q. FY 87.
Identify core technology requirements, FY 87-88.
Finalize knowledge base, FY 89.
Demonstrate autonomous component operation, FY 88.
Identify/develop human interface requirements, FY 88-89.
Demonstrate stand alone power system operation.
Demonstrate combined system operation, (power/thermal), FY 90.
Develop training manuals/procedures for power sys. ope., FY 90-91.
Determine best method of power system operation, FY 88-90.
Verify best method of power system operation, FY 90.

PRODUCTS:

The Power System Autonomy Demonstration Task will result in an accumulation of autonomy technolgy expertise for the operation and management of space power systems and the resources they produce; on-board electrical power and energy. Much of this expertise will also be applicable to and can be used by space systems other than the power system. Also, technology transfer and fallout to the commercial terrestrial sector is a distinct possibility. Specific identifiable outputs are:

- Fault detection/classification/isolation methodologies.
- System restoration strategies, (after a fault).
- Planning/replanning in the face of uncertainty for the use of the power and energy resource aboard a space station.
- Operator training methodologies for power system operation and resource management.
- Extensive data base on the application of ES/AI technologies to the design and autonomous operation of space systems.

BENEFITS:

Operation of a mature autonomous space power system has the potential for significant reductions in operational support costs. In addition, the application of mature autonomy logics to space systems will result in improved reliability in the operation of such systems with the added benefit of enhanced resource management capability.

SCHEDULE/RESOURCES:

ITEM	FY	87	88	89	90	91
Operational Test Bed.		X				
Core Technology Requirement		X	X			
Assemble Knowledge Base			X	X		
Autonomous Component Operation			X			
Develop Human Interface Requirements			X	X		
Stand Alone Power Autonomy Demo.					X	
Power System Operations Methodology			X	X	X	
Combined System Demo.					X	
Verify Best Method of System Operation					X	
Training Manuals Procedures Formalized.					X	X
FUNDING: $K			550	750	800	200
CS Person Years			10	10	10	10

LeRC Power Demonstration (Continued)

TECHNOLOGY NEEDS:

The following "CORE TECHNOLOGY" elements are needed by LeRC to support the Power Systems Autonomy Program Development and the 1990 Combined Systems Autonomy Demonstrations.

1. AUTONOMY, (ES/AI), ENVIRONMENT, Definition - Requirements.
   - Development Environment
   - Operating Environment
     - Stand alone systems operations
     - Combined/multiple systems operations

   The following items are needed from the "Core Technology" program:

   (a). Software/hardware definitions and requirements.
   (b). Structure and formant of the knowledge/rule base.
   (c). Knowledge base capture methodology and requirements.
   (d). Distributed vs Centralized data base requirements.

2. MACHINE/HUMAN INTERFACE DEFINITIONS AND REQUIREMENTS.

   - Intelligent display requirements
   - Domain specific interfaces and definitions.

3. TASK PLANNING AND REASONING. Guidelines on:

   - Prioritized vs random scheduling.
   - Reactive vs dynamic scheduling.
   - Scope of planning/scheduling program.
     - Resource manager
     - Task scheduling
     - On-board experiments/tasks.
     - Maintenaence/repair scheduling.
     - Requirements imposed by the interactions of multiple systems.

4. INTERFACES OF POWER SYSTEMS CONTROLLER/EXECUTOR WITH THE EXECUTIVE CONTROLLER/MONITOR.

   - Requirements for the 1990 Demonstration.
   - Requirements for the 1993-96 Demonstrations.
   - Specific requirements for Space Station DMS interaction.

5. MODELING REQUIREMENTS FOR ES/AI SYSTEMS.

   - Causal and heuristic modeling requirements.
   - Any special requirements to insure compatibity between the various systems for the combined/multiple systems demos.

6. VALIDATION METHODOLOGIES FOR ES/AI SYSTEMS

   - Definition of ES/AI system validation.
   - System specifications.

7. VERIFICATION METHODOLOGIES FOR ES/AI SYSTEMS.

Definition of ES/AI system verification.
System operating requirements.

These core technology program elements are required by LeRC for the demonstration of:

(a). Stand alone operation of Space Station Power Systems.
(b). Combined operation of the Space Station Power Systems operating in a cooperative mode with the Thermal Control System.
(c). Operation of the Spacce Station Power System for the 1993 and 1996 demonstrations.

A7. LEWIS RESEARCH CENTER.

A7.2. LeRC FACILITIES.

The following facilities at LERC are applicable to the POWER SYSTEMS AUTONOMY DEMONSTRATIONS/SYSTEMS AUTONOMY DEMONSTRATION PROJECT.

POWER TECHNOLOGY DIVISION FACILITIES.

- 100KW-20KHZ Component Test Laboratory.
  Testing of transformers, cables, RPS/RBI's load converters, etc.
  Full power thermal evaluation of Space Station and Power System Autonomy Demonstration hardware.

- Fault Tolerant Controller Development Laboratory.
  Develop and demonstrate fault diagnosis/prediction and reconfiguration hardware and algoriths.
  Microprocessor controller applications development and test facility.

- Power Semiconductor Test Laboratory.
  Characterization of developmental/commercial power semiconductors.
  Evaluations of degradations due to high temperature/radiation environments.

SPACE STATION DIRECTORATE ELECTRICAL POWER SYSTEM TEST BEDS AND DEVELOPMENT FACILITIES.

- Solar Dynamic/Power Management and Distribution Test Beds and Development Facilities.
  Primary candidate for advanced automation and enhancement for Systems Autonomy Demonstration Project.
  Generically closest to evolutionary Integrated PMAD Test Bed defined as near prototype IOC Space Station Electrical Power System with regard to end-to-end and top to bottom controls.
  Provide Ethernet port from Power Management Processor to advanced autonomy workstations and link processors.

- Photovoltaic/Power Management and Distribution Test Beds: GDC 25 KW, 20 KHZ Test Bed.

  Test/Evaluation of Space Station components in PMAD System.
  Provide data base/operational base.

- Software Development Facility.

  Provide controller software development on Test Beds.
  Host for Modeling/Simulations for Test Beds and Space Station Electrical Power System.

  Support AI/ES software development for Power System Autonomy Demonstration.

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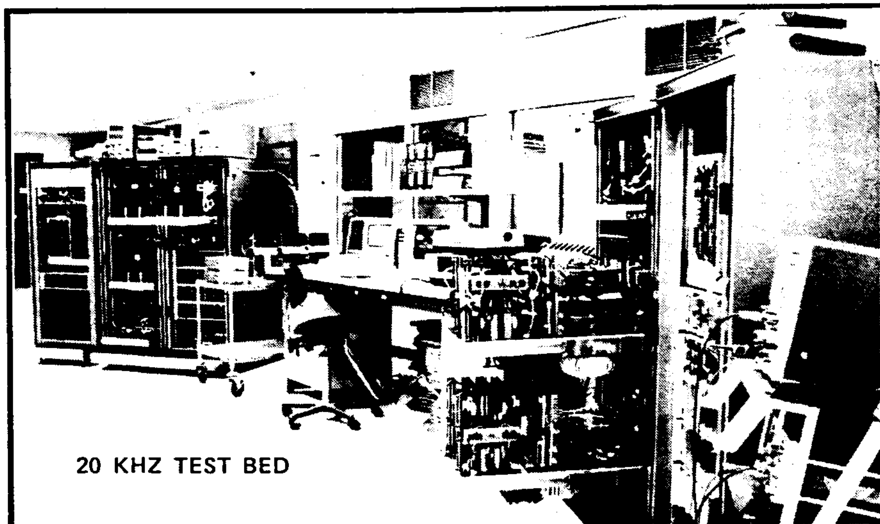
SYSTEMS AUTONOMY DEMONSTRATION PROJECT

SPACE STATION POWER SYSTEM OPERATION AND MANAGEMENT



20 KHZ TEST BED

OBJECTIVES

APPLY, EVALUATE AND DEMONSTRATE AUTONOMY TECHNOLOGIES FOR SPACE POWER SYSTEM AUTONOMOUS OPERATION

- DETERMINE AUTONOMOUS OPERATIONAL MODES FOR SPACE POWER SYSTEMS
- JOINTLY DEVELOP THE REQUISITE TECHNOLOGIES FOR THE AUTONOMOUS OPERATION OF A SPACE POWER SYSTEM
- DEMONSTRATE AUTONOMOUS OPERATION OF THE VARIOUS SUBSYSTEMS OF A SPACE POWER SYSTEM
- DEMONSTRATE A SPACE POWER SYSTEM OPERATING IN AN AUTONOMOUS MODE IN THE CONTEXT OF A TOTAL SPACE SYSTEM OPERATION UNDER THE CONTROL OF AN EXECUTIVE CONTROLLER

VERIFY THE BENEFITS OF AUTONOMOUS POWER SYSTEM OPERATION

PARTICIPANTS AND FACILITIES

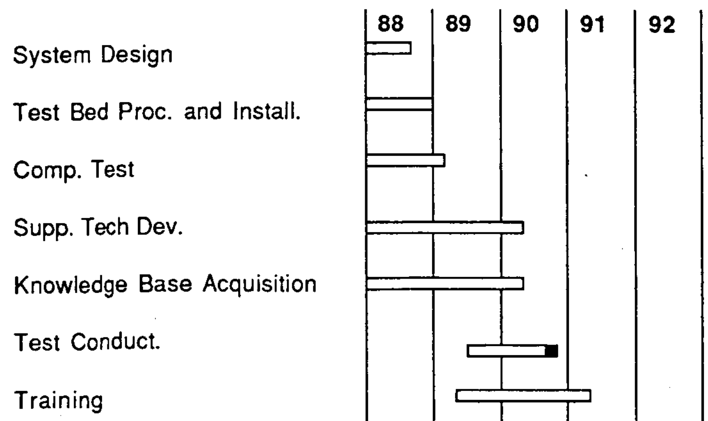
PARTICIPANTS

- AMES RESEARCH CENTER
- LEWIS RESEARCH CENTER
- MARSHALL SPACE FLIGHT CENTER
- JOHNSON SPACE CENTER
- INDUSTRY, (CONTRACT STUDIES)

FACILITIES

- ARC INTELLIGENT SYSTEMS LABORATORY
- ARC LAB-SCALE BRASSBOARD TESTBED
- LeRC POW. MAN. AND DISTR. LABS
- LeRC 20 KHZ TESTBED
- MSFC POWER LABORATORIES
- OTHER LeRC TEST FACILITIES AS REQUIRED

SCHEDULE AND FUNDING



	88	89	90	91	92
Funding ($K)	550	750	800	200	
Civil Service MY	10	10	10	6	

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A8. MARSHALL SPACE FLIGHT CENTER

A8.1 CORE RESEARCH AND TECHNOLOGY (Planning and Reasoning)

TITLE: Hubble Space Telescope Design/Engineering Knowledgebase (HSTDEK).

OBJECTIVES:

The short term objectives of this project are to capture as much of the design and engineering (construction/test) knowledge currently available within the HST development team as possible in an intensive knowledge acquisition effort. The resulting knowledgebase will be used to demonstrate the immediate utility of knowledge based systems by developing the HST Operational Readiness Expert (HSTORE) system which will support MSFC's Orbital Verification activity immediately following launch of the HST, now scheduled for November 1988.

RATIONALE:

The HSTORE knowledgebase will also be the focus of a long term effort to develop methods for capturing design/engineering knowledge on major NASA projects, involving multiple technical disciplines and a large number of experts, as well as for constructing large-scale knowledgebases. The extended HST Design/Engineering Knowledgebase (HSTDEK) will serve as the testbed for developing these methods, and will also support the development of a Ground-based Expert System for Space Telescope (GESST) intended to support the HST during its fifteen year operational lifetime. GESST will focus on the following four application areas: telemetry analysis for health maintenance (especially in the electrical power system), scheduling of HST activities, data analysis for science, and assistance to scientific investigators. In addition to defining and testing the methods required to support design/engineering knowledge capture on major projects at NASA's operational centers, this project will play a key role in developing a strong knowledge engineering capability at MSFC, oriented toward practical applications of the technology to achieve concrete enhancements of present engineering practices.

APPROACH:

This project is organized as a collaborative effort between MSFC and ARC. MSFC will manage the development of technology demonstrations in both the short and long term; i. e., knowledge engineering of the HSTORE knowledgebase and expert system in the short term, and the HSTDEK/GESST system in the long term. ARC will manage the research aspects of the HSTDEK project, and will use these knowledgebases as a testbed for their core technology efforts aimed at developing techniques for design/engineering data capture and constructing large-scale knowledgebases. HSTORE will be developed using currently available knowledge engineering technology, possibly augmented by interim results of the ARC research if it does not threaten the availability of HSTORE at HST launch. The HSTORE knowledgebase will be frozen at about six months prior to launch in order to support verification prior to its operational use. A copy of this knowledgebase will, in parallel, form the starting point of HSTDEK development utilizing the approach and methods produced by ARC research in this period. After serving as a testbed for ARC research in large-scale knowledgebase construction for about two years, a version of HSTDEK will be frozen to serve as the basis of GESST. GESST development will provide a check on the success of the large-scale knowledgebase design and construction effort. The methodology developed in this project will be documented and provided to other major projects at two points during the project. Methods for design/engineering data capture will be formalized, based on HST experience at about the midpoint of the project at the time of the HSTORE demonstration. A methodology for construction of large-scale knowledgebases will be formalized at the end of the project, in conjunction with the GESST demonstration. It is expected that the knowledge engineering capability developed at MSFC in the course of this project will be used for the first operational applications of these methods. The HSTDEK project itself will involve an extensive knowledge acquisition effort with the engineers responsible for the design, fabrication and test of the Hubble Space Telescope. The required expertise is presently spread across as many as two hundred engineers at six different sites, including Europe. Identifying a subset of these experts who can provide the required knowledge and which can be accommodated in a knowledge engineering project is a challenge in itself. New methods for accomplishing knowledge acquisition with multiple experts on this scale will have to be developed as part of the ARC Core Technology research. These challenges, coupled with the limited knowledge engineering capability presently available at MSFC and current lack of FY87 funding, may constrain the scope achievable in HSTORE at HST launch. It is expected that there will also be a few other collaborators on the HSTDEK project, in addition to MSFC and ARC. Lockheed Missiles and Space Company is the prime contractor for Space Telescope development, and most of the HST design knowledge resides at their Sunnyvale operation. They are also pursuing a related HST project as part of their Internal R&D program. We are planning to suggest some joint research with them as part of HSTDEK. The Knowledge Systems Laboratory at Stanford is very interested in participating in this project as a research vehicle for large scale knowledgebase development. The Computer Science Department at The University of Alabama in Huntsville is interested in supporting research on the integration of knowledge engineering techniques into the system development process at MSFC.

PLANNED ACCOMPLISHMENTS:

The HSTORE/HSTDEK project will demonstrate the value of knowledge based systems for both limited objectives such as the verification and checkout of the HST immediately after launch, and for broader types of support such as that provided by GESST/HSTDEK throughout the operational mission. Knowledgebase development in this project will also provide a real-world testbed, based on a significant and difficult domain, for research into design data capture and the construction of large-scale knowledgebases. The final products of this project will be two operational knowledge based systems supporting the HST, well defined methods for design data capture and the construction of large-scale knowledgebases which have been developed and tested in a significant NASA domain, and a cadre of knowledge engineers at MSFC who are experienced with these methods and are in a position to apply them within other major NASA projects.

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SCHEDULE:

Item	FY 88	89	90	91	92
HST Design/Engineering Knowledgebase Dev.	X	X	X	X	
HST Operational Readiness Expert Dev.	X	X			
HST Operational Readiness Expert Demon.		X			
Dev. of Design Data Capture Techniques	X	X	X		
Dev. of Large Scale Knowledgebase Mthds	X	X	X		
GESST Development	X	X	X		
GESST Demonstration			X	X	
Technology Transfer into Other Programs	X	X	X	X	X

RESOURCES:

Funding ($K)	471	500	500	500	500
Civil Service (MY)	4	4	4	4	4
Contractor (MY)	2	2	2	2	2

TECHNOLOGY DELIVERABLES:

Technology Concepts/Methodologies

- o An assessment of the traditional engineering activities which comprise a major development project will be used to construct a design data capture methodology based on a prioritized list of the data products from these activities as sources of knowledge.

- o An attempt will be made to develop a set of knowledge representations which are as general as possible with respect to the design data to be captured, as it exists in the HST data products.

- o A method for interfacing a knowledge based system to a traditional system in an operational environment will be developed and investigated.

- o Methods for utilizing a knowledge based system in support of design activities will be developed in the context of the Hubble Space Telescope (design of similar facilities such as AXAF, design of instruments to be added to the HST, construction of command messages, etc.).

Software Programs

- o Hubble Space Telescope Design/Engineering Knowledgebase (HSTDEK): March 1992.

- o Hubble Space Telescope Operational Readiness Expert (HSTORE): August 1989.

- o Ground based Expert System for Space Telescope (GESST): September 1992.

MSFC HST Design Knowledgebase (Continued)

Testing and Evaluations

- o The development of a comprehensive knowledgebase of design/engineering expertise for the Hubble Space Telescope will be used as a testbed for evaluating methods developed in other core technology elements for:

  - Capture of design data from the data products of traditional engineering activities involving multiple technical disciplines. (January 1990)

  - Capture of design expertise from multiple experts. (January 1990)

  - Construction of large scale knowledge bases. (March 1992)

Documentation

- o Technical Reports will be developed documenting:

  - Guidelines for effectively locating sources of design data in the data products of development projects. (September 1988)

  - Guidelines for selecting a generalized knowledge representation appropriate to different types of design data. (March 1989)

  - A method for interfacing a knowledge based system with a traditional system in an operational environment. (November 1989)

  - Methods for capturing design expertise and utilizing it in similar design activities. (September 1992)

A8.2 MSFC FACILITIES.

Knowledge Engineering Environments

There is no centralized facility for Knowledge Engineering at MSFC. Hardware and software to support the Knowledge Engineering activity in HSTDEK at MSFC will have to be procured by the project, and a portion of the HSTDEK funding has been set aside for this purpose. Discussions are ongoing with ARC as the NASA lead AI center to determine the most appropriate development environment for HSTDEK. At the present time, it is expected that two workstations and a central server will be procured in FY88 to support knowledge base construction at MSFC. This capability will be augmented as more people are assigned to the project and as additional capacity is required.

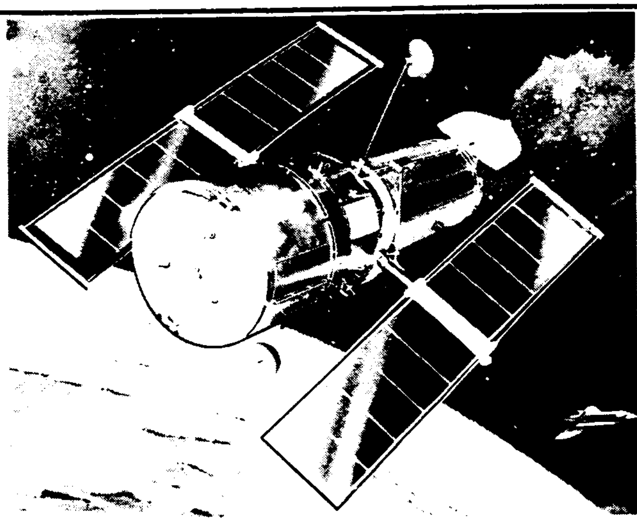
Stanford University will utilize the capabilities of their Knowledge Systems Laboratory (KSL) to support their research under the HSTDEK Grant, and also to support our MSFC representative at ARC. Facilities are also being made available at ARC in the Information Science Division Laboratory to support MSFC personnel detailed to the ARC area as part of the HSTDEK project. Facilities at the Lockheed AI Center will also be available to MSFC HSTDEK personnel who are assigned to the Knowledge Engineer Training Program there. This includes the three month practicum which follows the classroom instruction, during which HSTDEK personnel will be actively involved in augmenting the HST knowledge base.

Huntsville Operational Support Center (HOSC)

The first knowledge based system to be constructed as part of the validation of HSTDEK, called the HST Operational Readiness Expert (HSTORE), will be used to support the Orbital Verification (OV) activity for the HST. MSFC will conduct this activity in the HOSC. The HOSC will supply telemetry reduction, data distribution, data display, and facility support to the mission. HSTORE will have to be integrated in this operational environment. MSFC will supply facility support to HSTORE in the HOSC, as well as assistance in planning the HSTORE/HOSC interface. Development of the Ground-based Expert System for Space Telescope (GESST) to support HST nominal operations will also require some access to the HOSC, which will be provided by MSFC.

SYSTEMS AUTONOMY PROGRAM CORE TECHNOLOGY

PLANNING AND REASONING - HUBBLE SPACE TELESCOPE DESIGN/ENGINEERING KNOWLEDGE BASE



OBJECTIVES

- TO PROVIDE A TEST BED FOR ARC DEVELOPMENT OF LARGE SCALE KNOWLEDGE-BASE CONSTRUCTION METHODS, AND TECHNIQUES FOR DESIGN DATA CAPTURE
- TO SUPPORT THE DEVELOPMENT OF THESE METHODS AND TECHNIQUES BY PROVIDING KNOWLEDGE OF OPERATIONAL REQUIREMENTS AND ENVIRONMENTS
- TO DEVELOP A DEEP, COMPREHENSIVE KNOWLEDGE BASE FOR THE HUBBLE SPACE TELESCOPE WHICH CAPTURES THE EXPERTISE UTILIZED IN ITS DESIGN, FAB, AND TEST
- TO CONSTRUCT KNOWLEDGE BASED SYSTEMS WHICH UTILIZE THE TESTBED KNOWLEDGE-BASE AS A PROOF OF THE EFFECTIVENESS OF THE METHODS DEVELOPED
- TO DEVELOP AN MSFC KE CADRE READY TO APPLY THESE METHODS IN MAJOR PROJECTS SUCH AS SS AND AXAF

PARTICIPANTS AND FACILITIES

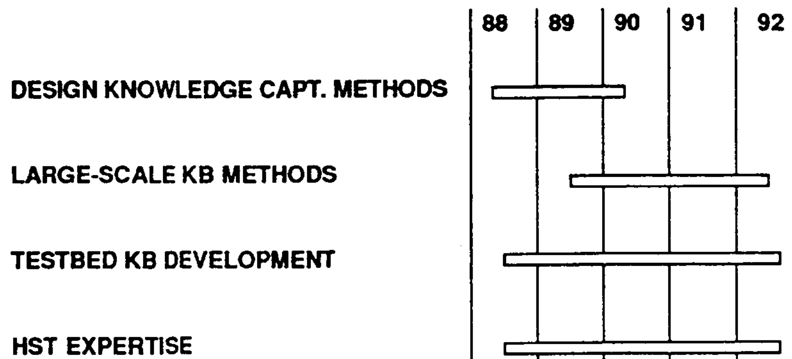
PARTICIPANTS

- MARSHALL SPACE FLIGHT CENTER (MSFC)
- AMES RESEARCH CENTER (ARC)
- INDUSTRY: LOCKHEED, TBD.
- ACADEMIA: STANFORD UNIVERSITY, UNIVERSITY OF ALABAMA, HUNTSVILLE, TBD.

FACILITIES

- MSFC ARTIFICIAL INTELLIGENCE WORKSTATIONS
- ARC INTELLIGENT SYSTEMS LABORATORY
- STANFORD KNOWLEDGE SYSTEMS LABORATORY
- UAH ARTIFICIAL INTELLIGENCE LEARNING CENTER

SCHEDULE AND FUNDING



	88	89	90	91	92
Funding ($K)	471	500	500	500	500
Civil Service MY	4	4	4	4	4

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16. Abstract

The National Space Strategy approved by the President and Congress in 1984 sets for NASA a major goal of conducting effective and productive space applications and technology programs which contribute materially toward United States leadership and security. To contribute to this goal, OAST supports the Nation's civil and defense space programs and overall economic growth. OAST objectives are to ensure timely provision of new concepts and advanced technologies, to support both the development of NASA missions in space and the space activities of industry and other organizations, to utilize the strengths of universities in conducting the NASA space research and technology program, and to maintain the NASA centers in positions of strength in critical space technology areas.

In line with these objectives, NASA has established a new program in space automation and robotics that will result in the development and transfer of automation technology to increase the capabilities, productivity, and safety of NASA space programs including the Space Station, automated space platforms, lunar bases, Mars missions, and other deep space ventures.

The NASA/OAST Automation and Robotics program is divided into two parts. Ames Research Center has the lead role in developing and demonstrating System Autonomy capabilities for space systems that need to make their own decisions and do their own planning. The Jet Propulsion Laboratory has the lead role for Telerobotics (that portion of the program that has a strong human operator component in the control loop and some remote handling requirement in space).

This Program Plan is intended to be a working document for NASA Headquarters, Program Offices, and implementing Project Management. It should be reviewed and updated at least once every year. The Program Plan includes contributions from all participating NASA Centers.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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