NASA Technical Memorandum 103860

Computational Needs Survey of NASA Automation and Robotics Missions

Volume I: Survey and Results

Gloria J. Davis

(NASA-TM-103860) COMPUTATIONAL NEEDS SURVEY OF NASA AUTOMATION AND ROBOTICS MISSIONS. VOLUME 1: SURVEY AND RESULTS (NASA) 30 p CSCL 13B

N91-23341

Unclas
G3/31 0014949

May 1991

National Aeronautics and
Space Administration

NASA Technical Memorandum 103860

Computational Needs Survey of NASA Automation and Robotics Missions
Volume I: Survey and Results

Gloria J. Davis, Ames Research Center, Moffett Field, California

May 1991

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

SUMMARY

NASA's operational use of advanced processor technology in space systems lags behind its commercial development by more than eight years. One of the factors contributing to this is the fact that mission computing requirements are frequently unknown, unstated, misrepresented, or simply not available in a timely manner. NASA must provide clear common requirements to make better use of available technology, to cut development lead time on deployable architectures, and to increase the utilization of new technology.

This paper provides NASA, industry and academic communities with a preliminary set of advanced mission computational processing requirements of automation and robotics (A&R) systems. The results were obtained in an assessment of the computational needs of current projects throughout NASA. The high percent of responses indicated a general need and desire for enhanced computational capabilities beyond the currently available 80386 and 68020 processor technology. Because of the need for faster processors and more memory, 90% of the polled automation projects have reduced or will reduce the scope of their implemented capabilities. The requirements are presented with respect to their targeted environment, identifying the applications required, system performance levels necessary to support them, and the degree to which they are met with typical programmatic constraints.

INTRODUCTION

Purpose and Goals

NASA's exploration of space began with the early satellites of Pioneer and Magellan in the 1950s, continued with manned missions in the 1960s, expanded to the Space Shuttle program and a grand tour of the planets with deep space probes in the late 1970s and 1980s, and has now progressed to the Space Station Freedom (SSF) Program, which began in the 1980s. Future plans include transfer vehicles to support colonization of the moon and eventually manned missions to Mars and the asteroids. Each program has built upon the knowledge base developed from previous experiences with the attendant increase in the requirements for supporting computational systems, automation and robotics. To date, NASA has typically used processors specifically designed for each project. For the SSF Program the mandate changed to apply "commercial off-the-shelf" technology whenever possible. This moved planning towards the consistent use of more general purpose processors.

Automation and Robotic (A&R) research has typically been based on symbolic and other specialized processing systems to match the characteristics of the languages and tools available to the researcher. General purpose computers have been used but performance results typically are not as good as that achieved with special purpose processors. To understand the long range impact of the move toward general purpose processors on A&R systems, a study was conducted to establish a preliminary set of requirements and project how well they can be met with general purpose processors.

This report provides NASA, industry and academic communities with a preliminary set of advanced mission computational processing requirements of A&R systems. The information was obtained by the Advanced Processing Technology group of the Information Sciences Division at NASA Ames Research Center, by canvassing the NASA centers and the aerospace community with prepared questionnaires and personal interviews. The process culminated in a workshop at Ames with invited presentations, followed by working group critique sessions.

The goals of this project were to: (1) quantify the requirements of spaceborne A&R systems, (2) given the requirements, determine whether sufficient capability was provided in the current space processing technology, and (3) if deficient, specify additional capabilities required, along with an approach to provide for these requirements. Identified within the context of this report are the requirements and insufficiencies of available technology. A subsequent report will outline one approach for NASA to follow to reconcile the deficiencies.

Objectives

NASA's missions are becoming increasingly complex and success of these missions will inevitably become more dependent on the use of A&R technology (ref. 1). This technology is gaining acceptance and support from a growing number of astronauts and scientists (ref. 2). NASA will move to allow A&R to take over historically tedious but necessary jobs, increase reliability and further enable our continued exploration and utilization of space. It is, however, commonly noted that NASA's spaceborne computational processing technology lags market technology by more than eight years. One reason is that requirements for spaceborne computation are usually not specified early enough to allow development of a long range upgrade plan. It should be noted that there will always be a delay of several years to convert commercial technology to the high reliability systems demanded by the space environment. The baseline SSF has attempted to explicitly provide hooks and scars for future support and implementation of automation and robotic systems (refs. 3-6). The Lunar/Mars Rover programs require automation and robotics technology for both a rover vehicle and for building a human habitat. Due to the nature of the environments and the functional capabilities, the computational requirements for these future systems will be greater than those for a mere collection of representative subsystems (i.e., the whole will be greater than the parts). The integration of subsystems, typically done by humans, must also be compensated for in computational processing (refs. 6, 7, and private communication from Robert W. Mah, NASA Ames Research Center, Moffett Field, Calif.).

Our motivation in this report was not to justify the use of A&R technology but given its use, determine the applications required; system performance levels necessary to support them; and the degree to which they are met with typical programmatic constraints.

Scope and Outline

Table 1 presents a spectrum of environments over which NASA's A&R applications occur. The range includes ground based systems, aeronautics, low earth orbit platforms and manned space stations, to Lunar/Mars exploration and deep space operations. For each environment, the computational processing requirements of support subsystems may vary significantly. It is the areas of similarity in these systems that are of special interest to the system designers and component providers. Some of the differences and similarities are indicated in this report in the Results section, following the description of the spectrum categories.

Table 1. Operational environment and sample applications

Environment	Sample application
Unmanned SEI—deep space	Voyager, Galileo, CRAF/Cassini
Manned SEI	Lunar/Mars Xfr. Vehicle, Rovers
Low-Earth orbit (Polar)	EOS, CSTI
Low-Earth orbit (Equatorial)	Space Station Freedom
Aeronautic/low Earth orbit	Shuttle, NASP, Launch Vehicles
Aeronautic	Experimentation/Scientific F-16, X-29
Ground: scientific	Scientific return processing
Ground: mission operations	Communication, ground control, support
Ground: development	Applications development

The next section describes the method used to perform the assessment in terms of the three basic survey techniques (questionnaire, interviews and workshop). The information and conclusions derived from this database is presented in a Results section, using tables and graphs. The significance of these data are presented in a general issues section, focusing on the impact for NASA. The last section presents the conclusions of the assessment.

METHOD

Questionnaire, Interviews, and Workshop

To assess the capabilities and limitations of NASA's A&R systems, the assessment was designed to be as comprehensive as possible, both in terms of projects polled and information collected. Three methods were used to perform the assessment: an in-depth questionnaire distributed widely across NASA, personal interviews conducted with selected project engineers at each of the centers, and a workshop held at Ames Research Center that specifically focused on computational processing requirements. Additional supporting information has been drawn from referenced reports. An in-depth description of the method and the questionnaire form are provided in Appendixes A and B, respectively.

RESULTS

The results of the assessment were extensive. The information presented in this section is distilled from the 35 completed questionnaires, 59 interviews and 21 presentations at the workshop. All who contributed to the content of this report, both formally and in "coffee room" discussions are listed alphabetically in Appendix C. Requests for anonymity were respected. The results contained in this report emphasize four key issues:

1. intended operational functionality

2. computational capabilities required to support full functionality in the targeted environment

3. achievability of functions

4. tradeoffs

NASA's Requirements

The requirements for NASA are not so simply stated as "NASA needs XXX amount of memory, YYY processing performance and ZZZ reliability with XYZ environmental tolerance." This simplification could indicate that all applications in all environments could be satisfied by a global, all encompassing capability, which is not the intent of this report. Organization and presentation of the data are key to understanding and fulfillment of the requirements. The results are therefore presented in the context of the environments (table 1). Within this format, similarities in basic requirements are highlighted. An illustrative subset of the results is presented in the following sections. This includes descriptions of the projects as well as their current and anticipated computational requirements.

There were many issues presented in the assessment, both technical and programmatic. This paper focuses on physical problems and solutions; discussion of those programmatic issues is deferred to a subsequent report.

The Global Picture

Although each NASA environment created unique requirements, some responses were overwhelmingly common and warranted special note. At least 90% of the respondents expressed concern about additional computational processing capability. Particularly requested were increased CPU performance, memory size and access time. Most did not quantify the increase desired, but rather said "as much as possible" and "whatever is provided, we will use" and "at least double what is currently available." It is important to note that many of the automation systems were (or are) developed with an end application in mind, leaving the specific hardware architecture to be determined later. In system designs, the hardware is less of a concern because the "fastest available at the time of deployment" was most often what will be used. Therefore, it is usually not until a fully functional application is established that hardware limitations can be quantified. By this time, however, automation is well underway and functionality has to be scaled back to fit the available hardware. On the other hand, the robotics projects by necessity design their software to the specific hardware.

Another major concern was fault tolerance, but respondents admitted that it usually is not seriously considered in the design until after the initial "prototype system" is developed. This is due to the desire to establish feasibility of a function first. Project funding was also commonly identified as a primary limiting factor to successful system design and deployment.

Many reported that "success" of a project is not what was the basis of the initial conceptual design. Due to design factors such as processor limitations and funding, sacrifices were consistently made and the definition of "success" was continually scaled back and redefined. This mission "success" was common. Such a process occurred recently, in the current SSF design and the ongoing scrub activities.

NOTE: A majority of those interviewed were from the research side of NASA as opposed to the operational side. Therefore, concepts of success tend to have a different meaning. Researchers strive for demonstration of proof of concept and tend to continually improve the end product as thoughts and requirements change during the development cycle. Program managers, in contrast, must live with specific budgets and schedules and are often willing to settle for less than perfection to meet a milestone and a delivery date. Neither of these views are wrong, both are reasonable in the evolution of space flight.

Environmental Implications on Computational Systems

The architectural design of a computational system depends not only on the application but also on the environment for which it is targeted. For each environment, issues will receive different levels of priority as presented in table 2. Although each area listed places different priority levels on the technical issues, all are of importance. It should be noted that the numbers given in each category are relative, both to the issues in each column and to the other environments in each row. For all environments other than ground development, fault tolerance and reliability was of utmost importance in the deployed system. The following is a description of the relevant issues for systems relative to their end environment.

Technical Issues– The technical issues listed in table 2 are categorized into three areas: (1) System Performance, which focuses on the final hardware used; (2) Environment, with considerations related to end deployment; and those which come from (3) the overall Mission. Although more issues were raised than are shown in table 2, those most referenced throughout the assessment are presented now with their definitions.

Performance issues definitions.

CPU performance: Typically the throughput of a specific set of benchmarks, measured in MIPS. In any computational processing system, speed is always a consideration. It is either a primary preference or mandated by application timing constraints. In those categories that speed is secondary, it is because compensation for environmental hazards is the primary factor.

Table 2. Program and mission priorities[a]

Issue	Application environment									
	Ground			Aeronautic		Low Earth orbit		Space SEI		Deep space
	Development	Operational	Science	Experiment	Launch	Equatorial	Polar	Manned	Unmanned	Platform communications
Performance										
cpu performance	3	2	2	2	2	2	2	2	2	2
Memory size	3	2	3	2	1	2	2	2	2	2
Communications bandwidth	4	2	3	2	2	2	2	2	2	2
Environment										
Power (watts)	4	3	4	3	3	1	1	1	2	1
Weight	4	3	4	1/2	2	1	1	1	1	1
Temperature	4	3	4	2/3	2	1	1	1	1	1
Vibration	5	5	5	2/3	2	3	1	3	2	4/5
Radiation hardness	5	5	5	4/5	2	2/3	1	1	1	1
Noise	5	5	5	2	1	4/5	4	3/4	2/3	4/5
Mission										
Mission duration	5	3	5	3	3	1	1	1	1	1
Real time performance	3	2	3	1	1	1	2	1	1	1
Fault tolerance	4	2	4	3	1	1	1	1	1	1

[a]top priority = 1, preferential = 3, little/no consideration = 5.

Data storage: Size of RAM and on-line memory. Data storage affects the application size and the amount of data that can be collected and stored. A prime resource in all off-ground applications, it is admittedly limited so as to enhance reliability and reduce maintenance costs.

Network bus bandwidth: The amount of data within the system that can be accessed and the time it takes to access it directly affect the end system speed. Necessarily an issue in system design, it is often readily accommodated, e.g., by fiber optic cabling.

Communication bandwidth: Amount of I/O data. Communication bandwidth is critical in telemetry situations and those where real-time applications are dependent upon constantly changing environmental data.

Environment issues definitions and comments.

Power: Required to keep the system running, typically in watts. Power becomes a prime design factor for space systems where power is a limited resource.

Weight (mass): System physical size is necessarily limited by the resources in the environment. Physical area is a resource for experimental aeronautic systems and for those in space. The smaller a system is, the less power it should consume, not only in the act of deploying but also in its continued use.

Temperature: Heat dissipation is a concern relative to the speed of the system (performance) and the deployed environment. This issue is typically satisfied by packaging techniques.

Vibration: Deploying a system to its end environment involves physical movement of the system. This includes inertial vibration, stability ranges, shock and spin. Vibration tolerance is also handled in the packaging.

Radiation hardness: Shielding of systems in hostile environments which may consider internal radiation (neutrons), rad-hard single dose and total dose, latchup-proof, cosmic rays and single event upsets. The levels for which designs are needed depend on the orientation in space. For example, radiation was a factor in placement of Space Station Freedom below 290 nautical miles. Beyond this altitude energy impacts increase significantly, which increases the probability of electronic data and command path disruptions.

Noise: Electrical noise both internal and external to the system affect the performance and reliability of the information input to and supplied by the system. Due to advancements in technology, this is not a restricting factor on system designs.

Mission specific issues.

Mission duration: the longer a mission, the more critical component reliability and system fault tolerance become to the system design process. Ground systems can be readily maintained by field support service personnel. Aeronautic systems, with missions varying from within one hour for aircraft to weeks for the shuttle receive regular ground maintenance. Deployed space systems have some capability for telemetered command reconfiguration but onboard hardware is a limited resource and is generally not maintainable.

Real time: the smallest unit of time allocated and its associated criticality for the task at hand. This is a critical issue for the operations support in life and mission-critical systems in aircraft and shuttle, as well as life support systems in SEI.

Fault tolerance: refers to the system ability to detect and tolerate both hardware and software system faults. System granularity and ranges of tolerance are based on mission, function, duration, and criticality to life.

Reliability: Typically cited with fault tolerance, the statistic often provided in MTBF and MTTR, indicating the ability of the system to perform designated functions in whole and reconfigured states.

As stated, the entries in table 2 are relative, not only among separate issues, but also between the different application environments. For example, environmental radiation has no impact on design of ground systems and limited influence on aircraft systems. However it becomes a much higher priority issue in designs for those systems that are deployed in space. Deep space systems are necessarily designed primarily to tolerate this processing hazard. Likewise, in striving to accomplish a mission, cpu performance, memory size and communications bandwidth are of concern to system designers for deep space missions, but these must be secondary to the environmental factors.

The questionnaire results are presented in tables 3-8 with their associated project descriptions found in Appendix D. The following sections summarize the general issues and concerns relative to the environments and the goals they sought. Although a limited set of projects are presented, they are representative of the most referenced issues identified.

The full set of results obtained in the assessment have been deferred to Appendixes D and E. The reader is encouraged to refer to these appendixes for supporting information. Programmatic and philosophical orientations and the impact these had on designs will also be found.

Ground Systems

Computational processing systems for ground use are not unique, relative to other environments. Any system designed for flight or space has a corresponding counterpart for ground, but not vice versa.

The top priority for selection of the ground-based systems was typically CPU performance. If unlimited resources were available, the fastest processors with the greatest available support would be used for development, mission operations and analytical applications. When necessary, reliability can be designed without regard to power and mass considerations. The software design is easily focused without much limitation in memory size. Maintenance tasks are readily accomplished when failures occur, allowing fault tolerance concerns to be less important than other issues. Within the scope of the assessment, the ground systems presented a relative lack of "issue concerns."

Aeronautic Systems

It can be argued that aeronautical systems are the most demanding on computational processing, primarily due to real-time interrupt and task-switching performance constraints. Reliability is of utmost importance to the mission and human life support, and must also be designed in from the outset. These systems must maintain ultrahigh reliability, facilitated by the extensive use of fault tolerance.

As seen in table 9, CPU power and memory size are primary limitations to deploying advanced automation capabilities. Enabled, these would enhance fault tolerance testing, increase system availability, and offset some of the pilot workload. Rather, with the exclusion of these capabilities, the pilot workload is increased as he or she must integrate increasing amounts of data, and from there the mission reliability is decreased.

Table 3. Survey responses

Flight/ Ground	Operational/ Reasearch	Project	Center	Year Deployed	Desirable Automation	Critical Functions For Automation
G	R	X-29 &	ARC/	91	Info. managementof all systems & interfaces	The testing of onboard software
		F-18/ ITF	Dryden	90	& evaluation of test results	--which is an enhancement
G	R	X-29A/ F-18 HARV	ARC/	91 / 90	System functional and	Performing v&v tests and
		CV-990 LSRA	Dryden	91	failure modeling	record results
F	O	PSC	ARC/Dryden	91	More memory and speed;	Minimize fuel flow with constant or
F	O	Research Display Con	ARC/Dryden		Interface with engineering control	maximize possible thrust
	O	KATE	KSC	92	HAL in 2001	Diagnosis and control (real-time)
G	O	OPERA	KSC	91	None	Knowledge aquisition & validation
						of system messages
Both	O	SSMEC	MSFC	93+10	Condition monitoring/failure prediction	Monitoring temp. and pressure, controlling valves
F	R	SHOOT	ARC	92	Error detection and diagnosis	Fault diagnosis and work-around
F	O	SSF	MSFC	99	House-cleaning robot to scrub walls	Dextrous manipulation
						and fault diagnosis
F	O	SSF (Payload Oper.)	MSFC	97	Expert systems,AI data collection applications	Mission planning,electronic mail & database management
Both	R	PMAD	MSFC	93+	Addition of indepth model	Normal operation, fault diagnosis, recovery
						isolation, scheduling, & load prioritization
F	O	FTS	GSFC	95	Smarter sensors,better algorithms	-
Both	O	ECLSS	MSFC	92+	Intell. control & instrumentation,testbeds,life support	Inferring & pattern matching in detect. system
Both	O	ECLSS for SSF	MSFC	95+	Further enhancement of existing functions	All automation is critical
F	O	PEGACUS	MSFC	96	-	Timing and ability to have correct orbital information
-	R	MSE	J.H. Univ.	92	-	-
Both	O	SADP	ARC	89 (demo)	Order of magnitude faster, rad. harden	All automation project
G/ maybe F	O	AANMS	Lockheed	91	Performance & fault management	Real-time, user interface flexibility
G	O	AAMP	MITRE	91	Each system covers all FDIR and dealing	AANMS: get data,detect faults and causes, find trends
					with uncertainty in the reasoning process	RPSA: alter configuration of communication subsystems
F	R	CRAF/ CASINI	JPL	95/96	Higher bdwth,more CPU thruput,less power	Fault detection and recovery
G	O	EASE	JPL	95	Uplink telemetry, spacecraft model	Real-time responsiveness
G	R	HST DADS	GSFC	93	Entire 30 Tbyte archive would be on-line	Operate optical disks
G	O	PAB	MSFC	N/A	Upgrade of automation capabilities	Enhance productivity of engineers
F	O	SEI	MSFC	00-20	-	Maintenance and repair
F	O	ASAL	LaRC	-	Planner to model entire sequence	Robotic techniques to assemble; error handling
F	R	NN Robotics	MSFC	ongoing	A robot could replace an astronaut	Stability & verifiability
Both	R	CSI	LaRC	95	-	Being defined
F	R	DTA-GC	ARC	91	Too early in project	All of the project is automation
F	R	CRIMS/ TIDE	MSFC	-	On-board heuristic analysis of data	Transmission of data
F	O	BATSE	MSFC	90	Enhance data reduction & searching	Accuracy
F	R	ALF/ HAL		ongoing	Data transmission bandwidth	Data transfer rate for video
G	O	SSE	JSC	93	Further development of AI & expert system application	Code generation, software release construction
F	O	SSF SW & verif.	JSC	95	Tests setup, run, and analyzed by s/w automation	Setup tests,analysis,results,build sequences
N/A	R	RTIAS	WPAFB	93	N/A	N/A

Table 4. Survey responses

Project	Selected Processor(s) or Syster	Processor Selection Requirements	Selection Lead Time	Computational Power	Computing Power Desired	Consider More Powerful Proc.	Will consider multiprocessors
X-29 &	X-29 -- 5301	Fastest, flight qualified	as long as 5 yr	A.M.A.P. (CRAY II level)	-	Cannot	-
F-18	F-18 -- 1750, 701E	X-29-- commercial off the shell	as long as 5 yr				
X-29A/ F-18 HARV		Flight qualified and	2 yr	-	1000% increase in	Yes	Yes
CV-990 LSRA		real-time performance			speed		
PSC		Existing hardware as a design req'mt.	2-3 yr	-	-	Unsure	No
KATE	80386	Lisp, path to real-time	2.6 yr	5-100 MIPS	As much as possible	Yes	Yes
OPERA	Explorer,	Symbolic, user I/F eff., reliab.	< 6 mo	Unknown	Unknown	Yes	No
	Sun, PC386						
SSMEC	68000 X 4	0.5 mips, space qual.	10 yr	.5 MIPS	10 MIPS	Limited	Yes
SHOOT	386	Mandated	N/A	-			No
SSF	386	Mandated	Unknown	Unknown	Unknown	Unknown	Unknown
SSF (Payload Opn.)	386	Evolutionary upgrades	Unknown	TBD	TBD	TBD	Evolutionary
PMAD	Symbolics & 386	Power, compilers	4 yr	27 MIPS	Significant increase	No	Yes
	Solbourne 5/ 501						
FTS	386	Performance,cost,qualifiability,Ada, reliability	in procurement	40 MIPS	As much as possible	Yes	Yes
ECLSS	386i	Compatability	1 yr	-	-	-	-
ECLSS for SSF	-	-	-	-	-	-	-
PEGACUS	VAX system	Compatibility	TBD	Unknown	-	Probably	Unknown
MSE	1750A	Performance, thruput analysis	3 yr	39,242 FLOPS (.2 MIPS)	25 MHz	Yes	Yes
SADP	Symbolics	Symbolic processing	2 yr	10 MIPS			Yes
AANMS	Transputers (Inmos)	Compatibility	2 yr	10 MIPS	400 MIPS	Yes	Yes
AAMP	AANMS: VME- based	Testbeds provide the platform	-	AANMS: >100 MIPS	Unknown	AANMS: yes	AANMS: yes
	RPSA: SUN (-3 or -4)			RPSA: <25 MIPS		RPSA: yes	RPSA: no
CRAF/ CASINI	SA3300	Performance, radiation harden	8 yr	0.4 MIPS	As much as possible	Too late	Yes
EASE	RISC/ SPARC	Color, graphics, hi- resolution	6 mo	2 MIPS (total 6 processors)	50 MIPS per processor	Yes	Yes
HST DADS	VAX 6000-210's	Performance, interface	3 yr	25 MIPS +20 MFLOPS	30 MIPS	Yes, but no funds	-
PAB	PE 3280/3260 / VAX	Compatibility	2 yr	>50 MIPS+ 10 MFLOPS	Significant increase	Depends on cost	Yes
SEI	Undecided	N/A	-	-	-	-	-
ASAL	386/ 68000/ VAX	Need real-time; 3D graphics	-	Unknown	Unknown	Yes	Yes
NN Robotics	AT&T DSP32C	Speed,array processor,flight qualified	1 yr	Unknown	Unknown	Yes	Yes
CSI	1750A	Qualifiable, thruput rate	-	15 MFLOPS	-	Yes	Yes
DTA-GC	-	Speed, supports Lisp	3+ yr	TBD	-	Yes	-
CRIMS/ TIDE	NS32016 X 2	Speed, power, radiation hardened	2 yr	Unknown	As much as possible	Yes	No
BATSE	SBP9900	Radiation hardened	3 yr	2 MIPS	N/A	Yes	Yes
ALF/ HAL	-	Personal experience	-	1 MIPS	-	Probably not	No
SSE	-	Support of communication tool vendors	-	-	-	Yes	-
SSF SW & verif.	V6000, K6000	Compatibility	1-2 yr	120 MIPS	120 MIPS	Yes	Yes
RTIAS	MIPS RX000 &	Compatibility	N/A	200 MIPS or more	200 MIPS or more	Yes	Yes
	INTEL 80960						

perf. = performance

Table 5. Survey responses

Project	Real-Time Requirement	Language	Software Size/ Type	Memory Size	Storage Space	Data Bandwidth An Issue/ Rate	Realistic Power	Volume (cu. ft)	Weight (lbs.)
X-29 &	Yes	Fortran,C,Asembly	32K loc	4-8 MB	-	-	-	-	-
F-18		Fortran,C,Ada,Asembly		(a.m.a.p)					
X-29A/ F-18 HARV	Yes, 8.25 to	Assembly, C, Ada	X-29 --28K/ F-18-- 32K/	-	Sims. need >800 MB	1 Mbit now, 10 to	-	.5 to 1	-
CV-990 LSRA	25 msec		CV990-- 10K/ all N		aircraft >10 MB	100 Mbit in future			
PSC	Not critical	Fortran 77	13K loc/N	1 MB		Minor issue, 20 Hz	-	-	-
KATE	10 msec	Lisp, Ada, C	10K loc/ M	8 MB +	100-300 MB	No	-	Board size	-
OPERA	Yes	Lisp, C	50K loc/ S	>40 MB	1100 MB	No	-	No constraint	No constraint
SSMEC	20 msec	C, Assembly	128K bytes/ N	64 KW	None	Not an issue	700 Watts	3.75	215
SHOOT	< 1000 msec	C	?/ M	10 MB	1 GB	1200 baud data	30- 60 Watts	Laptop size	-
SSF	Yes	Ada	Unknown/ M	Unknown	Unknown	TDRSS rate	Very low	Very small	Very small
SF (Payload Oper	5000 msec	Fortran, Ada	Evolutionary/ M	TBD	TBD	TBD	TBD	TBD	TBD
PMAD	Varies	CLOS, Lisp, Pascal	>50K loc/ M	30 MB	250 MB	1Mbyte/sec	Minimal power	-	-
FTS	10 msec	Ada	60K loc/ N	20+ MB	600 MB	Latency more imp.	200 Watts	Limited	Limited
ECLSS	-	Lisp, Ada	500 Kbyte+4 Mbyte/M	-	-	-	-	-	-
ECLSS for SSF	-	Ada	Unknown	-	-	-	-	-	-
PEGACUS	No	C	TBD/ Unknown	Unknown	TBD	-	-	-	-
MSE	2 Hz	Ada	55K loc (3 sys.)/N	768 KW	600 MB	No	50 Watts	0.486	20
SADP	< 30,000 msec	Lisp, KEE, Fortran	Unknown/M	80 MB	1050 MB	-	3 X 120V	-	-
AANMS	TBD	Ada, C, Assembler	30K loc/M	256 MB	45 GB/hour	12.5 MB/sec	Unknown	Unknown	Unknown
AAMP	AANMS: get data	Ada primarily, C	AANMS: 40K loc/S		Unknown	AANMS: 100MB/s	N/A	Unknown	Unknown
	100 Mb/sec.		RPSA: 5K loc/S	RPSA: <0.5 MB		RPSA: N/A			
CRAF/ CASINI	Yes	C	Unknown	12 MB	3.6 GB	1Mbit/sec	< 20 Watts		< 6 kg.
EASE	200 msec	C	100K loc/ M	16 MB	10 GB	1 GB/ sec	N/ A	N/ A	N/A
HST DADS	5000;<60000 msec	Fortran, C	250K loc / M	656 MB	25 GB; 30 TB	-	Unknown	<2000 sq. ft.	-
PAB	Yes	Fortran, C	6K loc X 5 to 10/ N	-	7130 GB	10 Mbit	N/ A	N/ A	N/ A
SEI	Yes	Too soon	Unknown/ M	-	-	-	-	-	-
ASAL	Yes	C, Fortran, Ada, Pascal	Unknown/M	Unknown	Unknown	Unknown	Unknown	-	-
NN Robotics	100 msec	C	2500+ loc / M	Unknown	Standard avail.	Not a problem	Unknown	Unknown	Unknown
CSI	Yes	Ada	Unknown/ M	TBD	-	-	-	-	-
DTA-GC	Few minutes	Lisp, KEE	5K loc/ S	TBD	TBD	Not in current plan	-	-	-
CRIMS/ TIDE	6000 msec	C	Unknown/N	1 MB	None	Yes	Unknown	Unknown	Unknown
BATSE	16 msec	Assembler	8K words mach. code/N	600 KB	3555 bits/sec	3555 BPS	< 100 Watts	4	150
ALF/ HAL	-	-	Unknown	4 MB	100 MB;1 wk. video	Yes	2-3 Kwatts	-	-
SSE	-	Ada	< 1M Sloc/ M	-	-	-	-	-	-
SSF SW & verif.	Yes	Ada, C	2M loc (current)/ N	-	157 GB	10 MB files	N/ A	N/ A	N/A
RTIAS	Yes	Ada	Unknown/ M	40 - 100 MB	N/A	Yes	< 50 Watts	JIAWG standard	JIAWG standard

S=Symbolic

N=Numeric
M=Mixed

Table 6. Survey responses

Project	Limitations Encountered	Limiting Factor For Success	End capabilities scaled back
X-29 &	Speed, qualification, design,	Limited on-board processing, some flight modes removed	Flight control modes removed, variable gain selectable by pilot
F-18	X-29: speed & memory limited.	Limited on-board processing	is limited, testing hooks not added to make s/w easier to test
X-29A/ F-18 HARV CV-990 LSRA			
PSC	-	Accuracy of an on-board engine model	No, original objectives were made with existing hardware in mind
KATE	Real-time, Lisp	Verification and validation	Yes, limit capability
OPERA	Speed, symbolic processing	Money & lifespan of architecture	No
SSMEC	Qualifiable	Parts reliability and workmanship flaws	No
SHOOT	None	Adequacy of ground testing	Yes, rule base was kept manageably small
SSF	Unknown	On-orbit resources (crewtime, power, etc.)	Not yet, but current requirements are not met
SSF (Payload Op'ns)	Probably	Timely communications;voice,data,video	-
PMAD	None	Loss of commitment and lack of communication	Yes, functionality was significantly scaled back due to initial design
FTS	Interfaces	Many technical challenges with little time	No
ECLSS	N/A	Computational resources on orbit	Yes, fault detection only on orbit and no deep diagnosis
ECLSS for SSF	-	System weight, power, and volume	-
PEGACUS	Unknown	Funding	TBD
MSE	None	Sensor ability to see as well as advertised	No
SADP	Speed	Speed of Symbolics 3650	Hypothetical reasoning - an order of magnitude improvement was needed
AANMS	COTS Advanced Automation	Unfavorable combination of individual parts	No
AAMP	AANMS: ability to capture data at network rate	Evolving configuration of testbeds,delays in procuring equipment,stability in staff assignments	No, operations determined by prototyping results
CRAF/ CASINI	None	Lack of sufficient funding	Not scaled back, but desires always exceed the capabilities
EASE	None	Access to real-time data	No
HST DADS	None	Funding	No
PAB	Funds	Integration and processing capability	Real-time test,data processing using expert systems to monitor tests
SEI	N/A	Resources	-
ASAL	Real-time 3D graphics	Use of algorithms and techniques developed	-
NN Robotics	Neural hardware processors	State-of-the-art in Neural Networks	N/A yet
CSI	Too soon	Adequate budget	Too soon
DTA-GC	None	Time and money	No, not yet
CRIMS/ TIDE	Qualifiable	-	Not yet but some complex floating pt. calculations may be given up
BATSE	None	Ability to analyze all of the data	No
ALF/ HAL	None	Program office support of the science	No
SSE	-	Imposing rules and tools on individuals with different tastes	-
SSF SW & verif.	None	Limited interfaces	-
RTIAS	N/A		N/A

Table 7. Survey responses

Project	Lessons Learned
X-29 &	-
F-18	-
X-29A/ F-18 HARV	Compilers are inefficient. Programs that start with higher order languages alwaysdo portions of software in assembly
CV-990 LSRA	
PSC	Would like to have been able to stick rigidly to the Fortran 77 ANSI standard;Interface is awkward, requiring many design compromises
KATE	Stay on one platform to avoid conversion effort; Don't change from Lisp; Maybe better use of packages
OPERA	Change to a UNIX CPU with Lisp coprocessor; conforming to standards other than proprietary lessens procurement hassles
SSMEC	Use a higher speed 32 bit CPU with a non-volatile EEPROM or similar; return to assembly language for speed and efficiency
SHOOT	-
SS	-
SSF	N/ A
PMAD	Would choose Symbolics or Explorer instead of VME; Used PCL which is going to CLOS, a good move
FTS	Upgrade to fiber optic networks within telerobot;more centralized processing,parallelism,faster CPU's; Ada is the right language
ECLSS	-
ECLSS for SSF	-
PEGACUS	-
MSE	Single processor for attitude system; like to have a MIPS type processor in a rad. hard version using 30 Watts
SADP	Try combining operator interface & expert system on a single Sym. procesor with more power; move away from KEE dependence
AANMS	Development platform located off-site; non-integrated development environment;no real-time extensions: no on-line tutoring
AAMP	-
CRAF/ CASINI	Would use a 32 bit microprocessor instead of a 16 bit
EASE	-
HST DADS	Would look at C or Ada languages
PAB	Would change to an all UNIX system: utilize TCP/ IP for all network functions
SEI	-
ASAL	-
NN Robotics	Will have to write own software
CSI	-
DTA-GC	-
CRIMS/ TIDE	-
BATSE	A higher level language and a cross compiler to the flight processor would be good
ALF/ HAL	-
SSE	Ada has limited commercial support. This is becoming less of a problem with time.
SSF SW & verif.	Don't use proprietary languages
RTIAS	-

Table 8. Survey responses

Project	Reference
X-29 & F-18	Joel Sitz; Aerospace Engineer
X-29A/ F-18 HARV CV-990 LSRA	Vince Chacon; Aerospace Engineer
PSC	Trindel Maine; Aerospace Engineer
KATE	Edwin E. New; Engineer and Barbara Brown
OPERA	Patrick T. Pinkowski; Computer Engineer
SSMEC	Michael Purvey; Computer Engineer
SHOOT	Tim Castellano; SHOOT software Project Manager
SS	Dale Thomas; Project Engineer
SSF	Steven R. Noneman; Payload Operations Director
PMAD	Louis F. Lollar and Bryan Walls; Electrical Engineers
FTS	Karen Halterman; Robot Control System Manager
ECLSS	Brandon S. Dewberry; Computer Engineer
ECLSS for SSF	Greg Schunk; Aerospace Engineer
PEGACUS	Belinda Mitchell Wright; Engineer, Data Systems
MSE	Harry K. Utterback; Software Engineer, Member Principal Staff
SADP	Brian J. Glass
AANMS	Boris Freydin; Computer Systems Analyst
AAMP	Tammy M. Pelnik; Member of the Technical Staff
CRAF/ CASINI	James A. Donaldson; MTS: CRAF/ CASSINI CDS COG-E
EASE	L. Stephen Coles, Ph. D.; Technical Manager
HST DADS	Elizabeth A. Citrin; HST DADS Manager
PAB	Frederick D. Bachler; Branch Chief
SEI	H. E. Brown; Engineer
ASAL	William Doggett; Mechanical Engineer
NN Robotics	Ralph Kissel; Sr. Engineer
CSI	Rudeen Smith-Taylor; Guest Investigator Manager
DTA-GC	Dr. David Thompson, Dr. Deepak Kulkarni, Rich Levinson, and Peter Robinson; workers
CRIMS/ TIDE	Dr. W. J. Selig; Computer Scientist
BATSE	Robert W. Austin; Supv. Electro-optical Systems
ALF/ HAL	Dr. Edwin Ethridge; Materials Scientist
SSE	Mark Mangieri; Computer Engineer AST -Flight Data Systems Division (FDSD)
SSF SW & verif.	John F. Muratore; Chief, Reconfiguration Management Division
RTIAS	Al Scarpelli; Electronics Engineer

Table 9. Aeronautic requirements

Vehicle	Function	Key requirement (current -> need)	Limitation	Sacrifice	Compensation
X-29	System information management	<0.5 -> 10 MIPS	CPU	Reduced control mode	Pilot load
F-18	Sys.model F.T.	Real-time, qualified	CPU, memory	Reliability	Defer to ground
CV-990	Optimum fuel use	Existing hardware	Memory	Model complexity	None

When more computing power becomes available, specified as a 10x increase over the current 0.5 MIPS, and more memory than the range of 128KB to 512KB, the following would be added:

- increased onboard testing,
- incorporation of vehicle system health monitoring,
- enhanced software programs which can adapt to and compensate for a range of hardware failures, and
- implementation of all of the above in a higher order language.

Low-Earth Orbit Systems

Launch vehicles present a new mix of processing requirements, involving the real-time performance of aeronautic systems and the environmental and extended mission considerations of space. System reliability is of primary importance and changes in software are not realized as quickly as for research aircraft. However, because aeronautic and launch systems are maintained regularly on ground, the upgrades are more readily achieved than for deployed space systems.

Technology programs necessary to demonstrate flight critical avionics architecture for next generation space launch vehicles have been identified (ref. 8). The Multi-path Redundant Avionics Suite (MPRAS) System/Subsystem presents requirements for advanced space launch vehicles, stressing that "autonomous flight and ground operations are key features" to the successful system. An analysis of the three candidate configurations defined and presented is summarized in table 10. Each configuration presents increasing degrees of autonomy, operating in the same mission scenario. Configuration 1 represents a partially reusable ascent stage with fully reusable flyback boost stage; configuration 2 is a partially reusable ascent stage with partially reusable boost stage; and configuration 3 represents a totally expendable ascent stage and boost stage. As stated in the report (ref. 8), "these

Table 10. MPRAS requirements

Function	CONFIGURATION 1				CONFIGURATION 2				CONFIGURATION 3			
	CORE STAGE		FLYBACK BOOSTER		CORE STAGE		FLYBACK BOOSTER		CORE STAGE		FLYBACK BOOSTER	
	KIPS	MEMORY (KW)	KIPS	MEMORY (KW)	KIPS	MEMORY (KW)	KIPS	MEMORY (KW)	KIPS	MEMORY (KW)	KIPS	MEMORY (KW)
Mission Management	57	8	57	4	57	8	19	1	59	7	0	0
Vehicle Health Monitoring	96	818	96	422	96	818	48	96	96	204	0	0
Telemetry,Tracking and Command	41	67	41	67	41	67	14	23	37	17	0	0
Navigation	1276	105	1321	140	1276	105	0	0	1173	18	0	0
Guidance	2722	318	12	8	2722	318	0	0	2722	289	0	0
Flight Control	77	37	1156	28	77	37	15	7	77	26	0	0
Propulsion	1779	178	3077	194	1779	178	2308	146	1186	119	1539	97
Structures and Mechanisms	54	31	43	25	54	31	7	4	10	6	4	2
Flight Termination (Guidance)	0.9	1	0.9	1	0.9	1	0.2	0.2	0.9	1	0.2	0.3
Electrical Power	23	22	23	22	23	22	7	7	16	15	12	11
Environmental Control	6	17	6	17	6	17	4	5	4	9	2	6
FLIGHT SUBTOTAL	6132	1602	5833	928	6132	1602	2422	289	5357	710	1557	113
GROUND ONBOARD CHECKOUT	-	1570	-	2014	-	1570	-	1031	-	360	-	199
SUBTOTAL	6132	3172	5833	2942	6132	3172	2422	1320	5357	1070	1557	312
HOL FACTOR (20%)	1226	635	1167	588	1226	635	484	264	1071	214	311	62
GROWTH MARGIN (200%)	12264	6344	11666	5884	12264	6344	4844	2640	10714	2140	3110	620
TOTAL	19622	10151	18666	9414	19622	10151	7750	4224	17142	3432	4978	994

requirements are intended to represent mid-term launch vehicles such as for the Advanced Launch System (ALS) and to provide the requirements from which a range of conceptual avionics architectures can be generated for each of the configurations." As can be seen, the performance requirements of the total system vary from 17 to 20 MIPS. The radiation dosage is relatively small, with a maximum reported at 4 rads Si for total dose to the vehicle. The full details of these requirements are found in the referenced report.

The upgrade to the new general purpose computer (GPC) of the space shuttle program, with a threefold increase in processor speed over the previous GPC, yields a potential for a 40% increase in system performance. It is unclear whether this capability will be sufficient for the studied configurations.

Three other projects assessed are outlined in table 11. Each of these is developed to be compatible with the Space Shuttle. The Knowledge-based Autonomous Test Engineer (KATE) is a large production system designed to support real-time diagnosis and control of systems. It can be applied to ground, flight or space systems. The primary focus of this system is analysis and intelligent control through software. Due to the type of application, this is a large system that could benefit from as much speed up as possible in system performance. Because KATE was designed to be general purpose, the computational processing requirements are necessarily dependent on the system to which it is applied. In the various current applications, 5 to 100 MIPS system throughput is required. However, unspecified increases in system performance are required for some applications, particularly off-ground, and desired for all others. For this system, the Lisp language, the dynamic memory allocation scheme associated with it, and the technology's inherent verification and validation issues were all cited as the limitations realized in achieving success in off-ground deployment. Investigations are currently underway in translating the system from Lisp into a conventional language, such as C or Ada. This example is typical of most automation programs currently in development.

To incorporate system health monitoring into the second generation main engine controller of the Space Shuttle requires a speedup of 20 times that available with the current system. The sacrifice is, as in most deployed systems, system testing.

The Super-fluid Helium On Orbit Transfer (SHOOT) project has been designed from the beginning as a single-time payload experiment, primarily as a demonstration of automation technology. The platform and interface were specified by the shuttle office. Successful automation will be demonstrated, however a more capable hardware system, with faster processor speed and larger memory, would enable deployment of a more sophisticated system with increased error detection and diagnosis.

Table 11. LEO launch requirements

	Functionality	Key requirement current (need)	Limitation	Sacrifice	Compensation
KATE	r.t. diagnosis and control	5-100 MIPS (as much as possible)	Language, v&v, 8MB	Usage in space	Translation?
SSMEC	Engine control health monitor	0.5 MIPS (10 MIPS)	Speed, parts reliability	Onboard testing	Assembly language
SHOOT	Fault diagnosis	4 MIPS (TBD)	Memory size, speed	Fault handling	None

Space Station Freedom Systems

The SSF is designed to sustain a 30 year mission with first element launch scheduled for 1995. Its mission is to support international scientific research labs investigating physics, material and life sciences and performing astronomical and earth observation. The SSF is also intended to support the Lunar/Mars missions.

In addition to those given in tables 3-8, specific requirements regarding advanced automation capabilities targeted to support the SSF are presented in table 12. The typical limitation identified for these functions is the projected real processing speed of the i80386 processor. Although the exact requirements necessary for fulfillment of the functions were not identified, it was clearly stated that the technology described in this paper is insufficient to perform the tasks as defined. The sacrifice realized because of the limitations is typically in system reliability, either by a reduced model of the system used in fault tolerance or as a loss of basic data. It was indicated that the functional capability of some payload operations would not be achieved at all, without the capability of a space qualified symbolic processor. This was indicated by two different advanced automation programs, currently developed in Lisp, using symbolic-processing machines.

Detailed in a recent report by Dr. Michael Ring of Advanced Technology and Research Corporation (ref. 10), the basic functions for the Flight Telerobotic Servicer (FTS) are achievable with currently available technology. Some of the requirements identified by the general software organization for the FTS are presented in table 13. Designed specifically for tele-operation, the hooks and scars are to be in place for upgrading to autonomous operation.

Optimally, the upgrades would include vision processing. Although detailed requirements were not indicated to support vision processing, table 14 presents a preliminary outline. The basic operational capabilities of the tele-operated robot would likely preclude this upgrade from being achieved. Indications are that support of the growth capabilities of the flight telerobotic servicer requires much more processor capability than is currently available.

Table 12. Space Station Freedom requirements

	Function	Key requirement now (need)	Limitation	Sacrifice	Compensation
SSF	House-cleaning robot	4 MIPS (TBD)	cpu speed	TBD	Crew
SSF	Mission planning payload operations	4 MIPS (TBD)	Symbolic process	Capability	Crew, electronic mail
PMAD (MSFC)	Management, diagnosis recovery	27 MIPS (significant increase)	cpu, memory	Model complexity	None
FTS	Telerobot	40 MIPS (TBD)	Algorithm (cpu)	None	N/A
ECLSS	Intelligent control life support system	Compatibility with SSF (symbolic)	cpu speed, memory, language	Fault detection handling	Defer to ground
TCS	Real time temperature control	10 MIPS (40 + MIPS)	cpu speed, language	Hypothetical reasoning	Ground
AANMS	Network monitor fault management	10 MIPS (400 MIPS)	cpu speed	Loss of data	Intermittent sampling

Table 13. General software organization of FTS

Level	Function	Clock rate	Proc. power	w/Data transfer
Manipulation primary level		20 Hz	17 kflops	26 kflops
Manipulation servo level (7 DOF w/FTT)	Sensor mod processing, rt control inertia, etc.		0.4 kflops	
		200 Hz	90 kflops	
		20 Hz	45 kflops	
			135 kflops	202 kflops
(6 DOF w/FTT)	Real-time inertia, etc.	200 Hz	60 kflops	
		20 Hz	30 kflops	
			90 kflops	135 kflops
Hand controllers			33.8 kflops	51 kflops
Total				212 - 279 kflops

Table 14. Processing requirements for vision incorporation to FTS (in Kflops)

Level	Vision	Safety	Manipulator	Total Kflops
Elementary	2000	2500	3300	7800
Primary	—	39	78	117
Servo	—	270	641	911
Total	2000	2809	4019	8828

Low Earth Orbit Polar Systems

The difference between this section and the previous is the mission type. Whereas the SSF is designed to support human life, low earth orbiting polar systems emphasize science experiments and have no crew. They tend to be the most benign of the off-ground systems to design because the environmental factors are comparable to those of the SSF and their mission functions are for communications and scientific return.

Responses in the assessment by the EOS management indicated that the use of the 1750A processor was more than adequate for their onboard processing requirements, which were admittedly minimal. There are no plans for upgrades to this system. Full details on this project are available in the appendices.

Unmanned Space Exploration Initiative Systems Mars Rover Telerobotics

The projects entailed within the SEI program are the most complex in terms of functional capability. This is due primarily to the integration of each of the resident subsystems of the robots and rovers.

Development of rover technology for Lunar and Mars exploration is a difficult task because requirements for this unique scenario do not exist. The overriding functionality is that the rover is to perceive its environment and plan its path. Every meter travelled requires *X* amount of processing. 100 Gflops capability for 60 meters/day should be sufficient.

The computational and data storage requirements for the planetary rover are presented in tables 15 and 16 (ref. 10). The planetary rover must sufficiently support computational requirements of onboard navigation activities, which involves manipulation and storage of large databases, stereo correlation, terrain matching and path planning. Robotic processing includes the real-time command, control and data management of science and engineering subsystems. The summarized requirements presented may vary by an order of magnitude, depending on the mission scenario used. These requirements are represented in table 15 in system form. This indicates a range of computational requirements for planetary rover navigation, based on specified mission scenario with rover velocity and roundtrip light time delays.

Table 15. Rover processing requirements

Function	Storage, Mbits	MOPS/ Cycle	Cycles/ Meter	MOPS/ 10 Meters	MIPS
Structured light vision	109	6.5	5	325	VAR
Full stereo imaging	337	1000	0.5	5000	VAR
Modified stereo imaging	TBD	76	0.5	380	VAR
Laser scanner	8.2	118	5	5900	VAR
Radar sensor	1.95	10	0.2	20	VAR
Path planner	80	250	0.1	250	VAR
Terrain matching	121	500	0.1	500	VAR
Traverse simulation	TBD	200	0.1	200	VAR
Execution monitoring	TBD	250	0.1	250	VAR
Sequence planning and generation	TBD	250	0.1	250	VAR
System monitoring and replanning	TBD	N/A	N/A	N/A	0.5
Vehicle control	TBD	N/A	N/A	N/A	0.3
Manipulator control and sampling	421	2.25	N/A	N/A	?
Telemetry handling	634	0.75	N/A	N/A	0.075
System fault protection	>1000	34	5	170	20% (total)
Command and data handling	8	1.0	N/A	N/A	0.3
Power and thermal management	0.004	0.001	N/A	N/A	0.05
Science	54000	?	N/A	N/A	?

Figure 1 shows the identified trends in computational requirements for navigation of planetary rovers (ref. 10). The simplest of scenarios indicates that requiring 0.5 to 2 MIPS capability are pushing current performance limits of available processors. The construction vehicles' requirements of 5000 to 50,000 MIPS are well beyond most processing capabilities of even advanced ground technology. The goal of relating this information to the available space-qualified processors, will probably never be met expeditiously without an active leadership role by those who need the extensive capabilities.

Table 16. Rover computational processing requirements by scenario

Vehicle	Lunar survey rover 8.3 cm/sec (5 m/cycle)	Mars exploration rover 1.2 cm/sec (10 m/cycle)	Mars construction rover 1.0 m/sec	Lunar construction rover 10 m/sec
Capability/function	CARD[a], human operator plans, telemeters commands	Semi-autonomous navigation	Continual movement, onboard sensing, perception and planning	
Onboard navigation requirement	0.5 to 2.0 MIPS	1 to 10 MIPS	500 to 5000 MIPS	50,000 to 500,000 MIPS
Average travel time per cycle	50 sec	1.66 min	Continual	Continual
Average planning time per cycle	10 sec	12.7 min.	Continual	Continual
Other	15 Krads total dose, SEU is TBD, temperature range –20 to +40°C			

[a]CARD = Computer Aided Remote Driving

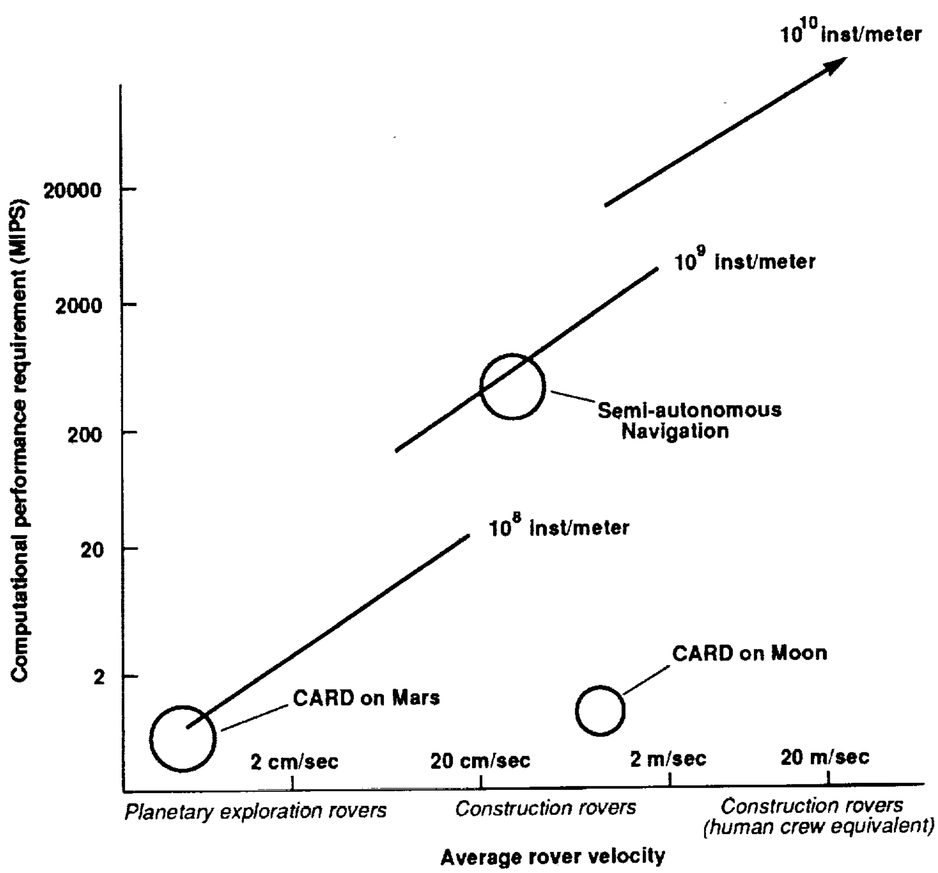

Figure 1. Estimated computation for navigation of planetary rovers.

Manned SEI

Planet surface systems– One presentation at the workshop was *Space Exploration Initiative Planet Surface Systems Computation Needs*. This talk identified case studies which were performed for the Office of Exploration (code Z) to point designs for potential Lunar and Mars exploration programs, including expeditions, observatories and outposts. The study resulted in the recommendation to establish a lunar outpost, followed by a Mars expedition, and then settling a Mars outpost.

The timeframe for establishing the outposts indicates a first piloted flight to the Lunar emplacement (enabling key capabilities and establishing of initial facilities) to be in the year 2000 and the first piloted expedition to Mars in 2014 and first piloted evolution to Mars in 2023. While it is still too early to select a processor or estimate the size of software required, definition of the top level requirements makes the architectural implications undeniable. The primary factor is providing a safe haven for crews of 4 to 8 people deployed on 6 to 12 month tours. The requirements for the construction vehicles given in the previous section are only the starting point. These can readily be extrapolated from the requirements presented in the Rover Technologies section.

Deep Space

For deep space systems, the influencing design factors are undeniable. Once deployed, the systems are unserviceable and therefore reliability must be built in. Also, autonomy in this arena carries its own definition. A requirement is to survive 24 hours with no commands, therefore being in "safe mode" of self-preservation. This is the "autonomy." The radiation levels and the temperature range to which systems are subjected continue to keep components available for these systems at a minimum. Finally, scientists set the requirements for the onboard computational processing capability. Typically, no matter what capability is offered, they want more, faster, capabilities. Scientific requirements are endless. Some of the basic requirements presented for deep space computers are:

1. Radiation: 100K to 200K RADS (Si)
2. Latchup proof
3. SEU resistant = <10E–10 Bit Flips/Bit-Day or >>37 Mev/mg/cm2
4. No dose rate or neutron requirements
5. Temperature = (–30 C to +85 C)
6. Voltage ±10%
7. >10 year mission life: high quality components (MIL-M-38510: Class S)

The platforms surveyed were Voyager, Galileo and CRAF/Cassini. The computational requirements necessarily increased as the capabilities of the systems grew. Table 17 provides the range of system requirements for three systems which "evolved".

Table 17. Space computational requirements

Mission	Year deployed, length	Processor performance	Other requirements	Problems
Voyager	1972 (12+) (extended past 3)	150 KIPS	Dual redundant; 538 Mbits Storage	Time and memory margins = 0
Galileo	1978 (10)	250 KIPS	Same as above + extra; finer granularity F.T.	Time and memory negative since 1983
CRAF/Casini	1995 (12)	400 KIPS	Automated FDIR	N/A

Providing a true evolutionary perspective, the most notable of these lessons learned are:

1. Control requirements, not data requirements, drive the computer needs
2. Speed margins are at least as important as memory margins
3. Beware new microcode: subtle bugs are detected through years and thousands of hours of operation.

CONCLUSIONS

Many issues have been raised throughout the assessment, some application-specific, but even more that are common to most NASA programs. Of the survey, workshop and interview data collected, 90% of those responding expressed concern that NASA's deployed systems are not as capable as they should be (indicating various reasons) and that available processing technology is one of the major problems. Although NASA has been forced to use what was available, this is not without mission sacrifice. This sacrifice is defined as either: 1) the initial functional design of a system could not be deployed with existing technology and thus had to be reduced in scope; or 2) that the end system functionality was intentionally defined to the existing hardware capabilities, fully recognizing that this system would not be as capable due to the end hardware being space qualified, rather than ground operational. The identified problems can all be categorized in two related areas: limited selection of qualified processors, and the fault tolerance of system designs. More explicitly, the following can be concluded:

1. "Qualifiable" Technology is sufficient for most kinds of applications.

2. A perception among the researchers is that AI and expert systems are limited by techniques (verification and validation) and hardware (support of programming language).

3. Image Processing with real-time control is the most demanding on computational processing and connectivity resources. These capabilities are not adequately met with existing technology.

4. Fault Tolerance was found to be the most neglected in system design, nominally taxing system throughput by 20 to 40%.

5. Benchmarks for evaluation of system performance are inadequate.

6. Technology standards is key to re-use, maintenance, and efficient, optimal system designs across missions of current and future time.

Most of the requirements cited can be satisfied by currently qualifiable technology. Many of the ground workstations are based on processors and designs that have no inherent limitations on being generated in a space qualified form. The problem is not in what could be qualified, rather what is qualified.

Factors used as tradeoffs in system design lend themselves to either restricting or enabling the end system functionality. The CPU performance, power allocation, memory size allocation, language used and funding are adjusted interdependently.

Everything depends on funding. Although the level of funding is necessarily a restriction, it is the fluctuation in funding once a design is set that results in reduction of capabilities and often reduced reliability. With this, system fault tolerance is typically the compromising catch all in system tradeoffs.

Finally, typically resolvable programmatic issues are often limiting factors of mission success. There are differences between operations-and-project and research-and-development perspectives. If identified and recognized early in system design, any ill effects could be minimized. These will be presented in a subsequent internal report.

To enable automation in space, AI and expert systems technology must be supported in the deployed system. This can be accomplished in various levels of the design, whether it be at the hardware architecture level of providing special purpose processors specifically supporting symbolic processing, or general purpose systems that make up for list processing in the raw speed. It is not so simple to indicate that special architectures should or should not be qualified. Automation must be supported. To enable its successful deployment in space, further accomplishments must be made, specifically in 1) v&v of the systems, and 2) support of the process execution efficiency, either in the hardware or the software, or both.

NASA cannot afford to continue operating in the status quo of focusing on isolated projects and their specific problems, finding quick solutions for the current problems. A plan must be adopted that will allow evolution of architectures based on projected mission requirements. Even though many requirements are not stated and researchers provide only guesses, they do represent preliminary requirements to be used as technology goals. In the end, it will be necessary to enable advanced automation technology, not limit it by default.

REFERENCES

1. A Review of Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation. The MITRE Corporation, MTR-88D000059, Dec. 1989.

2. Space Station Freedom Automation and Robotics: An Assessment of the Potential for Increased Productivity. Advanced Development Program Strategic Plans and Programs Division; Office of Space Station-NASA Headquarters; David J. Weeks, Task Manager, Dec. 1989.

3. Bayer, Steven E.: Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation. MITRE Corporation, Dec. 1988.

4. Automation and Robotics Plan. McDonnell Douglas Space Systems Company, June 1990.

5. Automation and Robotics Report. McDonnell Douglas Space Systems Company, May 1990

6. Study Reports for Space Station Technology Development Mission Requirement Definition for Advanced Automation and Robotics. A Reproduced Copy of N88-70310, Boeing Aerospace Company, D180-30636-1, reproduced by: NASA Scientific and Technical Information Facility, Nov. 1987.

7. Robotic Lunar Surface Operations: Engineering Analysis for the Design, Emplacement, Checkout and Performance of Robotic Lunar Surface Systems. Boeing Aerospace and Electronics, D615-11901, Jan. 1990.

8. Multi-path Redundant Avionics Suite (MPRAS) System/Subsystem Requirements Document. The Boeing Company, D180-30579-2, May 1989.

9. Ring, Michael: FTS Requirements for Data Management and Processing. Advanced Technology and Research Corporation, May 1990.

10. Lambert, Ken; Katti, Romney; and Manning, Robert M.: Planetary Rover Computational & Data Storage Requirements Version 1.3. Jet Propulsion Laboratory, JPL Doc #D-6948, Pasadena, Calif., Dec. 1989.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-103860

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Computational Needs Survey of NASA Automation and Robotics Missions
Volume 1: Survey and Results

5. Report Date
May 1991

6. Performing Organization Code

7. Author(s)
Gloria J. Davis

8. Performing Organization Report No.
A-91093

10. Work Unit No.
549-03-61

9. Performing Organization Name and Address
Ames Research Center
Moffett Field, CA 94035-1000

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes
Point of Contact: Gloria J. Davis, Ames Research Center, MS 244-4, Moffett Field, CA 94035-1000
(415) 604-4858 or FTS 464-4858

16. Abstract NASA's operational use of advanced processor technology in space systems lags behind its commercial development by more than eight years. One of the factors contributing to this is the fact that mission computing requirements are frequently unknown, unstated, misrepresented, or simply not available in a timely manner. NASA must provide clear common requirements to make better use of available technology, to cut development lead time on deployable architectures, and to increase the utilization of new technology.

This paper provides NASA, industry and academic communities with a preliminary set of advanced mission computational processing requirements of automation and robotics (A&R) systems. The results were obtained in an assessment of the computational needs of current projects throughout NASA. The high percent of responses indicated a general need for enhanced computational capabilities beyond the currently available 80386 and 68020 processor technology. Because of the need for faster processors and more memory, 90% of the polled automation projects have reduced or will reduce the scope of their implemented capabilities. The requirements are presented with respect to their targeted environment, identifying the applications required, system performance levels necessary to support them, and the degree to which they are met with typical programmatic constraints. Volume 1 includes the survey and results. Volume 2 contains the Appendixes.

17. Key Words (Suggested by Author(s))
Automation, Computational requirements, Automation and robotics, Robotics, Aeronautics, Space science

18. Distribution Statement
Unclassified-Unlimited

Subject Category - 31

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	A03

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield Virginia 22161