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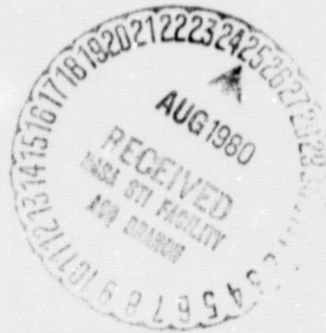
Machine Intelligence and Robotics: Report of the NASA Study Group

EXECUTIVE SUMMARY

September 1979

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

MACHINE INTELLIGENCE AND ROBOTICS
Members of the NASA Study Group
September 1979

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Preface

The NASA Office of Aeronautics and Space Technology (OAST) has established the goal of providing a technology base so that NASA can accomplish future missions with a several-orders-of-magnitude increase in mission effectiveness at reduced cost. To realize this goal, a highly focused program must be established advancing technologies that promise substantial increases in capability and/or substantial cost savings. The Study Group on Machine Intelligence and Robotics was established to assist NASA technology program planners to determine the potential in these areas. Thus, the Study Group had the following objectives:

(1) To identify opportunities for the application of machine intelligence and robotics in NASA missions and systems.

(2) To estimate the benefits of successful adoption of machine intelligence and robotics techniques and to prepare forecasts of their growth potential.

(3) To recommend program options for research, advanced development, and implementation of machine intelligence and robot technology for use in program planning.

(4) To broaden communication among NASA Centers and universities and other research organizations currently engaged in machine intelligence and robotics research.

Acknowledgement

Section I
Introduction

The NASA Study Group on Machine Intelligence and Robotics including many of the leading researchers and almost all of the leading research groups in the fields of artificial intelligence, computer science, and autonomous systems in the United States, met to study the influence of these subjects on the full range of NASA activities and to make recommendations on how these subjects might in the future assist NASA in its mission. The Study Group, chaired by Carl Sagan, was organized by Ewald Heer, JPL, at the request of Stanley Sadin of NASA Headquarters. It included NASA personnel, scientists who have worked on previous NASA missions, and experts on computer science who had little or no prior contact with NASA. The Group devoted about 2500 man-hours to this study, meeting as a full working group or as subcommittees between June 1977 and December 1978.

A number of NASA Centers and facilities were visited during the study. In all cases, vigorous support was offered for accelerated development and use of machine intelligence in NASA systems, with particularly firm backing offered by the Director of the Johnson Spaceflight Center, which we consider especially significant because of JSC's central role in the development of manned spaceflight.

This report includes the conclusions and recommendations of the Study Group. A complete report with supporting documentation will be published separately. The conclusions represent a group consensus, although occasionally there were dissenting opinions on individual conclusions or recommendations. While the report is critical of past NASA efforts in this field — and most often of the lack of such efforts — the criticisms are intended only as constructive. The problem is government-wide, as the Federal Data Processing Reorganization Project[1] has stressed, and NASA has probably been one of the least recalcitrant Federal agencies in accommodating to this new technology.

The Study Group believes that the effective utilization of existing opportunities in computer science, machine intelligence, and robotics, and their applications to NASA-specific problems will enhance significantly the cost-effectiveness and total information return from future NASA activities.

Section II
NASA Needs

NASA is, to a significant degree, an agency devoted to the acquisition, processing, and analysis of information — about the Earth, the solar system, the stars, and the universe. The principal goal of NASA's booster and space vehicle commitment is to acquire such scientific information for the benefit of the human species. As the years have passed and NASA has mustered an impressive array of successful missions, the complexity of each mission has increased as the instrumentation and scientific objectives have become more sophisticated; and the amount of data returned has also increased dramatically. The Mariner 4 mission to Mars in 1965 was considered a striking success when it returned a few million bits of information. The Viking mission to Mars, launched a decade later, acquired almost ten thousand times more information. Comparable advances have been made in Earth resources and meteorological satellites, and across the full range of NASA activities. At the present time, the amount of data made available by NASA missions is larger than scientists can comfortably sift through. This is true, for example, of Landsat and other Earth resources technology satellite missions. A typical information acquisition rate in the 1980s is about 10^{12} bits per day for all NASA systems. In two years, this is roughly the total non-pictorial information content of the Library of Congress. The

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[1] U.S. Office of Management and Budget, *Federal Data Processing Reorganization Study*, Available from National Technical Information Service, Washington, D.C.

problem is clearly getting much worse. We have reached a severe limitation in the traditional way of acquiring and analyzing data.

A recent study at JPL estimates that NASA could save 1.5 billion dollars per year by 2000 A.D. through serious implementation of machine intelligence. Given different assumptions, the saving might be several times less or several times more. It is clear, however, that the efficiency of NASA activities in bits of information per dollar and in new data acquisition opportunities would be very high were NASA to utilize the full range of modern computer science in its missions. Because of the enormous current and expected advances in machine intelligence and computer science, it seems possible that NASA could achieve orders-of-magnitude improvement in mission effectiveness at reduced cost by the 1990s.

Modern computer systems, if appropriately adapted, are expected to be fully capable of extracting relevant data either on board the spacecraft or on the ground in user-compatible format. Thus, the desired output might be a direct graphic display of snow cover, or crop health, or global albedo, or mineral resources, or storm system development, or hydrologic cycle. With machine intelligence and modern computer graphics, an immense amount of data can be analyzed and reduced to present the scientific or technological results directly in a convenient form. This sort of data-winnowing and content analysis is becoming possible, using the developing techniques of machine intelligence. But it is likely to remain unavailable unless considerably more relevant research and systems development is undertaken by NASA.

The cost of ground operations of spacecraft missions and the number of operations per command uplinked from ground to spacecraft are increasing dramatically (Figures 2-1 and 2-2). Further development of automation can, at the same time, dramatically decrease the operations costs of complex missions and dramatically increase the number and kinds of tasks performed, and therefore, the significance of the data returned. Figures 2-3 and 2-4 illustrate schematically how improved automation can produce a significant decline in the cost of mission operations. The projected reallocation of responsibility during mission operations between ground-based humans and spacecraft computer processing is shown in Figure 2-5. There are many simple or repetitive tasks which existing machine

intelligence technology is fully capable of dealing with more reliably and less expensively than if human beings were in the loop. This, in turn, frees human experts for more difficult judgmental tasks. In addition, existing and projected advances in robot technology would largely supplant the need for manned missions, with a substantial reduction in cost.
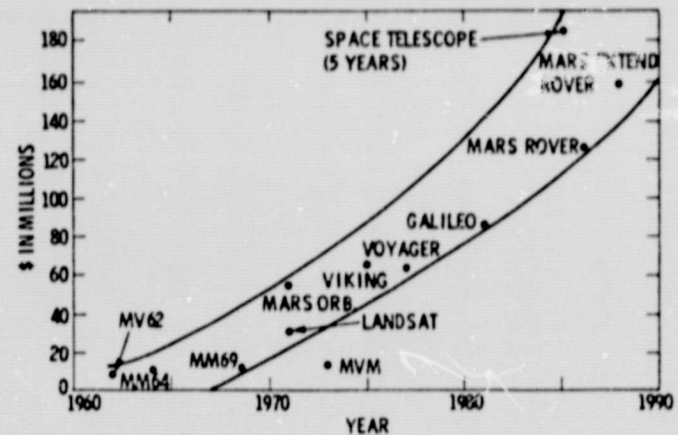
Figure 2-1. Trend of mission ground operations costs. Increasing mission complexity and duration contribute to the ground operation costs.
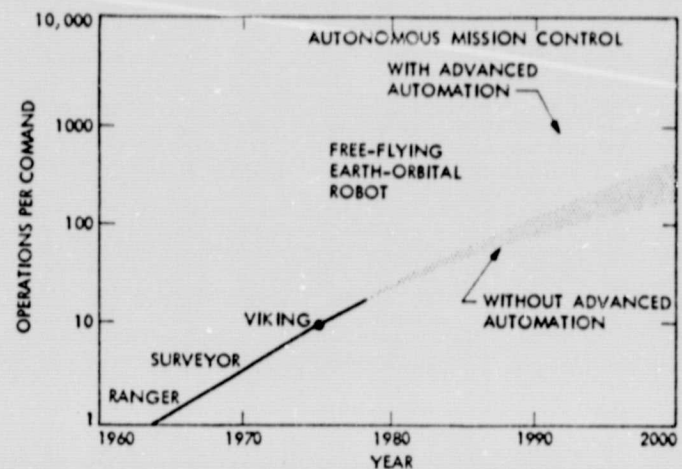
Figure 2-2. Trend of spacecraft automation. As a relative indicator, the level of automation is measured by the different elementary functions the spacecraft can perform in an unpredictable environment between ground commands. A 100-fold improvement through advanced automation is projected by the year 2000.
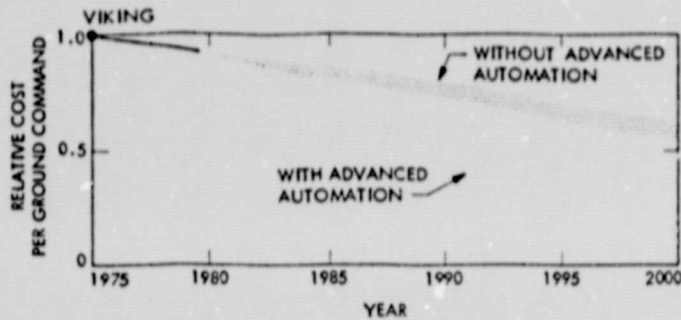
Figure 2-3. Trend of cost to generate ground commands. A four-fold improvement through advanced automation is projected by the year 2000 through (1) performing more ground functions on the spacecraft, and (2) automating the remaining functions on the ground.
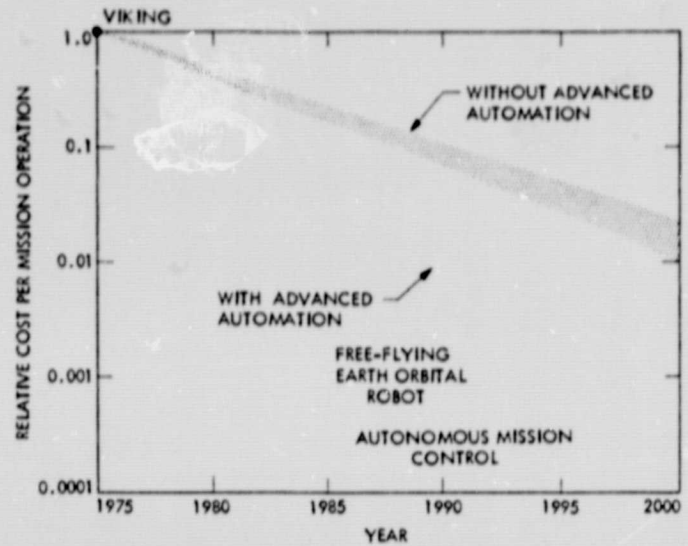
Figure 2-4. Trend of cost per mission operation. A 100- to 1000-fold improvement through advanced automation is projected by the year 2000 for executing a typical mission operation.

Figure 2-5. Trend of function (decision) allocation between humans and spacecraft. For the same typical operation, the machine takes over an increasing number of elementary functions, leaving high-level decisions to human beings.

Section III
Technological Opportunities

Machine intelligence and robotics are not only relevant but essential to the entire range of future NASA activities. Content analysis of Earth orbital and planetary spacecraft results is 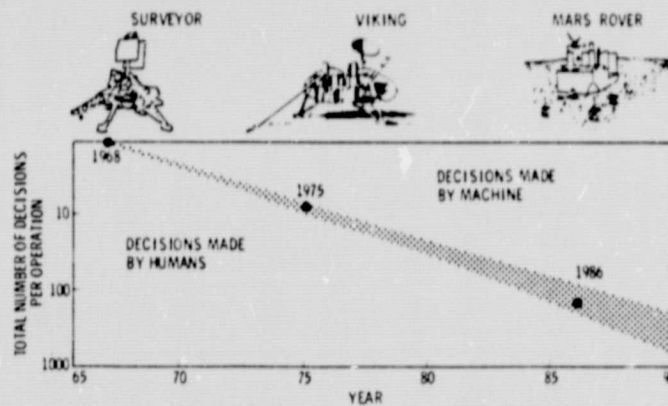merely one application. Other applications exist: in mission operations, in spacecraft crisis management, in large constructions in Earth orbit or on the Moon, and in mining in the lunar or asteroidal environments. These last applications are probably at least a decade into the future, but some essential preparations for them would seem prudent. These preparations might include the development of teleoperators, manipulative devices which are connected via a radio feedback loop with a human being, so that, for example, when the human on the Earth stretches out his hand, the mechanical hand of the teleoperator in Earth orbit extends likewise; or when the human turns his head to the left, the teleoperator's cameras turn to the left so that the human controller can see the corresponding field of view. Where the light travel times are on the order of a tenth of a second or less, the teleoperator mode can work readily. For repetitive operations, such as girder construction and quality control in large space structures, automation and machine intelligence will play a major role in any efficient and cost-effective design.

In planetary exploration in the outer solar system, the light-travel times range from tens of minutes to many hours. As a result, it is often useless for a spacecraft in trouble to radio the Earth for instructions. In many cases, the instructions will have arrived too late to avoid catastrophe. Thus, the Viking spacecraft during entry had to be able to monitor and adjust angle of attack, atmospheric drag, parachute deployment, and retro-rocket firing. Roving vehicles on Mars, Titan, and the Galilean satellites of Jupiter will have to know how to avoid obstacles during terrain traverses and how not to fall down crevasses. The development of modern scientific spacecraft necessarily involves pushing back the frontiers of machine intelligence.

In our opinion, machine intelligence and robotics is one of the few areas where spinoff justifications for NASA activities are valid. In most such arguments, socially useful applications, such as cardiac pacemakers, are used to justify very large NASA expenditures directed toward quite different objectives. But it is easy to see that the direct development of the application, in this case the pacemaker, could have been accomplished at a tiny fraction of the cost of the activity which it is used to justify — the Apollo program, say. However, because there is so little development in machine intelli-

gence and robotics elsewhere in the government (or in the private sector), spinoff arguments for NASA involvement in such activities seem to have some substantial validity. In the long term, practical terrestrial applications might include undersea mineral prospecting and mining, conventional mining (of coal, for example), automated assembly of devices, micro-surgery and robotics prosthetic devices, the safe operation of nuclear power plants[2] or other industries which have side effects potentially dangerous for human health, and household robots. A further discussion of future NASA applications of machine intelligence and robotics, and possible spinoff of these activities, is given in the supporting documentation.

With the development of integrated circuits, microprocessors and silicon chip technology, the capabilities of computers have been growing at an astonishing rate. Figures 3-1 through 3-4 provide an estimate of recent past and projected future developments. By such criteria as memory storage, power efficiency, size and cost, the figures of merit of computer systems have been doubling approximately every year. This implies a thousand-fold improvement in a decade. In another decade the processor and memory (four million words) of the IBM 370/168 will probably be housable in a cube about five centimeters on a side (although computer architecture different

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[2] An interesting possible application of general purpose robotics technology is provided by the nuclear accident at the Three Mile Island reactor facility near Harrisburg, Pennsylvania in March/April 1979. The buildup of a high pressure tritium bubble had as one possible solution the turning of a valve in a chamber under two meters of water impregnated with very high radiation fluxes. This is an extremely difficult environment for humans, but a plausible one for advanced multi-purpose robots. The stationing of such robots as safety devices in nuclear power plants is one conceivable objective of the development of robotics technology. Generally, such multi-purpose robots might be stationed in all appropriate industrial facilities where significant hazards to employee or public health or to the facility itself exists.

Shortly after the Three Mile Island reactor accident the operating company began recruiting "jumpers," individuals of short stature willing, for comparatively high wages, to subject themselves to high radiation doses thought inappropriate for permanent reactor technicians (*New York Times*, July 16, 1979, page 1). The functions are often no more difficult than turning a bolt, but in a radiation environment of tens of rems per hour. There would appear to be strong humanitarian reasons for employing small multi-purpose self-propelled robots for this function, as well as to redesign nuclear power plants to make much fuller use of the capabilities of machine intelligence. The competent use of machine intelligence and robotics is an important component of all recently proposed additional energy sources — for example, mining and processing shale and coal.

from that of the IBM 370/168 will probably be considered desirable). It is difficult to think of another area of recent technology which has undergone so many spectacular improvements in so short a period of time.

This steep rate of change in computer technology is one major factor in the obsolescence of NASA computer systems. New systems are being developed so fast that project scientists and engineers, mission directors, and other NASA officials have difficulty discovering what the latest advances are, much less incorporating them into spacecraft-mission or ground-operations design.

Another problem is the competition between short-term and long-term objectives in the light of the NASA budget cycle. Major funding is given for specific missions. There is a high premium on the success of individual missions. The safest course always seems to be to use a computer system which has already been tested successfully in some previous mission. But most missions have five- to ten-year lead times. The net result is that the same obsolete systems may be flown for a decade or more. This trend can be seen in areas other than computer technology, as, for example, in the NASA reliance in lunar and planetary exploration for 15 years on vidicon technology, well into a period when commercial manufacturers were no longer producing the vidicon systems and NASA was relying on previously stockpiled devices. This has been the case since 1962. Only with the Galileo mission, in 1984, will more advanced and photometrically accurate

Figure 3-2. Active devices technology. The number of active components per cubic centimeter is doubling every 1-1/8 years, whereas the average cost per logic gate is halving every 2-1/2 years.

Figure 3-1. Data storage technology. The storage capacity is doubling every 1-1/2 years, whereas the cost of random access memory is halving every 2-1/2 years. In 1960, the equivalent of 1 m³ stored a 15-page pamphlet; in 1980, the same space will accommodate a 2000-book library and in 1990, the entire Library of Congress.

Figure 3-3. Bubble memory technology. About 4 x 10⁸ bits/cm² would be reached in 1985. This implies a bubble diameter of 10⁻⁵ cm, which is ten times greater than the theoretical limit. (Adapted from A.H. Bobeck, Bell Laboratory, ELECTRO '77, N.Y.).
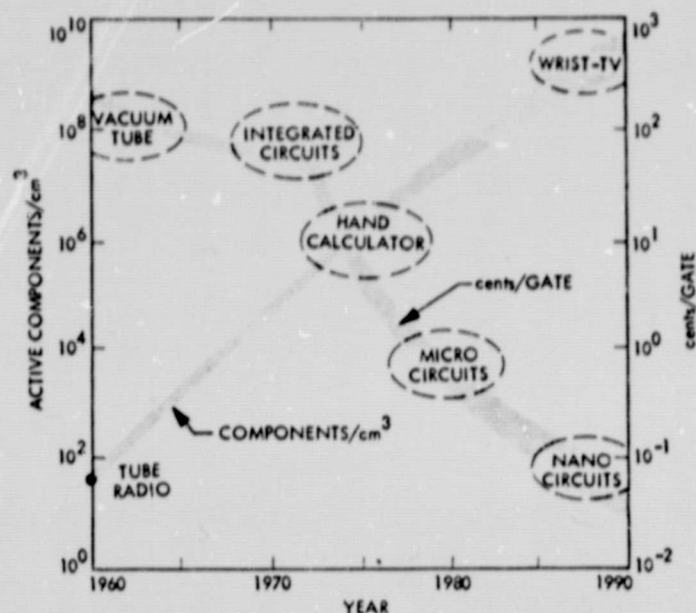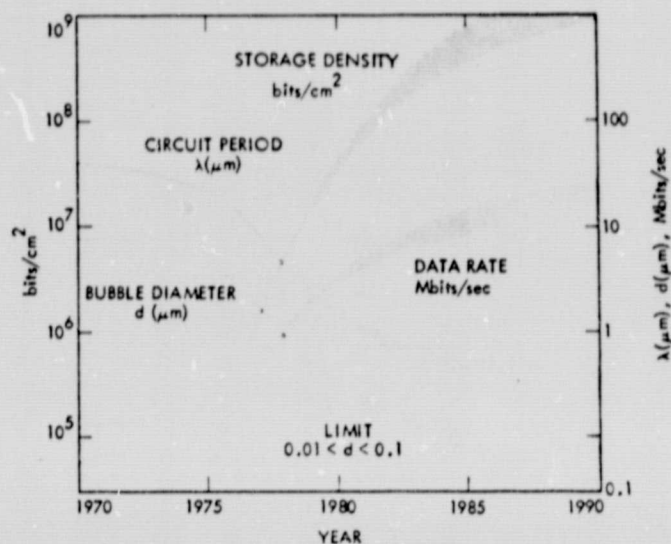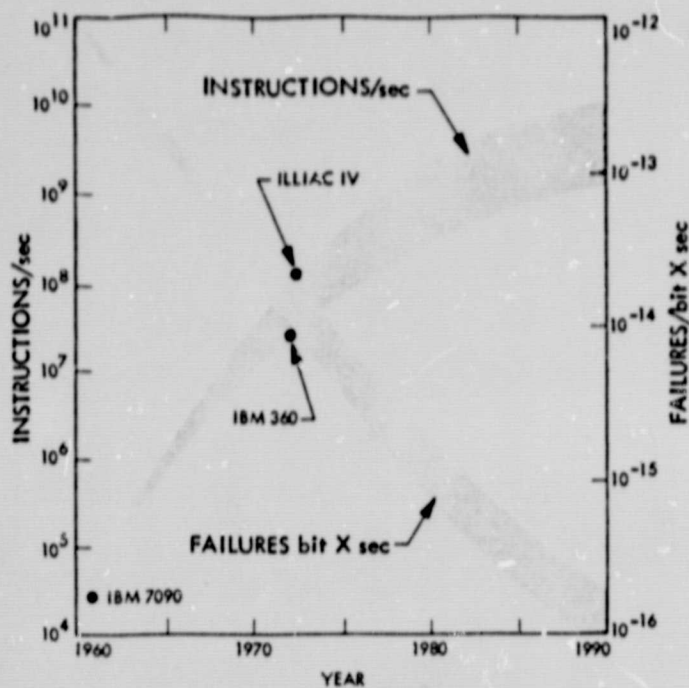
Figure 3-4. Computer systems technology. The average increase of computer speed is doubling every 1-1/2 years, whereas the failure rate is halving every 2-3/4 years.

charged-coupled device systems be employed. The problem is much more severe when it applies to a field undergoing such dramatic advances as computer technology. The management dynamics can be understood, but it is nevertheless distressing to discover that an agency as dependent on high technology as NASA, an organization identified in the public eye with effective use of computer technology, has been so sluggish in adopting advances made more than a decade earlier, and even slower in promoting or encouraging new advances in robotics and machine intelligence.

The general technological practice of adopting for long periods of time the first system which works at all rather than developing the optimal, most cost-effective system has been amply documented.[3] This phenomenon is by no means restricted to NASA. The need to handle radioactive substances led many years ago to the development of rudimentary teleoperators. At first progress was rapid, with force reflecting, two-fingered models appearing in the early 1950s. But this development all but stopped when progress was sufficient to make the handling of radioactive materials possible — rather than easy, or economical, or completely safe. This occurred in part because the nuclear industry, like NASA, became mission-oriented at this time. Since then, the development of computer-controlled manipulators has proceeded slowly on relatively sparse funding, and there has been little drive to understand in a general and scientific way the nature of manipulation. Major advances seem similarly stalled and likewise entirely feasible in such areas as locomotion research, automated assembly, self-programming, obstacle avoidance during planetary landfall, and the development of spacecraft crisis analysis systems.

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[3] Simon, Herbert, A., *The New Science of Management Decision*, Prentice Hall, Inc., 1977.

Section IV
Conclusions and Recommendations

We believe that NASA should institute a vigorous and long-range program to incorporate and keep pace with state-of-the-art developments in computer technology, both in its space-borne and its ground-based computer systems; and to ensure that advances, tailored to NASA's mission, continue to be made in machine intelligence and robotics. Such advances will not occur of their own accord. Many NASA requirements in computer architecture and subsystem design will in turn have a stimulating effect on the American computer and microprocessor industry, which now faces an extremely strong challenge by foreign competition. We believe that an agency such as NASA, which is devoted to the sophisticated acquisition and analysis of data, must play a much more vigorous role in the design and acquisition of data processing systems than has been its practice in the past.

These findings are supported by the recommendations independently arrived at by the Space Science Board of the National Academy of Sciences:[4]

> From experience with *mission operations* on previous space missions, we anticipate that there will be *even greater demands on data acquisition, processing, and storage;* on mission coordination; and on interaction with the spacecraft and scientific experiments. The complex nature of mission operations and the long time scale required to prepare, certify, and transmit routine commands in previous missions indicates that substantial changes will be necessary. We believe that significant technical and managerial advances must be made in anticipation of future planetary missions, in order to provide reliable, more efficient, and lower cost systems for operation of the spacecraft and scientific instruments.
>
> The testing of these systems on the ground as operational units including the participation of science teams should be carried out well before the mission. These tests should include the operation with possible failure modes. *These approaches will be more important in the future when extensive coordination must be obtained by use of more intelligent or autonomous control systems.* The

choice of onboard preprocessing versus earth-based processing and the utility of block telemetry formating and distributive data handling and control subsystems will require assessment. In the past, computing facilities and command and data-processing software were not always efficient, and early attention was not given to overall system design in laying out missions. Further, experience with past and current spaceflight missions has shown that complicated systems with higher levels of intelligence are difficult to handle without substantial experience.

> We are apprehensive about recommending that radical new approaches be utilized without further study; nonetheless, it appears that some significant changes must be considered. Recognizing that mission operations is the key to *the success of any complicated undertaking, we therefore recommend that an assessment of mission operations, including spacecraft control and scientific instrument and data management and the design and management of software control systems, be studied by the Agency at the earliest possible time and the evaluation be presented to the Committee.*

The Federal Data Processing Reorganization Project has indicated serious failings in virtually all government agencies in the utilization of modern computer technology. While the National Science Foundation and the Advanced Research Project Agency (ARPA) of the Department of Defense continue to support some work in machine intelligence and robotics, this work, especially that supported by ARPA, is becoming more and more mission-oriented. The amount of fundamental research supported by these agencies in machine intelligence and robotics is quite small. Because of its mission, NASA is uniquely suitable as the lead civilian agency in the federal government for the development of frontier technology in computer science, machine intelligence, and robotics. NASA's general engineering competence and ability to carry out complex missions is widely noted and admired. These are just the capabilities needed by any federal agency designated to develop these fields. Although we are hardly experts on federal budgetary deliberations, it seems to us possible that incremental funds might be made available to NASA, over and above the usual NASA budget, if NASA were to make a compelling case for becoming the lead agency in the development of frontier technology in computer science and applications.

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[4]*Strategy for Exploration of the Inner Planets: 1977-1987,* Committee on Planetary and Lunar Exploration, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council, National Academy of Sciences, Washington, D.C., 1978.

The beneficial impact of such a step for the industrial economy, for other branches of government, for the public well-being, and for NASA's own future effectiveness in an era of tight budgets is likely to be substantial.

We here state our overall conclusions and recommendations. The complete report with supporting documentation leading to these conclusions and recommendations will be published separately.

A. CONCLUSIONS

Conclusion 1. NASA is 5 to 15 years behind the leading edge in computer science and technology.

There are some examples of excellence, but in general we find NASA's use of computer technology disappointing. NASA installations still employ punched-card-based batch processing and obsolete machine languages. There is no NASA nationwide computer network and no widespread time-sharing use of computers. Although Viking was a brilliant technological success, given its design limitations, Viking's use of robotics technology and *in situ* programming was rudimentary. These techniques must be greatly advanced for the complex missions of the future, both planetary and Earth orbital. Most Earth-satellite and much planetary exploration imaging data remains unanalyzed because of the absence of automated systems capable of performing content analyses. Even missions being planned for the 1980s are being designed almost exclusively for traditional data collection with little apparent provision being made for automated extraction of content information.

Conclusion 2. Technology decisions are, to much too great a degree, dictated by specific mission goals, powerfully impeding NASA utilization of modern computer science and technology. Unlike its pioneering work in other areas of science and technology, NASA's use of computer science and machine intelligence has been conservative and unimaginative.

Strict funding limitations and an understandable aversion to mission failure cause mission directors to settle for proven but obsolete and, ironically, often very expensive technologies and systems. As machine intelligence and robotics continue to advance outside of NASA, the consequences of these traditions for higher cost and less efficient data return and analysis become more glaring. The inertial fixation on 15-year-old technologies, including slow processors and very limited memories, strongly inhibit NASA

contact with and validation of advanced machine intelligence techniques. Flight minicomputer memories are typically at 16,000 or 21,000 words, enormously restricting options. (For example, a very large number of scientific targets on Jupiter and the Galilean satellites, which otherwise could be acquired, had to be abandoned because of the memory limitations of the Voyager onboard computer.) But million byte memories are now routinely employed and, once space-qualified, could provide enormous flexibility.

Because of the long lead times in the planning cycle, many decisions relating to computers are made five to seven years before launch. Often, the computer technology involved is badly obsolete at the time hardware is frozen. Further, no deliberate effort is made to provide flexibility for software developments in the long time interval before mission operations. (Uplinking mission programs after launch is a small but significant step in the right direction.)

Conclusion 3. The overall importance of machine intelligence and robotics for NASA has not been widely appreciated within the agency, and NASA has made no serious effort to attract bright, young scientists in these fields.

In 1978/1979, the Space Systems and Technology Advisory Committee of the NASA Advisory Council had 40 members. Not one was a computer scientist, although two had peripherally related interests. Few, if any, of the best computer science PhDs from the leading academic institutions in the field work for NASA. There is a looped causality with NASA's general backwardness in computer science (Conclusion 1): An improvement of the quality of computer science at NASA cannot be accomplished without high quality professionals; but such professionals cannot be attracted without up-to-date facilities and the mandate to work at the leading edge of the field.

The problems summarized in Conclusions 1 and 3 cannot be solved separately.

Conclusion 4. The advances and developments in machine intelligence and robotics needed to make future space missions economical and feasible will not happen without a major long-term commitment and centralized, coordinated support.

A summary of various planned future space missions and an estimate of technology development efforts needed to automate their system functions is given in the Appendix. Without these automatic system functions, many of the missions will not be economically and/or technologically feasible.

B. RECOMMENDATIONS

Recommendation 1. NASA should adopt a policy of vigorous and imaginative research in computer science, machine intelligence and robotics in support of broad NASA objectives.

The problems summarized in the preceding list of conclusions have solutions. They require most of all an awareness that the problems exist and a commitment of resources to solve them. Table 4-1 gives the published R&D budgets of the seven largest computer corporations in the United States. In all cases, the total R&D spending is greater than 40% of total profits. The advanced R&D budget would be only a fraction of this amount. Leading corporations in computer science and technology characteristically spend 5 percent of gross earnings on relevant research and development. The same percentage of NASA's annual expenditure in computer-related activities would suggest an annual NASA budget for research in computer science, machine intelligence, and robotics approaching one hundred million dollars. An expenditure of half that would equal the combined annual budget for this field for ARPA and the National Science Foundation. If NASA were selected as lead agency (or lead civilian agency) for federal research and development in computer science and technology, such amounts might not be at all impractical. Any significant expenditures should have detectable benefits in three to five years, and very dramatic improvements in NASA programs in 10 years. If NASA were to play such a lead agency role, one of its responsibilities would be to study the long-term implications for individuals and for society of major advances in machine intelligence and robotics.

Recommendation 2. NASA should introduce advanced computer science technology to its Earth orbital and planetary missions, and should emphasize research programs with a multimission focus.

A balance is needed on board NASA spacecraft between distributed microprocessors and a centralized computer. Although function-directed distribution of processors might be useful, such architectures should not preclude the use of these computing resources for unanticipated needs. Distributed computer concepts emphasizing "fail-soft" performance should receive increased attention. For example, in the case of failure of a computer chip or a unit, a long-term goal is to effect migration of the program and data to other working parts of the systems. Such fail-soft systems require innovative architectures yet to be developed. Dynamically reconfigurable processors with large redundancy are badly needed in NASA.

NASA relies on 256-bit computer memory chips; 16,000 bit and 64,000 bit chips are currently available. A million-bit chip is expected to be available within a few years. The cost of space-qualification of computer hardware may be very high, but the possibility exists that high information-density chips may already work acceptably in the space environment. We recommend that NASA perform space qualification tests on the Shuttle of multiple batches of existing microprocessors and memory chips.

These two examples of developments in computer science and technology will have applications to many NASA missions. We also recommend a transitional period in spacecraft computer system design in which existing miniprocessors and new microprocessors are both utilized, the former as a conservative guarantor of reliability, the latter as an aperture to the future.

Table 4-1. R&D of the Big Seven Computer Companies

Company	1977 Sales in millions of dollars	1977 Profits in millions of dollars	R&D EXPENSE			Cost of Employees
			Actual in millions of dollars	As a percent of Sales	As a percent of Profits	
IBM	18,133	2,719	1,142	6.3	42	3682
Sperry Rand	3,270	157	168	5.1	197	1965
Honeywell	2,911	134	152	5.2	113	2009
NCR	2,522	144	118	4.7	82	1845
Burroughs	2,901	215	122	5.9	57	2386
Control Data	1,493	62	73	4.9	117	1592
Digital Eqpt	1,059	109	80	7.5	74	2218
Composite	33,764	3,700	1,995	5.9	43	2752

In planetary exploration, "... it is clear ... that more advanced mission techniques and instrumentation are required to fulfill the science strategy and achieve the objectives ..." of intensive study of a planet.[5] Surface rovers and return-sample missions will be required to meet the science goals for Mars, the Galilean satellites of Jupiter, Titan, and perhaps Venus, as well as for investigation of such specific locations on the lunar surface as putative volatile-rich deposits at permanently shaded regions of the poles. With the exception of the Lunakhod and other Luna-class missions of the Soviet Union, there is little experience with such systems. Because of the long lead times and the complex nature of rover missions, they provide an ideal testing ground for the implementation of the multimission focus of some of our recommendations.

Recommendation 3. Mission objectives should be designed flexibly to take advantage of existing and likely future technological opportunities.

Hardware should be designed to exploit state-of-the-art software and likely near-future software developments. Adoption of this recommendation implies a careful re-examination of missions currently in the planning stages. This recommendation applies not only to spacecraft systems but to ground-based computer systems as well. The man/machine interface, both in Shuttle systems and in mission operations ground equipment, has not, in our opinion, been optimized. In routine mission operations, particularly in mission crisis management, there is a severe short-term competition for human attention and intellectual resources. The problem is a combinatorial one, requiring systematic and exhaustive failure-mode analysis, which can be optimally provided by computer systems, via a probability analysis, analogous to existing computer programs in medical diagnosis. In addition to their value in crisis management, such computer systems will lead to the optimization of subsequent missions.

Recommendation 4. NASA should adopt the following plan of action:

(a) *Establish a focus for computer science and technology at NASA Headquarters for coordinating R&D activities.*

The pace of advance in computer science and technology is so great that even experts in the field have difficulty keeping up with advances and fully utilizing them. The problem is, of course, much more severe for those who are not experts in the field. By establishing

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[5] *Ibid*, p. 39.

a program in computer science, NASA can ensure that there is a rapid transfer of new technology to NASA programs. Space exploration offers a unique environment in which to develop and test advanced concepts in this discipline.

This leads to the following specific recommendation: NASA should consider Computer Science and Technology sufficiently vital to its goals to treat the subject as an independent area of study. The specific concerns of this field, enumerated below, should become research and technology issues within NASA on the same basis as propulsion technology, materials science, planetary science, atmospheric physics, etc. This means the creation of a discipline office for computer science with interests in the major subdisciplines of the field and with appropriate contacts within NASA. A suitable budget and program of research and technology grants and contracts would provide the focus in this field the Study Group has found lacking in NASA. On the one hand, it would help make the outstanding workers in the field aware of and interested in serving NASA's needs. Graduate students participating in such a research program would become a source of future employees at NASA centers and contractors. On the other hand, it would provide NASA Headquarters with a better awareness of the potential contributions of computer science to its programs. To be effective, the initial operating budget of such a program should not be below 10 million dollars a year, with a long-term commitment for at least a constant level of funding in real dollars.

Most of the fundamental research under such a program would be carried out at universities and at appropriate NASA centers. Collaboration with industry should be encouraged to expedite technology transfer. To meet the emerging mission requirements, parallel advanced development programs within all of NASA's mission offices are required.

Following is a list of problem areas that should set some goals for both the basic science research program and the advanced development effort:

- Smart sensing; automated content analysis; stereo mapping for eventual Earth and planetary applications.

- Manipulator design, particularly for autonomous use, including structures and effectors, force and touch detectors.

- Control and feedback systems, particularly those relevant to manipulation and teleoperator development.

- Spacecraft crisis analysis systems.

- Locomotion systems, particularly legged locomotion for difficult terrain.

- Attempts at space qualification of multiple batches of existing microprocessors and memory chips.

- Preliminary studies of automatic and teleoperator assembly of large structures for Earth orbital, lunar, and asteroidal environments.

- Vision systems, particularly for use in locomotion and automated assembly.

- Control and reasoning systems, particularly in support of lunar and planetary rovers.

- Computer architectures for space systems.

- Software tools for space system development.

- Algorithm analysis for critical space-related problems.

- Computer networks and computer-aided teleconferencing. (See paragraph (d) below.)

The current university-based support from NSF and ARPA in computer science and machine intelligence is about 15 million dollars each annually. The level of university funding recommended here would be larger by about 30 percent, allowing NASA to compete effectively for the best talent and ideas. Parallel programs conducted by NASA program offices, which would be based strongly at NASA centers and industry, would approximately double the support requirement. The total support might eventually approach the 100 million dollar level, if NASA were seriously to pursue a broad program of research in computer science.

(b) *Augment the advisory structure of NASA by adding computer scientists to implement the foregoing recommendations.*

NASA is far enough behind the leading edge of the computer science field that major improvements in its operations can be made immediately using existing computer science systems and techniques such as modern data abstraction languages, time-sharing, integrated program development environments, and larger virtual memory computers (especially for onboard processing). Such general improvements in sophistication are almost a prerequisite for a later utilization of machine intelligence and robotics in NASA activities. The advisory organizations should help plan and coordinate NASA's effort in the field and establish contacts with the centers of computer science research.

(c) *Because of the connection of the Defense Mapping Agency's (DMA) Pilot Digital Operations Project with NASA interests, NASA should maintain appropriate liaison.*

DMA has studied the advanced techniques in computer science with an emphasis on machine intelligence. There may be a strong relationship between many DMA concerns and related issues in NASA, particularly in scene analysis and understanding, large database management, and information retrieval. An evaluation by NASA of the DMA planning process associated with the DMA Pilot Digital Operations Project should aid in estimating the costs of NASA's development in this field.

(d) *NASA should form a task group to examine the desirability, feasibility, and general specification of an all-digital, text-handling, intelligent communication system.*

A significant amount of NASA's budget is spent in the transfer of information among a very complex, geographically and institutionally disparate set of groups that need to exchange messages, ideas, requirements, and documents quickly to keep informed, plan activities, and arrive at decisions.

Based on a rough estimate, we predict that such an all-digital network would lead to significant improvements over the present method of carrying out these functions. In addition to the cost savings, there would be improvements in performance. Although it would not eliminate the use of paper and meetings as a means of communication, it would save tons of paper and millions of man-miles of energy consuming travel. This system would facilitate and improve the participation of scientists in all phases of missions as well as enhance their ability to extract the most value from postmission data analysis.

The implementation of such a system would not be predicated on new developments in artificial intelligence, but on the tools that are in common use at artificial intelligence nodes of the ARPA network and are part of the developing technology of digital information and word processing. If such a development were carried out, it would provide the data base for sophisticated techniques, as they become available, for information retrieval, semantic search, and decision making; and a model for other public and private organizations, scientific, technological, and industrial.

The task group to investigate this development should include elements of NASA management, mission planning and operations, scientific investigators, and information scientists, as well as specialists in artificial intelligence.

Appendix
An Overview of Applications of Machine Intelligence and Robotics in the Space Program*

Introduction

The space program is at the threshold of a new era that may be distinguished by a highly capable space transportation system. In the 1980s, the Space Shuttle and its adjuncts will enable increased activities in the scientific exploration of the universe and a broadened approach to global service undertakings in space. The first steps toward utilizing the space environment for industrial and commercial ventures will become possible and can trigger requirements for more advanced space transportation systems in the 1990s. This will enable expanded space industrial activities and, by the end of this century, could lead to Satellite Power Systems for solar energy production, to lunar or asteroidal bases for extracting and processing material resources, and to manned space stations for commercial processing and manufacturing in space. A major objective for NASA is to develop the enabling technology and to reduce the costs for operating such large-scale systems during the next two decades. On examining potential NASA missions in this time frame we expect that machine intelligence and robotics technology will be a vital contributor to the cost-effective implementation and operation of the required systems. In some areas, it will make the system feasible, not only for technological reasons, but also in terms of commercial acceptability and affordability.

During the next two decades, the space program will shift at least some emphasis from exploration to utilization of the space environment. It is expected that this shift will be accompanied by a large increase in requirements for system operations in space and on the ground, calling for general-purpose automation (robotics) and specialized automation. What operations, tasks, and functions must be automated, and to what degree, to accomplish the NASA objectives with the most cost-effective systems?

Robots and Automation in NASA Planning

Whereas mechanical power provides physical amplification and computers provide intellectual amplification, telecommunication provides amplification of the space accessible to

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*Excerpted from *New Luster for Space Robots and Automation*, by L. Heer, Astronautics & Aeronautics, September 1978.

humans. By means of telecommunication, humans can activate and control systems at remote places. They can perform tasks even as far away as the planets. During the 1960s, this became known as teleoperation. Teleoperators are man-machine systems that augment and extend human sensory, manipulative, and cognitive abilities to remote places. In this context, the term robot can then be applied to the remote system of a teleoperator, if it has at least some degree of autonomous sensing, decision-making, and/or action capability. The concept of teleoperation has profound significance in the space program. Because of the large distances involved, almost all space missions fall within the teleoperator definition; and, because of the resultant communication delay for many missions, the remote system requires autonomous capabilities for effective operation. The savings of operations time for deep space missions can become tremendous, if the remote system is able to accomplish its tasks with minimum ground support. For example, it has been estimated that a Mars roving vehicle would be operative only 4 percent of the time in a so-called move-and-wait mode of operation. With adequate robot technology, it should be operative at least 80 percent of the time.

NASA saw the need to examine the civilian role of the U.S. space program during the last quarter of this century. A series of planning studies and workshops was initiated with the Outlook for Space Study in 1974, which included a comprehensive forecast of space technology for 1980-2000. In a subsequent NASA/OAST Space Theme Workshop, the technology forecasts were applied to three broad mission themes: space exploration, global services, and space industrialization. Based on the derived requirements for cost-effective space mission operations, five new directions were identified for developments in computer systems, machine intelligence and robotics: (1) automated operations aimed at a tenfold reduction in mission support costs; (2) precision pointing and control; (3) efficient data acquisition to permit a tenfold increase in information collection needed for global coverage; (4) real-time data management; and (5) low-cost data distribution to allow a thousand-fold increase in information availability and space-systems effectiveness. The machine intelligence and automation technologies for data acquisition, data processing, information extraction, and decision making emerge here as the major drivers in each area and call for their systematic development. In addition, for certain areas such as automated operations in space, the mechanical technologies directed at

materials and objects acquisition, handling, and assembly must also be further developed; robots doing construction work in Earth orbit or on the lunar surface will need manipulative and locomotion devices to perform the necessary transport and handling operations.

Future Applications

In space applications, robots may take on many forms. None looks like the popular science fiction conception of a mechanical man. Their appearance follows strictly functional lines, satisfying the requirements of the mission objectives to be accomplished. The discussion which follows briefly presents mission categories, mission objectives, and system characteristics pertinent to space robot and automation technology. Estimates of technology development efforts to automate system functions are given in Table A-1.

A. Space Exploration

Space exploration robots may be exploring space from Earth orbit as orbiting telescopes, or they may be planetary flyby and/or orbiting spacecraft like the Mariner and Pioneer families. They may be stationary landers with or without manipulators like the Surveyor and the Viking spacecraft, or they may be wheeled like the Lunakhod and the proposed Mars rovers. Others may be penetrators, flyers, or balloons, and some may bring science samples back to Earth (Figures A-1 — A-3). All can acquire scientific and engineering data

Figure A-2. Mars surface robot will operate for 2 years and travel about 1000 km performing experiments automatically and sending the scientific information back to Earth.
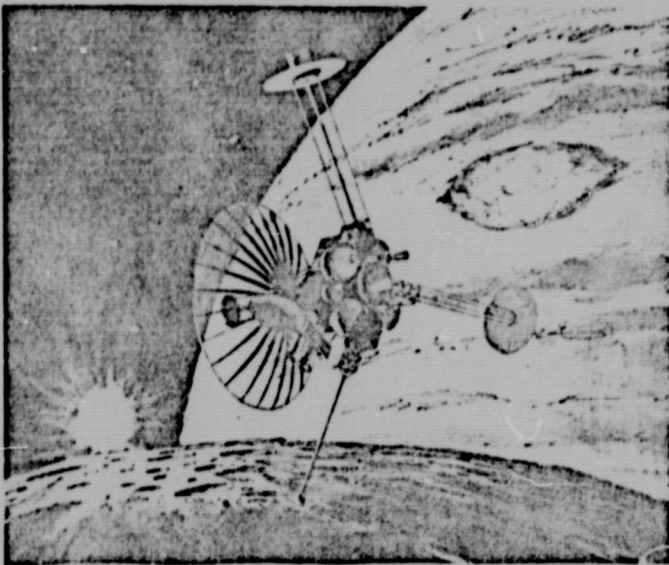
Figure A-1. Galileo spacecraft navigates between Jupiter and Galilean satellites in rendering. After sending a probe into the jovian atmosphere, the robot spacecraft will perform complex maneuvers at various inclinations with repeated close encounters with the satellites.
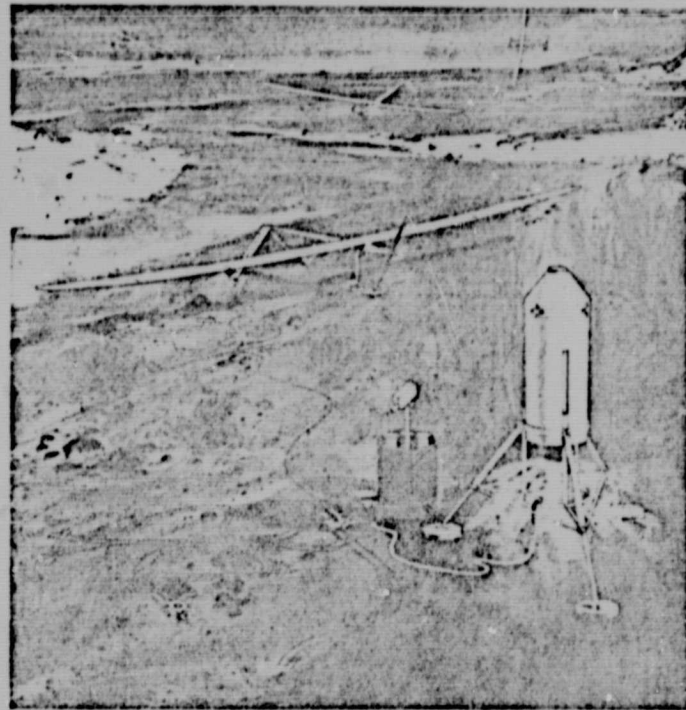

Figure A-3. Artist's concept of a Mars surface scientific processing and sample return facility. Airplanes transport samples into the vicinity of the processing station. Tetnered small rovers then bring the samples to the station for appropriate analysis and return to Earth.

Table A-1. Estimates of the technology development efforts to automate system functions

ESTIMATES OF TECHNOLOGY DEVELOPMENT EFFORTS TO AUTOMATE SYSTEM FUNCTIONS

SYSTEM FUNCTIONS

MISSION CATEGORIES

GROUND OPERATIONS:
- DATA INTERPRETATION
- DATA DISTRIBUTION
- ARCHIVING
- SEQUENCING
- SITE SELECTION
- SPACECRAFT MONITORING
- SIMULATION

ON-BOARD SPACECRAFT OPERATIONS:
- POINTING AND CONTROLLING
- GUIDANCE AND NAVIGATION
- RENDEZVOUS AND STATION KEEP.
- DOCKING
- LANDING AND ASCENT
- SURFACE TRAVERSING
- SCIENCE DATA COLLECTING
- SERVICE DATA COLLECTING
- DATA PROCESSING
- PLANNING/DECIDING
- RESOURCE CONTROL
- FAULT DETECTION, REPAIR
- SHAPE CONTROL

IN-SPACE HANDLING [2]:
- DEPLOYMENT
- TRANSFER
- ASSEMBLY AND JOINING
- INSPECTION
- SERVICING
- MAINTENANCE
- REPAIR
- MONITORING
- RETRIEVING
- RESCUE
- PROCESSING
- MANUFACTURING
- LUNAR MINING

EXPLORATION OF SPACE
Mission	Year
GALILEO-JUPITER ORBITER PROBE	1982
SOLAR POLAR MISSION	1983
VENUS ORBITAL IMAGING RADAR	1983
SPACELAB INSTRUMENT PROGRAM	1984
X-RAY OBSERVATORY	1986
SATURN ORBITER DUAL PROBE	1987
MARS SAMPLE RETURN	1988
MOBILE LUNAR SURFACE SURVEY [1]	1989
EARTH ORB. SOLAR OBSERVATORY	1992
ASTROPH. SPACE LABORATORY	1993
ATMOSPHERIC PHYSICS LAB.	1994
SPACE-BASED RADIO TELESCOPE	1995
AUTOMATED PLANETARY STATION	2000

GLOBAL SERVICES
Mission	Year
SEASAT FOLLOW-ON	1982
TIROS-O	1984
SOIL MOISTURE SATELLITE	1985
STORMSAT	1985
GLOBAL COMMUNICATIONS	1987
GLOBAL CROP FORECASTING	1988
HIGH RESOLUTION SEA SURVEY	1988
DISASTER WARNING SATELLITE	1989
EARTH ENERGY BUDGET MONITOR	1990
LGE-SCALE ALL-WEATHER SURVEY	1993
GEOLOGICAL MAPPING	1994
GLOBAL NAVIGATION	1996

UTILIZATION OF SPACE
Mission	Year
SPACE MANUFACTURING MODULE	1985
SPACE HEALTH CARE SYSTEM	1986
LUNAR PRECURSOR PROCESSOR	1990
NUCLEAR WASTE DISPOSAL	1995
TELEOPERATOR VEHICLE SYSTEM	1996
ROBOT VEHICLE EARTH ORBIT	1997
LUNAR BASE	1998
SPACE STATION	2000
SATELLITE POWER SYSTEM	2000

TRANSPORTATION SYSTEMS
Mission	Year
ORBITAL TRANSFER VEHICLE	1990
HIGH ENERGY OTV (PLANET)	1992
PRIORITY LAUNCH VEHICLE	1994
HEAVY-LIFT LAUNCH VEHICLE	1998

KEY: THE AUTOMATION OF THE IDENTIFIED SYSTEM FUNCTIONS REQUIRES:

/ INTEGRATION OF EXISTING TECHNOLOGY

X MODERATE ADDITIONAL DEVELOPMENTS

▓ EXTENSIVE TECHNOLOGY DEVELOPMENTS

▒ MAJOR TECHNOLOGY DEVELOPMENTS

■ MAJOR TECHNOLOGY DEVELOPMENTS WITH UNCERTAIN OUTCOME.

NOTE: EACH ENTRY REPRESENTS THE RELATIVE COLLECTIVE LEVEL OF EFFORT TO ACCOMPLISH THE FUNCTION FOR THE MISSIONS AS DESCRIBED IN THE NASA OAST SPACE SYSTEMS TECHNOLOGY MODEL, 22 MARCH 1978.

1) THE LUNAR ROVERS OF THIS PROGRAM WILL BE DEVELOPED WITH IN-SPACE HANDLING CAPABILITIES AND WILL SUPPORT THE LUNAR PRECURSOR PROCESSOR (1990) AND THE LUNAR BASE (1998).

2) HANDLING FUNCTIONS ARE GENERALLY ASSOCIATED WITH MOBILITY UNITS, MANIPULATIVE DEVICES OR TOOLS REQUIRING CONTROL OF ACTUATORS.

using their sensors, process the data with their computers, plan and make decisions, and send some of the data back to Earth. Some robots are in addition able to propel themselves safely to different places and to use actuators, manipulators and tools to acquire samples, prepare them, experiment *in situ* with them or bring them back to Earth.

Exploratory robots are required to send back most of the collected scientific data, unless they become repetitive. The unknown space environment accessible to the sensors is translated into a different, still uninterpreted environment, in the form of computer data banks on Earth. These data banks are then accessible for scientific investigation long after the space mission is over.

Projections into the future lead one to speculate on the possibility of highly autonomous exploratory robots in space. Such exploratory robots would communicate to Earth only when contacted or when a significant event occurs and requires immediate attention on Earth. Otherwise, they would collect the data, make appropriate decisions, archive them, and store them on board. The robots would serve as a data bank, and their computers would be remotely operated by accessing and programming them from Earth whenever the communication link to the robot spacecraft is open. Scientists would be able to interact with the robot by remote terminal. Indeed, the concept of distributed computer systems, presently under investigation in many places, could provide to each instrument its own microcomputer, and scientists could communicate with their respective instruments. They could perform special data processing on board and request the data to be communicated to them in the form desired. Alternatively, they could retrieve particular segments of raw data and perform the required manipulations in their own facilities on Earth.

Prime elements in this link between scientists and distant exploratory robots would be large antenna relay stations in geosynchronous orbit. These stations would also provide data handling and archiving services, especially for inaccessible exploratory robots, e.g., those leaving the solar system.

B. Global Services

Global service robots orbit the Earth. They differ from exploratory robots primarily in the intended application of the collected data. They collect data for public service use on soil conditions, sea states, global crop conditions, weather, geology, disasters, etc. These robots generally acquire and process an immense amount of data. However, only a fraction of the data is of interest to the ultimate user. At the same time, the user often likes to have the information shortly after it has been obtained by the spacecraft. For instance, the value of weather information is short-lived except for possible historical reasons. The value of information of disasters such as forest fires is of comparably short duration. The demand for high-volume on-board data processing and pertinent automated information extraction is therefore great.

The usual purpose of global service robots is to collect time-dependent data in the Earth's environment, whose static properties are well-known. The data are used to determine specific patterns or classes of characteristics and translate these into useful information. For instance, for Landsat and Seasat (Figure A-4), the data are currently sent to the ground, where they are processed, reduced, annotated, analyzed, and distributed to the user. This process requires up to
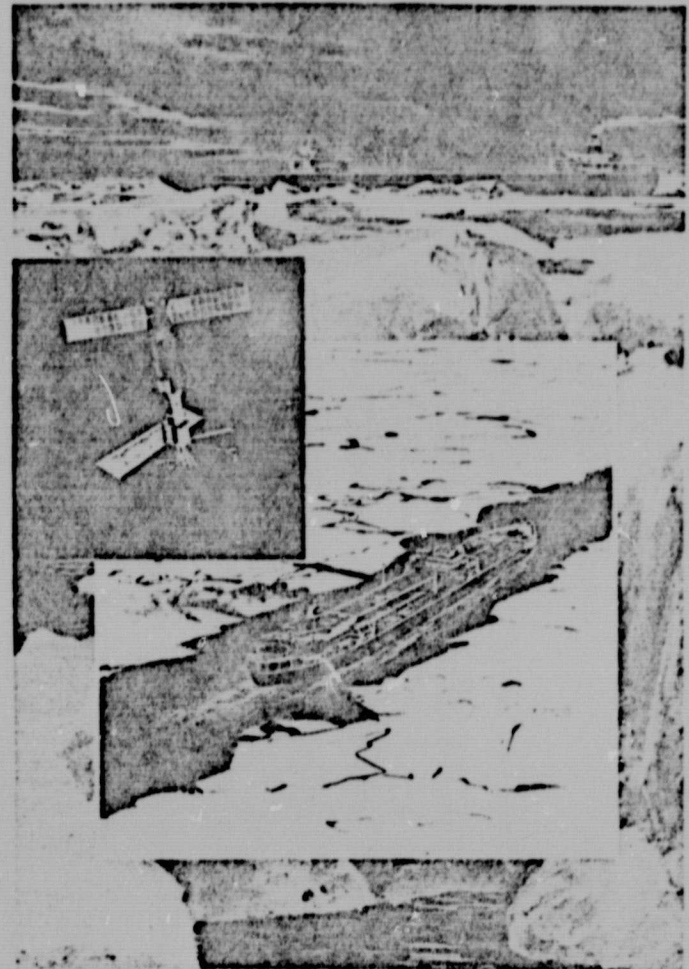

Figure A-4. Seasat. The oceanographic satellite's high-data-rate Synthetic Aperture Radar imaging device has provided data on ocean waves, coastal regions, and sea ice.

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3 months for a fully processed satellite image and costs several thousand dollars. The image must then be interpreted by the receiver; i.e., the information must still be extracted by the user.

Present developments in artificial intelligence, machine intelligence and robotics suggest that, in the future, the ground-based data processing and information extraction functions will be performed on board the robot spacecraft. Only the useful information would be sent to the ground and distributed to the users, while most of the collected data could be discarded immediately. This would require the robot to be able to decide what data must be retained and how they were to be processed to provide the user with the desired information. For instance, the robot could have a large number of pattern classification templates stored in its memory or introduced by a user with a particular purpose in mind. These templates would represent the characteristics of objects and/or features of interest. The computer would compare the scanned patterns with those stored in its memory. As soon as something of interest appeared, it would examine it with higher resolution, comparing it to a progressively narrower class of templates until recognition had been established to a sufficient degree of confidence. The robot would then contact the appropriate ground station and report its findings and, if required, provide the user with an annotated printout or image. The user would be able to interact with the robot, indeed with his particular instrument, by remote terminal much the same as with a central computer and, depending on intermediate results, modify subsequent processing.

For space exploration and global services, the ground-based mission operations can become extremely complex. A recent example of a planetary exploration mission, and perhaps the most complex to date, is Viking. At times there were several hundred people involved in science data analysis, mission planning, spacecraft monitoring, command sequence generation, data archiving, data distribution, and simulation. Although for earlier space missions sequencing had been determined in advance, on Viking this was done adaptively during the mission. The operational system was designed so that major changes in the mission needed to be defined about 16 days before the spacecraft activity. Minor changes could be made as late as 12 hours before sending a command. The turn-around time of about 16 days and the number of people involved contributes, of course, to sharply increased operational costs. The Viking operations costs (Figure 2-1) are for a 3-month mission. The planned Mars surface rover mission is expected to last 2 years, covering many new sites on the Martian surface. Considering that this mission would be more complex and eight times as long, ground operations would have to be at least ten times as efficient to stay within, or close to, the same relative costs as for Viking.

During the Viking mission, about 75,000 reels of image data tapes were collected and stored in many separate locations. The images are now identifiable only by the time when and the location where they were taken. No indication regarding image information content is provided, and the user will have to scan catalogs of pictures to find what he or she wants. For such reasons, it is expected that most of the data will not be used again.

The ground operations for Earth orbital missions suffer from problems similar to those of planetary missions. The overall data stream is usually much higher for Earth orbital missions, images are still very costly, and they take up to several months to reach the user.

These considerations strongly suggest that technology must be developed so that most ground operation activities can be performed as close as possible to the sensors where the data is collected, namely by the robot in space. However, examining the various ground operations in detail, we conclude that most of those that must remain on the ground could also be automated with advanced machine intelligence techniques. The expected benefits derived from this would be a cost reduction for ground operations of at least an order of magnitude and up to three orders of magnitude for user-ready image information.

C. Utilization of Space Systems

Space industrialization requires a broader spectrum of robotics and automation capabilities than those identified for space exploration and global services. The multitude of systems and widely varying activities envisioned in space until the end of this century will require the development of space robot and automation technology on a broad scale. It is here that robot and automation technology will have its greatest economic impact. The systems under consideration range from large antennas and processing and manufacturing stations in Earth orbit to lunar bases, to manned space stations, to satellite power systems of up to 100 km^2. These systems are not matched in size by anything on Earth. Their construction and subsequent maintenance will require technologies not yet in use for similar operations on Earth.

Space processing requires a sophisticated technology. First it must be developed and perfected, and then it must be transferred into the commercial arena. Basic types of processes currently envisioned include solidification of melts without convection or sedimentation, processing of molten samples without containers, diffusion in liquids and vapors, and electro-phoretic separation of biological substances. It is expected that specialized automated instrumentation will be developed

for remote control once the particulars of these processes are worked out and the pressure of commercial requirements becomes noticeable.

Large-area systems such as large space antennas, satellite power systems, and space stations require large-scale and complex construction facilities in space (Figures A-5 and A-6).
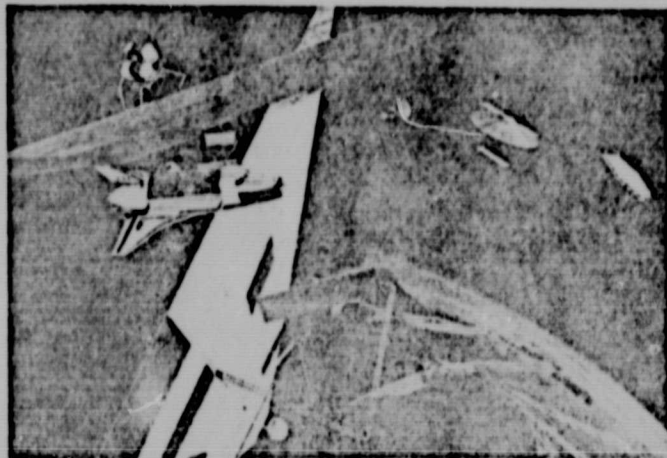
Relatively small systems, up to 100 m in extent, may be deployable and can be transported into orbit with one Shuttle load. For intermediate systems of several hundred meters in extent, it becomes practical to shuttle the structural elements into space and assemble them on site (Figure A-7).

Very large systems require heavy-lift launch vehicles which will bring bulk material to a construction platform (Figure A-8), where the structural components are manufactured using specialized automated machines.

Figure A-5. Large space systems require robot and automation technology for fabrication, assembly, and construction in space.

Figure A-7. Construction of a space station. Bulk material is brought by the Shuttle. Structural elements are fabricated at the construction facility and then assembled by remotely controlled manipulators.
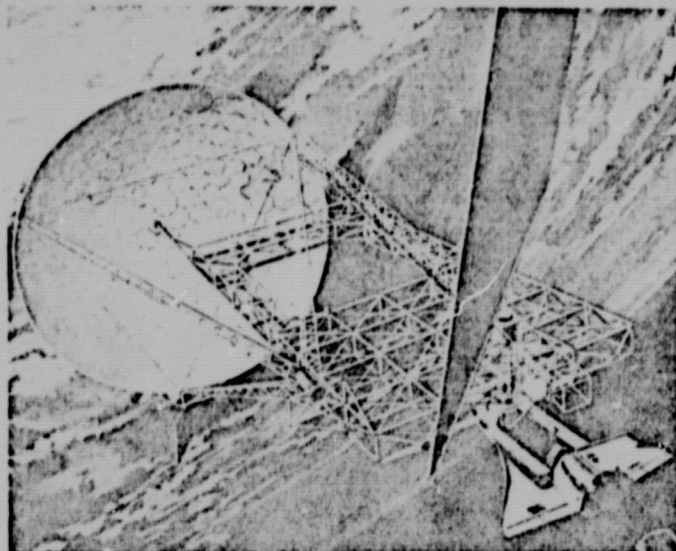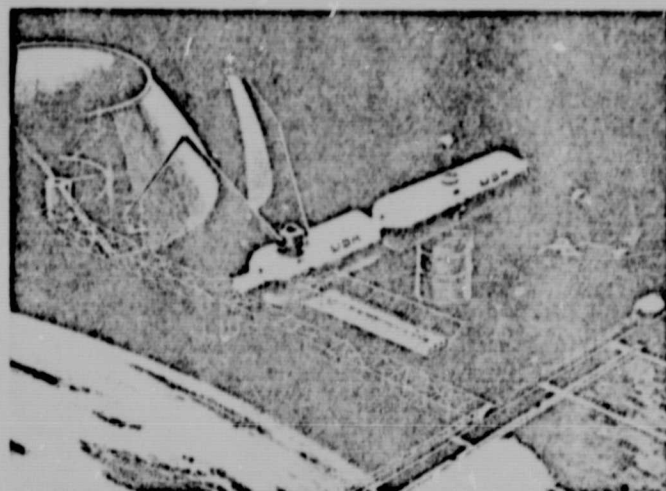

Figure A-6. Large space antennas are erected with the help of a space-based construction platform. The Shuttle brings the structural elements to the platform, where automatic manipulator modules under remote control perform the assembly.

Figure A-8. Complex construction facility in space with automatic beam builders, cranes, manipulators, etc., is served by the Shuttle.

A-6

The structural elements can be handled by teleoperated or self-actuating cranes and manipulators which bring the components into place and join them (Figure A-9). Free-flying robots will transport the structural entities between the Shuttle or the fabrication site and their final destination and connect them. These operations require a sophisticated general-purpose handling capability. In addition to transporting structural elements, the robot must have manipulators to handle them, and work with them and on them. Large structural subsystems must be moved from place to place and attached to each other. This usually requires rendezvous, stationkeeping, and docking operations at several points simultaneously and with high precision — a problem area still not investigated for zero gravity. Automated "smart" tools would also be required by astronauts to perform specialized local tasks.

These robot systems could be controlled remotely as teleoperator devices, or they could be under *supervisory control* with intermittent human operator involvement. Astronauts in space or human operators on Earth will need the tools to accomplish the envisioned programs. The technology for in-space assembly and construction will provide the foundation for the development of these space-age tools.

After the system has been constructed, its subsequent operation will require service functions that should be performed by free-flying robots or by robots attached to the structure. The functions which such a robot should be able to perform include calibration, checkout, data retrieval, resupply,

maintenance, repair, replacement of parts, cargo and crew transfer, and recovery of spacecraft.

During and after construction, there should be a robot on standby for rescue operations. An astronaut drifting into space could be brought back by a free-flying robot. Such devices could also be on stand-by alert on the ground. The delivery systems for these rescue robots need not be man-rated. They can deliver expendable life support systems or encapsulate the astronaut in a life support environment for return to a shuttle, space station, or Earth. They could also perform first-aid functions.

Another phase of space industrialization calls for a lunar or asteroidal base. After a surface site survey with robot (rover) vehicles, an automated precursor processor system could be placed on the Moon or the asteroid. This system would collect solar energy and use it in experimental, automated physical/chemical processes for extracting volatiles, oxygen, metals, and glass from lunar soil delivered by automated rovers (Figure A-11). The products would be stored, slowly building up stockpiles in preparation for construction. The lunar or asteroidal base would be built using automated equipment and robots as in Earth orbit. After construction, general-purpose robot devices would be necessary for maintenance and repair operations. In addition, the base would use industrial automation (qualified for operation in space) or a sort generally similar to those employed on Earth for similar tasks.
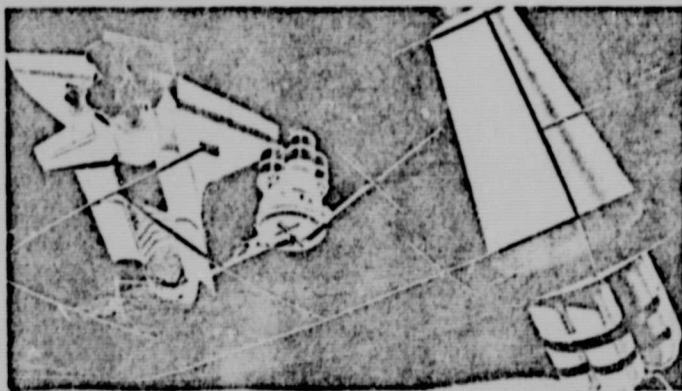

Figure A-9. Space construction of large antenna systems with automated tools, teleoperated manipulators, and free-flying robots.
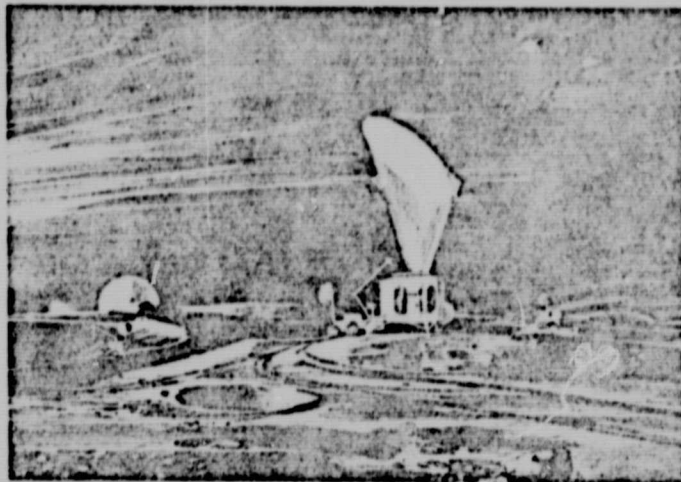

Figure A-10. Automated material processors on the lunar surface are serviced by robot vehicles with raw lunar soil.

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