CHAPTER 7

CONCLUSIONS AND IMPLICATIONS OF AUTOMATION IN SPACE

During the 1960s NASA proved that access to space is feasible for both manned and unmanned systems. During the 1970s NASA demonstrated that important scientific exploration and applications missions could be conducted in orbit. Simultaneously, imaginative and worthwhile future space missions were conceived and studied. However, two major constraints limited implementation – cost and technology. A great many proposed missions could be accomplished through application of current technology but at unacceptable costs. New technology is needed which is not only mission-enabling but also cost-reducing. The Space Shuttle is NASA's first major technology project to address these twin objectives. In years to come, advanced automation will play a major role in achieving similar objectives.

A space mission life cycle may be divided into three phases: (1) conception, design, development, test, and evaluation; (2) procurement of mission flight and ground articles; and (3) mission operations. At present, procurement is only about 10% of life-cycle costs. Most facility support equipment already is in place, also on the order of 10% of mission life-cycle costs. The first phase through conception, development, and test, and the last phase of flight operations, each is on the order of 40% of life-cycle costs. Consequently, reducing space hardware disbursements has small effect on total life cycle costs.

The present dominance of the first and last phases in mission accounting is due in large measure to their people-intensive character. Cost reductions are possible by focusing on two specific goals. First, increased personnel productivity can help make space affordable, in part by using computer technology to organize and integrate knowledge, for information extraction and retrieval, decisionmaking, scheduling, and for automatic problem-solving. The efficiency of human action may also be improved through advanced teleoperations and robotics. Second, costs may be cut by decreasing the requirements for human interaction and the need for terrestrial materials. This ultimately can be accomplished through more complete *in situ* machine intelligence and robotics.

Advanced automation can substantially contribute to both approaches. Applicable techniques range from intelligent computer assistants for enhanced human productivity to, ultimately, autonomous self-replicating systems utilizing extraterrestrial materials and energy. These latter automatons could be materially self-sufficient and produce immense economic returns if employed in production or service capacities.

The Mission Goals Symposium which took place at Pajaro Dunes in June 1980 (sec. 1.2.3) addressed a specific question: "What bold new NASA space missions could high levels of automation make possible 25-50 years hence?" In their deliberations the participants postulated levels of automation capability that might be achievable given adequate funding and a clear focus, and also a range of mission types that such capabilities could, at least in principle, make possible.

The Symposium concluded that if certain (very difficult) new levels of automation capability could be achieved, a whole new set of space missions having high economic and scientific value would become possible. In each case a decision to pursue one of these long-term goals would demand focused research beginning decades earlier, each having a series of rather sharply defined short-term goals of its own. Such subgoals provide valuable focus and stimulation for automation research generally, and suggest a natural stepping-stone developmental sequence of graded complexity in the areas of command and control, robot dexterity and repair capability, sensing and reasoning, and multirobot system organization.

7.1 Space Facilities and Programs Overview

The missions considered in this study are based on a broad array of activities which have been proposed to achieve various scientific and technical objectives. If cost as a factor were excluded, there would be little question of the impetus for doing most if not all of these missions. The costs involved, however, are such as to require an orderly progression of activities so that needed technologies can be developed in an affordable manner over the next several decades. The scenario that has emerged from this study is logical, with an orderly progression from early Shuttle operational phases to the establishment of self-replicating lunar factories and (possibly) space colonies. An underlying premise is the commitment to an ongoing program of space exploration and utilization.

While space exploration can be accomplished largely using unmanned, highly automated craft, space utilization involves a wide range of activities where human intelligence and versatility are invaluable. It can be argued that any activity involving human participation ultimately can be preprogrammed and accomplished by machine, but it is equally true that at present total automation would be prohibitively expensive. There is a tradeoff made between full- and nonautomation, as suggested by figure 7.1. There is no single optimum level of automation, but rather a range of performance hybrids from which the mission planner must choose. As a technology base develops, incorporating advances in computer science, artificial intelligence, and robotics, the cost of autonomous operations should decrease, thereby reducing mission costs and giving planners more options.

The Space Transportation System as described in the NASA Technology Model represents a well developed technology base amenable to future progress in advanced automation. Indeed, the scenario developed in the present study leads to a logical development of this capability. This is grounded on a rationale of blending man and automation for maximum productivity, together with the parallel evolutionary emergence of fully automated systems. The scenario provides a roadmap for actualizing NASA's commitment to advanced programs.

The study group considers a LEO base critical to later programs. Thus the facilities and programs plan can be considered in three phases: (1) early operations at LEO, (2) establishment of a permanent LEO base and extended operations at LEO, and (3) operations beyond LEO. Program development plans consistent with this strategy are continuously refined and updated within NASA. The transition from one phase into the next is not chronologically precise or even distinct, depending as it does upon the availability of skills and techniques permitting development of the next phase. Further, there is some flexibility in selection of activities within a given phase (see fig. 7.2). Priorities or technological breakthroughs may reorder or modify some programs. However, the development of technologies required to support this or some similar plan should progress roughly according to the timetable shown in figure 7.3 to maintain an orderly space program development.

7.2 A Consistent Space Program Strategy

This report has addressed several missions and numerous technologies and problems related to space activities that may be undertaken during the next several decades: the integration of satellite technology into an intelligent network capable of answering broad or narrow questions concerning Earth resources; the exploration of Titan by an automated, intelligent probe; the construction of an automated factory on the Moon which self-replicates and delivers useful products, such as energy via solar power satellites and other means; and the development and growth of a material economy independent of Earth supply using

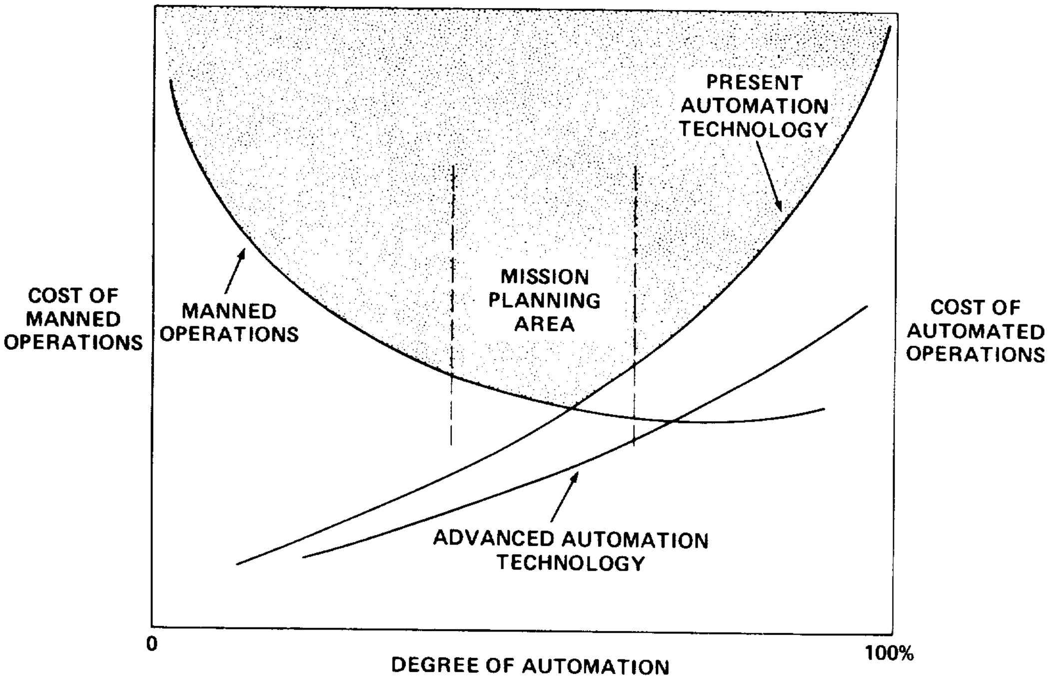

Figure 7.1.– Cost-effectiveness of automation in future NASA space missions.

extraterrestrial resources from the Moon and the asteroids. The Epilogue provides an opportunity to assess the broader perspective of space development – how to start, and how to grow in skill, knowledge, resources, and energy to accomplish long-term goals discussed in this report.

Studies of ecosystems as diverse as those of bacteria and whales suggest the maximization of information content and energy flow in all living systems (Miller, 1978; Odum, 1971). Examination of many species shows that diversity and adaptation to numerous habitats leads to survival. Humanity appears poised to accept the challenge of the frontier of space, and for the same fundamental reasons: knowledge, energy, resources, and room to grow; in short, for survival.

The space program has in the past been pursued for reasons of exploration, scientific knowledge, national security, and pride. In the future the *utilization* of space will take precedence over pure *exploration*. New resources from space can help put NASA programs on a sounder footing in providing benefits and services of great economic and national importance. If NASA clearly realizes the tremendous opportunity and makes these goals known to the public, it will accomplish feats and gain popular support far greater than ever thought possible.

The aim of the present discussion is to show how space activities undertaken by NASA in the immediate future and over the next several decades can help solve three major problems facing the United States today:

- Energy independence
- Material independence
- Increased productivity

The tools for solving these problems include:

- Space technology
- Teleoperators
- Automation and robotics

The American people have great pride in their technology and ability to confront challenges. Presently the United

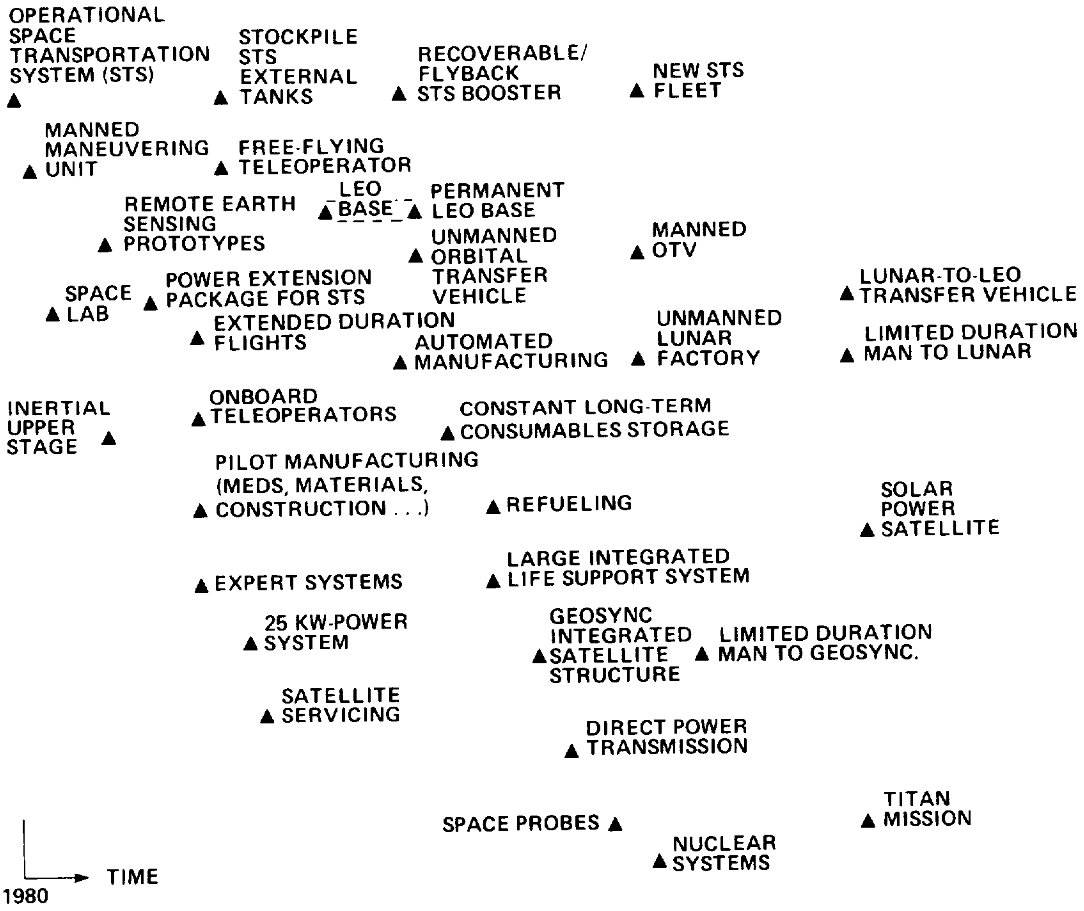

Figure 7.2.– Space facilities and programs.

States is faced with a situation in which national economic independence is held hostage to the critical resources of minerals (manganese, cobalt, chromium, titanium, and tantalum) and energy (OPEC petroleum) controlled by unstable or unfriendly nations. Space can provide energy and mineral resources to sustain steady growth of both our economy and that of the world for the foreseeable future. The notion that space can produce benefits that directly affect the way ordinary people live has the potential to mobilize strong public support and provide the funding and planning stability NASA now so desperately needs.

The requirements of energy, knowledge, and resources create markets for specific services. Already the communications and Earth resources satellites are experiencing rapid market growth. NASA gradually must develop new markets and new constituencies in the business and public user communities. Lift costs remain expensive and necessitate reducing Earth resupply. In the past this pressure has led, for example, to satellites able to survive unattended for years. In the near future, it will mean on-orbit assembly and checkout, and on-orbit repair and refueling. In the long-term, satellites can be manufactured directly from extraterrestrial materials in space.

According to United Nations' estimates, some 70% of humanity is poor, underfed, and undereducated. Most recent analyses of the future have concluded that the outlook for humanity is dark – an increasingly grim world of limited living space and resources on a finite planet. To our knowledge, *none* of these gloomy studies has considered the liberating potential of space, either the advanced technology necessary to master it or the possibilities for long-term solutions using extraterrestrial resources (Vajk, 1978).

7.2.1 Specific Goals for Growth Scenario

Some studies of space stations start by assuming full-scale activity or by ignoring the process of growth entirely. A central conclusion of the present study is that growth must be incorporated into policy planning, and must proceed from current or easily foreseeable capabilities toward desired goals in such a way that two principles are observed:

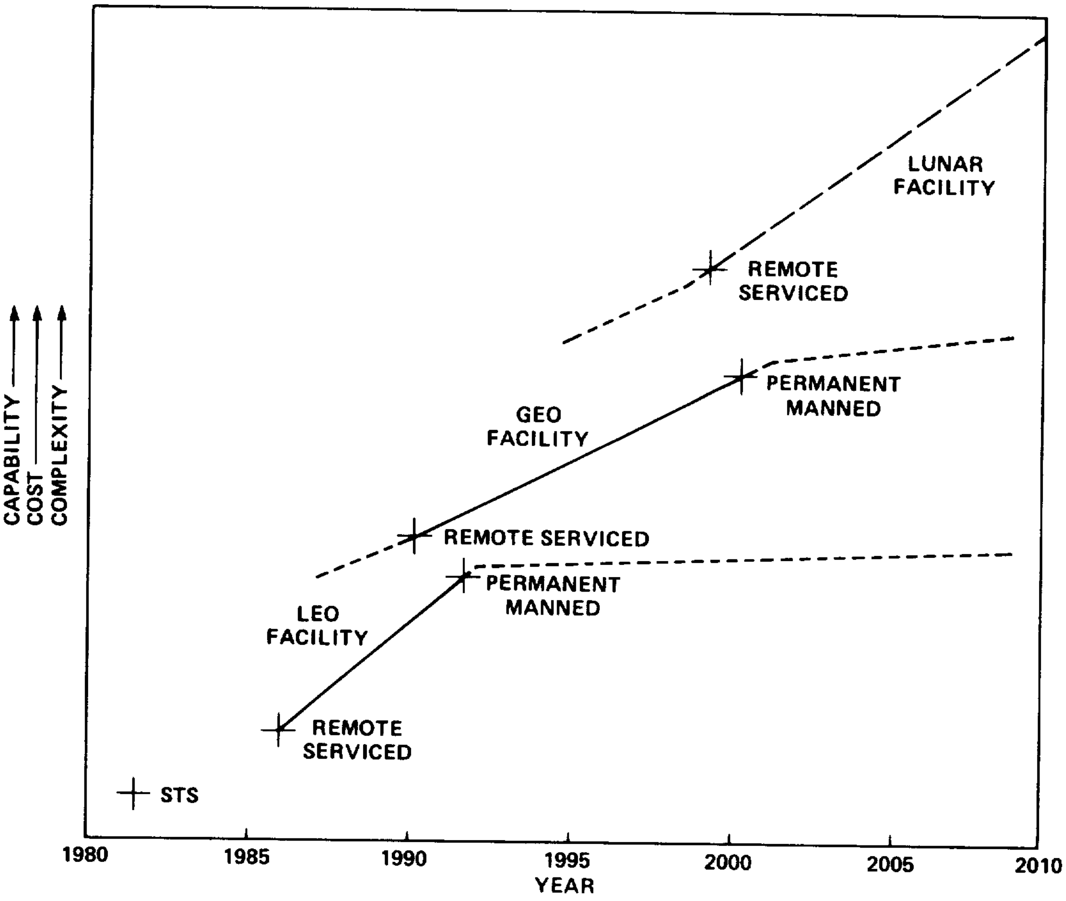

Figure 7.3.– Timetable for development of automated activities in space.

(1) Each growth step must be justifiable in its own right.

(2) Each growth step must lead clearly toward the defined goals.

The starting points for the growth scenario have been outlined in preceding discussions. The final goal, human operation in space with greater independence from Earth, is pursued through a series of interim goals – in particular, the development of the abilities to:

- Modularize equipment
- Tend co-orbiting free satellites
- Build, test, and transfer to orbit large complex systems
- Reduce station Earth dependence for control and resupply
- Automate space operations in support of in-space human activity
- Advance deep space exploration

In pursuit of these goals a program scenario is required. Figure 7.4 shows an overview of space activities starting

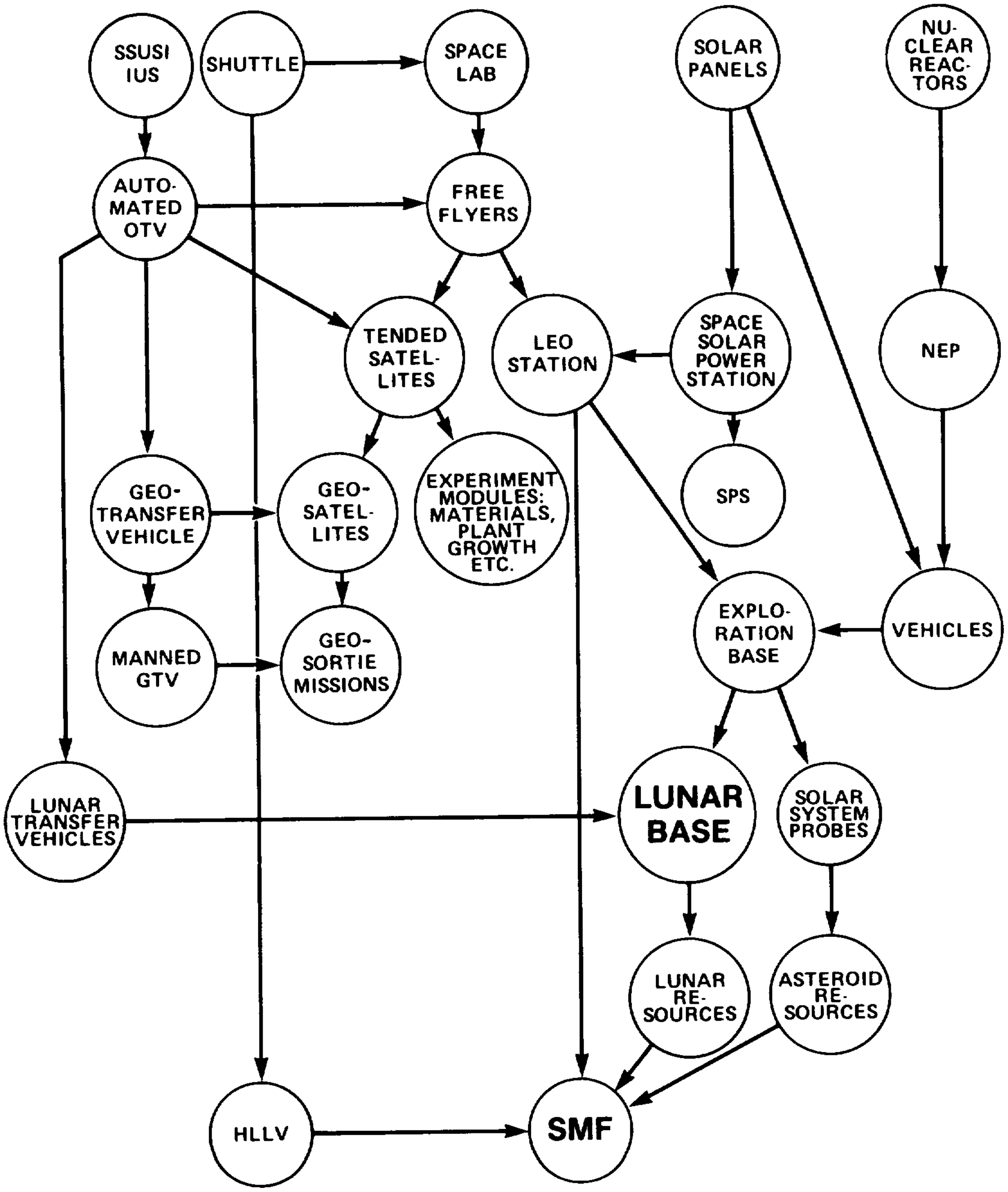

Figure 7.4.– Overview of space activities development.

from the present and continuing through the development of an increasingly independent space manufacturing capability. Figure 7.5 provides additional details on the possible development of a low Earth orbit station. Both suggest the kinds of facilities expected to be required to attain the desired goals. The use of a permanently manned LEO station as a Solar System exploration base and as a support station for tended free-flying unmanned satellites means that toward the end of this century many characteristics of manned and unmanned space endeavors will blend together.

Modularize equipment. Modularization of equipment reduces the mass of material that must be transported to and from orbit for repair and replenishment of orbital facilities. This is because only defective or depleted modules need be handled rather than the entire system. Overall system mass is higher for modular designs, but system maintenance mass is significantly reduced. The modification of an existing facility to accept new capabilities is greatly simplified through the use of plug-in modules. Parts installation and replacement already are prime candidates for early automation and these procedures are streamlined by modularization. Both station growth and the multiplication of capabilities become more feasible since the entire system need not be replaced as parts become inadequate or obsolete. The sizes of Spacelab and the Shuttle payload bay suggest a practical size limit for modules.

Modularization is not intended to replace space fabrication of stations and equipment but is to be used in parallel with on-orbit construction.

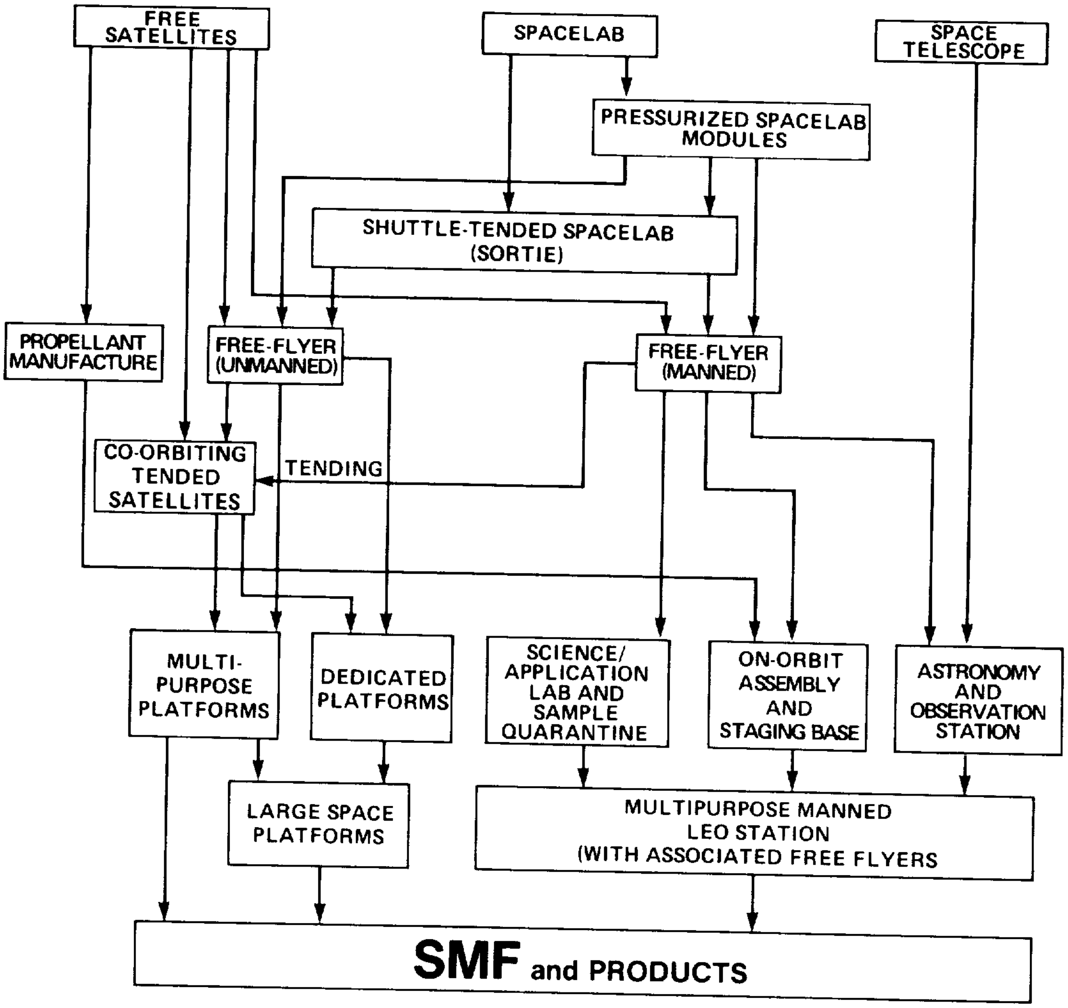

Figure 7.5. – Details of LEO station development.

C-5.

Tend orbiting satellites. These satellites are emplaced by and are under the control of the main station. They fulfill a single major purpose or a related series of purposes such as Earth sensing, plant growth experiments, or optical astronomy. The use of tended free-fliers solves the problem of conflicting priorities (e.g., pointing a telescope at a star and a sensor at the ground simultaneously). It enables scientific experiments or other tasks to be performed without continuous human supervision but which do require very low movement or very low containment levels. The satellite module can be resupplied, repaired, or given new tasks and then left undisturbed. The satellites should themselves be designed on the modular principle, and tending them will drive development of technologies required to repair satellites in LEO and GEO, to assemble large satellites and space probes, and to provide flight support for missions conducted farther from the Earth.

Build, test, and transfer to orbit large complex space stations. This capability derives from Shuttle beam building experiments and the assembly of modular structures and produces many of the products of this stage of development. These products include:

- SPS proof-of-concept and prototype devices
- Communications platforms
- Large antennas and antenna forms
- Clustered satellites and multipurpose platforms

The ability to construct very large space structures such as the solar power station depends heavily on automated construction and assembly techniques developed at this stage.

Reduce station dependence on Earth for control and supply. Solar and nuclear power modules, modules for atmospheric recycling and renewal, food production and waste recycling capabilities, and the ability to assemble platforms and station sections from supplied parts and then to make those parts from supplied raw materials, all contribute to the growing independence of the space industrial complex. Increasing independence demands progressively increasing capacity to generate electricity (energy self-sufficiency), to recycle air and water in an increasingly closed ecosystem, to monitor crew and station health (life-sustaining independence), to process materials and fabricate products in space (economic and manufacturing independence), and finally to acquire and utilize nonterrestrial resources (material independence).

The stages of independence may be pursued in parallel, and the progress toward self-sufficiency is quite gradual. There is no requirement that a facility be fully or even mostly self-sufficient at the outset.

Automate space operations to support in-space human activity. Automation will not eliminate human activity in space. Human-built machines are not people and space in the long run will have little meaning for humanity unless people are living in space. The purpose of automation is to make human tasks easier and less hazardous, to remove tedious and repetitive tasks from human responsibility, and to enable each individual to accomplish more. The term "automation" is loosely used to encompass the full range of autonomous or semiautonomous systems including robots and free satellites that perform a set of tasks and exercise judgment when faced with unforeseen developments, automatic processing machines with little or no judgment, and teleoperators controlled entirely by humans who provide the required judgment. Prime candidates for early automation are the assembly of stations and OTV modules, satellite assembly, emplacement, replacement and repair, and space processing techniques.

Advance deep space exploration. Advanced future deep space probes can build on the experience of earlier probes such as Voyager and Viking, but the new generation of machines may be larger and considerably more autonomous. They can be greater in size because of modular construction in LEO. On-board artificial intelligence will enable the probes to perform largely autonomous scheduling, sequencing, and contingency planning. Automation may also include on-board analysis, data correlation, and perhaps, even mechanized, hypothesis-formation development of models describing a remote planet. All of these capabilities, along with robotic systems, are required for the ambitious Titan mission described in chapter 3.

In the shorter term, space probes will serve as the automated prospectors of the utilization-oriented space age. Asteroid rendezvous missions currently being considered will only be the first of many missions to seek out possible extraterrestrial resources for in-space materials processing. Multiple asteroid prospecting in the asteroid belt, comet rendezvous and sample return, Mars rover and sample return, planetary and satellite lander/rover/sample return missions are believed credible but are not yet in mainstream space mission planning.

7.2.2 Recommended NASA Space Systems Technology Model Updates

The NASA/OAST Space Systems Technology Model (OAST, 1980) is intended to serve as a reference for planning technology programs and options, identifying technologies required for planning and potential future missions, assessing ongoing technical programs, and providing a technology reference source for mission planning. Ascertaining requirements for planned and future missions ensures that the focus of technology programs is coupled to the overall goals and missions of NASA.

The three volumes of the Model treat systems, programs, and technology from the present to the reasonable limits of projection. Volume I describes those systems and programs which the NASA program offices endorse as being within their 10-year planning horizon. Volume II contains trends and forecasts of space technology. Volume III provides information about innovative systems, programs, and technology. Part A presents novel systems and programs validated by program offices but which are either beyond the 10-year planning period or are still deemed speculative. Systems and programs in Part B derive from sources other than the program offices and, as such, are considered more speculative than Part A missions. Part C presents emerging technologies with little or no historical trend, and provides best possible forecasts of their potential.

An addition to the Model as a result of the present study should be made to Space Technology, volume II, under "Information Systems." Present categories include:

4.1 Sensors
4.2 Data processing
4.3 Communications

The Study Group recommends the following addition to section 4 of volume II:

4.4 Computer science and technology (including computer systems, software, management services, and systems engineering)

Further additions to volume II of the 1980 Model should be made under "Automated Operations." Present categories include only:

6.1 On-board automation
6.2 Automated problem solving
6.3 Machine vision

The study group recommends the following additions to section 6 of volume II:

6.4 Automated "World Model" based information systems (including land and ocean modeling, Earth atmosphere modeling, planetary modeling, automatic mapping, intelligent image processing and information extraction, "smart" sensors, plan formation and scheduling, and global system management);

6.5 Automated learning and hypothesis formation (including analytic, inductive, and abductive inferences);

6.6 Natural language and other man-machine communication (including machine understanding of keyed natural language, machine participation in natural language dialogues, machine recognition/understanding of spoken language, machine generation of speech, and visual and other means of communication such as iconic formats);

6.7 Automated space manufacturing (including automatic extraction and purification of raw materials, forming of product components, product component assembly and inspection, autonomous system control, and self-replicating machine systems generally);

6.8 Teleoperators and robot systems (including the remote manipulator system, the teleoperator maneuvering system and other free-flying teleoperators, on-board teleoperated "walkers" and mobile workbenches, robot devices, "telepresence" operator sensory environments, and replicating telefactor systems); and

6.9 Self-replicating systems (including automata self-reference and self-reproduction methodologies, materials and parts and assembly closures, man-machine divisions of labor, and large complex hierarchical system control techniques).

Finally, four additions should be made to Opportunity Systems/Programs, Volume III of the 1980 Model. Under the categories "Resource Observation" and "Global Environment" there are no entries. The Intelligent Earth Sensing Information System (IESIS), developed by the Terrestrial Applications Team, may be inserted in either category as it fulfills the mission descriptions of both. A System/Program Summary may be assembled from information provided in chapter 2 of this report.

Under the category of "Planetary Missions" should be added the Autonomous Titan Survey Demonstration mission conceived by the Space Exploration Team as a precursor to interstellar-capable exploratory systems. A System/Program Summary of the proposed Titan demonstration mission may be generated from information provided in chapter 3.

Under the category of "Utilization of the Space Environment" two additions should be made. First is the SMF mission devised by the Nonterrestrial Utilization of Materials Team as a self-contained, evolving automated orbital manufacturing capability eventually using extraterrestrial material resources. Full details are provided in chapter 4, which may be used to assemble a System/Program Summary. Second is the Self-Replicating Growing Lunar Manufacturing Facility proposed by the Replicating Systems Concepts Team as a prototype for an autonomous general-purpose factory able to reproduce its own substance from arbitrary raw material substrates. A System/Program Summary may be prepared from information provided in chapter 5 of this report.

All four missions should be entered in Part B of volume III since they are opportunity programs unsupported at present by NASA program offices. As such support materializes they may be upgraded to Part A.

7.3 Conclusions and Recommended Technology Priorities

Many detailed conclusions and recommendations regarding technology needs and development requirements have been identified and discussed elsewhere in this report. An effort is made here briefly to highlight the major themes and milestone recommendations of the entire study activity having highest priority.

An evolutionary NASA space program scenario was developed by the study group, based on various relevant planning documents and other information. The major scenario premise was that coordinated developmental initiatives would be undertaken by NASA in the next 20 years to establish the basis for an aggressive, multidisciplinary program of space exploration and utilization early in the next century. Although the specifics of such a program can vary significantly, several generic characteristics were thought probable for any intensive space exploration and utilization effort. These could be used as meaningful guides for the mission problems selected by the study group to identify future automation technology requirements, and include:

- A major Earth resources observation program
- Intensive exploration of the Solar System and beyond
- Major low Earth orbit activities requiring the continuous presence of man as troubleshooter, supervisor, and operations coordinator
- A significant capability for acquiring and utilizing nonterrestrial materials for products to be used in space, such as large structures, power systems, antennas, expendables, etc.
- An advanced mobile communications system. (The importance of this program element was recognized by the study group but was not specifically addressed by any of the selected mission teams since the automation requirements were not considered unique.)

Advanced machine intelligence and automation technology as described in this report is believed to be essential in evolving toward a major space program capability for exploration and utilization within realistic resource limits. To this end, the following general conclusions and technology recommendations are worthy of special consideration:

(1) Machine intelligence systems with automatic hypothesis formation capability are necessary for autonomous examination of unknown environments. This capacity is highly desirable for efficient exploration of the Solar System and is essential for the ultimate investigation of other star systems.

(2) The development of efficient models of Earth phenomena and their incorporation into a world model based information system are required for a practical, user-oriented, Earth resource observation network.

(3) A permanent manned facility in low Earth orbit is an important element of a future space program. Planning for such a facility should provide for a significant automated space manufacturing capability.

(4) New, automated space materials processing techniques must be developed to provide long-term space manufacturing capability without major dependence on Earth resupply.

(5) Replication of complex space manufacturing facilities is a long-range need for ultimate large-scale space utilization. A program to develop and demonstrate major elements of this capability should be undertaken.

(6) General and special purpose teleoperator/robotic systems are required for a number of space manufacturing, assembly, inspection, and repair tasks.

(7) An aggressive NASA development commitment in computer science is fundamental to the acquisition of machine intelligence/automation expertise and technology required for the mission capabilities described earlier in this report. This should include a program for increasing the number of people trained in the relevant fields of computer science and artificial intelligence.

7.4 References

Miller, James G.: Living Systems. McGraw-Hill Book Co., New York, 1978. 1102 pp.

Odum, Howard T.: Environment, Power, and Society. Wiley-Interscience, New York, 1971.

Office of Aeronautics and Space Technology (OAST): NASA Space Systems Technology Model, Volumes 1-3, NASW-2937, NASA Headquarters, Washington, D.C., May 1980.

Vajk, J. Peter: Doomsday Has Been Cancelled. Peace Press, Culver City, California, 1978.

GLOSSARY

FOR MACHINE INTELLIGENCE AND AUTOMATION IN SPACE

Algorithm – A procedure for accomplishing a given result by proceeding on a logical step-by-step basis. Computer programs and N/C routines for machine tools are developed in this way.

Analog – Computers of this type are designed to respond and control continuous process operations such as flows, temperatures, or other infinitely variable-type operations. Digital computers process only discrete digital data.

Automatic – Functioning in a predefined manner with a minimum of reprogrammability; possesses only limited process information closure.

Autonomous – Functioning independently of other components or systems; self-governing or self-controlling; possessing virtually complete information closure in normal operation.

Axis – A general direction of relative motion between N/C machine cutting tool and the workpiece.

Bit – A binary digit of either 0 or 1; the smallest unit of information.

Bootstrap – A technique for loading the first few instructions of a computer program into active memory and then using them to bring in the rest of the routine.

Buffer Storage – A place for storing information in either a computer or a control unit so that it is immediately available for action once the previous instructions have been completed. Buffers eliminate the need to wait for information to be transferred from a slower bulk storage medium into active memory.

Byte – A series of computer binary digits organized to represent an alphanumeric symbol; sometimes called a "word" of memory; 4-, 8-, and 16-bit bytes are common in computing.

CAD – Computer-aided design; the use of computers to aid in product design and development

CAM – Computer-aided manufacturing; the use of computers to assist in any or all phases of manufacturing. N/C is one form of CAM.

Cartesian Coordinates – A system of two or three mutually perpendicular axes along which any point may be located in terms of distance and direction from any other point.

CAT – Computer-aided testing; the use of computers to aid in the testing of manufactured output.

Chip – Small piece of semiconductor material upon which electronic components and subassemblies are formed. Integrated circuits, LSI and VLSI are made on chips.

Closed-Loop System – A system whereby signals from a control unit are acted upon by the machine effector or teleoperator, and a monitoring unit then returns the acted upon signals for comparison; operates using feedback from errors, thus achieving some level of self-correction; opposite of open loop.

Closure – Exists when system function or output exceeds system structure and input requirements. Closure may involve quality, quantity, or throughput rate, and may apply to mass (parts, materials), energy (power, collectors), or information (assembly operations, repairs).

Cognition – Programmed models which approximate the behavior of natural cognition, in the context of robotic and artificial intelligence systems.

Compatibility – The degree to which tapes, languages, and programming can be interchanged among various computer and computer-controlled systems.

CPU – Central processing unit; the basic memory or logic center of a computer that includes the circuits controlling the processing and execution of instructions.

CRT – Cathode ray tube; an electronic vacuum tube containing a screen on which graphic or alphanumeric information may be displayed.

CS&T – Computer Science and Technology.

Dedicated Computer – A computer devoted exclusively to a single application.

Degrees of Freedom – The state of a mechanism can be described by specifying the current value of each variable parameter, particularly rotating or sliding elements, of robot systems.

Digital – Information and values are expressed in discrete terms. In a digital computer such terms are generated by a combination of binary on/off or positive/negative signals, the opposite of analog wherein a fluctuating signal strength determines the fluctuations of values.

Digitize – The process of converting a scaled, but non-mathematical, image into digital data.

Disc – A random-access storage component of a computer system.

DOD – Department of Defense.

DOC –Department of Commerce.