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Pointing and Control System Enabling Technology for Future Automated Space Missions

J. B. Dahlgren

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PREFACE

In the fall of 1977, under the sponsorship of the NASA Office of Aeronautics and Space Technology (OAST) a study was initiated to identify enabling technology in pointing and control system disciplines which are required to implement unmanned automated missions out to the year 2000. NASA OAST Codes RX and RE supported this study because advanced development planning should be predicated on needs 10 and 20 years into the future rather than 5-year forecasts, which have preceded these enablement studies. Planning options, which form the principal product of this study, were expected to play an important role in future OAST development programs.

The mission set used principally in selecting missions which will drive future pointing and control system technologies were those from the OAST mission model; however, many other missions of opportunity were also considered.

ACKNOWLEDGMENT

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J. MacPherson - Marshall Space Flight Center

ABSTRACT

Future automated space missions present challenging opportunities in the pointing-and-control technology disciplines. A NASA-OAST sponsored study, recently completed, identified and assessed the enabling pointing and control system technologies for missions from 1985 to the year 2000. A generic mission set including earth orbiter, planetary, and other missions which predominantly drive the pointing and control requirements was selected for detailed evaluation. Technology candidates identified in the study were prioritized as planning options for future NASA OAST advanced development programs. The primary technology thrusts in each candidate program were cited, and advanced development programs in pointing and control were recommended for the FY80 to FY87 period, based on these technology thrusts.

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I. INTRODUCTION

Planning of an effective technology readiness program depends on a solid understanding of the driver mission/technology requirement relationships. In FY78 a NASA-OAST sponsored study, undertaken at JPL, had as its purpose to identify and assess the pointing and control technologies required to enable NASA missions from 1985 to year 2000. Enabling technologies are defined as those technologies which make viable the implementation of a particular mission. Viability may imply the technology makes the mission technically feasible; economically favorable; reliably acceptable; or a combination of these factors. Enabling technology therefore implies a technology representing a significant advancement or enhancement to near term available designs.

The objectives of the enablement study were to identify technology needs and development options in the areas of both pointing systems and control systems applicable to potential future missions. Specifically the study attempted to identify and assess the enabling technical developments in those disciplines which have the greatest benefit potential for application to future NASA missions. Opportunity-oriented technologies were also included which could enable new mission capability. Included in the assessment were technology requirements for precision pointing of sensors in earth orbit and deep space; rendezvous and docking of unmanned spacecraft; orbital transfer; station-keeping; attitude, articulation, automated assembly, and shape control of large structures; and others.

Typically, technology enablement studies are bounded by a representative mission set from which a technology assessment can be made. Referring to Figure 1-1, a flow diagram for technology identification was laid out which initially made up a representative mission set from various sources.[(2-5),(7)(11-20)(26)] The representative mission set was reduced to a generic set of earth orbiters and planetary missions. The set was considered to be those missions which generated the greatest demands on both pointing and control technologies. Key enabling technology areas were derived for this mission set by considering mission characteristics and system approaches to satisfy the technology requirements. Finally, from the key enabling technology areas, a list of technology development candidates was derived for future development. These candidates formed the basis for recommendations of pointing and control system technology developments to enable the generic missions cited.

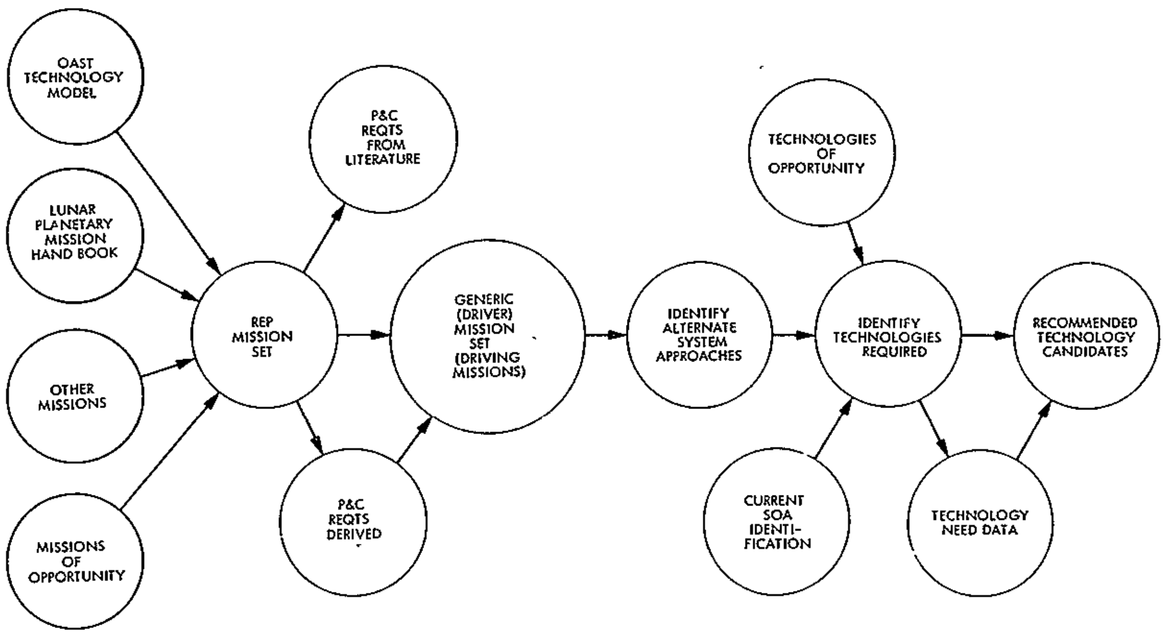


Figure 1-1. Road Map to Technology Identification

II. SUMMARY OF PRIORITIZED CANDIDATES

A. SCOPE OF CANDIDATES IDENTIFIED

This pointing and control system study identified 19 technology areas for which significant advancements are required to enable future missions from 1985 to year 2000. These candidates, described in the following paragraphs, are enabling technologies for planned missions beginning in 1985. Although some of these candidate areas are expected to be addressed by the Large Space Systems Technology (LSST) development program, there remains a significant set of critical technologies requiring development over the next seven years. Technology development program recommendations are given in Section VI. In September 1978, preliminary results of this report were presented to an AIAA conference(1) on future needs and capabilities.

B. CANDIDATE TECHNOLOGY DEVELOPMENTS

The 19 candidate technology developments to follow are listed in order of priority; however, it should be noted that only small differences in relative importance exist between the top and bottom of the list, with many candidates sharing the same ranking. For a more complete description of each candidate and the ranking system used refer to Sections V and IV respectively.

1. On-Board Controllers for Distributed Systems

Distributed control systems will require a huge amount of on-board computational capability in order to process the sensor data to accurately and dynamically model the physical system, and to output the proper control. In order to implement an efficient distributed control system distributed processors may be required. Each processor operating nearly independently would process sensor data locally, transmit commands to nearby actuators, and locally model the dynamics of portions of the overall structure.

2. Multiple Processor Systems for Large Structure Control Simulation

Comprehensive control system simulation of large space vehicles cannot be adequately performed on today's general purpose computers because of excessive computer time. A new computer architecture using parallel interconnected microprocessors is required to reduce control simulation computation time and make feasible the simulation of future large space systems.

3. Sensing Systems for Shape Control

Surface measurement systems will be required for many large space antennas for the determination of gain loss due to surface distortions, optimum feed location, direction of the RF boresight for pointing control, and for feedback to a surface control system. Mechanization concepts for these systems and efficient data reduction techniques are required. This is especially challenging since there may be thousands of points involved in surveying an antenna surface.

4. Distributed Control Actuators for Large Space Systems

Large space systems will typically be very lightweight and quite flexible. Because of their size the structures will have large inertias requiring large control torques. These control torques/forces must be distributed over the structure to reduce high point loading and minimize structural flexing. These problems will involve new techniques and concepts utilizing the distribution of actuator devices for control torques and forces.

5. Reduced Order Controllers

Modeling for controller design has been identified as a major problem in achieving precision attitude and shape control of large space structures because of size, flexibility, dynamic uncertainties, and the inability for ground verification. New formulations are required to determine the best reduced order models in order to retain the significant vehicle dynamics in the controller design.

6. Robust Adaptive Controllers

Inherent in a reduced-order model are model errors such as parameter uncertainties, truncated dynamics, internal disturbances and neglected nonlinearities. Robust controller designs must be developed with reduced sensitivity to modeling errors and with the capability to provide vehicle autonomy by adapting and compensating for the model errors.

7. Symbolic Manipulation Methods for Large Structure Control Simulation

Control simulation of large space structures cannot be performed adequately on currently available computers because of excessive computational time. New computer architecture and software techniques are required — this candidate technology involves the software development. Advanced symbolic manipulation methods are required to generate more efficient source codes and reduce computation time with the new computers. These new methods will increase computation speed by up to 10 times.

8. Environmental Torquing Systems for Large Space Structures

Large space systems in earth orbit will be subject to large environmental forces and torques. Development of control techniques is required to minimize the disturbances or use them effectively to reduce propellant mass requirements and increase mission life.

9. Rendezvous and Docking Sensors, Actuators, and Controllers

Future missions require the capability for automated rendezvous, station-keeping, and docking activities. Principal problem areas are in determining vehicle-to-vehicle relative position and orientation and the necessity of "acquiring" from arbitrary orientation. Advances in technology are required in the fields of scanning laser radars or CCD cameras combined with video object tracking and/or pattern recognition algorithms. Simple, efficient, lightweight coupling mechanisms do not currently exist and represent a required technology for docking actuators.

10. Passive Optical Rendezvous Systems

Many earth-orbital missions have been conceived which require rendezvous operations over ranges of perhaps 80 km to 300 m with passive targets that are not fitted with laser retroreflectors or RF transponders. Current rendezvous algorithms require range and range rate information as input, and this cannot be obtained for uncooperative targets unless the active vehicle can track the target. This approach requires a radar of greater power than will likely be available for Shuttle-era vehicles. An alternative approach requiring development involves tracking the target with optical sensors, e.g., star tracker, and processing the angular information to generate orbital parameters appropriate for rendezvous maneuvers. New techniques for data acquisition and filtering are required to implement this concept for on-board use.

11. Planetary and Precision Pointing Technology

Major improvements in stellar-inertial attitude reference systems are required for future earth pointing satellites to satisfy precision pointing accuracies of 1 $\widehat{sec}$ and below. Likewise for planetary missions, science instrument pointing accuracy must move to below 10 $\widehat{sec}$. These requirements represent improvements of 1 to 3 orders of magnitude beyond today's capability (ref: Landsat-D and Galileo). The reference system requires advanced attitude sensors combined with on-board controllers which autonomously transform the star-referenced inertial frame to the rotating earth-centered references with high precision.

12. Planetary Antenna Pointing and Control Development

Future planetary communication systems will include higher gain spacecraft antennas with narrower beamwidths requiring more precise pointing than current antennas. Pointing accuracy improvements of

5 times or greater over the current Galileo spacecraft are required to support missions such as Saturn Orbiter, Uranus Orbiter probe, and others.

13. Sensors and Actuators for Manipulator Control

Manipulator technology for large structures does not presently exist. Significant extensions to current technology are required. Further development is necessary to obtain adequate touch, force, and proximity sensors for manipulator hands. Actuator systems for manipulator hands and arms must be designed for application to the assembly and handling of large structures.

14. Inertial Sensor Technology

Mechanical gyros are limited in their use on long-life missions due to their mechanical "wear-out" properties, e.g., bearings. Solutions such as the fiber optic rotation sensor (FORS) concept have the potential of full-time operation and of meeting mission life requirements of 10 to 20 years. The principal technology requirements include the development of necessary integrated optical circuits, including the optical modulator, and waveguide interconnection techniques.

15. Automated Assembly Technology Development

Automated assembly technology for large systems will allow the construction of large space platforms that would be both cheaper and more extensive than would be the case of using a primarily manual approach to the task. Basic work is necessary in the conceptualization of operational techniques and algorithms for automated operations. Applications of computer vision systems combined with advanced manipulators are key technologies to this development.

16. Automated Manipulator System Development

Automated manipulators will be used to assemble structures in space, aid in space processing, and be used for repair and servicing of other equipment. Developments are required in effector mechanisms, sensors, computational hardware, and extensive software for control and sequencing.

17. Planetary Atmospheric Braking and Flight Control

Planetary orbiters or landers must remove the spacecraft approach velocity either propulsively or by using atmospheric braking. Large propulsive injection masses could be eliminated by use of atmospheric braking by precisely guiding the vehicle along an entry corridor and controlling the atmospheric entry lift vector. This requires advanced developments in on-board navigation and guidance and adaptive on-board flight control technologies.

18. Advanced Planetary Landers/Rovers

Advanced landers will be more autonomous and mobile. Autonomous roving will require development of advanced techniques for obstacle detection and avoidance. Obstacle detection necessitates further developments in computer vision technology such as three-dimensional vision, processing of visual data, and decisions based on visual information.

19. Momentum Bias Systems for Large Orbiting Systems

The pointing and attitude control of large space systems will require the development of large momentum exchange devices. Momentum storage requirements are in excess of 2×10^5 N-m-sec and the devices involved must be capable of generating large distributed moments.

III. DRIVER MISSIONS AND KEY ENABLING TECHNOLOGY AREAS

The driver missions, i.e., those missions which principally drive both pointing and control technologies, were selected from the representative mission set numbering over 100 missions (Appendix A). These driver or generic missions (see Table 3-1) present both demanding and sometimes unique requirements on future available technologies. The missions were placed in three major groups: earth orbiters, planetary, and other. The earth orbiters included the very large future antenna-based systems -- global communication systems; electronic mail[4]; sea survey systems; space-based radio telescopes[27], follow-on missions to the current Space Telescope[25]; and smaller systems such as the geodetic satellite[22][23], to observe earth crustal motions; and the pinhole satellite[19][24] to detect solar x-rays. The planetary missions[3] selected provided a number of unusual requirements uncommon to recent missions to Mars and Jupiter. The "other" missions group was used to include special missions or systems which were not common to the generic earth orbiters or planetary systems selected. Neither the space power relay satellite nor the space power satellite systems were examined in depth for the purposes of this study because they presented a host of pointing and control technology requirements driven by configuration, power source, assembly techniques, etc., which were outside the scope of the study. However, these missions were listed for completeness.

A. MISSION CHARACTERISTICS AND TECHNOLOGY REQUIREMENTS

For each mission identified for detailed study, principal characteristics which drive the pointing and control technologies and their technology requirements were derived. These characteristics and requirements are shown in Tables 3-2, 3-3 and 3-4. In a number of cases mission characteristics representing missions in the generic set were not completely defined, requiring derivation by making a "best guess" of what would likely be required by a program office to achieve the mission goals. The technical requirements were derived for the most part by "brainstorming" system approaches and solutions with a number of technical specialists in various control areas, e.g., analysis, robotics, actuators, systems, etc. Careful consideration was given to where the state-of-the-art was likely to be in the near-term (i.e., 3 years) versus what would be required to implement these future missions. These technology requirements were then used to establish the key enabling technology areas in pointing and control needed to support the missions.

Table 3-1. Generic Mission Set Driving Pointing and Control Technology

Earth Orbiters	Year	Planetary	Year
Global communication systems	85-87	Comet rendezvous	85
Electronic mail	85	Saturn orbiter dual probe	86
Geodetic survey satellite	84	Mars rover	86-88
Sea survey system and equiv	87-89	Mars sample return	88
Space-based radio telescopes	95	Automated planetary station	93+
Large space telescopes	85-90		
Pinhole satellite	87		

Others	Year
Solar Probe	85
On-orbit robotic manip	90
Space power relay satellite	90
Space power satellite	99

Table 3-2. Mission Characteristics and Technology Requirements--Earth Orbiters

System	Mission Characteristics	Technology Requirements
Global communication system	• Large antenna - up to 100 m - up to 30 GHz • Precise GEO operation • <10 $\widehat{sec}$ pointing control • <1 $\widehat{sec}$ stability • 1 mm (RMS) surface tolerance • Minimization of expendables • Automated assembly/deployment • Mission life >5 year	• Large momentum bias wheels up to 10^5 nms • Environmental torquing • Low-thrust, high-I_{SP} thrusters • Correlation tracking • Robust adaptive control • Laser range finding/IR interferometry • Angle measurement optical sensors • Autonomous on-orbit robotic manipulators
Large space telescopes	• X-ray, IR, solar telescopes • Extreme pointing accuracy 0.1 to 0.001 $\widehat{sec}$ • Precision deployment of multiple optics • Image motion compensation • Mission life >5 year	• Active control systems • Mirror and geometrical position control • Local damping and modal control • Ultra-fine guidance sensors • Robust adaptive controllers • Parameter/disturbance insensitive controllers • Active isolation devices
Pinhole satellite	• Free flying mask, 20-m dia., and detector systems • Vehicle-to-vehicle control • Range 1 km ± 20 mm • Angular alignment 0.05 $\widehat{sec}$	• Advanced alignment sensors, solar references • Multiple sensors for angular and translational position control • Precise stationkeeping control
Electronic mail	• Large 300-m erectable structure • GEO operation • Multibeam spherical reflectors, 91 thirty-meter antennas, 2-axis gimballed. Each antenna 30 m spherical • Pointing accuracy 10 $\widehat{sec}$ using uplink reference signals • Mission life ≥10 years	• Multiple antenna distributed control system • Control required during assembly and orbit transfer • Multiple reaction wheels of 2 x 10^5 nms • Structural deformation control (0.3 cm at antennas and 1 cm at platform) • Long-life/highly reliable systems and components
Geodetic survey satellite	• 1000-2000 km orbit • Precision pointing of laser range finder beam to specific ground points to accuracy of ~1 $\widehat{sec}$ • Measures earth crustal motions to within few centimeters • Retroreflector ground targets monitored each orbit • High scanning rates ($200^o/\widehat{sec}$) for multiple target coverage • Mission life 3-5 year	• Precision star tracking to <1 $\widehat{sec}$ accuracy • Active control of structure to suppress feedback and disturbances • High-precision electro-optic laser pointing system for selected ground targets • Compact high-resolution encoders >20 bits • Simple precision rate indicators
Sea survey system and equivalent	• High resolution radar and radiometer systems for sea, land, atmosphere, monitoring and forecasting • Large erectable antenna systems 50-1000 m dia., in 500 to 1000 km orbit • High slewing rates ~$2^o/\widehat{sec}$. • Pointing accuracy <20 $\widehat{sec}$ • Minimize on-board expendables • Surface tolerance λ/10 to λ/50 at 1 to 40 GHz	• Distributed and adaptive control system with large number of sensors and actuators for figure control • Large reaction wheels up to (TBD) nm torque • Control/structure interaction modeling and active structural damping to 0.5% • Deployment and assembly control concepts
Space-based radio telescopes	• Very large erectable antennas, 300-3000 m • Long-life >10 years • GEO operations • Pointing accuracy 0.1 - 2 $\widehat{sec}$ • Surface tolerance λ/20 at up to 1000 GHz • Retargeting up to 90^o in 1 hr	• Precision shape control of reflector to below 50 microns • Integrated, interactive distributed and adaptive control concepts • Large integrated hardware systems of reaction wheels, thrusters, positioners, dynamic sensors and actuators, adaptive estimators and others • Momentum conservative systems concepts for minimizing dependence on expendables • Precision star tracking to <1 sec accuracy

Table 3-3. Mission Characteristics and Technology Requirements--Planetary

System	Mission Characteristics	Technology Requirements

Comet rendezvous	• Close approach required
	• Zero-velocity encounter
	• Image motion compensation
	• Low thrust/ion propulsion, cross-axis acceleration $\leq 10^{-12}$G
	• Hostile environment
		• Correlation tracking/target body sensing
		• Closed-loop thrust vector control
		  • Low-G accelerometers
		  • Attitude/translation control
		• Adaptive sensors and actuators
		• Autonomous navigation at comet encounter

Mars sample return (MSR)	• Automated rendezvous and docking operations, dynamic range 25,000 km to 5 cm
	• Minimum lander ΔV
	• Atmospheric braking for orbit insertion
	• Entry corridor controlled to $\leq$5 km
		• Atmospheric flight control
		• Precision on-board navigation
		• Multiple tracking sensor systems
		  • Correlation/tracking sensors
		  • Rendezvous and docking sensors
		• Autonomous docking control strategies

Automated planetary station	• Low-thrust nuclear electric propulsion
	• Multiple satellite rendezvous and landing
	• Multiple maneuver/gravity assist
	• Near autonomy for 20 yr lifetime
		• On-board real-time guidance and navigation processing
		• Adaptive sequence modification/generation
		• Long-life multiple sensor/actuation systems
		  • Fiber optics rotation sensors
		  • Magnetic bearing actuators
		• Rover 2-yr lifetime, 1000-km range, 3 to 5 km in 24 hr
		• Hierarchical/supervisory controllers

Saturn orbiter dual probe	• Multipurpose spacecraft made up of orbiter, Saturn probe, Titan probe or lander • Mission life 10 years • Transfer mode by solar electric gravity assist • Saturn probe separated 65 days before encounter • Reorientation altitude maneuver and large propulsion maneuver at Saturn orbit insertion	• Galileo-based technology hardware with extended lifetimes • Autonomous approach guidance and navigation • Target body tracking • Long-life control components
Mars rover	• Rover lifetime on surface >6 mo. • Range 100-200 km • Rover position knowledge 5 m • Tracks objects at locomotive speed of <1 km/hr and <10°/s • Two rovers per lander • Obstacle detection at distances of 2-20 m	• Autonomous surface navigation and obstacle avoidance system • Optical proximity sensors • Obstacle detection algorithms • Advanced controllers

Table 3-4. Mission Characteristics and Technology Requirements--Other

System	Mission Characteristics	Technology Requirements
On-orbit robotic manipulator	• Autonomous free flyers • 6 to 7 degrees of freedom • 2 to 30 mm position control	• Vision sensing and control • Edge detection, label I.D., pattern recognition algorithms • Manipulation control system • TV, laser, proximity touch, force and torque sensing
Solar power satellite	• Large, lightweight, flexible structure ~20 km • Microwave antenna 1 km, pointing -'1 arc min. mechanical, 1 sec electronically • Minimization of expendables - 30-year life • On-orbit assembly	• Control structure interaction • Environmental torquing systems • Large momentum bias systems • Adaptive robust control • Model error compensation • Modal stiffness • Autonomous on-orbit robotic manipulators
Solar probe	• Exploration of solar corona to 4 solar radii (0.02 AU) • Orbit period 1 to 4 years • Large thermal shield, sun-pointed for spacecraft protection • Jupiter gravity assist ballistic trajectory or ion-drive low-thrust trajectory • Nongravitational acceleration to 10^{-10} G must be removed	• "Drag free" sensor control concept required for precision trajectory reconstruction • Combined attitude - translation systems • Reaction wheels for rotational control • Hydrazine thrusters for drag compensation • Wheels unloaded periodically by thrusters
Space power relay satellite	• GEO operation • Large 200-m erectable structure • System supplies 500 kW to satellites at 500 to 40,000 km range using laser transmission • Laser control system • Pointing accuracy 0.001 μrad • Tracking rate of 1°/sec. • 0.0005 μrad jitter • Mission life ~10 years	• Long-life/highly reliable systems and components • Active control of structures to suppress feedback of disturbances and maintain desired shape • High-precision pointing and tracking system

B. KEY ENABLING TECHNOLOGY AREAS

Having identified the technology requirements for each of the driver missions, the key areas of enabling technology for pointing and control were established by examining these requirements against anticipated near-term state-of-the-art technology (within 3 years). These areas were categorized into 6 major groups for convenience:

1. Autonomous operations
2. Distributed control systems for large structure
3. Precision pointing systems
4. Control analysis and modeling
5. Advanced control devices
6. Control system simulation for large space structures

Each of these groups embodies large and diverse technologies as indicated by the key technology areas associated with each group.

1. Autonomous operations

   Rendezvous and docking for planetary sample and return missions

   On-board guidance and navigation for planet and satellite rendezvous

   Control during assembly of erectable structures in space

   Planetary landers and rovers

2. Distributed control systems for large structures

   Precision surface measurement at potentially thousands of points

   Precision surface actuation and control

   Integrated attitude, shape, translation control

   On-board high-capacity fast controllers

3. Precision pointing systems

   Planetary antenna pointing and control

   Earth-orbital antenna pointing/slewing/retargeting control

   Vehicle-to-vehicle relative control

4. Analysis and modeling

   Comprehensive control structure interaction analysis tools

   Model error identification/reduction

   Highly adaptive controllers

5. Advanced control devices

   Precision surface measurement sensors

   Guidance and navigation sensors

   Large-structure torquing systems

   Precision star and target body trackets

6. Control system simulation for large space structures

   Multiple interconnected computer architecture

   Advanced symbolic manipulation methods

C. TECHNOLOGY TRENDS

For each of the key technology areas, trend projections could be developed which graphically illustrate where the state-of-the-art currently exists and where it is likely to go if the requirements of NASA's future missions are to be satisfied. Because of limited time available in the study only two trend projections were prepared as part of this report. These trend forecasts were identified with the key technology areas of (1) precision pointing systems for earth orbiters and planetary spacecraft and (2) on-board high-capacity fast controllers for distributed control systems. These forecasts were prepared because they reinforce projections made earlier in the NASA's Outlook for Space Study[6] for the period of 1980-2000.

In Figure 3-1, pointing accuracies and stabilities required for space instruments are shown projected to year 2000. The space systems shown were placed arbitrarily on the chart between the system accuracy and stability requirements. Current state-of-the-art earth-orbiter systems[21] such as MMS and Landsat-D require pointing accuracies of 0.01 degrees and stabilities of 10 to 100 times less. It can be seen that stability requirements for future systems will generally be about 2 orders of magnitude less than pointing accuracy. Also currently the planetary spacecraft requirements for Galileo of 0.2 degrees pointing accuracy represent today's capability for dual-spin spacecraft. Planetary spacecraft instrument pointing for missions in the late 1980's will require upwards of 10 times improvement over Galileo's number, as will many of the large earth orbiters.

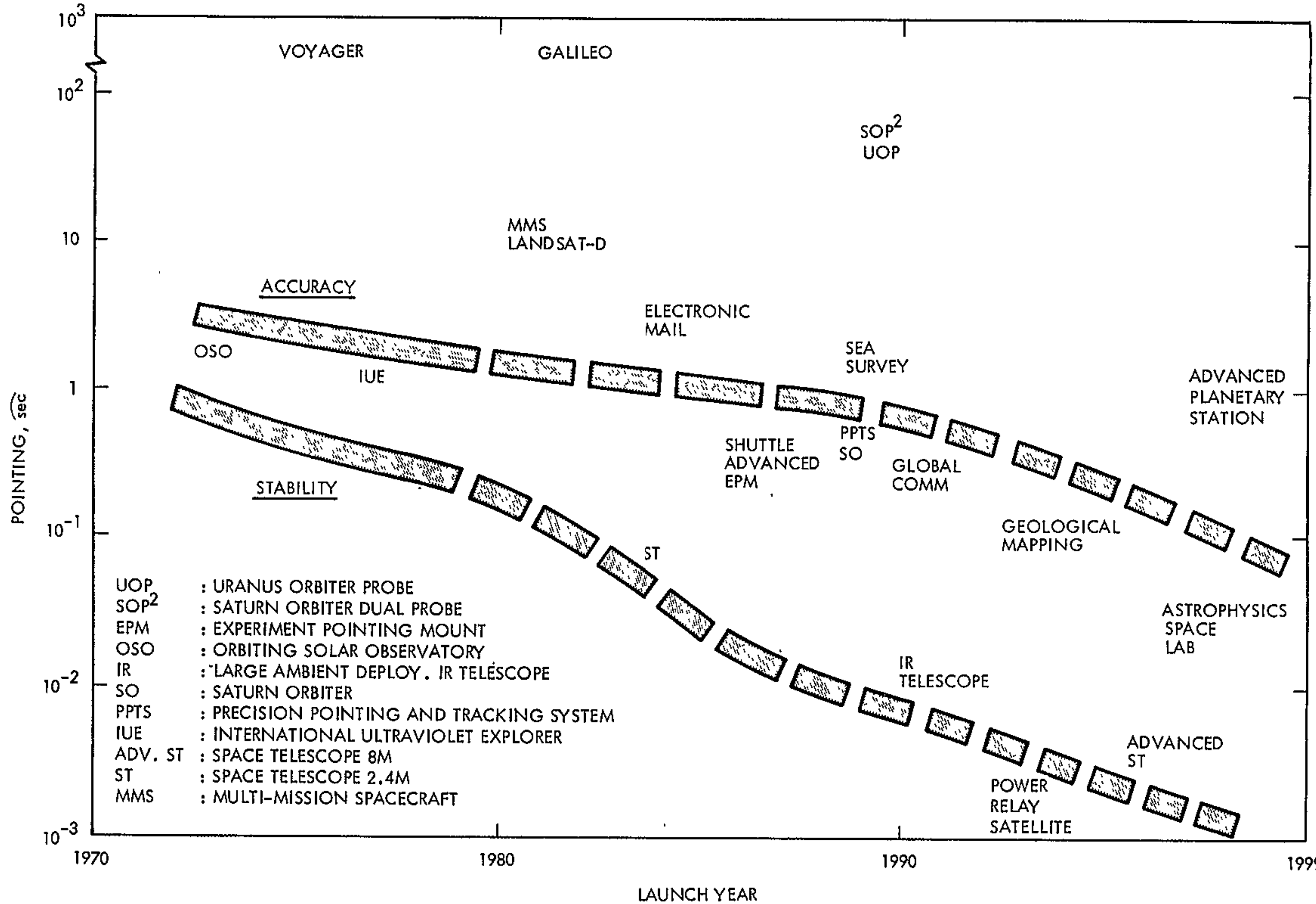


Figure 3-1. Instrument Pointing Trends (Requirements)

The pointing performance of future systems will continue to be limited primarily by the accuracy and noise of the attitude sensor. As space structures become larger, the influence of structural and thermal stability will play an important role. The stability or "jitter" required for these systems is one to two orders of magnitude better than the accuracy requirements. The most demanding requirements shown on the trend chart are those related to the power relay satellite mission concept(14). Pointing accuracy of 0.001 arcseconds is required for a laser power transmitter to transmit upwards of 500 kW of power to another satellite over a 40,000-km range.

The on-board processing capability of flight control computers will be required to grow significantly to support the control functions required for the large space systems (LSS) in the 80's and 90's. Centralized control processing for these systems will not be feasible because of limited operating speed and capacity, thus requiring the implementation of distributed processing. Figure 3-2 illustrates the shortcomings of centralized control processing. In the figure, the processing capability of Viking and Galileo flight computers, an IBM 360, and the ILLIAC IV ground systems are shown, assuming each is totally dedicated to the control problem. The processors operate at a fixed speed, but they may operate at a variety of sample frequencies. Diagonal lines in the figure are lines of constant number of operations per sample-time. With centralized processing, the number of multiplications per sample period required to output the control is proportional to 10 N^2 where N is the order of the control system (i.e., number of states to be controlled). As sample period increases or processor speed increases, the order of the system that can be controlled increases. LSS are estimated to require processing speeds in excess of large ground based control computing facilities.

The estimated processing requirements for LSS are shown by the shaded bar. Sample periods have been slightly increased from Viking and Galileo requirements and the dimensions of the system would range from N = 100 on up.

For distributed control processing the problem can be formulated as shown in Figure 3-3. For this case the processing requirements grow proportionally to αN where α* has a value of approximately 35. Large systems of dimension N greater than α can profit greatly using distributed processing. Notice how N grows much more rapidly on successive diagonal lines here as compared with the previous figure.

The state-of-the-art (SOA) flight processor capability of 1975 was taken as the equivalent to one Galileo processor. Ten such computers increase both the storage capability and computation speed by a factor of 10 when operating in a parallel distributed formulation which could satisfy the smaller of the large space structures. The capability of one hundred such processors is also shown.

*α = width of band in a banded matrix using finite element model methods.

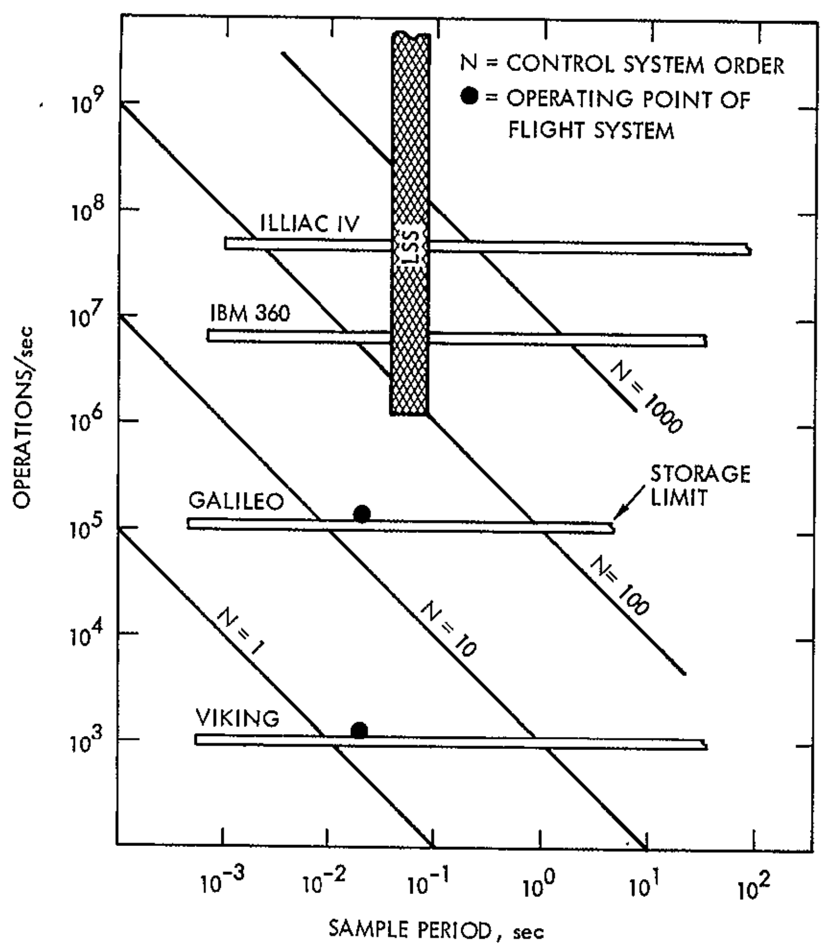


Figure 3-2. Centralized Control Processing

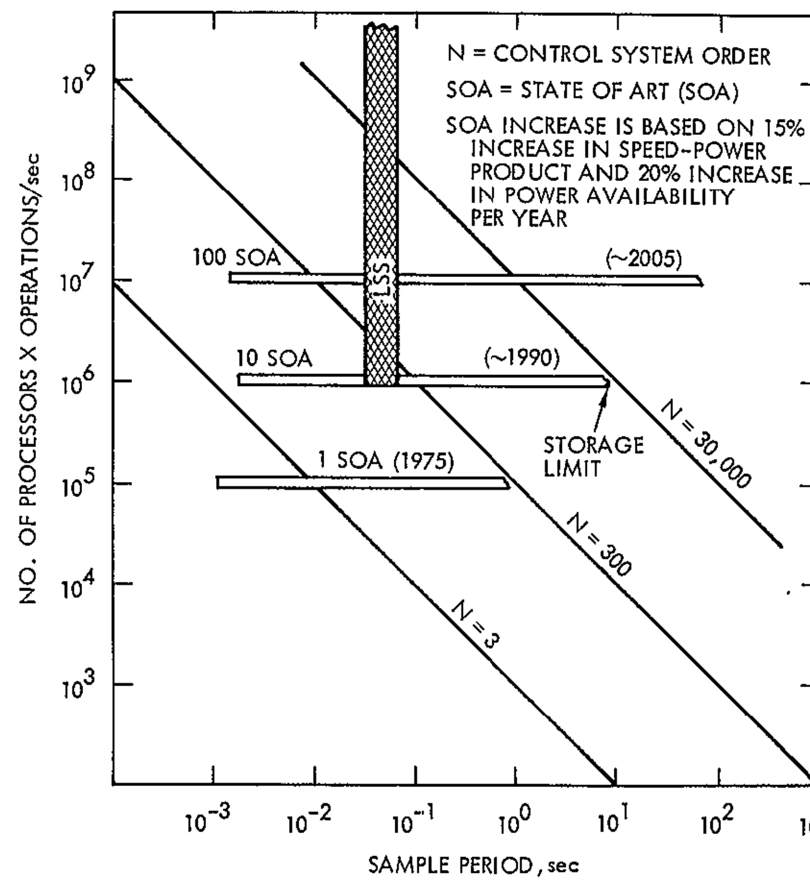


Figure 3-3. Distributed Control Processing Problem Formulation

By 1990 it is anticipated that the SOA improvements of 15% in processor speed-power product and 20% increase in power availability will allow one "new" centralized processor to control the smaller LSS. Carrying this example further, we also see for this same case that by 2005 another factor of ten in storage and speed can be realized. The message is clear that on-board processor technology must be operated in new parallel distributed formulations to cope with the large-order space systems of the future. Programs cannot wait for the supercentralized processor systems to enable these systems.

IV. RANKING METHODOLOGY

This section describes the procedures used to prioritize the candidate technologies identified in the study.

The task of prioritizing the candidate technologies is at best a difficult job when one considers that these technologies are enabling and as such the respective mission(s) requiring the technology cannot be accomplished without it. The requirement may come from the fact that the technical capability does not exist, without the technology, to accomplish the mission with a defined payload, or the costs would be prohibitive, or the risk to the mission would be excessive. Each of these points may be argued; however their priority provides a starting point in the process of selection for development support.

A. TECHNOLOGY RANKING METHODS

Recent enablement studies conducted at JPL in Environmental Control[8] and Communications[9] used ranking systems involving benefits, such as number of missions, need dates, contribution effect, multi-mission applicability, and others. A benefit analysis approach similar to these studies was used in the ranking of enabling technologies in pointing and control to provide a semi-quantitative figure of merit for each candidate program. The benefit criteria factors used in the analysis are described. A more recent study in power systems enabling technology[10] used the technique of benefit/cost/risk analysis as a primary discriminator in prioritizing technologies. Although an analysis of the type involved with the benefit/cost/risk approach was purposely not a part of the pointing and control technology enablement study, many of the factors used in such an analysis were considered in the ranking of the technology candidates.

B. RANKING FACTORS

The objective in selecting a ranking method was to develop a quantitative measure indicating which developments were more important or more critical to NASA from a global viewpoint i.e., would provide the highest payoff. Eleven benefit factors shown in Table 4-1 with associated criteria were selected for evaluation against each candidate technology. Each factor was weighted equally. Integer values of 3, 2, 1 and 0, with the value 3 having the highest ranking, were given to criteria applied to each benefit factor. Factors used in the evaluation along with their ranking criteria are discussed in the following paragraphs.

1. Launch Date

Technologies which benefit earlier missions were given higher rankings. Missions launched before 1988 were given the highest value because they are very near-term missions when one considers development

Table 4-1. Technology Benefit Factors and Associated Criteria

No.	Factors	Values for Criteria Shown 3	2	1	0
1	Launch date, year	<1988	<1992	<1996	≤2000
2	No. of launches	>5	3-4	2	1
3	Criticality to system	No alternative, economical	No alternative, expensive	Economically essential	Enabling but involves risk
4	Development cost - $M	<1	1-3	3-10	>10
5	Mission life, years	>7	<7	<3	<1
6	Technology Advance over SOA	>10X	≤10X	2-5X	1X
7	Commonality to other systems - No.	≥5	2-4	1	0
8	Development lead time, years	≤3	≤5	≤7	>7
9	Longevity of technology	≤2000	≤1995	≤1990	≤1988
10	Development difficulty or risk	Low	Mod.	Mod.-high	High
11	Cost Benefit	High	Mod.	Low	None

schedules of 3 to 5 years required before technology readiness demonstrations, and these demonstrations precede the launch dates by 3 and 4 years. The criteria applied to launch date and values assigned were: 3 points if before 1988, 2 points if 1988 or after but before 1992, one point if 1992 or after but before 1996. No points were given for missions in the last four years of the century.

2. Number of Launches

The greater the number of missions a technology enables in one or more generic groups the greater the economies one can realize. For each mission one space system has been assumed. 3 points were given if technology served 5 or more missions, 2 points if it supported 3 or 4 missions, and 1 point if it was required on 2 missions. No points were given if the technology was applicable to a single mission.

3. Criticality to System

This factor is related to how the technology enables a given mission. For the highest ranking, 3 points were given a candidate technology which was affordable and where no technology alternatives were known. 2 points were assigned if the technology was essential but potentially expensive, and 1 point was given a technology which was economically essential to enable a mission. Technologies which by their nature involve moderate but acceptable risk to the mission were not given points.

4. Development Cost

Cost of developing enabling technology was arbitrarily categorized as low, moderate, and high and assigned points as follows. Development cost less than one million dollars, 3 points; between one and 3 million dollars, 2 points; and between 3 and 10 million dollars, 1 point. Development costs exceeding 10 million dollars were given zero points.

5. Mission Life

In general the longer the mission life requiring the technology, the greater the payoff. 3 points were given to missions with mission life greater than 7 years, 2 points for less than 7 years, 1 point for mission life less than 3 years, and no points for missions less than one year.

6. Technology Advance over State-of-the-Art

The advance projected in performance by the enabling technology over near-term available technology was applied as the criterion in this factor. For advances greater than 10X, 3 points were assigned; equal to or less than 10X, 2 points; and 2 to 5 times advanced, 1 point. No advance received no points.

7. Commonality to Other Systems

Technologies having multi-mission application were rated highest. 3 points were given for technologies applicable to 5 or more mission groups, 2 points for 2 to 4 groups, 1 point for one other group, and zero for no commonality.

8. Development Lead Time

The lead time required to develop a given technology may not be an important factor in those cases where the mission launch date is well beyond the technology readiness date, but for a technology requiring a relatively short development schedule there is greater opportunity for earlier payoffs and alternate applications. Points were assigned based on estimated development time in years required to demonstrate technology readiness as follows: 3 points for 3 years or less, 2 points for 5 years or less, 1 point for 7 years or less, and zero points for greater than 7 years.

9. Longevity of Technology

This factor represents the life potential for the technology with expected enhancements and advancements before replacement by the next-generation enabling technology. Values were assigned based on technology utilization out to future mission launch periods as follows: 3 points to year 2000, 2 points to year 1995, 1 point to year 1990, and no points for missions to 1988.

10. Development Difficulty or Risk

This factor was not quantized. The criteria for assigning points were based on development risk in achieving performance goals with the arbitrary criteria of low - 3 points, moderate - 2 points, moderation to high - 1 point, and high - zero.

11. Cost Benefit

Elements which contribute to this final factor involve the relative economic benefits which may be realized from the enabling technology compared to alternative solutions. Elements include equipment cost savings, launch cost savings, standardized design savings, value of increased data, and others. Points were assigned each technology based on their composite potential for cost benefit as follows: 3 points - high potential, 2 points - moderate, 1 point - low, 0 - little or none. Quantitative levels of benefit were assumed as high - several millions of dollars, moderate - a few million dollars, low - less than a million and little or none - less than a quarter of a million dollars.

After assigning a value to each technology candidate against the ranking factors shown the values are summed and averaged to determine an overall value. Based on a criterion of 3.0 as the highest obtainable value, the candidate technologies are prioritized. The final ranking of the technologies and values given for each ranking factor are shown in Section V.

SECTION V

PRIORITIZATION OF TECHNOLOGY CANDIDATES

In Section IV the ranking factors and associated criteria were established for prioritizing the technology candidates. The technologies are listed in Table 5-1. Before addressing the technology rankings we'll look at the missions which are enabled by these technologies.

A. GENERIC MISSION ENABLING TECHNOLOGY

The pointing and control system technologies required to enable the generic missions are shown in Table 5-2. Each generic mission represents a class of future missions, with the first mission launch date shown. For example, the large global communication satellite with a projected launch date in the 1985 to 1987 period will be followed by many potential public service satellite missions requiring similar technology. Likewise, the Saturn-orbiter dual-probe mission in the planetary group will be followed by many potential missions to Uranus via Jupiter or Saturn, Neptune, and others, again requiring much of the enabling technology used in implementing the generic mission.

B. TECHNOLOGY CANDIDATE RANKINGS

Using the ranking methodology established in the previous section of the report, each technology candidate was graded against the ranking factors and associated criteria based on a rating of 0, 1, 2, or 3 points, with 3 being the highest obtainable value. The final ranking of the technologies and the values given for each ranking factor are shown in Table 5-3. Although the technology candidates are shown in numerical order it can be seen from examination of the total points applied to each candidate that many candidates share the same rankings. Also, in most cases there are only small differences between those candidates at the top and those at the bottom of the list.

Table 5-1. Pointing and Control Candidate Technology Developments

1. On-board controllers for distributed systems
2. Multiple processor systems for large-structure control simulation
3. Sensing systems for shape control
4. Distributed control actuators for large space systems
5. Reduced order controllers
6. Robust adaptive controllers
7. Symbolic manipulation methods for large-structure control simulation
8. Environmental torquing systems for large space structures
9. Rendezvous and docking sensors, actuators, and controllers
10. Passive optical rendezvous systems
11. Planetary and precision pointing technology
12. Planetary antenna pointing and control development
13. Sensors and actuators for manipulator control
14. Inertial sensor technology
15. Automated assembly technology development
16. Automated manipulator system development
17. Planetary atmospheric braking and flight control
18. Advanced planetary landers/rovers
19. Momentum bias systems for large orbiting systems

Table 5-2. Generic Mission Enabling Technologies

Generic Missions	First Mission Launch Year	Pointing and Control System Enabling Technologies Required*
Earth-Orbiters		
Global communication systems	85-87	1,2,3,4,5,7,8,10,11,13,15,16,19
Electronic mail	85	4,5,8,11,13,15,16
Geodetic survey satellite	84	11
Sea-survey system and equiv	87-89	1,2,3,4,5,6,7,8,10,11,13,15,16,19
Space-based radio telescopes	95	1,2,3,4,5,6,7,8,11,13,15,16
Large space telescopes	85-90	5,8,11
Pinhole satellite	87	9,11
Planetary		
Comet rendezvous	85	6,10,11
Saturn orbiter dual probe	86	6,11,12,14,17
Mars rover	86-88	6,13,16,18
Mars sample return	88	6,9,13,14,16,17
Automated planetary station	93+	6,9,12,14,17
Others		
Solar probe	85	1,6
On-orbit robotic manipulator	90	6,13,16
Space power relay satellite	90	2,4,5,7,8,11,13,14,15,16
Space power satellite	99	1,2,3,4,5,7,8,13,14,15

*Technology numbers correspond to Table 5-1.

Table 5-3. Technology Candidate Rankings

Ranking	Technology Candidates	Launch Date 1	No. of Launches 2	Criticality to System 3	Development Cost 4	Mission Life 5	Technology Advance over SOA 6	Commonality to Other Systems 7	Development Lead Time 8	Longevity of Technology 9	Development Difficulty/Risk 10	Cost Benefit 11	Total
		Ranking Factors											
1	On-board controllers for distrib. systems	3	3	3	3	3	3	3	2	2	2	3	30
2	Multiple processor systems for large-structure control simulation	3	3	3	2	1	3	3	3	3	3	3	30
3	Sensing systems for shape control	3	3	3	3	3	3	3	2	2	2	2	29
4	Distributed control actuators for large space systems	3	3	3	3	3	3	3	2	2	2	2	29
5	Reduced-order controllers	3	3	3	3	3	3	3	2	2	2	2	29
6	Robust adaptive controllers	3	3	3	3	3	3	3	2	1	2	3	29
7	Symbolic manipulation methods for large structure control simulation	3	3	3	3	1	3	3	3	2	2	3	29
8	Environmental torquing systems for large space structures	3	3	1	3	3	1	3	3	3	2	3	28
9	Rendezvous and docking sensors, actuators, and controllers	3	3	3	3	1	3	3	2	2	2	2	27
10	Passive optical rendezvous systems	3	3	3	3	1	3	3	3	1	1	3	27
11	Orbital precision pointing technology	3	3	2	2	2	3	3	2	2	1	3	26
12	Planetary antenna pointing and control development	3	2	3	3	2	2	1	3	2	2	1	24
13	Sensors and actuators for manipulator control	3	3	1	3	1	3	3	3	1	1	2	24
14	Inertial sensor technology	2	2	1	3	3	1	1	3	3	3	2	24
15	Automated assembly technology development	3	3	1	2	1	3	3	2	1	1	3	23
16	Automated manipulator system development	3	3	1	2	1	3	3	2	1	1	3	23
17	Planetary atmospheric braking and flight control	3	1	1	3	1	2	1	3	2	1	2	20
18	Advanced planetary landers/rovers	2	1	2	2	1	3	1	2	3	1	1	19
19	Momentum bias systems for large orbiting systems	3	3	0	1	3	1	2	1	3	0	1	18

SECTION VI

TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The purpose of this section of the report is to present recommendations for technology development based on the prioritized technology development programs in Section V, the mission technology readiness requirements, and assumed constraints on R and D program funding.

A. PRIMARY TECHNOLOGY THRUSTS

The candidate technology development programs identified in this study enable one or more missions, and therefore each program is critical to the implementation of these future missions. From examination of the ranking values given to each candidate it is apparent that the numerical spread between the candidates is in most cases slight. In attempting to conclude which programs should be recommended for near-term development in an environment of limited resources, it became clear that only a small fraction of candidate programs could be recommended for initiation in FY 80 or 81. However, examination of technology readiness (i.e., demonstration) dates required for each program, assumed as two years prior to launch, indicated that every program must be initiated before FY 81. Therefore, it follows that recommendations for technology development must encompass a broader set of requirements, such that all or most of the major requirements could be investigated at the same time. This approach led to examining each candidate's primary technology thrust and areas of commonality.

In Table 6-1 the primary technology thrust(s) in each candidate program is indicated using four principal technology development areas in pointing and control: (1) system design and development, (2) sensors and actuators, (3) controllers and estimators, and (4) control system simulation. In most programs a single major thrust in one of the four areas represents the major technology development activity, whereas in several others the programs have two or more major thrusts. In most of the technology candidates, a strong supportive activity will also be required in other areas. However, these supporting areas have not been specially called out for development.

For the primary technology thrusts shown in Table 6-1, the principal areas of technology not currently part of a development program were identified. These principal areas associated with each technology candidate requiring development have been briefly described in Table 6-2.

Table 6-1. Primary Technology Thrusts

Ranking	Technology Candidates	Primary Technology: System Design/ Development	Primary Technology: Sensors and Actuators	Primary Technology: Controllers/ Estimators	Primary Technology: Control System Simulation
1	On-board controllers for distributed systems	X		X	
2	Multiple processor systems for large structure control simulation				X
3	Sensing systems for shape control	X	X		
4	Distributed control actuators for large space systems		X		
5	Reduced-order controllers			X	
6	Robust adaptive controllers			X	
7	Symbolic manipulation methods for large structure control simulation				X
8	Environmental torquing systems for large space structures		X		
9	Rendezvous and docking sensors, actuators, and controllers		X		
10	Passive optical rendezvous systems		X		
11	Planetary and precision pointing technology	X	X	X	
12	Planetary antenna pointing and control development		X		
13	Sensors and actuators for manipulator control		X		
14	Inertial sensor technology		X		
15	Automated assembly technology development	X	X		
16	Automated manipulator system development		X		
17	Planetary atmospheric braking and flight control	X			
18	Advanced planetary landers/rovers		X		
19	Momentum bias systems for large orbiting systems		X		

Table 6-2. Primary Technology Thrusts and Development Areas of Technology Candidates

Technology Candidates	Primary Technology Thrust[a]	Principal Areas of Technology Development
1. On-board controllers for distributed systems	1,3	Comprehensive system models of distributed sensors, actuators, and controllers for large structure control. Integrated multiple processor system, with each processor providing local control in large flexible structures.
2. Multiple processor systems for large structure control simulation	4	A new computer architecture of multiple interconnected processors for high-order system simulation.
3. Sensing systems for shape control	1,2	System mechanizations, designs, and control law concepts for shape control. Sensing devices for measurement, alignment, and control of large precision structures.
4. Distributed control actuators for large space systems	2	New techniques and concepts for actuation devices for control torques and forces on large structure.
5. Reduced-order controllers	3	Model order reduction formulations for large structures and controller/estimator designs based on these formulations.
6. Robust adaptive controllers	3	Robust controller designs with reduced sensitivity and adaptive compensation for model errors in large and autonomous space systems.
7. Symbolic manipulation methods for large space structures	2	Advanced efficient methods of symbolic manipulation applicable to large structure control simulations.

(a) 1. System design and development
2. Sensors and actuators
3. Controllers/estimators
4. Control system simulation

Table 6-2. Primary Technology Thrusts and Development Areas of Technology Candidates (Continuation 1)

Technology Candidates	Primary Technology Thrust[a]	Principal Areas of Technology Development
8. Environmental torquing systems for large space structures	2	Effective and efficient orbital coupling actuation techniques using environmental disturbances to reduce on-board expendables and power requirements. Includes development of integrated system concepts.
9. Rendezvous and docking sensors, actuators and controllers	2	High-resolution docking sensors for orientation and ranging combined with video object tracking and/or pattern recognition algorithms.
10. Passive optical rendezvous systems	2	Optical sensor concepts combined with on-board control techniques for range and range-rate determination in autonomous rendezvous operations.
11. Planetary and precision pointing technology	1,2,3	Major advancements in attitude reference systems for precision pointing and control from earth orbit with 10^2 greater accuracy and stability. Advanced correlation, stellar, and inertial sensor concepts with performance of 10^3 greater than SOA. Precision instrument platform actuator concepts for planetary imaging with performance of 10^2 or greater than SOA. On-board controller/estimators with adaptive features for minimization of noise, and design for model uncertainties.
12. Planetary antenna pointing and control development	2	Advanced antenna pointing actuator concepts and mechanizations for 5X improvement in accuracy.

(a) 1. System design and development
2. Sensors and actuators
3. Controllers/estimators
4. Control system simulation

Table 6-2. Primary Technology Thrusts and Development Areas of Technology Candidates (Continuation 2)

Technology Candidates	Primary Technology Thrust[a]	Principal Areas of Technology Development.
13. Sensors and actuators for manipulator control	2	Advanced sensors for touch, force, vision, and proximity functions in large manipulator and rover systems and actuator devices for application to space assembly and handling of large structures.
14. Inertial sensor technology	2	Precision long-life, full-time inertial reference sensors for long-term (5-20 years) planetary missions.
15. Automated assembly technology development	1,2	Automated assembly system concepts for efficient and economical on-orbit construction or deployment of large space systems. Computer vision systems combined with advanced manipulation concepts for space assembly operations.
16. Automated manipulator system development	2	Effector mechanisms and special sensors combined with extensive control software for application to robust automated manipulators.
17. Planetary atmospheric braking and flight control	1	Adaptive flight control system with advanced on-board navigation and guidance technologies providing aerocapture of planetary vehicle.
18. Advanced planetary landers/rovers	2	Advanced sensors and software designs required in autonomous planetary landers/rovers. Includes dynamic control techniques and advanced 3D vision concepts for obstacle detection and avoidance for global navigation.

(a) 1. System design and development
2. Sensors and actuators
3. Controllers/estimators
4. Control system simulation

Table 6-2. Primary Technology Thrusts and Development Areas of Technology Candidates (Continuation 3)

Technology Candidates	Primary Technology Thrust[a]	Principal Areas of Technology Development
19. Momentum bias systems for large orbiting systems	2	Extended development of the annular momentum control device concept and associated software to wheels of 200-m-diameter for momentum and torque control of large space structures.

(a) 1. System design and development 3. Controllers/estimators
2. Sensors and actuators 4. Control system simulation

From the information contained in these tables the following comments and conclusions were evolved for use in forming the recommendations for technology development in pointing and control systems to enable future missions.

1. System Design and Development

The Large Space System Technology (LSST) program currently under development at several NASA centers is expected to cover technology candidates (TC)-1, -3 and most of -15. Other major thrusts in the systems area are in TC-11, and -17. Therefore, a system technology program is required to cover these three areas.

2. Sensors and Actuators

The LSST program is also expected to cover or be involved with sensor and actuator requirements for TC-3, -4, and parts of -8, -13, -15, and -19. All TC's from -8 through -16, and -18 and -19 involve major developments in the sensors and actuators with perhaps some commonality between them. A broad integrated program of development is required to address the sensor/actuator requirements for all the involved candidates with a focus on reducing the total effort through identification of commonality of requirements. Each of these programs will have a strong relationship with system design and constraints. Although only candidates -11 and -15 have been shown to also involve system development it is implied that a significant systems design and integration effort will be involved in the remaining candidate areas.

3. Controllers and Estimators

Work is planned in the LSST program which addresses TC-1 and -5, and a small part of -6, and -11. Therefore these later two candidates, which have very little commonality, will require controller/estimator developments.

4. Control System Simulation

TC-2 and -7 are not currently planned for development in the LSST program and therefore must be covered by future OAST development programs. These candidates represent an important complement to the control of all future systems characterized by large order structural models.

B. RECOMMENDATIONS

In the preceding discussion, four principal development areas associated with pointing and control system technology were examined to determine where the major technology thrust(s) are focused for each candidate technology development identified in the report. Inspection of the information shown in Tables 6-1 and 6-2 indicated that several thrusts for high-ranking candidates will be addressed to a large extent by the LSST program and are considered to be adequately covered by the LSST developments.

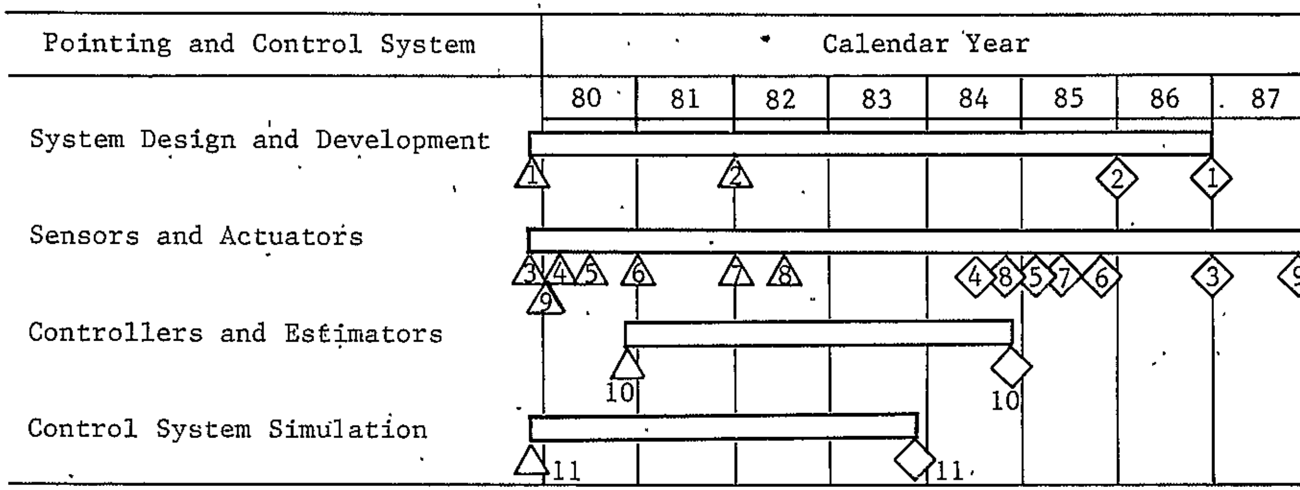
In the remaining candidate areas some commonalities exist which reduce the required development efforts and related resources. The remaining development programs coming out of this study for recommended development are based on pursuing these remaining candidates through developments within each of the four principal technology areas. Table 6-3 illustrates the four technology areas and the recommended development programs to be carried out over the 1980 to 1987 time period. Research and technology operating plans (RTOP's) are required in each principal area of pointing and control systems technology development to more fully describe the required development and their associated technical objectives and approach, and resource requirements. In lieu of these RTOP's, technical program summaries of these recommended programs have been prepared as part of this report and are contained in the following paragraphs. The cost to OAST to implement each of these advanced development programs is estimated at 200 K to 500 K per year, depending on the funding availability and NASA's commitment to moving rapidly to initiate the enabling development process for technologies required for future automated space systems.

Summaries of recommended technical programs are presented below.

1. System Design and Development

The long-range objective of this program is to develop and demonstrate the advanced system concepts capable of enabling communication,

Table 6-3. Recommended Pointing and Control System Development Program



1. Orbital Attitude Reference System Development for Precision Pointing and Control.

2. Planetary Atmospheric Braking and Flight Control System.

3. Advanced sensors and effector mechanisms development for robust automated manipulators and rover systems.

4. Optical sensor concepts for autonomous rendezvous, stationkeeping, and docking operations.

5. Precision antenna actuator concepts and mechanizations for planetary vehicles.

6. Advanced stellar-inertial sensor concepts for precision orbital pointing systems.

7. Orbital coupling actuation techniques development using environmental disturbance.

8. Inertial reference sensor development for long-life planetary missions.

9. Momentum bias systems for control of large space vehicles.

10. On-board adaptive controller/estimators for autonomous space systems.

11. Large space system control simulation methods and systems development.

Key △ Initiate activity

◇ Complete activity

radiometry, astrophysic, and planetary missions to achieve the precision pointing and flight control requirements demanded by these missions. Principal program targets are:

(1) Develop a planetary instrument pointing system capable of accuracies 2 orders of magnitude below current SOA (Galileo) by FY 84.

(2) Develop an adaptive flight control system with on-board navigation and guidance for aerocapture of a planetary vehicle to greatly reduce vehicle mass and increase payload by FY 85.

(3) Develop earth-pointing systems with accuracy improvements of 1 to 3 orders of magnitude beyond today's capability (Landsat-D) by the end of FY 86.

2. Sensors and Actuators

Control sensor and actuator technologies required to enable the large variety of future autonomous systems will involve many new concepts beyond today's state of the art. Efficient actuation methods, by coupling to the earth's environment and conserving vehicle momentum, will lead to long-life systems. Automated manipulators, roving vehicles, and rendezvous and docking systems for carrying out repair and servicing of space vehicles, or exploring a planetary surface place new demands on special mechanisms and advanced sensor technologies. New precision pointing systems from deep space and earth orbit will, in turn, require significant improvements in reference sensor systems to enable communications and observation missions. Principal program targets are as follows:

(1) Demonstrate advanced optical sensor concepts combined with on-board control techniques for autonomous rendezvous, stationkeeping, and docking operations by mid-FY 84.

(2) Develop precision pointing systems with 5X improvement for planetary communications and up to 10^3X improvement for earth-orbital missions by FY 85.

(3) Demonstrate technology readiness for a precision long-life inertial reference sensor concept for 5- to 20-year planetary missions by FY 85.

(4) Develop effective and efficient orbital coupling actuation techniques using environmental disturbances by mid-FY 85.

(5) By FY 87, develop effector mechanisms, special sensors, and associated software for application to robust automated manipulators and to roving vehicle systems.

(6) Develop an advanced momentum bias system with storage capacity in excess of 2×10^5 N-m-sec for control of large space vehicles by the end of FY 87.

3. Controllers and Estimators

Future space vehicles, including earth orbiters and deep-space planetary missions, will require more autonomy in achieving precision control. These high-order systems must use reduced-order models to minimize on-board computations. Inherent in a reduced-order model are model errors. The objective of this program is to develop on-board robust adaptive controllers and estimator designs. Robustness implies the system is tolerant or less sensitive to model errors and changes in parameters. To be adaptive the controller must compensate for the model errors. Principal program targets are:

(1) Develop system identification and adaptive control formulations for autonomous vehicles by FY 83.

(2) Mechanize and evaluate advanced controller/estimator concepts by FY 84.

(3) Conduct in-flight and/or ground test adaptive control demonstrations of concepts on a representative vehicle by FY 85.

4. Control System Simulation

The objective of this program is to develop a new computer architecture and symbolic manipulation methods to provide the requisite capability for a detailed control system simulation before launch of large space vehicles. Simulation of these vehicles on today's ground-based computers cannot be performed adequately because of excessive computational time. Large space systems scheduled for launch as early as 1985 are too costly to commit to flight without a comprehensive control system evaluation via simulation of the entire vehicle. Principal program targets are:

(1) Develop advanced processor system concepts and symbolic manipulation methods by FY 82.

(2) Perform control simulations using processor system software and manipulator methods on a representative large system to validate technology by FY 84.

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APPENDIX A

REPRESENTATIVE MISSION SET

Table A-1. Representative Mission Set

	Mission	Ref.
	Earth Monitoring	
1.	Stormsat	16,29
2.	Geodetic Survey	2,16
3.	Automated Atmospheric Physics	28
4.	All-Weather Survey	2
5.	Sea Survey -- High Resolution	28
6.	Geologically Oriented Satellite System (GOSS)	2,4
7.	Energy Monitoring	4,28
8.	Global Crop and Forecasting	2,4
9.	Disaster Warning	2
10.	Pollution Control	4
11.	Search and Rescue Operational System (SOS)	16
12.	Earth Radiation Budget Satellite System (ERBSS)	16
13.	Fire Detection and Control Satellite	11
14.	Stereosat	16
15.	Halogen Occultation Experiment (HALOE)	16
16.	Landsat H	26
17.	Advanced Resources/Pollution Observer	11
18.	Storm Monitor	4
19.	Earthquake Monitor	4
20.	Large Aperture Space Antenna (LASA)	15,4
21.	Soil Moisture Satellite (SOMOSAT)	30
22.	Gravity Wave Detector	30
23.	Earthwatch	26
24.	GEOS	26
25.	Texturometer	26
26.	Thermal Inertia Mapper (TIM)	26
27.	Radar Holographer	26
28.	Microsat	26
29.	Parasol Radiometer	26
30.	Radar Ellipsometer	26
31.	Ferris Wheel Radar	26
32.	Sweep Frequency Radar	26
33.	Geosynchronous SAR	26
34.	Satcloud	26
35.	Magsat II	26
36.	Gravsat II	26
37.	Radsat	26
	Communications	
1.	Electronic Mail	4
2.	Global Communications	2
3.	Global Navigation	2
4.	Orbiting Deep Space Relay Satellite (ODSRS)	15,30
5.	K_a-Band Antenna	30

Table A-1: Representative Mission Set (Continuation 1)

	Mission	Ref.
	Communications (contd)	
6.	Mobile Communications Satellite (MOBCOMSAT)	15
7.	Public Services Satellite (PSS)	16,29
8.	Advanced TV Broadcast Satellite	11
9.	3D Holographic Teleconferencing	11
	Planetary Flyby, Orbiter, Probes	
1.	Halley Flyby Tempel 2 Rendezvous	2,3
2.	Asteroid Multiple Rendezvous	3
3.	Saturn Uranus Probe (SUP)	30
4.	Saturn Orbiter Dual Probe (SOP^2)	3
5.	Mercury Orbiter (MeO)	3
6.	Uranus Orbiter/Probe (UOP)	3
7.	Jupiter Pluto Flyby	3
8.	Jupiter Neptune Flyby	3
9.	Planetary Surface Contour	4
10.	Mars Geochemical Orbiter	4
11.	Pluto Flyby Interstellar	30
12.	Uranus-Neptune Flyby with Probes	30
13.	Jupiter Orbiter/Buoyant Station	30
	Planetary Landers and Sample Return	
1.	Mars Sample Return (MSR)	2,3
2.	Automated Planetary Station	2
3.	Jupiter Orbiter Satellite Tour/Lander (JOST/Lander)	3
4.	Comet Sample Return	3
5.	Asteroid Sample Return	3
6.	Mars Rover/Explorer	10
7.	Venus Rover/Explorer	10
8.	Mercury Lander/Rover/Orbiter	10
9.	Venus Surface Sample Return	10
10.	Mercury Surface Sample Return	10
11.	Venus Large Lander	10
12.	Automated Mobile Lunar Surface Survey	2
13.	Galilean Satellite Rendezvous and Landing	30
14.	Mars Surface Exploration	30
15.	Automated Lunar Base/Rovers	30
16.	Titan Lander and Surface Exploration	30
17.	Jupiter Surface Exploration	30
18.	Extraterrestrial Resource Recovery Mission	30
19.	Venus Lander/Balloon	30
20.	Viking Mobile Lander	30
21.	Automated Precursor Processor	2

Table A-1. Representative Mission Set (Continuation 2)

	Mission	Ref.
	Astrophysics	
1.	Automated Space Laboratory	2
2.	Advanced X-Ray Astrophysical Facility (AXAF)	2,18
3.	Cosmic Ray Observatory (CRO)	2,18
4.	Gamma Ray Observatory (GRO)	2,18
5.	X-Ray Explorer	16,18
6.	X-Ray Observatory (XRO)	18
7.	Large Area Modular Array of Reflectors (LAMAR)	18,20
8.	Ultraviolet Photometric Polarimetric Explorer (UPPE)	16,18,20
9.	UV Optical Interferometer (UVOI)	18,20
10.	Large Ambient Deployable IR Telescope	18,20
11.	Orbiting Submillimeter Telescope	18,20
12.	Orbiting Very Long Baseline Interferometry (VLBI)	18,15
13.	Gravity Probe B	18
14.	Orbital Test of the Equivalence Principle	18
15.	Gravity Wave Interferometer (GWI)	18
16.	Astrophysics Transient Explorer (ATREX)	16
17.	International X-ray and Extreme Ultraviolet Explorer (IXEE)	16
18.	International X-ray Astrophysics Explorer (IXAE)	16
19.	Spaceborne Antenna and Microwave System (SAMS)	27
20.	8-meter Space Telescope	25
21.	2.5-meter X-Ray Observatory	25
22.	HEAO-C	2
23.	Search for Extraterrestrial Intelligence (SETI)	14,15
24.	Very Long Baseline Interferometry	15
25.	Space-Based Radio Telescope	2
	Solar-Terrestrial	
1.	Solar Cycle and Dynamics Mission (SCADM)	17
2.	Solar Probe	17
3.	Pinhole Satellite	17,19
4.	Solar Terrestrial Observatory	17
5.	Interplanetary Physics Laboratory (IPL)	17
6.	Geomagnetic Tail Laboratory (GTL)	17
7.	Polar Plasma Laboratory (PPL)	17
8.	Equatorial Magnetosphere (EML)	17
9.	Automated Solar Observatory	17
10.	Hawkeye II	16,17
11.	Active Magnetospheric Particle Tracer Experiment (AMPTE)	16,17
12.	Origin of Plasmas in the Earth's Neighborhood (OPEN)	17

Table A-1. Representative Mission Set (Continuation 3)

Mission	Ref.
Space Power	
1. Solar Power Satellite (SPS), Photovoltaic Array	2
2. SPS, Laser Transmission	4,14
3. Space Power Relay Satellite	4,14
Space Transportation	
1. Solar Electric Propulsion Stage	2
2. High-Energy Orbital Transfer Vehicle (OTV)	2
Miscellaneous	
1. Free-Flying Manipulators	30
2. On-Orbit Robotic Manipulator	31

APPENDIX B

CANDIDATE TECHNOLOGY DEVELOPMENT PROGRAM DESCRIPTIONS

TECHNOLOGY DESCRIPTION

Candidate Technology: On-Board Controllers for Distributed Systems

Mission Requiring Technology (From Generic Mission Set): Solar power satellites, large space antenna, large space structures.

Description:

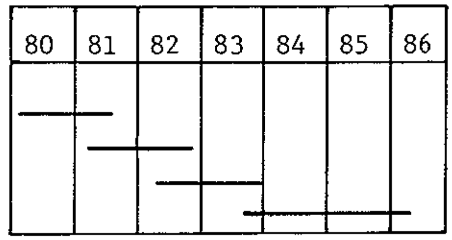
As space structures become larger and more flexible, the dynamic models for those structures become more complex. For a closed-loop control system to maintain a high level of performance for such a structure, distributed actuators and distributed sensing systems will be required. This leads rather quickly to requiring a huge amount of on-board computational power in order to process the vast amount of sensor data, accurately and dynamically model the physical system, and output the proper control. By today's standards, this need is paramount to operating a real-time simulation facility for a complex structure in orbit, and with today's flight computers this is not possible. Using the Voyager mission as an example, a 3-axis model including 24 flexible appendage modes and a good model of the thruster dynamics could be simulated, but only at the rate of 10 to 100 sec of computer time to 1 sec real time. Presumably, the controllers for large space structures will be much more complicated than this, and yet they must operate in real time.

An alternate approach to building a more massive super computer which must model the entire structure and process sensor and actuator data from the entire structure is to distribute the processing power. In this mode of operation, each of many processors is responsible only for processing local sensor data, outputting commands to nearby actuators, modeling a local portion of the overall structure, and making a small part of its information available to immediately adjacent processors. Advantages of this implementation method are (1) a reduction of the total computational work load due to the improved problem formulation, (2) an easing of the individual processor speed and storage requirements due to the distributed nature of the controller, and (3) a single processor failure in a distributed control system will not terminate the mission.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

System requirements defined
Concept develop/tradeoffs
Model developments
Test and evaluation



Alternate Solutions: None.

TECHNOLOGY DESCRIPTION

Candidate Technology: Multiple Processor Systems for Large-Structure Control Simulation

Missions Requiring Technology (From Generic Mission Set): Large space systems.

Description:

Comprehensive control system simulation is a prerequisite to the launch of any space vehicle, especially large space structures. Due to the intricacy and complexity of the dynamics and control of these large structures, the control simulation requirements increase substantially (perhaps a factor of 50 for even the smallest of the large space structures) over the requirements for missions such as Voyager and Viking. It was not uncommon for a single detailed simulation on one of these past missions to require hours of general-purpose computer time. To further illustrate the control simulation problem with these missions, 10 to 100 seconds of computer time were required to simulate 1 second of real time.

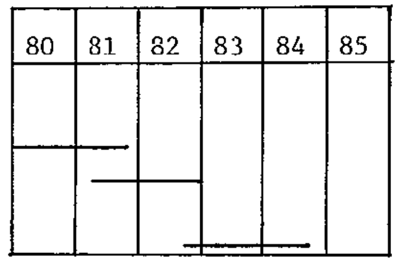
A new computer architecture, that of multiple interconnected mini- or microprocessors, would greatly reduce the control simulation computation time and would be required to make feasible the simulation of future large space systems. Distinct interconnected mini- or microprocessors would be responsible for simulating portions of the overall system with a reduction in computer time roughly proportional to the number of parallel processors. Carried to an extreme, simulation of a single finite element, with all its nonlinearities, and control and disturbance forces could be performed on a single processor. Many of these processor subsystems could be interconnected in an appropriate way to represent the entire vehicle.

The value of the concept of parallel interconnected microprocessors has been demonstrated using only a few microprocessors, with such systems often outperforming the huge general-purpose computers in terms of computation time.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

Parallel processor system technology development
Software development for parallel processors
Control simulation software using parallel processors



Alternate Solutions: None. See Symbolic Manipulation Methods Technology Candidate for related development.

TECHNOLOGY DESCRIPTION

Candidate Technology: Sensing Systems for Shape Control

Missions Requiring Technology (From Generic Mission Set): Global communications system, electronic mail, sea survey system, space-based radio telescopes.

Description:

The main application identified for surface sensing systems is in use on large (10-100 m-diameter) space antennas. Some requirements for large antenna missions demand high-frequency operation in the 1-Ghz to 300-Ghz range. This high-frequency requirement demands high surface accuracy on the order of .1 to .001 inches RMS. Also, due to the large antenna diameter, the beamwidth will be quite narrow, on the order of arc seconds, and therefore very accurate pointing is required. The antenna requires a surface measurement system for several reasons:

1. The RMS surface accuracy must be verified.
2. The RF boresight must be established accurately for pointing control of the narrow beamwidth.
3. The RF focal point must be established accurately for placement of the feed array. Otherwise, large gain losses would be possible due to the narrow beamwidth.
4. The surface shape may need adjusting to correct for surface deviations.

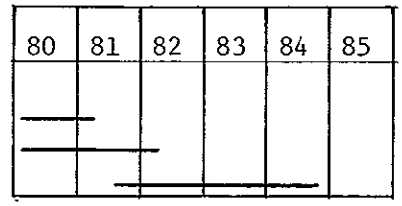
How System is Applied:

The surface measurement system will survey the surface by making a number of point measurements or scan a locus of points on the surface of the reflector. The coordinates of the points will be determined with respect to some reference and then used to compute the RMS surface error. Localized surface errors may be determined by comparison of measurement coordinates with coordinates of the best-fit paraboloid. This information could then be fed to a surface control system. From the equation for the best-fit paraboloid, the direction of the rf boresight and the location of the focal point are known. This information can be used for antenna pointing and feed translation control respectively. The RMS surface error is used to determine antenna gain loss due to the surface deviations.

Related Activities (RTOP No. and Title): Large Space Antenna Technology RTOP No. 524-70-05, PPACT RTOP No. 506-19-15.

Development Schedule (By Fiscal Year):

Analysis/computer program
Hardware feasibility
Flight hardware



Alternate Solutions: None.

TECHNOLOGY DESCRIPTION

Candidate Technology: Distributed Control Actuators for Large Space Systems

Missions Requiring Technology (From Generic Mission Set): Global communications system, Sea survey system, Space-based radio telescopes

Description:

Large space systems will typically be very lightweight structures because of the high cost penalties associated with launching large payloads. These structures present a new class of problems to such systems as attitude control as indicated in the following examples:

1. A large, lightweight structure will tend to be quite flexible. Control torques or forces would cause structural distortion and induce large oscillations if control is not distributed. Although light in weight, these structures will be characterized by large inertias leading to large torque requirements. The structure may not be able to support the stress of very large localized control torques.

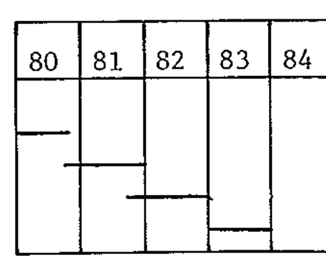
2. Shape control will be critical for vehicles such as large space antennas. Surface distortions due to thermal gradients represent a global problem.

A solution to these problems will involve new techniques and concepts utilizing the distribution of actuation devices for control torques and forces.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

Systems requirements
Actuator requirements and concept design
Detail design and BB development
Engineering model development and test



Alternate Solutions: Prohibitively heavy structure would be required with conventional actuation methods.

TECHNOLOGY DESCRIPTION

Candidate Technology: Reduced-Order Controllers

Missions Requiring Technology (From Generic Mission Set): Large space systems (e.g., global communication, electronic mail, space power satellite, etc.).

Description:

Modeling for controller design has been identified as a major problem in achieving precision attitude, shape, etc., control of large structures planned for the 1980s and beyond. The modeling problem for large structures is critical because of vehicle size and flexibility leading to potentially large model errors. The dynamical models used in a large structure control system will be at best reduced-order representations of the structure because: (1) large structures are in general infinite-dimensional and therefore cannot be characterized fully by any finite-dimensional model and (2) model order reduction is required to minimize on-board computations. The main objective of model order reduction for controller design is to systematically search for the best reduced structural model while, at the same time, retaining the significant structural dynamics. An additional objective is to design systems (estimators, controllers, ect.) based on these models.

A wide range of approaches for reduced-order controller design is potentially applicable to the control of flexible space vehicles. The idea of aggregation provides a conceptual framework to develop models with a coarser dynamical description state space than the original models. On the other hand, singular perturbation separates the system into a set of low and fast modes. Aside from aggregation and singular perturbation, other approaches have been suggested, such as truncation based on eigenvalues and eigen vectors and on controllability and observability. However, currently available theory is not sufficient, and the need for precision control of large flexible vehicles is now a main driver for further developments in the definition of new approaches and applications for model order reduction and reduced-order controller design.

Related Activities (RTOP No. and Title): None.

Development Schedule: (By Fiscal Year):

Task	80	81	82	83	84
Model order reduction formulations for flexible space vehicles	—				
Reduced-order controller designs for reference configurations		—			
In-flight and/or ground-test performance demonstration			—		

Alternate Solutions: Controller design based on ad hoc approaches and procedures, leading possibly to in-flight surprises (e.g., marginal performance, anomalies, etc.) caused by deficient designs.

TECHNOLOGY DESCRIPTION

Candidate Technology: Robust Adaptive Controllers

Missions Requiring Technology (From Generic Mission Set): Large space systems, deep-space planetary missions, autonomous space vehicles.

Description:

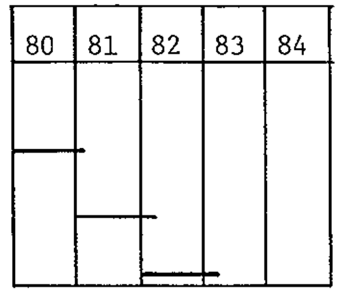
Modeling for controller design is a persistent problem in achieving precision control of a wide range of space vehicles. Controller models are always of a reduced-order because (1) space vehicles are, in general, ∞ dimensional and therefore cannot be characterized fully by any model (2) model order-reduction is required to minimize on-board computations. Inherent in a reduced-order model are model errors such as parameter uncertainties, truncated dynamics, internal disturbances, and neglected nonlinearities. Therefore robust controller designs must be developed with reduced sensitivity to modeling errors and with the capability to provide vehicle autonomy by adapting and compensating for the model errors.

A wide range of approaches for parameter-insensitive and adaptive designs are potentially applicable for space vehicle controller design. The methods of system identification (e.g., least-squares, maximum-likelihood, etc.) provide a powerful set of analytical tools for in-flight identification of dynamical models and for adaptation to their deficiencies. Promising results also exist in the area of model error estimation, where the main objective is to estimate a model error vector that is a lumped representation of errors in the models. However, currently available theory in these areas cannot guarantee the successful design of a fully autonomous vehicle control system. In order to solve the control problems peculiar to the next generation of space vehicles (e.g., large size, system uncertainty, autonomous operations, etc.) both the application of currently available theory and the definition and development of new concepts and approaches in system identification and adaptive control are required.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

System identification and adaptive control formulations
Numerical search subroutines for system identification/adaptive control
In-flight and/or ground test adaptive control demonstrations with reference configuration



Alternate Solutions: Increased ground-based mission operations support may provide a partial solution while vehicles are near earth.

TECHNOLOGY DESCRIPTION

Candidate Technology: Symbolic Manipulation Methods for Large Structure Control Simulation

Missions Requiring Technology (From Generic Mission Set): Large space systems.

Description:

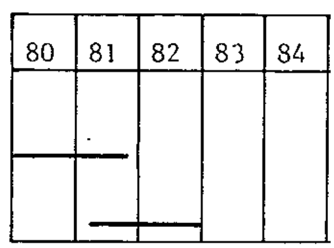
Detailed control simulation of a space vehicle is a prerequisite before launch. Simulation of large space structures on today's large general-purpose computers cannot be performed adequately because of excessive computation time. Advanced symbolic manipulation methods are required to generate more efficient source codes for control simulation problems. Lengthy system equations (which are too tedious to derive by hand) can be first coded by breaking the computation into many simple steps (as is usual) followed by the symbolic manipulator to expand series, make substitutions, combine like terms, analytically differentiate and integrate complex expressions, and, finally, compile the resulting code into a sequence of operations which are executed much faster than the original code. Some symbolic manipulators already exist, limited mainly by their library storage facilities. Development of advanced methods will expand this library; for example, increasing the functions that can be analytically differentiated or integrated. To be most useful the symbolic manipulation methods developed must, in themselves, be efficient such that they retain only important quantities in the manipulation process to reduce the total text.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

Methods development for advanced symbolic manipulators

Apply and validate manipulators to control simulation problems



Alternate Solutions: None. See Multiple Processor Systems Technology Candidate for related development.

TECHNOLOGY DESCRIPTION

Candidate Technology: Environmental Torquing Systems for Large Space Structures

Missions Requiring Technology (From Generic Mission Set): Large radio telescopes, space power systems, large radiometers.

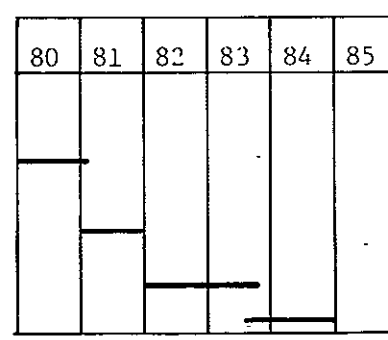
Description:

Large space systems in earth orbit will be subject to large environmental forces and torques. Control of vehicle attitude in the presence of these disturbances requires large mass expulsion or momentum storage systems unless the vehicle is configured to minimize disturbance effects or use the disturbance sources for control. Disturbances may include solar pressure, gravity gradient, gravity anomaly, aerodynamic, thermal, electromagnet orbital coupling with structure and others. Effective and efficient use of these disturbances is required to reduce the large burden of on-board expendables and/or large power requirements to drive prime movers.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

Define disturbance sources and concepts for A/C use
Define vehicle design guidelines to minimize disturbances
Develop hardware component designs and areas of applicability
Develop BB models and test



Alternate Solutions: Large mass expulsion systems and/or large momentum storage devices.

TECHNOLOGY DESCRIPTION

Candidate Technology: Rendezvous and Docking Sensors, Actuators, and Controllers

Missions Requiring Technology: Sample return (Mars, Comet, asteroid) missions, cooperative two-vehicle problem.

Description:

The missions indicated will require the capability for automated rendezvous, stationkeeping, and docking activities. There is a need for sensor development to support each area, especially for stationkeeping and docking. These areas involve the problem of determining vehicle-to-vehicle relative position and orientation and the necessity of "acquiring" from arbitrary orientations. Docking sensors must provide high-resolution orientation and ranging without interfering with with the docking mechanism itself.

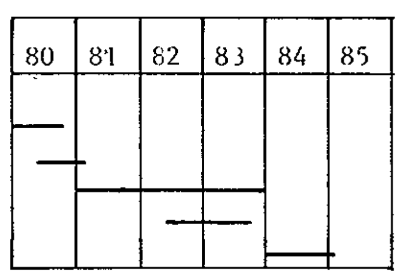
Possible advanced technology to be applied to these problems lies in the fields of scanning laser radar development or CCD cameras combined with video object tracking and/or pattern recognition algorithms.

Scanning laser radar has been under development for laboratory demonstrations and earth-based applications since the early 1970's, but application to flight programs has not been investigated sufficiently. Object tracking and pattern recognition algorithms are a state-of-the-art development but require substantial work before becoming flight ready.

Related Activities (RTOP No. and Title): RTOP's not known. Some work is ongoing at ITT and Norden on laser radar development.

Development Schedule (By Fiscal Year):

Requirements study
Tradeoff of concepts
Algorithm and software development
Hardware development
Test and evaluation



Alternate Solutions: Conventional RF radar systems (e.g., Apollo) may have some application, but they are considered too heavy, as well as lacking precision for close-in work required for stationkeeping.

TECHNOLOGY DESCRIPTION

Candidate Technology: Passive Optical Rendezvous Systems

Missions Requiring Technology: Automated assembly (non-Shuttle orbits), GEO rendezvous, satellite retrieval.

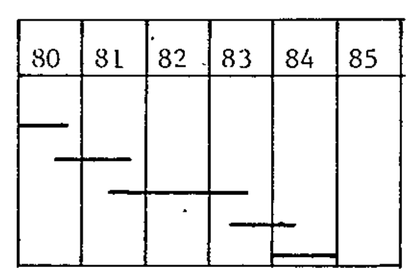
Description:

Many earth-orbital missions for the 1980's and 1990's have been conceived which require rendezvous operations over ranges of perhaps 80 km to 300 meters with passive targets that are not fitted with laser retro-reflectors or RF transponders. Rendezvous with such targets using range and range-rate information combined with on-board control techniques will significantly enhance the rendezvous problem as compared to using classical orbit determination methods with costly ground assistance and development of sensors, algorithms, and procedures which demand angular measurements. These new on-board techniques for data acquisition and real-time filtering must be developed together with control laws based on the use of a different type of information.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

System requirements
Conceptual design and tradeoffs
Algorithm development
Software development
Flight test engineering model



Alternate Solutions: Rendezvous can be accomplished using ground-based radar and computational facilities. This is cumbersome and wasteful of ground capability.

TECHNOLOGY DESCRIPTION

Candidate Technology: Planetary and Precision Pointing Technology

Missions Requiring Technology (From Generic Mission Set): All earth-orbiter missions, Saturn orbiter, automated planetary station.

Description:

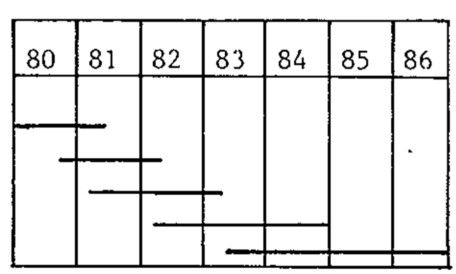
Precision pointing requirements of future earth and planetary missions represent a significant advance beyond current SOA technology. The current SOA in pointing accuracy and stability is represented by the LANDSAT-D requirement of 36 $\widehat{\sec}$ and ~ 1 $\widehat{\sec}$ respectively for earth observations; space telescope requirements of ~ 0.1 $\widehat{\sec}$ and 0.007 $\widehat{\sec}$ respectively for astrophysics; and 600 $\widehat{\sec}$ and 4 $\widehat{\sec}$ respectively for the dual-spin Galileo planetary spacecraft. These requirements are expected to tighten by 2 to 3 orders of magnitude, before the end of the century, for advanced missions. Likewise, for planetary missions, science instrument pointing accuracy will move from the current level to below 10 sec, with stability approximately 2 orders of magnitude lower.

Achievement of future earth-orbiter pointing requirements will depend on major improvements in stellar-inertial attitude reference systems. These systems determine attitude with respect to a star-referenced inertial frame based on an on-board star catalogue for automatic star selection during orbit. This inertial frame must be transformed to a rotating earth-centered reference using continuous satellite emphemeris data. Therefore the reference system requires advanced attitude sensors, i.e., sub-arc-second star tracker and correlation/feature trackers, combined with on-board controllers and estimators which autonomously transform the star-referenced inertial frame to the rotating earth centered reference with high precision. The performance of these systems will be primarily limited by the accuracy and noise of attitude sensors, and the accommodation of uncompensated structural and thermal stability of the satellite.

Related Activities (RTOP No. and Title): 506-19-15 Precision Pointing and Control Technology.

Development Schedule (By Fiscal Year):

Functional requirements
Performance eval/tradeoff criteria
Mechanization concepts
Performance eval and concept selection
New technology development



Alternate Solutions: None.

TECHNOLOGY DESCRIPTION

Candidate Technology: Planetary Antenna Pointing and Control

Missions Requiring Technology (From Generic Mission Set): Saturn orbiter dual probe, Uranus-orbiter probe, Jupiter Neptune

Description:

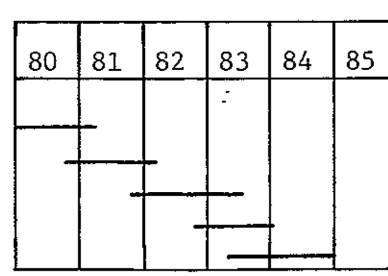
High data rates, combined with simultaneous receiving and transmitting at two frequencies on future planetary programs, require large improvements in spacecraft antenna pointing and control. As referenced from the present Galileo spacecraft communication system, future performance requirements will necessitate 5- to 15-meter high-gain antennas to be pointed with an accuracy of better than 0.05 degrees, a greater than 5X improvement over Galileo's 4.8-meter antenna, and 30-dB greater gain. Precision pointing and control of these antennas to provide receiving or transmitting data rates of 100 kpbs at planets Uranus or Pluto require development of integrated communication and control systems utilizing advanced concepts in electronic beam steering, such as closed-loop monopulse control to achieve the required objectives.

Three-axis and spin control of planetary spacecraft present different control problems to precision pointing because of dynamic relationships. Dual-spin spacecraft pointing capabilities, as represented by the Galileo spacecraft and the three-axis control system on Voyager, are grossly inadequate for planetary mission requirements ahead. Control system combined with communication system developments will be critical to satisfying these requirements.

Related Activities (RTOP No. and Title): 506-19-15.

Development Schedule (By Fiscal Year):

System requirements and concept development
Advanced sensors
Control estimators
Beam steering control
Test and evaluation



Alternate Solutions: Alternative solutions with higher-power spacecraft transmitters, more sensitive DSN receivers, etc., are not adequate to achieve required system performance.

TECHNOLOGY DESCRIPTION

Candidate Technology: Sensors and Actuators for Manipulator Control

Missions Requiring Technology (From Generic Mission Set): Automated planetary station, on-orbit robotic manipulator.

Description:

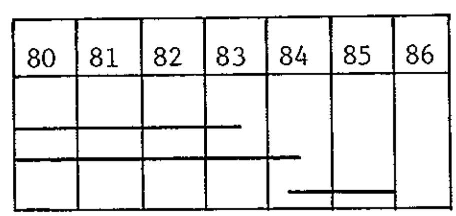
Large manipulators will be required to perform many of the operations for large space assemblies now being planned. Large manipulator technology does not presently exist. Control of such devices may require significant extensions to current technology.

Further development is necessary to obtain adequate touch, force, and proximity sensors for manipulator hands. The development of visual sensors is also necessary but will be done as part of the Mars rover technology development. Actuator systems must be designed for application to the assembly and handling of large structures.

Related Activities (RTOP No. and Title): RTOP 506-19-35 Robotics/Machine Intelligence: Automated Systems.

Development Schedule (By Fiscal Year):

Sensor developments
Actuator system development
Integration and test



Alternate solutions: None.

TECHNOLOGY DESCRIPTION

Candidate Technology: Inertial Sensor Technology

Missions Requiring Technology (From Generic Mission Set): Global communication satellites, sea-survey system, space-based radio telescope, Saturn orbiter, automated planetary station, and others.

Description:

The missions listed above have durations of 5 years or longer; some are 10 and 20 years. Inertial reference sensors should have the capability for full-time operation. Mechanical gyros can support these missions, but only in a limited way through redundancy and other considerations.

The fiber optics rotation sensors (FORS) based on the use of a closed-loop fiber optic interferometer as an inertial reference may provide a solution. The concept has been investigated by JPL. It can provide full-time use and an order-of-magnitude improvement in rate sensitivity and position error when compared with spun mass and ring laser gyros. In a hybrid control system using FORS and inputs from celestial references as well, very tight pointing accuracy and control are available.

Related Activities (RTOP No. and Title): 506-19-15, Precision Pointing and Control Technology.

Development Schedule (By Fiscal Year):

	80	81	82	83	84
Breadboard development and test	—	—			
Engineering model design, fabrication, test		—	—	—	

Alternate Solutions: Redundant rotating mass gyros used sequentially are required to achieve lifetime; also, very expensive classified military gyros may come closer to satisfying requirements.

TECHNOLOGY DESCRIPTION

Candidate Technology: Automated Assembly Technology Development

Missions Requiring Technology (From Generic Mission Set): Communication satellites, electronic mail, solar power satellites, radio astronomy satellites.

Description:

Many candidate space projects of the shuttle era, the 1980's and 1990's, involve the on-orbit assembly or deployment of large structures. There is a need to reduce the amount of human intervention traditionally required for assembly and construction tasks, and to determine where human intervention is necessary and appropriate. Assembly using automation/teleoperator technology is itself an area of current research, even for ground-based applications and under very limited varieties of geometrical arrangements and constraints. When extrapolated to the space environment, such problems as the lack of gravity and many sources of friction to provide stability, the extremely large size and relatively great flexibility of planned structures, the effects of orbital dynamics on separated elements, the complete three-dimensionality of all motions, thermal extremes, etc., pose real and extensive challenges for space construction programs. Many ideas and concepts have been generated in the assembly technology areas, but the necessary research to carry these concepts through to practice, and to verify their ultimate utility, has not been done. The ultimate payoff for completion of a technology development program in this area would be the development of an automated assembly capability that would allow the construction of large space platforms that would be both cheaper and more extensive than would be the case of using a primarily manual approach to the task. Applications of computer vision systems combined with advanced manipulators are key technologies to this development.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

	80	81	82	83	84	85
Review SOA and development concepts	—					
Hardware/software concepts development		—	—	—		
Engineering model flight test					—	

Alternate Solutions: The only alternate approach to increasing our capability to perform automated assembly tasks is to rely on "traditional" manual construction techniques. These, of course, also require development for orbital work.

TECHNOLOGY DESCRIPTION

Candidate Technology: Automated Manipulator System Development

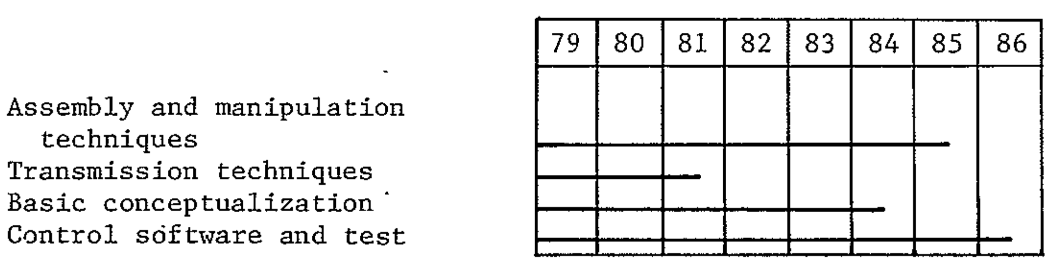
Missions Requiring Technology (From Generic Mission Set): On-orbit robotic manipulation, automated planetary station.

Description:

Automated manipulators can be used to assemble structures in space, aid in space processing, and be used for repair and servicing of other equipment. Such systems are composed of effector mechanisms, sensors, computational hardware, and extensive software for control and sequencing. Humans communicate with such systems through specially designed software interfaces that permit specification of desired actions. Then a "supervisory program" issues sequences of commands to the various subcomponents at the system. Adequate sensors and processing of sensory data are essential for robust performance.

Related Activities (RTOP No. and Title): 506-19-35, Robotics/Machine Intelligence: Automated Systems.

Development Schedule (By Fiscal Year):



Alternate Solutions: None, except through EVA.

TECHNOLOGY DESCRIPTION

Candidate Technology: Planetary Atmospheric Braking and Flight Control

Missions Requiring Technology (From Generic Mission Set): Mars rover, Mars sample return.

Description:

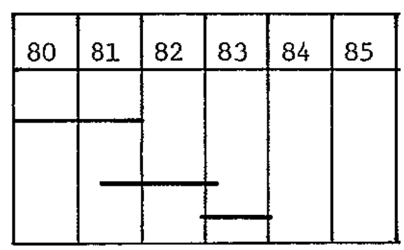
Planetary orbiters on landers must remove the spacecraft approach velocity, either propulsively or by using atmospheric braking. Generally, the large propulsive orbital injection mass required to enable these orbiter missions is excessive, making it impractical to inject into an acceptable interplanetary trajectory. Atmospheric braking can be achieved by precisely guiding the vehicle along an entry corridor and controlling the atmospheric entry lift vector. These controls can greatly reduce vehicle mass and increase payload.

Planetary atmospheric braking and flight control require advanced developments in on-board navigation and guidance and adaptive on-board flight control technologies.

Related Activities (RTOP No. and Title): None.

Development Schedule (By Fiscal Year):

System requirements for atmospheric entry
Conceptual design and hardware/software development
System simulations and verification tests



Alternate Solutions: Space-storable propulsion system for orbit injection.

TECHNOLOGY DESCRIPTION

Candidate Technology: Advanced Planetary Landers/Rovers

Missions Requiring Technology (From Generic Mission Set): Mars rover, automated planetary station, Mars sample return.

Description:

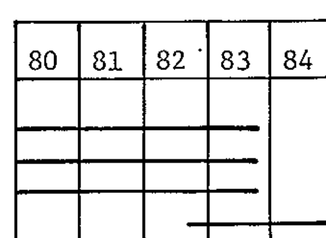
The effectiveness of landers can be increased by making them more autonomous and mobile. Autonomy reduces the impact of communications limitations and allows for a more timely operation of the lander or rover. Mobility permits a much larger portion of the planet to be explored.

Autonomous roving will require development of techniques for obstacle detection and avoidance for both local and global navigation. Global navigation may require the rover to travel to a particular longitude and latitude. While this might easily be accomplished using celestial references, it must be integrated with a local navigation operation of avoiding rocks, ditches or canyons, and steep grades and selecting paths. Obstacle detection necessitates further developments in computer vision technology, e.g., computer decisions based on TV images. Three-dimensional vision must be improved, possibly by use of stereo TVs or by coordinating a laser rangefinder with a TV. The long processing times needed for visual information must be reduced. This might be achieved by development of preprocessors for visual data control. Techniques and algorithms which use the visual information must also be developed for the dynamic control of the rover or manipulators.

Related Activities (RTOP No. and Title): RTOP 506-19-35 Robotics/ Machine Intelligence: Automated Systems.

Development Schedule (By Fiscal Year):

Three-dimensional vision
Data-processing systems
Obstacle avoidance/path planning
System integration and test



Alternate Solutions: None.

TECHNOLOGY DESCRIPTION

Candidate Technology: Momentum Bias Systems for Large Orbiting Systems

Missions Requiring Technology (From Generic Mission Set): Large space systems.

Description:

Pointing and attitude control of large space systems must be provided by means other than those using chemical propellants or ion expulsion to reduce excessive moment loads on the system, reduce the dependence on expendables, and reduce complexities of distributing large numbers of thrusters with associated propellant lines or power supplies, etc. Momentum storage requirements, in excess of 2×10^5 N-m-sec are required, together with devices capable of large distributed moments. A solution appears to be available by extension of the annular momentum control device (AMCD) under development at LaRC. The AMCD is a single wheel supported at three circumferential stations. LaRC is extrapolating the AMCD technology to the dual-wheel concept for large structures with wheels of 200 m diameter, counter-rotating, which are attached electromagnetically to the back of a large reflector (300 m) using 24 support stations. Station rotating moments are transmitted to the platform at points distributed along the outer circumference of the wheels. This technology is currently in the conceptual design phase, but is required to be taken to an inspace demonstration to establish technology readiness. Initial efforts required involve analysis of the structural/control interactions and evolving control schemes to account for imperfections in manufacture and assembly and to the stabilization of the wheels. These schemes must be verified using analytical simulations and an existing laboratory model. Construction of a larger laboratory model using multiple supports would follow.

Related Activities (RTOP No. and Title): RTOP 506-19-13.

Development Schedule (By Fiscal Year): An extensive development program of 5 to 8 years is required to bring a prototype model through relevant environmental testing. Testing in space with a suitable model would follow.

Alternate Solutions: Large numbers of thrusters, reaction wheels, CMG's, etc. in a distributed control system concept for a very large structure, such as a 300-m reflector, may be feasible but would be inefficient, complex, and pose a plethora of interface problems.

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