

ATTITUDE CONTROL WORKING GROUP REPORT

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1.0 INTRODUCTION

The Spacecraft 2000 Workshop was held at the Hollenden House in Cleveland, Ohio, on July 29-31, 1986. Dr. J. Stuart Fordyce, of NASA Lewis Research Center, served as the conference chairman. The workshop objectives were a) to identify the critical needs and technologies for spacecraft of the 21st century and b) to recommend technology development and validation programs.

The workshop was accomplished by forming a number of technology working groups. This report documents the activities of the Attitude Control group. The group was chaired by Dan Reid (GE) and co-chaired by Phil Studer (NASA GSFC). The major participants were John Sesak (LMSC), Bob Williamson (Aerospace Corp.), Charles Gartrell (General Research Corp.), Bill Isely (HI), Cliff Swanson (Singer), and George Stocking (Sperry).

The ACS working group used the following approach to satisfy the workshop objectives:

- o Establish the ACS requirements expected in the year 2000. These were based upon all missions, military and civil, for LEO and GEO. The group used a roundtable discussion to predict what the control needs would be in the 21st century.
- o Establish the constraints which were likely to be placed upon the ACS of the year 2000. These were established to be sure that real world considerations influenced the group's conclusions.

- o Predict the ACS technology state-of-the-art likely in the year 2000. This was a projection of where the technology would most likely be, without any extraordinary R&D effort, business-as-usual.
- o Develop the expected ACS technology shortfalls based upon the expected requirements and the predicted technology state-of-the-art.
- o Identify the critical ACS technology issues, where critical was defined as enabling. All of the identified shortfalls were discussed in detail. The critical were separated from the enhancing and desirable, and grouped into four related categories.
- o Develop recommended ACS technology programs to address the critical issues. Four programs covering the critical issues were developed. For each recommended program an objective, rationale/need, approach/methodology, and payoff were established.

2.0 SUMMARY OF RESULTS

It was the consensus of the ACS working group that critical technology issues will have to be solved, if we are to satisfy the requirements of spacecraft in the year 2000. Critical technologies were identified in ACS sensors, processing, actuators, and test. Four programs were defined which would address all of the critical issues.

The ACS working group recommends that development programs be established as follows:

- o ACS Validaton & Test - a ground and space-based test facility addressing both ACS hardware and software.
- o Flexible Structure Control - concerning both dynamic and form control involving the sensors, the actuators, the algorithms, and design tools/techniques.
- o ACS Autonomy - covering both navigation and operations with an

emphasis on fault detection and correction.

- o ACS Sensors - addressing low noise, high accuracy devices which could be made applicable to future ACS designs.

The working group is aware of technology programs being conducted at various government agencies addressing some parts of these recommended programs. In most cases, the technology activity is limited to mission particular issues and promising approaches for some missions are rejected when not applicable to the sponsor's mission. Often the results of such R&D receives limited distribution, and the entire community cannot benefit from the activity.

It is recommended that the detailed planning of these programs consider all of the other planned R&D, and attempt to serve as a focus or integrating function of related activity.

Appendix A is the charts used at the workshop for the ACS working group final briefing. Appendix B presents the ACS working group members' mailing addresses.

3.0 ACS REQUIREMENTS - 2000

Spacecraft Attitude Control Systems in the year 2000 will have to be capable of satisfying the following requirements:

Increased Bandwidth -- is driven by the higher performance requirements of precision pointing applications as well as by agile/dynamic applications; the bandwidth required ranges up to 100 Hz. Large, flexible structures also require higher bandwidths than those presently used.

Micro-g Performance -- Accelerations in orbit are very low. Performance under, and measurement of, micro-g accelerations are required for precision pointing and stationkeeping applications. Some payloads, such as material

processing, also require precise orientation and very low acceleration errors.

Modular -- Modularity is seen as the cost-effective approach to making modifications in a basic design in order to meet mission peculiar requirements.

Replaceable -- The capability of replacing entire functions with the spacecraft on station, in orbit; an example was the replacement of the ACS module on the Solar Max Mission spacecraft.

Serviceable -- Operating from the Space Shuttle or in the Space Station, replacement should be possible at lower levels, i.e., elements within a function, cleaning, refueling.

High Accuracy -- SDI missions push the state of the art in precision pointing. Future scientific missions also require very low jitter.

Fault Tolerant -- The ability to reconstitute the system, thus surviving and/or relieving ground station support.

High Reliability -- is necessary to protect the investment in a spacecraft system. Higher levels of reliability are driven by longer life.

Long Life -- 7 to 10 year life requirements are common today. Growth to a 10 to 15 year capability is necessary for many applications, with 30 years the goal for the Space Station; maintenance is permitted in the latter case.

Torque/Momentum Growth Capability -- To accommodate abrupt configuration changes. The configuration of large spacecraft (size and shape) will change

significantly during construction, as various vehicles dock, and as appendages are added or removed. This will allow the use of large, lightweight structures and provide stable control of evolving structures.

Multiple Payload Pointing -- Precision pointing of multiple payloads on a large, flexible structure, expected in 2000, requires alignment transfer and stabilization techniques not now available.

Minimum Weight -- Weight drives launch costs directly. Minimizing weight also implies decreasing volume and improving handling capability.

Autonomy -- reduces upon ground support and maximizes the mission return. This involves health check (fault detection and correction) and maintenance (recalibration) in the context of limited ground station availability. Autonomous navigation is required to passively (without outside assistance) evade threats, thus improving survivability.

Robust -- The capability to handle dynamic conditions markedly different from the design requirements, i.e., the unexpected environment.

Adaptive -- Design in the ability to handle a variety of scenarios, i.e., all the expected.

Maneuverable/Agile -- Rapid retargeting is a requirement particularly of the SDI scenarios. Evasive maneuvers are seen as a common requirement for all high value/high priority future spacecraft.

Low Jitter -- is necessary to achieve low smear on imaging systems, optical communications links, and to concentrate the energy of weapons systems.

Payload Sensor Control Capability -- The ability to use the payload's sensors

to control the spacecraft can reduce the mission cost and/or provide redundancy or the ability to reconfigure in the event of failure (robust).

SEU/Radiation Transient Immunity -- SEU immunity is necessary to avoid losing memory or the need to reload memory in regions where cosmic rays are plentiful. Transient immunity is necessary to operate through and/or survive a nuclear event.

4.0 ACS CONSTRAINTS - 2000

There will be significant constraints placed upon the spacecraft Attitude Control Systems in the year 2000. These constraints can be categorized at the component level and the subsystem level:

Component Constraints:

Low Cost -- components must be used in order to provide affordable redundancy.

Non-optimal -- components must be used which can satisfy the general needs of many different systems and configurations.

Demonstrated/Qualified -- components will have to be used to avoid any mission risk.

Limited Fields of View -- will be afforded to the attitude sensors because of the large structures and the payload priorities.

Subsystem Constraints:

Large Flexible Structures -- will be a major limiting factor for the subsystem. Not only will low frequency, undamped appendages exist on most spacecraft, but flexible structure will connect the ACS components and the payloads requiring control.

Variable Mass Properties -- of the spacecraft due to both expendable usage over long life and reconfiguration.

Limited Preflight Testing -- will be available because of the ACS hardware and software complexity, because of the test facility limitations, and because in some cases the hardware will already be on-orbit.

Alignment Transfers -- both to initialize payloads and filters and to correct for flexible structure will be needed for the ACS in 2000.

Distributed Components -- will constrain the subsystem. This will be necessary to accommodate payload requirements, to control large flexible structures, and provide serviceable configurations.

Radiator Pointing -- limitations will constrain not only the spacecraft attitude but also the allowable maneuvering. These large radiators will be needed to dump the heat generated on the anticipated high power spacecraft and will have to be pointed toward cold space at all times.

Uncompensated Momentum -- from articulated payloads, servicing, fluid transfer loops, and other moving mechanisms will have to be absorbed by the ACS.

Crew Safety -- for manned launches, manned servicing, or manned missions will constrain the ACS designs in 2000.

5.0 PREDICTED ACS TECHNOLOGY - 2000

The state-of-the-art in Attitude Control Systems technology is predicted to be as follows, assuming that only normal R&D is performed:

Multimode/Reprogrammable -- Generic ACS systems will be applied to a number

of systems/missions. Configuration for a particular requirement will be realized by S/W reprogramming.

Self-Alignment -- Prior launch boresighting of related elements may not be possible. Direct measurement techniques will provide alignment knowledge, or special maneuvers may be resorted to establish alignment.

Self-Calibrating -- Parameters which vary outside achievable ranges will be calibrated on line by techniques such as Kalman filters. Where on line is not practical, special self-calibrating modes will be implemented.

Adaptable to Variable Mass Properties -- The ACS will adjust to variable mass properties due to change in consumables or when docked with other platforms. The means of implementation is through robust design and adaptive control techniques.

Smart Sensors and Actuators -- ACS systems will evolve to include distributed processors associated with sensors and actuators which will better distribute function to help implement redundancy management and standardize interfaces.

Solid State Sensors -- Solid state area array sensors will complete the current trend in replacing older sensors in order to extend life and increase environmental tolerance.

Optical Components -- Where high speed computation in support of control of very large space structures requires optical computation and interfaces, that technology will be available.

High Speed Wheels -- High speed wheels with dynamic braking will be available to reduce weight and power.

Expert Systems -- Systems will be sufficiently complex to be able to provide

error detection and correction function as well as to make judgements on performance levels being provided.

6.0 ANTICIPATED ACS TECHNOLOGY SHORTFALLS - 2000

Increased performance in guidance, navigation, and control systems is driven by the need for large space structures, large optical assemblies, and high precision orbit determination. The newly emerging large systems will be a synthesis of active and passive control of pointing, vibration, and surface shape. These areas have been, and will likely continue to be, the topics of much research.

Near-earth navigational performance will need improvement to reach the subdecimeter range via improved atmospheric drag and solar pressure models, and extension of geoid measurement, to cover the oceans. Special attention is needed for interplanetary spacecraft that orbit or land upon extraterrestrial bodies, in view of poorly known gravity fields, erratic atmospheric drag, etc.

Many advances in spacecraft pointing, vibration, and figure control systems are needed. Measurement systems will be improved through new techniques, such as image motion compensation, to overcome inherent performance limitations. Active figure control systems will soon become commonplace as surface accuracies decrease to the equivalent of visible wavelengths and smaller. Continual research, experimentation, and data collection is needed to fully understand the behavior of large space structures. The control techniques, sensors, and actuators will drive the need for special avionics that are equivalent to many multiples of general purpose on-board computers. The actuators needed will require extended life and capabilities well beyond their currently expected performance.

6.1 SENSORS

A key item to implementing future ACS technology will be advanced sensing systems. To a certain degree, reduction in design costs and standardization of interfaces will reduce the difficulties that may be present in implementing new systems. Incorporating autonomy into sensor systems will permit fault isolation/detection, selection of alternative redundant devices and data paths, and enable designs which have operational capabilities in multiple modes.

Many of the needs associated with improved capability, high accuracy and reduced cost lead to requirements for automation of the navigation function. Automation also lends itself to rendezvous, stationkeeping, docking, and multiple vehicle traffic control. Current requirements have driven the automation of many ground navigation functions, especially for earth-orbiting spacecraft, and future projections indicate a continued trend in this direction. In addition to ground navigation system automation, requirements are evolving which require the development of totally on-board navigation systems and/or hybrid spacecraft/ground navigation algorithms, failure detection and correction techniques, and proximity sensors.

Increasing ACS performance requirements, both for more conventional spacecraft design and large space structures, also will require noise reduction in sensors and accuracy improvements in high precision star trackers. Improved system reliability, and possibly reduced mass, can be gained by extended lifetimes for gyros (IRUs). Lightweight, integral structural shape and vibration sensors are needed for the future. It has been estimated that the sensor/actuator system for a 500-lb flexible structure may weigh several thousand pounds. These types of devices simply do not exist in a suitable form.

6.2 PROCESSING

The processing shortfalls in ACS technology occur in two broad areas: analytical design methods and software design tools. Analytical methods must be developed to perform critical design tasks; additionally, reliable control design software must be developed to cope with high-order systems design and simultaneously handle the new design methods.

Algorithm development is required for unified ACS/structural design, adaptive structural filters and autonomous design. Shape control, shape estimation, and agile systems are also included under the unified design ACS/structural design procedures.

Software development is required for high-order/multi-rate/ multi-loop systems design. Large flexible spacecraft design is one of the main drivers of the new technology requirements.

Each of these technology areas may be defined as follows:

Unified ACS/Structural Design -- This area involves the interdependent and simultaneous design of the control system and spacecraft structure. Current design practice separates the spacecraft structural design from that of the control system; i.e., the control system is designed as an add-on. Although this procedure is satisfactory for small satellites requiring only altitude control, it is unsatisfactory for large flexible spacecraft requiring active control of the various vibration modes. A unified system design capability will allow the design of extremely lightweight structures with structural optimization procedures incorporating the control system parameters as design constraints.

Design Tools -- Computational algorithms and reliable software must be developed for high-order multi-rate/multi-loop control systems. Flexible spacecraft design will employ dynamic models of 100th order and greater.

Additionally such systems will employ many actuators and many sensors with attendant non-linearities and system noise. The slewing of flexible articulated vehicles involves an additional class of non-linear control problems. The complexity of these problems is beyond the state of current design software. Numerically stable software packages need to be developed that provide reliable answers for these design problems.

Adaptive Structural Filters -- Large platforms are subject to berthing, docking, and evolutionary structural modifications. To ensure stable control, adaptive filter algorithms must be developed for system identification and adaptive control. All aspects of the system require identification: mass properties, mode shapes, mode frequencies, damping, and system disturbances. As performance requirements increase, the accuracy of the model required for control design increases; the maintenance of stability and performance in the presence of large system modifications requires precise knowledge of system parameters, and adaptive structural filtering is a critical technology.

Autonomy Techniques -- Autonomous satellite operations will be required for deep space missions, long-life satellites, and emergency conditions when ground station communication is impossible.

6.3 ACTUATORS

The attitude control systems to meet the mission requirements of the year 2000 will need actuators with greater capabilities and of types not currently used in space.

The need for advanced capabilities are derived from higher accuracy autonomous operational needs of multi-payload (platform) and flexible

structures. Low noise is needed for better resolution over a wider bandwidth and to reduce structural interactions. Noise sources are unbalance, bearing noise, sampling rate, and magnetic and mechanical imperfections.

A critical technology issue is wider and variable dynamic range required to provide greater accuracy, less jitter, and lighter weight by operating at higher rotational speeds with good power efficiency. The recent discovery of new magnetic materials and high efficiency power conversion techniques can be exploited to provide a new generation of attitude control devices with large systems benefits and tighter control loops. These are needed to implement ACS systems capable of adaptive control to handle "growth" requirements and permit autonomous and self-optimizing control.

A second critical technology need is for structural actuators which are devices to react forces within the structure rather than on inertial elements. They are needed for shape control (remove distortion) and active control of structural dynamics which affect pointing of multiple payloads on a common platform. These may be linear actuators rather than classical rotary devices. They can potentially raise fine pointing bandwidths from the fractional Hz cutoff of the primary ACS to approximately 100 Hz with equivalent improvements in jitter control and accuracy. These are needed to provide large multiple payload systems the same degree of (sensor limited) performance previously possible only with dedicated spacecraft and/or image motion compensation systems which are a costly penalty on each instrument. Providing active vibration control integrated into the structure can provide broadband damping to eliminate the numerous multi-mode resonant peaks characteristic of large complex lightweight structures. Piezo-electrics and shape-memory alloys offer the prospect of static shape control with

minimal power. Electro-magnetic devices have sufficient bandwidth and inherent rate sensing which will minimize the distributed control system penalty. These new actuator developments are required to implement the jitter-free platforms as a precision pointing platform and reduce the need for stringent disturbance restrictions, individual isolators, and multiple gimbaled fine pointing mounts for individual instruments and payloads. They will provide a stable base for observations, science, and future narrow beam optical communication links.

Standard interfaces are needed to provide economy, reliability, and growth potential so that future systems upgrades can be made by software, servicing by direct replacement facilitated, and "growth" additions readily accommodated. Major harness weight reductions by fiber-optics and the insertion of ACS tags into payload data packets will be possible.

6.4 TEST

There is a need for attitude control engineers to have test beds to enable them to validate attitude control system performance. Test beds are an essential capability that permits the control engineer to confidently predict performance capability and to establish performance margins. Tools such as these are needed if reliable first flight performance is to be achieved. Often the control engineer is permitted a single opportunity to accomplish the task. Exercising simulation test beds can be an important step in the process of gaining the necessary confidence and reduces risk. Test beds are used for operational support and can be used to evaluate performance of possible growth options. They can also be essential to evaluate the viability of new applications such as autonomous control, or telerobotic/robotics, etc.

Typically, many types of test beds are utilized to gain the necessary confidence in the attitude control system design. In the ground based environment there are software development test beds to exercise operational code, a variety of mainframe computer performance simulations to validate specific phases of operation and associated performance, and hybrid simulations that employ both hardware and software for more comprehensive evaluations of performance.

In the process of developing a dynamical model for subsequent simulation purposes, the control designer usually develops an analytic model first. Typically, this model is verified experimentally by ground test. However, with the evolution in spacecraft design towards designs with multiple payloads requiring precise pointing, satellites with many modes of operation involving widely varying mass states, or satellite designs involving large structures, the feasibility of experimental verification on the ground is at issue. This is particularly true for large spacecraft that may not even be supportable in a gravity environment. Providing the necessary support can substantially alter the dynamics of the model to be tested. Thus testing in a zero gravity environment may be the only recourse. From a practical viewpoint, if testing in space is deemed necessary, then it might be desirable to employ subsystem scale model testing to confirm analytical models, and then extrapolate to the actual flight article. The issue of scalability can be a concern, however. The request for a space test bed anticipates the needs outlined above, and may ultimately be the only viable method to derive a validated dynamical model that can subsequently be used to extrapolate performance on orbit. As a by-product, a space test bed would have other advantages such as providing opportunities to qualify new technology in a space environment.

7.0 ACS CRITICAL TECHNOLOGY ISSUES - 2000

The ACS technology shortfalls which are enabling, not just enhancing, have been classified as critical issues. All of them can be grouped under one of the following four categories:

ACS Validation & Test -- includes the critical issues of component and subsystem modeling and test; simulation model validation; and software development/validation (which is meant to include the multi-variable, adaptive, FDC, and autonomy software).

Flexible Structure Control -- to provide dynamic and form control including structural sensors and actuators; adaptive filters/algorithms; multi-rate, multi-loop design tools; a unified ACS/Structural design approach; and variable dynamic range systems.

ACS Autonomy -- including fault detection and correction for both autonomous navigation and autonomous spacecraft operations.

ACS Sensors -- covering low noise sensors; high accuracy star trackers; and long distance proximity sensors.

8.0 RECOMMENDED ACS TECHNOLOGY PROGRAMS

The following four technology programs are recommended to address the ACS critical technology issues for spacecraft in the 21st century. A brief description of the objectives, rationale/need, approach, and payoff is provided. Time did not permit any detailed planning nor coordination with existing or planned technology programs. In general, most of the latter programs are planned to address mission unique technology needs that could, in some cases, be applicable to the spacecraft 2000 state-of-the-art. If the recommended programs are considered for implementation, the planning should include a survey of the related technology programs already planned or funded, and coordinated activity to avoid duplication in the fundamental technology issues.

The recommended programs are listed in the order of priority with the most urgent listed first. The first two programs were both considered to be of the highest priority because of their potential impact on so many different mission areas.

8.1 ACS VALIDATION & TEST PROGRAM

Objective

The objective of this program is to ensure that the Attitude Control System's hardware and software, when subjected to the orbital environment, provides the required mission performance.

Rationale/Need

The complexity of the ACS has grown considerably to recent years because of the availability of unlimited computational capability. Adaptive designs are difficult to test and require extremely accurate analytical models

which have to be validated to avoid risking the mission's success. As the complexity has grown, the performance capabilities have improved beyond the current and projected test capability. The test equipment is not as accurate as the ACS sensors and truth models or references aren't available to validate performance. Ground testing involves significant test limitations due to gravity effects, earth's rotation, atmospheric effects, and environmental disturbances.

Operational support will require validated models of the ACS hardware and software to evaluate anomalies, new configurations, mission modifications, and servicing. Missions which plan on-orbit growth will have to have a method of ACS validation and test to provide the confidence that the new configuration will be stable and will meet the required performance.

Autonomous missions will require a sophisticated ACS that will be a major challenge to validate and test. A means of exercising the autonomous features prior to flight, to insure design adequacy, is needed.

Approach/Methodology

Both a ground based test bed and an on-orbit test facility should be developed particularly to serve the Attitude Control System needs.

The ground test bed would be used to not only validate the ACS software, but also to serve as a software development facility. The test bed would include a detailed digital simulation of the ACS running in a large mainframe which would interface with the ACS hardware and software under test. A hybrid capability of introducing either the actual ACS hardware or a simulation into a test would be provided. The test bed would be used for operational support to validate new configurations or software.

The space test bed would be used to provide flight qualification on ACS components and to validate ground test results and simulation models. The test scaling between ground and flight would be validated or established such that reduced scale ground tests could be used with confidence.

Payoff

Reliable first flight performance could be ensured by using these test beds. Improved ACS testing will find problems or weaknesses prior to the mission use.

New ACS technology could be qualified with no program risk. New technology is considered unproven until space qualified. Advanced hardware cannot be flown unless the related performance is urgently needed and can justify the mission risk.

The ACS performance and margins could be quantified to allow improved mission performance and growth.

8.2 FLEXIBLE STRUCTURE CONTROL PROGRAM

Objective

A systematic technology program involving sensors, actuators, design software and algorithmic development is required to meet mission objectives for the year 2000. The new spacecraft will be large, lightweight, and in most cases have flexible appendages. The large size and low mass density of these vehicles lead to many closely spaced low frequency vibration modes. This low frequency dynamic behavior coupled with stringent control requirements leads to a new class of satellite control problem.

Current design processes that place all vibration modes outside the control system bandwidth, or simply notch out an offending vibration mode, are not adequate for mission success. The new class of satellite requires more sophisticated approaches.

Rationale/Need

Some of the more challenging problems associated with large spacecraft control are as follows:

Multi-Payload Precision Pointing -- This problem occurs on large satellites with diverse payloads, each of which have stringent pointing requirements. The problem becomes one of providing precision pointing for each of the payloads and preventing destructive interference between the various payloads and the associated flexible space platform.

Pointing and Control Stability -- Precise pointing for large flexible structures calls for new design processes that provide active vibration control for the modes and pointing control for the rigid body. This will of necessity lead to high-order dynamic systems that have many actuators and many sensors; i.e., high-order, multi-input/multi-output control with many major and minor loops operating at different sampling speeds. There exists little practical design experience with such multi-loop systems.

Shape Control and Estimation -- Large spacecraft require two classes of shape control. The first class can be termed geometric or configuration control wherein various spacecraft components are maintained in a preferred alignment or configuration; i.e., each component is treated as a rigid body and aligned accordingly. Our example would be the reflector, boom, and feed orientation in an offset antenna class spacecraft. The second class of shape control involves constraining a subsystem to maintain some idealized geometric shape. An example would be shape control of a parabolic reflector. This class of shape control requires a sophisticated system of shape estimation such that correction forces can be generated in real-time. Currently there is no industrial experience base that copes with this problem. Most of the work is in the conceptual state.

Abrupt System Control -- Abrupt systems are those wherein the system parameters, dynamic order, or configuration change abruptly in step response fashion. Such changes occur during berthing and docking of spacecraft. Changes of smaller magnitude, but similar nature, occur during evolutionary growth when new elements are added to an existing space structure. Control must be maintained before, during, and after such step changes in system configuration. Currently there exists no unified approach to cope with control across such system discontinuities.

Large Agile Flexible Structures -- Agile flexible systems under going fast large angle maneuvers are another area requiring development. Work is required in both dynamics and control. Currently there exists no way to perform the necessary computations for guidance and control in real time.

Approach

In order to correct deficiencies in the technology program are required in the following areas:

Structural Sensors & Actuators -- An extensive structural sensor and actuator program is required. Hardware development is lagging behind theory development in structural control technology. Devices that respond to low frequencies are lacking; i.e. responses from DC to 1 hertz are required. Inertial devices and devices that respond point-to-point within the structure are required. Structural shape sensors and actuators do not exist at this time. Low frequency vibration control devices tend to be bulky and cumbersome; i.e., a typical proof-mass actuators currently available for operation at 0.12 Hertz weigh approximately 70 lbs. The lack of available hardware for control structure interaction (CSI) technology forms a critical

block. The most elegant scheme cannot function without proper sensors and actuators.

Design Tools -- A computer software program is required for estimation and control algorithm development. A specific lack exists in software for high-order systems design required for structural control.

Unified Structural/ACS Design -- Methodology and algorithms must be developed that allow unified design of both the structure and control system. This process ensures maximum use of structural mass and control capability and represents the next step toward a mature active structural control capability.

Real Time Alignment Transfer -- The precision pointing of multiple payloads from large space platforms calls for the development of real time attitude reference transfer systems. The technology is necessary if large space platforms are to perform their missions.

Payoff

The vigorous development of technology for flexible structure control will ensure the use of large lightweight structures with improved pointing capability and enable stable control of evolutionary structures. The payoff to the nation's space program in terms of increased capability and reduced development costs is tremendous.

8.3 ACS AUTONOMY PROGRAM

Objective

The objective of this program is to eliminate or minimize the ground support operations. The ground support manpower costs associated with long-life spacecraft can be the major cost element depending upon the level

of ACS autonomy. An autonomous ACS will also maximize the mission return by avoiding or minimizing downtime due to equipment failures.

Rationale/Need

The ever-increasing complexity of spacecraft ACS has increased both the quantity and quality of ground support required to ensure continuing on-orbit performance. Critical timelines can necessitate multi-shifts and numerous ground stations. Limited ground station coverage and availability also dictates minimum ACS autonomy for future spacecraft. An autonomous ACS and navigation system helps satisfy the need for attitude data and ephemeris data for on-board payload use. The immediate availability of such data to the payload is needed in many missions.

Approach/Methodology

An autonomous fault detection and correction system would be developed to establish when an ACS element has failed, to establish the optimum replacement policy, and to implement the replacement without ground assistance. This would build upon the automatic control modes already provided in many of today's systems.

An autonomous navigation system would be developed to provide ephemeris data on-board without the need for ground tracking nor uplinked data. It will interface with the autonomous ACS to provide extended periods of independent spacecraft operation.

Artificial intelligence techniques, extending the expert systems expected in the immediate future, will be used to replace extraordinary ground support functions.

Payoff

High availability is the ultimate payoff. Safe reconfigurations of

the ACS will be provided avoiding any potential ground command errors. The TT&C bandwidths, supporting the ACS and payload telemetry and commands, could be reduced since data need not be interchanged with the ground. Life cycle costs would be significantly reduced for long-life spacecraft. The ephemeris accuracy for an autonomous system would in most cases be more accurate than ground generated with on-board reconstruction. An autonomous ACS would make the spacecraft more survivable in the event of war because ground dependency would be eliminated.

8.4 ACS SENSORS PROGRAM

Objective

The objective of this program is to develop the technology for low noise attitude sensors, to develop a high accuracy star tracker, and to develop a long distance proximity sensor.

Rationale/Need

Low noise sensors and high accuracy star trackers are needed to enable spacecraft to perform precision pointing missions. With unlimited computational capabilities, the limiting item for pointing accuracy is the sensors. Rendezvous and docking requirements will be more commonplace for the 21st century spacecraft in order to facilitate servicing, repair, and reconfiguration. An accurate long distance proximity or ranging sensor with general applicability is needed.

Approach/Methodology

The approach would be to develop improved image motion compensation techniques, to explore fiber optic and other advanced rate sensing instruments, and to apply payload sensor technology advances to the ACS sensing approaches. A three axis solid state star tracker would be developed

to provide sub arc second accuracies. A long distance range/orientation sensing system would be developed to address the anticipated rendezvous and docking needs.

Payoff

This program would result in improved payload performance, improved attitude reference data, longer life spacecraft, and would provide a critical component for an autonomous navigation system. It would enable automatic rendezvous and docking.

APPENDIX A

SPACECRAFT 2000

ATTITUDE CONTROL

- WORKING GROUP MEMBERSHIP
- REQUIREMENTS - 2000
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- PREDICTED TECHNOLOGY STATUS - 2000
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 - ACS SENSORS

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ACS REQUIREMENTS - 2000

- INCREASED BANDWIDTHS
- MICRO G PERFORMANCE
- MODULAR
- REPLACEABLE
- SERVICEABLE
- HIGH ACCURACY
- FAULT TOLERANT
- HIGH RELIABILITY
- LONG LIFE
- TORQUE/MOMENTUM GROWTH CAPABILITY
- MINIMUM WEIGHT
- AUTONOMOUS
- ROBUST
- ADAPTIVE
- MANUEVERABLE/AGILE
- LOW JITTER
- PAYLOAD SENSOR CONTROL CAPABILITY
- SEU/RADIATION TRANSIENT IMMUNITY
- MULTIPLE PAYLOAD POINTING

ACS CONSTRAINTS - 2000

COMPONENT

- LOW COST
- NONOPTIMAL
- DEMONSTRATED/QUALIFIED
- LIMITED FOV

SUBSYSTEM

- LARGE FLEXIBLE STRUCTURES
- VARIABLE MASS PROPERTIES
- LIMITED PREFLIGHT TESTING
- ALIGNMENT TRANSFERS
- DISTRIBUTED COMPONENTS
- RADIATOR POINTING LIMITATIONS
- UNCOMPENSATED MOMENTUM
- CREW SAFETY

PREDICTED ACS TECHNOLOGY - 2000

- MULTI-MODE REPROGRAMMABLE
- SELF-ALIGNING
- SELF-CALIBRATING
- ADAPTABLE TO VARIABLE MASS PROPERTIES
- SMART SENSORS & ACTUATORS
- SOLID STATE SENSORS
- OPTICAL COMPONENTS (PROCESSING)
- HIGH SPEED WHEELS
- EXPERT SYSTEMS

ACS TECHNOLOGY SHORTFALLS - 2000

SENSORS:

AUTONOMY

- * LOW NOISE SENSORS (M)
- LONG LIFE GRYOS
- LOW COST DESIGN
- STANDARD INTERFACES
- MULTI-MODE SENSORS
- * HIGH ACCURACY STAR TRACKERS (M)
- * STRUCTURAL SENSORS
- * AUTONOMOUS NAVIGATION (M)
- * PROXIMITY SENSORS (M)

-
- * - CRITICAL OR ENABLING TECHNOLOGY
 - (M) - POSSIBLY MISSION UNIQUE/DEPENDENT

PROCESSING:

- * UNIFIED ACS/STRUCTURAL DESIGN METHODS
- * DESIGN TOOLS FOR HIGH-ORDER MULTI-RATE/MULTI-LOOP SYSTEMS
- * ADAPTIVE STRUCTURAL FILTERS FOR CONTROL AND ESTIMATION
- * AUTONOMY TECHNIQUES
- LOW COST DESIGN METHODS
- STANDARD INTERFACES

ACTUATORS:

- LOW NOISE ACTUATORS
- * VARIABLE DYNAMIC RANGE
- * STRUCTURAL ACTUATORS
- STANDARD INTERFACES

ACS TECHNOLOGY SHORTFALLS - 2000

- TEST:
- HARDWARE COMPONENT MODEL VERIFICATION
 - * ● CONTROL ALGORITHM ASSESSMENT
 - * ● SOFTWARE VALIDATION
 - * ● ZERO G MODEL VERIFICATION
 - * ● SOFTWARE/HARDWARE SUBSYSTEM PERFORMANCE PREDICTION
USING VALIDATED SIMULATIONS
 - * ● SCALING VALIDATION
 - OPERATIONS SUPPORT
 - FDI/AUTONOMY/AI VALIDATION
 - * ● COST EFFECTIVE EVALUATION

ACS CRITICAL TECHNOLOGIES

1. ACS VALIDATION & TEST
 - COMPONENT AND SUBSYSTEM MODELLING AND TEST
 - SIMULATION MODEL VALIDATION
 - SOFTWARE DEVELOPMENT/VALIDATION (MULTI-VARIABLE, ADAPTIVE, FDC, AUTONOMY)
2. FLEXIBLE STRUCTURE CONTROL (DYNAMIC & FORM)
 - STRUCTURAL SENSORS & ACTUATORS
 - ADAPTIVE FILTERS/ALGORITHMS
 - MULTI-RATE, MULTI-LOOP DESIGN TOOLS
 - ACS/STRUCTURAL UNIFIED DESIGN
 - VARIABLE DYNAMIC RANGE SYSTEMS
3. ACS AUTONOMY
 - AUTONOMOUS OPERATIONS/NAVIGATION
 - FAULT DETECTION & CORRECTION
4. ACS SENSORS
 - LOW NOISE SENSORS
 - HIGH ACCURACY STAR TRACKER
 - PROXIMITY SENSORS

I. TECHNOLOGY PROGRAM - ACS VALIDATION & TEST

OBJECTIVE:

- VALIDATE ACS PERFORMANCE
 - SOFTWARE
 - HARDWARE

RATIONALE/NEED:

- ACCURATE MODELS FOR COMPLEX ADAPTIVE DESIGNS
- PERFORMANCE INCREASE BEYOND TEST CAPABILITY
- GROUND TEST LIMITATIONS
- OPERATIONAL SUPPORT
- GROWTH VALIDATION
- AUTONOMY VALIDATION

APPROACH/METHODOLOGY:

- DEVELOP A GROUND TEST BED
 - SOFTWARE DEVELOPMENT
 - MAINFRAME PERFORMANCE SIMULATION
 - HYBRID SIMULATION CAPABILITY
- SPACE TEST BED
 - FLIGHT QUALIFICATION
 - ZERO & MODEL VALIDATION
 - SCALING VALIDATION

PAYOFF:

- RELIABLE FIRST FLIGHT PERFORMANCE
- QUALIFIES NEW TECHNOLOGY
- QUANTIFY PERFORMANCE CAPABILITY/MARGIN
- COST/RISK REDUCTION

II. TECHNOLOGY PROGRAM - FLEXIBLE STRUCTURE CONTROL

OBJECTIVE:

- STABLE CONTROL OF LARGE FLEXIBLE SPACECRAFT
- SHAPE CONTROL OF LARGE SPACECRAFT APPENDAGES

RATIONALE/NEED:

- MULTI-PAYLOAD PRECISION POINTING
- POINTING STABILITY/CONTROL STABILITY
- SHAPE CONTROL
- ABRUPT CONFIGURATION CHANGE
- LARGE AGILE FLEXIBLE SYSTEMS

APPROACH/METHODOLOGY:

- DEVELOP STRUCTURAL SENSORS AND ACTUATORS
- DEVELOP DESIGN TOOLS
- DEVELOP UNIFIED STRUCTURAL/ACS DESIGN METHODS
- DEVELOP REAL-TIME ALIGNMENT TRANSFER TECHNIQUES

PAYOFF:

- ALLOWS LIGHT WEIGHT LARGE STRUCTURES
- IMPROVED PRECISION POINTING OF FLEXIBLE STRUCTURES
- STABLE CONTROL OF EVOLUTIONARY STRUCTURES
- REDUCED DEVELOPMENT COSTS
- APPLICABLE TO MULTI-AXIS ROBOTIC CONTROL

III. TECHNOLOGY PROGRAM - ACS AUTONOMY

OBJECTIVE:

- REDUCE GROUND SUPPORT OPERATIONS (MANPOWER/COST)
- MAXIMIZE MISSION RETURN

RATIONALE/NEED:

- INCREASED ACS COMPLEXITY/SUPPORT
- CRITICAL TIMELINES
- LIMITED GROUND STATION AVAILABILITY
- ACS/PAYLOAD DATA CORRELATION

APPROACH/METHODOLOGY:

- DEVELOP AUTONOMOUS FAULT DETECTION DETECTION & CORRECTION SYSTEM
- DEVELOP AUTONOMOUS NAVIGATION SYSTEM
- USE AI AS APPLICABLE

PAYOFF:

- HIGH AVAILABILITY
- SAFE ACS RECONFIGURATION
- REDUCES TT&C BANDWIDTH
- REDUCES LIFE CYCLE COSTS
- IMPROVED EPHEMERIS ACCURACY
- IMPROVED SURVIVABILITY

IV. TECHNOLOGY PROGRAM - ACS SENSORS

OBJECTIVE:

- DEVELOP:
 - LOW NOISE SENSORS
 - HIGH ACCURACY STAR TRACKER
 - PROXIMITY SENSOR

RATIONALE/NEED:

- PRECISION POINTING MISSIONS
- RENDEZVOUS & DOCKING

APPROACH/METHODOLOGY:

- DEVELOP 3-AXIS SOLID STATE STAR TRACKER
- DEVELOP IMPROVED IMC
- EXPLORE FIBER OPTIC AND ADVANCED RATE SENSORS
- DEVELOP LONG DISTANCE RANGE/ORIENTATION MEASUREMENT SENSOR

PAYOFF:

- IMPROVED PAYLOAD PERFORMANCE
- IMPROVED ATTITUDE REFERENCE
- LONGER LIFE
- CRITICAL AUTO NAV COMPONENT
- AUTOMATIC RENDEZVOUS & DOCKING

APPENDIX B

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