CHAPTER 5
REPORT OF THE ATTITUDE CONTROL AND ATTITUDE DETERMINATION PANEL

INTRODUCTION

This chapter presents the output of the Attitude Control and Attitude Determination Panel of the NASA Flight Technology Improvement Workshop.

The following approach was used by the panel in determining its recommendations:

1) Past failures and deficiencies in flight programs were reviewed with recommendations as to how they could be avoided.

2) The panel was divided into four subpanels covering the specific subareas of:

   a) Control system dynamics, analysis, and simulation
   b) Sensors and devices
   c) Software, estimations, and autonomy
   d) Designing, integration, and testing

3) Preliminary recommendations were prepared by the subpanels and presented to the whole panel for discussion. Final technology candidates were then chosen by the group as a whole. These technologies are not meant to be complete or all-inclusive, and reflect the background of the panel members.

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Control Configured Vehicle Design

A number of spacecraft have failed shortly after launch because they were unstable. These failures were manifested by the loss of the control system authority over the vehicle. When disturbances on the vehicle exceed the capability of the control system, the spacecraft and the mission are generally lost. With future spacecraft becoming larger, more flexible, and more complex, the problem of dynamic stability intensifies.

The possible dynamic interaction between the structure and the control system is a principal concern on every spacecraft. The difficulty in adequately modeling and predicting the control system performance before launch has been somewhat improved by development of sophisticated analysis tools for dynamic modeling and control synthesis. However, in most vehicle designs, the control system is not adequately considered as an integral part of the total spacecraft system, but rather it is generally thought of as being bolted on the structure. This ultimately leads to a more costly control system and structure, reduced performance, and greater risk. Therefore the thrust of this technology task is to develop the required technologies and design tools to make possible the design of future vehicles configured for a more effective integration of the control system. This effort will require integration of three principal technical areas during vehicle design: structures, dynamics, and control. A new modeling criterion for these future configured vehicles must be established so that a more effective analysis of vehicle performance can be carried out. Along with this criterion, new and improved control synthesis techniques can be developed which will lead to more robust systems, that is, systems which are less sensitive to system or component changes during the mission lifetime.

The output of this technology task will greatly assist in the reduction of costs for future complex systems and will reduce the risk in meeting performance goals. Lastly the technology has broad application to all future space vehicles (e.g., platforms or stations).

Gyros

High accuracy, long life devices for sensing spacecraft inertial attitudes and rates will be a continuing requirement for spacecraft in both the near and distant future. Existing gyro technology to satisfy this need is based on mechanical technologies and is sensitive to the well-known failure modes and finite life associated with bearing lubrication and gas flotation contamination systems.

There are several emerging technologies that offer the potential to either replace existing devices or augment the technology in specific applications. Some of these offer the inherent stability and reliability of solid-state equipment. Examples of possible technology are laser gyros, gyros utilizing the principle of nuclear resonance, electrostatic gyros, cryogenic gyros, and others.

These alternative devices have, in specific instances, moved out of the laboratory and into the working environments of aircraft and missiles. A concerted effort to rigorously examine and develop their potential for the unique requirements of spacecraft - extremely long life, high precision, and comparatively low rates - is an essential prerequisite for their future availability as a viable component.

Solid-State Star Sensor

Presently available attitude determination technology has neither the precision nor the flexibility to support many future missions, especially those at high altitudes. Current attitude determination methods are effective primarily at low altitudes and do not offer the high accuracy (approximately 1-2 arc sec) potentially required for many future spacecraft. Most systems are optimized for only one particular mission and are not readily adaptable to other missions. Also, precision attitude determination systems to date do not operate autonomously. Instead, they usually require extensive data processing support to be done on the ground. This can be costly and complex, and does not provide real time data.

Future satellites will require precise, real time attitude determination for some of the following purposes:

1) Precise pointing of narrow field-of-view and high resolution sensors (for better acquisition and tracking and reduced smear effects).

2) Precise target location through accurate determination of sensor line of sight.

3) Support of precise onboard navigation (position information is needed to augment attitude system, to support precise pointing of sensors, etc.).

4) Precise thrust vector alignment (insertion, stationkeeping, rendezvous navigation, on-orbit maneuvering, etc.).

5) Alignment determination and flexure monitoring of very large space structures (active shape control).

A principal element of many spacecraft attitude control and determination systems is a star sensor. Although a few star sensors already employ solid-state detectors (namely star scanners), the vast majority of star sensors in operation today rely on the limited capability of the Image Dissector Tube (IDT). IDT star sensors, however, suffer from certain fundamental limitations imposed by the construction of the tube itself. Limitations, such as the ability to track only a single star, electron multiplier gain instabilities, susceptibility to image deflections caused by external electric fields, high voltage requirements, and accuracy, make a replacement for the IDT highly desirable.

Recent advances in the development of charge transfer device technology, namely the Charge Coupled Device (CCD), now make a solid-state star sensor possible. A star sensor employing a CCD detector focal plane can achieve an order of magnitude better accuracy (attitude determination) than the current IDT sensors, and it is free of the problems inherent in IDT devices. A CCD star sensor has a fully active focal plane and thus has the capability to track multiple stars continuously as long as they are in the field-of-view of the sensor. The key advantage here is that several CCD star sensors can provide essentially continuous attitude information and therefore can operate in an all stellar mode without the need for gyros.

Some future satellite programs (i.e., large antennas, solar power systems, etc.) will involve the development of very large space structures which will require precise structural shape control. For many of these applications, it will not be feasible to use autocollimators because of visibility and distance constraints. However, a single CCD star sensor could provide three-axis attitude information by simultaneously tracking several stars. Independent, compact star sensors at remote locations could provide a means of relative alignment determination and flexure monitoring without range or relative visibility constraints. Both NASA and the Air Force share common interests in these types of applications.

There appear to be two classes of sensor requirements: a moderate accuracy star sensor to replace the present standard star tracker and a very accurate system for applications requiring 2 arc seconds and better performance.

Based on the rationale mentioned herein, it was the unanimous opinion of the group that NASA should actively pursue the development, acquisition, and operational employment of a CCD star sensor. The JPL has some experience with CCD star sensor design with their engineering model of the stellar sensor. The Air Force has an active CCD star sensor development program underway (MADAN program). In addition, other services and industrial firms are pursuing CCD star sensor technology. An interagency working group was recently formed between the Air Force Space and Missile Systems Organization and the JPL to address the feasibility of a joint CCD star sensor development program. Preliminary estimates have indicated a potential savings to the government of about 3 million dollars if a joint program could be agreed upon. In that case, the prototype CCD star sensor could be tailored to both agencies' requirements and could be available as early as 1982. NASA's vigorous support of the interagency star sensor working group would appear to be prudent.

Control Instrumentation

Presentations made by panel members which addressed on-orbit experience demonstrated a clear and significant lack of the means to understand readily and thoroughly on-orbit behavior and performance. In the context of significant increases in system complexity and limitations of both ground-based test and predictive analyses, strong motivation exists for the development of the necessary on-orbit instrumentation and related technology. This will insure demonstrable knowledge of on-orbit behavior and enhance the potential to achieve ultimate performance with both reduced risk and cost. In some cases, such instrumentation can be viewed as essential to achieving the required performance.

The panel anticipates the technology to require a fresh approach which allows both on-orbit and ground-based evaluation. The control instrumentation technology focuses on the development of instrumentation and sensing techniques required for determination of position and rate of articulated elements, relative alignment of spacecraft elements, shape control, etc. Other attitude and rate sensors are the subject of a separate task.

Development of the methodology and technology for on-board monitoring, and assessing of performance is also important. This includes not only the instrumentation techniques but also the technology related to on-board real-time decision making for data reconstruction (post-factum detail assessment) and the implementation of such a capability (data processing and storage, interfaces, etc.).

Technology development for self-test at the system (or component group) level and for built-in test at the component level is also an element of this task. This needs to be addressed from the standpoint of instrumentation technology as well as hardware complexity and feasibility for implementation. The application must include integration of this technology with ground test (bench, subsystem, and spacecraft level) as well as system level design for overall on-orbit performance monitoring.

Demonstration of the effectiveness of such technology is essential. Furthermore, key hardware and software technology elements must be developed to a level which would insure reliability for incorporation into flight programs.

Tolerant/Accommodating Control Systems

Both near-term and next generation spacecraft required to meet high performance objectives will have to be sufficiently cost effective and low in risk while satisfying the performance objectives. One way of accomplishing this is to extend the control configured design philosophy to include system configuration changes after flight initiation. Three specific areas are recommended for investigation.

1) On-orbit/ground calibration, reconfiguration, and adaptive control. Observation of overall system performance using either on-board instrumentation and diagnostic data processing or ground-based data processing may suggest or necessitate desirable changes in attitude control, payload control, or stability augmentation system characteristics. Both on-line and off-line methods to readjust or reconfigure these control systems are required when plan parameter and modeling uncertainty and/or unreasonable physical size make ground verification of performance inadequate to bound the risk of on-orbit failure. Methods incorporating identification before control (discussed below) or real-time adaptive or so-called learning systems might be considered.

2) Microprocessor-based or array-processor-based algorithms for structural dynamics identification. Identification of plant dynamics plays several roles in the design of advanced control configured type spacecraft. Analytical models used to synthesize controls must be verified and subsequent modeling errors quantified. This establishes requirements for parameter insensitive capability in control system synthesis and provides criteria for evaluating the meaning and validity of ground tests. In addition, fast, efficient identification algorithms allow both evaluation of closed-loop system performance vis-à-vis the original design goal and modification of the control law based on accurate knowledge of on-orbit system dynamics.

3) Demonstration of system level architecture design techniques. The principal intent of this task is a hardware demonstration of a reconfigurable system using both system identification and resynthesis of control laws to accommodate unanticipated changes in the vehicle/payload system.

Large Momentum Exchange Device

Momentum storage requirements increase rapidly as a function of spacecraft size. Future large spacecraft will require considerably larger momentum storage and transfer capability than presently exists in the Skylab control moment gyros. The purpose of this task is to identify the requirements for future momentum storage devices and the technology developments required and to initiate development of a prototype or brassboard model of such a device. The Annular Momentum Control Device (AMCD) developments are representative of the type of technology that may be required; however, whether or not the AMCD is the proper approach is uncertain.

The necessity for this work arises from the fact that neither the requirements nor the existing technology can realistically be scaled up through the required order-of-magnitude increase in size.

The benefits of this work are to provide realistic momentum storage equipment designs and confidence in the technology necessary to support near-term large spacecraft (such as the Power Module and Erectable Space Platforms) design and development activities.

Autonomous Rendezvous and Docking

There is a gap between the technology and the proven systems for accomplishing automatic rendezvous and docking. Many techniques have been proposed and analyzed. During the Gemini/Apollo time period some of these techniques were flown in six-degree-of-freedom laboratory simulations. Actual rendezvous and docking in the U.S. space program has always been done under astronaut control, whereas the U.S.S.R. has used automatic techniques, both in near-Earth missions and in a lunar sample return.

Future applications for a fully-automated system include:

1) Planetary sample returns where the two-way light time precludes real-time manual control.
2) On-orbit assembly of large structures in high orbits, including docking and latching of very long structural interfaces.
3) Recovery or close inspection of disabled or unknown orbiting bodies.
4) Capture of asteroids or meteorites.
5) Remote resupply of spacecraft or spacelabs.

Additional Concerns for Consideration

During the discussion of the Attitude Control and Attitude Determination Panel, there were several historical deficiencies identified which could be avoided in future systems without the performance of new work in the technology, device, or technique areas. The panel, however, feels that these areas deserve centralized attention by NASA in order to exchange experience among projects and to preclude repetition of deficiencies experienced in the attitude control and determination area to date. These areas are design and testing, fault tolerance, and information exchange.

Many instances of inadequate pre-launch testing have been reported. The problem is driven by several pressures: schedule time, complexity of the hardware and software, inadequate test facilities, and weak correlation of the system requirements, its design, and the test planning.

Techniques and computer tools are evolving (primarily for use in software design and test) which could probably be adapted to overall Attitude Control and Determination (AC&D) subsystem design and test. Some of these techniques are (1) top-down structured definition of requirements and design, (2) programs for cross-checking requirements compliance and compatibility, and (3) flow charters. Although much of the AC&D system is hardware, its functions are normally modeled in software for analysis and simulation and could be made compatible with this approach.

This approach

1) Better insures that no design or test oversights exist.

2) Provides an organized approach to design and test of increasingly complex systems.

3) Helps to design a complete test program which avoids duplication, but can still highlight important parameters for trend analysis throughout the design, test, and flight.

4) Provides a clear road map to aid management in making costs and schedule decisions.

Experience has indicated the practical advantage of a broadly based approach to fault tolerance. In the specific area of AC&D, the practical utility of generically dissimilar backup approaches has been proven to substantially enhance system fault and damage tolerance, although the advantages are difficult to demonstrate using classical reliability analysis, and the additional hardware and design required is typically difficult to justify on a project-by-project basis.

Coordinated planning and requirement definition would maximize the efficiency of implementation of backup approaches, enhance the coordination of the overall AC&D system, and insure that the benefits of previous experience are realized. Many of these goals are difficult to achieve within the environment of constrained program resources.

In the attitude control area as well as in other areas of this workshop, it has been emphasized that a technology data bank should be established and maintained. In addition to including historical and general data on the various AC&D devices, it would be most helpful to share on-orbit flight successes, failures, and anomalous behavior along with a knowledgeable contact. At one point in time, NASA maintained a document similar to this in the form of nomographs. This was discontinued several years ago. In addition, the Space Systems Technical Committee of the AIAA also maintained such a log until it became too large and expensive for the organization to handle. At the present time, the panel does not know of any centralized location or summary of this information.

The panel feels that a rich legacy of spacecraft experience exists, and if it were disseminated, it would be potentially useful for future design activities. Problems already experienced could be prevented in the future.

SUMMARY OF RECOMMENDATIONS

The following paragraphs summarize the recommendations of the Attitude Control and Attitude Determination Panel.

Control Configured Vehicle Design

1) Integrate control, structure and dynamics design/selection.
   a) Establish modeling criteria, modeling, and simulation techniques
   b) Develop and demonstrate control synthesis techniques for robust/insensitive design

Control Instrumentation and Sensing

1) Develop high performance, moderate cost, long life attitude/rate sensors, such as:
   a) Gyros
   b) Solid-state Star Sensor

2) NASA support an assessment and appropriate development of non-conventional gyros (lasers, etc.).

3) NASA support development of charge transfer device star sensor technology.

Control Instrumentation

1) Develop structural position/rate sensing and techniques.

2) Develop on-board diagnostics/performance/health monitoring and assessment.

3) Develop self-test, built-in test, and integration with ground test methods.

Tolerant/Accommodating Control Systems

1) Develop methods/techniques for on-orbit and ground calibration, reconfiguration and adaptive control.

2) Develop microprocessor/array processor based structural dynamics identification algorithms.

3) Demonstrate system level architecture design techniques.

Large Momentum Exchange Device

1) Identify requirements for large momentum storage devices, and initiate prototype development of a wheel or CMG suitable for large spacecraft control.

Automated Rendezvous and Docking

1) Develop methods, sensors, and system designs for automatic rendezvous and docking. Select at least one design and demonstrate in laboratory dynamic simulation.

Additional Development Areas

The following areas were identified as ones which deserve additional attention, possibly at the Chief Engineer level, while they do not require new technology, many historical deficiencies have indicated the importance of emphasis in these areas:

1) Development of well-structured design and test techniques.
2) Establishing and maintaining a data bank in the Attitude Determination and Control Technology components and systems.
3) Consideration of dissimilar backup approaches to provide fault tolerance.