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LARGE STRUCTURE CONTROL DEVELOPMENT CONCEPTS

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This paper presents viewpoints on large structure control evolving from the solar sail study conducted recently at JPL. The objective is to make optimum use of insights gained in the study in order to assess required large structure control developments. While the Halley's comet rendezvous mission for which the sail was under prime consideration is no longer in NASA's plans, the sail is an ideal reference configuration to identify control development needs as it may have been the first large structure to be considered seriously for a near-future NASA mission.

OVERVIEW (Figure 1)

In the paper, the major sail control challenges are identified as configuration development, size and flexibility, and system uncertainty. These challenges are illustrated with the sail control design evolution. Distributed and adaptive control are identified as two major conceptual areas requiring development in order to fly the sail and more general large space structures.

- MAJOR CHALLENGES
- FUNDAMENTAL TRADEOFFS
- SOLAR SAIL CONCEPTS
- SAIL CONTROL DESIGN PROBLEMS
- REQUIRED CONTROL DEVELOPMENTS
- CONCLUSIONS

Figure 1

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SOLAR SAIL LARGE STRUCTURE CONTROL (Figure 2)

The single major sail control challenge was the development of a structure/control integrated configuration. Fundamental to configuration development were: the selection between spinning and nonspinning concepts, the definition of control mechanizations (mass expulsion, solar pressure, etc.), the design of vehicle shape to minimize disturbances including those of the solar pressure itself, and the need to provide failure protection. Of course, these considerations are common to most spacecraft designs. The unique challenge of the sail was that the control mechanization had to be an integral part of the structure not just an attachment as a gas jet would be in many current spacecraft. This challenge created a need for close working interfaces among a variety of technical disciplines such as structures, control, thermal control, etc. This point can be illustrated with the sail design evolution as discussed in the sequel.

SOLAR SAIL LARGE STRUCTURE CONTROL

- SINGLE MAJOR CHALLENGE
  - STRUCTURE/CONTROL INTEGRATED DESIGN
- FUNDAMENTAL TRADEOFFS
  - SPINNING VS NONSPINNING
  - CONTROL MECHANIZATION OPTIONS
  - ENVIRONMENTAL DISTURBANCES
  - FAILURE SENSITIVITY

Figure 2

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NONSPINNING SAIL (Figure 3)

A solar sail vehicle would have as one of its main components a large, lightweight reflective sail. Propulsive force within the solar system would be derived from sunlight reflection from the sail. Photons striking the sail would be reflected back, a change in momentum is experienced which would be expressed as a force acting on the sail. Two fundamental sail concepts were under study: nonspinning and spinning. The nonspinning sail is a three-axis stabilized vehicle formed by a sail module and a support structure. The sail has four sides and is roughly pyramidal in shape. Each side is 800 m in length, and the sail apex is 63 meters above its base.

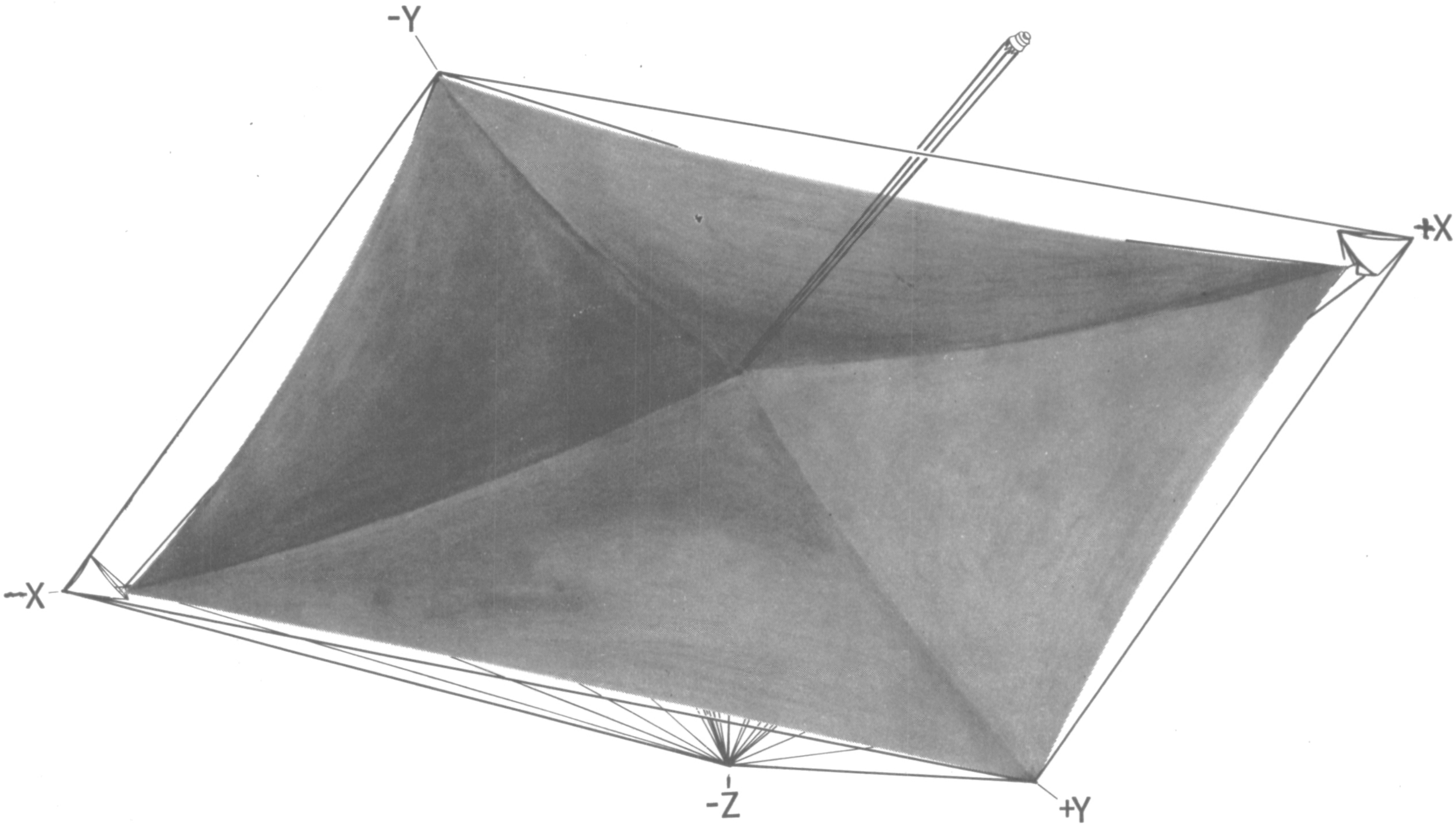
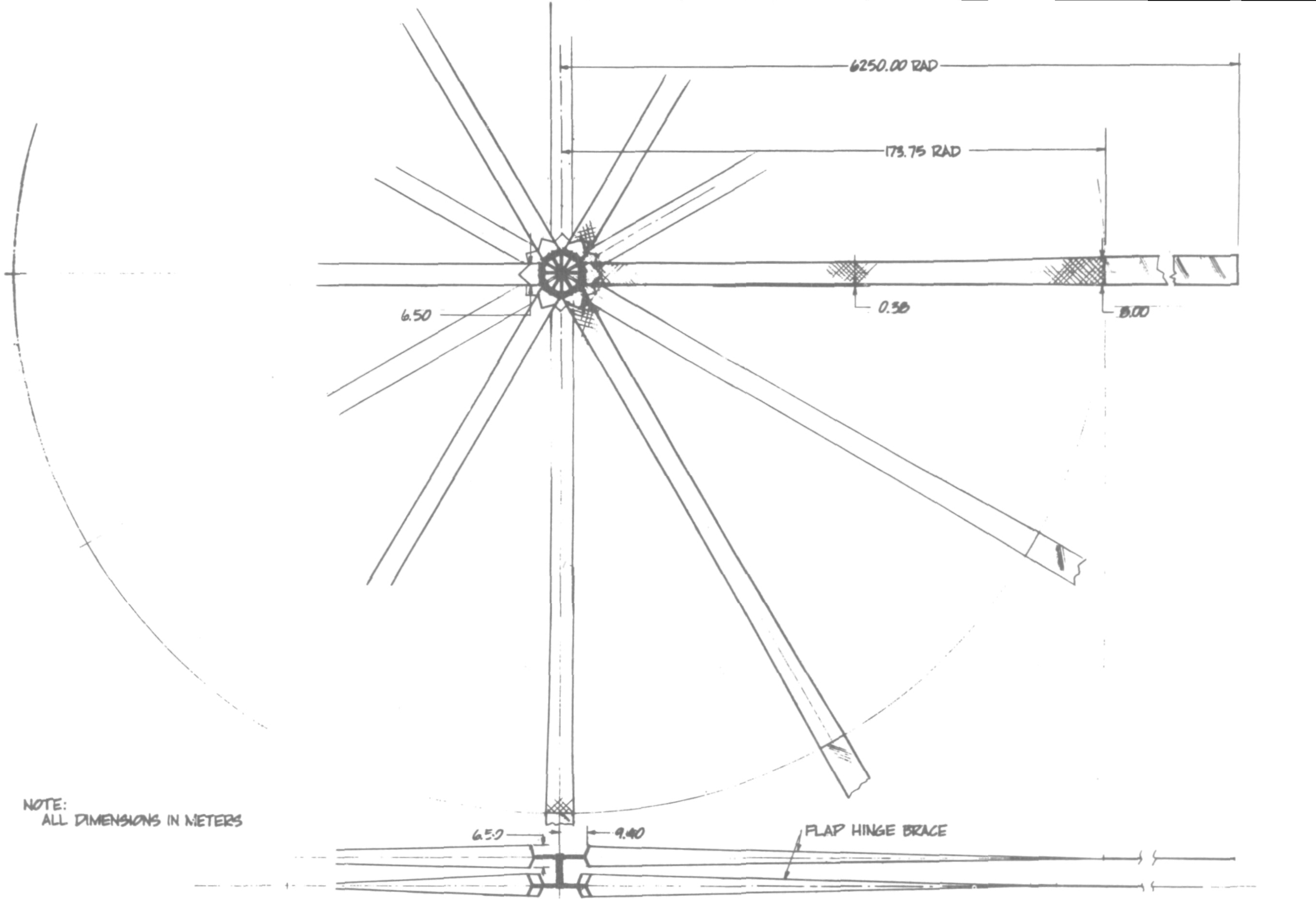


Figure 3

SPINNING SAIL (Figure 4)

The spinning sail is a long multiblade spinner based on the heliogyro concept developed by R. H. MacNeall and J. M. Hedgepeth at Astro Research Corp. in the late sixties and studied further by them and JPL in the recent studies. The heliogyro dynamics and control are very similar to those of a helicopter with control being achieved by pitching or rotation of the blades about their long axis. The nonspinning and spinning configurations were developed in parallel with the common objective among all sail team members to optimize both configurations. At a given point in time, a selection between the two was made and the heliogyro was closer to satisfying the overall mission objectives. However, the remainder of the paper concentrates on the nonspinning concept with which the author was involved primarily.



6250.00 RAD
173.75 RAD
6.50
0.38
13.00
NOTE:
ALL DIMENSIONS IN METERS
6.50
9.40
FLAP HINGE BRACE

Figure 4

NONSPINNING SAIL CONTROL CONCEPTS (Figure 5)

Many candidate concepts were studied for control of the nonspinning sail. The vane, sheet and ballast mass concepts illustrate best the sail control design evolution.

NON-SPINNING SAIL CONTROL CONCEPTS

- VANE
- SHEET
- BALLAST MASS

Figure 5

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VANE CONTROL CONCEPT (Figure 6)

The vane attitude control option uses four single-degree-of-freedom vanes to supply three-axis control. The gimbal degree of freedom for vane i (V_i) is γ_i. Pitch (x) control can be obtained by rotating V_3 through 90 deg or less, shifting the center of solar pressure along -y, and thus producing a torque about x. Similarly, yaw (y) torque is generated by rotating V_2. Roll (z) control is produced by differential rotation of V_1 and V_3, or V_2 and V_4, or both sets simultaneously. This concept was suggested by a Battelle Columbus Laboratories 1973 study and had intuitive appeal at JPL because of its similarities with thrust vector control mechanizations in recent Mariner spacecraft.

CONTROL CONCEPTS
FOUR SINGLE DEGREE OF FREEDOM VANES OPTION

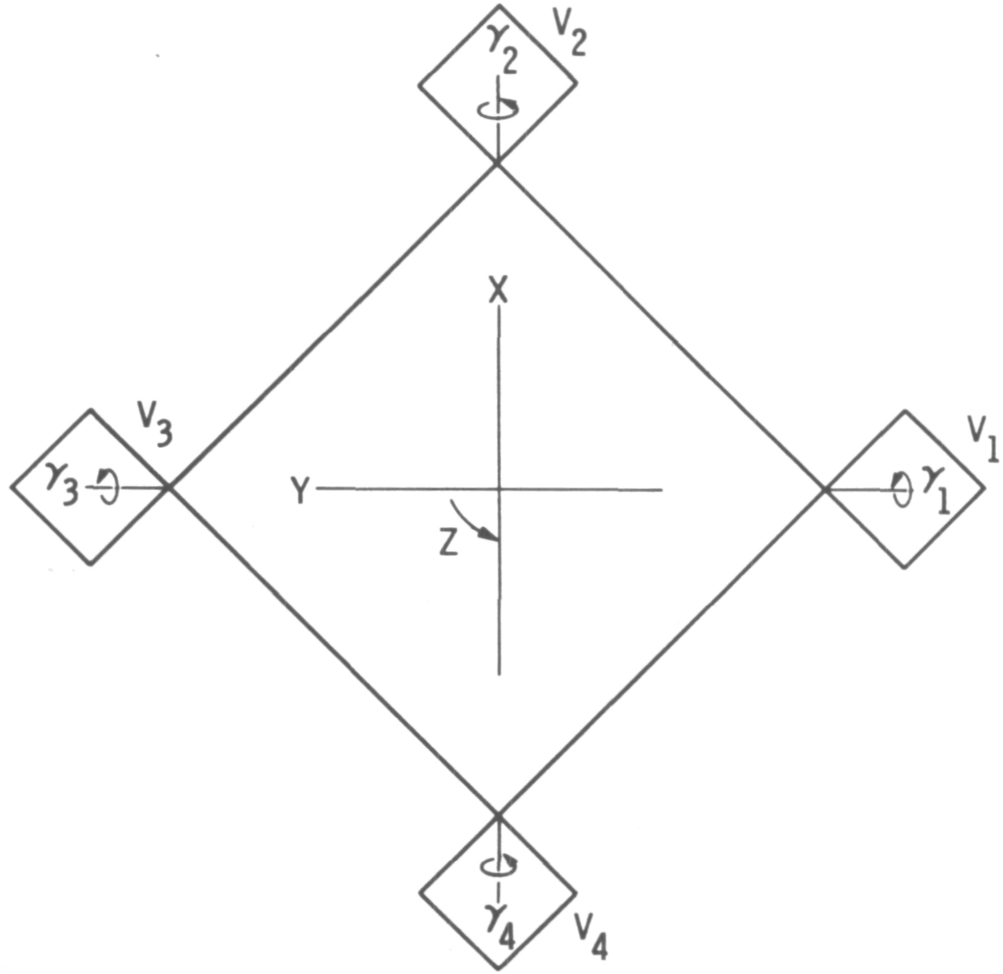

Figure 6

VANE CONTROL CONCERNS (Figure 7)

A number of limitations in the concept were, however, identified such as: large vane size (200 m on each side) required to offset huge (500 n-m) disturbance torques caused by solar pressure acting on the sail surface; packaging and deployment problems caused by large vane size; failure sensitivity, as a single vane failure implied loss of three-axis control capability; structure/control interaction, as vane rotation disturbed the main sail structure; and inaccurate control torque knowledge due to unpredictable effects such as sail deformations, nonhomogeneous sail reflectivity changes, mass and pressure center shifts, sail holes and tears, etc. For these and other reasons, the design proceeded to the sail translation concept.

VANE CONTROL CONCERNS

- LARGE VANE SIZE (200 m)
- PACKAGING AND DEPLOYMENT
- FAILURE SENSITIVITY
- STRUCTURE/CONTROL INTERACTION
- UNPREDICTABLE CONTROL TORQUES

Figure 7

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SAIL TRANSLATION CONCEPT (Figure 8)

The sail translation scheme utilizes only two vanes for roll control as described above. However, pitch and yaw control are produced by translation of the sheet material parallel to the pitch and yaw axes. This is accomplished with outhaul winch actuators at the sail corners together with inhaul winch actuators at the sail center. With the translation of vehicle mass and pressure centers, pitch and yaw torques are generated. This concept was considered attractive at first because it did not require large vanes and reduced vehicle weight by using winch actuators for the dual purpose of attitude and shape control.

CONTROL CONCEPTS
SINGLE SAIL TRANSLATION, ROLL VANES

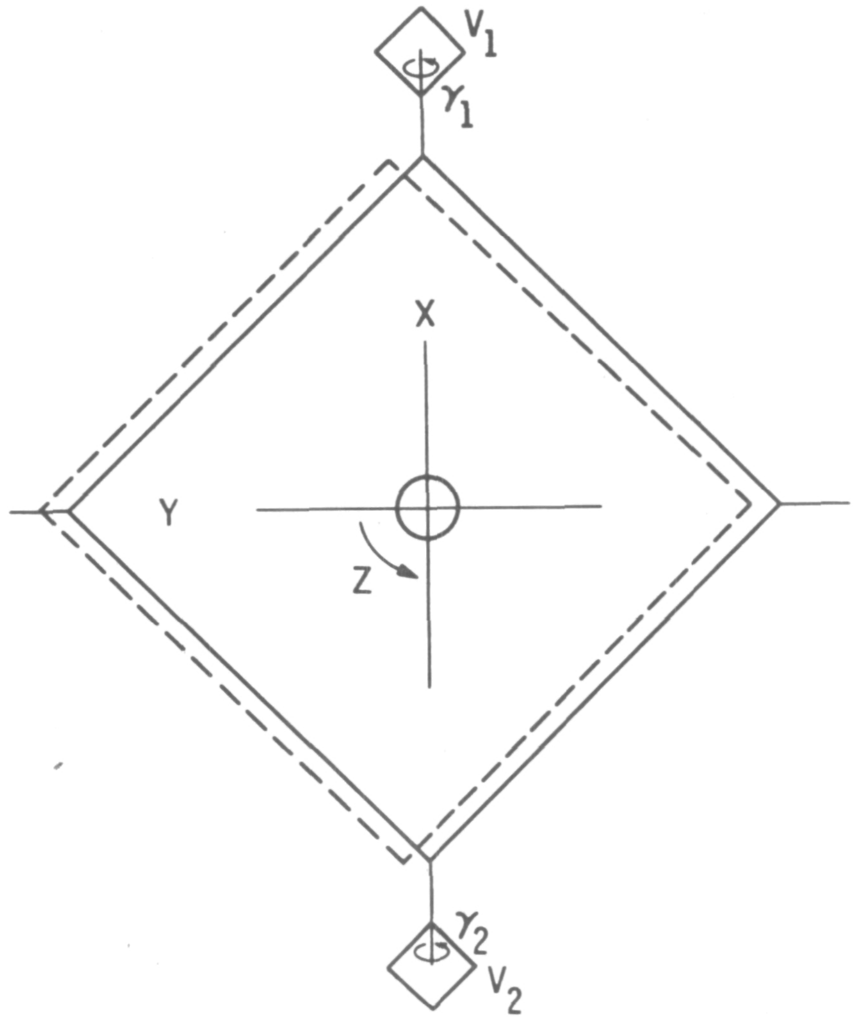

Figure 8

SAIL TRANSLATION CONCERNS (Figure 9)

Sail translation concept concerns included: the need to move half the vehicle mass (4000 kg) to accomplish the translation maneuver, sail wear due to sail distortion, failure sensitivity, structure/control interactions, complicated dynamical modeling, and inaccurate control torque knowledge as sail translation implied unpredictable sail distortions and solar pressure disturbance torques. The design proceeded to the ballast mass idea.

SAIL TRANSLATION CONCERNS

- LARGE MASS (2000 kg) MOTION
- SAIL WEAR DUE TO SAIL DISTORTION
- FAILURE SENSITIVITY
- STRUCTURE/CONTROL INTERACTIONS
- COMPLICATED DYNAMICAL MODELING
- UNPREDICTABLE CONTROL TORQUES

Figure 9

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BALLAST MASS CONCEPT (Figure 10)

In the ballast mass configuration, roll control vanes are still present. However, control for the other two axes is accomplished by pure mass center control. This is provided by suspending a ballast mass by cables from the four sail corners. The mass is located on the Sun side of the vehicle. By controlling the lengths of the cables, the vehicle mass center can be shifted in the x,y plane. Noncoincidence of the mass and pressure centers generates pitch and yaw torques.

CONTROL CONCEPTS
BALLAST MASS, VANES OPTION

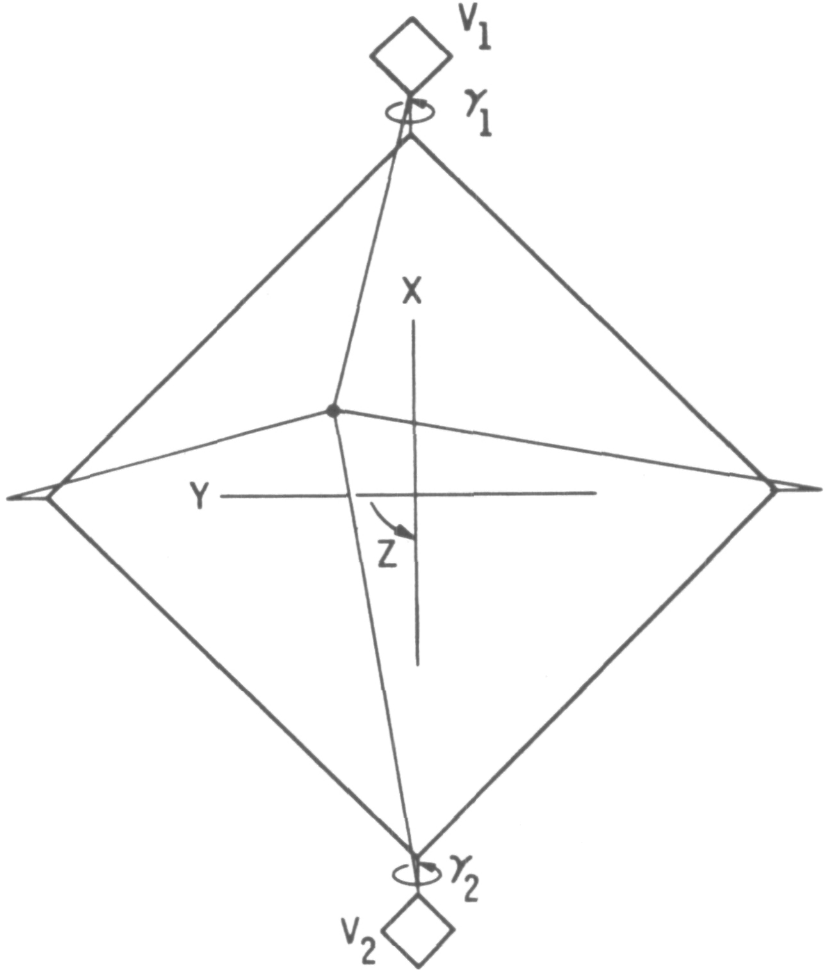

Figure 10

BALLAST MASS CONSIDERATIONS (Figure 11)

The ballast mass idea has some positive features such as its reliable mechanization by cables instead of actuators and its ability to generate large control torques with relatively small masses (100-200 kg) in spite of possible major failures in the sail sheet. There were deployment concerns because the ballast mass had to be deployed after the sail structure deployment. Inaccurate knowledge of control torques was a problem common to most of configurations studied. Although several other square sail configurations were considered, the two-vanes ballast idea was selected as the final nonspinning baseline concept in the JPL studies. Significant efforts remained to improve this design in order to overcome the many control challenges summarized in the sequel.

BALLAST MASS CONSIDERATIONS

- RELIABLE MECHANIZATION
- LARGE CONTROL TORQUES
- DEPLOYMENT CONCERNS
- UNPREDICTABLE CONTROL TORQUES

Figure 11

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SUMMARY OF SAIL CONTROL DESIGN PROBLEMS (Figure 12)

In addition to configuration development, the sail control design problems were due to vehicle flexibility and system uncertainty. Vehicle flexibility had the potential for degradation of attitude/shape control performance, implied complicated mechanization and modeling interfaces (structure, control, thermal, disturbance, etc.), and required that the controller design account for low natural frequencies within its bandwidth (0.01 - 0.001 Hz) and for system uncertainty due to inaccurate dynamic response characterization and vehicle shape knowledge. On-board thrust vector control and a high-precision low-thrust accelerometer may have been required to reduce resultant thrust vector errors.

SUMMARY OF SAIL CONTROL DESIGN PROBLEMS

- CONFIGURATION STRUCTURE/CONTROL INTEGRATED DESIGN
- VEHICLE FLEXIBILITY
  - POTENTIAL PERFORMANCE DEGRADATION
  - COMPLICATED INTERFACES
    - STRUCTURE/CONTROL
    - THERMAL
    - DISTURBANCE ENVIRONMENT
    - MODELING
  - ANALYTICAL CONTROLLER DESIGN
    - LOW NATURAL FREQUENCIES
    - SYSTEM UNCERTAINTIES

Figure 12

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REQUIRED CONTROL DEVELOPMENTS (Figure 13)

Two major conceptual areas can be identified where advances are required in order to solve problems due to size and flexibility and system uncertainty. Distributed control where the control system mechanization (actuators, sensors, etc.) are mounted throughout the structure could provide: active shape and vibration control, a potential reduction in vehicle weight, and inherent redundancy and fault tolerance. Adaptive control where the control system monitors and adjusts its own performance could provide: vehicle autonomy, a trend toward performance optimization, and fault tolerance/correction including automatic transfer of the vehicle to a safe operational state in case of major failures (e.g. a sail tear). Vehicle autonomy also implies nondedicated mission operations. There is agreement among the NASA centers participating in the LSST program on the need for developments in these two areas. The following outline presents a view of what may be involved in these developments.

SUMMARY OF SAIL CONTROL DESIGN PROBLEMS

- SYSTEM UNCERTAINTY
  - VEHICLE DYNAMICS RESPONSE CHARACTERIZATION
    - CONTROL TORQUES
    - STRUCTURAL FREQUENCIES/MODE SHAPES
    - DAMPING
  - SAIL SHAPE KNOWLEDGE
    - DISTURBANCE TORQUES
    - RESULTANT THRUST VECTOR

Figure 13

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DISTRIBUTED CONTROL DEVELOPMENT CONSIDERATIONS (Figure 14)

Advances are required in the areas of mechanization definition, modeling, analytical controller design and flight performance verification. Structure, control, disturbance, etc. models with clean interfaces are required for pre-flight analysis and controller design. Models are not end items but are intended to provide optimum support to the large structure control developments. Analytical controller design includes control hardware placement, reduced-order controller design (due to the large number of degrees-of-freedom characterizing a large structure), and adaptive control. Flight data analysis is required for in-flight dynamic response evaluation, control system and vehicle calibrations, and overall reduction in system uncertainty.

REQUIRED CONTROL DEVELOPMENTS

- DISTRIBUTED CONTROL
  - SHAPE, VIBRATION CONTROL
  - REDUCE VEHICLE WEIGHT
  - REDUCE ACTUATOR SIZE
  - REDUNDANCY / FAULT TOLERANCE
- ADAPTIVE CONTROL
  - VEHICLE AUTONOMY
  - PERFORMANCE OPTIMIZATION
  - FAULT TOLERANCE/ CORRECTION
  - NONDEDICATED MISSION OPERATIONS

Figure 14

SUMMARY (Figure 15; Figure 16)

The single major sail control challenge was configuration development, as illustrated by its design evolution. Other challenges are due to size and flexibility and system uncertainty. Advances are required in the areas of distributed and adaptive control for active attitude/shape control and to provide vehicle autonomy and reduce system uncertainty. Although distributed and adaptive control may not necessarily be required in all cases, these two areas have the best potential for providing a systematic solution to the challenges of large structure control.

DISTRIBUTED CONTROL DEVELOPMENTS

- MECHANIZATION
  - SURFACE SENSING SYSTEMS
  - ACTUATING SYSTEMS
  - COMPUTER NETWORKS
- MODELING
  - STRUCTURE, CONTROL, DISTURBANCE, ETC. PRE-FLIGHT DYNAMIC MODELING
  - MODEL ORDER REDUCTION FOR CONTROL DESIGN
- ANALYTICAL CONTROL DESIGN
  - CONTROL HARDWARE (SENSOR, ACTUATOR, ETC.) PLACEMENT
  - REDUCED-ORDER CONTROLLER DESIGN
  - ADAPTIVE CONTROL
- IN-FLIGHT PERFORMANCE VERIFICATION
  - FLIGHT DATA PROCESSING
  - ANALYTICAL MODEL VERIFICATION

Figure 15

SUMMARY

SINGLE MAJOR CHALLENGE: CONFIGURATION DEVELOPMENT

PROBLEMS:

- SIZE AND FLEXIBILITY
- SYSTEM UNCERTAINTY

ADVANCES:

- DISTRIBUTED CONTROL
- ADAPTIVE CONTROL

Figure 16