CONTROL CONCEPTS FOR LARGE SPACE STRUCTURES

R. C. QUARTARARO

ROCKWELL INTERNATIONAL
JANUARY, 1978

CONTROL CONCEPTS FOR LARGE SPACE SYSTEMS

INTRODUCTION (Chart 1)

The large space systems planned for the next decade and beyond present a major challenge to control engineers. Many control technology advancements will be required to satisfy new requirements.

A comprehensive program to develop the required control technology has been started at Rockwell International's Space Division. A few of the concepts under consideration for attitude, figure, and vibration control of large, flexible space systems will be highlighted in this presentation. In addition, an overview of the Space Division's IR&D program will be presented. The direction of the IR&D program has been influenced by requirements for electro-optical systems, Shuttle erectable structures and Satellite Power Stations (SPS).

CONTROL CONCEPTS FOR LARGE SPACE SYSTEMS

- ADVANCEMENTS REQUIRED FOR CONTROL OF LARGE SPACE SYSTEMS

- CONCEPTS UNDER DEVELOPMENT AT ROCKWELL
  - ATTITUDE CONTROL
  - FIGURE CONTROL
  - VIBRATION CONTROL

- IR&D PROGRAM HAS BEEN DRIVEN BY
  - ELECTRO-OPTICAL SYSTEMS (5-50 METERS)
  - SHUTTLE ERECTABLE STRUCTURES (100-1,000 METERS)
  - SPACE POWER SYSTEMS (1-30 KILOMETERS)

NEW CHALLENGES (Chart 2)

The need for control system advancements stems from the many new challenges resulting from the greater size and new performance requirements for large space systems. In order to accommodate the many new aspects of large space systems, advancements are required in all areas of control technology. New control concepts are needed to cope with the problems of all-flexible systems; upgraded analytical techniques and computer programs are needed for the more demanding problems of synthesizing a control system for spacecraft with distributed actuators and uncertain dynamics, and systems which must perform attitude, vibration and figure control simultaneously; new sensors and actuators are needed to provide much larger control forces and to deal with the new problems of structural control; improved control electronics with greater capacity and longer life are required; and laboratory and flight experiments will be needed to verify newly developed concepts and hardware and to provide a data base to aid designers of operational systems.

NEW CHALLENGES

NEW CONTROL REQUIREMENTS

INCREASED SIZE ⟹

- GREATER ENVIRONMENTAL EFFECTS
- LARGER CONTROL TORQUES AND FORCES ✓
- MORE FLEXIBLE ✓
- NO FULL-SCALE GROUND TESTS
- SPACE ASSEMBLY

NEW PERFORMANCE REQUIREMENTS ⟹

- ACTIVE FIGURE CONTROL ✓
- RAPID MANEUVERS OF LARGE SYSTEMS ✓
- ORBIT TRANSFER OF LARGE SYSTEMS
- LONGER LIFE

ADVANCEMENTS NEEDED

- CONTROL CONCEPTS ✓
- ANALYTICAL TECHNIQUES, COMPUTER PROGRAMS
- SENSORS, ACTUATORS
- ELECTRONICS
- LAB AND FLIGHT EXPERIMENTS

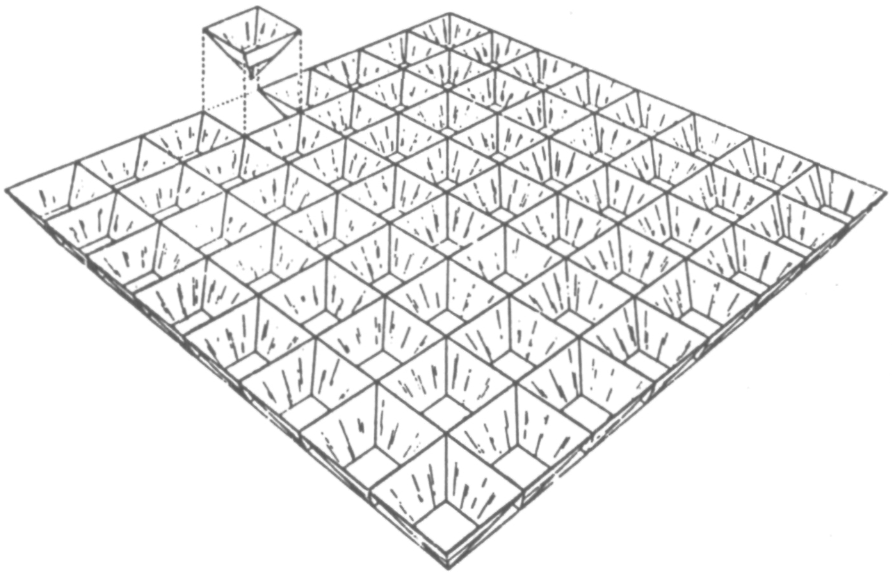
CONTROL CONCEPTS (Charts 3 - 10)

Control concepts are required to deal with requirements of varying degrees of difficulty, as can be illustrated by results from a recent study of Shuttle erectable structures performed by Rockwell for LaRC.* Chart 3 pictures a high concentration ratio solar array which could be erected from the Shuttle by using struts of practical minimum gauge and lengths compatible with the Shuttle bay to form the structural truss work. Such a system exhibits a relatively high fundamental vibration frequency for sizes up to 1 kilometer by 1 kilometer. If a 1200m x 1200m array, or smaller, is in low Earth orbit and required to point towards the Sun with 1° accuracy, it will "appear" to the attitude control system to be rigid. That is, the control system will not excite significant vibrational motions, and there will be no possibility of unstable interactions between the structure and the attitude control system. The attitude of solar arrays of this class can be controlled by conventional techniques with scaled-up actuators.

Structural vibrations can couple with the control system and they can be excited by oscillating gravity gradient torques if the array is larger than 1200m x 1200m. In general, this larger class of vehicles requires a structural vibration control system. The complexity of the control system increases as the number of vibration modes in the <0.04 Hz range increases. New concepts are required for all-flexible systems in which many vibration modes must be controlled.

A new class of control problems is also introduced if there is an additional requirement to accurately maintain a prescribed structural figure (shape).

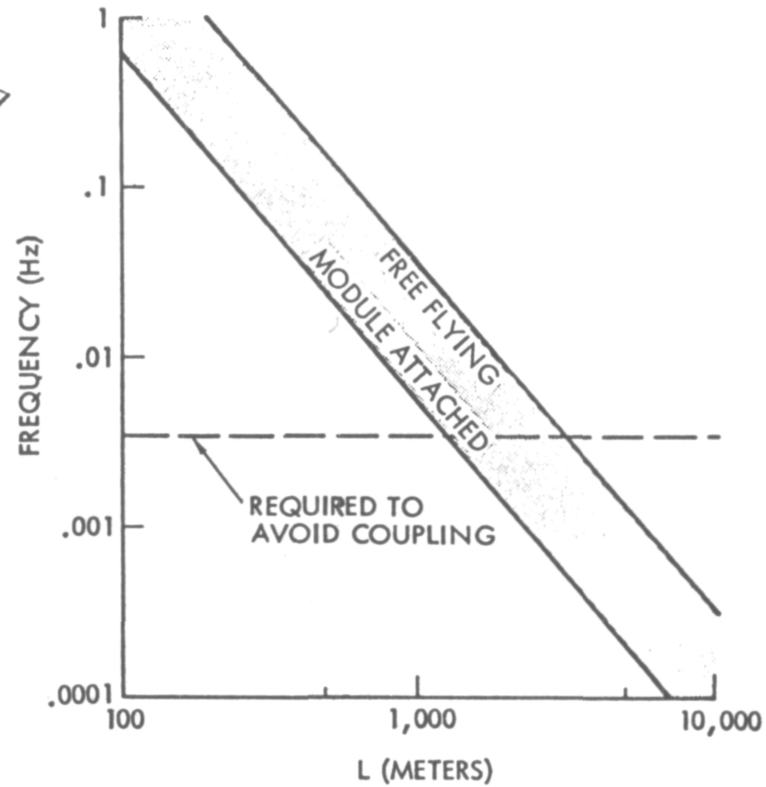
*Reference: NASA CR-145206, "Advanced Technology Laboratory Program for Large Space Structures, "Parts 1 & 2, Final Report," Revised May 1977



HIGH CONCENTRATION RATIO SOLAR ARRAY

- L × L × 14.26 M
- PENTAHEDRAL TRUSS
- 1° POINTING
- LOW EARTH ORBIT
- GRAVITY GRADIENT

FUNDAMENTAL VIBRATION FREQUENCY

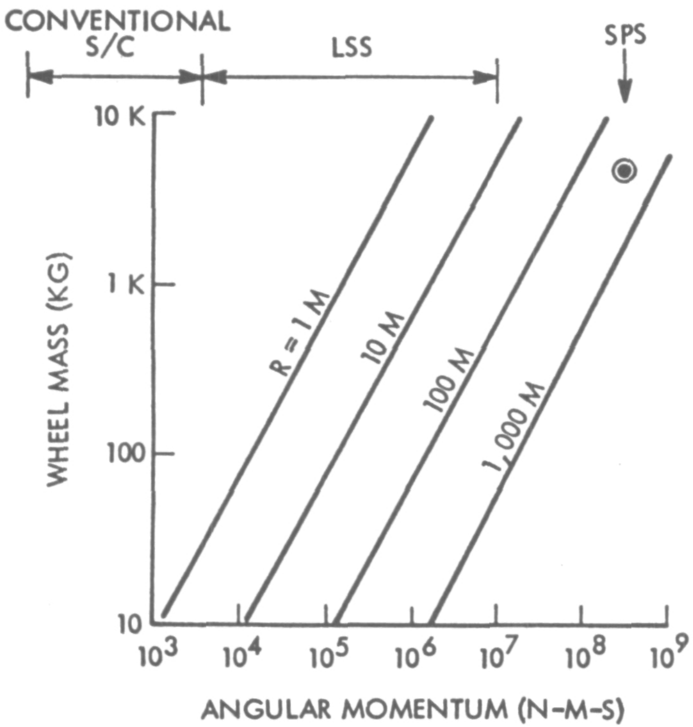


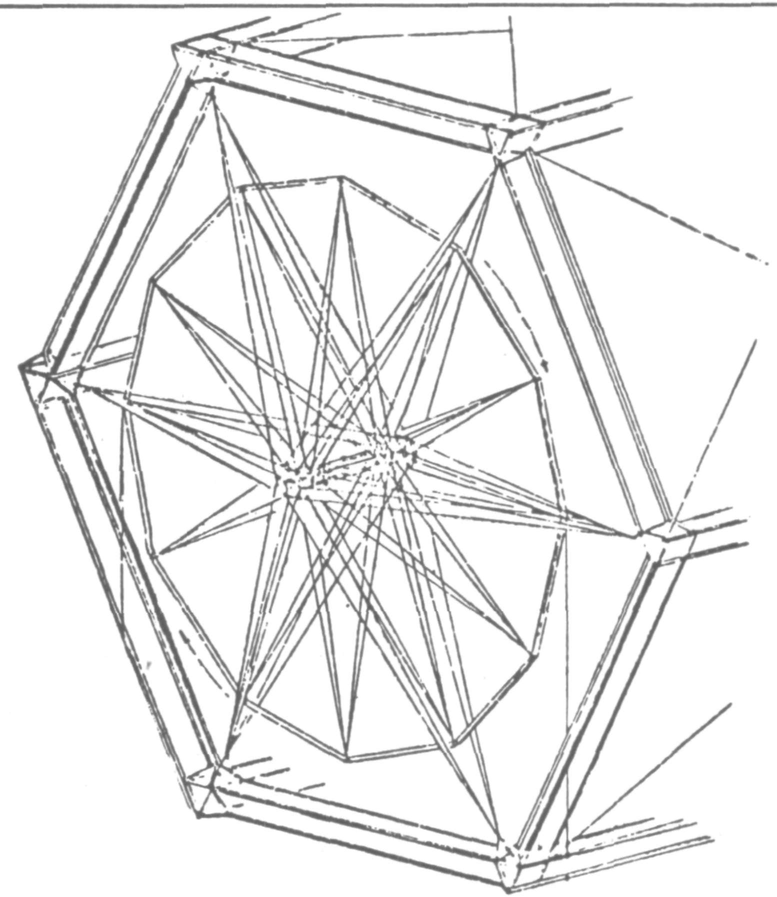
MOMENTUM WHEELS

Chart 4 addresses the application of momentum-storage attitude-control techniques to systems for which scaled-up conventional techniques are applicable. The parametric plot of wheel mass versus angular momentum storage requirement for various wheel radii indicates that there is a great saving in wheel mass if the wheel's radius is increased. For example, a large space system which must store 10^5 n-m-s will require several wheels having a total mass approximately 1,000 kilograms if the wheel radii are 1 meter; but a 100 kilogram wheel will suffice if a 10 m radius is selected. A point design for an SPS wheel is pictured in the right half of Chart 4.

The more demanding challenges of vibration and figure control of a large, flexible space structure have been addressed at Rockwell. Much of the effort has dealt with the application modal control techniques. With this method, all (attitude, vibration and figure) small displacements of the vehicle are represented as a summation of modal vectors (shape functions). One special method for controlling modal displacements - independent mode control - has been applied in large space system studies. The concept involves the simultaneous use of several actuators to force displacements in one mode without disturbing some other modes. The concept is illustrated by comparing it with a more "conventional" approach.

MOMENTUM WHEELS FOR ATTITUDE CONTROL





SPS DESIGN EXAMPLE

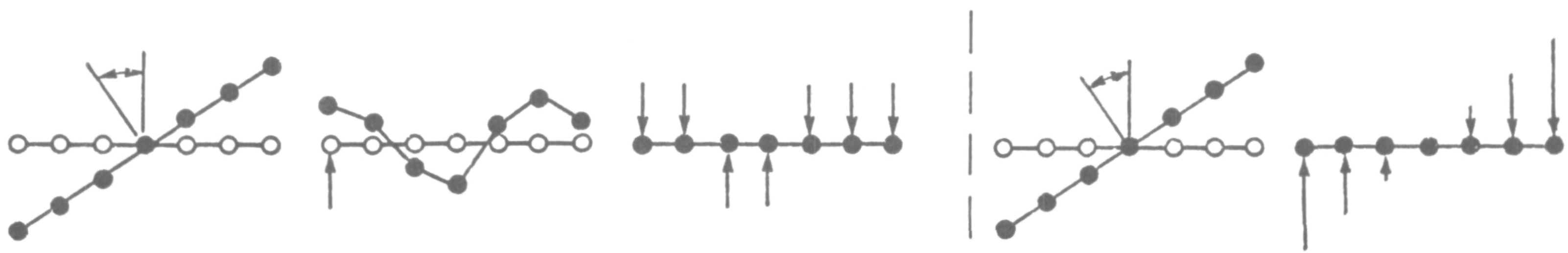
- RADIUS: 350 M
- MAX SPEED: 6.1 RPM
- MTL: ALUMINUM
- FREQ: 0.22 Hz

INDEPENDENT MODE CONTROL

The schematic sequence in the lower left portion of Chart 5 illustrates a method for correcting the attitude of a flexible space system. Jet firings made to correct an attitude error are shown to excite vibrational motions which are then settled by an active or passive vibration control scheme. In contrast, an independent mode controller corrects an attitude error by firing several jets (or combinations of jets and structural actuators) with the relative ratio of forces selected to cause attitude motions without exciting low frequency vibrational motions. Thus, the attitude error can be corrected without inducing unwanted vibration oscillations. This control concept is also applicable to figure control.

INDEPENDENT MODE CONTROL

- APPLICABLE TO ATTITUDE, FIGURE AND VIBRATION CONTROL
- MODAL REPRESENTATION: DISPLACEMENT = SUMMATION OF SHAPE FUNCTIONS (MODES)
- INDEPENDENT MODE CONTROL
  - FORCE ONE MODE WITHOUT FORCING OTHERS
  - SIMPLIFIES CONTROL SYNTHESIS
  - ELIMINATES SOME INTERACTIONS
  - INSIGHT



- INITIAL ATTITUDE ERROR
- ATTITUDE CONTROL CAUSES VIBRATION
- VIBRATION CONTROL
- INITIAL ATTITUDE ERROR
- CORRECT WITHOUT VIBRATION

CONTROL CONCEPTS, MODAL CONTROL

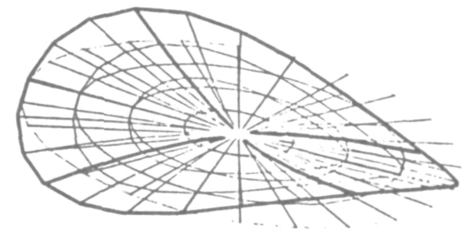
The next two charts (Charts 6 and 7) illustrate an application of independent mode control to a 300 meter, Shuttle-erectable platform. The vehicle modes (Chart 6) include six rigid body modes to represent translational and rotational motions with no structural distortion. The first nine modes (six rigid body plus three vibration) can be controlled independently by nine or more actuators. For illustrative purposes, nine thrusters are employed. (In practice, some structural actuators would be used).

CONTROL CONCEPTS
MODAL CONTROL EXAMPLE

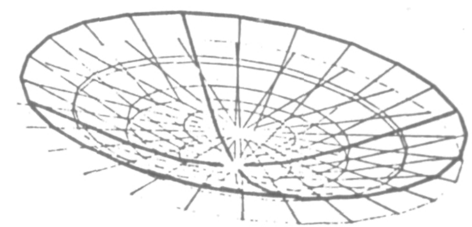
MODES FOR A 300 METER PLATFORM

453590 kg (1,000,000 lb) MISSION EQUIPMENT
22680 kg (50,000 lb) STRUCTURE

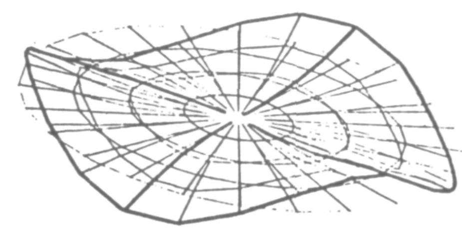
MODE NUMBER	FREQUENCY (Hz)
1-6	0
7	0.191
8	0.191
9	0.329
10	0.447
11	0.447
12	0.753
13	0.753
14	0.795
15	0.795
16	1.24
17	1.24



$f_7 = 0.191$ Hz



$f_9 = 0.329$ Hz



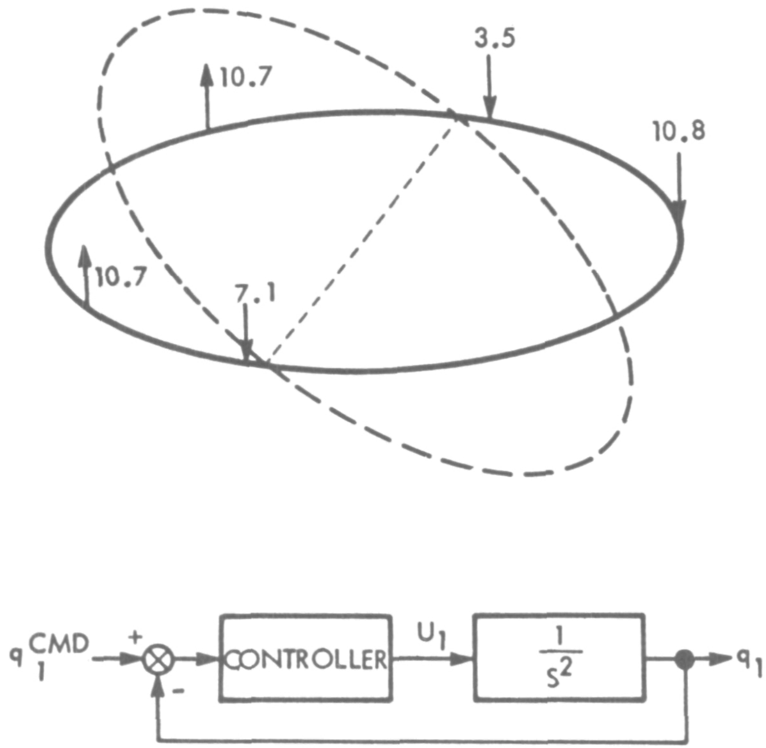
$f_{10} = 0.447$ Hz

CONTROL CONCEPTS, MODAL CONTROL (Continued)

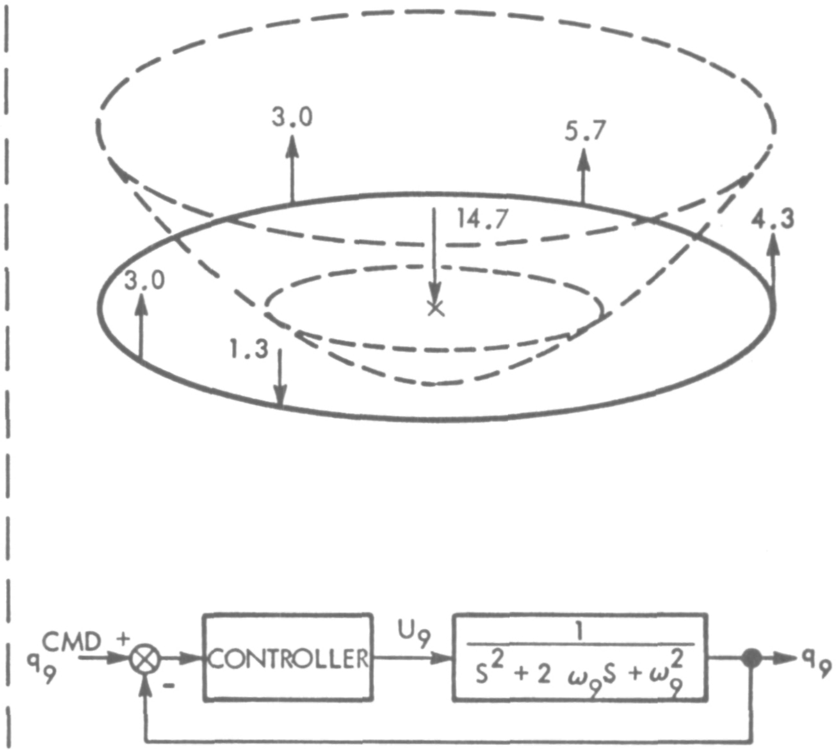
Control of two of the modes is illustrated in Chart 7. The nonzero forces which must be applied are indicated. The control forces must be applied so as to preserve the ratio of forces illustrated. The absolute force level is determined by the control system, and each mode is controlled by a single, independent control loop.

CONTROL CONCEPTS
MODAL CONTROL EXAMPLE (CONTD)

INDEPENDENT MODE CONTROL



RIGID BODY (POINTING) MODE



3rd VIBRATIONAL MODE

MODE CONTROL CONSIDERATIONS

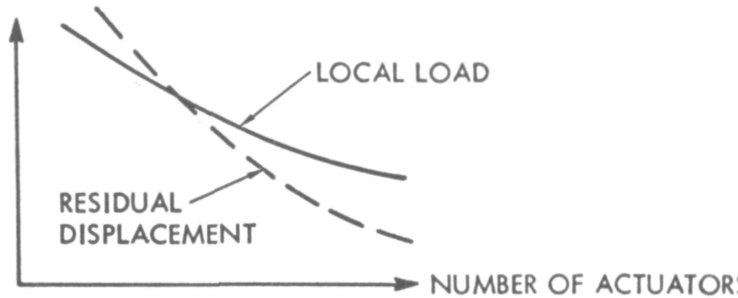
Important considerations in designing a mode controller (independent or otherwise) are listed in Chart 8. The number and placement of actuators must be carefully selected in order to limit the force required to displace the controlled modes while simultaneously limiting the displacements in the uncontrolled modes. The types of actuators selected may also have a significant affect on performance. As the number of modes to be controlled increases, the system's dynamic behavior (at least as determined by unconfirmed analyses) becomes more uncertain and adds to the difficulty in locating actuators and establishing force ratios.

MODE CONTROL CONSIDERATIONS

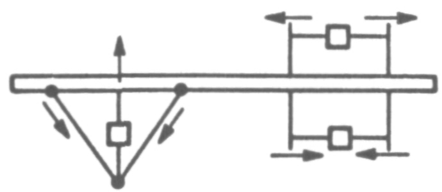
- PLACEMENT OF ACTUATORS

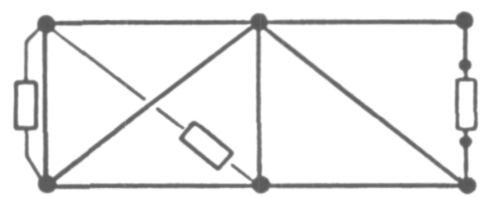
LOCATION CRITERIA: MINIMIZE $\dfrac{\text{(DISPLACEMENT IN UNCONTROLLED MODES)}}{\text{(DISPLACEMENT IN CONTROLLED MODES)}}$

- NUMBER OF ACTUATORS



- TYPES OF ACTUATORS





- MODEL UNCERTAINTIES

UNCERTAINTY INCREASES AS NUMBER OF MODES TO BE CONTROLLED INCREASES

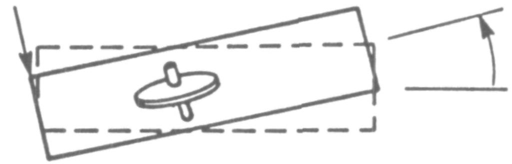
TWO-BODY CONTROL

Another concept under development at the Space Division is two-body control (Chart 9), which provides advantages for some large systems which must reorient rapidly. It is accomplished by dividing a vehicle into two parts, the pointed and the reaction bodies, connected by a two-axis gimbal. The pointed body is reoriented by activating the interbody gimbal drive.

In one study of a system involving the four features noted at the bottom of the chart, the two-body concept was found to be significantly lighter.

TWO-BODY CONTROL

- ALTERNATIVES FOR RAPID REORIENTATION
  - CMG's
  - THRUSTERS
  - TWO-BODY CONTROL



- TWO-BODY CONTROL OFFERS ADVANTAGES FOR SOME APPLICATIONS
  - POINTING WITHIN SEVERAL DEGREES OF NOMINAL POSITION
  - LARGE VEHICLE
  - POINTED BODY LARGE FRACTION OF VEHICLE
  - RAPID REORIENTATION

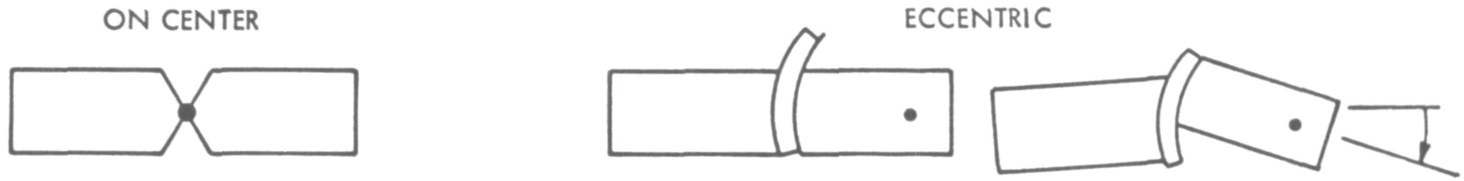
TWO-BODY CONTROL, GIMBAL DEVICES

A variety of gimbal devices are available; and they may be divided into two general categories (Chart 10) - on center (hinge-like) and eccentric. Both translation and rotation take place in eccentric gimbals to provide an apparent pivot point projected forward of the mechanism. Selection of the preferred gimbal device is based on trade studies involving type, pivot location, drive torque, and gimbal relative displacements. One recent study favored an eccentric gimbal.

Applications requiring high-torque reorientation followed by very precise pointing can be accomplished by using the interbody gimbal to produce very large torques together with a smaller CMG for vernier control and precision pointing. (See bottom of Chart 10).

TWO-BODY CONTROL

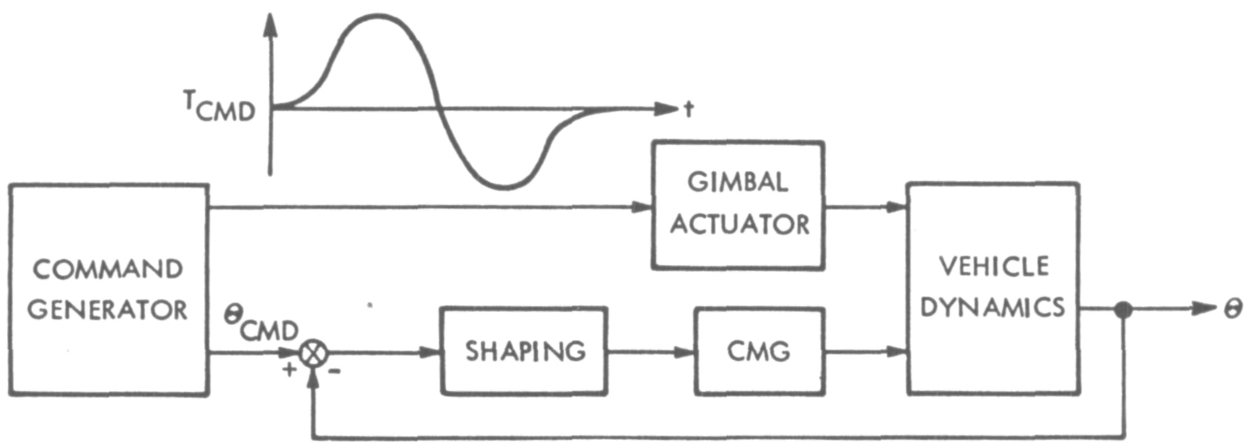
- GIMBAL TYPES



- TRADES

PIVOT LOCATION VERSUS TORQUE, GIMBAL ROTATION, AND GIMBAL TRANSLATION

- LARGE-ANGLE AND PRECISION POINTING



ROCKWELL IR&D PROGRAM

The foregoing discussion highlighted some developments studied in Rockwell's IR&D program. Those concepts were studied in the "Control of Large Space Systems" project, which started in mid-1976, and the "Precision Point" project (Chart 11). So far, the IR&D program has been analytically oriented, but that will soon change with start of new project to construct a flexible vehicle control simulator in the laboratory.

CHART 11

ROCKWELL IR&D PROGRAM FOR CONTROL OF LARGE SPACE SYSTEMS