SYSTEM DYNAMICS AND SIMULATION OF LSS

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SYSTEM DYNAMICS AND SIMULATION OF LSS (Figure 1)

Large Space Structures have many unique problems arising from mission objectives and the resulting configuration. Inherent in these configurations is a strong coupling among several of the designing disciplines. In particular, the coupling between structural dynamics and control is a key design consideration. The solution to these interactive problems requires efficient and accurate analysis, simulation and test techniques, and properly planned and conducted design trade studies. This paper deals with these subjects and concludes with a brief look at some NASA capabilities which can support these technology studies.

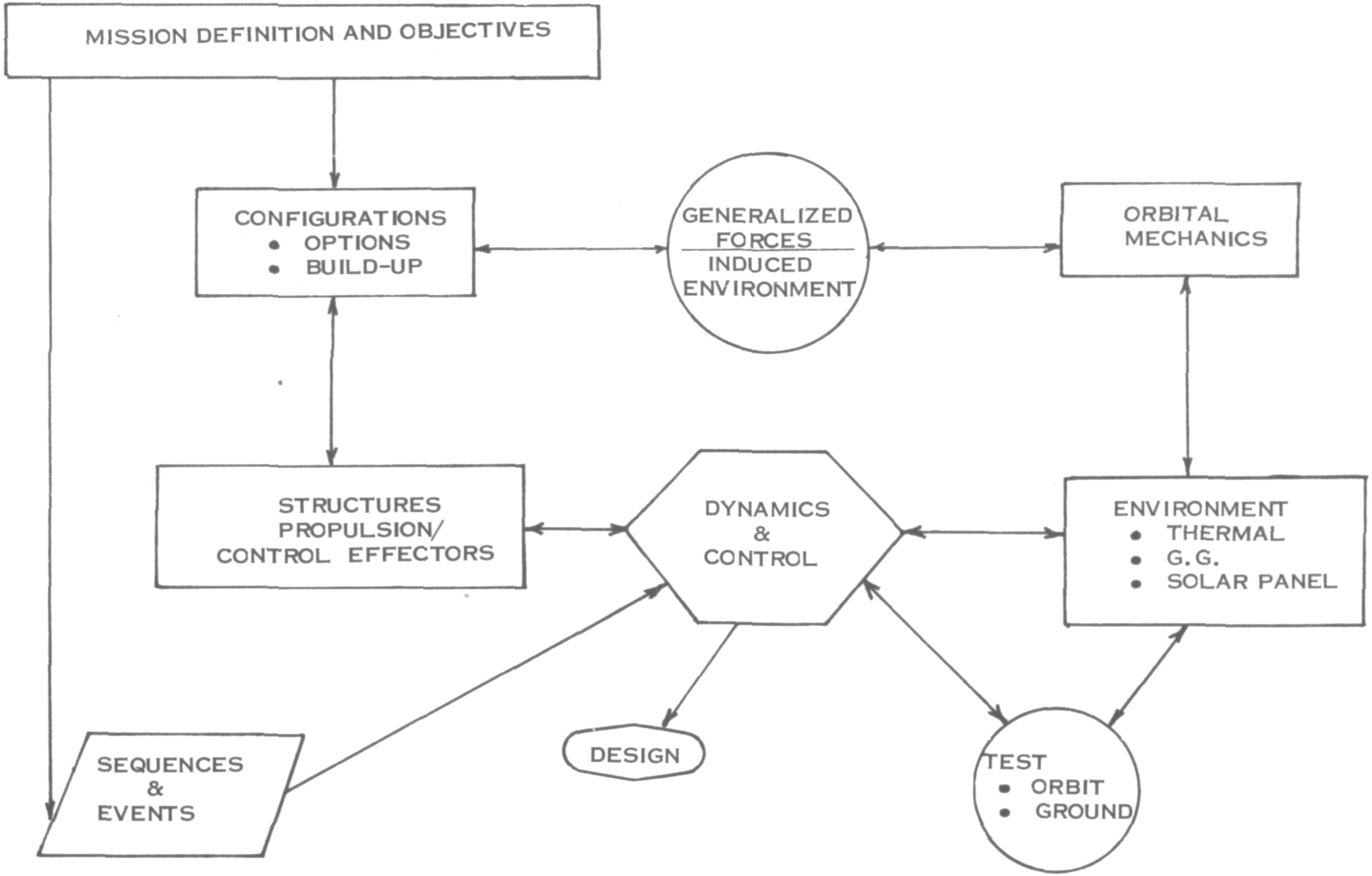
SYSTEM DYNAMICS AND SIMULATION OF LSS

- CHARACTERISTICS OF SYSTEM DYNAMICS
- THE ROLE OF SIMULATIONS
- STATE-OF-THE-ART LIMITATIONS
- TECHNOLOGY REQUIREMENTS/PLANS
- NASA FACILITIES TO COMPLEMENT PLANS

Figure 1

SYSTEM DYNAMICS (Figure 2)

Experience during Skylab and now with Space Shuttle has taught the necessity of assuming a system focus during concept and design. In these two programs, there occurred a strong bonding among dynamics, control, aerodynamics, trajectories, and environment. In addition, large sensitivities in response occurred for small changes in system parameters. These are aggravated by the multibody configurations and nonlinearities arising from many joints. The same generic problems of multibody, multijointed, constraining control requirements and unique environments recur for LSS and demand the same system focus. This chart depicts the disciplines envisioned as being important in an interactive mode for LSS. Starting with the mission definition objectives, one can define configuration options and sequence of events, then proceed to conduct trade studies in order to understand the system and arrive at the optimum configuration and design. More than one configuration is required to achieve an optimized design since critical use must be made of configuration options, control system capabilities, materials, and manufacturing and assembly approaches. All arrows go in both directions depicting trade studies and feedbacks which are among two or more disciplines and within the total system to insure success. In summary, system analysis is a necessary focus for the technology phase to insure a successful program.



SYSTEM DYNAMICS DEFINED: THE CHARACTERIZATION OF A SPACE VEHICLE SYSTEM THROUGH SIMULATION OF DISCIPLINES THAT STRONGLY COUPLED WITH OR INFLUENCE THE DYNAMICS AND ASSOCIATED TRADE STUDIES NECESSARY FOR EFFICIENT DESIGN.

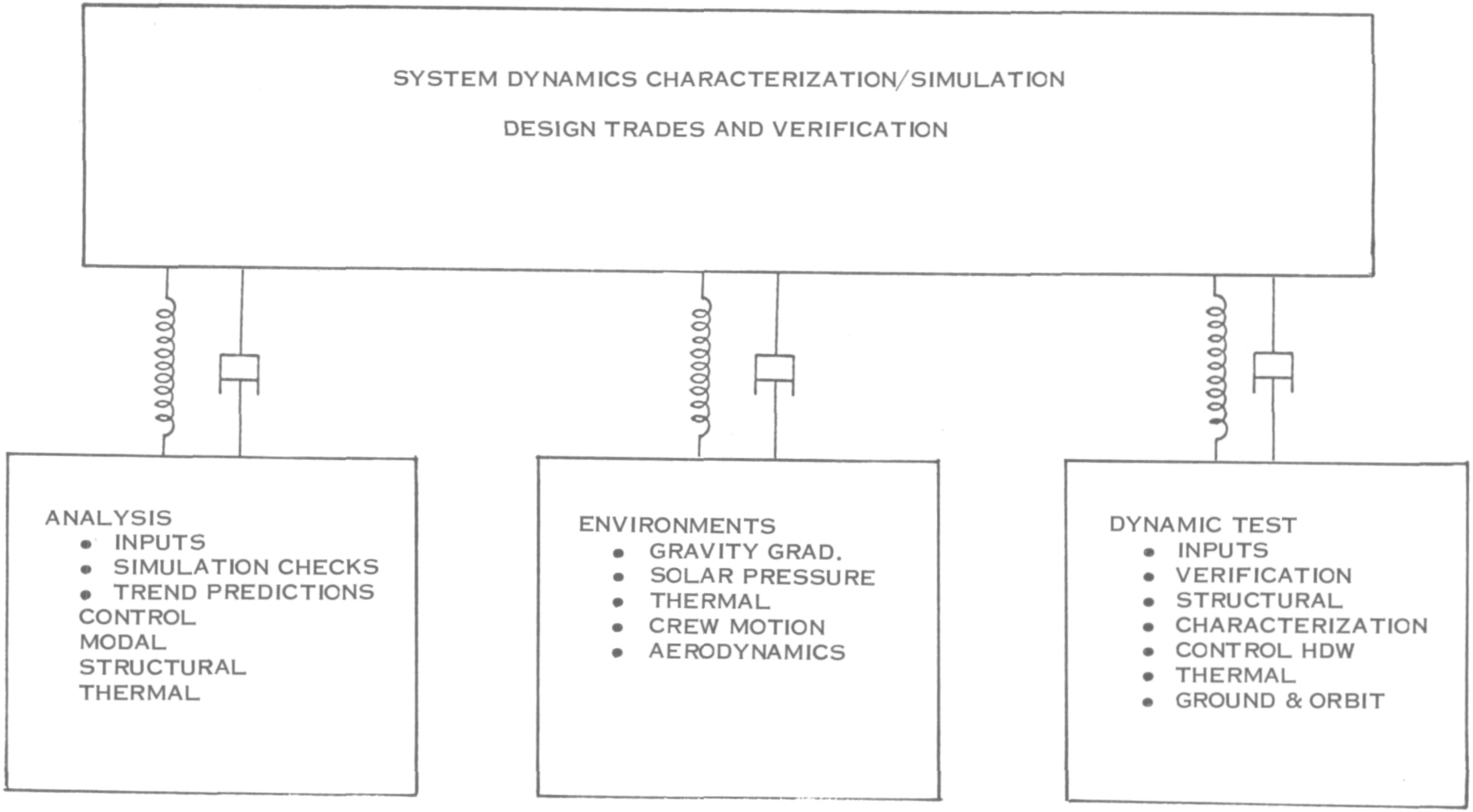
Figure 2

THE ROLE OF SIMULATORS (Figure 3)

The previous chart addressed the need for detailed systems analysis. This chart addresses the roles of simulation, analysis, and test. Simulation of the system, as discussed previously, is one key to proper design. It is the tool that can efficiently accomplish the inter-discipline trades required. Analysis supports the simulation by providing input check cases for the simulation and trends. Experiences on Skylab and Shuttle have demonstrated the merit of using very simplified analysis to bracket parameters and show trends, using the complex simulations for detail trades and design. The incorporation of springs and dampers between the support efforts and simulation was deliberate to demonstrate that this support must be a dynamic interaction with damped characteristics. This implies information feed forward and back. Environment was separated from test and analysis for emphasis, even though it splits between the two. The accurate prediction of critical environments is mandatory for unconservative design. Test is very important in terms of input data and verification. Although no interaction is shown between analysis and test, obviously there is one. With Large Space Structures, there exists a complex trade required among control system complexity, accuracy of structural characterization, analysis, and test requirements.

A brief look has been taken at the role of the different aspects of system dynamics in development of the LSS program. The next two charts address state-of-the-art limitations and LSS technology needs in these areas.

THE ROLE OF SIMULATORS



SYSTEM DYNAMICS CHARACTERIZATION/SIMULATION

DESIGN TRADES AND VERIFICATION

ANALYSIS
- INPUTS
- SIMULATION CHECKS
- TREND PREDICTIONS

CONTROL
MODAL
STRUCTURAL
THERMAL

ENVIRONMENTS
- GRAVITY GRAD.
- SOLAR PRESSURE
- THERMAL
- CREW MOTION
- AERODYNAMICS

DYNAMIC TEST
- INPUTS
- VERIFICATION
- STRUCTURAL
- CHARACTERIZATION
- CONTROL HDW
- THERMAL
- GROUND & ORBIT

Figure 3

STATE-OF-THE-ART LIMITATIONS (Figure 4)

Limitations in the state-of-the-art technology in the areas of analysis, test, and simulations are well known. A partial summary of these limitations is shown on this chart. Basically, analysis is limited to linear approaches or very simplified nonlinear ones. Test is basically high g with size limitations and inefficient data acquisition and evaluation approaches. Simulations have been very useful but are limited in the degrees of freedom that can be simulated. Facilities cost can be excessive unless all the stops are pulled in terms of ingenuity and skills. Large space structure technology requirements follow.

SIMULATIONS:

- LIMITED DEGREES OF FREEDOM
- BASICALLY ONE G
- FACILITIES/COST
- INEFFICIENT WITHOUT ANALYSIS SUPPORT FOR TREND

ANALYSIS:

- STRUCTURAL INTERACTION
  - DIGITAL CONTROL SYSTEMS (FIXED SINGLE SAMPLE RATE) AND CONTINUOUS CONTROL SYSTEM
  - PARTIAL STATE FEEDBACK, ANALOG, AND DIGITAL FILTERS
  - PRIMARILY LINEAR
  - LIMITED DEGREES OF FREEDOM
- STRUCTURAL DYNAMICS
  - PRIMARILY LINEAR
  - FINITE ELEMENT
  - MODAL SYNTHESIS
  - SUBSTRUCTURING

TEST:

- ONE G EXCEPT SMALL SCALE MODELS
- PRIMARILY GROUND TEST
- EXCITATION POINT FORCE SHAKER
- TIME CONSUMING
  - RANDOM EXCITATION (EXCESSIVE EVALUATION)
  - MODAL EXCITATION (EXCESSIVE TEST TIME)
- TEST/ANALYSIS CORRELATION INEFFICIENT, MAN-IN-LOOP JUDGMENT

Figure 4

LSST REQUIREMENTS (Figure 5)

Large Space Structures, or more precisely the different programs or uses of large space structures in space, levy a unique set of requirements on design and, therefore, on technology. Not only must some configurations have specific orientations in space; but, in addition, their shape must be controlled. The structure must be assembled or manufactured in space or both. This leads to growth accommodation requirements, joints, and various roles of man manipulator interactions. Size limits ground testing as do design requirements that are stiffness-driven instead of strength-driven. Digital control systems need the fullest exploitation to lessen the structural design impacts and reduce the need for development of specific materials.

Large Space Structures technology must develop simulations that are large-scale, nonlinear, time-scaled with growth potential. This is not only important for design, but also for realtime support during buildup and operations. Skylab demonstrated this through the use of a time-scaled Skylab orbit simulation that included dynamics and control to plan practically daily the most optimum maneuvers for experiments in terms of fuel usage (RCS propellant). In addition, simulations are needed for optimal design approaches, man loop interaction with system and closed loop control, and special trade studies. In addition to the items discussed, the development of good simulations requires the development of vehicle performance criteria. The developments must continue toward simplifying the simulations without losing any essential characteristics.

In the area of analysis, techniques for analysis using all the uniqueness of digital control systems are needed (e.g., multi-sample rate, variable skip, and nonlinear filtering). The old problem of state estimation is with us and has even more importance in Large Space Structures without detailed all-up dynamic test verification. Testing is a real problem. The low g environment coupled with the structure size basically eliminate ground testing. Some means must be devised to couple limited ground testing (component and scaled) with on orbit testing and analysis in an optimum way as a verification tool.

Backup charts are provided which delineate the state-of-the-art limitations and LSST requirements as they relate to various future programs. The first backup chart is flight regimes versus disciplines and covers all aspects from ground up and back. A generic notation is used to show gaps. The second chart shows the breakdown in much greater detail in terms of discipline or discipline subsets versus various concepts of Large Space Structures. The last chart provides the same generic information for control technology.

SIMULATION:

- LARGE SCALE NONLINEAR TIME VARYING, TIME-SCALED SIMULATION INCLUDING ORBITAL MECHANICS, CONTROL, THERMAL, DYNAMICS, ENVIRONMENTS
  - TRUNCATION CRITERIA/APPROACHES
  - IDEALIZATION CRITERIA
  - PERFORMANCE CRITERIA
- OPTIMAL DESIGN APPROACHES
- MAN-IN-LOOP CONTROL/CLOSED LOOP CONTROL
- DISTRIBUTED SENSORS AND ACTUATORS (EFFECTORS)

ANALYSIS:

- CONTROL
  - MULTI-SAMPLE RATE, VARIABLE SKIP, DIGITAL CONTROL SYSTEM ANALYSIS, AND DESIGN APPROACHES
  - GROWTH ACCOMMODATING
  - MULTI-VARIABLE CONTROL TECHNIQUES
  - PARAMETER ESTIMATION METHODS
  - DISTURBANCE ACCOMMODATING CONTROLLER
- COMBINED ANALYSIS/TEST VERIFICATION APPROACH
- DETAILED DYNAMIC MODELS
  - NONLINEAR ELEMENTS COMBINED WITH LINEAR ELEMENTS
  - JOINTS, MACRO ELEMENTS, ETC.
  - IDEALIZATION CRITERIA
  - TRUNCATION CRITERIA
  - DECOMPOSITION CRITERIA

TEST:

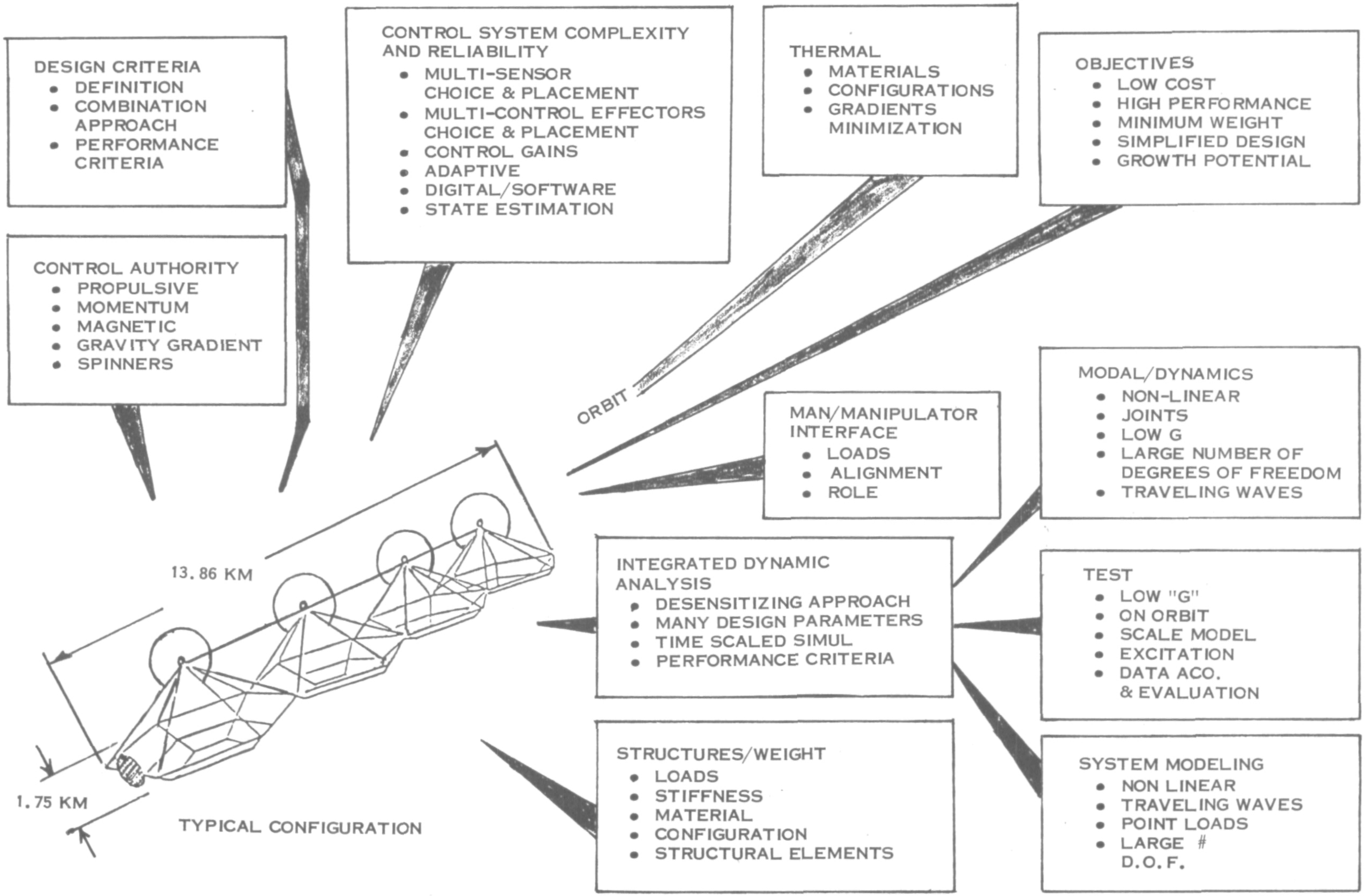
- LOW G SIMULATION
- ON ORBIT TESTING APPROACHES
- GROUND TESTING APPROACHES, ELEMENTS, SCALE
- IMPROVED/OPTIMIZED EXCITATION, ACQUISITION, REDUCTION, EVALUATION, AND CORRELATION TECHNIQUES

Figure 5

KEY ISSUES (Figure 6)

This chart lists some of the key issues in various disciplines important to system dynamics and the associated trade studies. The listing is not intended to be all inclusive and is biased by the author's experience. Major issues occur in each discipline area as well as among the disciplines (e.g., in the integrated dynamics area, key issues involving test and analysis roles and the resulting technologies as discussed previously). How to model and simulate nonlinearities is a key area, as well as whether to design for stiffness requirements structurally or depend on control systems to provide the equivalent stiffness. The source for control authority is very important as is the sensor choice, location, and control logic. In the area of design criteria, the choice of unconservative approaches for parameter variations and methods of combining these in design studies is necessary if low cost/high reliability are to be achieved. Other key issues deal with choice of materials, role of man-in-the-loop, verification approaches for models, and the role of on-orbit test, control system update, etc., versus all-encompassing ground test and development. The approach of desensitizing the system to variations of system parameters versus brute force design approaches could lead to efficiency and cost savings. Based on these issues and the LSS technology requirements discussed previously, a plan of attack is now developed.

KEY LSST ISSUES, SYSTEM DYNAMICS



DESIGN CRITERIA
- DEFINITION
- COMBINATION APPROACH
- PERFORMANCE CRITERIA

CONTROL AUTHORITY
- PROPULSIVE
- MOMENTUM
- MAGNETIC
- GRAVITY GRADIENT
- SPINNERS

CONTROL SYSTEM COMPLEXITY AND RELIABILITY
- MULTI-SENSOR CHOICE & PLACEMENT
- MULTI-CONTROL EFFECTORS CHOICE & PLACEMENT
- CONTROL GAINS
- ADAPTIVE
- DIGITAL/SOFTWARE
- STATE ESTIMATION

THERMAL
- MATERIALS
- CONFIGURATIONS
- GRADIENTS MINIMIZATION

OBJECTIVES
- LOW COST
- HIGH PERFORMANCE
- MINIMUM WEIGHT
- SIMPLIFIED DESIGN
- GROWTH POTENTIAL

ORBIT

MAN/MANIPULATOR INTERFACE
- LOADS
- ALIGNMENT
- ROLE

MODAL/DYNAMICS
- NON-LINEAR
- JOINTS
- LOW G
- LARGE NUMBER OF DEGREES OF FREEDOM
- TRAVELING WAVES

INTEGRATED DYNAMIC ANALYSIS
- DESENSITIZING APPROACH
- MANY DESIGN PARAMETERS
- TIME SCALED SIMUL
- PERFORMANCE CRITERIA

TEST
- LOW "G"
- ON ORBIT
- SCALE MODEL
- EXCITATION
- DATA ACQ. & EVALUATION

STRUCTURES/WEIGHT
- LOADS
- STIFFNESS
- MATERIAL
- CONFIGURATION
- STRUCTURAL ELEMENTS

SYSTEM MODELING
- NON LINEAR
- TRAVELING WAVES
- POINT LOADS
- LARGE # D.O.F.

Figure 6

TECHNOLOGY PLANS (Figure 7)

This chart breaks out the six major tasks required to develop appropriate technology for LSS. Emphasis is placed in the dynamic and control areas where NASA has unique facilities and experience. Tasks that arise in other areas were not addressed due to the author's limited time and may be just as important. Neither do these omissions signify that NASA does not have other unique skill areas important to LSS. This program as outlined would provide the technology for ferreting out the basic characteristics, in a dynamic and control sense, of LSS and for optimal design and verification. A look is taken next at some of the NASA facilities readily adaptable to support this technology plan.

TECHNOLOGY PLANS

- DETERMINE THE LIMITATIONS OF CURRENT STATE-OF-THE-ART DYNAMIC ANALYSIS APPROACHES FOR CURRENT LSST CONFIGURATIONS THROUGH DESIGNING, ANALYZING, AND TESTING (SCALE MODEL) ONE SYNTHESIZED CONFIGURATION (INCLUDING FLIGHT EXPERIMENTS).

- DEVELOP AN OPTIMIZED TEST/ANALYSIS APPROACH MAKING MAXIMUM USE OF NASA UNIQUE FACILITIES.

- DEVELOP A MULTI-DISCIPLINED OPTIMIZED DESIGN APPROACH WHICH PROPERLY WEIGHS OR TRADES THE VARIOUS ASPECTS REQUIRED FOR LOW COST, HIGH PERFORMANCE SPACE STRUCTURES.

- DEVELOP DETAILED SYSTEM SIMULATIONS USING NONLINEAR AND LINEAR ELEMENTS COUPLED TOGETHER AND EXISTING NASA CAPABILITIES IN ORDER TO EFFICIENTLY CONDUCT KEY TRADE STUDIES AND EVALUATE MAN-IN-THE-LOOP ROLES.

- DEVELOP AND VALIDATE EFFICIENT AND ACCURATE ANALYSIS TECHNIQUES FOR DYNAMIC MODELS, DIGITAL CONTROL SYSTEMS, DISTRIBUTIVE CONTROL SYSTEMS, SPIN STABILIZATION, SYSTEM MODELS, AND INCORPORATION OF SYSTEM PARAMETER VARIATIONS.

- DEVELOP CONTROL TECHNOLOGY IN TERMS OF EFFECTOR CHOICE, SENSOR CHOICE, CONTROL LOGIC, DIGITAL CONTROLLERS, SOFTWARE, AND STATE ESTIMATION.

Figure 7

SIMULATION (Figure 8)

This chart is a layout of one of NASA's simulation setups to support docking type dynamic analysis. The point with this chart is to show the components and their flexibility and not the particular application. Key elements are the hybrid computer which simulates all dynamics and control not simulated with hardware and acquires and reduces all data as well as the six degrees of freedom motion base which can carry the docking mechanism for contact dynamics or simulate a moving vehicle. Visual displays are shown with control system sensor interfaces, etc. Finally, the man-in-the-loop control panels, etc., are illustrated. In addition, there is available a T-27 (cockpit) with visual displays, flat air bearing table, buoyancy simulator, etc.

SIMULATION DIVISON - BLDG. 4663

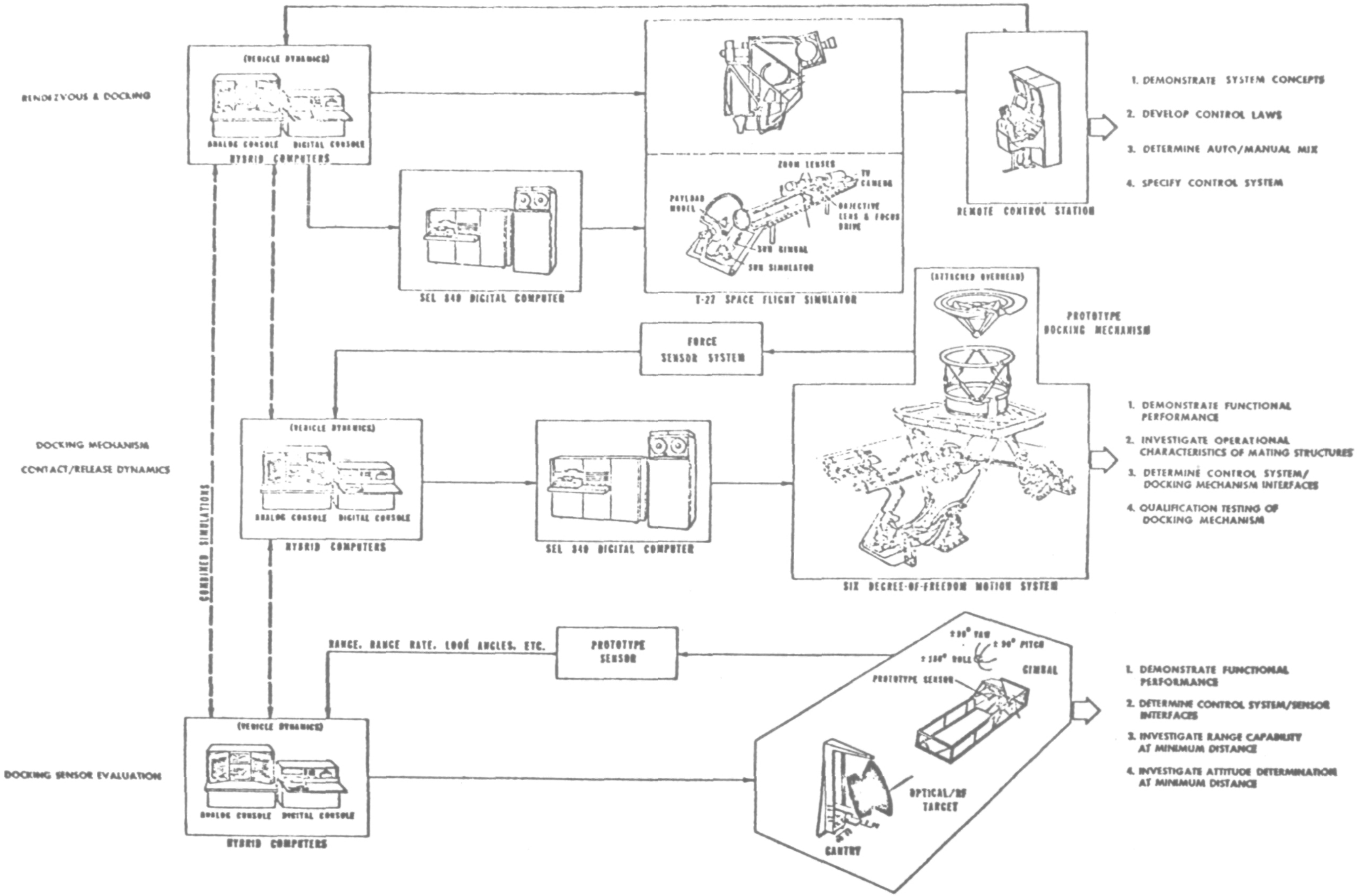
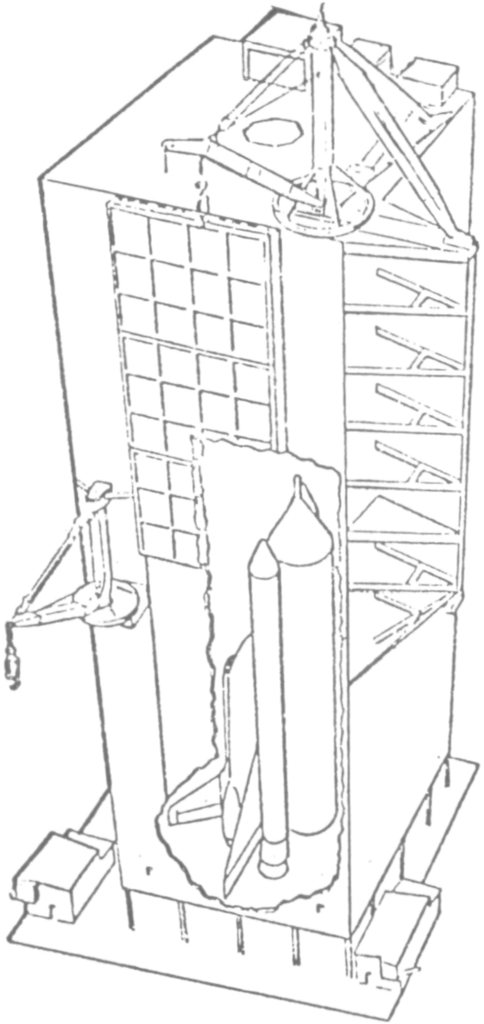


Figure 8

TESTING (Figure 9 - Figure 13)

All aerospace programs to date have used full scale dynamic tests to verify dynamic models used in design and verification. This chart shows the Saturn dynamic test stand modified to handle the full scale dynamic test of Space Shuttle in its two configurations. This test is to be conducted this year. The facility, with its support equipment, can be modified for many LSS tests. There exist small dynamic test facilities, such as the one presently being used for Shuttle lox tank modal survey test, and structural test facilities, currently in use to verify the Shuttle External Tank design.



SHUTTLE CONFIGURATION

MATED VEHICLE GROUND VIBRATION TEST

(MVGVT)

Figure 9

FUTURE TECHNOLOGY AND
DISCIPLINE REQUIREMENTS

FLIGHT REGIMES	ACOUSTIC/ OVERPRESSURE	AEROELASTIC	VIBRATION MODEL	DYNAMIC TEST	LOADS AND RESPONSES	OPTIMIZATION COUPLING
LAUNCH						
• LIFTOFF	G	E	E	G	G	G
• ASCENT	E	E	E	G	G	G
ORBIT						
• OPERATIONS	E	-	G	G	G	G
• DEPLOYMENT	-	-	G	G	G	G
• REBOOST	E	-	G	G	G	G
REENTRY AND RECOVERY	G	G	G	-	G	G
LARGE SPACE STRUCTURES		ENVIRONMENT PREDICTION				
• TRANSPORTATION		T	G	T	T	-
• MANUFACTURING AND ASSEMBLY		T	G	T	T	T
• SHAPE AND POINTING (MISSIONS)		T	G	T	T	T
• REBOOST		G	G	G	G	G

E - EXPERIENCE G - EXPERIENCE WITH GAPS T - NEW TECHNOLOGY

Figure 10

STRUCTURAL DYNAMICS TECHNOLOGY STATUS SUMMARY

		PROJECT					
PRESENT CAPABILITY	TECHNOLOGY REQUIRED	ERECTABLE STRUCTURES	DEPLOYABLE PLATFORMS	DEPLOYABLE REFLECTORS	SPACE BASED POWER	506 RTOPS	LARGE LIFT VEHICLES
COMPUTATIONAL							
-STATIC	-HYBRID, DIRECT INTEGRATION/MODAL	X	X	X	X		X
-EIGENVALUE							
-SUBSTRUCTURE	-CONSTRAINTS & LINKS	X	X	X	X		X
-MODAL SYNTHESIS	-MAN-IN-LOOP SIMULATIONS	X	X	X	X		
-COMPLEX EIGNEVALUE	-INTERACTIVE MODES	X	X	X	X		X
-HYBRID & DIGITAL SIMULATIONS	-TRANSIENT & DOCKING	X	X	X	X		
-NONLINEAR DOCKING							
OPTIMIZED TEST ANALYSIS							
-MOUSE	-SCALE MODEL	X	X	X	X		X
	-EXCITATION	X	X	X	X		X
	-ACQUISITION/EVALUATION	X	X	X	X		X
	-ON ORBIT	X	X	X	X		X
OPTIMIZATION							
-LAUNCH VEHICLE CONTROL/LOADS/PERFORMANCE	-LOADS/CONTROL/CONFIGURATION/MATERIALS	X	X	X	X		X

Figure 11

STRUCTURAL DYNAMICS TECHNOLOGY STATUS SUMMARY (CONT'D)

		PROJECT					
PRESENT CAPABILITY	TECHNOLOGY REQUIRED	ERECTABLE STRUCTURES	DEPLOYABLE PLATFORMS	DEPLOYABLE REFLECTORS	SPACE BASED POWER	506 RTOPS	LARGE LIFT VEHICLES
ELEMENTS (SPAR)							
-FLAT PLATE	-SOLID HYBRID					X	X
-STRAIGHT BEAM	-ELEMENT OF REVOLUTION	X	X	X	X	X	X
-SHELL OF REVOLUTION	-CURVED BEAM, SHELL	X	X	X	X	X	X
-FLUID	-FLUID FLOW						X
-MATRIX	-MACRO	X	X	X	X	X	X
	-JOINTS & FILLETS	X	X	X	X	X	X
AMPLITUDE & RESPONSE							
-MODAL/ENVIRONMENT	-MATERIAL NONLINEAR	X	X	X	X		
MULTIBODY	-GEOMETRIC NONLINEAR	X	X	X	X		
MULTICOAST	-DIRECT INTEGRATION	X	X	X	X		
DIGITAL	-WARPED ELEMENTS	X	X	X	X	X	
HYBRID	-TRAVELING WAVES	X	X	X	X		
-DIFFERENTIAL STIFFNESS							

Figure 12

ORBITING LARGE SPACE STRUCTURES CONTROL TECHNOLOGY REQUIRED

CONTROL TASKS	CENTRALIZED/ DECENTRALIZED CONTROL	MULTIVARIABLE CONTROL TECHNIQUES	GROWTH ACCOMMODATING CONTROL	SENSOR/ACTUATOR CONCEPTS	LARGE SCALE ANALYSIS/SYNTHESIS METHODS	SPIN STABILIZATION	OPTIMAL STRUCTURE/CONTROL DESIGN	ACTIVE BEAM/TRUSS CONFIGURATION DESIGN	EXPANDED DISTURBANCE MODELS	DISTRIBUTED SYSTEM CONTROL	DOCKING CONTROL ALLOCATION COLLISION AVOIDANCE	MANIPULATOR CONTROL TECHNOLOGY	PARAMETER ESTIMATION METHODS	ADVANCED DIGITAL DESIGN TECHNIQUES	CONTROL SYSTEM DYNAMIC INTER-ACTION ISOLATION
FABRICATION		IN PLACE		NEW ITEM				NEW ITEM	IN PLACE						
ASSEMBLY	IN WORK	NEW ITEM	IN WORK	IN PLACE	NEW ITEM				IN PLACE		IN WORK				IN WORK
TELEOPERATORS/FREE FLYERS/MANIPULATORS		IN PLACE		IN PLACE	IN PLACE							NEW ITEM		NEW ITEM	NEW ITEM
ON-ORBIT DYNAMIC TESTING		IN PLACE		IN WORK	IN PLACE		NEW ITEM		NEW ITEM	NEW ITEM			NEW ITEM	NEW ITEM	IN WORK
TRANSPORTATION		NEW ITEM			NEW ITEM		NEW ITEM		NEW ITEM	NEW ITEM			IN PLACE		NEW ITEM
DOCKING		NEW ITEM		IN PLACE	IN PLACE						IN WORK				IN WORK
STATION KEEPING	NEW ITEM	NEW ITEM		NEW ITEM	NEW ITEM		NEW ITEM		NEW ITEM	NEW ITEM			IN PLACE	IN PLACE	NEW ITEM
ATTITUDE CONTROL	IN WORK	NEW ITEM	IN WORK	IN WORK	NEW ITEM	IN WORK	NEW ITEM		NEW ITEM	NEW ITEM			IN PLACE	IN WORK	IN WORK
POINTING CONTROL	NEW ITEM	NEW ITEM	IN WORK	IN WORK	NEW ITEM	IN WORK	NEW ITEM		NEW ITEM	NEW ITEM			IN PLACE	IN WORK	IN WORK
SHAPE CONTROL	NEW ITEM	NEW ITEM	NEW ITEM	NEW ITEM	IN WORK	NEW ITEM	NEW ITEM		NEW ITEM	NEW ITEM			NEW ITEM	NEW ITEM	NEW ITEM

IN PLACE → CURRENT TECHNOLOGY ADEQUATE

IN WORK → TECHNOLOGY DEVELOPMENT UNDERWAY

NEW ITEM → TECHNOLOGY DEVELOPMENT REQUIRED

☐ → NOT APPLICABLE

Figure 13

COMMENTS OF GENERAL INTEREST FROM QUESTIONS AND ANSWERS

System Dynamics and Simulation of LSS

Simulations in Support of LSS

At this point in time simulations of LSS systems should begin with simplified simulation models. The models should grow in concert with the developments of LSS configurations using results from simulations and experience with equipment as complements. The past experiences with a rather complete simulation for the Sky Lab - gyros, environments, etc. allowed real time predictions in support of Flight events. The ability to keep an accurate budget of the propellant, to modify a maneuver as a result of a misdock, all contributed to the achievement of the long term mission. A similar goal seems appropriate for a LSS system with the effort beginning as relatively simple simulations to aid toward defining the most appropriate control concepts for Large Space Systems.