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SPACE SYSTEMS COMPUTER-AIDED DESIGN TECHNOLOGY

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ABSTRACT

Capabilities and advantages of a systems-oriented interactive computer-aided design and analysis system are presented. A single user at an interactive terminal can create, design, analyze, and conduct parametric studies of Earth-orbiting spacecraft such as space station, large antenna and technologically advanced Earth-orbiting spacecraft. The approach is particularly useful in the conceptual design phase where various missions and spacecraft options are to be evaluated in a timely, cost-effective manner.

The Interactive Design and Evaluation of Advanced Spacecraft (IDEAS) system consists of an integrated system of about 40 multi-discipline technical applications programs; efficient executive, data base, and file management software, and extensive interactive graphics display capabilities. Current capabilities and planned and potential augmentations to the IDEAS system are reviewed.

INTRODUCTION

A concerted effort has been underway for several years to develop an integrated system of interactive computer-aided design and analysis software to evaluate the system concepts and technology needs for future spacecraft. Typical spacecraft include manned Earth-orbiting space stations, large antenna systems and space platforms, and small spacecraft with technologically advanced subsystems. Rapid, cost-effective, labor-saving approaches were needed to design and analyze the numerous missions and total spacecraft system options under consideration. The Interactive Design and Evaluation of Advanced Spacecraft (IDEAS) system was developed to meet these needs. The purposes of this paper are to describe the IDEAS system and to identify planned augmentations to the IDEAS capabilities. Examples of results from spacecraft conceptual design studies are used to illustrate the salient features embodied in the IDEAS system.

IDEAS SYSTEM DESCRIPTION

Overview of Capabilities

The IDEAS computer-aided design and analysis system functional capabilities are shown in Fig. 1. The system is divided into two distinct disciplines--interactive graphics and interactive computing. The interactive graphics produce the graphical representations of concept models and data displays on the interactive terminal, and the interactive computing is the actual multidisciplinary analysis programs on the system available to the user. The design process begins with the creation of the three-dimensional geometry model for concept visualization and verification. An analysis model must then be created for input into the analysis programs. These models could be finite-element, finite-difference, or other mathematical representations of the system. Mass properties are generated also for input into analysis programs. The spacecraft subsystems are synthesized for a total systems concept definition. The model can then be analyzed using various analytical tools under the IDEAS system.

IDEAS consists of about 40 technical modules;[1-8] efficient executive, data-base,[9] and file management software; and interactive graphics display capabilities. The software modules reside on both mainframe and super minicomputer systems. A single analyst at the interactive terminal can rapidly model the structure and design and analyze the total spacecraft and mission. The coupling of on-orbit environmental computational algorithms with analysis and design modules permits rapid evaluation of competing spacecraft concepts. Parametric studies and technology-level tradeoffs are accomplished using IDEAS. Data and graphical summary information are presented to the analyst on graphic display terminals for immediate assessment and interactive modification of the spacecraft or mission design, as appropriate.

Prior to the development of IDEAS, most existing computer codes for large advanced spacecraft analysis were either large, long-running, highly generalized, single-discipline codes or did not have the breadth of capabilities needed to perform complete parametric tradeoffs of the total spacecraft, its supporting subsystems, and the on-orbit operational environment. Data generation, finite-element modeling, and the transfer of data between single-discipline programs were generally lengthy, time-consuming processes requiring several engineers and sometimes months to complete. IDEAS can be rapidly run in a few wall-clock hours by a single spacecraft analyst.

This process has been facilitated because of a number of developments which include automated finite-element modeling and structural synthesization. Data files created by any upstream technical module are automatically formatted for subsequent modules. User prompts for file names and unformatted data inputs are provided. Further, much of the necessary computer command protocol has been directly coded into the software thereby freeing the analyst to concentrate on the design task at hand.

Spacecraft concepts evaluated using IDEAS include microwave radiometer satellites, communication satellite systems, solar-powered lasers, power platforms, and orbiting space stations.

Ideas Software

The IDEAS technical programs are shown in Fig. 2. The IDEAS software currently includes all technical modules from the following software development efforts:

(1) Large Advanced Space Systems (LASS) computer program[1-3] which emphasized structural, thermal and controls analysis/design, and costs for large structures (11 software modules).

(2) Spacecraft Design and Cost Module (SDCM)[4] which performs subsystem design and cost analyses through data base searches and iteration (six modules).

(3) Advanced Space Systems Analysis (ASSA) software[5] which emphasizes structural synthesizers, environmental modeling, orbital transfer, and simplified radio frequency (RF) analyses (eight modules).

(4) Space Station Conceptual Design Model (SSCDM) program[6] which sizes habitable modules and laboratory space, designs life support and related spacecraft subsystems, and computes logistic requirements (15 modules).

(5) Earth Observation Spacecraft (EOS) programs[7] which emphasize structural deployment and expanded RF and orbital environmental analysis capabilities (five new and five upgraded modules).

Additional IDEAS capabilities include antenna packaging algorithms, plate and shell analysis modules for space station, rigid body control system expansions, and extensive augmentations to output graphic displays, including solid modeling and color. Programs are being developed to analyze the kinematics and kinetics of large structures during deployment and to accomplish space station design and operations analyses.

SOFTWARE MODULES

Modeling Programs

Solid Geometry Modeling. An important step in the initial modeling of a space system concept is the visualization of the proposed system to be analyzed. Figure 3 shows two versions of one of the many space station concepts being studied--an initial version powered by 75-kW solar arrays and a growth version with expanded modules and 150 kW of power. The geometry models were generated using a solid modeling geometry generator under development at NASA. Through the use of various primitive geometric entities such as cylinders, cones, rectangles, and volumes of revolution, combined with rotation, translation, and Boolean operations, an analyst can model a concept in order to determine concept feasibility. By refining the concept at the geometry level, one may save time and effort due to the fact that there are no analytical models created. Through the use of more powerful commercial geometry display software such as MOVIE.BYU,[10] the models could be placed in orbit and one could observe the time passage of Sun-cast shadows over the model. Shuttle orbiter/space station docking and logistics supply sequences can also be examined using solid modeling geometry display capabilities as shown in Fig. 4.

Structure Synthesizers. IDEAS has an automated finite-element modeling capability using mathematical synthesization to rapidly generate lattice-type structures of any size, shape, and structural density for several classes of repeating structures. The structural classes include tetrahedral and box trusses, box-ring trusses, hoop-and-column, and radial-rib as shown in Fig. 5. From single user inputs, which include the antenna dish or platform diameter, number of bays, ribs or cable/mesh segments; focal length over diameter; platform structural depth; material and section properties; and hinge and mesh masses, the synthesizers rapidly create the mass and inertia properties and the finite-element model in formats compatible with subsequent design and analysis programs in the IDEAS system. The automated modeling and synthesis computations typically can be completed in less than 2 wall-clock minutes and with less than 1 minute CP time.

IDEAS also has stand-alone, finite-element modeling software for off-line model generation and digitizing hardware and software. Post-processor software can read input NASTRAN formatted files and can convert these data to IDEAS program compatible files.

Appendage Synthesizers. The program allows the user to design and add structural appendages to the dish or platform and to locate spacecraft subsystems on the structure. This process results in an updated finite-element model and mass/inertia properties for the entire spacecraft. Standard structural members include the hollow rod, a mass-efficient isogrid, a relatively stiff triangular strut, and tension cables. These members are automatically designed to user-specified Euler buckling loads (or tensile loads for the pretensioned cables).

An example of a preliminary configurations for a spacecraft is shown in Fig. 6 which depicts an antenna dish, added appendages, and subsystems required for an autonomous Earth-orbiting microwave radiometer satellite. Subsequent multidisciplinary design and analysis programs in IDEAS can then be run to size the various spacecraft subsystems and to refine further the finite-element model, mass, inertia, and area properties of the spacecraft.

Modeling Deploying Structures. Three classes of deployable structural appendages are modeled in this program as shown in Fig. 7. They are elastically deformable longeron masts (usually limited to about 1-m diameter), two types of triangular masts (usually limited to less than 3-m diameter based on Shuttle orbiter packaging volume constraints) and box-truss masts (which are repeating elements of the box-truss dish that can range up to 15-m to 20-m width). The triangular masts provide moderate stiffness to the overall spacecraft. The box-truss mast, which compactly folds into the Shuttle orbiter, offers a high-stiffness, low-flexibility potential for future space applications.

Limited research effort has been devoted to the important areas of deployment, kinematic, and kinetic analyses of large structures. The spacecraft undergoes large changes in center of gravity and inertia that may influence spacecraft stability and rigid-body control system design. Figure 8 shows the large changes in inertia about the z-axis (along the column centerline) associated with deployment of a hoop-and-column antenna.

Deployment times can range from less than 1 minute up to approximately 1 hour for the various antenna concepts. For the fast-deploying structures, such as the tetrahedral truss, it is critical that the kinetic behavior be fully understood. The high stress buildup in the structural members at latchup can be the major structural design driver. Deployment-induced vibrations may also lead to undesirable dynamic behavior of the spacecraft. Further efforts are required in these areas. Near-term plans include the extension of IDEAS capabilities to calculate inertia changes and center-of-gravity shifts for all the structural concepts and the initiation of preliminary studies in the design and characterization of the kinetic behavior of the structures and mechanisms.

Analysis Programs

Rigid-Body Controls Analysis. The Rigid-Body control Dynamics (RCD) module calculates the on-orbit environmental forces, maneuver forces, and their corresponding torques on the spacecraft at user-specified circular orbital altitude, spacecraft orientation, and mission duration. It then determines momentum storage and desaturation requirements, sizes the control system, and calculates the propellant needed for stationkeeping, attitude control, and user-specified maneuvers. The principal features of RCD are shown in Fig. 9. The total torque and force time histories are analyzed to determine cycling momentum for momentum exchange system sizing and desaturation requirements. Momentum storage device desaturation requirements are met using reaction control system (RCS) thrusters. The mass and inertia properties of the spacecraft are updated in the data base upon completion of the RCD analyses.

Another labor-saving feature incorporated into the IDEAS system is the automated computation of effective drag areas for lattice structures with porous reflective antenna mesh. The process is generally lengthy and time-consuming. However, it is mandatory that this be an input for computation of orbital propellant requirements. In single discipline analyses, the structural analyst may have no need for these areas and the aerodynamicist is sometimes faced with the formidable task of generating these data for various structural elements and orientations from design drawings. Drag areas can range from a low percent of the solid spacecraft area up to multiples of solid area depending on such factors as the spacecraft size and orientation and the type and quantity of structural members. The IDEAS programs rapidly accumulate these areas for the rigid-body controls analysis from the data base and finite-element model data created in the synthesizer programs.

The atmospheric drag area approximation approach is illustrated in Fig. 10. Each node, which consists of the intersection of several structural members at various orientations, is reduced from the finite-element model to an equivalent solid structural area normal to the spacecraft velocity vector. The blockage effects of upstream areas on downstream areas are factored into the solution. In addition, the program will incorporate the drag effects of the variable transmissibility mesh into the solution from user-specified inputs on the porosity of the reflective mesh and the orientation angle at which mesh appears solid to the incident molecules. Solid areas of supporting subsystems (such as solar arrays) are included.

Interactive Thermal Analysis. The finite-element model files can be transferred automatically to the Thermal Analyzer program in order to calculate the transient temperature response for each structural member at a given position in the spacecraft orbit. Heat sources are solar radiation, Earth albedo, and Earth thermal radiation. The balance between absorption of energy from the three heat sources and reradiation of energy from the elements out into deep space is used to compute the transient thermal response. Earth shadowing is included. Three major assumptions are used which are consistent with sparce structures with relatively small diameter structural members fabricated of low conductive materials such as graphite composites. First, each element is considered to be an isothermal element. Secondly, the radiation exchanges between structural members are neglected due to small radiation view factors. Finally, structural member-to-member shadowing is neglected. Input into this module consists of the model geometry, thermal characteristics of the materials used in the structure, and the positions in the orbit where the thermal analysis begins and ends. Output yields elemental temperatures and heating rate time histories.

Color graphics capabilities have been implemented to depict temperature histories of the structural members. By assigning different colors to represent separate temperature bands, the analyst can readily observe, on a color graphics terminal, the overall thermal performance of the complete structure throughout the orbit.

Structural Analyses. The structural elements created in the synthesizer programs are individually designed to support user-specified Euler buckling loads. These loads are initially estimated at the beginning of the design study. Actual on-orbit and spacecraft-induced static loads such as gravity gradient, drag, static thrust, and pretension loads are computed in the static loads program. These loads, plus the structural member temperature data, are then read into the structural analysis program, SAP (a general purpose structural analysis program for static or dynamic linear analyses of three-dimensional structural systems) where actual static loads carrying capabilities, nodal deflections, and internal stresses are calculated. SAP is run in a batch mode with no user interaction.

Following the SAP static run, the static loads program outputs summary data of the actual loads on the structural members, compares them to the design loads, and permits the user to redesign the members if the actual loads differ considerably from the initial design loads. If many members are poorly designed, the user can instruct the program to recycle through the appropriate synthesizer modules with the updated design loads and revise the member sectional areas. If the spacecraft mass and inertia properties are significantly modified, the RCD module can redefine the control system requirements. Continuous iterations can be performed under user control until a satisfactory solution is obtained for the structural loads; member sizes; spacecraft mass, inertia, and drag properties; and the control system requirements. At any step in the design and analysis process, the user may decide that he has a poor design and may revise the design or change subsystems (which may be either current space-qualified hardware or advanced technology subsystems) and continue with the design process.

Mode shapes and frequencies are computed in SAP dynamic for flexible bodies. Typical results are shown in Fig. 11 for a box-truss antenna. Also shown for comparison in that figure are the first two flexible body frequencies and mode shapes computed from the NASTRAN program.

For missions where high slew rates are required, the dynamic loads program is used to calculate the dynamic response of the structure and individual member loads from user-specified, time-varying force functions. The force functions can represent thruster firings or control moment gyro torques. The program will also estimate the mass of vibration control system devices required to suppress flexible body motions.

Subsystem Synthesis

Spacecraft Design and Cost Modeling. The Spacecraft Design and Cost Module (SDCM) performs subsystem design and cost analyses through data base searches and iterations of spacecraft components that meet or exceed user-specified requirements. An overview of the program and major subsystems included in the design are shown in Fig. 12. Although the principal use of the SDCM to date has been in the design and costing of small Earth-orbiting satellites, some of the components and subsystems have been modeled and integrated into the larger spacecraft designs. A wide range of space-qualified and state-of-the-art components are included in the data base. Efforts are continuing to expand the data base to include additional state-of-the-art and technologically advanced components and subsystems.

Subsystem and Sensor Properties. The basic program architecture has been developed for modeling the bulk properties (mass, volume, and performance capabilities) of subsystems and sensors.[7] A limited set of models are currently available and these will be extended in future efforts.

Environmental Controls/Life Support Systems. A manned space station Environmental Control and Life Support System (ECLSS) computer-aided design program[8] has been developed at NASA Langley Research Center. The ECLSS program consists of a data base and methodology to rapidly assess technology options for life support systems such as water reclamation and air revitalization based on missions options that include crew size, mission duration, resupply intervals, etc. The key uses and features of the program are shown in Fig. 13. Basically, the program incorporates a data base for each technology option, metabolic design loads associated with crew activity, mission model variables to accommodate evolving mission requirements, and algorithms to produce data for comparison with specific assessment criteria. These data, including life cycle costs, are used to provide recommendations relative to candidate technology selection and development.

Evaluating Performance and Technology Options

Specialized programs within IDEAS can be used to evaluate the overall performance of various spacecraft concepts and to generate advanced technology options suitable for trade studies. For example, for large-aperture systems, surface distortions, boresight offset, and defocus are important parameters leading to the establishment of RF antenna or solar concentrator performance and figure control requirements. The IDEAS Surface Accuracy (SA) program establishes these first-order effects on performance. Overall surface roughness (distortions) and changes in focal length, boresight direction, and boresight displacement are computed for reflective surfaces. The SAP static module files supply SA with the finite-element model data for all original and statically displaced node point locations. SA plots the local normal displacement and distortion contours for the surface nodes. The shapes of surfaces available are parabolic, spherical, or flat.

The RF analysis program takes the evaluation process one step further by predicting primary beam gain and losses due to RMS surface distortions, focal length changes and aperture blockage.

Many of the programs previously discussed in this paper have been coded to provide supplementary performance and technology assessment data. For example, the Rigid Body Controls Program gives the user the option to select several subsystems for attitude control and maneuvering including state-of-the-art control moment gyros and highly advanced Annular Momentum Control Devices (AMCD).[12] The AMCD, consisting of two large diameter counterrotating rings, magnetically suspended in many race supports, can provide low-mass, three-axis pointing and slewing capabilities while requiring little or no expendables. The RCD program also includes options for evaluating the advantages of high specific impulse electric thruster systems over space-qualified chemical thrusters to support long-duration missions.

The tetrahedral truss structure synthesizer provides the user with the capability to optimize the structural design based on Shuttle orbiter mass and packaging volume constraints. The truss structure is folded and packaged for launch, removed on-orbit from the Shuttle cargo bay, and then deployed to its full size. The tetrahedral truss structure synthesizer has been coded to establish packaging volumes and structural mass based on the diameter and thicknesses of the individual structural members. This capability is shown in Fig. 14 for a 55-meter-diameter (when fully deployed) tetrahedral truss structure, fabricated of high strength graphite epoxy composite material. Truss packaging diameters for both inward- and outward-folding, center-hinged surface struts, and structural mass data are shown.

As can be seen from the figure, the user is restricted in terms of sizes and mass available for a single Shuttle orbiter flight depending on the on-orbit loads. These particular data were generated[13] for a potential land mobile communication mission operating at geosynchronous Earth orbit. Noncylindrically shaped, packaged spacecraft will probably be restricted to 4.2 m to 4.3 m widths in the Shuttle orbiter. Further, in order to accommodate an upper stage orbital transfer vehicle, it is estimated that the structural mass (which typically ranges from 10 to 30 percent of the total spacecraft mass) will be constrained to a range of 3000 to 5000 kg (maximum) for geosynchronous Earth orbital spacecraft. Based on these constraints, an outwardly folding structure was tentatively selected for this mission with 4.0-cm diameter, 0.1-cm-thick structural members designed to support 1000-N compressive loads. The 1000-N load was established for another study[14] using the IDEAS software and was based on worst-case, on-orbit, thermally induced loads.

IDEAS AUGMENTATIONS

Near-Term Plans

Several of the planned near-term augmentations to IDEAS have been discussed, including the kinematics/kinetics software, subsystem, and sensor data base updates. Vibration and dynamic loads analyses capabilities are being strengthened. Heating and thermal response analyses will be expanded to flat plates. Heat pipe thermal radiator analysis and simulation codes will be developed to support some of the early space station configuration studies. Expansion of the environmental control life support system modeling capabilities to cover a wide range of technologically advanced subsystems is proposed.

Potential Future Additions

IDEAS was developed as a systems analysis tool to evaluate numerous spacecraft at the conceptual design level. Capabilities will be expanded in the future for a wider range of concepts and missions. It is also expected that more detailed design and analysis capabilities will be incorporated in IDEAS to support preliminary design and test requirements for approved near-term spacecraft programs.

Potential future additions to IDEAS include the incorporation of an integrated system of second-order analysis software to perform structural, thermal, and control system analyses, the simulation/emulation of spacecraft subsystems and improved cost/reliability/risk analysis capabilities. Software to correlate ground and flight test data can be developed. Subsystem and sensor data base updates for new or improved hardware will occur on a continuing basis.

Ultimately, since total costs and performance are determined not only by the as-built spacecraft, but also by the ground and orbital transportation systems and by operations, then meaningful tradeoffs and compromises could be achieved by using software simulations of all of these major systems.

CONCLUDING REMARKS

Capabilities and advantages of a systems-oriented interactive computer-aided design and analysis system have been presented. A single user at an interactive terminal can create, design, analyze, and conduct parametric studies of Earth-orbiting spacecraft. The approach is shown to be particularly useful in the conceptual design phase where various missions and spacecraft options are to be evaluated in a timely, cost-effective manner.

The IDEAS computer-aided design and analysis program was developed specifically to provide spacecraft system analysts with the interactive capabilities to rapidly analyze and evaluate spacecraft performance across the major disciplines. Simple and efficient executive, data base, and file management systems relieve the analyst of much of the tedium associated with computer system command protocol and formatted data inputs, reduce possibilities for input errors, and greatly increase throughput capabilities. Extensive graphical displays let the analyst rapidly evaluate the results, make timely design changes, and continue in the interactive processing mode.

The interactive design and analysis capabilities for advanced spacecraft systems are by no means complete; however, the IDEAS program represents a substantial start in that direction. The program demonstrates that rapid modeling, analysis, and design of integrated spacecraft can be accomplished with user interactive computer-aided design software. Spacecraft redesign is easily accomplished and baseline designs can be altered in an orderly manner for subsystem and mission design trades. Top-level systems data are available to discipline analysts for subsystem reexamination and/or refinement and for more rigorous analysis.

REFERENCES

[1] Garrett, L. Bernard: "Interactive Design and Analysis of Future Large Spacecraft Concepts." NASA TP-1937, 1981.

[2] Leondis, A. F.: "Large Advanced Space Systems (LASS) Computer Program." AIAA Paper 79-0904, May 1979.

[3] Leondis, Alex: "Large Advanced Space Systems Computer-Aided Design and Analysis Program." NASA CR-159191, 1980.

[4] Campbell, R. E.: "Spacecraft Design and Cost Model Development." Final Report, Aerospace Corporation Report ATM-76(8191)-3 June 30, 1976. (See also Campbell, B. H.: "Systems Cost/Performance Analysis." Aerospace Corporation Reports ATM-75(7363)-3 Vol. I-II, March 1975.)

[5] Farrell, C. E.; and Zimbelman, H. F.: "Advanced Space Systems Analysis Software--Technical, User, and Programmer Guide." NASA CR-165798, September 1981.

[6] Darby, H. R.; Coomer, T. N.; and Collins, F. M.: "Manual for the Space Station Conceptual Design Model" General Dynamics Corporation, Fort Worth, Report MR-0-243, April 1969.

[7] Farrell, C. E.: "Advanced Earth Observation Spacecraft Computer-Aided Design Software--Technical, User, and Programmer Guide." Final Report NASA CR-166063, April 1983.

[8] Hall, J. B., Jr.; Sage, K. H.; Pickett, S. J.: "Manned Space Station Environmental Control and Life Support System (ECLSS) Computer-Aided Technology Assessment Program." To be presented at the Fourteenth Annual Intersociety Conference on Environmental Systems (ICES), San Diego, California, July 16-18, 1984.

[9] Wilhite, A. W.; and Rehder, J. J.: "AVID: A Design System for Technology Studies of Advanced Transportation Concepts." AIAA Paper 79-0872, May 1979.

[10] Christiansen, H.; and Stephenson, M.: "MOVIE.BYU Training Manual" 1982.

[11] Cronk, M. J.: "Solid SAP: User's Manual." CASD-CIH-74-008, General Dynamics/Convair Division, October 1977. (Revised October 1978).

[12] Montgomery, C. and Johnson, C. R., Jr.: "Adaptive Control System for Large Annular Momentum Control Device in the Microwave Radiometer Spacecraft" Ed. Robert L. Wright. NASA RP-1079, December 1981.

[13] Garrett, L. B. and Ferebee, M. J., Jr.: "Comparative Analysis of Large Antenna Spacecraft Using the IDEAS System." AIAA Paper 83-0798-CP, May 2-4, 1981.

[14] Garrett, L. B.: "Thermal Modeling and Analysis of Structurally Complex Spacecraft Using the IDEAS System." AIAA Paper 83-1459, June 1-3, 1983.

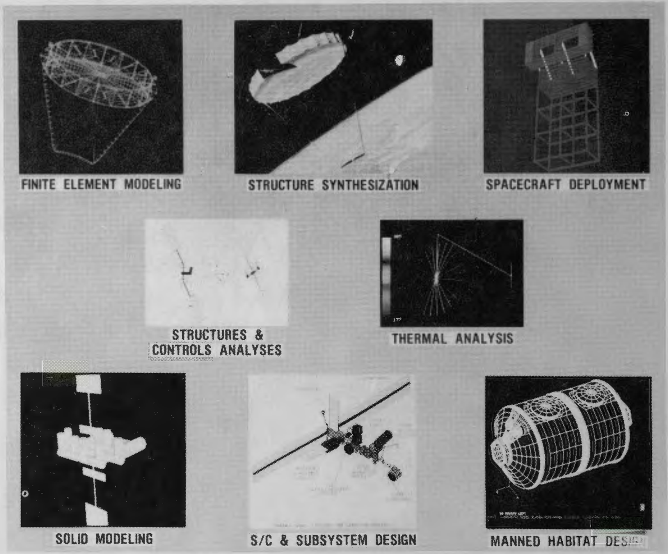


Figure 1. IDEAS Capabilities

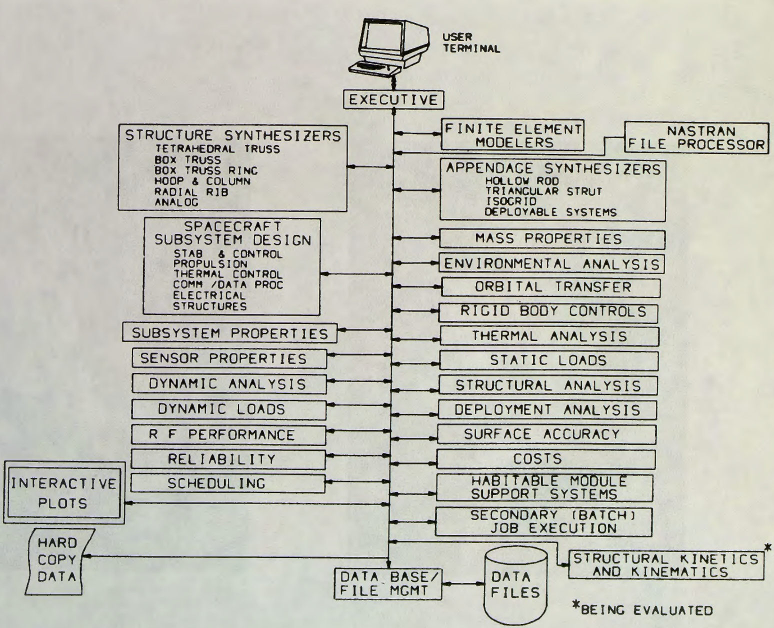
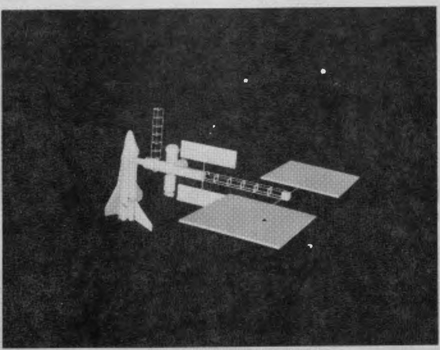
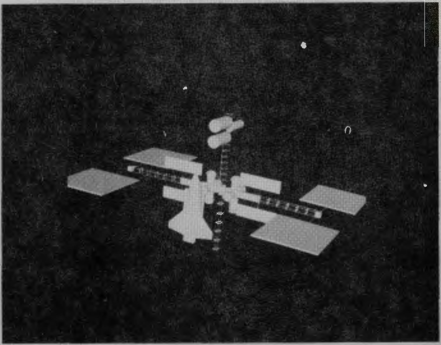


Figure 2. IDEAS Software

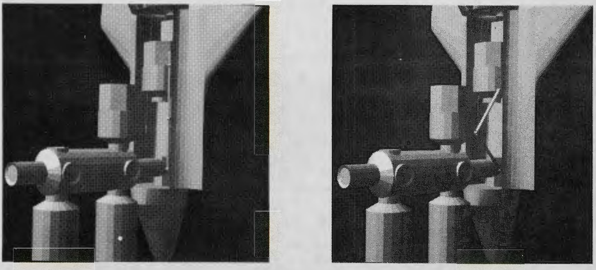


(a) Initial Configuration



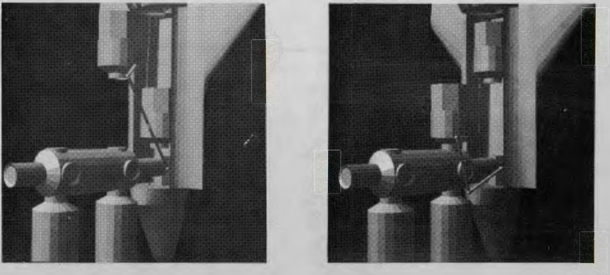
(b) Growth Configuration

Figure 3. Space Station Concepts



(a) Orbiter/Space Station Docking

(b) Replacement Module Transfer in Cargo Bay



(c) Spent Module Removal from Space Station

(d) Replacement Module Connected to Space Station

Figure 4. Module Replacement Sequence

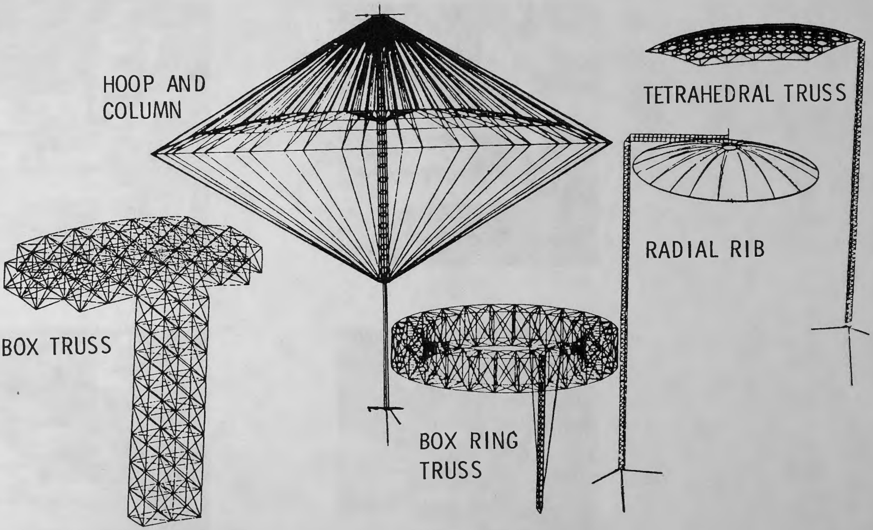
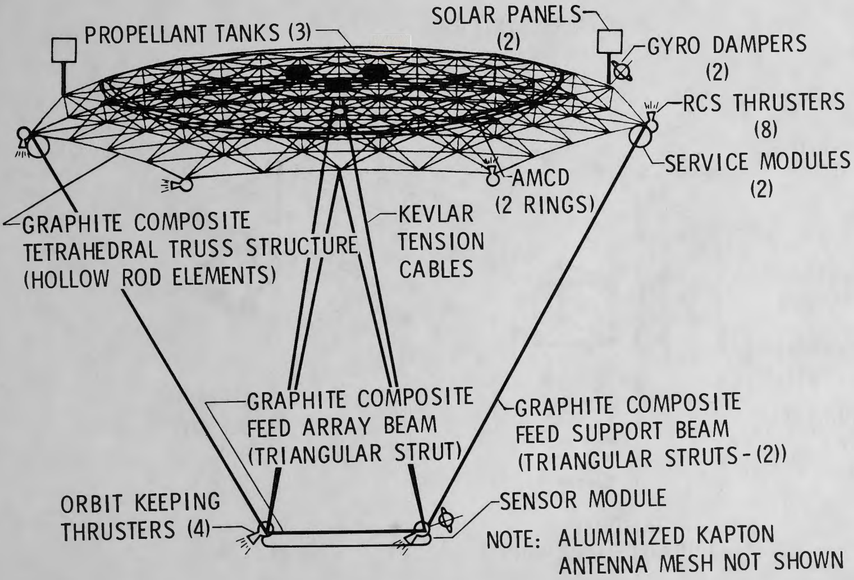


Figure 5. Antenna Structural Concepts



NOTE: ALUMINIZED KAPTON ANTENNA MESH NOT SHOWN

Figure 6. Microwave Radiometer Satellite Spacecraft

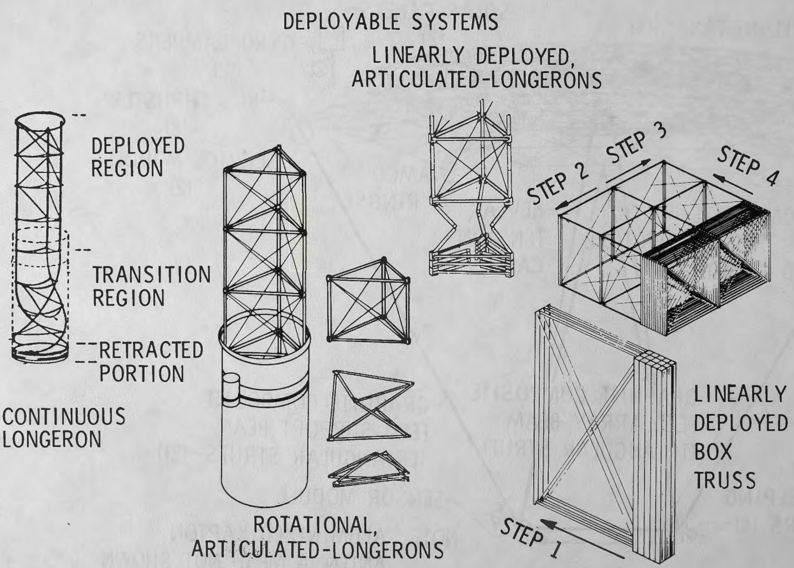


Figure 7. Structural Member Types in the Appendage Synthesizer Modules

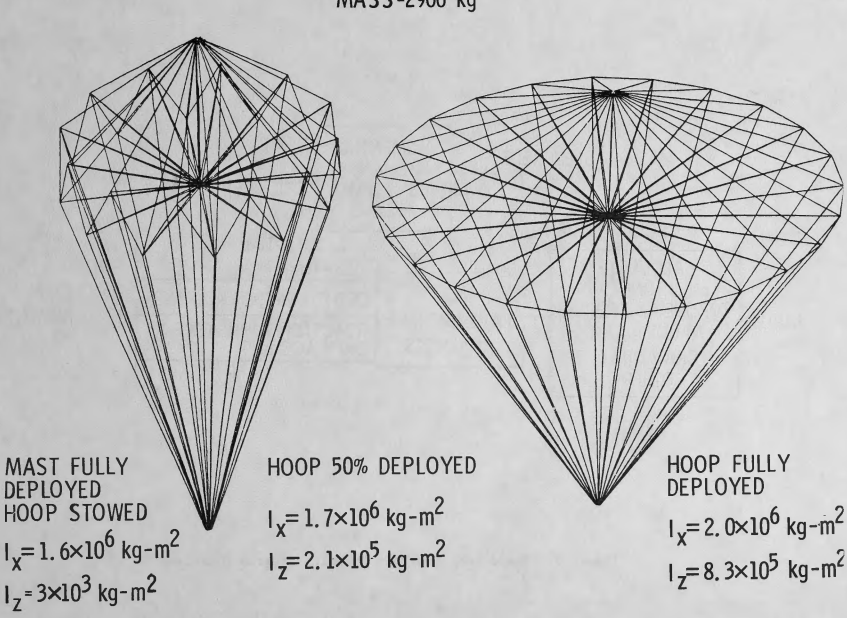


Figure 8. IDEAS Deployment Analysis Module

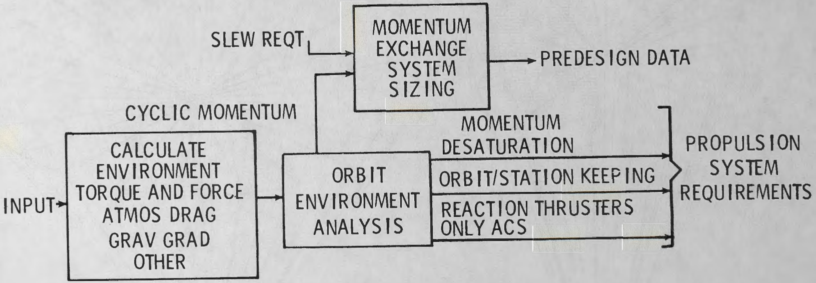
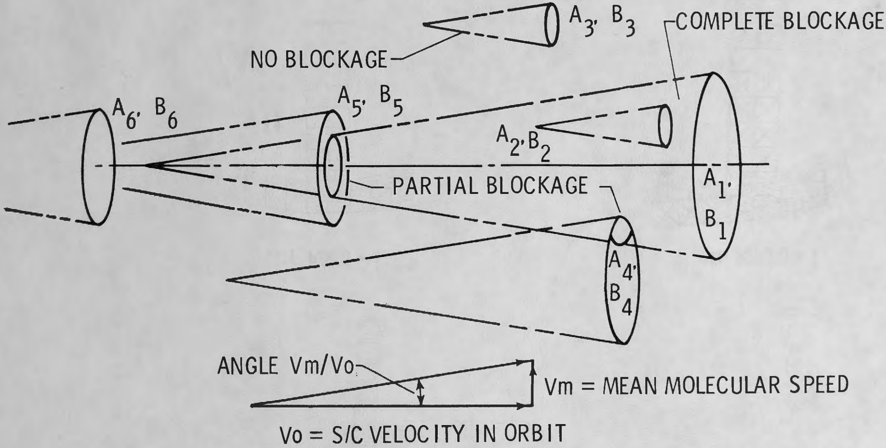


Figure 9. Rigid-body Controls Dynamics Program Overview



EACH NODE POINT REDUCED TO EQUIVALENT CIRCULAR AREA
EACH AREA HAS A BLOCKAGE FACTOR, B (= 1 IF SOLID)
MASKING AREAS REDUCED IN PROPORTION TO DOWNSTREAM DISTANCE
DRAG IS FUNCTION OF MASKED AREA TIMES BLOCKAGE FACTOR

Figure 10. Atmospheric Drag Approximation

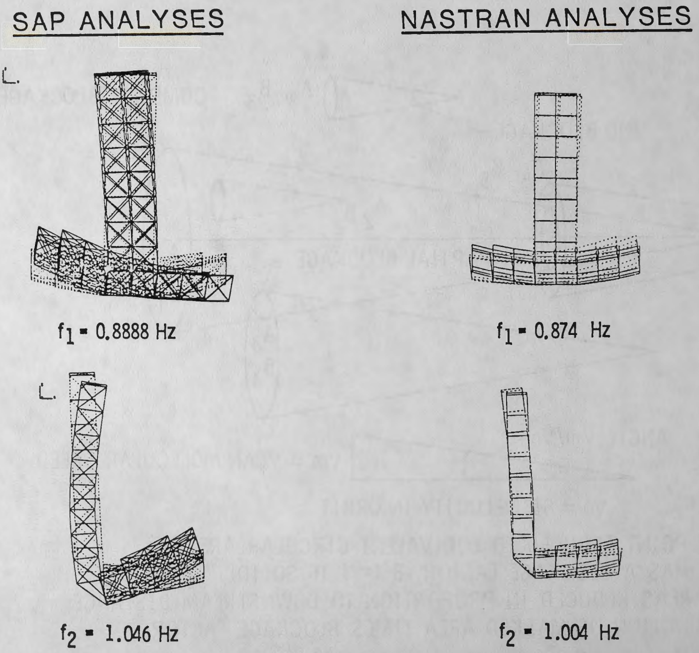


Figure 11. Box Truss Antenna Dynamic Analyses

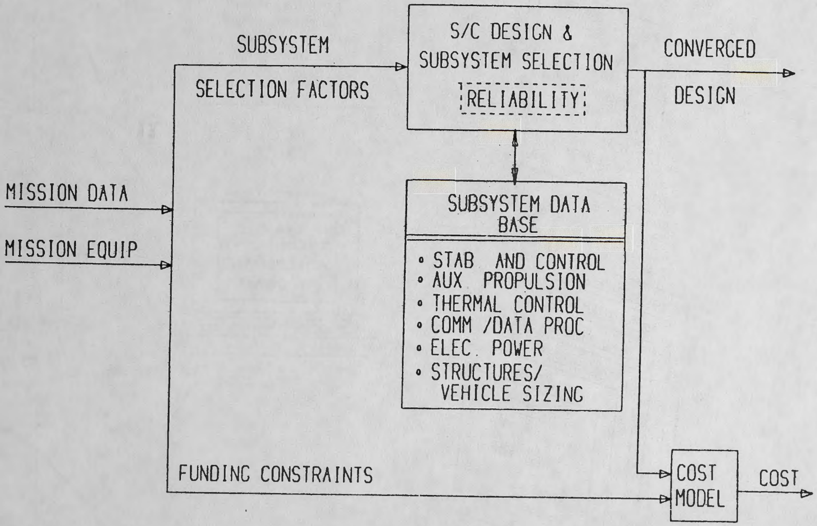


Figure 12. Spacecraft Design and Cost Module Overview

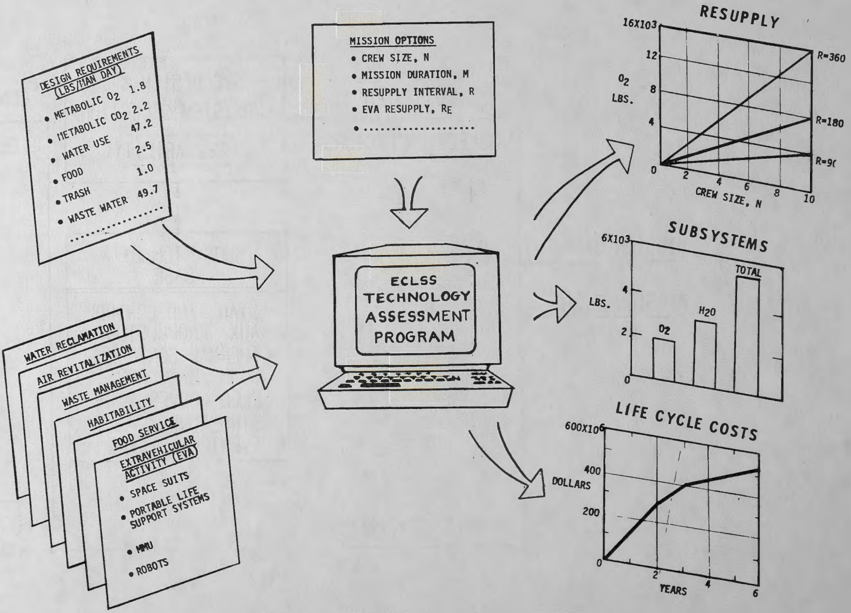


Figure 13. Environmental Control and Life Support System (ECLSS) Computer Aided Technology Assessment Program

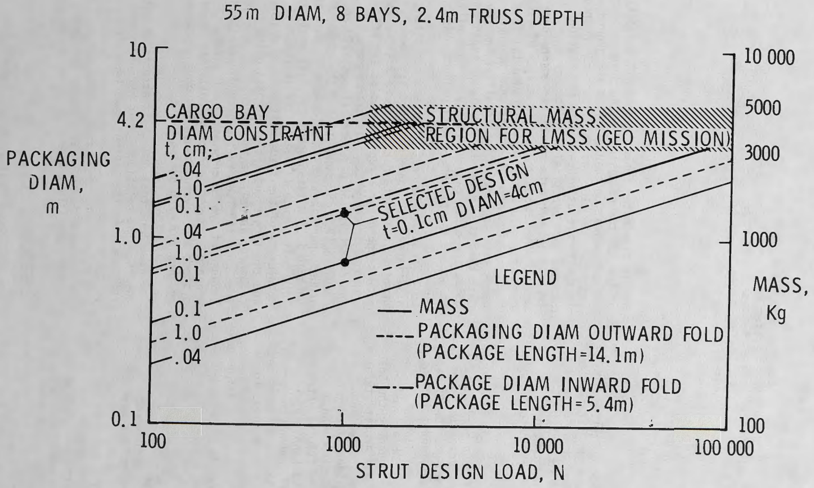


Figure 14. Packaging Study for the Tetrahedral Truss Antenna Dish