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# SPACE STRUCTURE (DYNAMICS AND CONTROL) THEME DEVELOPMENT

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# 1.0 Introduction

Future spacecraft will be larger and more complex, and their performance requirements will be more demanding. Advancements in many technology areas are needed if the increased performance requirements are to be met. Long range technology goals need to be identified, and a logical progression of experiments and demonstrations must be established so that these goals will be reached.

Many technology development experiments have been proposed that will be conducted from the Orbiter or while attached to the Space Station. The Space Station experiments are described in the Space Station Mission Requirements Data Base (MRDB). Others were proposed at the Office of Aeronautics and Space Technology (OAST) In-Space Research Technology and Engineering (RT&E) Workshop held in October of 1985. Experiments in seven technology "theme areas" were described at the workshop.

This study addresses the technologies in the Space Structure (Dynamics and Control) theme area. The first part of this study was to define the long-range technical objectives and goals for the Space Structure (Dynamics and Control theme area. The second part was to evaluate the past and current (e.g., ACCESS/EASE and COFS) and the proposed technology activities (e.g., MRDB and the RT&E Workshop results). One of the major products of this evaluation was the identification of technology gaps and thin spots that should receive more attention to reach the long-range objectives. The final part was to identify and recommend experimental activities in the 1988-2000 time period, listing the experiments by year and identifying the technical objectives of each and their interrelationships.

## 2.0 Long-Range Technical Objectives and Goals

The long-range goals in the Space Structure (Dynamics and Control) theme area relate to the construction of structural systems in space, the determination of their characteristics, and the development of control systems and actuators to point them and maintain their configuration. These goals, divided into the categories of Structures, Control/Structures Interaction, and Control, are listed in Figure 2-1.

Technology goals in the structures area include all types of in-space construction (e.g., deployment, assembly and fabrication) as well as methods and techniques for repair. Development and demonstration of nontraditional methods of construction, such as inflatables and other advanced concepts, are envisioned. Test methods and sensors are also required to determine structural precision, dynamic characteristics, damping, thermal deflections, structural loads and environmental effects. Structurally-embedded sensors and actuators are desirable to enhance performance, to reduce the probability of accidental damage to external instruments and wiring, and to eliminate the need for routing wire bundles during construction in orbit (note: the connection of the sensors to a power supply and to data retrieval systems are still issues to be resolved). System identification techniques are required to determine the structural dynamic characteristics of large space structures for engineering evaluation and to supply system information for control system functions.

With the increasing size of space structures envisioned for the future, the importance of control/structures interaction also increases. Structural frequencies are lower and can fall within the bandwidth of the controller, making the task of stabilizing, controlling, maneuvering, articulating, pointing, maintaining structural alignment, and mitigating the effects of internal and external disturbances much more difficult. The control philosophies and techniques to accomplish these tasks need to be developed and demonstrated. The dynamics and control of tethered systems also need to be understood and demonstrated in orbit.

Control system sensor and actuator technology needs to be advanced to meet ever increasing accuracy and precision pointing requirements over a wide range of frequencies. Control techniques, particularly important for Space Station, that need to be developed include station keeping (MMU, OMV, STS, free-flyers), maneuvering (MMU, OMV, STS), docking and berthing (STS, OMV, MMU), robotics (inspection, servicing, construction, maintenance and reconfiguration), and failure detection and isolation.

Figure 2-1: Long Range Technical Objectives and Goals, Space Structures (Dynamics and Control)

- Structures
  - In-Space Construction
    - Deployment, Assembly, Fabrication
    - Modification/Repair
    - Advanced Structural Concepts
  - Structural Characterization
    - As-built Accuracy
    - Dynamics & Loads Characterization
    - Damping Evaluation (joints, passive, etc.)
    - Environmental Effects
    - Test/NDE Methods
- Control/Structure Interaction
  - Structurally Embedded Sensors/Actuators
  - System Identification
  - Control of Large, Flexible Structures
    - Stability
    - Pointing
    - Articulation
    - Modal control
    - Maneuvers/slewing
    - Shape and Figure Control
  - Dynamics and Control of Robots & Manipulators
  - Disturbance Control
  - Vibration Isolation
  - Fluid/Structure Interaction
  - Tether Dynamics
  - Control Technology
    - Distributed, Multi-loop, Hierarchical, Adaptive
  - Modeling, Synthesis and Analytical Tools
- Controls
  - Sensors & Actuators
    - Improved Actuator Efficiency (e.g., torque/mass, force/mass)
    - High Accuracy Surface Sensor (Multi-DOF)
    - Real-Time Photogrammetric Concepts
    - Mid-Range Momentum Actuators
    - High Speed, High Capacity Flight Computers for CSI
    - High Speed, High Capacity Data Bases
    - Multi-Body Alignment Transfer & Pointing Systems
    - Relative Alignment Sensor
    - Vibration Actuators
    - Low-Frequency Actuators
    - Optical/Inertial Vibration Sensors
    - Low-G Accelerometers
    - Low-Thrusters for Reboost
  - Control Technology
    - Station keeping
    - Maneuvering
    - Docking/Berthing
    - Robotics
    - Failure Detection, Isolation and System Reconfiguration
    - Guidance for Proximity Operations and Satellite Retrieval

## 3.0 Evaluation of On-going and Proposed Activities

This section provides an overview of past, current and proposed flight experiments that relate to technologies within the Space Structure (Dynamics and Control) theme area. A significant amount of research, development and testing is being conducted in many areas to provide the technical basis for these experiments. However, this review covers only Shuttle flight tests and proposed Space Station experiments.

### 3.1 On-going Activities

Prior to the Challenger accident, two experiments were performed from the Shuttle that demonstrated structures and controls theme technologies: the Solar Array Flight Experiment (SAFE) and the EASE/ACCESS experiments. The Control of Flexible Structures (COFS) series of experiments will be flown after Shuttle flights resume.

### 3.1.1 Solar Array Flight Experiment (SAFE)

SAFE (OAST-1) was conducted on STS Mission 41-D on August 31, 1984. Its primary objective were (1) to demonstrate the readiness, and determine the performance of a large low cost, light weight, deployable/retractable photovoltaic solar array; (2) to demonstrate methods to define the structural dynamic behavior of large space structures; and (3) to evaluate solar cell calibration techniques as well as calibrate various types of solar cells. Two measurement systems were used to determine structural deformations: a photo-grammetric system that determined the 3-dimensional location of targets using four closed circuit television (CCTV) cameras for triangulation, and a Dynamic Augmentation Experiment (DAE) laser measurement system. The deployment and retraction objectives of the 32 x 4 meter solar array were successfully achieved, and measurements of solar array motion were obtained. Preflight predictions of the dynamic characteristics were verified with flight measurements, however the measured structural damping was higher than predicted (3.5 percent vs 0.5 percent). The SAFE solar array blanket also exhibited unexpected curvature during the dark portions of the orbit, and persistent low frequency oscillations were experienced. These unexpected results demonstrate the value of on-orbit demonstration tests.

### 3.1.2 EASE/ACCESS

These two experiments were flown on STS Mission 61-B on November 26, 1985.

#### Experimental Assembly of Structures in EVA (EASE)

The EASE experiment consisted of repeated EVA assembly and disassembly of a six-element tetrahedron, using struts 3.6 m long. The astronauts were unconstrained (no foot restraints) during the assembly process. Timelines were obtained and compared with those obtained during tests conducted in a neutral buoyancy simulator on Earth. Flight test results show that most of the activities were accomplished more rapidly in space than they were in neutral buoyancy training.

### Assembly Concept for Construction of Erectable Space Structures (ACCESS)

The objective of the ACCESS flight experiment was to study the orbital assembly of a space truss. A 10 bay truss beam structure, 45 feet long was assembled by two EVA astronauts in fixed foot restraints. A fixed work station; assembly line method was used to assemble the 93 tubular struts and 33 nodal joints. In the second portion of the experiment, an astronaut in the mobile foot restraint (MFR), attached to the remote manipulator system (RMS), demonstrated structural assembly and repair of space structures, the installation of cables, and the manual manipulation of the truss beam. All of the tasks were successfully completed, and the construction times agreed well with neutral buoyancy training simulations. The astronauts preferred the constrained workstation assembly concept used during ACCESS over the free-floating EASE assembly method.

### 3.1.3 Control of Flexible Structures (COFS)

COFS is a three phase program whose overall objective is to develop and validate the technology data base required for confidence in the design and control of large flexible spacecraft by the mid 1990's. The approach is to develop and validate design and analysis tools, to develop and demonstrate ground test methods, and to conduct generic in-space experiments to validate the ground tests and analysis.

### COFS I

COFS I consists of the Mast Flight System, a triangular cross-section, joint dominated, deployable truss beam. It is 60.4 meters in length (fully deployed), 1.4 meters in diameter, and is made up of 54 bays. It includes a 180 kg tip mass that also contains primary actuators, collocated sensors, and a parameter modification subsystem. Deployment will be accomplished in two-bay increments from a deployment canister system. Sensors and proof-mass actuators distributed along the beam will be used for dynamic parameter identification, for introducing damping into the structure, and for the development of distributed controls techniques. In addition to the basic experiment, a guest investigator program has been initiated by NASA Langley Research Center (LaRC) to allow industry and universities to suggest and develop ground tests and flight experiments that could be conducted using this flight article. Scale model ground tests are also planned to develop scale model testing techniques that can be applied to structures too large or fragile to be tested in full scale on the ground.

### COFS II

COFS II expands on the COFS I Mast experimental hardware by attaching a short beam, a two-axis gimbal system and a 15 meter deployable hoop-column antenna to its tip. The objectives are to develop and evaluate the methodologies involved in modeling and controlling large, flexible, 3-dimensional structures in space. In the area of structural dynamic characterization, the goals are to measure deployment dynamics, to perform structural evaluations, to accomplish system identification, and to evaluate fault detection, isolation and recovery methods. Systems control goals are to demonstrate alignment and shape control, vibration suppression, pointing (LOS stabilization), articulating and slewing, adaptive control, and maneuver load alleviation.

Development and ground based tests of a 15-meter hoop-column antenna, its components and subsystems are currently in progress at LaRC. Many COFS related technologies are under development, including methods for measuring and adjusting reflector surfaces, for pointing and slewing (SCOLE), and for fault detection and isolation.

### COFS III

The technology goals for COFS III are to validate control/structures interaction (CSI) analysis tools for multiple-body concepts, to evaluate modeling sensitivities, to develop vibration suppression methods, to develop ground test methods, to correlate scaled ground tests with full-scale flight data, and to provide timely development of Space Station supporting technology. The vehicle to be used to accomplish these goals will be a dynamically scaled model of the Space Station that will use modular construction for buildup stages, interchangeable elements, realistic joints and members, manual articulating joints, and realistically attached payloads. A Large Spacecraft Laboratory (LSL) facility at LaRC is being planned to accommodate the ground testing of this scale model.

## 3.2 Proposed Activities

Proposed activity for development and demonstration of space systems technology is contained in the Space Station Mission Requirements Data Base MRDB) and in the results of the OAST In-Space Research, Technology and Engineering Workshop. This section describes these two sources of technology development experiments.

### 3.2.1 TDMX Missions

Near the beginning of the Space Station definition (in the early 1980's), NASA solicited ideas from industry, universities, NASA centers and foreign countries for technology development experiments and missions that can be conducted on or deployed from the Space Station. This list became the basis for the Space Station Mission Requirements Data Base (MRDB), that helped to define the need for a Space Station. NASA efforts and study contracts have resulted in more detailed definitions of these experiments.

The MRDB is divided into four mission categories: Commercial (COMM), Science and Applications (SAAX), Technology Development (TDMX), and Foreign. This study will consider only the TDMX missions, although the other missions help to identify areas for which technology development is required. There are currently 74 TDMX missions in the MRDB, with several others being considered. Of these, 23 missions are in the Space Structures area. NASA has identified 7 of these missions as candidates that will most likely be conducted in the IOC time-frame, i.e. with the first three years after Space Station IOC (Initial Operational Capability). These experiments range from tests of sensors and components to the constructions and test of large space structures (including portions of Space Station facilities), and from the demonstration of Space Station operational capabilities to the determination of the space environment and its effect on orbital systems.

### 3.2.2 RT&E Workshop Results

On October 8-10, 1985, NASA Langley Research Center hosted an OAST In-Space Research, Technology and Engineering (RT&E) Workshop held in Williamsburg, Virginia. The purpose of the workshop was to bring together representatives of the university community, the private sector, and government agencies to discuss future needs for in-space experiments, in support of space technology development. The resulting experiments, in seven theme areas, also serve to define requirements for Space Station facilities to support in-space RT&E. The theme area that will be considered in this study is "Space Structure (Dynamics and Control)."

In the Space Structure (Dynamics and Control) theme area, there were 31 experiments described, 16 of which were TDMXs already listed in the MRDB. The experiments presented were categorized into five key technology areas: component technology, control/structure interaction, Space Station dynamic characterization, Space Station construction technology, and advanced structural concepts. An eleven-member panel reviewed the experiments presented to determine technology gaps, the need for in-space tests, impacts to the Space Station, and critical areas for development. The workshop assessment is a major input to this study.

## 3.3 Activity Summary

The experiments listed in the MRDB and those proposed at the OAST In-Space RT&E Workshop are summarized and discussed in this section. Technology gaps noted by the RT&E Workshop panel and others resulting from a review of the experiments are also identified.

### 3.3.1 Proposed Experiments

The experiments proposed at the OAST In-Space RT&E Workshop were reviewed and compared with the experiments listed in the MRDB. A composite list of these experiments, grouped into the five categories used at the Workshop, is shown in Figure 3.3.1-1. The figure lists the title of each experiment, its TDMX number (if it has one), the source of the experiment description, and its proposed flight schedule. Many of the experiments were included in both the TDMX list and the Workshop. Within each category, the experiments are listed in chronological order based on the originally-proposed flight date (year). At the time that most of the

Figure 3.3.1-1: PROPOSED SPACE STRUCTURE (DYNAMICS & CONTROL) EXPERIMENTS

| EXPERIMENT \ PROPOSED FLIGHT > | | | YEAR | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDMX | REF. | 88 | 89 | 90 | 91 | *92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 2000 |
| 1. COMPONENT TECHNOLOGY | | | | | | | | | | | | | | | |
| 1. Berthing and Docking Sensor | | 2 | X | | | | | | | | | | | | |
| 2. Fiber Optic Sensors in Space Applic. | | 2 | | | X | | | | | | | | | | |
| 3. S/C Strain & Acoustic Sensors | 2072 | 1,2 | | | | | X | | | | | | | | |
| 4. Attitude Control & Energy Flight Exp. | | 2 | | | | | X | | | | | | | | |
| 5. Thermal Shape Control | 2422 | 1,2 | | | | | X | | | | | | | | |
| 6. Advd. Expmt. Pointing and Isolation | 2432 | 1,2 | | | | | X | | | | | | | | |
| 7. Advanced Control Device Technology | 2431 | 1,2 | | | | | | | X | | | | | | |
| | | | | | | | | | | | | | | | |
| 2. CONTROL/STRUCT. INTERACTION EXPERIMENTS | | | | | | | | | | | | | | | |
| 1. COFS Flight Experiments | | 2 | | X | X | X | X | | | | | | | | |
| 2. In-Space Actively Controlled Struct. | | 2 | | X | | | | | | | | | | | |
| 3. Flight Dynamics Identification | 2071 | 1,2 | | | | | X | | | | | | | | |
| 4. Active Optic Technology | 2421 | 1 | | | | | X | X | | | | | | | |
| 5. Advanced Adaptive Control | 2411 | 1,2 | | | | | | X | | | | | | | |
| 6. Distributed Control Experiment | 2412 | 1,2 | | | | | | X | | | | | | | |
| 7. Dynamic Disturbance Control | 2413 | 1,2 | | | | | | X | | | | | | | |
| 8. Tethered Experiments | 2541-4 | 1 | | | | | | | X | | X | X | X | | X |
| 9. Dynamic Stabilization of F/F Robot | 2433 | 1 | | | | | | | | | X | | | | |
| | | | | | | | | | | | | | | | |
| 3. SPACE STATION DYNAMIC CHARACTERIZATION | | | | | | | | | | | | | | | |
| 1. Advanced Controls Technology | 2414 | 1,2 | | | | | X | | | | | | | | |
| 2. Sp. Sta. System Perf. Technology | | 2 | | | | | | X | X | X | X | X | X | X | X |
| | | | | | | | | | | | | | | | |
| 4. SPACE CONSTRUCTION TECHNOLOGY | | | | | | | | | | | | | | | |
| 1. Struct. & Assy. Verif. Exp. (SAVE) | | 2 | | | | X | | | | | | | | | |
| 2. Large Space Structure | 2061 | 1,2 | | | | | X | | | | | | | | |
| 3. Space Station Modifications | 2062 | 1,2 | | | | | X | | | | | | | | |
| 4. On-Orbit S/C Assembly & Test | 2063 | 1,2 | | | | | | X | | | | | | | |
| 5. Large Space Antenna (Reflectors) | | 2 | | | | | | X | X | | X | X | | | |
| 6. Environ. Influence on Struct. Dynamics | | 2 | | | | | | | X | | | | | | |
| 7. Precision Optical | | 2 | | | | | | | X | | | | | | |
| 8. TDM for LDR | | 2 | | | | | | | | X | | | | | |
| 9. Inflatable/Rigidizable Struct. Element | 2066 | 1,2 | | | | | | | | X | | | | | |
| 10. Large Deployable Reflector (LDR) | SAAX020 | | | | | | | | | | | X | | | |
| 11. Adv. Antenna Assembly/Performance | 2064 | 1,2 | | | | | | | | | | X | | | |
| | | | | | | | | | | | | | | | |
| 5. MATERIALS & FABRICATION TECHNOLOGY | | | | | | | | | | | | | | | |
| 1. Polymeric Mat'ls for Space Mechanisms | | 2 | | X | | | | | | | | | | | |
| 2. Spacecraft Materials & Coatings | 2011 | 1 | | | | | X | | | | | | | | |
| 3. Micrometeorite Protection | | 2 | | | | | | | | X | | | | | |
| 4. Ion Beam Cold Welding | 2065 | 1,2 | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 6. STRUCTURAL CONCEPTS RESEARCH FACILITY | | 2 | | | | | | | X | | | | | | |

* Originally assumed Space Station IOC
1 Space Station Mission Requirements Data Base (MRDB)
2 In-Space Research, Technology and Engineering (RT&E) Workshop

experiments were proposed, the year of Space Station Initial Operation Capability (IOC) was assumed to be 1992.

A brief description of the primary objectives of each of the experiments, in the Space Structure (Dynamics and Control) theme area, is shown in Figure 3.3.1-2.

### 3.3.2 Observations

The review of the proposed experiments revealed technical objectives that duplicated, overlapped or complemented each other. Also, several of the experiments supported technology development in different areas but could be contributors to the same project. The following paragraphs discuss these observations for each of the experiments.

#### 3.3.2.1 Component Technology

Berthing and Docking Sensor - Development of these sensors should be conducted in conjunctions with berthing and docking mechanism development and ground tests. A Space Shuttle demonstration mission needs to be defined for this sensor system.

Fiber Optic Sensors in Space Application - A demonstration mission needs to be defined for the fiber-optic gyro after ground-based development. Fiber-optic elongation sensors could be used on the SAVE experiment and, possibly, COFS II to demonstrate the technology for Space Station.

Spacecraft Strain and Acoustic Sensors, TDMX2072 - SAVE and/or COFS II can be used as testbeds for the demonstration of strain and acoustic emission sensors. Acoustic sensors would be used for Space Station monitoring, e.g., truss integrity and micrometeoroid/debris impact detection and triangulation in common modules.

Attitude Control and Energy Flight Experiment - A mission duration of at least 30 days is required to satisfy flight test objectives, i.e., it requires the Space Station or a free-flyer. This experiment is similar to TDMX2431, Advanced Control Device Technology.

Thermal Shape Control, TDMX 2422 - Although this experiment is designed to be conducted on the Space Station, the technology could be demonstrated on SAVE or COFS II.

Advanced Experiment Pointing and Isolation, TDMX2432 - Limited testing probably could be conducted on the Orbiter prior to IOC.

Advanced Control Device Technology, TDMX2431 - Similiar to "Attitude Control and Energy Flight Experiment," above, presented at the OAST In-Space RT&E Workshop.

Figure 3.3.1-2: PRIMARY OBJECTIVES OF PROPOSED SPACE STRUCTURE (DYNAMICS & CONTROL) EXPERIMENTS

| EXPERIMENT | TDMX | PRIMARY OBJECTIVE |
|---|---|---|
| 1. COMPONENT TECHNOLOGY | | |
| 1. Berthing and Docking Sensor | | Demonstrate berthing & docking techniques |
| 2. Fiber Optic Sensors in Space Applic. | | Fiber optic gyro & sensor development |
| 3. S/C Strain & Acoustic Sensors | 2072 | NDE methodology development |
| 4. Attitude Control & Energy Flight Exp. | | Develop CMG for attitude control & energy storage |
| 5. Thermal Shape Control | 2422 | Shape control using distributed thermal controllers |
| 6. Advd. Expmt. Pointing and Isolation | 2432 | Precision pointing, disturbance suppression |
| 7. Advanced Control Device Technology | 2431 | Evaluate combined energy storage & momentum device |
| 2. CONTROL/STRUCT. INTERACTION EXPERIMENTS | | |
| 1. COFS Flight Experiments | | System identification, test method development |
| 2. In-Space Actively Controlled Struct. | | Control of alignment, dynamics, precision pointing |
| 3. Flight Dynamics Identification | 2071 | System identification, sensor architecture & testing |
| 4. Active Optic Technology | 2421 | Assembly & operation of segmented optics system |
| 5. Advanced Adaptive Control | 2411 | Adaptive control techniques, strategy & algorithms |
| 6. Distributed Control Experiment | 2412 | Distributed control techniques, strategy & algorithms |
| 7. Dynamic Disturbance Control | 2413 | Disturbance suppression & isolation |
| 8. Tethered Experiments | 2541-4 | Develop technology for tethers |
| 9. Dynamic Stabilization of F/F Robot | 2433 | Free-flyer stability & station keeping |
| 3. SPACE STATION DYNAMIC CHARACTERIZATION | | |
| 1. Advanced Controls Technology | 2414 | Dynamics & control of large, flexible spacecraft |
| 2. Sp. Sta. System Perf. Technology | | Verify & validate analysis & pre-flight predictions |
| 4. SPACE CONSTRUCTION TECHNOLOGY | | |
| 1. Struct. & Assy. Verif. Exp. (SAVE) | | EVA assembly & characterization of S.S. truss & utilities |
| 2. Large Space Structure | 2061 | Deploy & characterize planar truss (SS facility) |
| 3. Space Station Modifications | 2062 | Space Station structural evolution (servicing area) |
| 4. On-Orbit S/C Assembly & Test | 2063 | Spacecraft assembly & checkout on the Space Station |
| 5. Large Space Antenna (Reflectors) | | Antenna deployment, assembly & characterization |
| 6. Environ. Influence on Struct. Dynamics | | Determine long-term effects of space environment |
| 7. Precision Optical | | Assembly, alignment & dynamics of segmented optics |
| 8. TDM for LDR | | Deploy, align and control segmented optics |
| 9. Inflatable/Rigidizable Struct. Element | 2066 | Development of advanced structural concepts |
| 10. Large Deployable Reflector (LDR) | SAAX020 | Construct & operate large segmented optics system |
| 11. Adv. Antenna Assembly/Performance | 2064 | Assemble & characterize 100m dia. antenna |
| 5. MATERIALS & FABRICATION TECHNOLOGY | | |
| 1. Polymeric Mat'ls for Space Mechanisms | | Effect of space environment on material performance |
| 2. Spacecraft Materials & Coatings | 2011 | Determine effect of space env. on materials & coatings |
| 3. Micrometeorite Protection | | Micrometeorite protection technique development |
| 4. Ion Beam Cold Welding | 2065 | Develop ion beam welding tech. for in-space fabrication |
| 6. STRUCTURAL CONCEPTS RESEARCH FACILITY | | Facility to study structural concepts & components |

### 3.3.2.2 Control/Structures Interaction Experiments

COFS Flight Experiments - As discussed in Section 3.1.3, these experiments will satisfy some of the goals for both structures and control/structure interaction.

In-Space Actively Controlled Structure - This experiment is a testbed for a number of technology demonstrations (structural alignment, disturbance attenuation, precision pointing).

Flight Dynamics Identificaton, TDMX2071 - The antenna hardware used for this experiment is also used on TDMX2411, 2412, 2413, and the "Large Space Antenna (Reflectors)" experiment.

Active Optic Technology, TDMX24231 - This experiment was not presented at the OAST In-Space RT&E Workshop. It supports Large Deployable Reflector (LDR) technology goals. It is similar to "Precision Optical" and may be the same as "TDM for LDR," although different flight dates are listed.

Advanced Adaptive Control, TDMX2411 - The antenna hardware identified for this experiment is also used on TDMX 2071,2412, 2413, and the "Large Space Antenna (Reflectors)."

Distributed Control Experiment, TDMX2412 - The antenna hardware identified for this experiment is also used on TDMX2071,2411, 2413, and "Large Space Antenna (Reflectors)."

Dynamic Disturbance Control, TDMX2413 - The experiment is called "Large Space Structures Disturbance Control" at the OAST In-Space RT&E Workshop. The antenna hardware used for this experiment is also used on TDMX2071,2411,2412, and "Large Space Antenna (Reflectors)."

Tethered Experiments, TDMX2541-4 - These four experiments were not presented at the OAST In-Space RT&E Workshop, but they have dynamic implications for Space Station. These missions demonstrate the application of tether technology. The first tether mission probably should be designed to demonstrate tether operation with a dummy mass.

Dynamic Stabilization of a Free-Flying Robot, TDMX2433 - This experiment was not presented at the OAST In-Space RT&E Workshop. It demonstrates stability and station keeping technology for a servicing robot.

### 3.3.2.3 Space Station Dynamic Characterization

Advanced Controls Technology, TDMX2414 - This experiment makes use of the Space Station and the Mobile Service Center (MSC) to study system identification and control algorithms for large, flexible space structures.

Space Station System Performance Technology - The Space Station structure is instrumented to determine its dynamic characteristics during build-up and post-IOC operation.

### 3.3.2.4 Space Construction Technology

Structures and Assembly Verification Experiment (SAVE) - Similar to "Structural Assembly Experiments" presented at the OAST In-Space RT&E workshop, it demonstrates Space Station truss construction.

Large Space Structure, TDMX2061 - This mission demonstrates the deployment of a truss platform to be used as a permanent Space Station facility (Construction/Storage/Hangar) after the experiment. The facility's purpose is similar to TDMX2062, "Space Station Modifications."

Space Station Modifications, TDMX2062 - This experiment adds a "servicing support area" to the Space Station. Its purpose is similar to TDMX2061, "Large Space Structure."

On-Orbit Spacecraft Assembly and Test, TDMX2063 - The objective of this experiment is to demonstrate Space Station capability for satellite assembly and servicing.

Large Space Antenna (Reflectors) - The antenna hardware identified for this experiment is also used on TDMX2071,2411, 2412, and 2413.

Environmental Influence on Structural Dynamics - This experiment studies the effects of space exposure on the behavior of materials and joints. It could be combined with TDMX2011, "Spacecraft Materials and Coatings."

Precision Optical - This experiment supports LDR technology. It is similar to TDMX2421 and "TDM for LDR," except that a modular construction approach is used.

TDM for LDR - This experiment supports LDR technology. It may be the same mission as TDMX2421, "Active Optic Technology," although different flight dates are specified. It is also similar to the "Precision Optical" experiment.

Inflatable/Rigid Structure Elements, TDMX2066 - An advanced structural concept is proposed as an alternative to conventional construction methods. Inflatable structures are proposed for Space Station facilities such as airlocks and hangars.

Large Deployable Reflector (LDR), SAAX020 - This is the science and applications mission that is the culmination of many of the TDMX missions.

Advanced Antenna Assembly and Performance, TDMX2064 - The objective of this experiment is to demonstrate the assembly of a large (100 meter diameter antenna on the Space Station. Its large size is the volume driver for Space Station experiments.

### 3.3.2.5 Materials and Fabrication Technology

Polymeric Materials for Space Mechanisms - The purpose of this experiment is to determine the effects of space exposure on self-lubricating polymeric materials under sliding/rolling contact for space mechanisms. It could be combined with TDMX2011, "Spacecraft Materials and Coatings."

Spacecraft Materials and Coatings, TDMX2011 - This is a long term exposure experiment to study the effects of the space environment on materials and coatings. It was presented in the Space Environmental Effects theme area at the Workshop.

Micrometeorite Protection - This is an experiment to investigate micrometeorite protection techniques. No details were presented.

Ion Beam Cold Welding, TDMX2065 - This experiment demonstrates the use of ion beam cold welding techniques for fabricating large structures in space.

### 3.3.2.6 Structural Concepts Research Facility

This is a Space Station facility proposed for the advancement of structural concepts for future spacecraft. The low-g environment is ideal for testing structural components and assemblies that cannot be tested adequately in 1-g. It also could be used to evaluate materials and coatings from TDMX2011.

## 3.4 Technology Gaps

One of the tasks of the Space Structure (Dynamics & Control) themearea panel at the OAST In-Space RT&E Workshop was to identify technology gaps based on the experiments presented. A matrix was created whose rows are the proposed experiments, and whose columns are technology areas of importance to the theme area. The technology areas that are not adequately addressed by the experiments were identified and presented in the Workshop documentation.

During this study, the matrix was expanded to include the TDMX missions that were not presented at the Workshop. All of the missions were reviewed to verify the panel's assessment and to expand it to include omitted and secondary technology goals for each of the experiments. The 37 technology topics identified by the Workshop panel were grouped into six categories: sensors, control devices, control techniques, dynamics, modeling, and structures and materials. The resulting technology assessment matrix is shown in figure 3.4-1. By observing the number of X's in each column (technology area), the technology gaps and thin spots were identified.

The determination of technology gaps and thin spots is accomplished in two steps. First, the Workshop panel's assessment of the technology gaps is reviewed considering the additional TDMX missions included in the list. Then, other technology needs are determined based on the updated technology matrix.

Figure 3.4-1: TECHNOLOGY AREAS ADDRESSED BY PROPOSED EXPERIMENTS
SPACE STRUCTURE (DYNAMICS & CONTROL) THEME AREA

| EXPERIMENT TECHNOLOGY --> | | TECHNOLOGY AREAS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SENSORS | | | | | | CONTROL DEVICES | | | | | | CONTROL TECHNIQUES | | | | | | | | | | | | DYNAM. | | | MODELING | | | | | STRUCT & MATLS | | | | |
| | TDMX | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| 1. COMPONENT TECHNOLOGY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Fiber Optic Sensors in Space Applications | | X | | X | | X | X | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | |
| 2. Spacecraft Strain & Acoustic Sensors | 2072 | X | | | | X | X | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | |
| 3. Berthing and Docking Sensor | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4. Attitude Control & Energy Flight Experiment | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5. Advanced Control Device Technology | 2431 | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6. Thermal Shape Control | 2422 | | X | | | | | | | X | | X | | | | | | | | | | X | | | | | | | | | | | | | | | | |
| 7. Advanced Experiment Pointing and Isolation | 2432 | | | X | | | | | | | | | X | | | | | X | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2. CONTROL/STRUCTURE INTERACTION EXPERIMENTS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. COFS Flight Experiments | | X | | X | | X | X | | | X | | X | | | X | X | X | X | X | X | X | X | X | | | X | X | | X | | | | | | | | | |
| 2. Flight Dynamics Identification | 2071 | | | | | | X | | | | | | | | | X | | | | | | | | | | | X | | X | | X | | | | | | | |
| 3. Dynamic Disturbance Control | 2413 | | | | | | X | | | | | | | | X | X | X | X | X | X | X | | X | | | | X | | X | | | | | | | | | X |
| 4. Distributed Control Experiment | 2412 | | | | | | X | | | | | | | | X | | | X | X | X | | | X | | | | X | | X | | | | | | | | | |
| 5. Advanced Adaptive Control | 2411 | | | | | | X | | | | | | | | X | | | X | X | X | X | | | | | | X | | X | | | | | | | | | |
| 6. In-Space Actively Controlled Structure | | | X | | | X | | | | X | | X | X | | | | | X | | X | X | X | X | | | | | | X | | | | | | | | | |
| 7. Active Optic Technology | 2421 | | X | | | X | | | | | | X | | | X | | | | | | | X | | | | | | | | | | | | | | | | |
| 8. Dynamic Stabilization of Free-Flying Robot | 2433 | | | X | | | | | | | X | | X | X | | | X | | X | | | | | | | | X | | X | | | | | | | | | |
| 9. Tethered Electrodynamic Power Generation | 2541 | | | | | | X | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | |
| 10. Tethered Constellation | 2542 | | | | | | X | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | |
| 11. Tethered Transportation | 2543 | | | | | | X | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | |
| 12. Tethered Fluid Storage and Transfer | 2544 | | | | | | X | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3. SPACE STATION DYNAMIC CHARACTERIZATION | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Space Station System Performance Technology | | | | | | | X | | | | | | | | | X | | | | | | | | | | X | X | | X | X | X | | X | | X | | | X |
| 2. Advanced Controls Technology | 2414 | | | | | | | | | | | | | | | X | | X | | X | | X | X | | X | | | | X | X | X | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4. SPACE CONSTRUCTION TECHNOLOGY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Advanced Antenna Assembly and Performance | 2064 | | | | | | | | | | | | | | | X | | | | | | X | | | | | | | X | | | | | | | | X | X |
| 2. Precision Optical | | | X | | | X | X | | | | | | X | | X | X | | | X | | | X | X | X | | | | | X | | | | | | | | X | X |
| 3. On-Orbit Spacecraft Assembly and Test | 2063 | | | | | | X | | X | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | X |
| 4. Space Validation of Underwater Tests | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X |
| 5. Large Space Antenna (Reflectors) | | | | | | | | | | | | | | | | X | | | | X | | X | | | | X | | | X | | | | | | | | X | X |
| 6. Large Space Structure | 2061 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | X | | | | | | | | | X |
| 7. Space Station Modifications | 2062 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X |
| 8. Structural Assembly Experiments | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X |
| 9. Large Deployable Reflector (LDR) | | | X | | | X | | | X | | | | X | | X | | | | X | | | X | X | X | | | | X | X | | | | | | | | X | X |
| 10. Polymeric Materials for Space Mechanisms | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | X | | |
| 11. Micrometeorite Protection | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | X | |
| 12. Environmental Influence on Structural Dynamics | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | X | X | | X | X | X | X | |
| 13. Spacecraft Materials & Coatings | 2011 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | X | | X | X | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5. ADVANCED STRUCTURAL CONCEPTS & FABRICATION TECHNOLOGY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Inflatable/Rigidizable Structural Element | 2066 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | X | | X | X | X |
| 2. Ion Beam Cold Welding | 2065 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | X |

LEGEND

Sensors:
1. Integrated Sensors
2. Alignment Sensors
3. Inertial Sensors
4. Berthing/Docking Sensors
5. Shape/Configuration Sensors
6. Test & Verification Sensors

Control Devices:
1. Low Cost Concepts
2. ORU Concepts
3. Integrated Structure/Control
4. Attitude Control Devices
5. Structural Control Actuators
6. High Accuracy Pointing Devices

Control Techniques:
1. Precision Stationkeeping
2. Alignment Techniques
3. System Identification
4. Maneuvering Techniques
5. Disturbance Suppression
6. Articulated System Control
7. Active Modal Control
8. Adaptive Control
9. Shape Control
10. Distributed Control
11. Multi-Loop Control
12. Hierarchical Control

Dynamics:
1. Deployment Dynamics
2. Articulated Multibody Dynamics
3. Tether Dynamics

Modeling:
1. Dynamic Modeling
2. Joint Modeling
3. Damping Models
4. Environmental Modeling
5. Disturbance Characterization

Structures & Materials:
1. Structural Materials (Coatings
2. Passive Damping
3. Long Life Materials
4. Strucural Concepts
5. Orbital Assembly

### 3.4.1 OAST In-Space RT&E Workshop Panel's Assessment

Each of the technology areas identified by the OAST In-Space RT&E workshop panel as requiring additional attention are reviewed in the following paragraphs. The comments following each topic reflect the inclusion of TDMX missions that were not included in the Workshop review.

Validation of Space Station structure (construction techniques, utility integration, long-term integrity) - The Structures and Assembly Verification Experiment (SAVE) addresses this need. However, experiments to demonstrate other aspects of Space Station construction are needed (e.g., module attachment, equipment and subsystem installation, etc.). Although in a different theme area, robotic assembly technology should be identified as an important requirement for future in-space construction. The dynamics and control of robots must be understood. Potential Space Station disturbance caused by robotic assembly is also a significant concern.

In-space loads characterization - Structural loads will be measured on COFS and SAVE. Space Station loads environments for events such as docking and reboost will be measured during the Space Station Structural Characterization Experiment.

Passive damping - With proper instrumentation, as-built structural damping characteristics can be measured during experiments such as COFS, SAVE and TDMs for LDR. Designed-in passive damping experiments are needed to verify damping designs and to validate ground tests and analysis. Passive damping studies are currently being funded by the Air Force (PACOSS, RELSAT, etc.)

Embedded sensors and actuators - These should be developed and validated using ground tests. They have wide applications for many types of space structures. Embedded sensors should be developed early to support Space Station and other experiments.

Vibration control devices - Some active vibration control devices are being developed (proof mass actuators, piezo-electric devices, etc.). Proof-mass actuators will be used on COFS I.

Shape control devices - Shape control of the 15-meter hoop-column antenna is being developed at LaRC. Techniques and devices for the control of other types of reflector surfaces need to be studied and demonstrated. The embedded sensor and actuators mentioned above are prime candidates.

Low frequency vibration isolators - Air Force studies are in progress to develop low frequency vibration isolators and pointing systems.

Fluid-structure interaction - Disturbances resulting from fluid-structure interaction may be a significant contributor to Space Station, OMV and OTV dynamics and control. Orbiter flight experiments would be valuable, since ground tests cannot adequately duplicate the micro-g environment.

Advanced structural concepts - Advanced structural members, elements, joints, surfaces, construction techniques, etc. need to be developed and demonstrated.

In-space fabrication - The only experiment currently being considered in this area is "Ion Beam Cold Welding" (TDMX2065). On-orbit fabrication technology (e.g. beam-builders) needs to be revived and advanced for future large space structures.

Docking/berthing sensors - One such experiment has been suggested. Other candidates need to be designed and developed. Orbiter flight experiments should be defined to demonstrate the capability for Space Station.

Structural development/test facility - A permanent Space Station facility is needed to provide the low-g and other environmental conditions required to characterize new sensors, actuators and advanced structural concepts.

### 3.4.2 Other Technology Concerns

The technology matrix (figure 3.4.-1) indicates other areas that need to be addressed to advance the technologies for future space systems:

Low cost concept - No experiments explicitly identify this as a technical objective, but it is a goal for all space systems.

ORU concepts - Orbital replacement units (ORUs) are becoming a requirement for more spacecraft to permit on-orbit servicing. The design of "standard" ORUs and interfaces is an important method of reducing the cost of future space systems. The Space Station goal of commonality will promote the development of low cost ORUs.

Attitude control devices - Some magnetically-suspended reaction wheels have been developed, and magnetic suspension CMG's are being studied; but other types of devices (e.g., low level thrusters) need to be developed.

Failure detection and isolation - Flight experiments are needed to demonstrate techniques currently being developed. System reconfiguration to accommodate the loss of one or more sensors is an important aspect of this technology.

Precision station keeping - Advancement of this technology is a requirement for MMU and OMV proximity operations at the Space Station.

Hierarchical control - Coarse and fine control techniques are needed for LDR and other instruments and experiments that require precision pointing.

Multi-loop control - Advancement in this technology area is needed to control the various systems for Space Station and other future spacecraft.

Maneuvering techniques - The operation of the MSC (mobile service center) will require this technology to transport objects from place to place on the Space Station. OMV operations will also require maneuvering techniques.

Tether dynamics - Four experiments (TDMX2541-4) are defined whose primary objectives are to demonstrate tether applications rather than the determination of tether dynamics and its effect on the Space Station.

Joint modeling - The dynamics of joint-dominated structures are a function of the joint characteristics. Joint analysis methods and test procedures are currently being developed at NASA and under NASA contracts. On-orbit verification of these techniques for specific types of structural joints will be accomplished with the COFS and SAVE experiments.

Environmental modeling - Three experiments will contribute to the definition of the Space Station environment: "Spacecraft Materials and Coatings" (TDMX2011), "Micrometeorite Protection" and "Environmental Influence on Structural Dynamics." Other measurements of the Space Station environment will be accomplished in the Space Environmental Effects theme area.

Disturbance characterization - Knowledge of the potential disturbances for Space Station is required to quantify the environment for experiments, particularly those that require micro-gravity.

## 4.0 Recommended Experimental Activities

The review and evaluation of on-going and proposed in-space experimentation leads to the identification of a proposed road map for technology in the Space Structure (Dynamics and Control) theme area. First, near-term and long-term technology goals dictate a prioritization of technology topics. Second, the prioritization helps to define a timetable for space experiments needed to demonstrate the technology areas. And, finally, the scope of the proposed experiments results in interrelationships with experiments within this theme area and to other technology theme areas.

### 4.1 Prioritization of Technology Areas

By reviewing the technology needs for Space Station and other near-term missions, a prioritization of technology topics was established. This was accomplished by experienced personnel in both the structural dynamics and controls technology areas. The prioritization is shown in Figure 4.1-1. In some cases, the priority is based on the need of the technology in the near future. In other cases, the prioritization is the result of an assessment of the lack of existing technical maturity. Even though some missions may occur in the far future, the development of the required technologies needs to start now. Some of the experiments in the list have been grouped into broader categories to ease the complexity and difficulty of prioritization.

With increasing size and flexibility of future spacecraft, the highest priority technology area is associated with the ability to characterize and control large flexible structures. The dynamic characteristics of deployable structures are dominated by the behavior of the many joints that permit its deployment. The three phases of the COFS program, including the guest investigator program, will advance the technology in this area, and will demonstrate the techniques needed for Space Station and other large space systems.

The next two experiments on the prioritized list deal with the ability to perform structural assembly in space. Two Orbiter-based experiments (EASE and ACCESS) have already been conducted that demonstrate structural assembly using EVA. SAVE is another Orbiter flight experiment that will demonstrate the EVA assembly of the 5-meter truss and utility tray integration for the Space Station. In the long run, the goal for in-space assembly is to use robotics to eliminate the potential hazards of EVA. Although Automation and Robotics is a separate theme area, the robotic or telerobotic aspects of the On-orbit Spacecraft Assembly and Test experiment are high on the priority list to advance the ability to analyze and predict the behavior of controllable, multi-body, jointed structures.

Next on the priority list are two experiments in that address component technology. Advanced control devices are needed to implement the techniques developed to control large flexible space structures and the Space Station. Advanced experiment pointing and isolation systems are

Figure 4.1-1: Structures/Dynamics/Controls Technology Priorities

| Priority | Experiment |
|---|---|
| 1 | Control of Flexible Structures (COFS) |
| 2 | Structures and Assembly Verification Experiment (SAVE) |
| 3 | On-Orbit Spacecraft Assembly and Test (Robotics) |
| 4 | Component Technology |
| | Advanced control devices |
| | Advanced experiment pointing and isolation |
| 5 | Materials Technology |
| | Materials and coatings |
| | Polymeric materials for space mechanisms |
| | Environmental influence on structural dynamics |
| 6 | Space Station Performance Experiment |
| 7 | Space Station Facilities |
| | Large space structures |
| | Space Station modifications |
| | Structural Concepts Research Facility |
| 8 | Large Deployable Reflector (LDR) |
| | TDM for LDR |
| | Precision optical |
| | Active optic technology |
| 9 | Component Technology |
| | Docking/berthing Sensor |
| | Structurally embedded sensors and actuators |
| | Attitude control and energy flight experiment |
| | Thermal shape control |
| 10 | Antenna Experiments |
| | Large space antenna (reflectors) |
| | Advanced adaptive control |
| | Distributed control experiment |
| | Dynamic disturbance control |
| | Advanced antenna assembly/test |
| 11 | Advanced Controls Technology |
| 12 | Tethered Experiments |
| 13 | In-Space Fabrication |
| | Ion beam cold weld |
| 14 | Inflatable/Rigid Structural Elements |

needed to provide pointing accuracy and stability for spacecraft systems/components and for antennas and experiments mounted on the Space Station.

The fifth item on the list includes several experiments whose goal is to determine the behavior of materials in the space environment and to develop durable and stable materials and coatings for space applications. Although the influence of the space environment on materials is extremely important and should be pursued, many of the major effects of the space environment have already been identified (not necessarily quantified), however, there are materials that are able to withstand the space environment. Also, the methods for in-space experimentation require little technological advancement.

The next three items relate to the characterization and assembly of large space structures such as the Space Station, its evolutionary features, and the large deployable antenna (LDR). The Space Station should be instrumented to determine its dynamic behavior during the many stages of assembly. This will provide data for the verification of ground tests and analysis techniques. Through the addition of new Space Station facilities, additional knowledge of in-space assembly will be obtained. Construction of LDR will not only advance the technology for both EVA and robotic structural assembly, but also for alignment and control of a high precision, segmented reflector surface.

Prioritization of the remainder of the experiments becomes more and more difficult and subjective. Advancement of sensor and actuator technology is highly desirable and docking and berthing sensors will be required for Space Station, but today's technology is judged to be sufficient with the current rate of advancement. Advancement of some of the technologies needed for large antenna systems will occur as a result of the higher priority technology topics for the control of flexible structures. Application of the technologies for tether systems, in-space fabrication and advanced structural concepts will require an operational Space Station and are, therefore, lower priority.

In summary, all of the technology development experiments and topics listed are vital to the advancement of the Space Structure (Dynamics and Control) theme. Development of the technologies for all of the experiments should continue. The priority for the development of some smaller experiments (e.g., sensors, actuators, control techniques, etc.) could be raised if an application can be found on a higher priority mission.

## 4.2 Experiment Timetable

The identification of a technology timeline was accomplished by the theme panel at the OAST In-Space RT&E Workshop in October, 1985, and is shown in Figures 4.2-1 through 4.2-5 for the five areas within the theme area. With proper adjustments to account for the slide in the date of Space Station IOC, the flow of technology development shown is accurate.

A more experiment-oriented timetable is presented here, based on the prioritization of the experiments shown above and on a model set of TDMX missions listed in Figure 4.2-6. This mission model is a reference set of experiments provided to Code S (Office of Space Station) by Code R (Office of Aeronautics and Space Technology) so that an early assessment of Space Station accommodation requirements can be made. They represent the types of experiments that could be conducted in the near-IOC timeframe (within three years following IOC).

Figures 4.2-7 through 4.2-9 present the recommended in-space experiment activity for the late 1900's, assuming that Space Station IOC will be in 1995. The proposed experiments were categorized, according to their primary objective, into three categories: structures, control/structure interaction, and controls. Each figure lists experiments whose primary and secondary objectives are in that category. Comments are also provided to indicate missions that have already flown and experiments that are similar or use the same hardware. Many of the experiments would benefit from precursor Shuttle experiments, some of which are identified in the figures.

## 4.3 Interrelationship of Activities

It is clear that many experiments span several technology areas, no matter what categories are used. For example, all of the experiments need some kind of structure. Therefore, the construction of the test article falls into the structures area, while the primary purpose of the experiment may be to demonstrate controls technology. So there is a great amount of synergism among the experiments. Also, even though robotics technology is a separate theme area, the dynamics of the robotic structure is an important factor in determining its performance.

By careful planning, design and coordination, the objectives of several experiments may be realized with a single test article. For example, the series of antenna experiments proposed by JPL have been planned so that the same antenna structure will be used for several of the experiments. Also, as previously mentioned, some smaller experiments that demonstrate sensors, actuators, and control techniques can be combined with larger experiments to enhance their position in the stream of technology development.

Figure 4.2-1: Component Technology

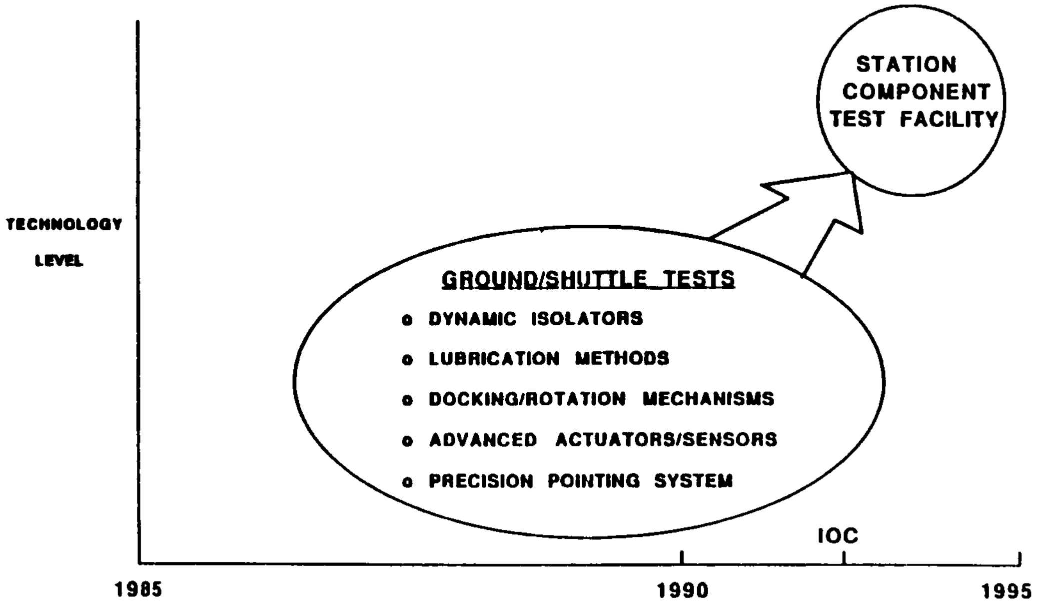

Figure 4.2-2: Control/Structures Interaction (CSI)

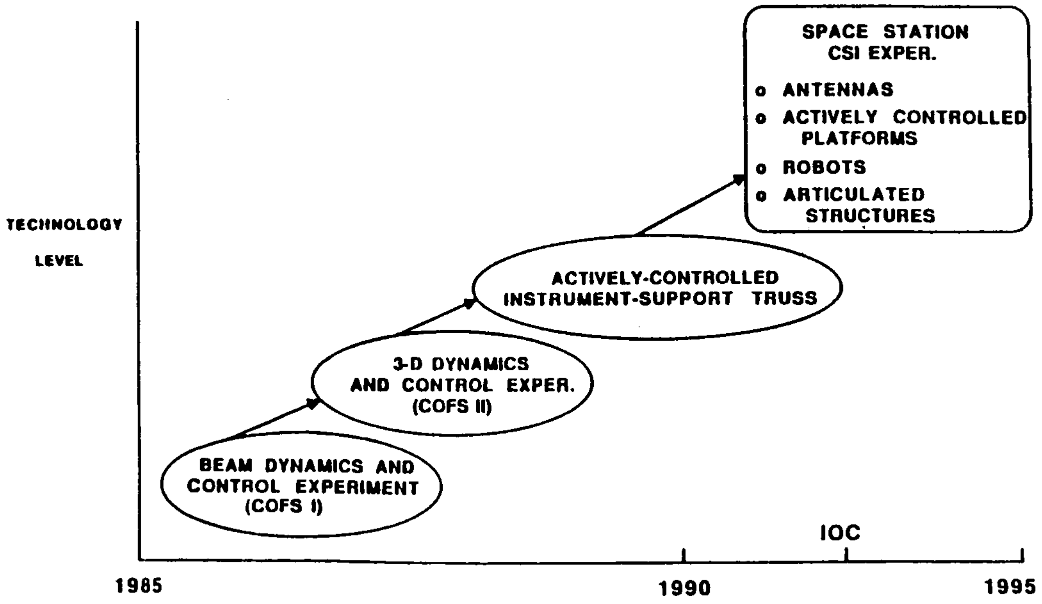

Figure 4.2-3: Space Station Dynamic Characterization

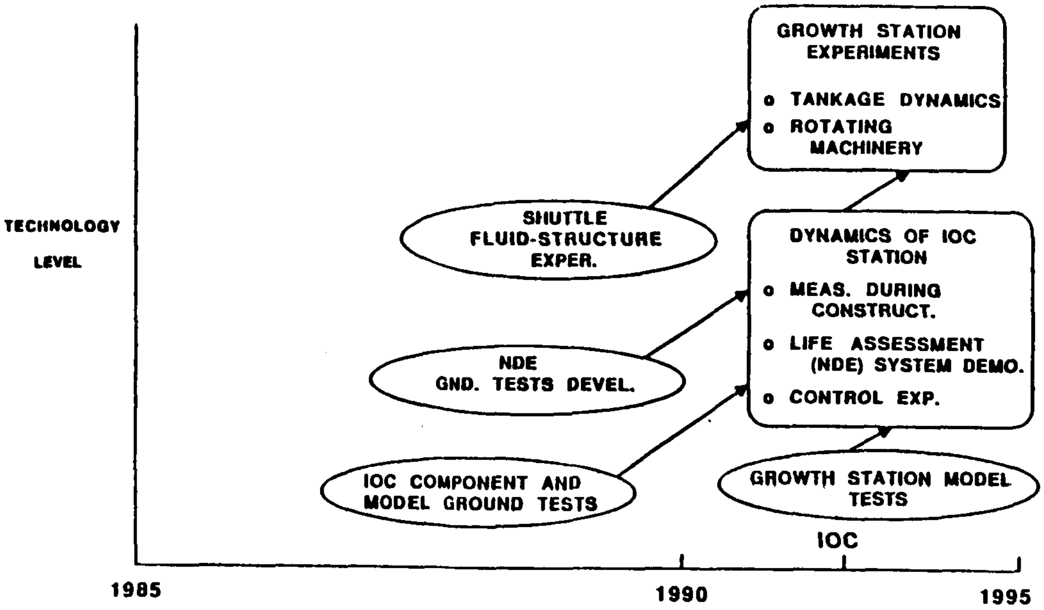

Figure 4.2-4: Construction Technology

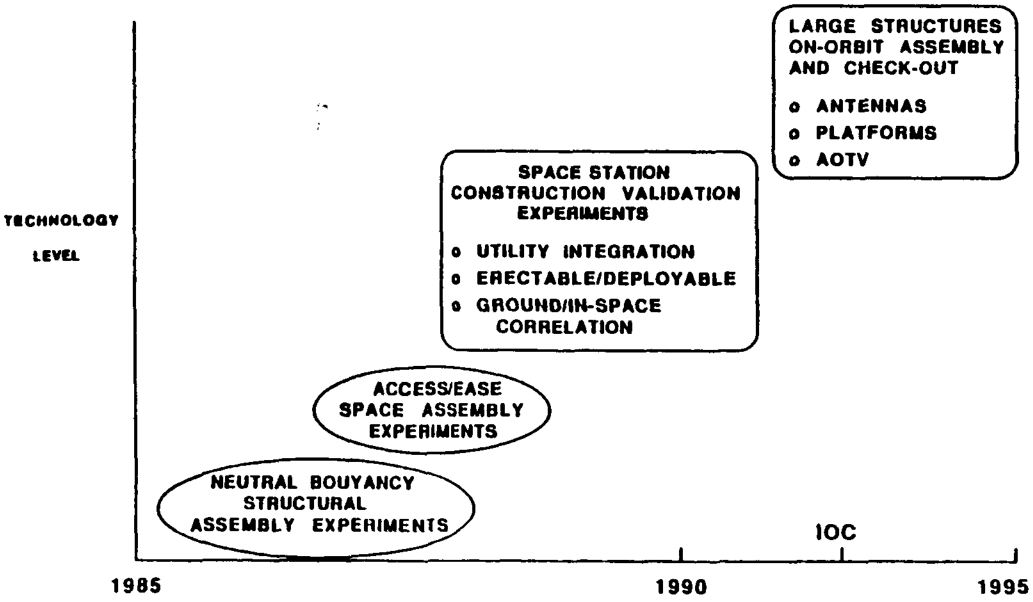

Figure 4.2-5: Advanced Structural Concepts

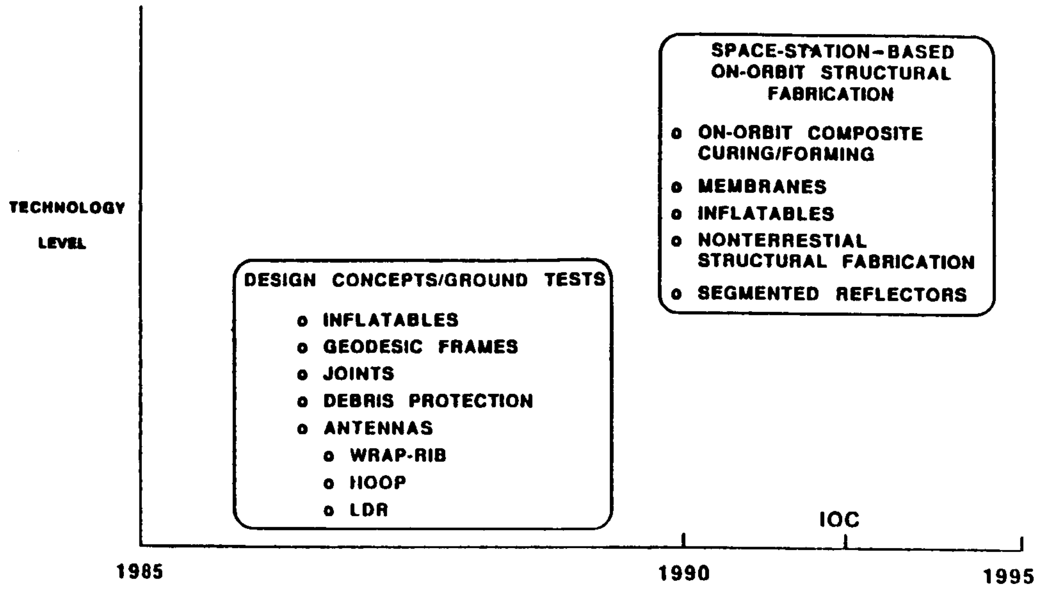

Figure 4.2-6: TDMX Model Set

| TDMX No. | Title | Sponsor |
|---|---|---|
| 2071 | Flight Dynamics Identification | JPL |
| 2411 | Advanced Adaptive Control | JPL |
| 2412 | Distributed Control Experiment | JPL |
| 2413 | Dynamic Disturbance Experiment | JPL |
| 2441 | Microelectronics Data System Experiment | JPL |
| 2462 | Dextrous Teleoperator Technology | JPL |
| 2461 | Teleoperated Structure Assembly | JPL |
| 2132 | Advanced Radiator Concepts | LeRC |
| 2153 | Advanced Solar Dynamic Power | LeRC |
| 2311 | Long-Term Cryogenic Fluid Storage | LeRC |
| 2011 | Spacecraft Materials and Coatings | LaRC |
| 2072 | Spacecraft Strain and Acoustics Sensors | LaRC |
| SPE | Space Station Structural Performance Experiment | LaRC |
| 2442 | Transient Upset Phenomena in VLSI Devices | LaRC |
| 2443 | VHSIC Fault Tolerant Processor | LaRC |
| 2561 | Satellite Servicing and Refurbishment | MSFC |
| 2562 | Satellite Maintenance and Repair | MSFC |
| 2572 | Cryogenic Propellant Transfer/Storage/Reliquifaction | MSFC |
| 2573 | OTV Docking and Berthing | MSFC |
| 2574 | OTV Maintenance Technology | MSFC |
| 2571 | OTV/Payload Interfacing and Transfer | MSFC |

Figure 4.2-7: IN-SPACE RESEARCH, TECHNOLOGY AND ENGINEERING (RT&E) ROADMAP
SPACE STRUCTURE (DYNAMICS & CONTROL) THEME AREA

STRUCTURES EXPERIMENTS

| EXPERIMENT TITLE | TDMX | Notes | YEAR | | | | | | | | | | | | | PRIMARY OBJECTIVES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | |
| | | | | | | | | | | * | * | * | | | | |
| 1. SOLAR ARRAY EXPERIMENT | OAST-1 | 2 | | | | | | | | | | | | | | Deploy continuous longeron beam & solar array |
| 2. EASE/ACCESS | | 3 | | | | | | | | | | | | | | EVA assembly of truss structures |
| 3. [ COFS I ] | | 1 | | | | X | X | | | | | | | | | Deploy truss beam |
| 4. SAVE | | 5 | | | | X | | | | | | | | | | EVA assembly of 5-meter truss beam & utility trays |
| 5. [ COFS II ] | | 1 | | | | | | X | X | | | | | | | Deploy & articulate truss beam & antenna |
| 6. Large Space Structure | 2061 | | | | | | | | | | | | X | | | Deploy & characterize planar truss, (SS facility) |
| 7. Space Station Modifications | 2062 | | | | | | | | | | | | X | | | Space Station structural evolution (servicing area) |
| 8. LDR | SAAX020 | | | | | | | | | | | | | | X | Assemble Large Deployable Reflector (LDR) |
| a. [ Active Optics Technology ] | 2421 | 4 | | | | | | | | | | | X | | | Assembly & operation of segmented optics system |
| b. Precision Optical | | 4 | | | | | | | | | | | X | | | Modular assembly of segmented optics system |
| c. TDM for LDR | | 4 | | | | | | | | | | | X | | | Deploy & assemble segmented optics system |
| 9. [ Flight Dynamics Identification ] | 2071 | 6 | | | | | | | | X | | | | | | Deploy antenna, measure shape |
| 10. Large Space Antenna (Reflectors) | | 6 | | | | | | | | X | | | | | | Antenna deployment, assembly & characterization |
| 11. On-Orbit S/C Assembly & Test | 2063 | | | | | | | | | | | | | X | | Spacecraft assembly & checkout on the Space Station |
| 12. Inflatable/Rigidizable Struct. Element | 2066 | | | | | | | | | | | | | X | | Development of advance structural concepts |
| 13. Adv. Antenna Assembly/Performance | 2064 | | | | | | | | | | | | | | X | 100 meter dia. antenna assembly & characterization |
| 14. Materials & Fabrication Technology | | | | | | | | | | | | | | | | |
| a. Polymeric Mat'ls for Space Mech. | | | | (X) | -> | | | | | | | | X | | | Effect of space environment on material performance |
| b. Spacecraft Materials & Coatings | 2011 | | | | | | | | | X | | | | | | Determine effect of space environment on materials |
| c. Micrometeorite Protection | | | | | | | | | | | | | | X | | Micrometeorite protection technique development |
| d. Ion Beam Cold Welding | 2065 | | | | | | + | | | | | | | | X | Develop ion beam welding tech. for in-space fabrication |
| 15. Structural Concepts Research Facility | | | | | | | | | | | | | X | | | Facility to investigate new structural concepts |
| 16. Teleoperated Structure Assembly | 2461 | | | | | | | | | X | | | | | | Assemble structures using telerobotics |

Notes:
1 - [ ] Indicates that the prime objectives are in a different category
2 - Flown on Mission 41-D, 8/31/84
3 - Flown on Mission 61-B, 11/26/85
4 - Similar experiments
5 - Similar experiment "EVA Large Structure Assembly" (RT&E Workshop) deleted
6 - Same experiment hardware as TDMX2411, 2412 & 2413 (Control/Structure Interaction Exp.)

* - IOC timeframe
+ - Suggested precursor flight experiment

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Figure 4.2-8: IN-SPACE RESEARCH, TECHNOLOGY AND ENGINEERING (RT&E) ROADMAP
SPACE STRUCTURE (DYNAMICS & CONTROL) THEME AREA

CONTROL/STRUCTURES INTERACTION EXPERIMENTS

| EXPERIMENT TITLE | TDMX | Notes | YEAR |  |  |  |  |  |  |  |  |  |  |  |  | PRIMARY OBJECTIVES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 |  |
|  |  |  |  |  |  |  |  |  |  | * | * | * |  |  |  |  |
| 1. [ SOLAR ARRAY EXPERIMENT ] | OAST-1 | 1,2 |  |  |  |  |  |  |  |  |  |  |  |  |  | Dynamics of deployable solar arrays |
| 2. COFS I |  |  |  |  |  | X | X |  |  |  |  |  |  |  |  | System identification, test methods |
| 3. [ LDR ] | SAAX020 | 1 |  |  |  |  |  |  |  |  |  |  |  |  | X | Control of large deployable reflector |
| a. Platform Active Control |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  | Control of alignment, dynamics, precision pointing |
| b. Active Optics Technology | 2421 | 4 |  |  |  |  |  |  |  |  |  |  | X |  |  | Assembly & operation of segmented optics system |
| c. [ Precision Optical ] |  | 1,4 |  |  |  |  |  |  |  |  |  |  | X |  |  | Adjustment, alignment, dynam. of segmented optics syst. |
| d. [ TDM for LDR ] |  | 1,4 |  |  |  |  |  |  |  |  |  |  | X |  |  | Adjustment, alignment, control of segmented optics |
| 4. [ SAVE ] |  | 1 |  |  |  | X |  |  |  |  |  |  |  |  |  | Dynamics of 5-meter assemblable truss beam |
| 5. COFS II |  |  |  |  |  |  |  | X | X |  |  |  |  |  |  | Articulation, pointing, shape control, alignment |
| 6. [ Advanced Controls Technology ] | 2414 | 1 |  |  |  |  |  |  |  |  |  |  | X |  |  | Dynamics & control of large, flexible spacecraft |
| 7. Antenna Experiments |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| a. Flight Dynamics Identification | 2071 | 3 |  |  |  |  |  |  |  | X |  |  |  |  |  | System identification, sensor architecture & testing |
| b. Advanced Adaptive Control | 2411 | 3 |  |  |  |  |  |  |  |  |  | X |  |  |  | Adaptive control techniques, strategy & algorithms |
| c. Distributed Control Experiment | 2412 | 3 |  |  |  |  |  |  |  |  | X |  |  |  |  | Distributed control techniques, strategy & algorithms |
| d. Dynamic Disturbance Control | 2413 | 3 |  |  |  |  |  |  |  |  | X |  |  |  |  | Disturbance suppression & isolation |
| 8. Sp. Sta. Perf. Technology Validation |  |  |  |  |  |  |  |  |  | X | X | X |  |  |  | Verify & validate analysis & pre-flight predictions |
| 9. Tethered Experiments | 2541-4 |  |  |  |  |  | + |  | + |  |  |  |  |  | X | Develop technology for tethers |
| 10. Environ. Influence on Struct. Dynamics |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  | Determine long term effects of space environment |
| 11. Teleoperated Structure Assembly | 2461 |  |  |  |  |  |  |  |  | X |  |  |  |  |  | Assembly of structures using telerobotics |

Notes:

1 - [ ] Indicates that the prime objectives are in a different category
2 - Flown on Mission 41-D, 8/31/84
3 - Same experiment hardware (See also Struct. Exp. "Large Space Antenna")
4 - Similar experiments

* - IOC timeframe
\+ - Suggested precursor flight experiment

Figure 4.2-9: IN-SPACE RESEARCH, TECHNOLOGY AND ENGINEERING (RT&E) ROADMAP
SPACE STRUCTURE (DYNAMICS & CONTROL) THEME AREA

CONTROLS EXPERIMENTS

| EXPERIMENT TITLE | TDMX | Note | YEAR | | | | | | | | | | | | | PRIMARY OBJECTIVES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | |
| | | | | | | | | | | * | * | * | | | | |
| 1. Component Technology | | | | | | | | | | | | | | | | |
| a. Berthing and Docking Sensor | | | X | | | | | | | | | | | | | Demonstrate berthing & docking techniques |
| b. Fiber Optic Sensors in Space Applic. | | | | | X | | | | | | | | | | | Fiber optic gyro & sensor development |
| c. S/C Strain & Acoustic Sensors | 2072 | | | | | + | | + | | X | | | | | | NDE methodology development |
| d. Attitude Control & Energy Flight Exp | | 2 | | | | | + | | | | | | X | | | Develop device for attitude control & energy storage |
| e. Thermal Shape Control | 2422 | | | | | | | | | | | | | X | | Shape control using distributed thermal controllers |
| f. Advd. Expmt. Pointing and Isolation | 2432 | | | | | | | | | | | | | X | | Precision pointing, disturbance suppression |
| g. Advanced Control Device Technology | 2431 | 2 | | | | | | | | | | | X | | | Eval. combined energy storage & momentum storage device |
| 2. [ COFS I ] | | 1 | | | | X | X | | | | | | | | | System identification, test methods |
| 3. [ LDR ] | SAAX020 | 1 | | | | | | | | | | | | | X | Control of large deployable reflector |
| a. [ Platform Active Control ] | | 1 | | X | | | | | | | | | | | | Control of alignment, dynamics, precision pointing |
| b. [ Active Optics Technology ] | 2421 | 1,4 | | | | | | | | | | | X | | | Assembly & operation of segmented optics system |
| c. [ TDM for LDR ] | | 1,4 | | | | | | | | | | | X | | | Adjustment, alignment, control of segmented optics |
| 4. [ COFS II ] | | 1 | | | | | | X | X | | | | | | | Articulation, pointing, shape control, alignment |
| 5. [ Advanced Controls Technology ] | 2414 | 1 | | | | | | | | | | | X | | | Dynamics & control of large, flexible spacecraft |
| 6. Antenna Experiments | | | | | | | | | | | | | | | | |
| a. [ Advanced Adaptive Control ] | 2411 | 1,3 | | | | | | | | | | X | | | | Adaptive control techniques, strategy & algorithms |
| b. [ Distributed Control Experiment ] | 2412 | 1,3 | | | | | | | | | X | | | | | Distributed control techniques, strategy & algorithms |
| c. [ Dynamic Disturbance Control ] | 2413 | 1,3 | | | | | | | | | X | | | | | Disturbance suppression & isolation |
| 7. Dynamic Stabilization of F/F Robot | 2433 | | | | | | | | | | | | | X | | Free-flyer stability & station keeping |
| 8. [Telerobotic Structure Assembly] | 2461 | | | | | | | | | X | | | | | | Assembly of structures using telerobotics |
| 9. Dextrous Teleoperator Technology | 2462 | | | | | | | | | X | | | | | | Advancement of dextrous teleoperator technology |

Notes:
1 - [ ] Indicates that the prime objectives are in a different category
2 - Similar experiments
3 - Same experiment hardware (See also Struct. Exp. "Large Space Antenna")
4 - Similar experiments

* - IOC timeframe
+ - Suggested precursor flight experiment

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## 5.0 Summary and Conclusions

Long range technology objectives and goals within the Space Structure (Dynamics and Control) theme area were identified based on proposed spacecraft and missions. Current NASA activities within the theme area were reviewed. The Space Station Mission Requirements Data Base (MRDB) and the results of the OAST In-Space Research, Technology and Engineering (RT&E) Workshop were also reviewed to evaluate activity that has been proposed within the theme area. As a result of this evaluation, technology areas that need more attention to achieve the long-range goals were identified. Prioritization of technology topics within the theme area was accomplished to aid in the development of an experiment timetable for the late 1900's. This timetable is, of course, very tentative for two reasons: the uncertainty of the Space Shuttle flight schedule and the Space Station construction schedule. The availability of the Shuttle to begin Space Station construction will depend on the redesign activity resulting from the Challenger accident. The construction of the Space Station must also progress to a point such that technology development experiments can be accommodated.

In general, the experiments proposed in the Space Station Mission Requirements Data Base (MRDB) and the OAST In-Space RT&E Workshop cover a wide range of topics in the Space Structure (Dynamic and Control) theme area and constitute a comprehensive plan for the demonstration of technologies required for future space missions. There are many duplicate or complementary objectives among the experiments. There are, however, several areas that require more attention, particularly in the definition of in-space demonstration experiments. These technology areas include berthing/docking sensors, ORU concepts, precision station keeping and proximity operations, multi-loop control, hierarchical control, joint modeling, disturbance characterization and passive damping.

Coordination between experiments within the Space Structure (Dynamics and Control) theme area and also between theme areas should be accomplished whenever possible to make maximum use of the Space Station resources. For example, some of the smaller experiments (sensors, actuators, structural joints, damping, etc.) could be consolidated with larger ones to enhance their priority, and at the same time serve to benefit the larger experiment. Experiments that utilize common or similar hardware, that have similar objectives or that complement each other, should be combined into testbeds whenever practical. An example of inter-theme coordination is in the area of robotics. Space Structure (Dynamics and Control) and Robotics are separate theme areas, but the dynamics and control of robots is an important issue, and robotics is envisioned as a prime candidate for assembling structures in space. Therefore, coordination between two or more theme areas is required for some experiments.

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16. Abstract

A study was performed to define the long-range technical objectives and goals for the Space Structure (Dynamics & Control) theme area. The approach was to evaluate on-going and proposed technology activities such that the technology gaps and voids could be identified. After the technology needs were identified, a set of recommended experimental activities were defined including the technical objectives of each and their interrelationship.

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