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SPACE STATION FULL-SCALE DOCKING/BERTHING MECHANISMS DEVELOPMENT

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ABSTRACT

One of the most critical operational functions for the Space Station is the orbital docking between the station and the STS+ orbiter. This paper describes the program to design, fabricate, and test docking/berthing mechanisms for the Space Station. This 3-year program (May 1985 to April 1988) was conducted by McDonnell Douglas under a NASA Marshall Space Flight Center (MSFC) research and development contract. The design reflects Space Station overall requirements and consists of two mating docking mechanism halves. One half is designed for use on the shuttle orbiter and incorporates capture and energy attenuation systems using computer-controlled electromechanical actuators/attenuators. The mating half incorporates a flexible feature to allow two degrees of freedom at the module-to-module interface of the Space Station pressurized habitat volumes.

The design concepts developed for the prototype units may be used for the final Space Station flight hardware.

INTRODUCTION

Figure 1 shows a full-scale mockup of the docking/berthing mechanism. Figure 2 illustrates the orbiter's approach to dock with a Space Station module. The analysis and simulations of the STS orbiter docking to the Space Station have shown that an active capture and energy attenuation system is required in contrast to a passive system used on previous space docking systems. The location of the docking module in the orbiter forward cargo bay results in a 12.16 m (40 ft) offset between the docking line of action and the orbiter center of gravity. This offset produces an orbiter pitching movement at docking contact. The system designed to provide capture and energy attenuation consists of a capture ring with six degrees of freedom and remotely operated capture latches. The ring is supported and extended by eight computer-controlled, electromechanical actuators/attenuators. Through the proper design of the ball-screw actuators and the electronics that control them, these mechanical devices act as variable-rate, over-damped springs through the capture and attenuation phase of docking. Through the use of this active servo system that utilizes both force and position feedback loops, the docking forces and moments are minimized. After the docking energy is absorbed, the actuators align and pull the structural interfaces together.

The configuration of the Space Station uses a closed-loop pressurized module pattern. This pattern allows the crew to have dual egress from each module, but it presents mechanical problems in the assembly of the pattern because of module dimensional tolerances. For compensation, flexible couplings must be incorporated at

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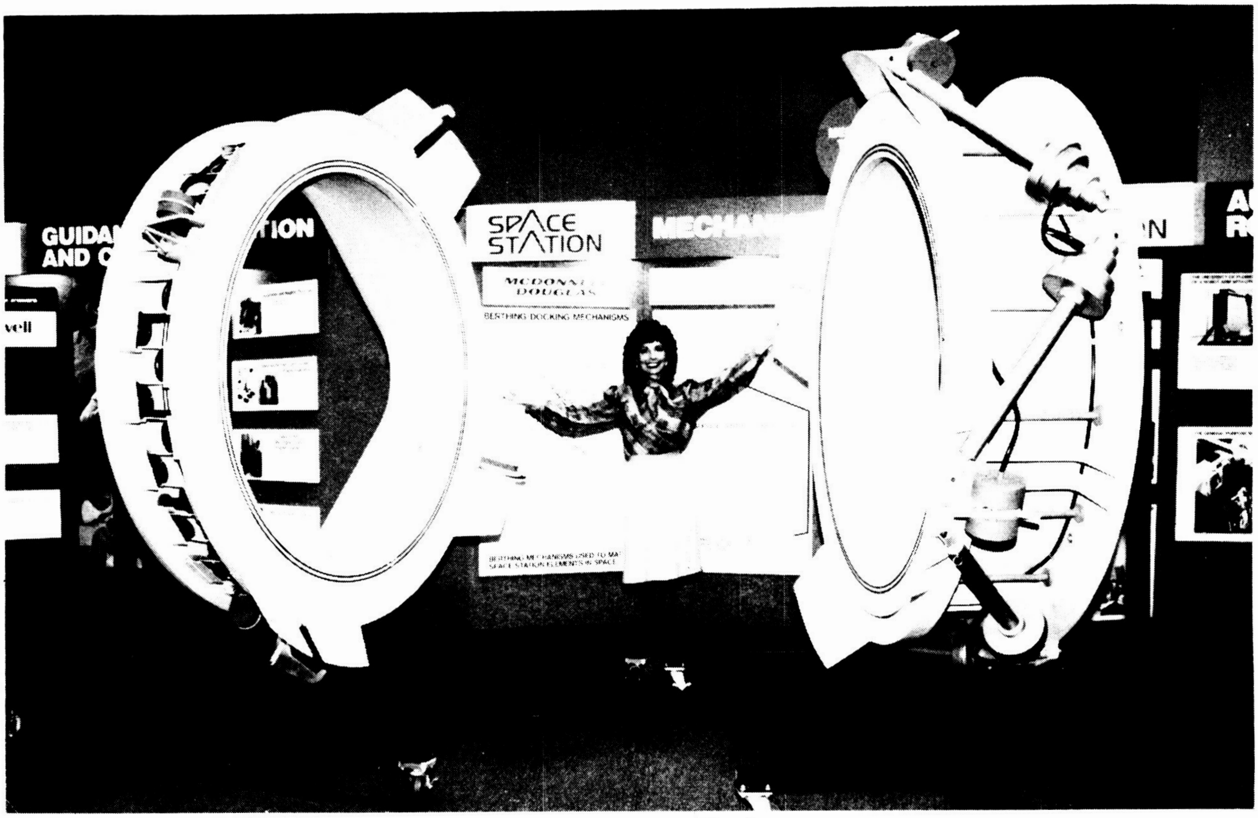


Figure 1. Space Station Berthing Mechanisms Mockup

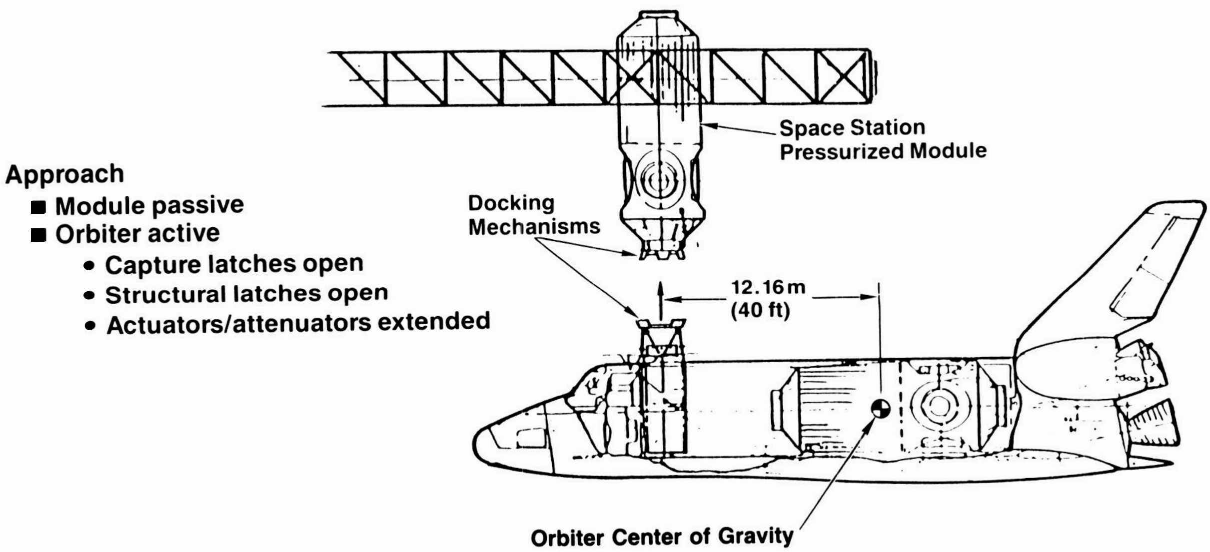


Figure 2. Orbiter Docking to Space Station

selected interfaces within the pattern. The berthing mechanism that was designed and fabricated uses a 1.6 m (63 in.) diameter, 2 ply, 2219 aluminum bellows to provide this flexibility. A cable and pulley restraint system is used to resist the axial force on the bellows produced by the 1-atm internal pressure while at the same time allowing the interface two degrees of motion flexibility. The fabrication and assembly of the large-diameter aluminum bellows represents a significant development issue.

The structural interface between the berthing mechanism halves uses manually operated structural latches and a triple redundant, androgynous pressure sealing system.

MECHANISM REQUIREMENTS

The two berthing/docking mechanism halves are designed specifically for two different sets of Space Station functional requirements plus a common set of general requirements.

The general requirements were established by the Space Station program during the concept definition phase and the Phase B preliminary design effort. The general requirements that apply to both of the mechanisms are as follows:

1. Provide androgynous mating between any two berthing mechanism halves.
2. Accommodate a clear 1.27 m (50 in.) square passageway.
3. Provide 90-deg indexing for mating positions.
4. Provide a redundantly sealed interface for an internal air pressure of 1 atm; air leakage to be less than 0.02 kg/day (0.05 lb/day).
5. Furnish manual override backup capability for mechanical functions.
6. Provide indefinite life through maintenance.
7. Provide capture latches to engage and position the mating mechanism.
8. Provide structural latches which are operable from both sides of the interface.
9. Provide for internal module interconnect umbilicals for nonhazardous gases, liquids, electrical power, and data.
10. Provide docking/berthing guides which will initiate indexing.
11. Provide the capability to absorb the energy of berthing or docking of the orbiter to the Space Station.

The load-attenuating half of the berthing/docking mechanism is mounted in the orbiter cargo bay and provides the capture, energy disposition, alignment, and mating functions of the orbiter to Space Station interface. The conditions for both berthing and docking were analyzed to determine the worst case requirements for the mechanisms. Computer simulations of the STS orbiter's remote manipulator system (RMS) established berthing capture envelope and contact velocities. RMS joint runaway was considered in establishing maximum berthing contact velocities.

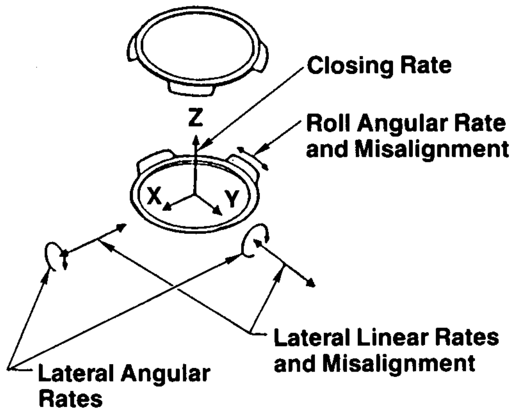
The Shuttle Engineering Simulator (SES) at NASA JSC was used to establish docking parameters. This man-in-the-loop simulation of docking the orbiter to the Space Station provided data on lateral and angular misalignments and rates at initial contact. The results of these two simulations were combined to establish the design parameters for the load-attenuating mechanism. Table 1 provides the berthing/docking contact conditions that the load-attenuating mechanism was designed to meet.

The flexible berthing mechanism half was developed to accommodate pattern assembly and tolerance compensation. It was determined that if two-degree-of-freedom, flexible interfaces were selectively placed within the module pattern, six degrees of freedom would result at the final or closing interface. Thus the requirement for the flexible berthing mechanism half is that it have ±2 deg of deflection capability about the X and Y axes and be restrained in the Z axis. The Z-axis restraint must be capable of supporting the load produced by the internal pressure of 1 atm multiplied by the area of the flexible interface.

Table 1. Berthing/Docking Contact Conditions

Condition (3)	(4)(5) Berthing Module	Berthing Orbiter	(6) Docking Orbiter
Closing Velocity (m/sec) (1)	0.049	0.049	0.06
Lateral Velocity (m/sec)	±0.049	±0.027	±0.018
Angular Velocity (deg/sec)			
— Roll	±0.20	±0.02	±0.05
— Lateral	±0.52	±0.22	±0.15
Lateral Misalignment (m) (2)	±0.076	±0.101	±0.114
Angular Misalignment (deg) (2)			
— Roll	±1.5	±2.0	±3.0
— Lateral	±1.5	±2.0	±4.5
Relative CG Velocity (m/sec) (7)			
— Closing	0.039	0.018	0.063
— Lateral	0.012	0.012	0.021

Notes
1. Minimum closing velocity for docking shall be 0.015 m/sec
2. Maximum misalignments until capture (normal berthing)
3. Velocities and misalignments are defined relative to the docking ports
4. Berthing velocities are based on RMS joint runaways (PDRSS)
5. Berthing misalignments are based on nominal conditions
6. Docking values are based on SES data
7. Berthing CG velocities are based on elbow joint runaways (which give highest port closing velocities)



TRADES AND DESIGN CONCEPT SELECTIONS

OVERALL CONCEPTS

The overall berthing/docking mechanism concept was principally dictated by the requirements. The requirement for a clear passageway determined that the capture and latching be accomplished outside the passageway clearance. The size of the mechanism is dictated by the passageway size (hatch size) which was established by the Space Station Phase B study. The Space Station configuration and operational procedures dictate that four different and distinct functions must be accomplished at various berthing interfaces. A family of four berthing mechanism halves which satisfy these functions are: (1) a load-attenuating berthing mechanism for the orbiter side to capture, absorb energy, stabilize, and align the interface during an orbiter to Space Station berthing/docking maneuver; (2) a flexible berthing mechanism half to compensate for tolerances and allow assembly of a closed-loop module pattern; (3) a rigid berthing mechanism half to be used at all pressurized module interfaces where energy attenuation or flexibility is not required; and (4) an unpressurized berthing mechanism half to be used to berth the orbiter to the Space Station truss structure during buildup and that can potentially be used for unpressurized structural attachments and payloads. All of the four berthing mechanism halves will mate with each other and all berthing mechanism family members use common parts. Because of their complexity, the load-attenuating and the flexible mechanism halves were selected for advanced development.

Figure 3 illustrates the berthing mechanism evaluation areas and selections used in starting the final design. The following discussions summarize the choices and selections in each of the areas evaluated during this phase of the program.

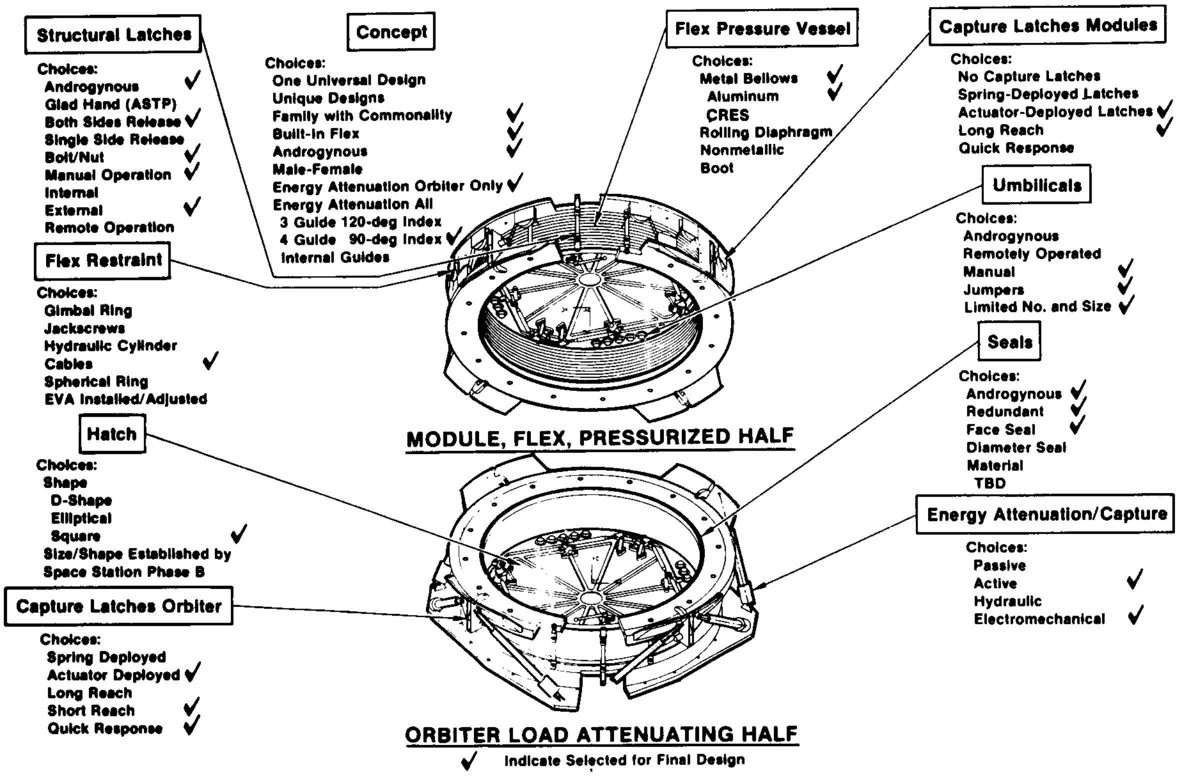


Figure 3. Berthing Mechanisms Evaluation Areas and Selections

STRUCTURAL LATCHES

The concept chosen for the structural latch utilizes the bolt/nut attachment principle. The features are androgynous, both sides release, and manual operation. Although the basic latch design operates manually, a design for the incorporation of an electromechanical actuator was also included. The motor-driven latch may be operationally desirable for frequent docking operations such as orbiter to Space Station, logistics module to Space Station, and unpressurized interfaces.

FLEXIBLE PRESSURE VESSEL

A formed, two-ply, metal bellows was selected for the flexible pressure vessel. The material is 2219 aluminum which can be welded directly to the aluminum structure of the berthing mechanism. Twelve convolutions 38.1 mm (1.5 in.) deep provide 2-deg deflection about two axes.

FLEX RESTRAINT

A system of cables and pulleys carries the pressure-created tension load across the flexible bellows. The cable system transmits the tension load from one end of the bellows to the opposite end while allowing two-degree-of-freedom flexure of the bellows. The bellows structure provides adequate shear and torsion strength for the interface. Rigid struts may be added to the design to lock out the flexibility during Space Station buildup when the berthing port must be used for a cantilever module support.

CAPTURE LATCHES

The family of berthing mechanisms required the use of two capture latch designs. The requirements for the module-to-module interface dictate that the capture latch have a relatively long reach, but may be slow acting. The orbiter-to-Space Station interface requires that fact-acting, short-reach capture latches be provided for the berthing/docking operation. Both latch mechanisms use a conventional linkage powered by electric motors.

UMBILICALS

The internal umbilicals associated with the berthing mechanism interface incorporate manually installed jumper cables which will be attached to identical connectors installed in each berthing mechanism half. The connectors are located around the periphery of the hatch opening. The hook-ups will be accomplished in a shirtsleeve environment after the interfaces are mated and pressurized. Although space has been allocated in the design for umbilicals, no connectors have been installed in the prototype mechanisms.

HATCH

The size and shape of the hatch opening were established by the Space Station Phase B study. A 1.27 m (50 in.) square opening with 1.52 m (60 in.) diagonal to the corner radius has been selected. The size and shape of the hatch passageway establishes the overall size of the berthing mechanisms.

SEALS

Redundant, androgynous face seals were selected for the berthing mechanism design. Because of the androgynous nature of the interface, the face seal will mate and seal with an identical seal on the mating half. This seal-on-seal arrangement will be used to hold pressure at the interface until a replaceable seal is installed on orbit by a crew member.

ENERGY ATTENUATION/CAPTURE

The orbiter berthing mechanism half utilizes an extendable ring with guides and capture latches to engage the mating berthing mechanism half on the Space Station. The ring is supported on eight electromechanical actuators/attenuators which capture, absorb energy, stabilize, align, and retract to engage the structural latches of the interface. The active electromechanical approach allows the spring rates and damping to be tailored to provide a low spring rate during capture and then change to a high rate during stabilization. The eight actuators/attenuators are controlled by a processor which reads load position from the actuators and stabilizes the interface in accordance with a preprogrammed control law.

MECHANICAL DESIGN

The structure of the berthing mechanism halves is welded 6061 and 2219 aluminum construction and is generally not unique except for the large size, i.e. over 2 m (79 in.) in diameter.

The actuator/attenuator illustrated by Figure 4 has a relatively simple mechanical design. It utilizes a ball-bearing jack screw with a pitch diameter of 19.05 mm (0.75 in.) and a lead of 25.4 mm (1.0 in.). The jack screw is directly

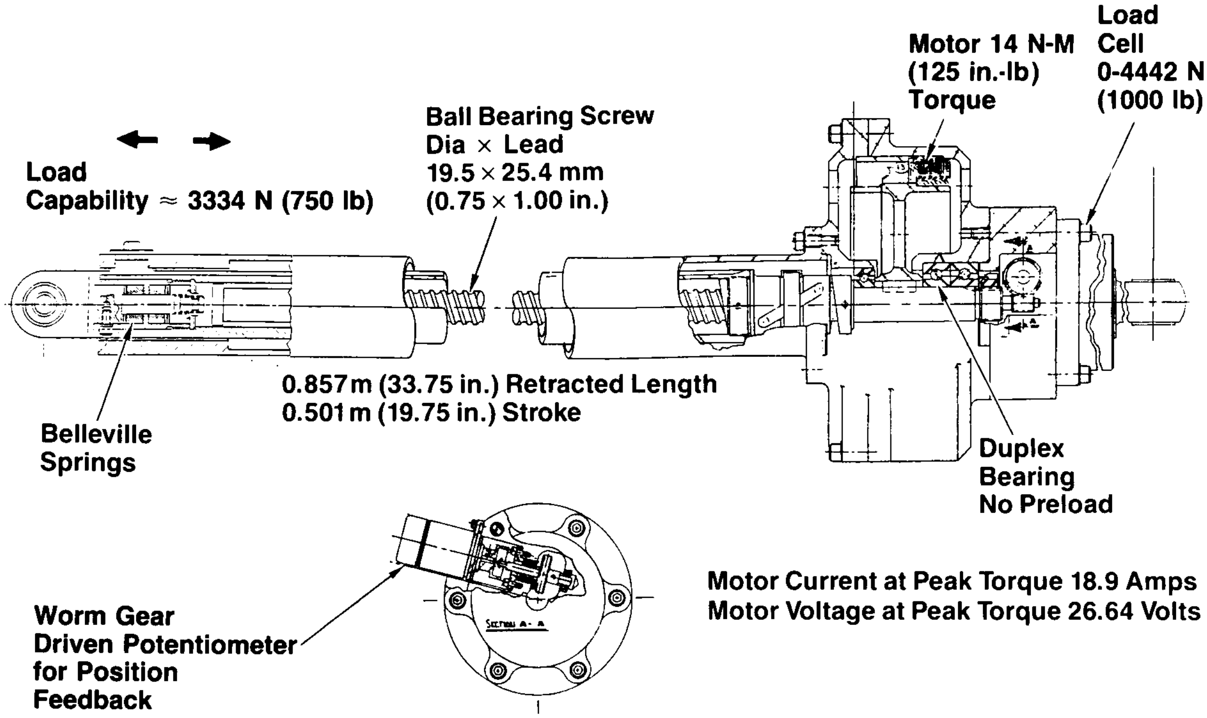


Figure 4. Berthing Mechanism Actuator/Attenuator Design

driven by a 40-pole brushless DC motor. The unit also contains a load cell and a potentiometer for control system feedback. A key design goal for the attenuator was to reduce back-drive friction and inertia to a minimum allowing the motor torque to shape the force stroke relation as a function of the control laws. The actuator rod incorporates a cartridge containing Belleville washers providing a spring rate of 874 Newtons/mm (5000 lb/in.). This compliance reduced the initial contact load spike allowing the servo loop to respond and control the load.

Figure 5 shows the orbiter docking module with the capture ring extended before the initial contact. The extension of the eight actuators/attenuators positions the active mechanism to latch securely with the mating mechanism, attenuate the energy, align the interfaces and retract to mate the seals and structural latches. The cross sections illustrated in Figure 6 show the capture ring in the retracted and extended positions. Four contact switches in the capture ring are connected in series to operate the four motor-driven over-center capture latches. The capture latches operate in approximately 50 m/s after the four contact switches are closed. The structural latches that tie the mated Space Station elements together are illustrated by Figure 7. These are 16 latches located around the periphery of the mechanism halves outside of the interface seals. The latch design features a nut and bolt principle with alternating units to provide androgynous mating. The bolt/nut combination uses a 0.500-20 UNF thread with a tailored nose on the bolt to allow misaligned entry and start without cross threading. The bolt and nut are fabricated of A286 CRES and use DOD-L-85645 (Dicronite) dry film lubrication. The attachment can be manually torqued from inside the pressure hull of the Space Station module after the interface has been placed into contact. The floating bolt/nut assemblies are intially retracted below the interfacing surfaces. By using friction-clamped, Delrin worm gears engaged to a thread on the external suface of the nut/bolt assembly, rotation of the assembly causes it to advance toward the mating half. When the bolt/nut advancement is restricted by engagement of the mating half, the clamped

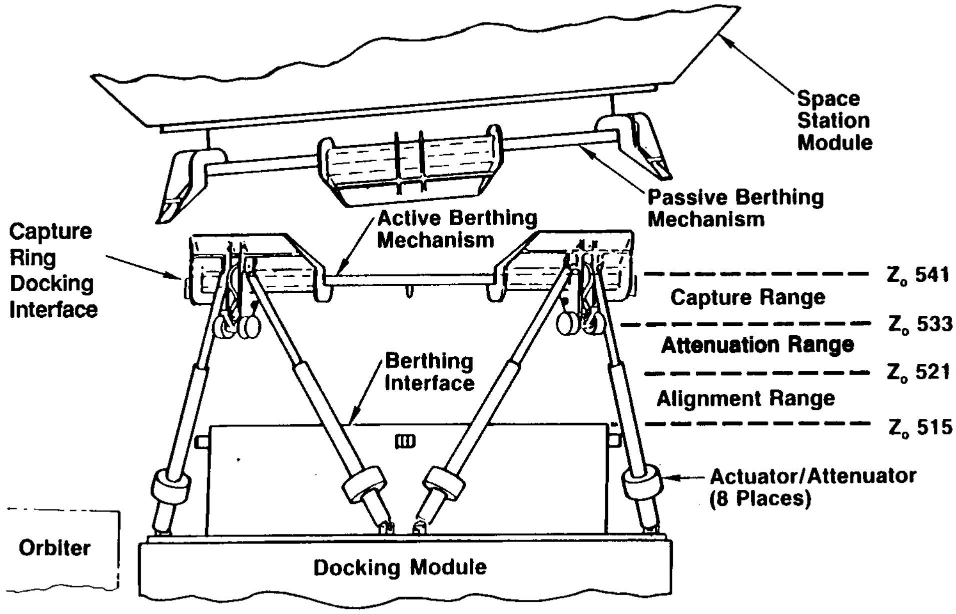


Figure 5. Initial Contact

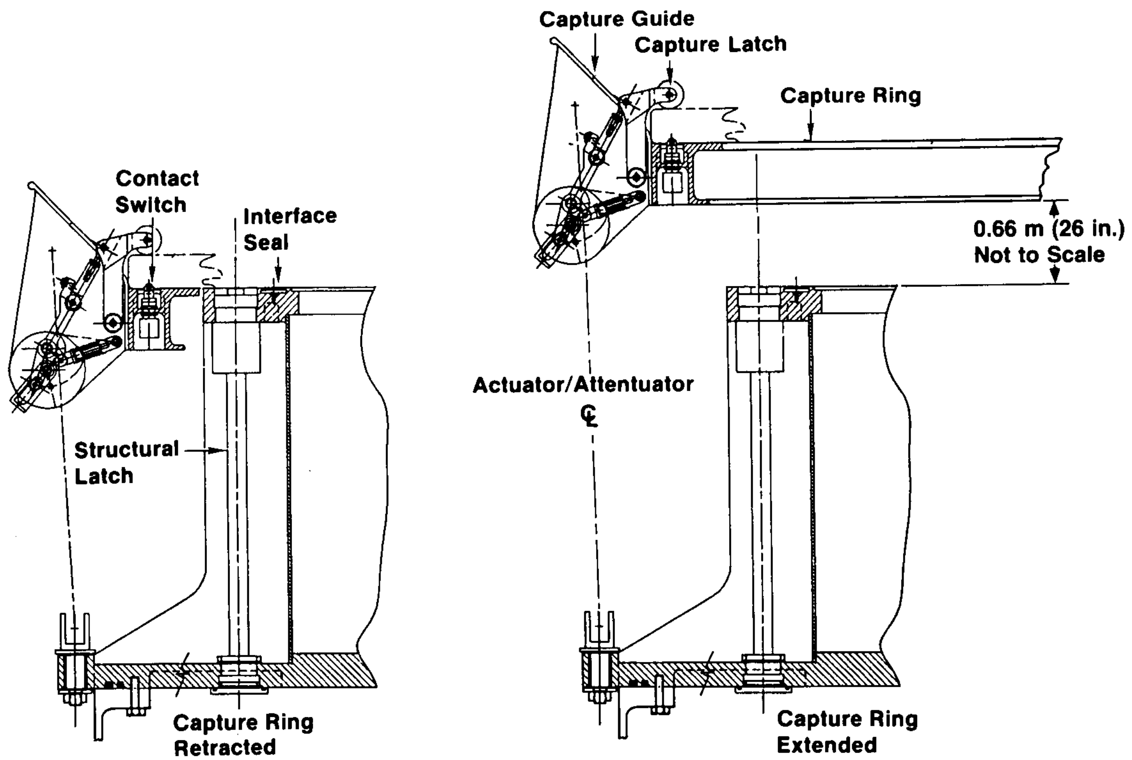


Figure 6. Capture and Load-Attenuating Berthing Mechanism

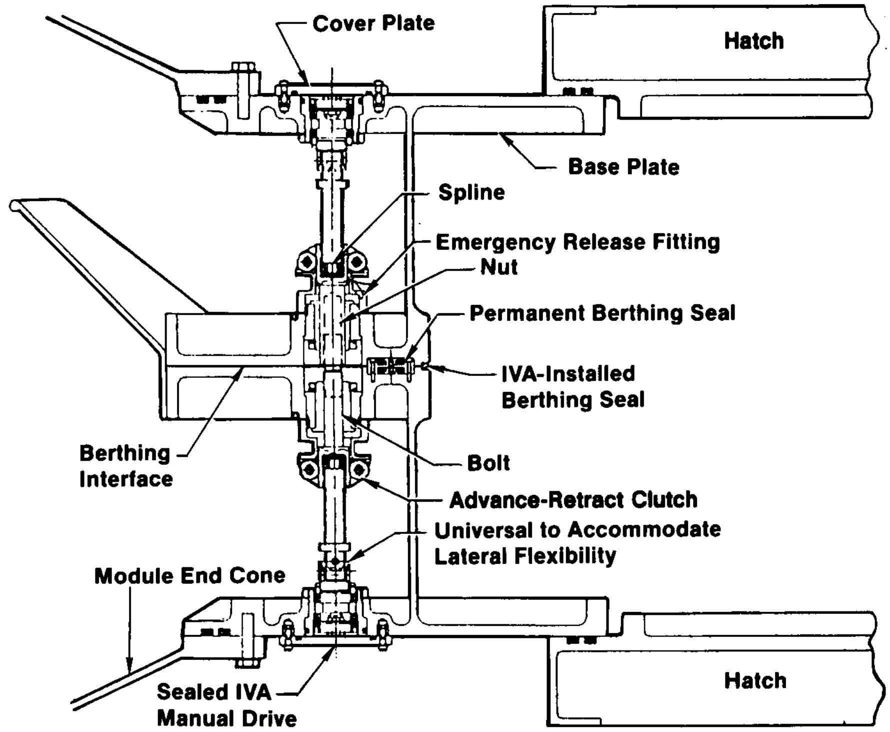


Figure 7. Manually Driven Bolt/Nut Structural Latch

gears rotate and allow the bolt/nut assembly to rotate without advancement. The structural latch may be operated from either side of the interface. Each structural latch is designed for a tension load of 44,470 Newtons (10,000 lb).

The bellows and the cable restraint system for the flexible berthing mechanism half are illustrated by the cross section in Figure 8. The bellows are 1.6 m (63 in.) ID and are formed from 2 ply, 0.81 mm (0.032 in.) 2219 aluminum. The convolutions were roll formed with the material in the 0 temper condition (annealed). The bellows were not heat treated after forming for the prototype demonstrations because of the complex requirements for the process. Flight hardware will be heat treated to the T62 condition after forming and welding to the end rings.

The extension load caused by the internal module pressure is resisted by a closed-loop continuous cable/pulley system outside of the bellows. This system allows the two degree of freedom motion of the bellows while supporting the internal pressure load of approximately 221,233 Newtons (49,733 lb) at 1-atm internal pressure. The system is formed by a single cable and 47 pulleys; 24 attached to the base plate and 23 attached to the interface plate. The rigged cable compresses the bellows approximately 12 mm (0.5 in.) producing a total load in the system of 3706 Newtons (833 lb) for a bellows spring rate of 309 Newtons/mm (1767 lb/in.). For this load the tension in the cable is 77 Newtons (17.3 lb). The tension load in the cable at 1-atm internal pressure on the bellows is 4608 Newtons (1036 lb).

CONTROL SYSTEM DESIGN

The control system must accommodate three distinct phases of the docking operation: precapture, capture, and attenuation. During precapture, the capture ring is commanded from a start-up position to a new position at which initial contact with the approaching berthing mechanism occurs. The controller must maintain a stable

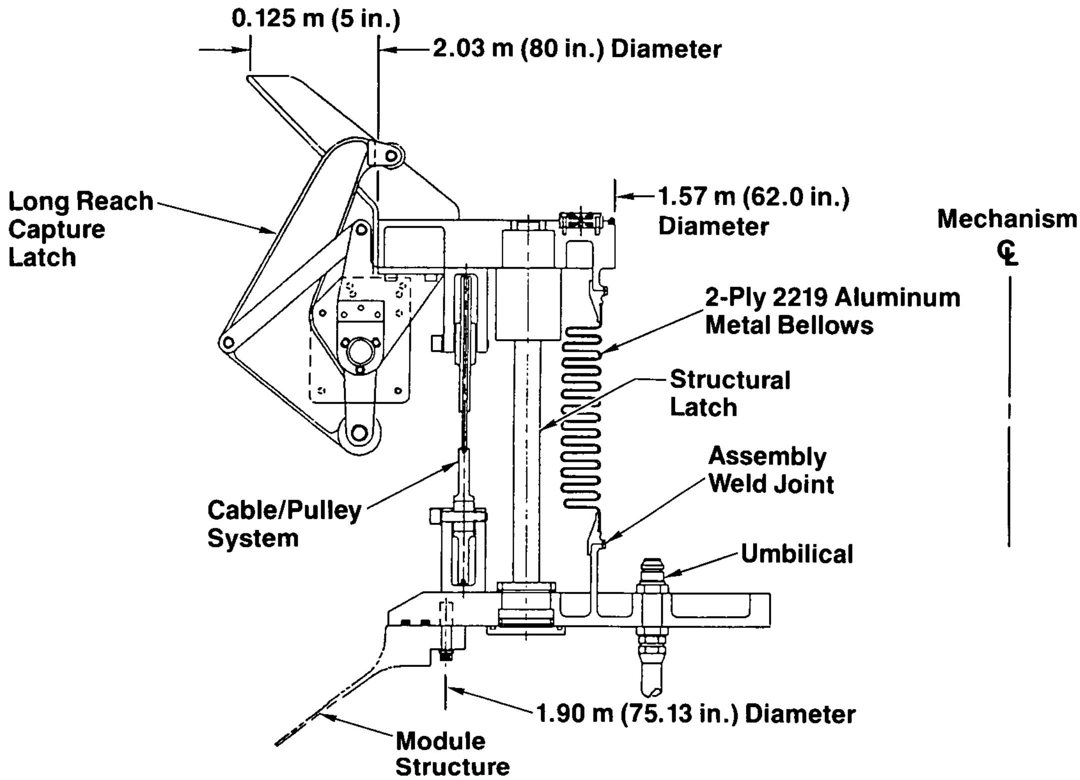


Figure 8. Flexible Berthing Mechanism Half With Cable/Pulley Structural Restraint

position without drifting. System loads consist only of the small mass associated with the capture ring.

Capture involves initial contact, camming of the capture ring for alignment with the mating interface, and clamping of the two berthing mechanisms together with the capture latches. The dynamics must consider the large orbiter CG offset from the berthing mechanism location.

During the attenuation phase, relative motion is zeroed out with the constraints that the capture ring position be within prescribed limits to maintain adequate clearances and that the individual actuator loads not exceed their force capability of about 2224 Newtons (500 lb). The effective controlled mass has increased from the capture ring to one that is equivalent to the station/orbiter. Control during follow-on centering and retraction for structural attachment is consistent with the attenuation phase because relative motion of the large station/orbiter masses is involved.

The control system design consists of an analog controller for each of the eight actuators and a digital controller that coordinates the motion of the actuators as a unit. An IBM PC-AT computer processes the measured actuator positions and commands a force to each actuator based upon programmed algorithms or control laws. Different algorithms are used for the various operational phases to compensate for the drastic changes in mass properties and for significant changes in functional requirements (i.e., soft spring during capture and stiff spring during attenuation). Figure 9 is a block diagram of the integrated control system.

Two computer tools were generated to analyze and develop the control system: a nonlinear time domain simulation written in FORTRAN to investigate system performance

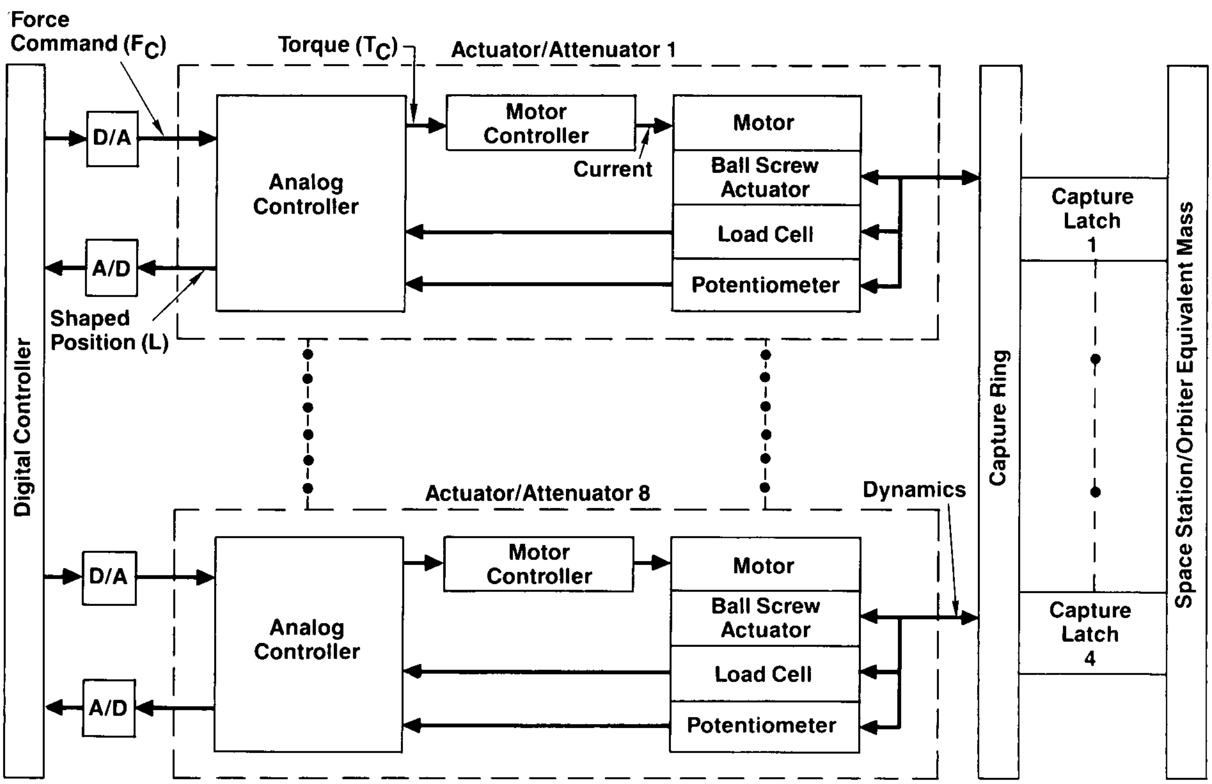


Figure 9. Control System Block Diagram

and a frequency response model written in CONTROL-C to check stability. The use of these analytical tools coupled with breadboard single-axis testing of an actuator/attenuator has resulted in the present controller design. Testing of the breadboard unit verified that our control technique was valid and led to actuator design changes that helped to simplify the control system. These changes included a reduction in motor inertia, an increase in ball screw lead, and the addition of a known compliance in the extension rod.

The analog controller for each actuator consists of a force loop that compensates for actuator friction and modeling errors, and a rate loop derived from actuator position that provides damping during the precapture and capture phases. Figure 10 provides a block diagram of this controller. It has been designed so that stability is independent of the mass driven by the actuator.

The digital controller uses actuation position data and algorithms to control force and make the eight actuators work as a unit. The algorithms are different as shown by Figure 11 for each phase of the docking operation. Note that with an input of position and output of force, the algorithm transfer function is analogous to the rate of a mechanical spring. For precapture, each actuator is controlled independently with a gain constant to prevent capture ring drifting. A force bias is used to compensate for gravity effects.

With capture, the same force bias is used to facilitate transition from precapture. In addition a small spring constant for each actuator coupled with a relatively high axial stiffness keeps the interfaces in contact while the capture ring cams into alignment. The axial stiffness component is accomplished by generating a force that is a function of the average of all the actuator lengths.

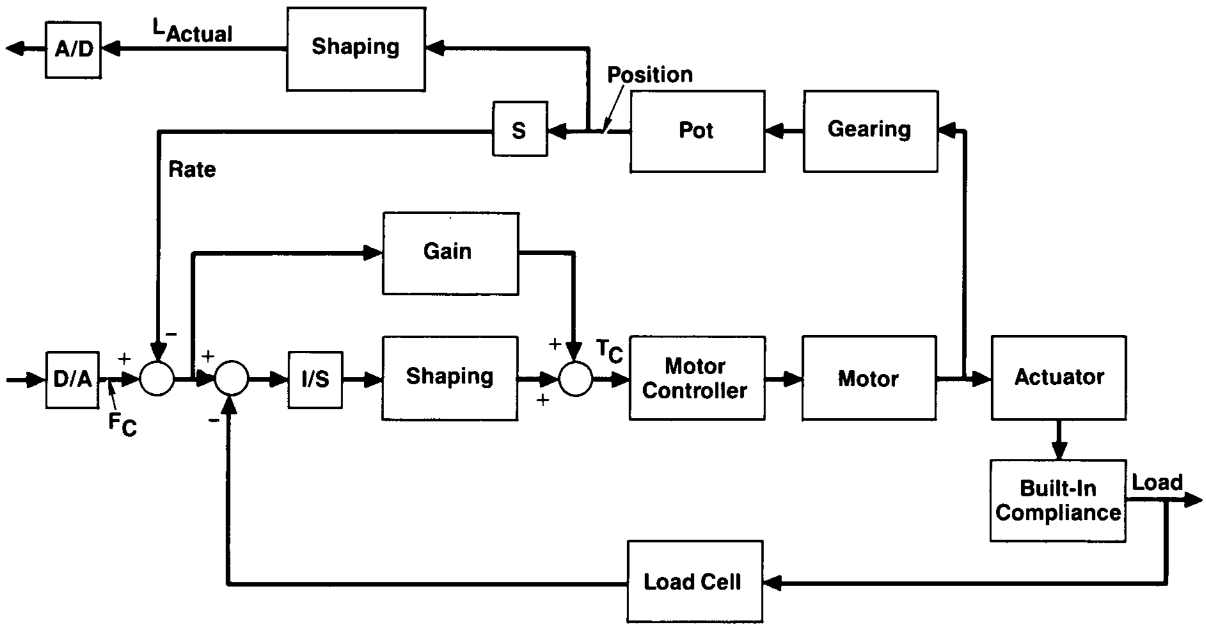


Figure 10. Actuator Analog Controller

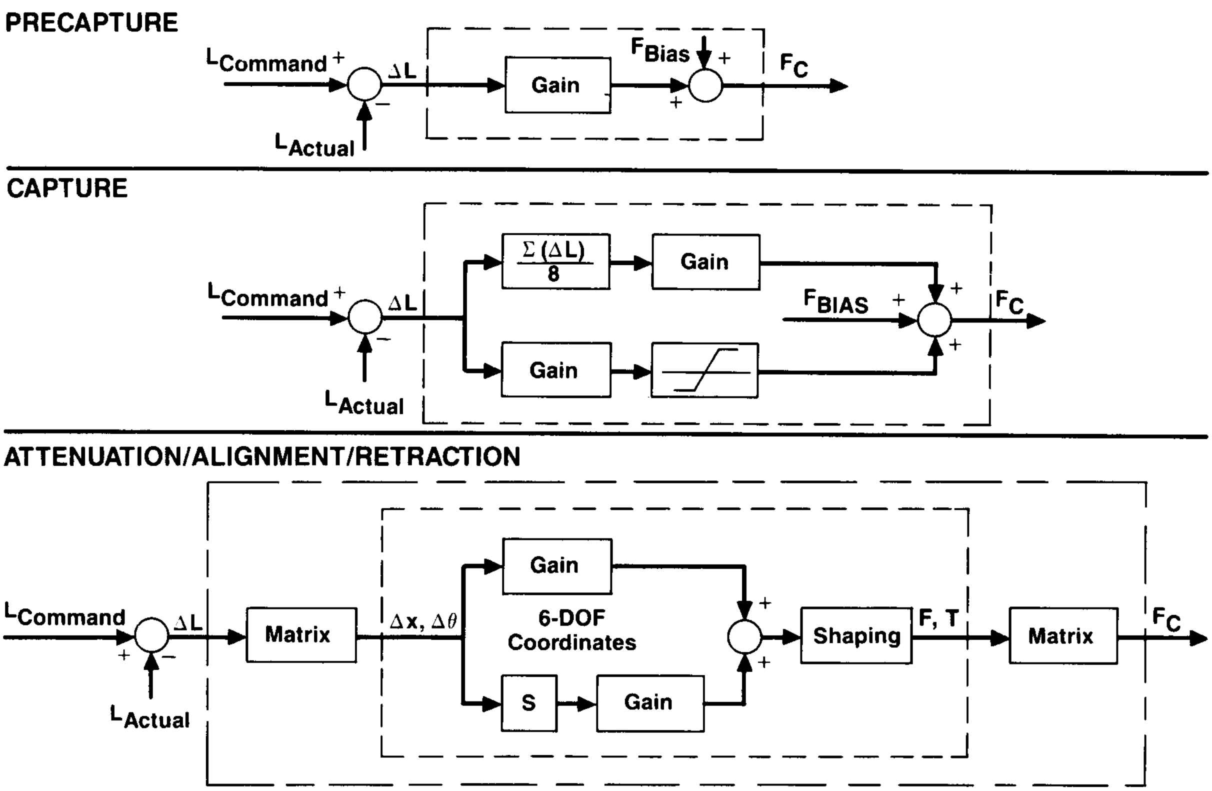


Figure 11. Digital Control Laws

For attenuation, analysis has shown that six-degree-of-freedom control is necessary to limit actuator force and provide reasonable damping in all axes. Following transformation, position and rate gains generate forces and torques in the three translational and three rotational axes. Another transform provides commanded forces for each actuator. Analysis has shown that the transformation matrix can be normalized with respect to the precapture position thus avoiding the necessity of updating at each new position.

Examples of control system capture and attenuation performance obtained from the simulation are shown by Figures 12 through 15. Capture showing relative position and orientation for a very low approaching velocity of 15.2 mm/sec (0.5 ft/sec) is provided by Figures 12 and 13. This is a worst-case condition because it is difficult to make the capture ring cam into position at the low rates without rotating away from the interface.

The net axial attenuation force for a maximum contact rate of 61 mm/sec (0.2 ft/sec) imposed upon the berthing mechanism supporting structure is shown by Figure 14. The initial 890 Newtons (200 lb) impulsive force provides a 2.5 margin with respect to an arbitrarily imposed structural limit of 2224 Newtons (500 lb). Maximum actuator force during the same period is about 1780 Newtons (400 lb). Figure 15 provides an indication of the maximum generated torques.

FABRICATION AND TESTING

The two berthing/docking mechanism halves and the control system electronics were designed and fabricated as prototype one-of-a-kind units. The operating mechanisms such as actuators/attenuators, structural latches, capture latches, interface plates, bellows, bellows restraint system, capture ring and guides were designed to closely resemble the final flight designs. The structure used welded plate stock and is intended only to provide a pressure vessel with geometric accuracy for mounting the

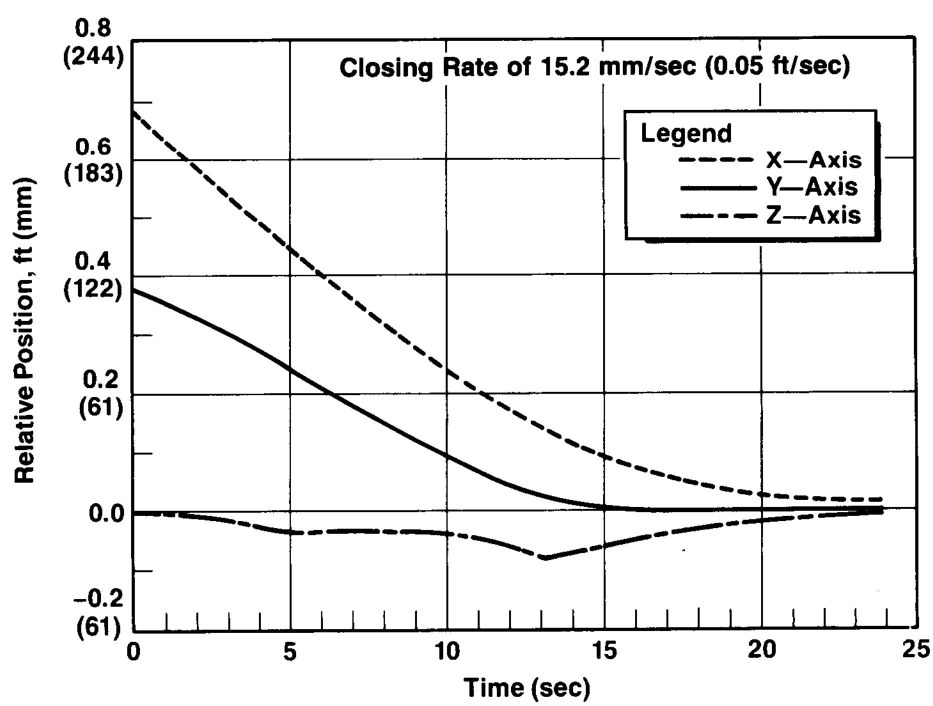


Figure 12. Relative Position Between Mating Interfaces

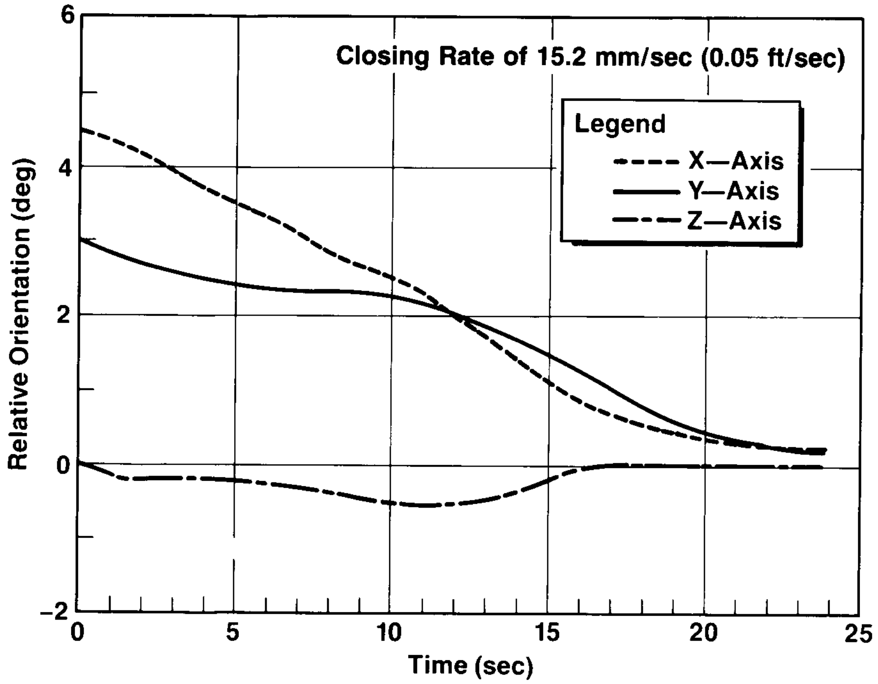


Figure 13. Relative Orientation Between Mating Interfaces

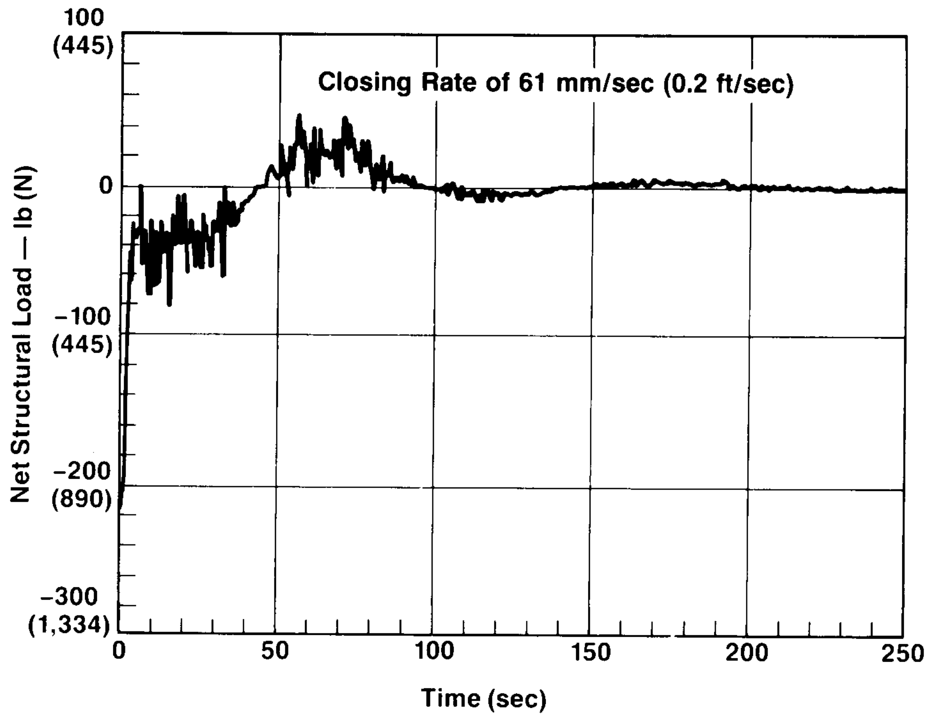


Figure 14. Axial Attenuation Force on Structure

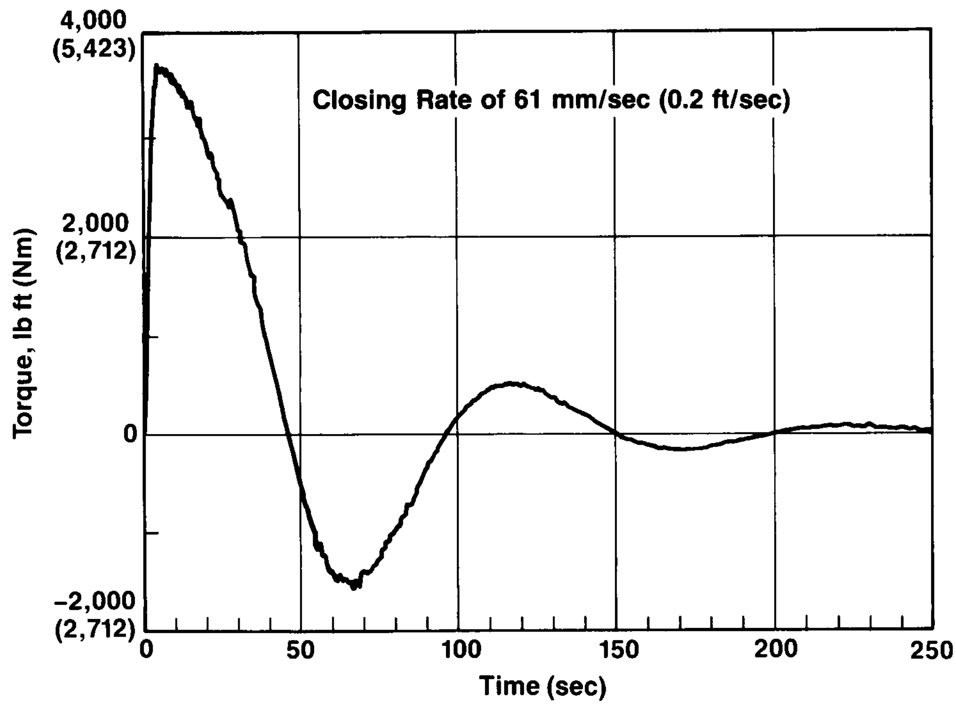


Figure 15. X-Axis Attenuation Torque

operating mechanisms. The hatch openings in the base plates were not cut out on the prototype unit which allow the two halves to be mated and pressurized for seal development.

The overall design of the mechanisms and the design and fabrication of the control system electronics were done by McDonnell Douglas Astronautics Company in Huntington Beach, California. The structure fabrication and the final assembly of the units were done by United Technologies Space Flight Systems in Huntsville, Alabama. Other suppliers participating in the program were: Beaver Precision Products, Troy, Michigan, actuators/attenuators; Sierracin Magnedyne, Carlsbad, California, actuator/attenuator motors; and Pathway Bellows Company Oak Ridge, Tennessee, bellows.

This paper was prepared in November 1987. Testing on this project is scheduled to be accomplished from January through April 1988. Testing results should be available for the oral presentation of the paper in May 1988. Pressure testing and overall systems checkout will be done at United Technologies. Dynamic testing will be done at NASA's Marshall Space Flight Center (MSFC) using a six-degreee-of-freedom (6 DOF) simulator. The MSFC six-degree-of-freedom moving base simulator has the capability to simulate the dynamics in space of the Space Station and the STS orbiter during the docking maneuver.

Figure 16 illustrates the MSFC six-degree-of-freedom facility on which the dynamic docking testing will be done. A total of 64 cases will be run encompassing the total range of contact velocities and misalignments expected.

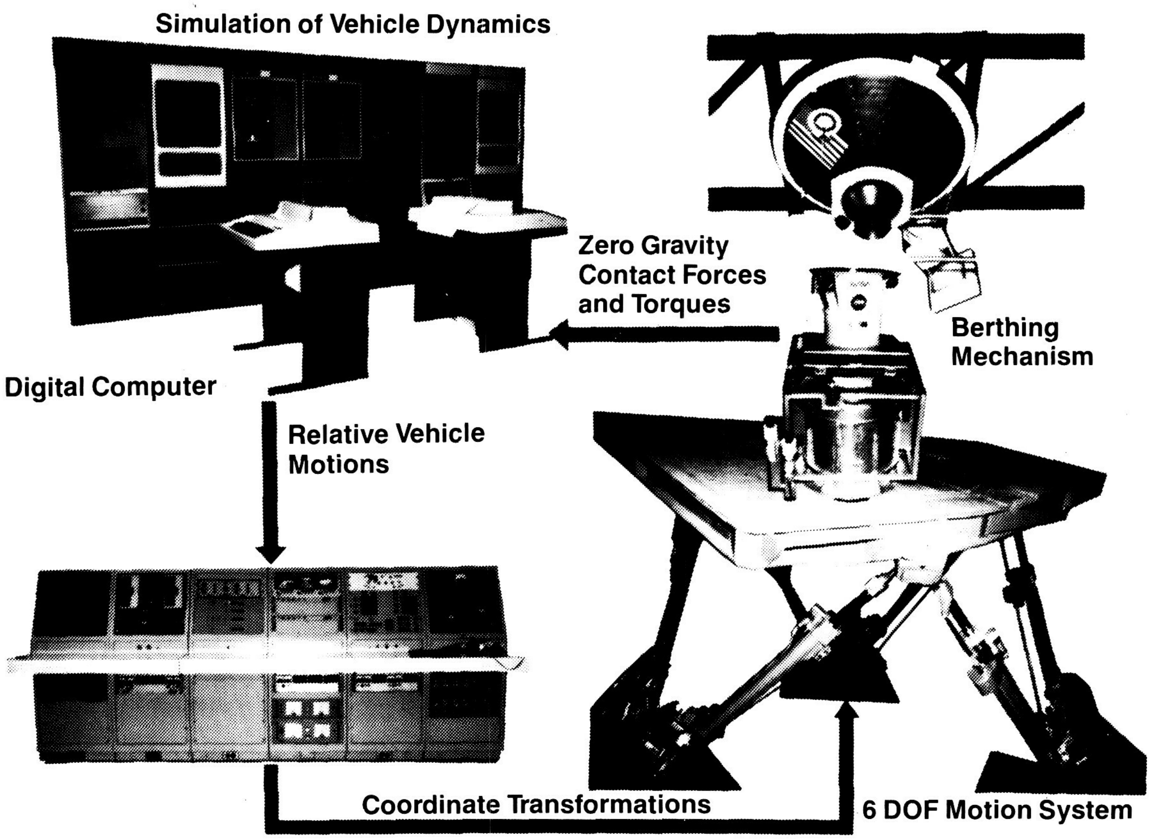


Figure 16. The MSFC 6-DOF Facility

CONCLUSIONS

This program has provided proof-of-principle for a computer-controlled electromechanical system for docking the STS orbiter to the Space Station. In addition it has taught us valuable lessons in the mechanical design and fabrication of relatively large space mechanisms. During this program analysis demonstrated that an active docking system is required (1) to provide capture at low approach rates and (2) to reduce forces and moments to an acceptable level at maximum approach rates. An active docking system could be designed using either an electromechanical approach or a hydromechanical approach. The hydromechanical approach is considered undesirable for use in the orbiter cargo bay because of potential fluid leakage contamination. The active computer-controlled electromechanical energy attenuation system will meet the requirements for capture, energy attenuation, and structural attachment in space of the STS orbiter and the Space Station.

Further refinements are called for in the design of the actuator/attenuator and the control system to reduce the total electrical power requirements. The prototype system has a potential peak power requirement which could exceed 4 kW; this would be excessive for a flight configuration powered from the STS orbiter fuel-cell electrical power system.

Further refinement is needed in the design and fabrication techniques for the aluminum bellows used in the flexible mechanism. It required several attempts to fabricate the bellows using 2219 aluminum alloy. The bellows were not heat treated after forming because of the high temperature required and the potential distortion of the finished product. Other aluminum alloys should be considered as well as improved forming techniques and heat treat requirements for the flight system design.