AN ELECTROMECHANICAL ATTENUATOR/ACTUATOR FOR SPACE STATION DOCKING

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ABSTRACT

The development of a docking system for the Space Station and beyond has identified the need for reusable and variably controlled attenuators/actuators for energy absorption and compliance. One approach to providing both the attenuator and the actuator functions is by way of an electromechanical attenuator/actuator (EMAA) as opposed to a hydraulic system. The use of the electromechanical devices is considered to be more suitable for a space environment because of the absence of contamination from hydraulic fluid leaks and because of the cost-effectiveness of maintenance. A smart EMAA that uses range/rate/attitude sensor information to preadjust a docking interface to eliminate misalignments and to minimize contact and stroking forces is described. A prototype EMAA has been fabricated and is being tested and evaluated at the NASA Lyndon B. Johnson Space Center Robotics and Mechanical Systems Laboratory. Results of preliminary testing and analysis already performed have established confidence that this concept is feasible and will provide the desired reliability and low maintenance for repetitive long-term operation typical of Space Station requirements.

INTRODUCTION

A technology development task titled "Construction Equipment/Soft Docking Technology" was sponsored by the NASA Office of Aeronautics and Space Technology to study Space-Shuttle-Orbiter-based construction equipment required to support space construction, assembly, and satellite servicing. Later, this task was expanded with emphasis on docking and berthing. Requirements were proposed for minimum-disturbance (low force) docking with large flexible structures and with satellites having sensitive operating systems. This study was concentrated on the docking/berthing function, with emphasis on isolating the requirements for, and exploring the technology of, soft docking/berthing.

The methodology of this study comprised a simultaneous evaluation of mission requirements, hardware design concepts, and systems performance. The central study element was a combined conceptual-design/dynamic-performance analysis that produced the identification of docking/berthing component technology needs.

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System design specialists reviewed the design evolution of past docking hardware to maximize the benefit of that experience. In reviewing component technology efforts, two key areas were identified for immediate component development activity needs. Achieving soft docking for a range of spacecraft masses and contact velocities requires the use of smart attenuator/actuators which can provide variable force/stroke characteristics and highly accurate proximity sensors to provide the necessary intelligence. These design specialists identified sensors and smart attenuator/actuators as the key components of the docking system that warrant proof-of-concept development testing.

A prototype smart electromechanical attenuator/actuator (EMAA) was fabricated for proof-of-concept development testing to support the Construction Equipment/Soft Docking Technology study. The development of a laboratory prototype microprocessor-controlled smart EMAA from which the development technology can be applied to Space Shuttle Orbiter and Space Station docking/berthing systems is described.

SOFT DOCKING SYSTEM OVERVIEW

A smart EMAA is one of four subsystems of a soft docking system concept consisting of (1) a laser docking sensor (LDS) subsystem, (2) an androgynous, four-fingered, ring-and-guide docking interface subsystem, (3) the EMAA subsystem, and (4) a docking microcomputer system (DMS) (Figure 1). The LDS provides position, velocity, attitude, and attitude-rate data of the approaching vehicle. The androgynous, four-fingered, ring-and-guide docking interface provides the rigid structural coupling of the two docking vehicles and permits 90° interval indexing of the two mating ports, while providing two axes of inverse symmetry that coincide with the two major axes of the vehicles. The DMS queries the LDS subsystem for data necessary to process the kinematic equations that are required to position the EMAA's. The EMAA's preadjust the docking interface. As a result, intolerable misalignments are eliminated, and contact forces are minimized. The DMS performs real-time processing to provide the EMAA's with data including energy absorption, fault detection, and error management during the attenuation process. The DMS also provides interface to embedded Space Station management subsystems and crew systems. The EMAA performs the soft docking energy absorption (attenuation) and actuation for the system. The EMAA receives high-level control instruction and attenuator/actuator performance characteristics from the DMS and transmits status information back to the DMS.

EMAA DESIGN REQUIREMENTS

The requirements for the smart EMAA were baselined upon the likely event of soft docking an Orbiter weighing 108 775 kg (240 kips) to the Space Station weighing 181 292 kg (400 kips) using a conceptual-design soft docking interface system from the Construction Equipment/Soft Docking Technology study. This interface system accommodates four pairs of smart EMAA's to control the docking interface relative to the base ring. The following are the general smart EMAA requirements for soft docking:

1. Absorb the relative kinetic energy necessary for the docking interface between the two vehicles with typical approach velocity of 0.003 m/s (0.01 ft/s) to 0.031 m/s (0.10 ft/s)
2. Draw the docking interface with mating vehicle together for structured connection
3. Assure durability for repeated docking and undocking
4. Provide both attenuation and actuation functions
5. Change attenuation performance characteristics in real time

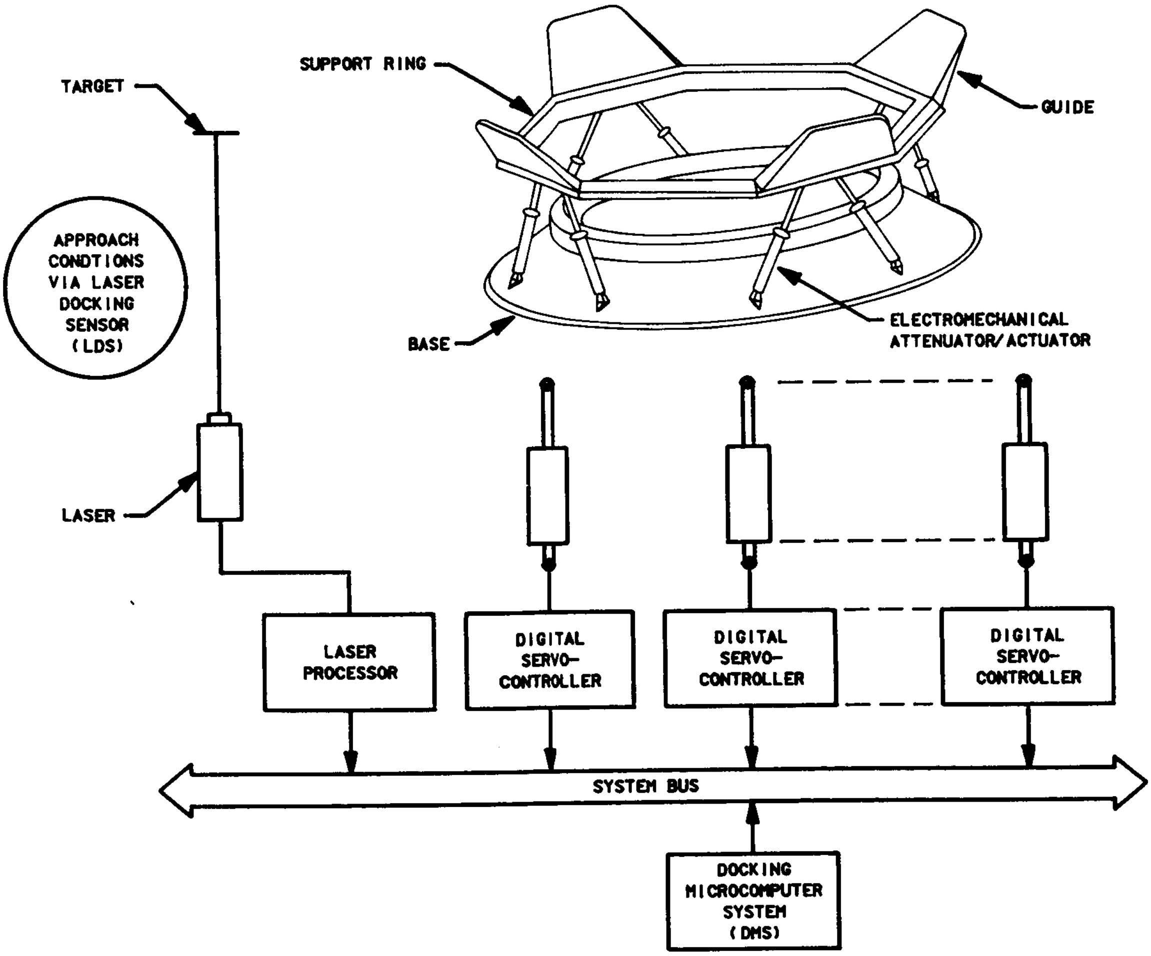


Figure 1 Soft Docking Interface System

6. Require little or no maintenance for long-term operations
7. Provide precise position control for prealignment of docking interface
8. Allow 0.457 M (18 in.) of attenuation/actuation stroke
9. Provide constant force attenuation

EMAA COMPONENT DESCRIPTION

The eight components of an EMAA are (1) a digital servocontroller, (2) a digital-to-analog converter (DAC), (3) an amplifier, (4) a direct-current (dc) motor, (5) an optical encoder, (6) a gear pair, (7) a roller screw, and (8) a mechanical housing (Figure 2).

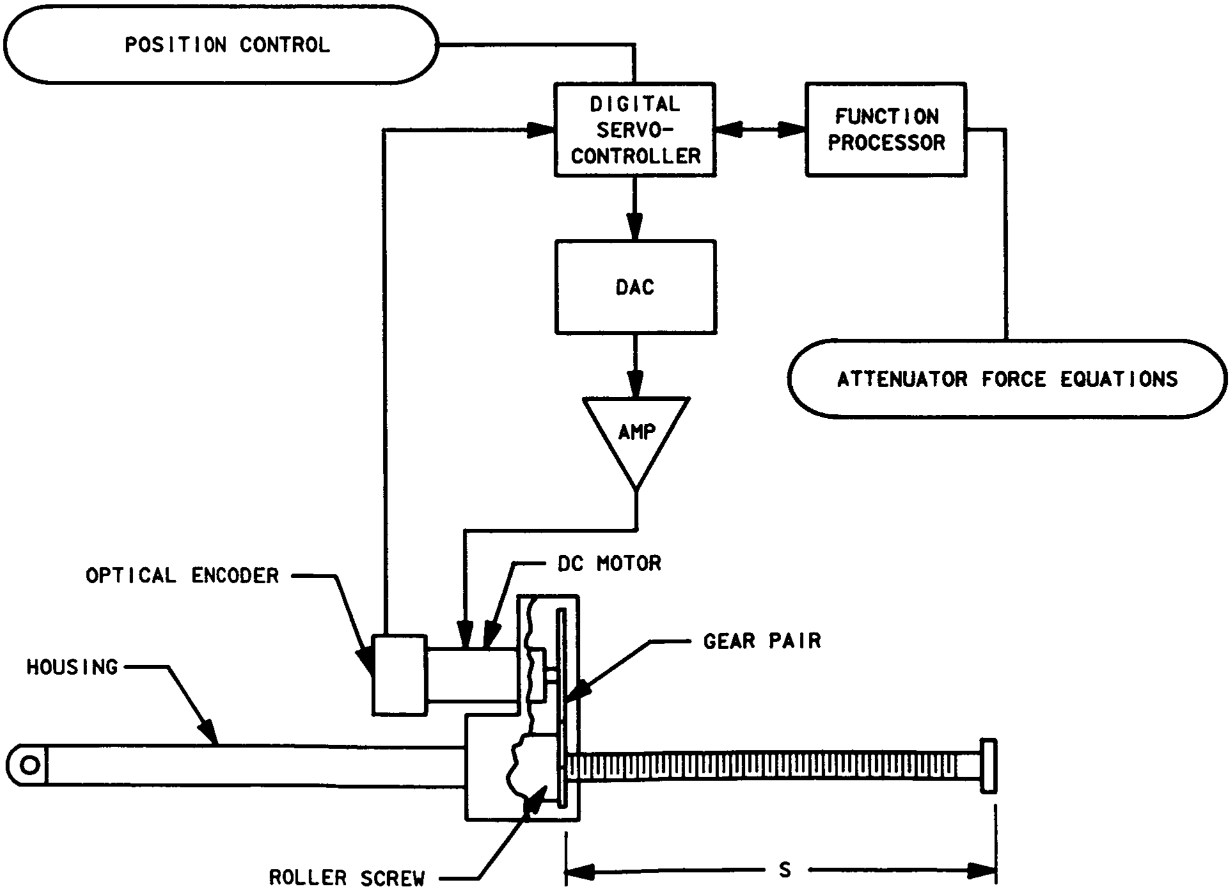


Figure 2 EMAA Components

The digital servocontroller is a 16-bit microcontroller based on a register-to-register architecture which allows digital filter control algorithms to execute faster than in accumulator-based architecture in which data transfer is bottlenecked. The controller receives data from both the DMS and the optical encoder, calculates a digital voltage command, and reports the current status and error conditions back to the DMS. This digital voltage command is converted to an analog voltage by the DAC, a 12-bit bipolar voltage-output device. The voltage is then applied to the amplifier and held constant until the controller completes another sampling period.

The pulse-width-modulated (PWM) amplifier receives the analog voltage from the DAC and provides the electrical power to drive the motor. Based on the average polarity of the amplified voltage, the dc motor will respond by rotating clockwise or counterclockwise. A permanent-magnet-field dc servomotor, with a peak rated torque of 0.490 N-m (70 oz-in.), converts the electrical power into rotary motion, which drives the optical encoder and the gear pair.

Shaft position feedback is determined by a 500-count-per-revolution optical incremental encoder. Two channels in quadrature are transmitted by the optical encoder to the controller, which resolves rotational direction by determining that channel "A" leads "B," or vice versa. By counting encoder increments or decrements and knowing the lead of the roller screw, the shaft's linear position can be determined.

Through the 1:1 gear pair, the mechanical motion from the dc motor is applied to the roller screw. One of the gears is attached to the motor shaft, and the other is attached to the nut of the roller screw.

The high-efficiency (0.845) roller screw with a lead of 0.005 m (0.2 in.) consists of a threaded shaft and an internally threaded nut with threaded rollers. The nut assembly rotates at a fixed location in the mechanical housing so that only the shaft is allowed to translate. Rotation of the shaft is restrained by a keyed bushing located at the end of the shaft sliding in the mechanical housing.

An aluminum structure mechanically supports the dc motor/encoder assembly and the roller screw. The housing is built to be easily mounted to a test fixture so that performance evaluations can be made.

EMAA FUNCTION

The smart EMAA is unique in its capability to provide programmable attenuator forcing functions. The digital servocontroller permits real-time, external-sensor data inputs to its attenuator force equations and allows for real-time performance parameter changes. Most attenuator forcing functions can be implemented using only position control and an algorithm to calculate a position profile of that function as it relates to energy absorption. This discussion will be limited to constant force attenuation using position control.

In position control, a digital servocontroller will often command a motor to move and lock onto a final position. This action is accomplished by the controller determining a desired position and then calculating the position error, the difference between the desired position and the actual position. The position error is then digitally filtered, and the filtered output is applied to a motor through a DAC and an amplifier.

Constant velocity of a motor using position control is obtained by changing the desired position by constant discrete amounts every sampling period. Since the desired position is changing, a controller can take position feedback and compare it to the new desired position to obtain position error. A smooth constant velocity is sustained by minimizing this error through a digital filter. The controller follows the constant discrete changes allowing the filter to maintain stable motion.

Position control can also be used to accelerate or to decelerate a motor. The method is similar to the previous constant velocity control, except that the discrete changes in desired position are not constant. Again, the digital filter minimizes position error and maintains a stable acceleration or deceleration position profile.

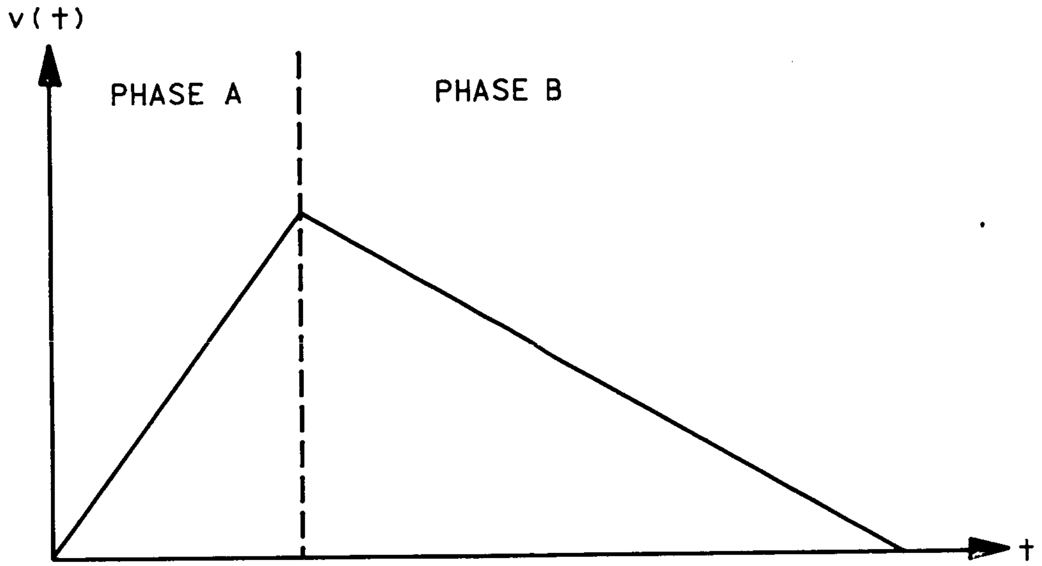
Constant force attenuation is obtained from the EMAA using only position control. The force F can be expressed using Newton's second law of motion

$$F = ma$$

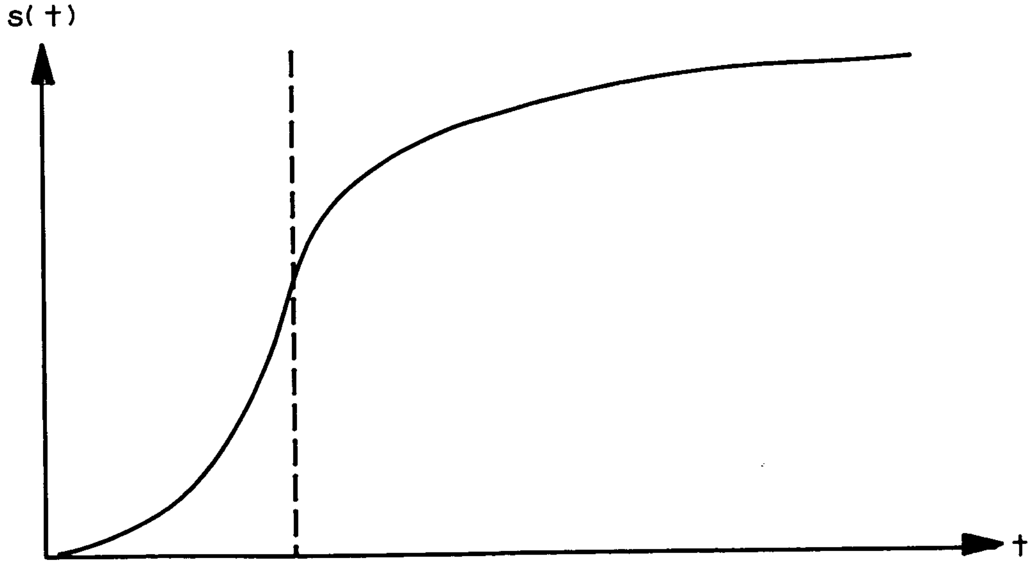
where m is the combined mass of the capture mechanism and the approaching body, and the acceleration a is defined by the deceleration position profile. The total work required to absorb the kinetic energy of the combined mass with a velocity v is expressed as

$$1/2\ mv^2 = Fs$$

where s is the differential displacement (EMAA stroke) of the combined mass. Figure 3 best illustrates this method. Figure 3a is a velocity versus time ($v(t)$) profile of the roller screw shaft, and Figure 3b is the shaft's parabolic position profile ($s(t)$), the double integral of the constant acceleration. In phase A, the roller screw is accelerating to match the velocity of the approaching mass. Phase B shows the constant deceleration of the roller screw during the capture and the constant force attenuation of the mass. This parabolic position profile is generated by the digital servocontroller and applied to the dc motor, which drives the roller screw to provide constant force attenuation.



a. VELOCITY PROFILE



b. POSITION PROFILE

Figure 3 Capture and Attenuation Profile

EMAA TESTBED EVALUATION

A smart EMAA testbed was developed to test a single-axis EMAA system. The testbed is shown in Figure 4. It consists of (1) a test stand, (2) the load cells, (3) a mass simulator, (4) the EMAA, (5) a sonar ranging system (similar to the LDS), (6) a docking computer (a scaled-down DMS), and (7) a data acquisition system.

The mass simulator is an independently computer-controlled electromechanical mechanism similar to the EMAA. It drives the mating surface to simulate a free-moving mass in space. The mass-simulator computer receives force information from the load cell and uses the selected mass value to calculate a deceleration position profile to drive the mating surface.

Testing and verifying the soft docking concept required the fabrication of the single-axis EMAA system. The docking computer coordinates the data between the sonar and the EMAA; then, using the sonar range-rate data, the computer sends control parameters to the EMAA to capture and attenuate the mass. The sonar is an inexpensive system which is used only in this test setup for proof-of-concept purposes. In proximity, it provides range rate information similar to that of a laser sensor.

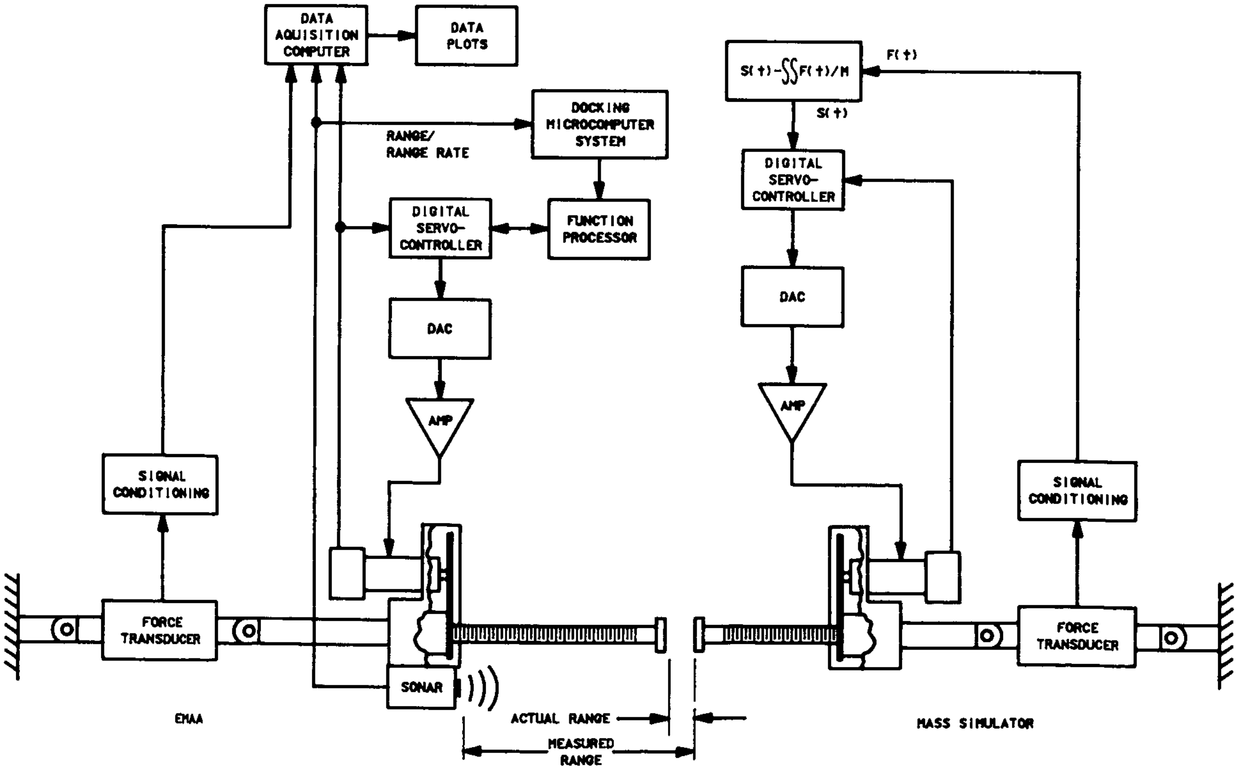


Figure 4 EMAA Testbed

The digital servocontroller, employing a position control system, was breadboarded and tested with laboratory equipment to verify the DAC update time, which corresponds to the sampling period of the position control algorithm.

In order to establish torque versus speed curves, the dc servomotor was first dynamometer tested at voltages ranging from 5 to 40 volts dc. Peak torque established the maximum constant force output of the attenuator. In its current configuration, this output was found to be 515 N (115 lbf).

The roller screw selected provides a 0.457-m (18 in.) stroke and the capability to withstand a 5440-N (1223 lbf) axial load (safety factor 3). Load-handling capability was obtained from the manufacturer's published specifications, and after numerous EMAA tests, no degradation has been observed. Also, from analysis of the load data based on a six-degree-of-freedom, three-body simulation program (SOFTDOCKSIM), it was concluded that these actual force loads to the roller screw shaft in a docking ring configuration would not be exceeded.

The data acquisition system obtained force-versus-time, position, velocity, and motor-current data from the soft docking attenuation process. These data verified the performance requirements of the smart EMAA.

CONCLUDING REMARKS

A proof-of-concept smart EMAA system has been described. The technology derived was based on current off-the-shelf components and can be applied to present and future space docking systems. Special new designs have been considered that incorporate a brushless dc motor around the roller screw and include a permanent-magnet rotor attached directly to the roller screw nut. This concept will eliminate the use of gears by producing a more compact size with reduced friction and inertia of moving parts. The attenuation technique, which uses a position controller to provide a motion profile, gives a high degree of flexibility to any attenuator/actuator system. This technology applies not only to a docking system, but also to berthing and to positioning and holding aids by controlling the motion of large, massive objects.

Some inherent, unresolved difficulties remain which include both the complexity of coordinated control of an overconstrained multiaxis system and the instability and mechanical binding of a coupled system. The control system development for the soft docking system will be the prime instrument in overcoming the difficulties of stability and control.

This unique concept has great potential for current and future docking/berthing systems. The use of microcomputers enables the real-time updating of attenuator/actuator parameters and allows for programmable attenuator forcing functions. This capability greatly enhances the performance of the docking/berthing system because of the high degree of flexibility and programmability of the microcomputer.

ACKNOWLEDGMENTS

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