LINEAR ACTUATOR SYSTEM FOR THE NASA DOCKING SYSTEM

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ABSTRACT

The Linear Actuator System (LAS) is a major sub-system within the NASA Docking System (NDS). The NDS Block 1 will be used on the Boeing Crew Space Transportation (CST-100) system to achieve docking with the International Space Station. Critical functions in the Soft Capture aspect of docking are performed by the LAS. This paper describes the general function of the LAS, the system's key requirements and technical challenges, and the development and qualification approach for the system.

NDS OVERVIEW

NDSB1 general summary

The NASA Docking System Block 1 (NDSB1) is a mechanism designed to achieve spacecraft to spacecraft docking on-orbit. Docking and berthing have been extensively defined by others [1]. The NDSB1 is classified as docking mechanism because it is able to achieve a pressurized and structural connection between two spacecraft without the aid of a robotic arm. The system is not considered Androgynous. Key features to support androgynous docking, such as capture latch strikers are not present within the NDSB1.

Like all typical docking mechanisms, the operation of the NDSB1 is divided into three phases: Soft Capture, Load Attenuation, and Hard Capture. During the Soft Capture docking phase, the first physical connection is achieved between the two mating vehicles. At this point in the docking sequence, some relative motion between the two vehicles is still present. During Load Attenuation, all relative motion between the two vehicles is removed and proper alignment to support Hard Capture is achieved. In the final phase of docking, Hard Capture, a structural connection is established between the two vehicles, supporting pressurization and providing for crew transfer.

The NDSB1 is divided into two subsystems which support the functions described above: Soft Capture System (SCS) and Hard Capture System (HCS). The SCS performs Soft Capture and Load Attenuation. The focus of this paper is on the SCS. The HCS performs the Hard Capture function and will not be addressed in this paper. The two systems are depicted in Fig. 1. The NDSB1 is designed to dock with systems that are compliant with NASA's International Docking System Standard (IDSS) Interface Definition Document (IDD).

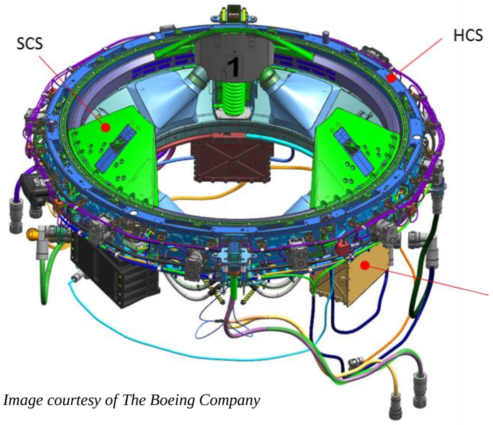

Image courtesy of The Boeing Company

Figure 1. NDSB1 Schematic

NDS block terminology

The NDSB1 is a descendant of NASA's development of a docking system for the ISS. Starting in the 1990s, NASA produced a series of docking system prototypes, starting with the Low Impact Docking System (LIDS). When the International Docking System Standard (IDSS) was adopted in 2008, the LIDS became the International Low Impact Docking System (iLIDS), retaining much of the SCS from LIDS but implementing a HCS based on the Russian Androgynous Peripheral Attachment System (APAS). The iLIDS was also termed the NASA Docking System Block 0 configuration. The "Block" terminology is used to designate future upgrades envisioned for NDS applications in Lunar, Mars, or other deep space environments. In 2013, the IDSS was further refined to utilize a narrow ring configuration similar to APAS. NASA contracted with Boeing to design, develop, and produce a docking system based on the narrow ring configuration, which is referred to as NDSB1.

NDS development and production state

The NDSB1 project is in a mature state, having completed all development and qualification testing.

Production of the first flight unit is finished and all acceptance testing has been successfully accomplished. The completed flight article in shown in Fig. 2.

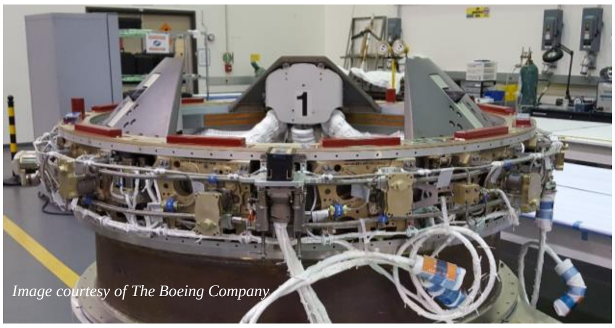

Figure 2. NDSB1 First Flight Article

Applications of the NDS

The NDSB1 will be used on the Boeing CST-100 Starliner within NASA's Commercial Crew Program, as shown in Fig. 3. As a part of the CST-100, the NDSB1 will facilitate transportation of astronauts to and from the International Space Station (ISS). The ISS includes International Docking Adapters (IDAs) attached to the Node 2 Forward and Zenith ports, which have a passive SCS and active HCS to support use of the NDSB1.

Figure 3. NDSB1 on CST-100

Soft capture concept of operations

When NASA shifted from the Block 0 design to the narrow ring for NDSB1, the concept of operations was also changed to include the following features. First, as mentioned, the NDSB1 SCS ring is narrow and compatible with APAS. Like most docking systems, the actuators used to maneuver the SCS ring are arranged in a Stewart platform. Unlike other systems, the NDSB1 SCS actuators act in relative independence, being neither mechanically linked nor connected via a closed loop control. Finally the actuators are load limiting and can have those limits adjusted on-orbit for greater operational flexibility.

The NDS SCS operation concept includes the following operational modes: Stow, Extend to Ready to Capture, Lunge, Attenuation, Alignment, Retract. Each mode moves the SCS Ring to a different position, with a unique (or potentially unique) force characteristic.

The development of these conceptual operational features and modes into the NDSB1 will be discussed later in this paper.

Soft Capture System general summary

The Soft Capture System includes the SCS Ring, the Capture Latches, Capture Sensors, and the Linear Actuator System (LAS), as shown in Fig. 4. The SCS Ring includes three petals which align and mate with corresponding petals on the mating docking ring. A Capture Latch is included on each petal and locks the two mating rings together during docking. Two Capture Sensors on each petal provide an indication of successful soft capture or loss of soft capture to the NDSB1 avionics. Finally, the LAS is responsible for maneuvering the SCS Ring during all phases of soft capture. The LAS includes six Linear Actuators, a control avionics box – the Linear Actuator Controller (LAC), and all associated cabling between the Linear Actuators and the LAC. See Fig. 5 and Fig. 6.

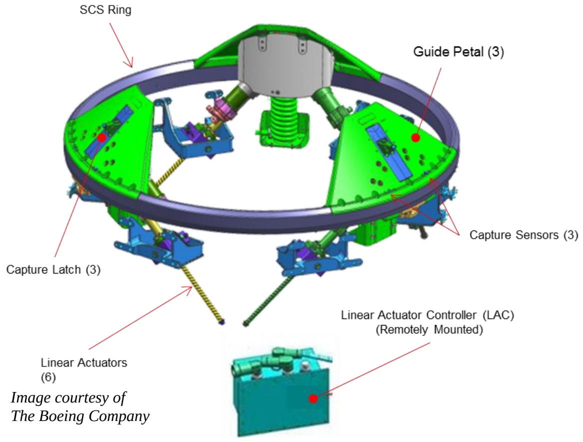

Figure 4. SCS Major Components

KEY REQUIREMENTS OF THE LAS

The functional elements of the LAS present challenges for a generalized actuation system. The initial capture mechanism design acts as a six degree of freedom platform with engaging guide petals to allow mechanical engagement between the two mating structures. The concepts of operations for initial docking require the mechanism to apply energy in the engaging direction, yet comply to reactionary forces once the docking ring engages with the mating alignment guide petals. Once the docking ring is fully aligned and latched in place, the actuation mechanism is responsible for attenuating dynamics between the coupled structures and mass bodies. Once motion is fully attenuated between the mass bodies, the actuation system is responsible for motion control for fine alignment of the vehicles to allow completion of Hard Capture.


Image courtesy of Moog, Inc.

Figure 5. Linear Actuator Controller

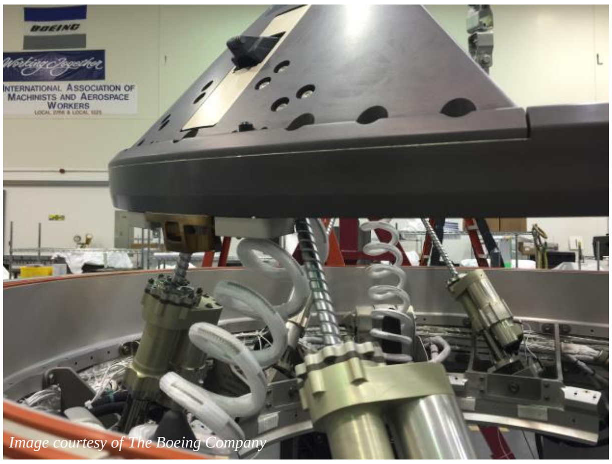
Image courtesy of The Boeing Company

Figure 6. Linear Actuators Installed in NDSB1

DESIGN CONSTRAINTS

In addition to the functional requirements of the LAS, vehicle integration and operational environment constraints also significantly impacted the design of the LAS. While the LAS is a critical element of the NDSB1, its operation is relatively short when compared to the overall host vehicle’s mission. As a result, the LAS must survive and operate through a variety of environmental conditions, respect mass limitations, maintain a power budget within the host vehicle's power allocation, and allow for flexibility of operation for system integration, testing, development, and crewed flight operations. Perhaps most importantly, it must achieve these requirements while providing positive margins of safety, appropriate levels of failure tolerance, and high reliability.

Taking these requirements and design considerations into account, system design decisions by system integrators led to the following specific design driving constraints.

Limited system sensory feedback

The LAS had to be designed as an actuation system with minimal sensor feedback. This permitted a significant reduction in mass and – more importantly – increased system reliability by eliminating possible failure modes of the system. The design axiom that “a component that is not there cannot fail” means that fewer sensors increases system reliability. As a result, the system design excluded the use of force, temperature, and dedicated absolute position feedback sensors for each actuator.

Strut domain control

The concept of operations and the complexity of computations led to a trade of conducting six degree of freedom platform control versus six independent strut control for force regulation and position control. There is a known relationship between cost and space grade radiation tolerant electronic devices required to provide the computational resources for six degree of freedom platform control. With this relationship being understood and an objective to provide a cost effective solution, the system design maintained strut control throughout all operations.

Environmental requirements

The system components must survive launch operations and environments, operate through a large range of thermal environments while on-orbit, and sustain without damage atmospheric re-entry and landing loads applied by the host vehicle.

Flexibility for development

Given the complexity and uniqueness of operations for the system, system integrators needed the ability to adjust and modify operational characteristics throughout development. As a result the linear actuator system design included parameter based control laws which allowed for adjustability during development. The range of flexibility became a design objective and constraint on the system design.

OPERATIONAL CHARACTERISTICS

To aid in the management of the linear actuator system's performance, the concept of operations is separated into three main operations: lunge, attenuate, and position control.

Position control

Controlling the position of the actuation system is necessary for multiple operational elements. As a part of preparing for docking, the full stroke capability of all six actuators is checked to ensure no mechanical issues are present in the mechanism. Additionally, the ring is placed into a ready-to-capture position where the ring's position is actively controlled while waiting for initial detection of contact with the mating adaptor. These first two maneuvers are conducted requiring the actuators to control position of an unloaded ring.

After initial docking is complete, the ring is mated to the interfacing adaptor, and motion is arrested, the position control functions maneuver the host vehicle into an aligned position. Effectively, all six actuators are commanded to the same length, and are commanded to reach the same length at the same time. The linear actuator controller must create a commanding profile with acceleration and velocity limits, commanding a position loop to achieve the synchronized movement of all six actuators. Position control loops of the actuation system must control the six actuator lengths while rejecting large inertial load disturbances from the host vehicle mass.

Additionally, during all position maneuvers, each actuator is limited to a force output, as such, to not overload overall mechanical structures. If a force limit is reached on an actuator, the actuator is required to slip at that force until the force is reduced.

Lunge

The lunge function is used immediately after contact is detected and functions to add energy into the system to force alignment of the ring's guide petals with the mating adaptor's guide petals. The actuator will displace in the positive direction along the load curve shown until the maximum force limit is reached. Once the force limit is reached, the actuator must slip in the negative direction, maintaining the constant force value during the slip. In order to limit the amount of off axis displacement of the ring during the lunge function, a centering term is required in the control law, which adjusts the force output curve of an actuator based on the delta distance from the average of all six actuators.

Attenuate

Following the lunge function and after initial capture has been detected by the docking system controller, the linear actuation system must attenuate the motion between the two mating structures. Effectively, the linear actuators must hold a position and allow a minimal amount of displacement until a specified force limit is reached; at which the actuator is backdriven until the force applied is lower. Once slip has occurred, the actuator must hold the position delta equivalent to the distance slipped. Additionally, for operational conditions resulting in off nominal operations, the attenuate function is used as a position hold function to maintain control of the system and allow for system safing.

DEVELOPMENT APPROACH

Linear actuation systems have been used to control various applications in space flight. While heritage exists for actuation in space systems, the complex use and interaction with the docking mechanisms presented a unique challenge for any actuation system. A comprehensive set of actuation development capabilities, including design, manufacturing, and testing, were required in order to realize a successful system design. With significant heritage of designing and developing actuation systems and components for space, aircraft and industrial systems, Moog was selected a supplier partner to collaborate with the NDS team and develop the entire linear actuator subsystem. The development approach utilized design cycles, reducing technology risk and maturing the system design with each cycle. The linear actuator design cycles were categorized into three main maturity phases prior to building qualification and flight deliverable units: Proof of Concept (POC) phase, Engineering Development Unit (EDU) phase, and Functional Equivalent Unit (FEU) phase.

Proof of concept

Image courtesy of Moog, Inc.

Figure 7. LAS Proof of Concept Test Stand

The first phase of development, the proof of concept phase, was focused on understanding limitations of linear actuators as applied to the system's conceptual operations and creating the first iteration of dynamic models. In addition, the first iteration of test systems were developed to support flexible dynamic actuator testing.

The POC phase was began with a fly sheet specification and a technical interchange meeting to review the scope of the study. Moog procured two (2) linear electromechanical actuator drive trains to acquire data for the actuation system trade studies. A rollerscrew drive and a ballscrew drive were evaluated in order to compare drivetrain efficiency and the effect on slip force control.

The test platform developed during the proof of concept phase created the opportunity to evaluate multiple test cases and conditions. The first generation of the test stand architecture was a linear load stand with a hydraulic actuator for the test load control. A real-time control electronics platform was used to control both the EMA under test and the load actuator simultaneously. The real-time platform also served as the data collection system. The architecture of the load stand and control electronics served as a rapid prototyping platform to quickly iterate control algorithms for both the load system and unit under test through system identification techniques. Fig. 7 shows the test platform and proof of concept actuator developed.

The proof of concept phase resulted in the following conclusions:

1. Testing of the hardware demonstrated feasibility of an EMA behaving within the required limits for the soft capture system.
2. Drive-train efficiency versus helix angle of output drives were evaluated for determining actuator sizing.
3. Drive-train friction, brushless-DC motor cogging and torque ripple, and backlash showed as the primary concern for model uncertainties.
4. Drive-train efficiency had a direct impact on forward-driving versus back-driving force output for a given current input.

Engineering development unit

Following a successful test and demonstration proof of concept phase, the design of the system entered into the next maturity phase, referred to as the Engineering Development Unit (EDU) phase. The main objective of this phase was to reduce integrated system risks by producing development units for system testing with an integrated ring assembly. This phase also allowed for component risk reduction testing to be conducted in parallel with the commencement of component flight designs. The test equipment approach continued to evolve through the EDU phase of the project to meet deliverables.

The EDU system consisted of six linear actuators, a controller with separate electrically isolated strings, a set of interconnect cable assemblies, and a command and interface test console emulating the docking system controller's soft capture operations. The EDU linear actuator design expanded on the lessons learned from the proof of concept phase and was sized in order to meet updated performance requirements. The design was targeted towards reducing risk and demonstrating capability for performance while meeting major interface requirements for six degree of freedom testing. Additional goals for the EDU linear actuator included understanding the impact of thermal, vibration, and shock environments, and the impact of moment loads on the actuator performance.

The EDU actuator consisted of the following subcomponents:

1. Custom Moog dual wound, skewed stack brushless-DC motor with two (2) resolvers for rotor position feedback
2. Custom actuator housing and attachment interfaces
3. Custom jack gear
4. Off-the-shelf high-lead linear ballscrew
5. Absolute linear position feedback resolver
6. Integrated strain measurement for force telemetry

Image courtesy of Moog, Inc.

Figure 8. Six-Axis Test Stand Configuration

The EDU actuator was subjected to a series of test conditions to evaluate both performance and survivability to environmental conditions. As mentioned, the test system for evaluating performance continued to improve during the EDU phase. The linear load system hydraulic load actuator was replaced with an electromechanical actuator to improve dynamic control and response. System identification techniques were used, similar to the proof of concept phase, to validate modeling assumptions of the linear actuators. Additionally, an inertial simulation control scheme was developed for the linear load stand. The inertial simulator enabled flexible and continuous testing of the entire docking sequence on a linear load stand without the need for a coupled mechanism. All six linear actuators in the system were then capable of being tested independent of each other. Fig. 8 shows the six axis linear load stand configuration.

Environmental tests were conducted with the EDU actuator to prove design compliance and provide data for the continued flight mechanism development. Extensive design of experiments and testing resulted in design elements to improve slip performance over the temperature requirements. Vibration testing demonstrated margin for component survivability and operation. Additionally, the EDU actuator was subjected to a series of shock tests, providing valuable data that led to further design improvements of the flight design.

In addition to extensive testing at Moog, the EDU actuation system, integrated into a prototype NDSB1 Soft Capture System, was tested at NASA's Six-Degree-of-Freedom Dynamic Test System (SDTS) facility located in the Johnson Space Center in Houston, Texas, as shown in Fig. 9. The SDTS facility has the capability to simulate full scale docking of two bodies in space. In this case the facility ran multiple simulations of the NDSB1 attached to a spacecraft similar to CST-100 docking to the IDA on the ISS. During docking simulations, the SDTS simulates different vehicle velocities and misalignments under accurate vehicle mass conditions. The system was subjected to numerous test cases, simulating nominal and off-nominal extremes of docking scenarios. The six degrees of freedom docking simulator allowed for testing the linear actuator system's functional compliance to ISS docking requirements. Data collected from the docking scenarios supported model correlation and validation activities.

Data from Moog and Boeing's EDU testing progressed the design and requirement maturity significantly. The EDU phase resulted in the following:

1. Reduced risk and increased system TRL
2. Detailed model correlation and flight model predictions of mechanism performance
3. Validation of the system design concept as an integrated subsystem
4. Demonstration of environmental margin
5. Matured integrated test systems

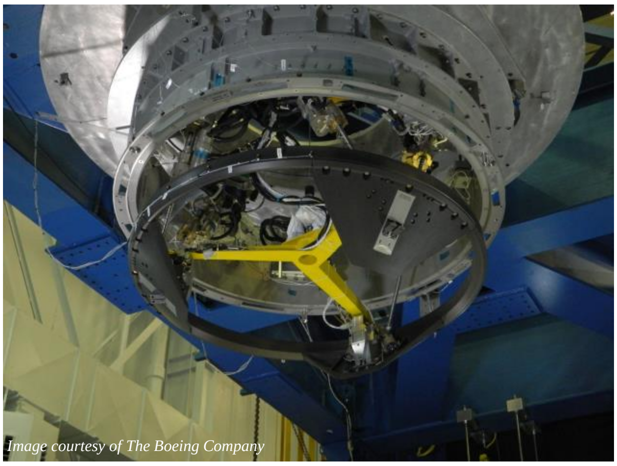

Figure 9. EDU SCS in 6DOF Test

Functional equivalent unit

The final design maturity phase of the linear actuation system development was referred to as the Functional Equivalent Unit (FEU) phase, also referred to as the Pathfinder phase. The FEU phase was focused on producing flight like hardware for a final set of risk reduction tests. The FEU phase also proved manufacturing processes and demonstrated supplier capabilities to meet the procurement needs of the flight hardware.

The pathfinder actuator used by Moog focused on the final set of control law development. The linear actuator flight system utilized non-reprogrammable logic devices which required a locked set of control laws and gains to be baselined for firmware development. The actuator was procured quickly following the EDU phase and consisted of all flight pedigree hardware components. The existing test system developed for EDU actuator testing was used for in-depth system identification and qualification of the actuator's friction characteristics over temperature and slip velocities. After the control laws were baselined, the final set of functional performance requirements for the actuator were baselined. The flight assembly acceptance verification relied on friction and slip requirements. A final iteration of the linear actuation system performance model was also baselined with the data from the pathfinder testing. The dynamic model, again, was utilized in the docking system dynamic model to support verification of requirements.

Given the similarity to the flight design, the FEU assemblies were procured for system integration testing and NDS qualification testing at Boeing. This allowed for a family of actuators to be used for manufacturing, assembly, and test process-proofing. In addition to developing production processes, a pathfinder actuator was exposed to the latest baselined environmental requirements to reduce risk and demonstrate margin.

The FEU phase was successful in reducing risk (design, operational, supplier) and continued to increase the TRL level of the actuation system.

QUALIFICATION APPROACH

The qualification of the LAS follows the typical NASA systems engineering approach. LAS functional performance and environmental requirements were allocated from NDSB1 system specifications. Verification of requirements was divided into analytical (analysis and inspection) and test approaches. System performance verification was apportioned between the LAS and the NDSB1 as appropriate based on the level of requirement and its suitability for verification at the different levels. Significant portions of this verification were analytical in nature, and will not be discussed here. Instead, a summary of the testing performed for qualification is provided.

LAS qualification test summary

Qualification testing at the LAS level demonstrated the full subsystem capability under benchtop (laboratory) and representative environmental conditions. During functional testing of LAS at Moog, the six actuators were not mechanically connected in a Stewart Platform configuration. Instead, each actuator was on its own test stand with a load actuator, permitting simulation of the mechanical interconnectedness of the Stewart Platform as well as the loads imparted by the mating vehicle. These test stands were adapted and upgraded from the versions used during EDU testing earlier in the program. Using this setup, system performance was tested by simulating docking events and making precise measurements of the system performance (forces, displacements, velocities), confirming proper docking operation. Testing was also performed to verify actuator performance under operational environmental conditions, including extreme hot and cold temperatures, vacuum, and electromagnetic interference (EMI) environments. Operation during exposure to launch vibration is not required, however, system performance was demonstrated after exposure to launch vibration. Finally, the LAS was subject to a rigorous life cycle test which demonstrated performance after completing four times the expected operational life cycles in accordance with NASA's Design for Minimum Risk (DFMR) requirements. The LAS completed all Qualification tests without issue. Along with completion of the companion analytical and inspection verifications, the system is fully qualified.


Image courtesy of The Boeing Company

Figure 10. Flight Configuration SCS in 6DOF Test

M1/6DOF Test Summary

NDSB1 level testing of the LAS was also conducted in NASA's SDTS facility, as shown in Fig. 10. The NDSB1 test article used for this operation is referred to as the M1 or 6DOF unit. The M1 test article only included the SCS and the NDSB1 tunnel. The purpose of the M1 testing in the SDTS was to correlate the dynamic models of the NDSB1 and LAS, providing for verification of the NDSB1 system dynamics requirements. All M1 testing was completed without issue and demonstrated successful performance of the NDSB1 and LAS.

Q1 Test Summary

The performance of the LAS at the NDSB1 system level under environmental conditions was demonstrated in the Q1 test article configuration. The Q1 test article was a complete representation of the NDSB1 flight design, as shown in Fig. 11. This unit was subjected to the full suite of environmental conditions, including docking under vacuum at extreme hot and cold conditions (TVAC). The TVAC testing was conducted at NASA's MSFC Environmental Test Facility. The Q1 test article was also subject to system level random vibration testing followed by functional performance testing. Finally, the unit was subjected to EMI testing. The LAS and NDSB1 successfully passed all system level tests.

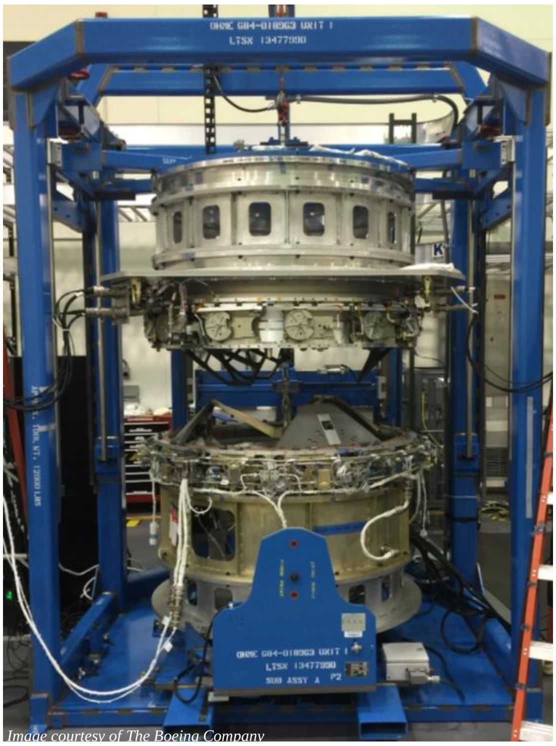

Image courtesy of The Boeing Company

Figure 11. Qualification NDSB1 in Mated Test Stand

Conclusion

The LAS is a major sub-system of the NDS and performs critical functions of the Soft Capture phase of docking. The LAS implements the a new concept of the Soft Capture portion of docking into a practical, flight ready form. The LAS and NDSB1 together have completed a series of development and qualification operations and are certified to dock to the ISS, starting with the Commercial Crew Program CST-100 Starliner spacecraft.

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