NASA Docking System Block 1: NASA's New Direct Electric Docking System Supporting ISS and Future Human Space Exploration

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Abstract

The NASA Docking System (NDS) Block 1, shown in Figure 1, is a key component of NASA's vision for space exploration. It is designed to provide capability for visiting vehicles to dock to the International Space Station's recently-installed International Docking Adapter ports. It is the first docking system to be developed by NASA since the Apollo-Soyuz Test Project (ASTP) of the 1970's. The NDS Block 1 includes provisions for capture, structural attachment, power/data transfer, and undocking. It uses a direct-drive electromechanical Stewart Platform capture system architecture, along with an innovative automated control scheme, to achieve an unprecedented level of performance and simplicity. Its design implements the new International Docking System Standard, which will be a key enabler of diverse and flexible exploration missions. NDS qualification was completed in 2017 to support a planned first flight in 2018 on the Boeing CST-100 Starliner.

Figure 1. NASA Docking System Block 1

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Introduction

The technical fascination with spacecraft rendezvous and docking is unmistakable. The attraction of watching complex vehicles carrying humans approach, align, collide, attach, park, and structurally anchor is timeless. For as long as travelers have set off on perilous voyages, onlookers have been mesmerized by their departure, return or arrival in a foreign port. The vocabulary of spacecraft docking harkens back to the days of wind driven ships. Docking, berthing, ports and other mating system terminology are vestiges of our maritime traditions. The special allure of spacecraft docking is evident in popular culture. Most space travel motion pictures inevitably include a detailed technical scene depicting how the spacecraft docks or undocks, complete with the whoosh of a hatch opening and the clunk of the final structural connection to symbolize the consequence and finality of arrival and departure.

NASA’s newest docking system evolved from systems developed during ASTP. This paper will trace the considerations that drove that evolution to the current design. It will provide an overview of the NDS architecture, components, and operation, and will recount a few of the key technical challenges and lessons learned during system development and qualification. System performance as demonstrated by dynamic testing is also summarized.

Historical Context

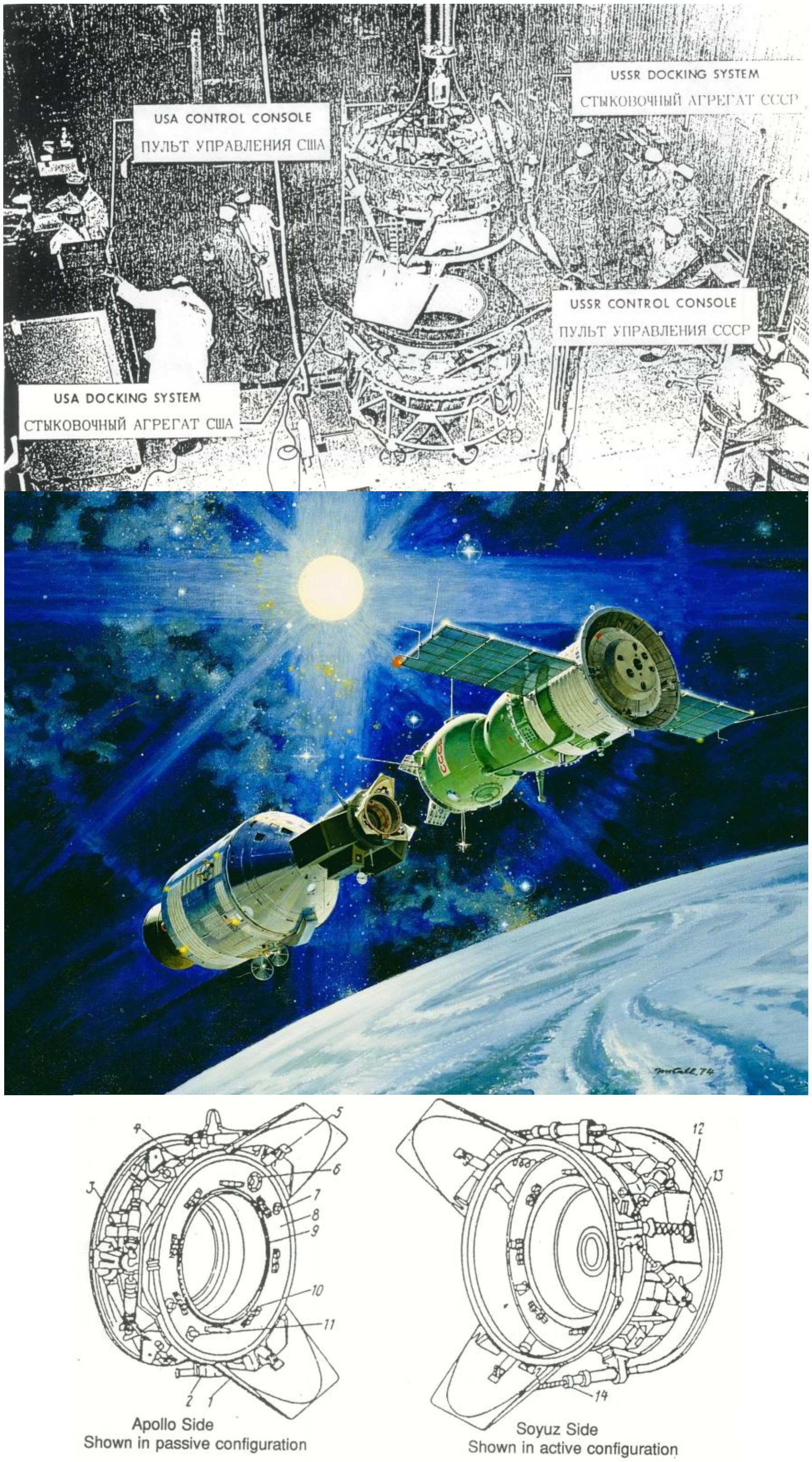
NASA makes a distinction between docking and berthing operations. Docking is defined as the process of connecting two spacecraft without external assistance. Continuing with the maritime analogy, docking represents the combination of a port and a ship for which the captain in a boat is able to navigate, make land and tie up to a boat dock without external aid. Berthing, on the other hand, is analogous to the large ship scenario where a harbor master or pilot boat is required to aid moving the boat into the boat dock. Wigbert Fehse defines docking and berthing in *Automated Rendezvous and Docking of Spacecraft* as follows [1]:

> In the case of *docking*, the guidance, navigation and Control (GNC) system of the chaser controls the vehicle state parameters required for entry into the docking interfaces of the target vehicle and for capture.
>
> In the case of *berthing*, the GNC system of the chaser delivers the vehicle at nominally zero relative velocities and angular rates to a meeting point, where a manipulator, located either on the target or chaser vehicle, grapples it, transfers it to the final position and inserts it into the interfaces of the relevant target berthing port.

In the current International Space Station (ISS) berthing operations, the pilot boat is replaced by the space station robotic arm. Visiting vehicles or other external hardware are plucked from a station keeping position or removed from a cargo bay, and placed onto an attachment mechanism on the ISS. Berthing allows for a lighter and less complex attachment mechanism than docking, but requires an external robotic manipulator to be present at all berth and unberth events. The safe handoff of the payload from the robotic arm to the berthing mechanism presents technical challenges as well.

In docking, the attachment mechanism includes its own robotic manipulator, known as the Soft Capture System (SCS), for maneuvering the vehicles after soft capture into final position for hard mate. The SCS has a capture envelope large enough to accommodate the inaccuracies of the Guidance, Navigation and Control (GN&C) system. It attenuates the relative motion of the two vehicles, and then slowly brings them together with enough accuracy to engage the shear features of the interfacing tunnels.

The development of ISS created several different mechanisms for berthing, most notably the Common Berthing Mechanism (CBM). CBMs are used to connect the pressurized elements of the space station and allow crew to move between elements. Several other berthing mechanisms are used around the space station to attach the unpressurized truss elements. Despite its array of berthing mechanisms, NASA lacked a man-rated pressurized docking system design before the development of NDS. The last US built docking system, shown in Figure 2, flew in support of the Apollo Soyuz mission.



Apollo Side
Shown in passive configuration

Soyuz Side
Shown in active configuration

Figure 2. Images of NASA's last US built human rated docking system - circa 1975

All of the docking that occurred during the Space Shuttle and Space Station era has used hardware procured from Russia. The systems were developed by Russian (then Soviet) contractor RSC-Energia and had been used previously in the Russian MIR space station complex. The Space Shuttle docking system was known as the Androgynous Peripheral Attachment System (APAS), which is shown in Figure 3. APAS was a variant of the Apollo Soyuz design with the petal direction reversed. The interface requirements of the new International Docking System Standard trace much of their heritage to the APAS in terms of hard capture and soft capture hardware geometry. The soft capture design of the APAS capture system was largely mechanical. The three bi-pods were all mechanically connected via a triple differential. In simple terms, pushing down on one petal pushed the other two up. This was a significant advantage in terms of capture success but the mechanical transmissions were extremely complicated. The system needed a large contingent of electromechanical hardware including; motors, brakes, slip clutches, fixers, eddy current damper and 9 control boxes.

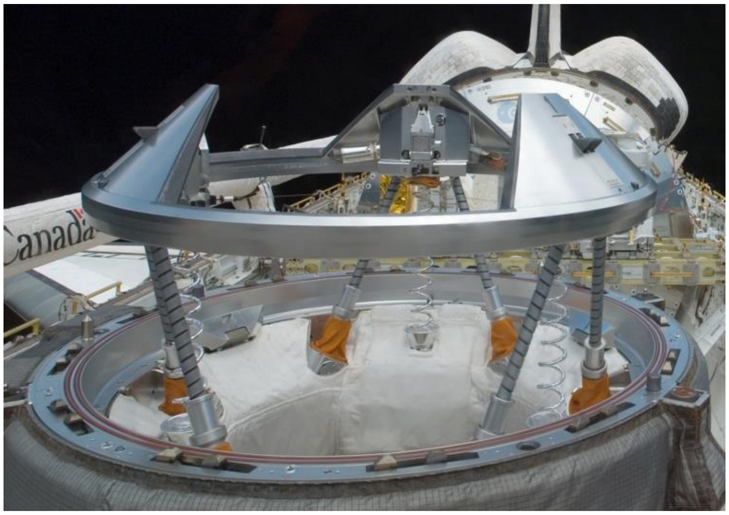


Figure 3. NASA image of the Space Shuttle with Russian APAS docking mechanism

In the early 1970s NASA commissioned the Space Division of North American Rockwell to conduct trade studies on docking technologies in support of the Apollo Soyuz Test Mission [2]. The contract produced detailed analysis and sub-scale mechanisms to evaluate most of the major technology areas of docking. Many of the technical parameters identified in this study remain in today’s docking system. The study selected a cable retracted hydraulic actuator for the US soft capture system design. It also built and modeled the Russian mechanical soft capture system and postulated the viability of two other architectures.

The other architectures were direct servo electric (shown in Figure 4) and cold gas pneumatic-hydraulic soft capture systems. The cold gas system was undesirable due to a low cycle associated with the gas consumables. Reduced weight and lower friction were identified as key improvements of a direct servo system. The development time, weight, power consumption and reliability of the electronics needed to control an electric platform of the early 1970s prevented this architecture from being selected. Today’s electronics and the NDS controls approach have overcome these problems, allowing the NDS to implement a direct electrically controlled soft capture system.

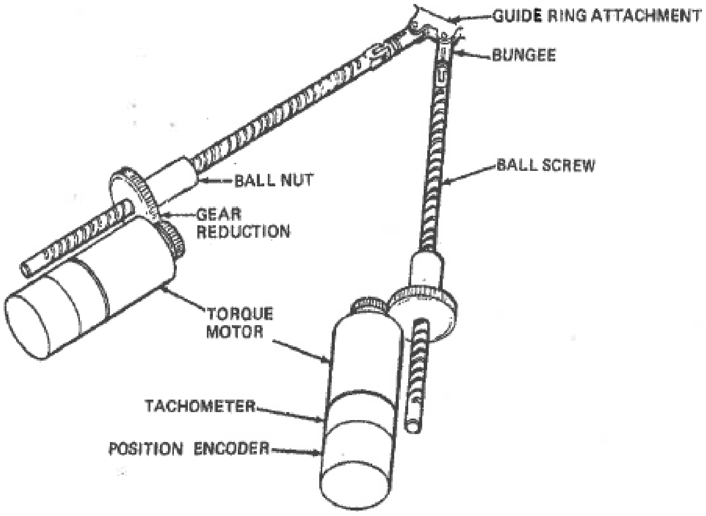


Figure 4. Torque Motor Servo System from Apollo Soyuz study

There are several unique characteristics of this system. The design employs a control approach originally envisioned in 2003 by Boeing in support of the Orbital Space Plane Program [3]. The NDS soft capture system externally appears very similar to APAS, but the control and effector architecture is completely different. Unlike the APAS ball screws, the NDS linear actuators are mechanically independent of one another, each being driven by a dedicated motor. Because of this lack of mechanical coupling, the coordination required to accomplish capture and alignment must be provided by the controller. In most ground-based Stewart Platform applications, the coordination involves calculating the position and orientation of the motion platform using the measured lengths of the six actuators. The lengths of the actuators can then be adjusted to accomplish the desired motion of the platform. In these ground-based systems, the calculation of the platform position and orientation, known as the forward kinematic solution, must be performed numerically using a processor-based computer due to the lack of a closed form solution. During the early phases of NDS development, the cost and schedule impact of developing a processor-based controller certified for the space environment were identified as a major program risk for architectures that required it. This risk was one of the key discriminators that led to the selection of a SCS architecture that does not require the forward kinematic solution.

The arrangement of the NDS linear actuators is such that the soft capture ring is coaxially aligned with the tunnel whenever the six actuator lengths are the same. The NDS control architecture makes use of this fact to simplify the commanding of the actuators during capture and ring alignment. During capture, the controller calculates the average length of the six actuators at every instant of time and uses it as a point of reference for commanding current to the motors. This logic gives the soft capture ring a central tendency as it complies to accommodate vehicle misalignments. The simple coordination algorithms used in the SCS allow for an implementation that does not require a processor-based controller. During soft capture operations, the NDS relies solely on position and current feedback to control the six linear actuators as they bring the vehicles together and engage the structural mating features of the two tunnels. Major components of the NDS are shown in Figure 5.

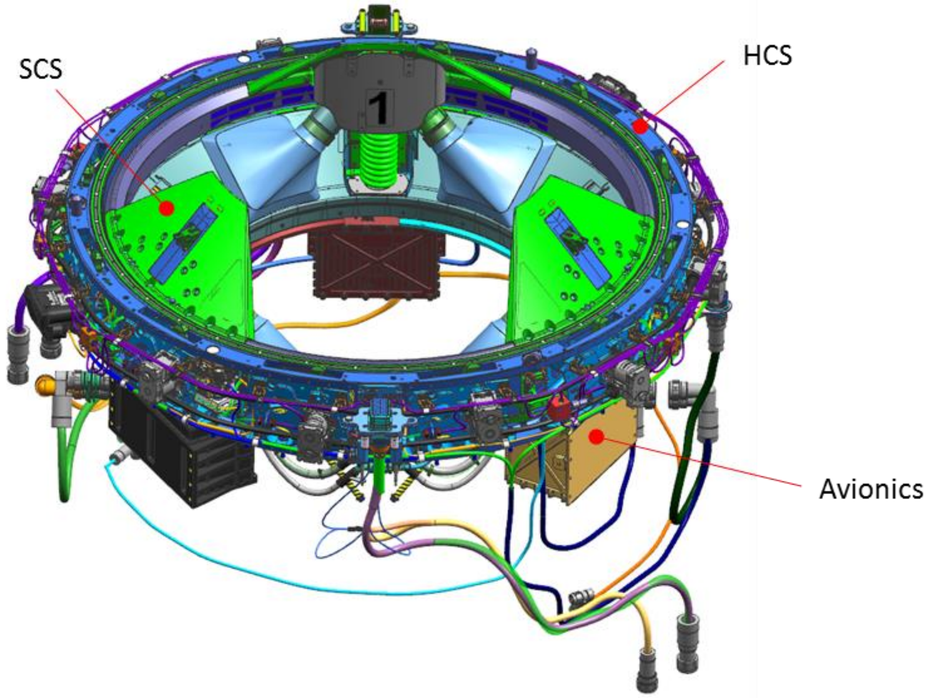


Figure 5. NASA Docking System Schematic

Operational Sequence

The docking event is an automated sequence punctuated by several discrete events. During the approach, the SCS is extended to the “ready to capture” position, where it awaits initial contact between the two spacecraft. The GN&C system of the chaser vehicle ensures that initial contact occurs within the capture envelope of the docking system. From initial contact onward, the chaser vehicle is in free drift and relies on the docking system to capture and maneuver the vehicles to hard mate. This approach distinguishes NDS from previous docking mechanisms, which all relied on the host vehicle thrusters to push the soft capture features together after contact to achieve capture. The design of the NDS SCS has eliminated this need. Qualification testing of the SCS in the summer of 2016 demonstrated 100% capture success for a robust set of initial contact conditions, without the use of post contact thrust.

At contact, the forces between the coarse alignment guides cause the NDS linear actuators to be displaced from the ready to capture position. This event signals the controller to initiate a maneuver known as the Lunge. During Lunge, the soft capture system extends in a compliant manner to accommodate vehicle misalignments and engage the soft capture latches, one of which is mounted in each of the three guide petals on the soft capture ring. Each latch engages an opposing striker plate mounted behind the passive side soft capture ring. The interface between the capture latch and the striker is shown in Figure 6.

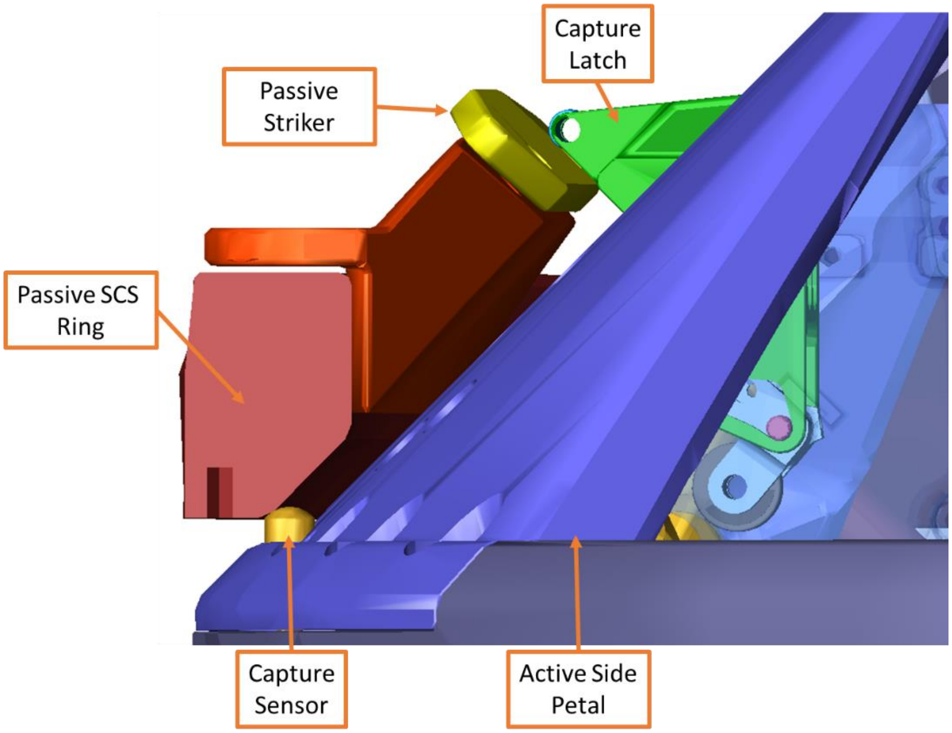


Figure 6. Soft Capture Latch Interface

Once the capture latches are engaged, sensors mounted in the soft capture ring indicate that capture is achieved, signaling the system to begin attenuating the relative motion of the two vehicles. At this point, the two soft capture rings are loosely held together by the capture latches such that the incoming vehicle cannot escape. Once the time allocated for attenuation expires, the controller begins adjusting the lengths of the actuators to equalize them, thereby aligning the two mating tunnels. With alignment complete, the linear actuators retract, closing the gap between the two tunnels and engaging their shear features.

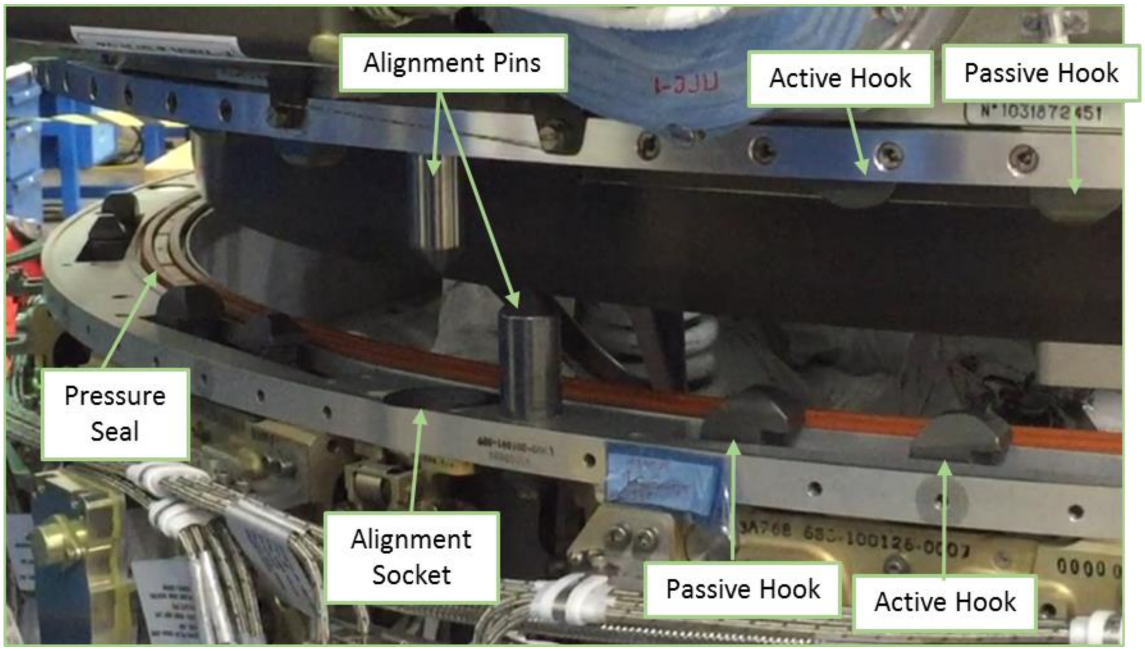


Figure 7. Hard Capture Interface

Once the two structural tunnels are in close proximity, a set of twelve structural hooks are driven, which engage corresponding compliant passive hooks on the opposing tunnel. The structural hooks close the remaining gap between the tunnels, compressing an elastomeric seal and creating an airtight structural interface. With the hard part finished, motorized umbilical connectors can then be driven, allowing for power and data transfer between the docked spacecraft. The major hard capture interface components are shown in Figure 7.

Technical Challenges

The thermal environment in Low Earth Orbit presented one of the key technical challenges to the docking system design. The temperature of hardware in space varies from extreme heat when in direct sunlight to extreme cold when facing deep space. Even with the protection afforded by insulating blankets, the linear actuators must perform over a wide temperature range. In order to perform the delicate capture operation, the actuators must control their force output accurately. The NDS is able to accomplish this feat without the use of load sensing because of its highly efficient ball screws. As a result, the current feedback from the motors is able to provide a reliable indication of actuator force output.

The risk of collision between the chaser vehicle and the space station was another key technical challenge faced by the NDS designers. Because of the direct electric design of the soft capture system, a power loss or avionics failure during docking results in loss of ability to control vehicle relative motion. The high efficiency ball screw actuators present little resistance when unpowered, and therefore introduce the risk that the chaser vehicle could drift into the space station after a failure, with catastrophic consequences. To mitigate this risk, a redundant string of avionics was included in the NDS design, which can be activated in a time-critical failure scenario during docking. The redundant string is able to slow the vehicle’s motion enough to give it time to open the capture latches and perform a controlled abort, after which the docking can be reattempted. To protect against the unlikely event that both avionics strings fail during docking, a secondary capture latch release, independent of both avionics strings, was also included in the design. The secondary release uses a non-explosive separation mechanism that, while irreversible, is fast enough to separate the soft capture interface and allow the incoming vehicle to escape without collisions and return home safely.

System Performance

The Six Degree of Freedom (6DoF) test system at Johnson Space Center provides a sophisticated hardware-in-the-loop simulation of the docking event. As shown in **Error! Reference source not found.**, the target vehicle side is represented by a qualification-fidelity test article of the space station’s docking adapter, mounted to a motion table. The motion table is driven by a computer simulation of the relative motion of the two spacecraft in zero gravity. Although the active docking system test article is mounted to fixed structure in the test, the simulated motion of both vehicles is incorporated into the table’s motion. The 6DoF facility is able to introduce misalignments and off-axis rates to simulate the inaccuracies of the spacecraft GN&C systems.

Figure 8. NDS 6DoF Docking Test

In order to characterize the NDS capture performance in a statistically representative manner, the test cases were randomly distributed within limits that envelope the expected GN&C performance of the target and chaser vehicles. The initial contact condition limits are shown in Table 1. The simulated chaser vehicle masses were selected to bound the lightest and heaviest cargo and crew vehicles planned to dock to the space station (10 t and 18 t). At the outset of the NDS design, it was established that missed captures are acceptable in up to 1% of misalignment cases, provided that the system is capable of safely recovering for a second docking attempt. Despite this allowance, the NDS successfully captured all misalignment cases during the 6DoF test, while remaining within load and vehicle relative motion limits. For practical reasons, the 6DoF test was performed in the ambient air environment. As a result, the final verification of capture performance comes from an analysis that incorporates the temperature-dependent component data into a test-correlated computer simulation.

Table 1. NDSB1 Initial Contact Condition Limits

Initial Conditions	Limiting Value
Closing (axial) rate	3 to 6 cm/s
Lateral (radial) rate	up to 4 cm/s
Angular rate	up to 0.2 deg/s about closing axis up to 0.2 deg/s about any lateral axis
Lateral (radial) misalignment	up to 11 cm
Angular misalignment	up to 5 deg about closing axis up to 5 deg about any lateral axis

A test case used to validate the docking simulation was the case of an 18 t host vehicle docking to the ISS Node 2 Forward docking port with an approach velocity of 4.5 cm/s and a Yaw misalignment of -5 deg about the nadir axis. At initial contact the NDS is tilted towards Petal 1, located in the starboard direction of the chaser vehicle, as shown in Figure 9. Initial contact occurs between the capture latch on Petal 1 and the corresponding striker on the passive. Contact is detected when the SCS ring at the base of the petal contacts the passive SCS ring. Struts 1 and 2, which are attached to Petal 1, are then driven backwards during Lunge due to the contact at the SCS ring. During this time, the Lunge control law causes the other four SCS struts to extend and engage the latches on Petals 2 and 3. The time history of strut lengths is shown in Figure 10.

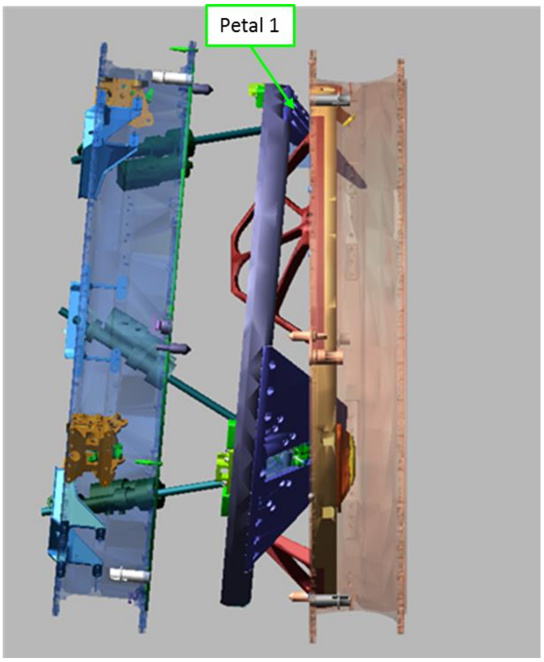


Figure 9. Initial Contact at -5 deg Yaw

After the capture sensors are activated, the SCS transitions into Attenuate, where the actuators counter the momentum of the chaser vehicle while limiting force output via current limiting. After the initial high load event in Attenuate, the motion of the chaser is essentially arrested, with only small motion remaining within the space between capture latches and the strikers. The measured and predicted motor currents for the -5 deg Yaw case are shown in Figure 11.

For the test program as a whole, the results showed good agreement with analytical predictions. The docking simulation parameters were adjusted based on test results to match the performance observed in the single-axis extreme misalignment cases. After completion of the model correlation activity, the results of the randomly distributed contact cases were compared to the model. The results of this comparison, shown in Figure 12, indicate good agreement between test results and predicted system performance.

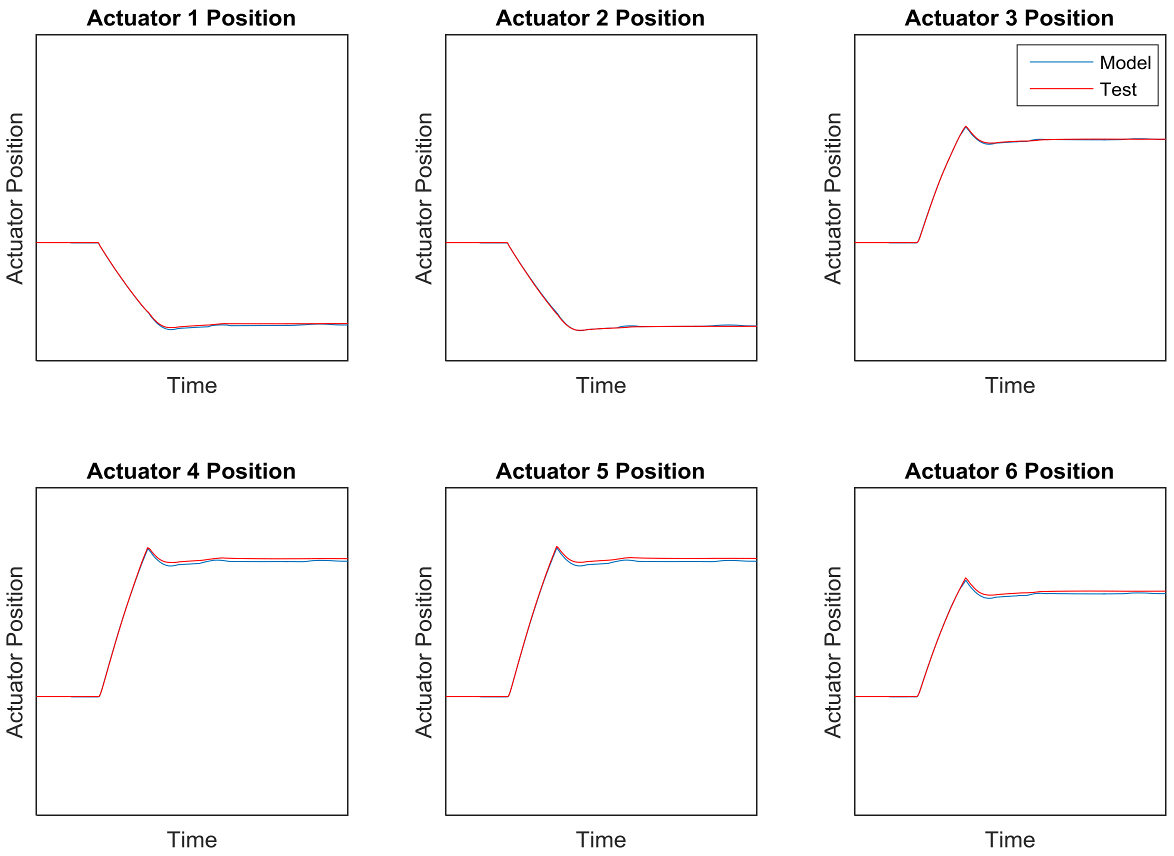


Figure 10. Linear Actuator lengths for 18 t Host Vehicle, -5 deg Yaw, 4.5 cm/s approach velocity

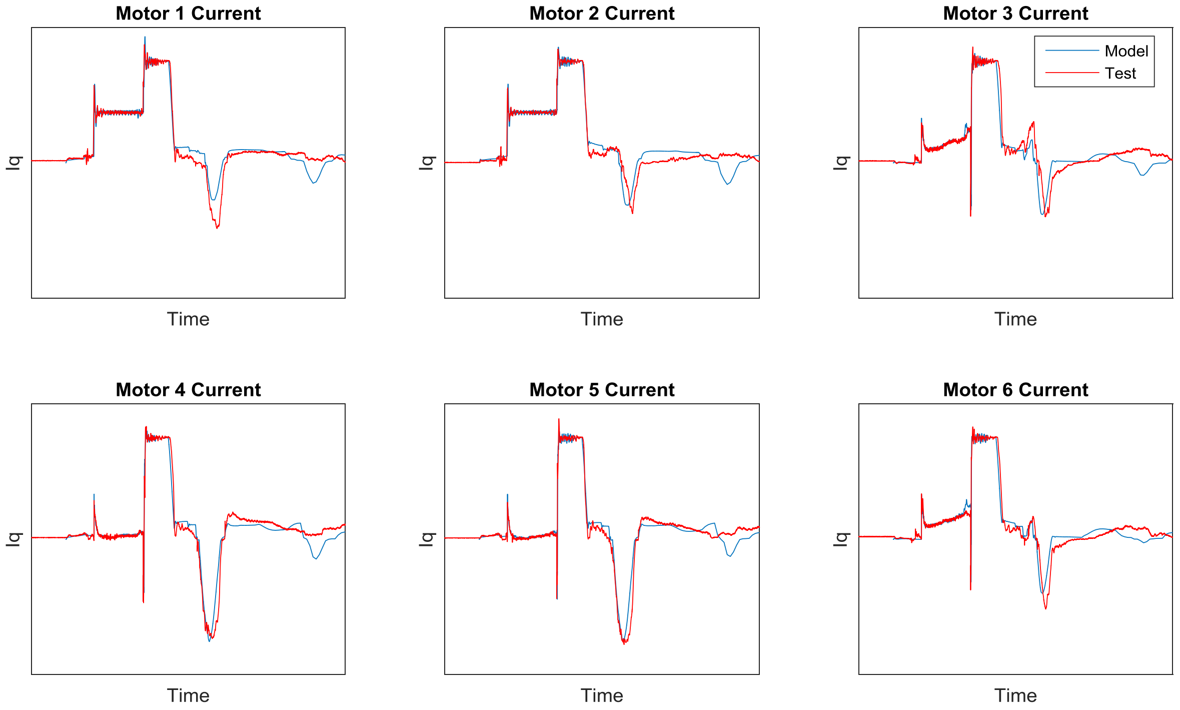


Figure 11. Linear Actuator Currents for 18 t Host Vehicle, 5 deg Yaw, 4.5 cm/s approach velocity

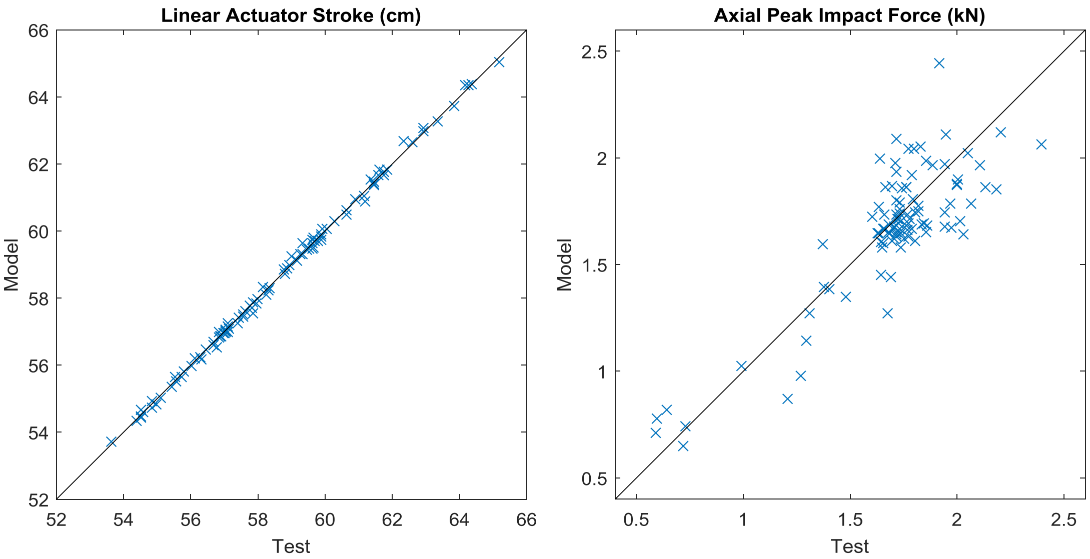


Figure 12. 6DoF Test Results

To demonstrate safety and robustness, the system was tested with a number of simulated failure conditions including missed captures, single string avionics failures, and failure of a single capture latch. In all cases, the system was able to recover safely either by bouncing off without collision or by safely terminating the docking attempt. To round out the test program, the flexibility of the system for other mission scenarios was demonstrated by adjusting the control law gains to optimize for lighter vehicles. With this alternate configuration, the system successfully docked a 15 t chaser vehicle to a 5 t payload with single-axis misalignments of 5 deg and 11 cm. The ability to support light vehicles is key to exploration missions that may involve docking a crew capsule to a Mars or Lunar surface lander or other small payload.

Lessons Learned during 6DoF Testing

Successful engagement of the soft capture latches is indicated by the activation of a set of capture sensors embedded in the active soft capture ring at the base of the coarse alignment petals. Each capture sensor is activated by a simple spring-plunger mechanism that is depressed by contact with the opposing soft capture ring. The arrangement of these sensors is shown in Figure 13.

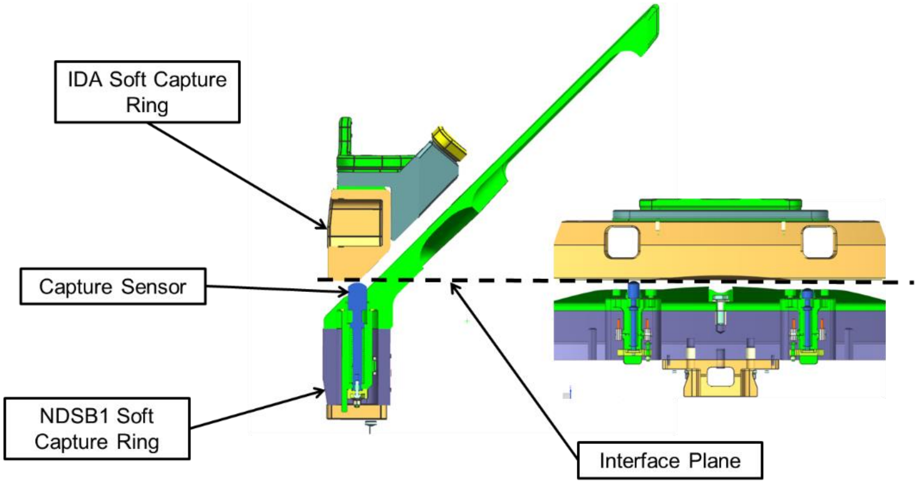


Figure 13. Soft Capture Sensors

Both the button and shaft of the capture sensor are coated with a polytetrafluoroethylene (PTFE) impregnated hard anodize. During development-level 6DoF testing in 2014, capture sensors began seizing intermittently after approximately 400 docking cycles. This condition prevented the capture latches from successfully engaging the strikers on the passive test article. The seizing was caused by damage to the anodize coating on the button and shaft wear surfaces of the capture sensor, due to repeated impact against the passive soft capture ring. Figure 14 below shows the condition of the capture sensor plunger and housing at the end of the development test program. In order to improve the durability of the capture sensor flight design, a grease lubricant was added to the wear surfaces of the capture sensor, with a plan to maintain the lubricant between flights. When qualification 6DoF testing of the modified design was completed in 2016, the unit completed 216 docking cycles with one re-lubrication midway through the test matrix. The lubricated sensors showed no visible signs of wear on the anodize coating or opposing ring contact area, indicating that the grease lubricant was effective at mitigating damage to these surfaces.

Figure 14. Capture sensor and opposing ring wear pattern during development testing

A key design decision that was validated during 6DoF testing was actuator optimization. The selection of actuator type and careful design of actuator components were important in optimizing the responsiveness of the soft capture system. Because system requirements allowed enough time for the docking vehicles to be slowly maneuvered into position, relatively little force output was needed from the linear actuators. As a result, the need for aggressive gearing was avoided.

Due to the fidelity compromises in the engineering development unit (EDU) used for the first round of 6DoF testing, the linear actuators were less optimized than the flight design. The capture sensors on the passive space station side of the docking interface (similar to those on the active side) were also omitted. The second round of 6DoF testing used a high-fidelity qualification test article for both the active and passive halves of the docking system. In the qualification 6DoF test, the linear actuator‘s design fidelity was increased, and the passive side capture sensors were included. The optimized actuator design reduced the impact energy between the soft capture rings at the instant of capture, while the addition of the passive-side capture sensors helped further cushion the impact. The net effect of these changes is evident in the axial docking loads measured by the 6DoF facility load cells that were mounted underneath the passive test article. Figure 15 compares the axial docking loads for the EDU and Qualification 6DoF tests for the case of an 18 t chaser vehicle docking to the ISS forward docking adapter, with a 5 deg Roll offset between the two mechanisms at the instant of contact, and a 4.5 cm/sec approach velocity. The results indicate a significant reduction in peak axial force at the moment of capture.

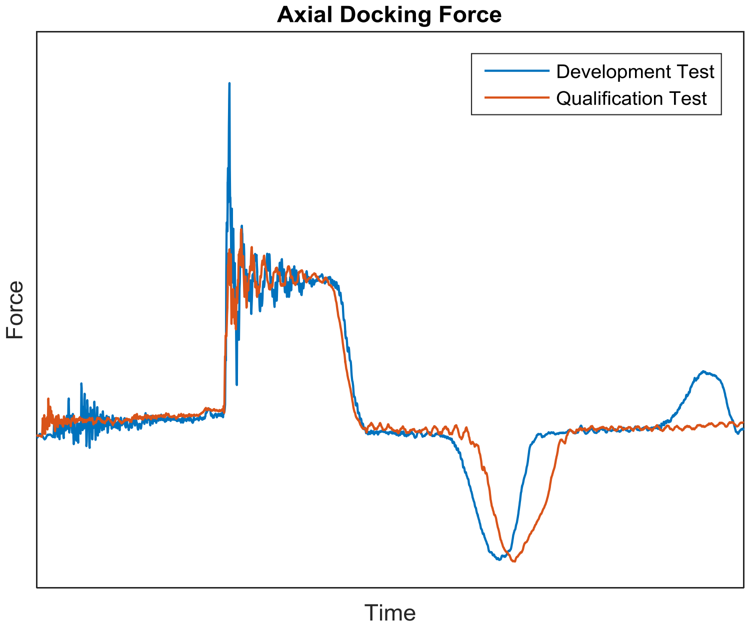


Figure 15. Axial docking force from 6DoF testing of an 18 t chaser vehicle with ISS with a 5 deg Roll misalignment

The results of the 6DoF testing validated the SCS design approach. The use of optimized linear actuators allows the SCS to control its motion and limit interface loads without the need for force feedback. As demonstrated by component-level thermal testing of the linear actuators, this capability extends over the expected range of on-orbit thermal environments. Furthermore, the design is extensible to a variety of target and chaser vehicle mass properties through adjustment of control law parameters.

Conclusion

The NDS is NASA's first docking system since the Apollo-Soyuz Test Project of the 1970's, and the first implementation of the new International Docking System Standard. Its direct electrical architecture leverages modern technology to greatly reduce mechanical complexity compared to the heritage APAS design used for the space shuttle. Its innovative controls approach eliminates the need for post contact thrusting to effect capture, reducing operational complexity for vehicle providers, flight controllers and crew. Its flexible architecture allows for controller settings to be adjusted either on the ground or in flight in order to capture target vehicles ranging from small 5 t landers to the 450 t International Space Station. Importantly, it also provides a robust capability to recover safely from a wide variety of failure scenarios. As a key enabler of modular mission architectures, NDS will be critical to making NASA's vision for space exploration a reality.

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