Docking System Mechanism Utilized on Orbital Express Program

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Abstract

Autonomous docking operations are a critical aspect of unmanned satellite servicing missions. Tender spacecraft must be able to approach the client spacecraft, maneuver into position, and then attach to facilitate the transfer of fuel, power, replacement parts, etc.

The philosophical approach to the docking system design is intimately linked to the overall servicing mission. The docking system functionality must be compatible with the maneuvering capabilities of both of the spacecraft involved. This paper describes significant features and functionality of the docking system that was eventually chosen for the Orbital Express (OE) mission. Key analysis efforts, which included extensive dynamic modeling, are also described. Zero-g simulation tests were performed to validate the dynamic analyses.

The docking system was flown and operated on the Orbital Express mission. The system performed as intended and has contributed to demonstrating the feasibility of autonomous docking and un-docking of independent spacecraft.

Introduction

Once on orbit, typical spacecraft have limited lives. The harsh environment and lack of access make any type of external support or maintenance nearly impossible. Anything from simply running out of fuel to failure of a significant component can end the life of an otherwise useful spacecraft. If some type of servicing capability were possible, flight operators could potentially get more out of their flight systems.

While limited servicing capability has been available through the Space Transportation System, or Shuttle, high cost has limited its use to very expensive systems within the Shuttle’s orbital reach, notably the Hubble Space Telescope. Over the past decade there has been a push to develop the capability of autonomous servicing of orbiting spacecraft. The intent is to create autonomous, un-manned, tender spacecraft that might provide services such as spare propellant, or new or replacement parts to already orbiting client spacecraft.

Several practical needs can be met through autonomous servicing

• Extension of the life of spacecraft due to propellant replenishment
• Replacement of components that are obsolete or have failed
• Capture and move spacecraft to more effective orbit
• Recovery of a spacecraft with a failed deployment by assisting deployment
• Examination of a spacecraft to determine cause of failure

The company began working on a docking mechanism concept and prototype docking system on an Air Force Research Laboratory (AFRL) Small Business Innovative Research (SBIR) program in 1999. As the docking mechanism design matured, the Orbital Express program was developing requirements for docking hardware. These eventually converged and our docking system was chosen for the flight demonstration.

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Docking Mechanism Evolution

Initial Prototype Docking Mechanism
Beginning in 1999, SRC undertook a design effort to develop autonomous soft docking. The project began with a Phase I SBIR grant from AFRL, who provided bounding conditions to the problem that included an estimated spacecraft size and mass (a cylinder, 50-cm OD x 130-cm L, 50 kg) and a requirement to dock two small microsat spacecraft and transfer fluid and/or electrical data between them. Yet, definition of the various needs that might arise when servicing obsolete or exhausted spacecraft had to be formulated. A key challenge became one of both establishing concept requirements as well as designing to address those requirements.

Evaluation of existing designs revealed a myriad of related technology. Most available technology related to extra-vehicular activity (EVA) interfaces, robotic boom end-effector configurations, or impact docking mechanisms. Much of this technology, by nature, required manned intervention. Most of these systems were primarily intended for large spacecraft and impact docking applications, and were not well suited for the more precise requirements of autonomous soft docking and alignment of fluid and electrical couplings. A critical component in identifying design requirements involved defining the eventual use and application of the intended mechanical docking system. Further research did not yield any definitive mission scenarios, but did present general ideas regarding potential applications. Two mission scenarios were conceived:

Client (on-orbit spacecraft needing service) / microsat (spacecraft servicing the client): A microsat could be launched on an as-needed basis to directly service an orbiting client. This would provide very specific refurbishment based on the individual needs of the client. Response time would include arranging a specific launch for the re-supply microsat.

Various client satellites and a microsat base station (both on-orbit): The client calls on the microsat base as needed. This could provide faster service, but would be limited to common, more generic types of refurbishment or repair.

In either of these scenarios, the tender would need to approach the client, match velocity and orientation, establish initial mechanical contact, pull together to rigidize, establish electrical contact, and finally, the pair must fly together as a single unit while docked.

Prototype Trade Studies
In parallel with organizing general mission requirements, the design team looked at many different methods of joining, grappling, and aligning. Four techniques that seemed reasonable with respect to a plausible flight control approach were traded in more detail:

1. “Harpoon”
2. A telescoping probe
3. Impact docking with a large conical guide
4. “Claw-type” linkages interfacing with a trefoil

The harpoon configuration, in which a probe is launched at a target, latches on, and is reeled back into guide features, seemed unpredictable and presented complications concerning the alignment of fluid and electrical couplings. A telescoping probe, where a telescoping pole extends to the mating spacecraft, engages a target feature, and retracts to join the two, turned into a complicated multi-mechanism apparatus not well suited for the direction and vision taking form. Impact docking was eliminated as an option because soft docking seemed safer for the two spacecraft and better suited to precisely align fluid and electrical couplings and prevent potential damage of components.

After extensive evaluation, SRC selected a three arm grapple design (Figure 1). The design would consist of two main subassemblies: an active mechanism and a passive structure. The active mechanism would consist of a motor driven lead screw that would actuate three individual linkages. The linkages would engage the passive structure, whose geometry would allow it to be constrained by the linkages. Further retraction of the linkages would seat the passive structure into a three point kinematic mount,
establishing a rigid interface. Release of the structure would be achieved by reversing these steps, with separation velocity provided by the spring loaded kinematic mounts. Construction on the prototype developed under the Phase I SBIR was completed in the early part of 2000. Figure 2 shows a picture of the completed design.

![Figure 1: SRC grappling concept](image1.png)  
![Figure 2: SRC prototype](image2.png)

**Prototype Testing**
Beginning in early 2000, SRC began extensive testing on the prototype hardware in order to evaluate its effectiveness and limitations. The test program included two significant components:

- **In-house off-load testing**: An off-load fixture was designed and manufactured to assist in understanding various dynamics of docking as well as to prove system ability to dock and transfer cryogenic fluids (LN2).
- **Micro-gravity flight**: A test plan was developed and executed to test the prototype in a micro-gravity environment.

**Counter Balanced Off-load Testing**
In order to gain a general understanding of the docking system dynamics, a test was constructed using a simulated inertia mass and cable/pulley system. Figure 3 shows the system with the prototype mounted in the lower left hand corner. The passive side was mounted to an adjustable tip/tilt fixture allowing tests to be performed in various misalignment configurations. Adjustment of the cable attachment point (universal joint) and offload weights provided an approximation of a zero-g environment. During development, more than 200 mechanical mate/de-mate cycles were successfully completed.
Micro-gravity Testing
The second component of testing included a flight on NASA’s modified KC-135 aircraft flown from Ellington Field near Johnson Spaceflight Center (JSC), Houston (Figure 4). The experiments focused on the grappling and capture events that could be accomplished within the 25-second micro-g window each parabola. The experiment was designed to have two separate, free-floating simulators that represent the relative mass and inertia of a client and a servicing satellite (approximately 2:1, client to servicing). The active and passive halves of the prototypes were each mounted to their respective mass/inertia simulator. With JSC crew assistance, the two halves were positioned within capture range. The active docking mechanism was immediately powered in an attempt to demonstrate “zero” gravity docking. Because of the limited time in micro-gravity, consecutive phases of the docking sequence were performed throughout a series of parabolas. Despite these limitations, the micro-gravity tests proved instrumental in demonstrating the mechanism behavior. The basic functionality of the docking system was demonstrated. Observations of dynamic behavior during the test led to improvements of the design prior to the next prototype build.

Development of 2nd Prototype and Orbital Express Flight Design
The OE program was intended to develop an industry-wide standard architecture to perform cost effective autonomous satellite servicing. To demonstrate the technology, OE planned to use two spacecraft: the client vehicle, referred to as NEXTSat, and the servicing vehicle, referred to as ASTRO. An illustration of the OE vehicles is shown in Figure 5. The demonstration mission launched both vehicles together and performed a series of mating and servicing operations on-orbit.

Orbital Express and the Phase II SBIR
A major criterion for autonomous docking success is the reliability of the capture system. SRC already had developed and tested a functional prototype, and the capture requirements were well suited to the SRC design. OE was still in the proposal stage and the design of the mechanical docking system (MDS) [this was the second generation prototype/engineering unit] was proceeding under AFRL funding. It therefore became necessary to balance the design objectives of OE within the practical limits of the SBIR scope. At the onset of the MDS design effort, SRC worked closely with Boeing, who was providing much of the initial insight into the technical requirements.
Significant Changes from Initial Prototype

Mechanism Capture Capability
During the initial prototype design, a clear definition regarding the capture capability envelope did not exist. In light of the emerging requirements, the prototype capability was not sufficient to meet the requirements of the OE program. Therefore, the capture capability would need to increase in order to accommodate the precision of the guidance and navigation controls. The required capture capability would be achieved from scaling up the design, with minimum impact to the overall mechanism configuration. In short, the mechanism size and stroke were increased to create a much larger “capture zone”.

Mechanism Structural Capacity
The initial prototype had also been developed for use with a microsat, and its structural capability was not suited for large vehicle payloads. Thought was given to refining the load paths in order to handle the increased strength and stiffness requirements. The drive train also needed to be enhanced in order to achieve the necessary mated interface stiffness. As a starting point, it was decided that the capacity would be designed to accommodate the largest operational vehicle payloads encompassed in the scope of the OE program.

Mechanical Docking System (MDS)
From a functional standpoint, the design that emerged looked very much like a scaled-up version of the original hardware. The design had nearly doubled with respect to the prototype. However, the design had not only grown in size, but had matured in complexity to accommodate its enhanced capabilities, both internally and externally. Figure 6 displays the second generation prototype hardware, officially designated MDS. The requirements that encompassed the design effort are displayed in Table 1.

MDS Testing

In-house Development Testing
SRC completed in-house testing of the MDS design that contributed additional information for the parallel effort of the OE flight unit design. In house testing included stiffness characterization, off-load testing, and mated interface load. All tests performed proved the MDS unit design accomplished the main goals of the program.

Computer Simulation
Latch arm stiffness measurement was one of the several tasks undertaken on the MDS hardware. The lateral and radial stiffness of the linkage assemblies had been measured in both the deployed and captured position. By considering these measured stiffness values together with analysis of dynamic
simulation results, higher fidelity results and conclusions were produced. Dynamic Analysis and Design System (DADS) software was used to model the capture and retraction features of the MDS. The model included complete mass properties of two satellites, a zero gravity environment, and contacting features of the MDS.

In excess of 400 cases were simulated to explore performance issues using a uniform distribution of initial condition parameters. The analysis concluded that the mechanism was always capable of positive captures given reasonable limits of relative initial test conditions.

![Figure 6: MDS, second generation prototype](image)

**Table 1: MDS Phase II Design Requirements**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Capture Distance:</td>
<td>15 cm</td>
</tr>
<tr>
<td>Angular Capture Misalignment Tolerance</td>
<td>±5 degrees</td>
</tr>
<tr>
<td>Pitch/Yaw Roll</td>
<td>±5 degrees</td>
</tr>
<tr>
<td>Lateral Misalignment Tolerance:</td>
<td>±5 cm</td>
</tr>
<tr>
<td>Linear Contact Velocity Tolerance:</td>
<td>3 cm/s</td>
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<td>Preload:</td>
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<tr>
<td>Capture Time:</td>
<td>&lt; 10 s</td>
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<tr>
<td>Capture and Latch Time:</td>
<td>&lt; 240 s</td>
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<tr>
<td>Interface Outer Diameter:</td>
<td>&lt; 46 cm</td>
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<tr>
<td>Active Side Mass:</td>
<td>&lt; 23 kg</td>
</tr>
<tr>
<td>Passive Side Mass:</td>
<td>&lt; 11.5 kg</td>
</tr>
</tbody>
</table>

**6 Degree of Freedom (6 DOF) Tests**
The main goals of these tests were to correlate/verify the dynamics analysis model and to demonstrate functionality and performance of the hardware in a flight-like environment. 6-DOF testing was performed with the test equipment as shown in Figure 7. The test simulated full, relative six degrees of freedom with the actual hardware in the loop. During testing the active half of the hardware was mounted to a moveable platform supported by six hydraulic actuators. The passive half was mounted above the active half at a fixed location with a force/moment sensor in the load path. Software commanded the six legs to...
start the test at a user-specified set of relative initial conditions between the active and passive halves. Once the test was started, software simulated the complete relative dynamics of the two vehicles due to the real contact between the active and passive halves during the capture sequence. The test results were then compared to the dynamic model simulation predictions. Comparison of the test data confirmed the model accurately depicted the capture dynamics. The information gained from the MDS tests was critical to the flight design effort.

![Figure 7: 6-DOF testing facilities at MSFC](image)

Docking System Mechanism Description

Following are more detailed descriptions of some of the significant features of the docking mechanism final design as it was flown on the Orbital Express program.

![Figure 8: Docking system major components and schematic layout, as configured for Orbital Express](image)
Orbital Express Capture System (OECS)

The capture system consists of an active side and a passive side. The active side contains the grappling arms and the drive system; this side would normally be part of the supply spacecraft. The passive side provides capture features and a sensor to indicate proper engagement of the grappling arms; this side would normally be a part of the client spacecraft. Figure 8 shows a general schematic of the system configuration.

Capture Sequence
To understand the OECS unit, a description of its functionality is necessary. Figure 9 displays the typical steps involved in a capture operation.

1. The linkages of the active mechanism begin in a deployed (open) state. The passive structure is held in a station keeping envelope within the capture capability of the active mechanism.

2. Upon receipt of command, the motor begins to actuate a ball screw which translates an internal piston along the length of the active mechanism canister. The piston moves three separate four-bar linkages that make up the grappling linkages. The linkages then move downward over a roller feature. The camming action of the roller causes the linkages to constrict, engaging the passive structure. The wedge shaped architecture of the passive structure guides the tips of the linkages into center grooves. Capture is achieved as the passive structure is constrained within the bounds of the linkages.

3. As the linkage tips move down along the grooves, they engage a shelf feature, allowing the active and passive structures to be drawn together. As retraction proceeds, alignment occurs in stages. Continued motion of the linkages causes the interface plate of the passive structure to contact push-off rod struts that act as a three point alignment mount on the active mechanism. The alignment features each consist of a spring loaded pin with conical ends that seat into tapered cups on the passive structure. These features provide a gross alignment. With further retraction, additional features align the electrical couplers within their allowable tolerance.

4. At the final stages of retraction, the passive structure becomes fully constrained by a final set of cup/cone features. Rigidization then occurs as the motor applies the necessary preload to provide the required interface stiffness.

Figure 9: Orbital Express Capture Mechanism Capture Sequence
Active Mechanism
The Active mechanism is composed of a top plate assembly to which the canister assembly is attached (Figure 10). Within the canister assembly is a drive train consisting of a motor, ball screw, and radial/thrust bearings which transfer load into the housing. All three linkages are fixed to a piston, which is connected to a ball screw via a ball screw nut. The linkages consist of one upper grappling linkage and two lower linkages which make up a four bar connection. Mounted to the canister is a reaction roller that guides the linkages through deployment. Alignment occurs via two separate features: push-off rods, and alignment pins. The three push-off rods are spring loaded features that seat into alignment cups on the passive end to provide gross alignment. The cone mounts are hard mounted features that also seat into cup features on the passive side. This geometry provides a statically determinate final position after mate.

Passive Damping
The need for passive damping was identified during simulation and prototype testing. Concerns had been raised regarding difficulties that could arise during capture; specifically, the passive half impacting the push-off mount and rebounding. While it was agreed that the passive side would need to be held within a station keeping envelope during capture, a non-zero relative velocity would likely exist between the two spacecraft. This could result in slight amounts of contact between the two faces of the active and passive halves, making it difficult to maintain the passive structure in the required envelope. Also of great concern was unintentional impact involving even larger than nominal velocity deltas, and the possibility of damage to the mechanism.

Another motivation to introducing damping involved oscillations occurring during the capture event. Testing of the prototype in a micro-g environment exhibited a tendency for the passive structure to oscillate within the constraints of the linkage tips and the push-off mounts. Computer simulations performed by Boeing confirmed this behavior. In order to address this issue, a spring damper system was added to the push-off struts on the active mechanism. Figure 11 depicts a cross section view of the push-off mounts with the spring damper system.
Torque Sensing Mechanism
Running the motor/actuator until proper preload is achieved was accomplished using a torque sensing mechanism (Figure 12). To apply a preload in the mated position, a specific torque from the motor is required. The torque sensing mechanism is adjusted to activate limit switches at the set torque needed for proper preload. Once the limit switches are activated, the motor is commanded to stop. In the stop mode, the motor/actuator applies a brake holding the preload developed.

Passive Assembly
The passive assembly (Figure 13) is a three wedge shaped trefoil. The faces of each wedge terminate at a center groove that runs along its length. The passive interface consists of an interface plate that is mounted to the three trefoils. Part of this geometry includes retention lips, or shelves, which provide the linkage with a positive feature to grapple. The interface also includes kinematic cup features which help to align the structure and institute preload. The OE program required a sensor to confirm that capture had been successfully accomplished (Figure 9, step 2). Light Emitting diodes (LED’s) located on the passive assembly detect when the active assembly arms are in the captured position (Figure 14)
Figure 12: Torque sensing mechanism

Figure 13: Passive assembly
OECS Flight Unit Testing

**Acceptance Testing**
Based on the experience gained with the two prototypes, SRC developed and performed comprehensive acceptance test program. In-house testing included many of the same elements that were present in the prototype and MDS testing: mate and de-mate verification, stiffness characterization, and off-load testing. In addition, thermal, thermal vacuum, and vibration testing were performed.

**Computer Simulation**
Dynamic models were updated to include all modifications incorporated after development. Significant load cases were analyzed to verify that mechanism performance met the Orbital Express requirements. The same software and methodology were used as for the development unit design effort.

**6 DOF Testing**
The final phase of qualification and flight testing included 6-DOF testing similar to that which was performed on the MDS. Although the MDS and OECS mechanism features important for capture and alignment are almost identical, small changes were made to the design based on the results of 6 DOF testing of the MDS. Furthermore, the manufacturing fidelity of the OECS qualification components was flight-identical, unlike the MDS which was of engineering development unit quality. For these two main reasons, a second 6-DOF test of the qualification unit was performed. The goal was to once again confirm that the dynamic modeling accurately depicted the dynamics encountered during capture and alignment.
For the Orbital Express mission, the two spacecraft were launched attached together with an adapter coupling ring. The OECS docking mechanism was engaged in a unique, preloaded condition for launch, but was not the primary load path for support of launch loads for NEXTSat. After system checkout and stabilization, the robotic arm was used to attach the two spacecraft together. Prior to free flight operations, the robotic arm was used as a safety measure to keep the two spacecraft connected while the adapter coupling ring was released and jettisoned. The first docking operation was performed by moving the spacecraft with the robotic arm (the two spacecraft were already de-mated and were held together by the arm) and operating the OECS docking mechanism. This operation was successfully performed and confirmed that further docking operations could be performed. After proving out a “captured” docking operation several distinct free flying docking operations were performed. In each case the separation of the spacecraft, the proximity flying, and the subsequent re-docking were performed autonomously by the two spacecraft without ground control intervention.

While docked, key refurbishment operations were performed:
- The electrical connections were utilized for direct communication and electrical power transfer between the spacecraft.
- The fluid connector was engaged and transfer of propellant was successfully performed.
- The robotic arm was utilized to install an electronics box on a mating port on the NEXTSat spacecraft.

Overall, all mission goals were successfully completed. The two spacecraft have since been decommissioned.
Conclusions

The OECS flight mechanism performed as expected and has supported demonstration of the effectiveness of the soft docking approach enabled by the design. The blending of technology and vision yielded a simple and effective concept. Through a series of design trades and system testing, the application of minimal mechanisms, and the use of common proven technology (i.e. motors, lead screws, and linkages), a highly functional design resulted. What began, during the primary phase, as a well developed concept quickly evolved into a commercially viable product.

References


2. DARPA website http://www.darpa.mil/orbitalexpress/