Design, Development, and Test of the Advanced Apollo Orbital Assembly System

Marc Jarmulowicz*, and Aaron Miller**

Abstract

As spaceflight moves toward commercial solutions for Crew Vehicles and Space Stations, opportunity exists to lower costs with novel designs. Probe and cone docking systems provide a lightweight, low cost, and high-performance docking solution. This work revisits the Apollo probe and cone design and modifies it for the requirements of today's computer-controlled spacecraft. This new system is called the Advanced Apollo Orbital Assembly (APOA) system, and is intended to support satellite, cargo, and space station assembly missions. A simulation of the APOA was programmed, components were sized, and a design was created by scaling the probe to the size of an EELV Secondary Payload Adapter (ESPA) tunnel. Prototype test hardware was 3D printed using Fused Deposition Modeling (FDM) methods with Polylactic Acid (PLA) material. Testing of the APOA-ESPA was conducted at Marshall Space Flight Center's (MSFC) Flat Floor, and a test-correlated simulation is used to evaluate a Monte-Carlo of Initial Contact Conditions (ICC's) to establish baseline performance. The successful development, test, and correlation of the APOA-ESPA proves the design validity and increases Technology Readiness Level (TRL) from 2 to 4. This work opens the door to construction of an APOA-ESPA from flight like materials, and to develop a larger scale prototype APOA. When the full scale APOA is incorporated with the Common Berthing Mechanism (CBM), becomes the Hybrid Berthing System (HBS), which allows for berthing without a robotic arm.

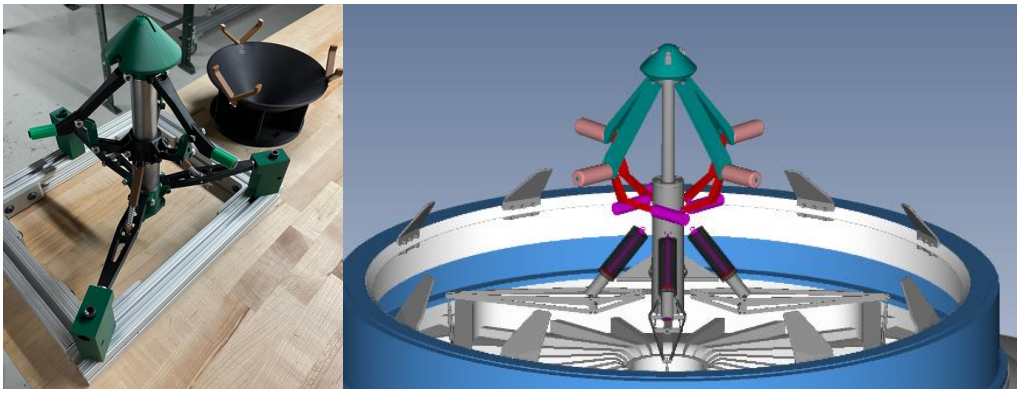


Figure 1. APOA-ESPA (Left), APOA-HBS (Right)

Introduction

There are many advantages to using a probe and cone for docking, berthing, or orbital assembly. Probes can have better capture performance than peripheral International Docking System Standard (IDSS) mechanisms due to their natural inclination to be stiffer axially rather than laterally. In addition, they have a lower mass and can have reduced cost due to the smaller size of high tolerance parts. For the Probe, the highest tolerance parts are limited to the probe head and capture latch system, as opposed to the entire ring/petal structure of a peripheral system.

A key characteristic of the APOA is that it can be scaled in size to accommodate different mass properties, Hard-Capture Systems (HCS), and tunnel diameters. For instance, the APOA is intended to be combined

* Dynamic Concepts LLC, an Astion subsidiary, Huntsville, AL; marc.jarmulowicz@astrion.us

** Marshall Space Flight Center, Huntsville, AL; don.a.miller@nasa.gov

with the CBM to create the HBS, which allows for CBM ports to be berthed without the assistance of a robotic arm. For the purposes of design, development, and testing using NASA/MSFC Technology and Innovation Development (TID) funding, the APOA was scaled down to fit inside of a 15 inch ESPA Tunnel, with mass properties suitable for satellite assembly or refueling.

Description

The APOA system consists of a soft capture probe that is based loosely on the Apollo probe. A diagram of the system, sized for an ESPA tunnel, is shown in Figure 2. The APOA has two major changes from the Apollo probe: the first is a dramatic decrease in bending stiffness about the probe base, and the second is a modification of the Pitch Arms to become Pitch-Roll Arms.

The Apollo probe had a load relief system for bending moments, called the Shock Strut or Strut Assembly, which was fitted with a Bellevue washer stack. The APOA replaces the Shock Strut with a spring/damper attenuator which tunes the bending stiffness of the probe to the Pitch and Yaw Moment of Inertia of the vehicles. From the development of the Apollo probe [1], there is a note that "… [Manned Spacecraft Center] tests showed that a relatively flexible or pivotable probe was superior". This was the basis for the work in [2], which evaluated reducing the stiffness of the Apollo Probe's Shock Strut to improve capture performance. Note that the APOA replaces the central gas piston of Apollo with a rigid acme screw that enables retraction.

There is a nuance to this design which is critical: a pure kinematic constraint of a cylindrical joint connection between Support Arms and HCS, will result in mechanism "lock up" as it is over constrained. To overcome this constraint, there is a gap between the sphere and the cylinder as well as a controlled stiffness at this interface. This approach reduces the alignment accuracy of the probe, however high accuracy is not required. The philosophy of this design is that a multi-step alignment is used, requiring alignment features at the HCS interface, like the CBM's guide petals. Balancing the requirements for alignment between Soft and Hard Capture Systems results in a lighter and less costly system overall.

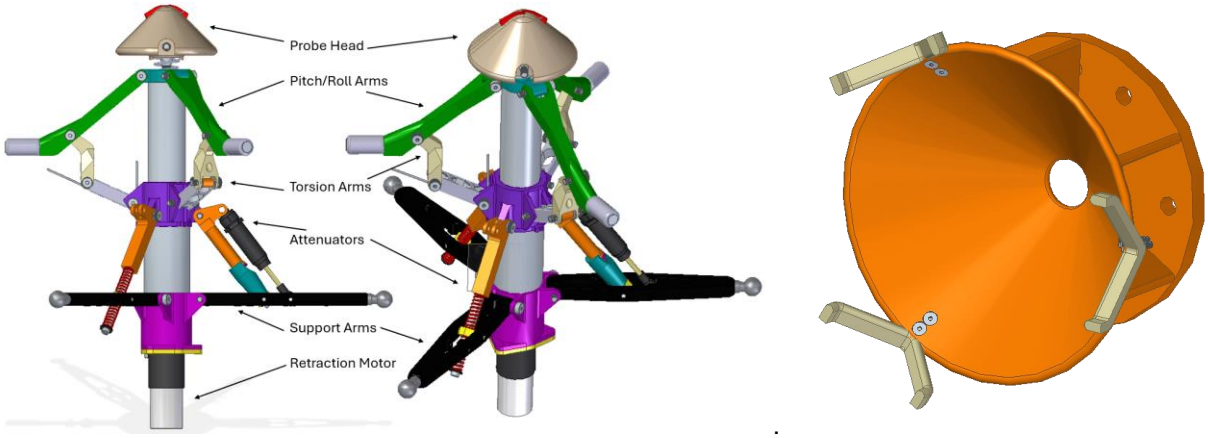


Figure 2. APOA-ESPA Diagram

To align in roll, Apollo's Pitch Arms were modified to be Pitch-Roll Arms with the introduction of rollers onto the end of the Pitch Arms. The IDSS roll limit of 4 degrees was chosen as a design parameter to create reasonable corresponding notches in the Cone. With this geometry, Roll and Wobble result in defections of the Pitch-Roll Arms, which are reacted by preloaded torsion springs. At the scale of the APOA-ESPA it was not possible to add in a damper other than friction, however in larger scales it is intended that an explicit damper would be installed.

The APOA is intended to be a mostly passive system which requires minimal motors, software, and sensors. Passive spring/damper designs are significantly easier to certify than electronically controlled ones and have a similar, if lower, performance [3].

APOA-ESPA Design

The APOA-ESPA prototype was constructed from printed PLA parts bonded to metallic tubes and commercial off the shelf parts. This design choice was enabled by the low forces predicted in the docking simulation. Printed parts allowed for rapid design iteration. The APOA-ESPA is shown in Figure 3.

At this scale, the effects of friction can be much larger than at full-scale. Because of the friction, there was no need to use explicit dampers in the system. Dampers were designed for and were used in early testing, but the spring forces at this scale were too low to overcome damper seal stiction. For design simplicity, two springs were used to provide bi-directional tension and compression forces. There are other single-spring designs which can provide a better transition from tension to compression under preload, but the PLA printed designs had insufficient strength.



Figure 3. APOA-ESPA Construction

Simulation

A multi-body dynamics simulation of the APOA-ESPA mechanism was developed in support of the design and performance evaluation. The modeled elements include the soft-capture components such as the Probe Head, Pitch/Roll Arms, Attenuator Arm linkages and interfaces between Soft Capture System (SCS) and Hard Capture System (HCS). The simulation was generated in DCI's Light Architecture for Model-Based Dynamics Analysis and Simulation (LAMBDAS). This simulation is a C code written in Linux.

The APOA simulation was modified to support testing by incorporating the tested mass properties and features such as the Service Pad slope, drop mass used to accelerate the testbed, and Location Rod

Displacement. There was a logical lockout that did not transfer any out of plane forces like pitch or roll, since those forces are reacted by the Flat Floor.

The APOA mechanism simulation predicts the dynamics of all soft-capture modes of operation: pre-capture, capture, attenuate, and retract phases. The LAMBDAS-based simulations excel in large batch-run Monte Carlo simulations where variations of the ICC's or other parameters (like mechanical properties) can be evaluated for thousands of iterations.

Test

The APOA-ESPA was tested in conditions similar to orbital conditions, using the service pad section of MSFC's Flat Floor. The intention of this test was to provide load and displacement data to correlate the APOA simulation.

The APOA-ESPA testing did not follow a typical path for mechanism testing. Typically docking systems are tested and validated starting with the smallest components, like springs and dampers, moving up to sub-assemblies like integrated attenuators and linkages, kinematic testing of a complete system, and then finally dynamic testing of a complete system. The APOA-ESPA testing included an approximate kinematic test, and then dynamic testing of the complete system, doing no component testing. There was insufficient time to design and build component tests before system testing, and ideally component tests will be completed in follow on projects.

Test Description

The APOA-ESPA was tested using a fixed base, anchored to the floor as the Target, and a floating Chaser. Table 1 shows the mass properties of the Chaser. Figure 4 shows an image of the APOA-ESPA test hardware at MSFC's Flat Floor facility. To set the ICC for each test configuration, three Positioning Rods create a unique location and orientation. The Positioning Rods are set at the beginning of the test and then released simultaneously by three test workers.

Table 1. Testbed Mass Properties

Mass [kg]	AHcs wrt CG X [m]	Y [m]	Z [m]	Izz [kg-m2]
173	0.5	0	0	141

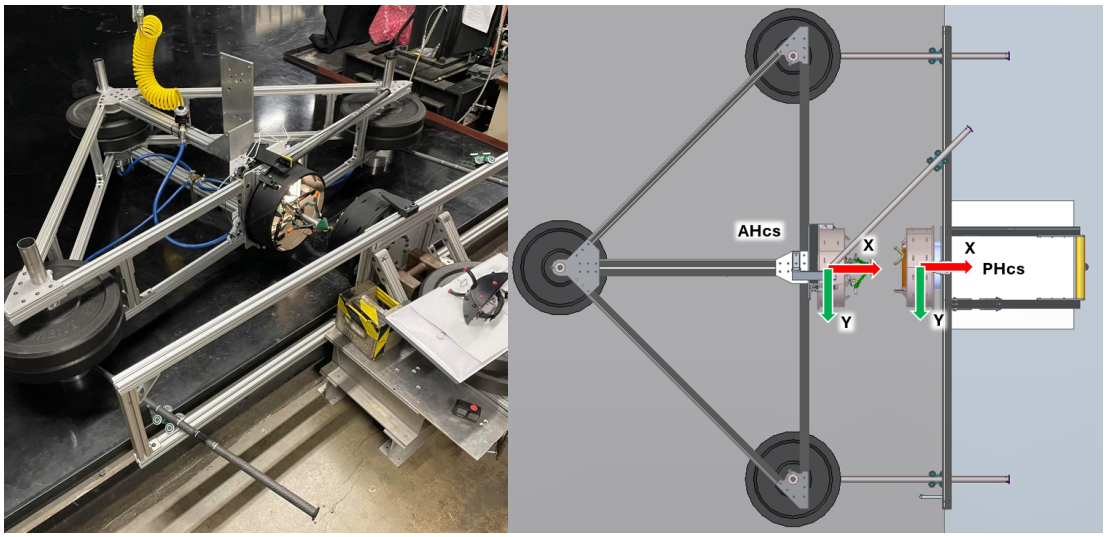


Figure 4. APOA-ESPA Mechanism in the MSFC Flat Floor Facility

Test Plan

The APOA-ESPA testing was planned to evaluate maximum limit cases for Lateral and Yaw motions. Other variables such as closing velocity and system mass were also considered for testing, but there was insufficient time to support testing these variables. Due to the nature of using three positioning rods, and positioning and releasing these rods by hand, only static translations and rotations could be set, no lateral velocities or angular rates were possible.

Test Matrix Overview

Hardware test conditions were separated into three Phases. Phase 0 consisted of three kinematic runs, in addition to nine test cases. The nine test cases were the same set used in Phase 1, but with a single person setting up the test orientation and location. This had the result of significant error in the ICC's, but provided data for debugging the test setup. Phase 1 had the nine test cases shown in Table 2 but had additional test support to provide higher accuracy ICC's. Phase 2 took the same ICC's as Phase 1, and added a 4 deg static roll to the Active HCS, which includes the probe and tunnel, for each of the nine cases.

Table 2. Test ICC's for Phase 1

Case	Case ID	Pitch [deg]	Yaw [deg]	Roll [deg]	Tx [mm]	Ty [mm]	Tz [mm]
Central Impact	1000	0	0	0	-366.6	0	0
+Y Lateral	1001	0	0	0	-366.6	35.36	0
-Y Lateral	1002	0	0	0	-366.6	-35.36	0
+Yaw	1003	0	4.0	0	-366.6	0	0
-Yaw	1004	0	-4.0	0	-366.6	0	0
Combo +Yaw / +Y Lateral	1005	0	4.0	0	-366.6	35.36	0
Combo -Yaw / +Y Lateral	1006	0	-4.0	0	-366.6	35.36	0
Combo +Yaw / -Y Lateral	1007	0	4.0	0	-366.6	-35.36	0
Combo -Yaw / -Y Lateral	1008	0	-4.0	0	-366.6	-35.36	0

Test Results

The Test Results were evaluated to verify that they were suitable for correlation with the simulation. Several interesting findings apply to this test program. Overall, the testing was successful, and the data is adequate, however better test data would result from: a higher resolution loadcell, testing on the standard location of the flat floor (not the service pad), a more accurate system for setting ICC's, and more accurate frame definitions.

Simulation to Test Correlation

In this section, an evaluation of the APOA-ESPA docking mechanism model is presented by comparing simulated responses to the corresponding hardware test responses. The simulation used the test trajectories as inputs up until first contact, then simulated dynamics took over the response. This allowed for the test ICC's to be less accurate, while increasing the accuracy of the simulation to the test conditions.

Simulation Tunings

There were several tunings that drove the simulation correlation. These tunings were to both the test facility and to the APOA-ESPA mechanism:

- The test facility tunings included:
  - A non-linear slope on the Flat Floor service pad
  - Changing the point of application of the slope thrust force to be aft of the CG
- The APOA-ESPA tunings included:
  - Adding a gravity force to the Probe to deflect it down
  - Adding friction to the attenuator force

- Modifying attenuator hardstop location and stiffness
- Modifying Pitch-Roll Arm initial angle
- Increasing the torsional stiffness of the Pitch-Roll Arm springs
- Adding in a friction model to the Ball and Cylinder interface between the SCS and HCS

Modeling of the slope of the service pad of the Flat Floor was more complex than originally anticipated. A non-linear slope was applied to the CG location as a thrust force. What was noticed is that in certain tests, the testbed would not return to center after docking, but it would stay at a constant Yaw angle. This could not be reproduced by applied force to the CG alone. The point of application of the thrust force had to be moved further back from the CG, and even then, the correlation was limited. Moving the point of application further back emulates an average force vector from all three bearings, indicating that the rear air bearing likely had more effect on the thrust than the other two forward bearings. What may be needed for a better correlation is a map of the floor height over the area of the service pad, allowing for individual calculations of force vector for each air bearing. Alternatively, using the flat part of the Flat Floor when there are no conflicts with other tests.

Kinematic / Phase 0 Loads

Kinematic tests are those which force the testbed to move in a cyclical motion, similar to a base drive. These tests are excellent for drawing out behaviors like slops and gaps which are critical to the mechanism, but are often very short duration during dynamics. The axial kinematic forces and moments are shown in Figure 5, and the axial force correlation is very good with exception to the lack of slop/gap in the transition from tension into compression. The off-axis peaks and moments are due to the attenuator hardstops.

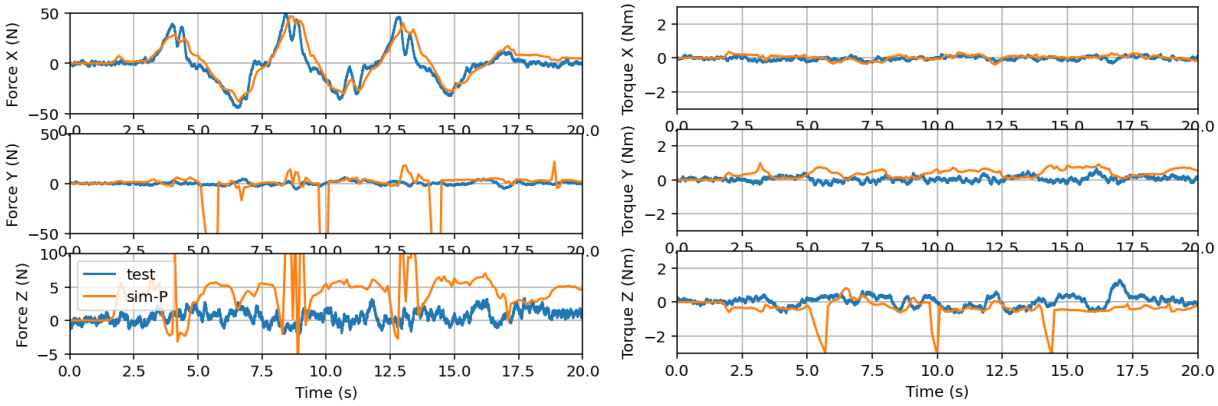


Figure 5. Run 0000 Force and Moment Time History

Figure 6 is the lateral kinematic motion, and for the initial motion the correlation is quite good, with the initial hardstop peak at 5 seconds being captured, and with excellent correlation in the moment about Z. However, despite using the measured testbed location to drive the simulation, there is some discrepancy which results in the attenuator hardstop engaging and overshooting the lateral loads.

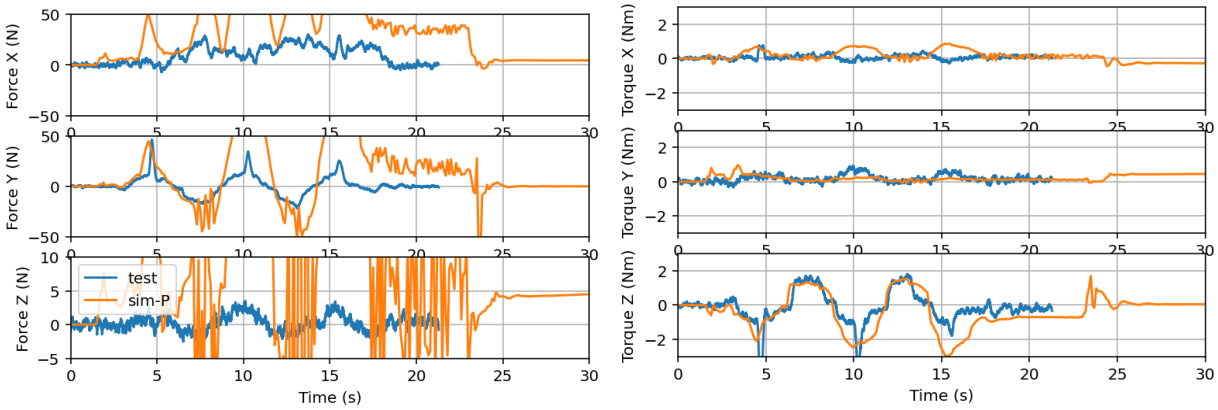


Figure 6. Run 0001 Force and Moment Time History

Phase 1 Loads

Comparing loads of the simulation and the test for Phase 1, the correlation is average. It is not clear why the central impact run 1000, shown in Figure 7, does not correlate better. There is some interaction with the attenuator hardstops, and that could be part of the case here, since a hardstop would help add the spike.

Figure 8 has a comparison of the forces and moments, for Run 1001, which is a Max Lateral along +Y. The correlation for this case is much improved, almost laying on top of the test data for the first 1.5 seconds of contact.

Run 1002 in Figure 9 is a Max Lateral in the -Y direction, and notably the Z moment has excellent correlation with several minor peaks and valleys aligning.

Runs 1003 and 1005 are shown in Figure 10 and Figure 11 respectively. They continue to highlight the trend that the more complex the ICC's, the better the correlation. It also reflects a trend in better correlation between simulation and test, when the CG of the testbed is on the -Y side, as happens when the Yaw orientation is positive.

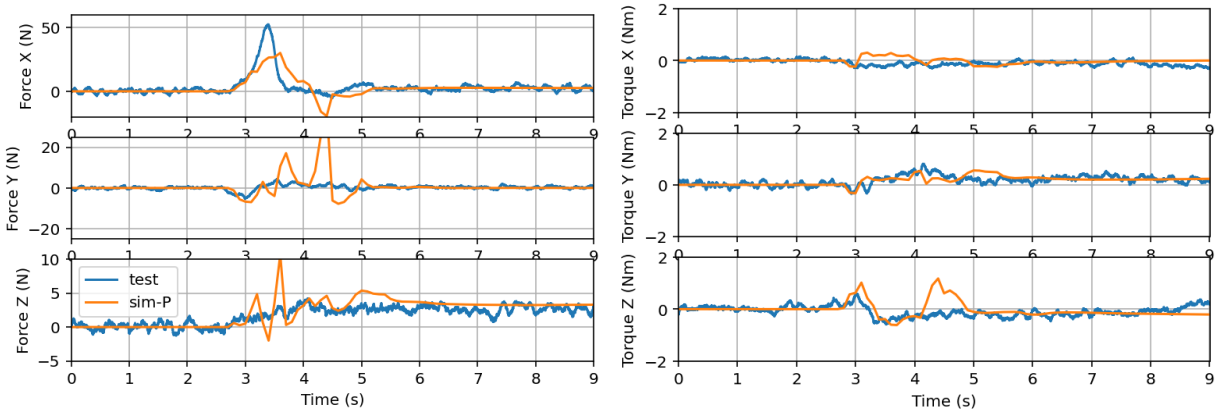


Figure 7. Run 1000 Force and Moment Time History

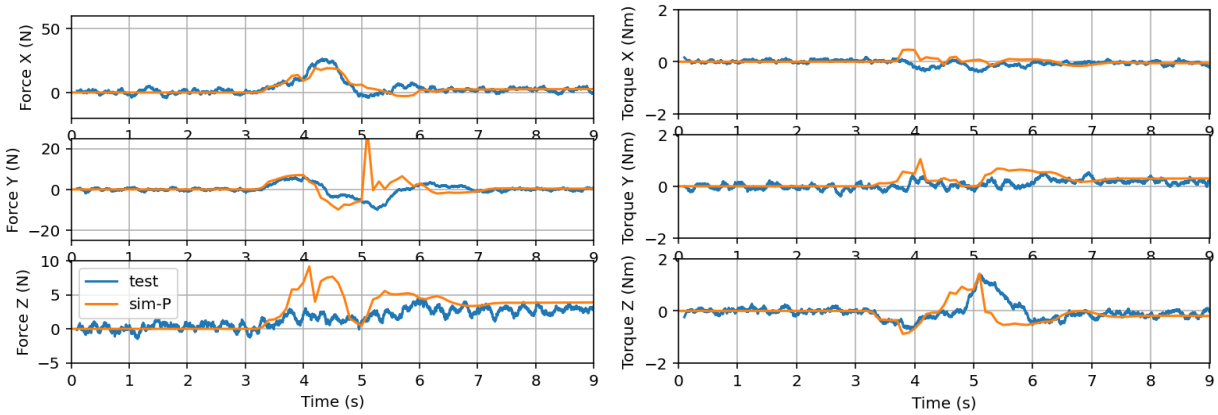


Figure 8. Run 1001 Force and Moment Time History

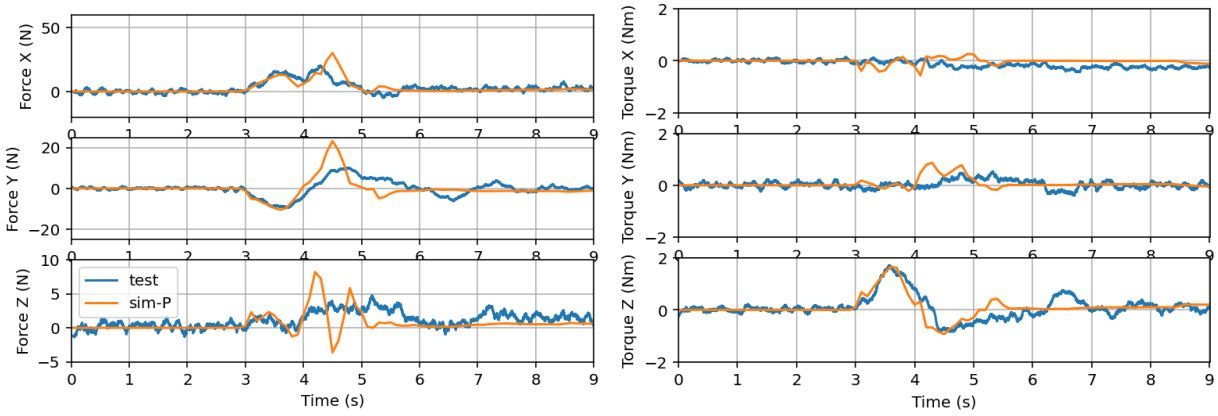


Figure 9. Run 1002 Force and Moment Time History

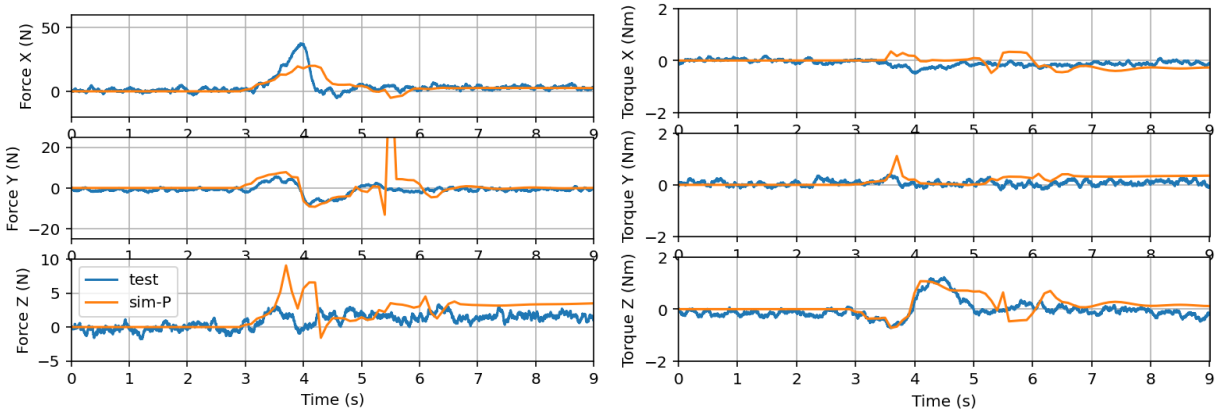


Figure 10. Run 1003 Force and Moment Time History

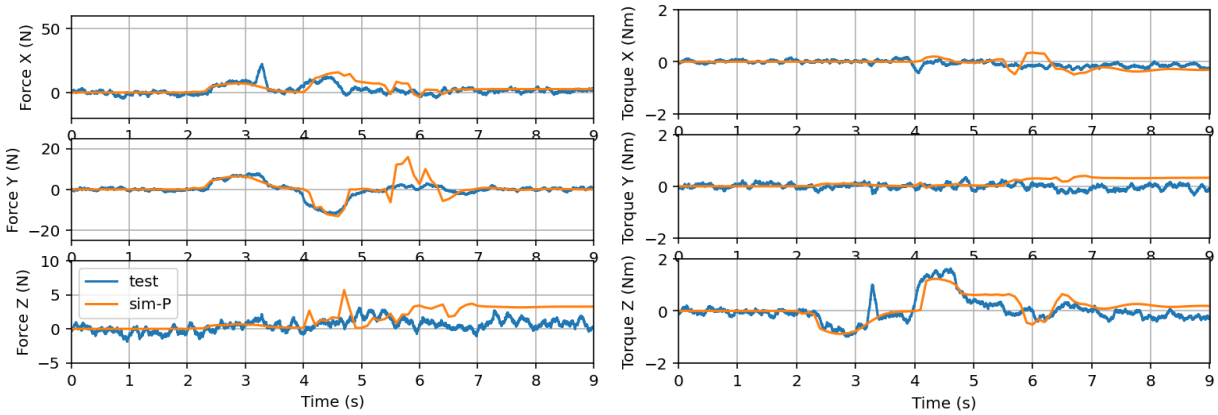


Figure 11. Run 1005 Force and Moment Time History

Estimated Orbital Performance

With a "correlated" simulation, the test models are removed, leaving an orbital simulation. There are several caveats in this specific situation, the first is that this prototype is made from 3D printed PLA parts with few bearings. The consequence is that the friction forces are higher than if there were ball bearings or if the parts were machined aluminum. This means that these monte-carlo results are approximate, but do not necessarily represent flight hardware performance.

The ICC's used in the Monte-Carlo analysis were modified from the test set. They used half-IDSS limits for all misalignments and velocities, which is different than the tested limits which had a mix of IDSS limits with no lateral velocities and wobble rates. A 1000 case Monte-Carlo was run, varying ICC's according to the limits shown in Table 3 below. Mass properties were modified from testing but attempted to keep the same equivalent mass with both the Target and Chaser using identical 400kg masses. This results in a similar equivalent mass as the test, which used a Chaser mass of 173kg and an infinite Target mass. A closing velocity of 6cm/s was used, which is similar to the test closing velocity.

For a set of 1000 runs, 955 captured, resulting in a 95.5% capture rate. As can be seen from Figure 12 below, the failure to capture resulted from: lower approach velocity, higher lateral velocity, and higher lateral misalignment. The successful captures have blue dots, missed captures are larger red dots.

Table 3. ICC Misalignment Table

ICC	Units	Nominal	Magnitude	Distribrution
Y	mm	0	50	Normal
Z	mm	0	50	Normal
Pitch	deg	0	2	Normal
Yaw	deg	0	2	Normal
Roll	deg	0	2	Normal
Vx	cm/s	6	1	Uniform
Vy	cm/s	0	2	Uniform
Vz	cm/s	0	2	Uniform
Ome x	deg/s	0	0.1	Uniform
Ome y	deg/s	0	0.1	Uniform
Ome z	deg/s	0	0.1	Uniform

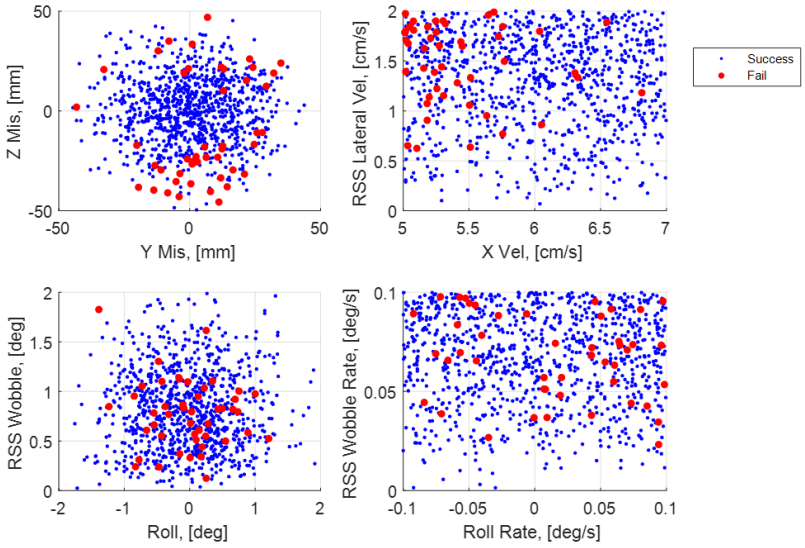


Figure 12. Monte Carlo Capture Success vs. ICC

The forces and moments at the Passive HCS are shown in Figure 13, along with the relative motion of the Active HCS (Chaser) to the Passive HCS (Target). The peak force is less than 40 N, and the peak moment is less than 1.8 Nm. A crucial feature of the APOA is shown in the relative motion of the Active HCS. During a failed capture, the stored energy in the attenuators pushes the Chaser back away from the Target. This is a feature which creates a safe separation between vehicles without intervention by flight software and/or GNC.

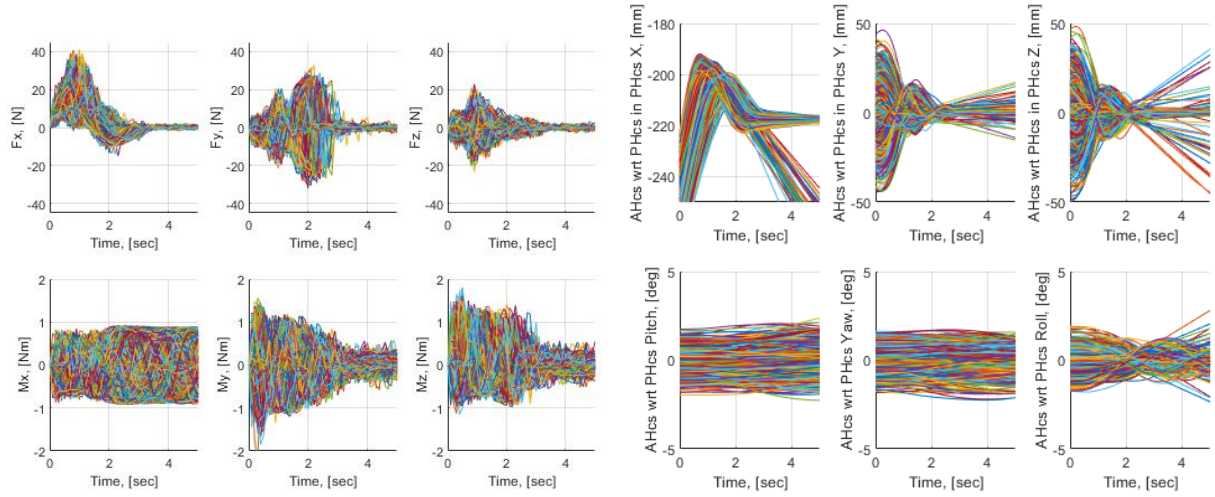


Figure 13. Monte Carlo PHcs Loads and AHcs Displacement Time Histories, all Runs

Lessons Learned

There were numerous lessons learned over the course of the APOA TID project, and these are broken up into Design, Development, and Testing lessons.

<u>Design</u>

The torsion springs which supported the Pitch-Roll Arms were a lower stiffness than was desired, but no larger springs could be conveniently fit. Fitting in the capture latch and release mechanisms were a significant difficulty due to the small space available. It may be worth considering a release mechanism on the passive cone side to simplify design requirements on the capture latches. The Ball and Cylinder

interfaces at the end of the Support Arms had a gap of 0.0254 mm, which may not have been a large enough gap. A larger gap may have reduced friction in the sliding joint.

Development

A lesson learned in the development of the APOA-ESPA was the value of rapid prototyping. The APOA can have multiple interactions which can be difficult to model. Rapid prototyping allows for fast and low-cost design optimization.

The capture latches went through several design iterations due to their small size and limited space in the probe head. This small size created difficulties in sizing components such as springs and release mechanisms. Several attempts were made to try and use 3D printed plastic springs on the capture latches, but none would work without permanent deformation. Eventually, two small torsion springs per latch were used to enforce capture, and a release cable was routed through down the probe for manual release.

Testing

A lesson learned in testing was that with proper expectations, testing can be low cost and provide excellent data. Knowing that tested position time histories were going to be used in the simulation, eliminated the need for the test hardware to perfectly match ICC's, reducing the complexity of the test. Furthermore, the loadcell used was much too large for this application, but with filtering, the data was still useful. This allowed for lower cost testing using existing equipment.

A final lesson learned during testing was that MSFC's Flat Floor Service Pad is a marginal location. The service pad has a slope which supports refilling of high-pressure gas to floating systems. This slope both helped and hurt testing. It helped in that it reduced the amount of drop mass that was needed to achieve docking velocity, which reduced complexity. However, the slope also applied a constant thrust force, which improves docking performance. This constant thrust is commonly called Post Contact Thrust (PCT), and as a result there was never any "bounce out" from a failed capture. Although there were failed captures where latches did not lock.

Conclusions

With the support of NASA/MSFC TID funding, the APOA-ESPA was designed, developed, and tested. The successful testing, completed at MSFC's Flat Floor test facility, provided essential data for simulation correlation and validation. This testing demonstrated the system's ability to dock under a variety of ICC's. Monte-Carlo orbital simulations provided additional insight into the APOA's potential.

This work represents an initial step to prove the APOA concept. The prototype proved that an over-constrained mechanism with designed-in compliance could be successful, as well as balancing the alignment accuracy between the SCS and HCS systems. Future development of the APOA should follow a two-path approach that leverages design similarities between smaller ESPA versions, with the larger scale CBM version. With the development of the APOA-CBM, the dream of the Hybrid Berthing System can be realized: assembling large space structures without a robotic arm.

References

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