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# Launch Hardened Cup-Cone Docking Mechanism for Small-Sats

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## ABSTRACT

A dual-use docking mechanism that can provide soft dynamic coupling in space and a rigid connection for launch would provide significant benefit to launch cost and weight savings. PSI has developed the Toothed Cup-cone Launch-hardened Androgynous Docking (T-CLAD) mechanism as a solution. The T-CLAD mechanism is an androgynous docking mechanism capable of withstanding launch loads while simultaneously providing self-alignment docking capabilities for on-orbit servicing and refueling. The mechanism is nominally designed for half-ESPA-class satellites but can be sized up and down to different class satellites while keeping full capabilities. The system incorporates an alternating, toothed cup-cone interface and SepNuts to "launch harden" the system. Furthermore, this cup-cone interface provides a self-alignment system to improve engagement of on-orbit docking. With additional hard-dock latching systems, fuel ports, and electrical ports, the T-CLAD mechanism enables on-orbit servicing within the confines of a launch restraint system. The research covered in this paper presents the design work, concept of operations, mechanism capabilities, and initial testing of the T-CLAD mechanism. An overview of the concept of operations and the versatility of the mechanism for thruster and robotic arm driven docking will be discussed. Furthermore, the ISAM-related missions that the T-CLAD mechanism can be used for will be covered as related to future research and missions. The unique cup-cone interfaces were designed based on expected launch loads and the dynamics of on-orbit docking. The initial design of these interfaces will be compared to the experimental results and motion studies. Alongside the main interfaces, the use of shock dampers will be discussed on how to handle the gentle impact of two satellites and complete a successful soft dock. The hard docking mechanism was designed to provide a stiff interface for on-orbit slewing and fuel transfer. An experimental prototype was designed and fabricated to validate the initial design work, and the experimental results will be presented along with future plans for development, testing, and integration into an operational system.

## SUMMARY

With the advancement of space mechanisms and the miniaturization of technologies, In-space Servicing, Assembly, and Manufacturing (ISAM) has become viable for the small-sat industry. The suite of capabilities that fall within ISAM promote a sustainable space environment, expand scientific discoveries, and create more enduring infrastructure in space. A key technology within ISAM is the docking and undocking mechanism, which is crucial for missions that involve refueling, servicing, and tugging. A handful of docking mechanisms have been flown on larger scale spacecraft, notably the International Docking and Berthing Mechanism (IDBM) developed by the European Space Agency. None of these docking mechanisms are designed to also act as the main interface to the launch vehicle, capable of surviving launch loads.

A docking mechanism for small spacecraft (27U CubeSat to ½ ESPA) that can survive launch loads in the docked state would provide [a method for refueling small satellites and extending their mission]. With the expanded development of spacecraft capable of performing on-orbit servicing and refueling, a docking mechanism that can double as the connector to the launch vehicle is preferred to save weight, volume, and cost. Several concepts and prototypes of docking mechanisms for this class spacecraft currently exist, but none are designed to survive launch loads.

In this research, the research team at Physical Sciences Inc. (PSI) demonstrated the feasibility of our Toothed Cup-cone Launch-hardened Androgynous Docking (T-CLAD) mechanism by designing, fabricating and testing a prototype T-CLAD docking interface, and completed the supporting analysis to show that the

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system can withstand the required launch and on-orbit operational loads. PSI showed that the system can meet mission-relevant needs through the Key Performance Parameters (KPPs), shown in Table 1.

**Table 1: Key Performance Parameters of the T-CLAD Mechanism**

| Parameter | Metric | PSI T-CLAD |
|---|---|---|
| Angular self-correction | deg. | 5.0 |
| Rotational self-correction | Deg. | 8.0 |
| Axial self-correction | in. | 1.0 |
| Launch-state 1st mode stiffness | Hz | 25 Hz |
| Data transfer rate | Mb/s | 10,000 |
| Engage/disengage cycles |  | 200 |

T-CLAD is an androgynous docking mechanism capable of withstanding launch loads while simultaneously providing self-alignment docking capabilities for on-orbit servicing and refueling. The mechanism is nominally designed for half-ESPA-class satellites but can be sized up and down to different class satellites while keeping full capabilities. The system incorporates an alternating, toothed cup-cone interface and SepNuts to "launch harden" the system (Figure 1). Furthermore, this cup-cone interface provides self-alignment system to improve engagement of on-orbit docking. With additional hard-dock latching systems, fuel ports, and electrical ports, the T-CLAD mechanism enables on-orbit servicing within the confines of a launch restraint system.

During the research, PSI performed Finite Element Analysis (FEA) of the cup-cone interface to show that the T-CLAD system made from common space-grade metals will survive quasi-static loads with a corresponding Hold Down Release Mechanism (HDRM). We analyzed the cup-cone geometry, showing it can handle misalignment up to ±0.5 in. and ±2.0°. PSI designed a hard docking mechanism capable of initially capturing the other satellites interface and docking with a preload up to 500 lbf. Alongside the docking mechanism, PSI developed a Concept of Operations (CONOPS) for the operational modes of the system and the layout the operational steps for on-orbit docking. Lastly, PSI began the design and fabrication of an experimental model for initial soft-docking and misalignment experiments.

## INTRODUCTION

The overall goal of T-CLAD program is to develop an androgynous, launch-hardened docking mechanism for on-orbit servicing and refueling missions, specifically for ESPA class satellites. The work demonstrated survivability of the T-CLAD mechanism in the launch environment, meeting Technical Objectives 1 and 4. Surviving launch loads is important in showing that the system can act as a stiff connector to launch vehicle. The team showed the reliable operation of the mechanism in docking and undocking states, achieving Technical Objective 2. A reliable docking and undocking mechanism is vital to mission viability and the experimentation and design developed in this research highlights the T-CLAD mechanism as a flexible system that meets the reliability required for on-orbit operations. A handful of off-the-shelf connectors were identified that meet the requirements laid out in Technical Objective 3. A brief overview of the Technical Objectives is listed above in Table 1, and are discussed in more detail in a later section.

The Key Performance Parameters (KPPs) laid out above in Table 1 list the main requirements that drove the design of the T-CLAD mechanism in this research effort. The self-correction parameters highlight the importance of a flexible design that can accommodate misalignment in the docking process. PSI's initial design met or

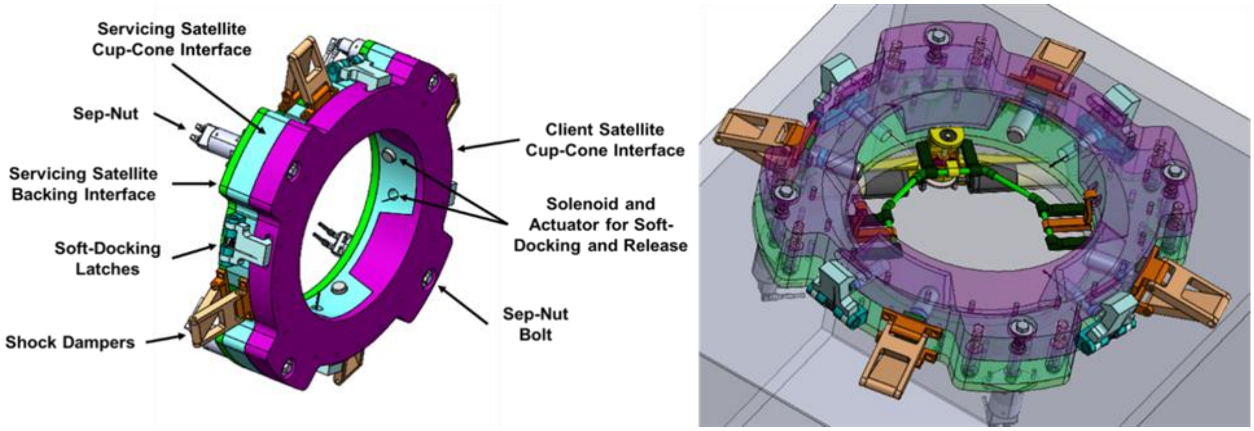


**Figure 1: Overview of T-CLAD Mechanisms Attached to Half-ESPA Satellite**

exceeded the objective requirements and identified potential geometry changes to improve upon or adjust depending on the misalignment specs of different vision systems or attitude control capabilities. This design meets the launch loading environment, including quasi-static loading and random vibration, as shown in the simulations detailed in the results section. PSI identified several off the shelf fuel and electrical ports that meet the requirements for fuel and data transfer. Lastly, PSI showed the reliability of the T-CLAD mechanism in docking and undocking through experimentation of a full-scale prototype developed in the program.

### *Cup-Cone Interface Background*

Cup-cone interfaces are a type of kinematic launch restraint mechanism commonly used for deployable systems on satellites. Usually paired with an appropriate Hold Down Release Mechanism (HDRM), cup-cone interfaces interlock two bodies together and act to withstand lateral loads of a launch environment [1]. A compression load is applied perpendicular to the flat interfaces of the cup-cone elements, which act as the primary contact interface, depicted in Figure 2. These surfaces counteract bending moments produced by the cantilevered structure during launch. Increasing the diameter of this interface or increasing the preload on the system will in turn handle more cantilevered weight or a worse launch environment. The angled tooth surfaces resist shear forces in the lateral direction during launch conditions. Usually angled at 60° or more, these interfaces are crucial in keeping the restrained structure stationary. The angled surfaces are typically undersized to not over-constrain the interface and create binding. These surfaces interact only when shear forces are present from large lateral loads [2], such as from high G's during launch.

Because of their shape, cup-cone interfaces offer internal area inside the cup or cone to integrate data and power connectors, release mechanisms, kick off springs, and other operational based components such as sensors and cameras. This efficient use of space allows additional components and mechanisms to operate while reducing mass and volume, critical aspects of small satellites. Most structures use cup-cone elements of only a few inches in diameter, but the efficient space use is still present when expanding these interfaces to a larger diameter.

## METHODS, ASSUMPTIONS, AND PROCEDURES

### *Structural Analysis of the Cup-Cone Interface*

The research team completed finite elemental analysis (FEA) of the quasi-static loading parameters. We identified the flight environment factors for this loading case in the previous reporting period, which are summarized in Table 2 and Figure 3. The environment factors were taken from MOOG ESPA User's Guide [3] while the safety factors and durations were gathered from the General Environmental Verification Standard (GEVS) by NASA Goddard Space Flight Center [4].

To meet the qualification standards defined by MOOG and NASA, PSI selected a satellite with a mass of 293 lbs. experiencing a vector sum acceleration of 16.5G's as the loading condition for the FEA simulation. This corresponds to an applied load of 6,040 lbf. at 20 in., the maximum center of gravity distance from the port, which translates to a bending moment of 121,000 in.-lbs. applied to the cup-cone interfaces. The SepNut restraint mechanisms then must apply 16,100 lbs. of total load at minimum to restrain the satellite fully to the launch vehicle. PSI set up two mating cup-cone interfaces in the launch state for simulation. PSI applied a fixed boundary condition to the backside of one of the interfaces. A contact interaction with a friction coefficient of 2.0 was specified between the mating surfaces of the two cup-cone interfaces. The preload and quasi-static load previously defined were inserted as loads on the unfixed cup-cone component. Figure 5 below depicts the FEA simulation setup as well as the mesh sizing used. A preload of 32,000 lbs. was applied. The preload was selected as double the calculated minimum from the bending moment but near the maximum load the SepNuts can produce.

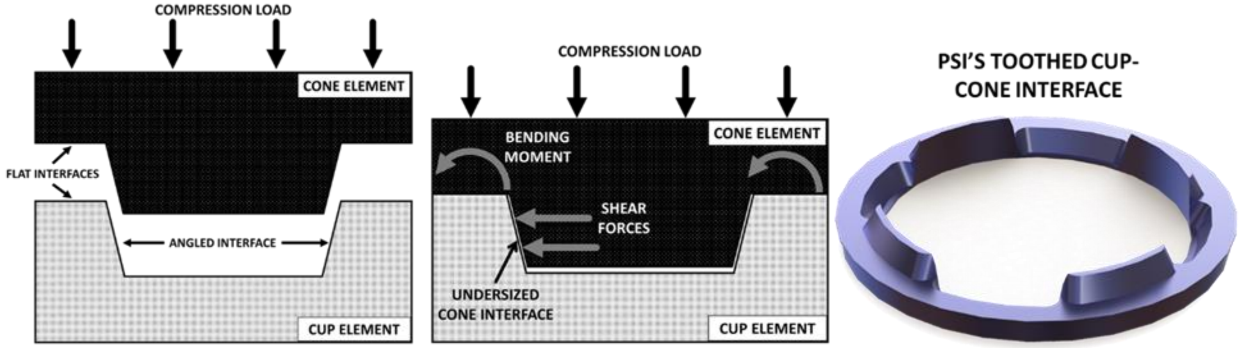


**Figure 2: Cross-sectional Depiction of Cup-cone Interfaces**

**Table 2: Quasi-static Load Factors from ESPA Mass Acceleration Curve, Test Factors/Duration**

| Loading Parameters | Acceptance [Threshold] | Qualification [Objective] |
|---|---|---|
| Satellite Mass (lbs.) | 198 | 293 |
| Lateral and Axial Acceleration (G's) | 11.7 | 9.7 |
| Vector Sum Acceleration (G's) | 16.5 | 13.7 |
| Quasi-Static Load | 1.25 x Limit Load | 1.25 x Limit Load |
| Duration | 30 seconds, 5 cycles | 1 minute, 5 cycles |

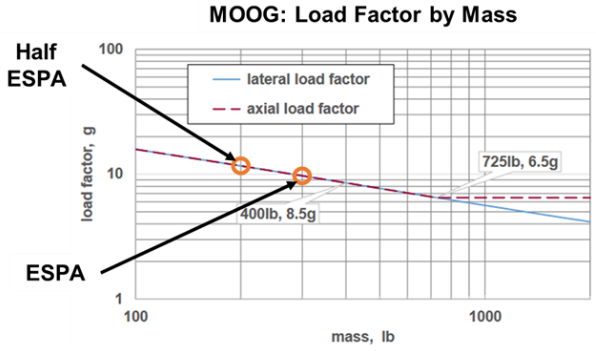


**Figure 3: Quasi-static Load Factor by Mass [3]**

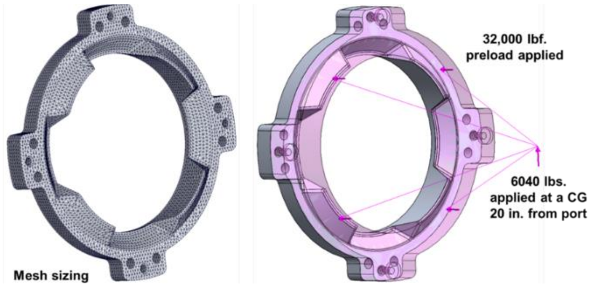


**Figure 5: Simulation Setup and Mesh Sizing for the Cup-cone Interfaces**

***Concept of Operations***

PSI defined the concept of operations (CONOPS) for the T-CLAD mechanism that governs the operating states, steps between states, and sub-requirements. The chart in Figure 4 shows five modes that fit under the two main operating states: launch-hardened restraint and on-orbit docking/undocking.

First, T-CLAD is in the **Launch** condition with the launch restraint mechanism (SepNuts) applying high preloads to resist the launch environment. Once in orbit, the launch restraint mechanisms release, and the system moves to the **ESPA Initialization** mode. Now in the on-orbit operation state, the T-CLAD mechanism moves to the **Soft Dock** mode to prepare for the **Release** mode from the ESPA ring. Two variations of the release mode are needed to change the state of the kickoff springs depending on the scenario, and they are described in more detail below. Once released, the servicing ESPA satellite moves to the client satellite through a robotic arm or thrusters. The servicing satellite then enters back into the Soft Dock mode, providing the initial connection of the two satellites with self-alignment and shock dampening. The satellite then moves to the Hard Dock mode to establish a complete connection ready for servicing operations. Finally, the system goes back into the Soft Dock mode before Release to complete the servicing or refueling. The servicing ESPA satellite will cycle through these three modes as it completes the docking and undocking process with the main ESPA ring and various client satellites it services. Though two undocking scenarios exist dependent on a robotic arm assist; the docking process remains the same. The step-by-step details of this process by mechanism is listed below.

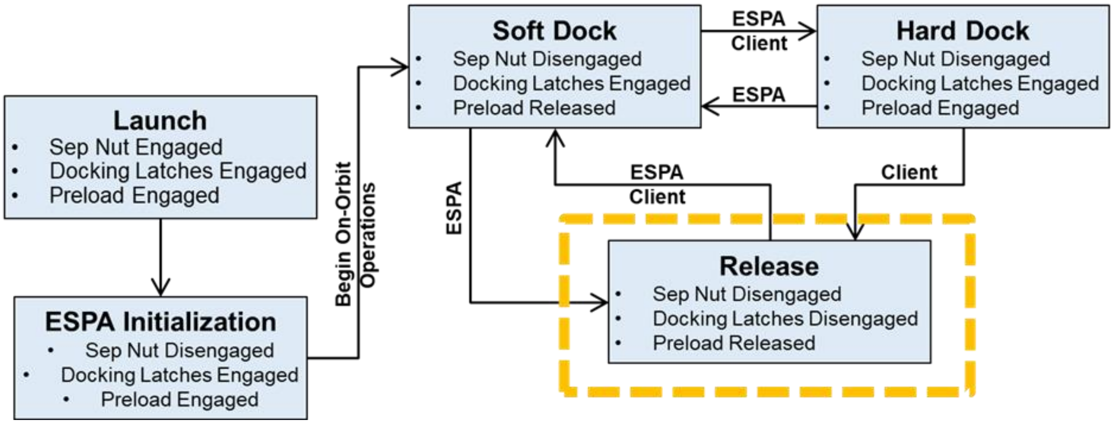


**Figure 4: CONOPS of the T-CLAD Mechanism**

### Docking: Thruster driven and robotic arm assist

1. As the two cup-cone interface become in contact, the soft-docking latches on the servicing satellite clamp onto the client satellite's interface.

2. The hard-docking mechanism actives and hooks onto the client satellite's interface. As the hooks clamp down, the shock-dampers collapse.

3. The solenoid latch actives and locks the servicing cup-cone interface to the base plate.

During a propulsion-undocking scenario, the kickoff springs actuate after the release of the soft-dock latches, and the springs separate the client satellite from the service satellite. This kickoff force is unwanted in a robotic arm driven undocking, as the arm is not equipped to handle the reaction forces from the springs. In this secondary release scenario, the kick-off springs are released first, before the robotic arm grabs the satellite yet still while the soft-dock latches are clamped on. The steps for each mechanism are listed below for the two scenarios.

### Undocking: Propulsion driven system

1. First, the hard-docking mechanism releases its hooks.

2. The soft-docking latches then release.

3. The solenoid latches holding together the cup-cone interface and the base plate release.

4. Immediately following that release, the shock-damper mechanism extends and provides a kickoff between the two satellites.

### Undocking: Robotic arm

1. First, the hard-docking mechanism releases its hooks.

2. The solenoid latches holding together the cup-cone interface and the base plate release.

3. The shock-damper extends to its released state.

4. The robotic arm can then grasp onto the satellite in prep for separation.

Lastly, the soft-docking latches release and the satellite is undocked with the robotic arm.

## RESULTS AND DISCUSSION

### *Structural Analysis of the Cup-Cone Interface*

The FEA results of the cup-cone interface simulations, shown in Figure 6, display the contact pressure with one interface hidden. The results show pressure still being applied around the whole ring, indicating that the interfaces remain in complete contact through the quasi-static loading. No contact pressure is seen on the cup or cone faces as they have been sized with a 0.010 in. gap to prevent interference and over definition. Additionally, the max yield stress was 4.7 ksi, significantly below the yield strengths of common space-grade aluminum and titanium alloys. This low yield stress offers significant room to remove material and mass in future design iterations.

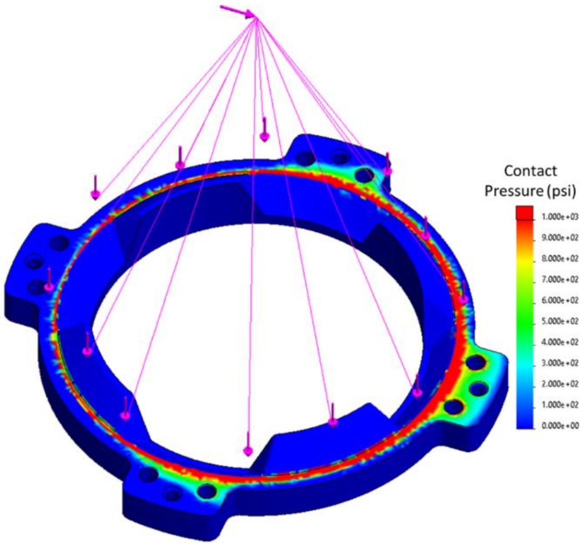


**Figure 6: FEA Simulation Results of the Cup-cone Interfaces Under Quasi-Static Loading (Top Interface Hidden for Clarity)**

To validate the simulation results of the quasi-static loading, a quarter-scale model of the two cup-cone interfaces was fabricated in aluminum (Figure 7). A 5-thou gap was kept between the cup and cone "tooth" features to ensure the main point of contact was the outer ring face. Boltholes for ¼-20 bolts were placed in the same position that the SepNuts would be located and were oversized slightly to allow the cup-cone interface to shift slightly without applying shear loads on the bolts.

The model was tested in an Instron machine in a cantilever bending setup, as seen in Figure 7. The quasi-static loads of the full-scale interface, called out in Table 2, were scaled down appropriately for this smaller interface. A quasi-static load of 380 lbs. was applied at 5 in. from the interface, which corresponds to a bending moment of 1,890 in-lbs. The preload on the ¼-20 bolts to survive this loading was 1,080 lbs., or 270 lbs. at each bolt. The quarter-scale cup-cone interfaces were preloaded to the previously listed loads and loaded in the Instron under a constant displacement of 0.2 in./min. The results of the cantilever bending test in the Instron machines are depicted in Figure 8. The plot shows a close to linear response as the interface is loaded, and notably a smooth response. Any jumps or sharp drops in the response would indicate that the interface slipped and failed to survive the quasi-static loading. The plotted results do not show any slipping or failure, and therefore the interface survived the quasi-static loading at the calculated preload. This supports the modelling of the full-scale interface and validates that the system can survive loading.

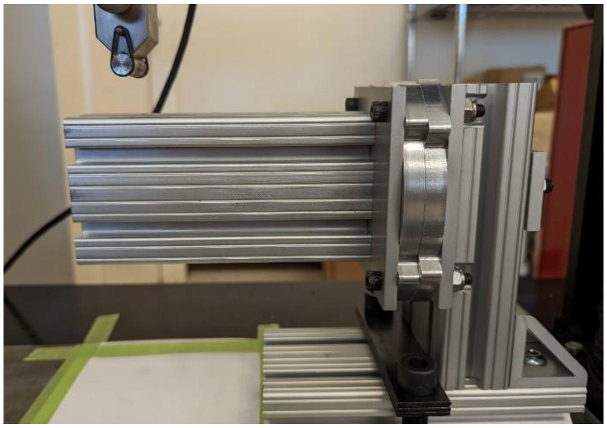


**Figure 7: Cantilever Bending Test Setup of the Cup-cone Interface**

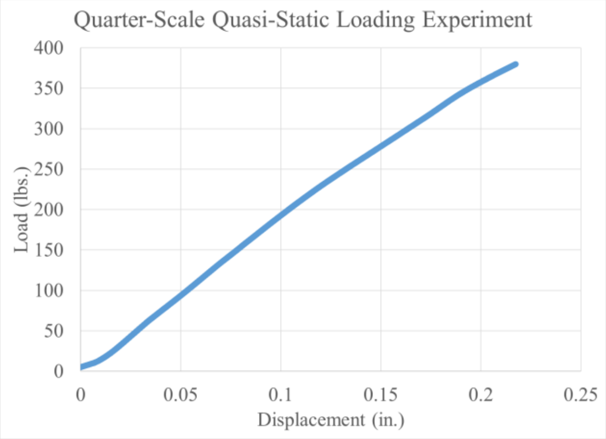


**Figure 8: Displacement vs. Load of the Quarter-scale Cup-cone Interface**

### *Preliminary Design of the Hard-Dock Mechanism*

PSI investigated several Hold Down and Release Mechanisms (HDRMs) to determine the most appropriate solution for the T-CLAD mechanism. Four systems were setup in a comparison table to identify the strength and weaknesses and highlight the best system for our system. Marman clamps, motorized Marman clamps, LightBand, and SepNuts were compared with cost, mass, separation debris, reusability, and shock. The results are listed below in Table 3 on a scale of 1 to 4 where 1 is the best and 4 is the worst. The SepNuts perform best in almost all categories due to their simplicity and size. Reusability is not an important factor in the separation system as they are intended only for launch vehicle separation. This metric was included as PSI was considering using the separation system to apply the on-orbit docked preload but went to a single-use launch restraint to reduce cost and complexity. HDRMs are not designed for repeated use, especially in space, and using them directly in the docking/undocking process would require them to be reevaluated and proven for this situation. PSI selected SepNuts as the separation system due to both the results of the trade study and the long historical use of SepNuts on ESPA class satellites.

**Table 3: Separation System Comparison Table**

| **System** | **Cost** | **Mass** | **Debris** | **Reusable** | **Shock** | **Sum** |
|---|---|---|---|---|---|---|
| Marman | 2 | 3 | 4 | 4 | 4 | 17 |
| Motorized Marman | 3 | 4 | 1 | 3 | 1 | 12 |
| LightBand | 4 | 4 | 1 | 2 | 1 | 12 |
| SepNut | 1 | 1 | 1 | 4 | 1 | 8 |

PSI also investigated the self-alignment capabilities of the cup-cone design. The requirements for self-alignment, as listed in tech objective #2, are ± 0.5 in. translationally, ± 2.0° rotationally, and ± 1.0° angularly. The translational and rotational parameters are defined as in plane with the cup-cone diameter, and the angular parameter is the offset of that plane. PSI designed the cup-cone interfaces to handle the three misalignments individually and combined as a worst-case. This worst-case misalignment is depicted in Figure 9 as the eight corners of the green region. The critical point is the corners of the cone interfaces where binding or interference will first occur if the misalignment is greater than the defined limits of the cup-cone design. A cross-sectional view of this region showing the translation and rotational components is also shown in Figure 9.

Because the cup-cone interfaces of the T-CLAD mechanism are designed to handle the worst-case sum of the three misalignment requirements, the TCLAD interface can accommodate greater misalignments in any one of the individual directions. These self-alignment capabilities are listed in Table 4.

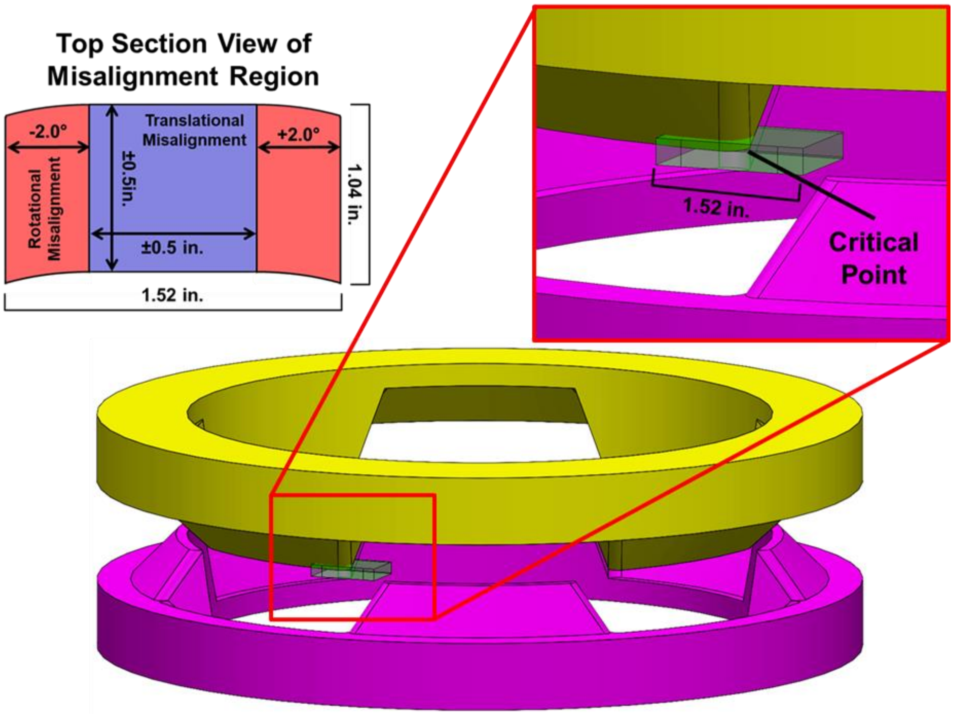


Figure 9: Visualization of the Self-alignment Capabilities of the Cup-cone Interfaces.

**Table 4. PSI's T-CLAD Self-alignment Capabilities by Individual Parameters**

| Misalignment Parameter | Listed Requirement | PSI's T-CLAD Capability |
|---|---|---|
| Translational | ± 0.5 in. x ± 0.5 in. | ± 0.76 in. x ± 0.52 in. |
| Rotational | ± 2.0° | ± 8.0° |
| Angular | ± 1.0° | ± 2.0° |

As a precursor to designing and sizing the spring-damper mechanism that helps capture the satellite during docking, a kinematic analysis of the forces present during docking was conducted. This analysis was completed to confirm that the two cup-cone interfaces self-align and latch before the satellites bounce apart. The assumptions of this first pass analysis are as follows: 1) the client spacecraft has significantly more inertia than the servicing spacecraft, 2) docking is done free flying with thrusters off during the docking process, 3) the servicing spacecraft approaches with an initial velocity of 1.0 in/sec, and 4) friction and rotation of the spacecraft have been neglected. A representative figure of the analytical model is shown in Figure 10.

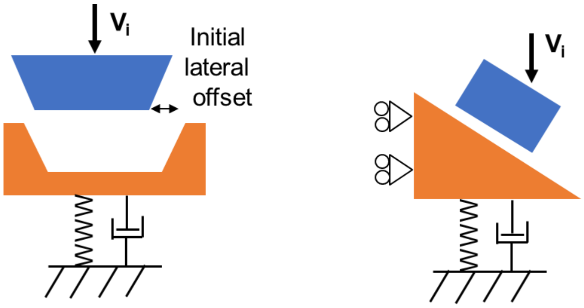


Figure 10. Graphic of the 2D Analytical Model

The results of the model are summarized in Figure 11. For the load case in the assumptions above, the model shows that the spring damper needs to accommodate approximately 80% as much axial motion as the initial amount of orthogonal misalignment. For example, a 0.5 in. misalignment requires 0.4 in. of axial motion in the shock absorber. This 80% value can be adjusted slightly by increasing or decreasing the damping ratio, producing more or less accommodation respectively.

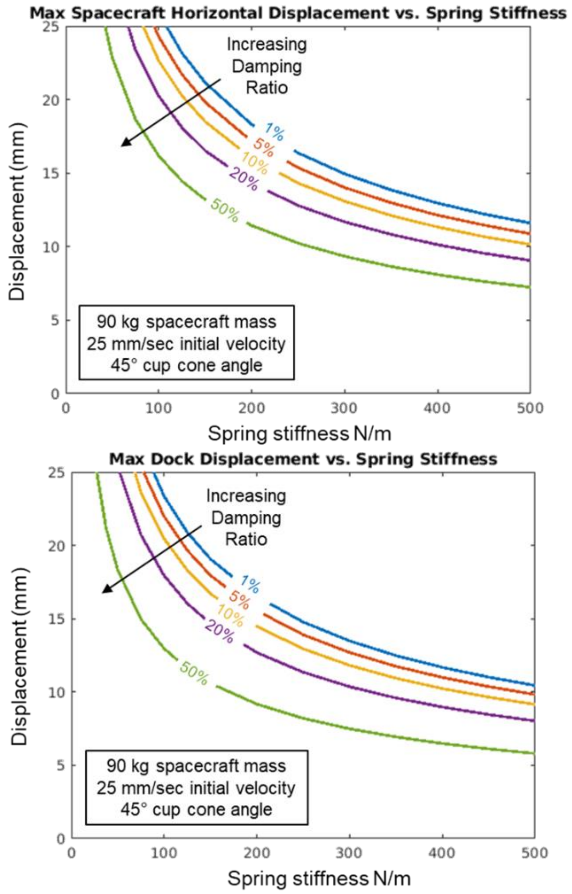


**Figure 11: Spring-damper Sizing by the Spacecraft Orthogonal Displacement (Left) and Axial Docking Displacement (Right)**

Based on the results of the analytical model discussed above, the spring damper mechanism was sized, and parts selected. A conservative 0.75 in. of axial displacement was chosen based on curve in Figure 11 of a 20% damped system with a spring stiffness of 0.57 lbf/in (100 N/m). This correlates to a torsion spring of 0.66 in-lb./rad acting on a 2.0 in. lever arm (Figure 12).

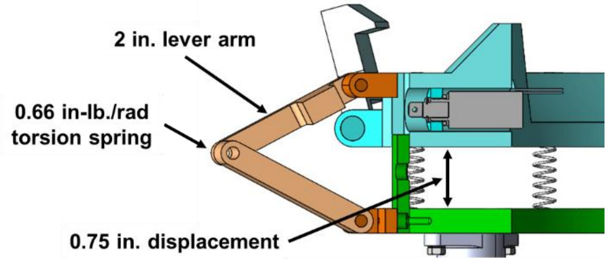


**Figure 12. Side View of the Spring-damper Mechanism**

PSI developed a preliminary design of the docking mechanism. This design work involved the selection of the motor and gearbox system as well as an investigation of various architectures for the hard docking mechanism. For the motor system, depicted in Figure 13, the team selected an architecture with two motors operating in parallel driving a shaft with a bevel gear system. Two Maxon 24V BLDC motors were selected that provide 50 mNm of torque at 8000 RPM. With a 295:1 planetary gearbox and a 2:1 bevel gear reduction, the two motors provide an output shaft torque of 38 Nm. This torque can provide 2000 N [450 lbf] of preload between cup-cone interfaces. The initial estimate for this preload is described in further detail in Task 3. To provide redundancy, each motor can run the full docking mechanism in the case that the other motor fails.

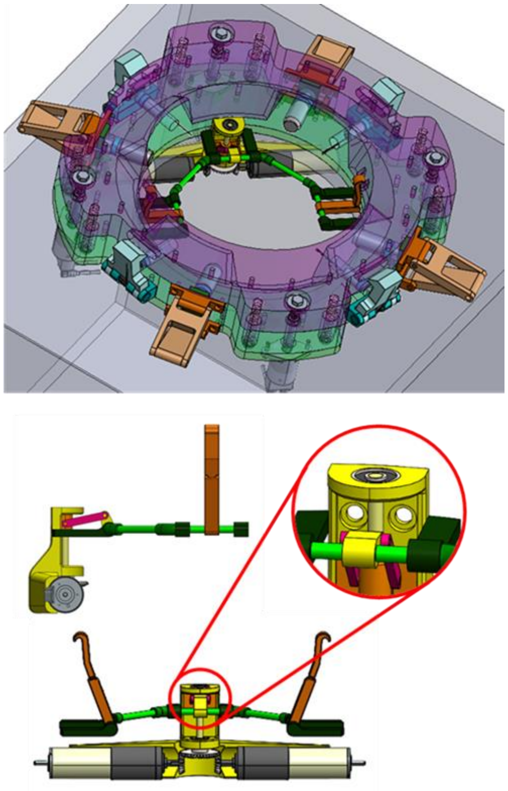


**Figure 13: Overview of the Dual Motor and Gearbox System**

PSI also investigated other docking mechanism architectures to ensure the rotating shaft and hook design was the best option for the T-CLAD mechanism. A comparison table, Table 5, was created with categories of mechanical efficiency, cost, volumetric efficiency, complexity, heritage, and reliability on a scale of 1 to 5 (5 ranking the best). The team weighed the categories and determined a total value to rank all the systems. The original design of the rotating shaft with hooks scored highest, followed closely by a similar design that replaces the hooks with a 2-bar linkage.

**Table 5: Comparison Table of Various Architectures for Docking Mechanisms**

| Mechanism | Mech. Efficiency | Affordability | Volumetric Efficiency | Simplicity | Heritage | Reliability | Total |
|---|---|---|---|---|---|---|---|
| Weight | 10% | 25% | 15% | 12.5% | 12.5% | 25% | 100% |
| Original rotating rods w/ larger hooks | 3 | 3 | 2 | 5 | 3 | 5 | 3.60 |
| Threaded rods (vertical axis) | 2 | 4 | 2 | 3 | 3 | 5 | 3.50 |
| Rack and pinion (vertical axis) | 2 | 4 | 3 | 2 | 1 | 5 | 3.28 |
| Two bar linkage actuated by rotating rods | 4 | 3 | 2 | 3 | 4 | 5 | 3.58 |
| Two bar linkage actuated by expanding radial mechanism | 2 | 1 | 1 | 1 | 3 | 2 | 1.60 |
| Tensioning Cable | 2 | 5 | 5 | 4 | 1 | 1 | 3.08 |

The motor system was integrated into the full T-CLAD assembly and positioned to sit below the cup-cone interface of the servicing satellite as seen below in Figure 14. The motors power a ball screw, which connects to the hooks via a set of linkages. This position offers ease of design and assembly of the prototype system for the program. Future work will move the motors to fit inside of the cup-cone interface and not interfere with the satellite's bus volume. Additionally, work to optimize the size and weight of the linkages will be completed in follow-on efforts.

As seen in Figure 15, the hard docking hooks are a two-piece construction with a torsion-spring-driven hinge between the two hook segments. The spring holds the hook segments in line with one another until the hook makes contact with the latch. The lower segment of the hook continues to rotate, pulling the magenta and blue rings down to the green ring, compressing the spring-damper assemblies. The mechanism is designed so when all three rings make contact the hook sections form a 90-degree angle, as can be seen in Figure 15. The right angle ensures all the torque from the green torsion linkage is transferred into force normal to the flat ring surfaces and is therefore fully utilized for clamping the fuel and electrical ports together. This new design allows for a smaller hook shape and reduces the amount of travel needed compared to a single piece hook, leaving more room for ports in the center of the docking mechanism.

PSI also conducted a study to ensure the force generated by the ball screw will be sufficient for clamping the rings together. This study also considered the deflection, both bending and torsional, that the components within the load path will experience. The results show that the ¼" torsion members (shown in green in Figure 15) will need to be enlarged, but that all components can be made to survive the loads within reasonable packaging constraints.

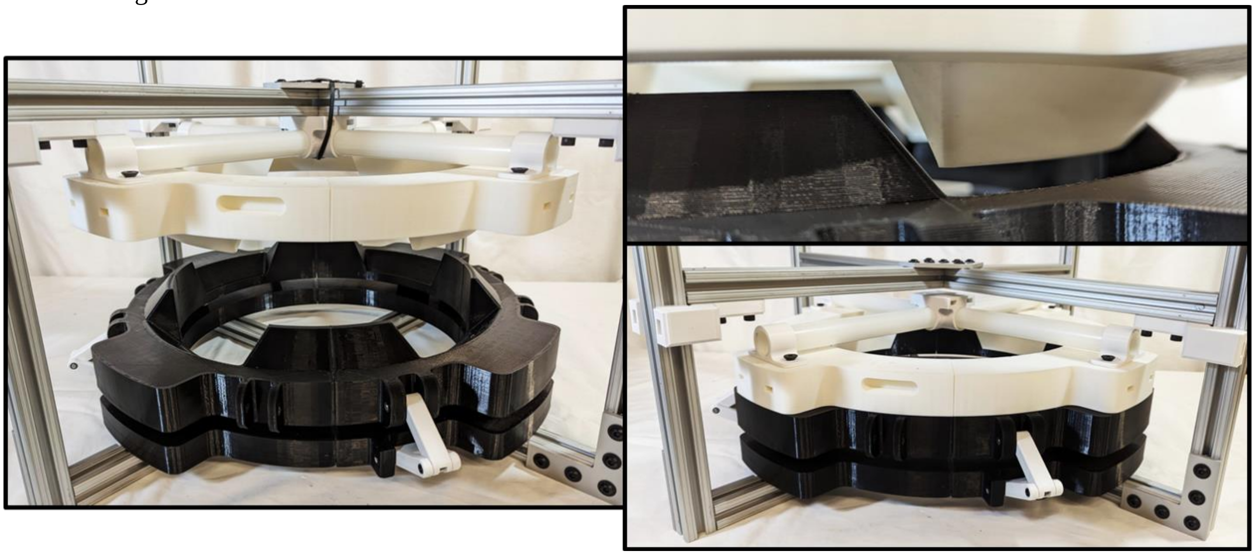


**Figure 14: Setup of the Soft-docking and Misalignment Experimentations**

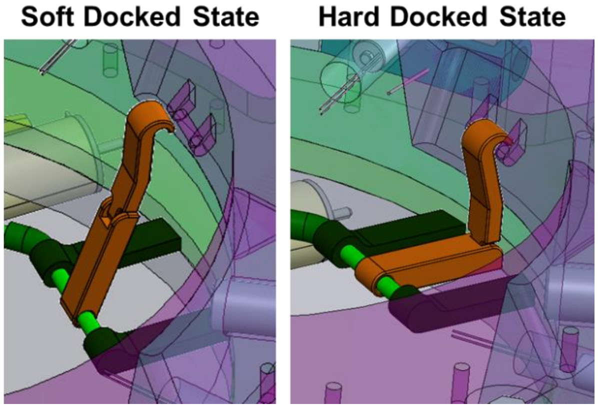


**Figure 15: Articulation of the Hard Dock Hooks**

### *Preliminary Design of the Fuel Ports*

Early, in the research effort, PSI identified two potential fuel port manufacturers that have developed fuel couplings for on-orbit fuel transfer: Vacco Industries and Orbit Fab Inc. Vacco sells a variety of fuel couplings for hazardous fuels, cryogenics, and pneumatics (shown in Figure 16). They provided the couplings for DARPA's Orbital Express Mission, a 2007 mission that achieved a historical first of transferring fuel between two robotic satellites in orbit. PSI met with a Vacco representative and discussed if their products were suited for the T-CLAD mechanism. Vacco's fuel connectors are not the best solution, because they specialize in custom fittings, which cost at least $50,000 and have lead times a year or longer.

**Figure 16. Examples of Vacco's Hazardous Fuel Couplings**

PSI created an initial preload estimate based on fuel pressure, connection force, kickoff springs, and slewing loads. To calculate the resistive force of the fuel pressure, it was assumed a 650-psi Maximum Expected Operating Pressure (MEOP) and 0.31" port diameter, which matches the flow rate of the RAFTI port. The breakdown of PSI's preload estimate is seen below in Table 6.

**Table 6. Initial Estimate of Preload Requirements**

| Subsystem Driving Preload | Preload Requirement |
|---|---|
| Resist fuel pressure* | 0.64 kN [144 lbf] per port |
| Move valve core | 0.06 kN [13.5 lbf] per port |
| Resist slewing loads | 0.10 kN [22.5 lbf] |
| Overcome kickoff springs | 0.20 kN [45.0 lbf] |
| **Initial Total Estimate** | **1.00 kN [225 lbf] per port** |

### *Prototype Fabrication and Integration*

PSI integrated a simplified prototype involve two cup-cone interfaces, the soft docking latches, and the spring-damper mechanism. These components have been sized and selected for preliminary testing of the self-alignment capabilities and soft docking. The model was fabricated from 3D printed parts and off-the-shelf components for quick assembly, shown in Figure 14. Changes to this prototype and the integration of the hard-docking mechanism are later discussed. Self-alignment and soft-docking experimentation were conducted with incremental changes from a fully aligned state to a worst-case misalignment state. Shown below in Table 7 is a list of test cases using the objective misalignment parameters. The prototype successfully met the self-alignment capabilities of the eight listed cases and showed a smooth transition from the misaligned state to the aligned state. Furthermore, the spring-damper system displayed a slow and controlled retraction as the top cup-cone interface fell into place.

**Table 7: Checklist of Self-alignment and Soft-docking Experiments**

| Testing Case | Alignment | Soft-Dock |
|---|---|---|
| Fully Aligned | ☑ | ☑ |
| Orthogonal Displacement (± 0.5 in.) | ☑ | ☑ |
| Angular Displacement (± 1.0°) | ☑ | ☑ |
| Rotational Displacement (± 2.0°) | ☑ | ☑ |
| Orthogonal + Angular | ☑ | ☑ |
| Orthogonal + Rotational | ☑ | ☑ |
| Angular + Rotational | ☑ | ☑ |
| Orthogonal + Angular + Rotational | ☑ | ☑ |

The soft-docking hooks successfully captured the top cup-cone interface in all of the listed testing cases in

Table 7. Shown below in Figure 17, the soft-docking latch opens up slightly as the top interface descends, then latches into the cutout on the top interface.

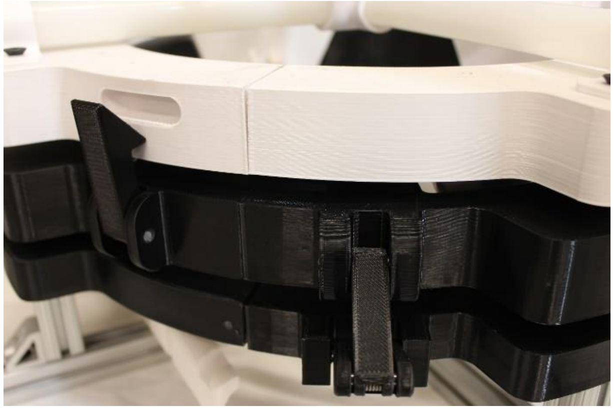


**Figure 17: Up-close image of the soft-docking latch in the middle of capture.**

### *Prototype Demonstration and Testing*

PSI fabricated the hard docking mechanism and integrated the subsystem into the test setup (Figure 18) described previously. Two types of tests were conducted with the hard-docking mechanism. First, PSI tested the system's repeatability by running through the CONOPS states, going from undocked, to fully hard docked, then back to the undocked state. Secondly, PSI tested the hard-docking mechanism's reliability by letting it run through the latching and unlatching process continuously.

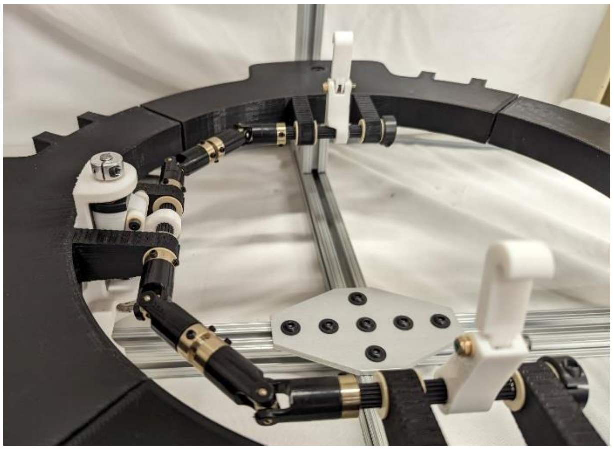
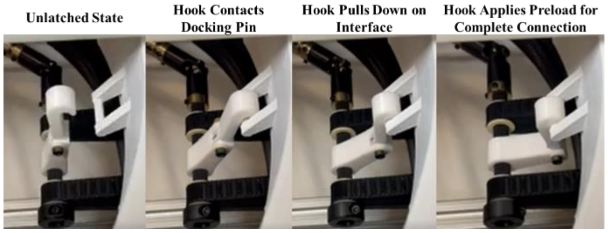


**Figure 18: Hard-docking mechanism integrated into the experimental test setup.**

The experimental model was tested through the soft docking state, hard docking state, and released 10 times. In every case, the experimental model successfully captured the receiving interface, and pulled the interface into a secure, preloaded connection. Screen captures of recorded video of one of these trials (Figure 19) show the process going from the unlatched state through a complete connection. Release of the hard-docking latches was simply completed reversing the motor motion. The latches opened back up and the two interfaces separated slightly due to the spring-loaded dampers.



Unlatched State

Hook Contacts Docking Pin

Hook Pulls Down on Interface

Hook Applies Preload for Complete Connection

**Figure 19: Images of the hard-docking hook through the docking process to a complete preloaded connection.**

Repeatability tested was conducted by running the hard docking mechanism in a continuous loop for 100 cycles. No noticeable changes were measured during this testing process and the mechanism behaved as expected throughout the many cycles. Though preload was not directly measured from the receiving interface, it was estimated that the hard-docking mechanism was applying approximately 25 lbs. of preload. Though the motor assembly was designed to apply the 200 lbs. of preload defined in the Technical Objective, the preload was limited out of concern of breaking some of the 3D printed parts in the experimental setup. Overall, the hard-docking testing mostly achieved the goals laid out in the second technical objective. Further repeatability testing and fabrication of stronger metal parts would enable a complete success of this objective in the potential follow-on efforts. There was no indication that the design of the mechanism would not be able to succeed with these changes and further testing.

## CONCLUSION

In this research, PSI designed and fabricated a prototype launch hardened docking mechanism (T-CLAD). Using a toothed cup-cone interface, alongside HDRMs, the T-CLAD system provides a stiff, launch-hardened connection to the launch vehicle. While in orbit, a set of latches and a docking mechanism provide the capabilities of on-orbit docking and undocking with the same toothed, cup-cone interface. Paired with a properly sized spring-damper system, the cup-cone interfaces provide passive self-alignment and damping to ensure a successful dock of a client and servicing satellite. The unique cup-cone interfaces provide ±2° of angular and rotational misalignment along with ±0.5 in. of orthogonal misalignment. The docking mechanism can provide up to 500 lbf. of preload, which provides a stiff, docked connection enabling the integration of fuel ports for refueling services.

PSI fabricated an experimental prototype and tested it through misalignment, soft-docking, and hard-docking tests. Results from these tests showed that the design can meet the objective misalignment parameters as a sum and can exceed these parameters individually. The soft-docking latches catch the receiving interface in all the tested misalignment cases, and the hard-docking mechanism can repeatedly and reliably dock the receiving interface. In addition to this full-scale prototype, PSI fabricated a quarter-scale model of the cup-cone interfaces to validate the FEA results in quasi-static loading. The interface successfully maintained a solid connection under appropriately scaled loading, validating the simulation results.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] M. A. P. Baonza.United States Patent US 2011/0113605A1, 2011.

[2] R. L. Fusaro, "NASA Space Mechanisms Handbook," NASA STI Program, Cleveland, 1999.

[3] MOOG Space and Defense Group, "ESPA User's Guide," 2018.

[4] NASA Goddard Space Flight Center, "General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects," Greenbelt, 2019.