Secure Passive Attachment and Docking Equipment

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Abstract

As NASA continues to refine extravehicular activity (EVA) systems for the International Space Station (ISS) and future exploration missions, reliable and efficient tool storage remains critical for astronaut safety and mission success. S.P.A.D.E. (Secure Passive Attachment and Docking Equipment) is a dual-button mechanical docking system that enables astronauts to securely store and retrieve EVA tools with one hand. The design incorporates a spring-loaded locking mechanism that enables single-fault tolerance while maintaining intuitive operation in microgravity. By guiding the tool's buckle into a spring-assisted locking interface, the system allows tools to be quickly secured and released in varying orientations. S.P.A.D.E. aims to improve EVA task efficiency, reduce the risk of tool loss, and enhance the safety and ergonomics of astronaut maintenance operations. Experimental testing conducted post production verified reliable blind docking and release under 20 lbs of force with only 2.9 lbf of activation force. Future work will optimize lid geometry and fatigue life, enhance debris-resistance, and integrate space-qualified alloys and polymers for operational flight testing.

Index Terms

docking apparatus, extravehicular activity, fault tolerance, spring-loaded locking mechanism, spring-loaded locking interface

I. Introduction

Extravehicular Activity (EVA) missions subject astronauts to extreme physical and cognitive demands in one of humanity's most unforgiving environments [1]. During spacewalks, astronauts must complete cumbersome tasks with restricted fields of vision and limited fine motor function. During these high-stress missions, astronauts are forced to operate and rely on an intricate, multi-step passive capture tool docking device, which drastically hinders their ability to complete their missions effectively [2]. Small, menial tasks on Earth, such as screwing or holding a tool, are extremely difficult to do in microgravity. One small mistake can endanger the entire mission, putting the astronaut and crew aboard the spacecraft in immediate danger.

The National Aeronautics and Space Administration (NASA) developed the Micro-g Neutral Buoyancy Experiment Design Teams (Micro-g NExT) [3] challenge to address vulnerabilities like these by sourcing space-walking tools. In the 2025-2026 cycle, the program tasked student teams with developing a passive-capture tool dock that allows astronauts to safely stow and retrieve equipment during Extravehicular Activities (EVAs). To mitigate the risks of microgravity tool operation, any proposed mechanism must meet several stringent design requirements [4]. Operationally, the passive-capture tool docking mechanism must operate with at least a 15 lb tool and allow for one-handed, blind installation using minimal manual force (< 10 lbf), as astronauts face severely restricted mobility and visibility. Physically, the dock must be compact (under $5 \times 5 \times 5$ inches) and lightweight (under 2lbs in Earth gravity) to avoid adding restrictive, unnecessary bulk and optimize usability. Finally, to ensure astronaut safety, the device must eliminate or mitigate all pinch points and entrapment hazards to prevent suit lacerations and potential equipment damage. Furthermore, the mechanism should employ single-fault tolerance (requiring two independent actuations for release) to prevent accidental tool detachment and orbital debris.

S.P.A.D.E. (Secure Passive Attachment Device) is a one-handed passive-capture tool dock designed to reduce operational hazards and cognitive load during EVA tool management. This work illustrates the S.P.A.D.E.'s architecture, detailing how each component works together as a mechanical structure that actuates the EVA tool. It also provides technical validation of the device using mathematical proofs. For further validation, S.P.A.D.E. underwent rigorous experimental testing, yielding qualitative and quantitative data on its performance under simulated microgravity conditions during EVA missions. These results validate the safety of S.P.A.D.E and the environmental risks it mitigates, establishing it as a viable passive-capture tool-docking mechanism for astronauts during spacewalks.

The remainder of the paper is organized as follows: Section Two provides a literature review of previous EVA tool docking mechanisms and spacesuit limitations. Section Three details the S.P.A.D.E. architecture and its mechanical components. Section Four presents the methodology and results of the experimental testing regarding S.P.A.D.E. in a simulated microgravity environment. Section Five outlines the safety and hazard analysis, and Section Six concludes the paper with a summary of the device's performance and future design recommendations.

II. Literature Review

Human Factors and Spacesuit Constraints in Microgravity

Because EVA missions are not performed by robots, it is important to consider constraints caused by human factors and spacesuit limitations in a microgravity environment. Beard finds that stress contributes heavily to sleep deprivation among astronauts on the ISS. It has also been concluded that rigorous work schedules are one of the main contributing factors of stress among astronauts[5]. In addition, 30% of their time is consumed by managing support equipment and tool equipment[6]. This likely leads to frustration on the job, increasing both workload and stress. A high operational workload, such as managing tools 30% of the time, combines with spacesuit resistance to drive physical fatigue. S.P.A.D.E's simple design aims to decrease any extra fatigue for the astronauts.

Physical injury and compromised performance can also become a concern during EVA operations. Pressurized EMU gloves severely limit mobility, finger movement, etc. which makes finger gripping highly fatiguing and reduces hand efficiency to just 10%[7]. The stiff glove internal pressure requires constant force to flex the fingers, making hands the most injured anatomy during operations, accounting for 47% of all reported symptoms and injuries [7]. Because upcoming exploration missions will demand up to 24 hours of EVA per week per crewmember, tool interfaces must eliminate repetitive fine-finger grip forces [7]. S.P.A.D.E. addresses this constraint by replacing high-dexterity pinch motions with a low-force (¡3 lbf) push-button interface.

Spacewalk Efficiency and Tool Management

With factors such as fatigue and injury risk, efficiency is key during spacewalks. A time-motion study of ISS spacewalks revealed that astronauts spend only 42% of their time completing actual task objectives. 30% of that time is used for tool and equipment management[8].

For over two decades, studies evaluating EVA hardware dexterity constraints have highlighted the operational burden of traditional manual latches and PIP pins[9]. Focusing on complex motor functions and equipment places a high stress burden on astronauts. S.P.A.D.E. replaces these difficult interfaces with a single-fault-tolerant capture mechanism. By replacing multi-step interfaces with a single-fault-tolerant, one-handed capture mechanism, S.P.A.D.E. minimizes equipment handling overhead and reduces task-completion time.

Complexity of Existing EVA Hardware

The guidelines of NASA's Micro-g NExT state that all designs should "carefully consider the ergonomics of your device's operations"[10]. Due to suit pressurized resistance and friction in the joints, hand movements require constant effort. Current legacy retention hardware requires two hands or precise positional alignment that forces astronauts to work against suit joint resistance for longer periods, accelerating fatigue[10]. Due to internal suit pressure, overcoming joint friction during basic arm and leg movements requires continuous mechanical effort, rapidly depleting an astronaut's limited physical energy[11]. Every movement an astronaut makes during a spacewalk uses their limited energy. S.P.A.D.E aims to utilize a wide-funnel, blind-entry interface and low-force (¡3 pounds) push-button mechanics, allowing astronauts to secure tools quickly without fighting their suit's natural joint resistance.

Gap in Existing Solutions

A critical conflict exists in current EVA tool design: while legacy retention systems ensure hardware security, their complex actuation places heavy cognitive and physical demands on astronauts operating in pressurized EMU gloves. Although tools are safely and securely stored, too much responsibility is being placed on the astronaut in the already stressful work environment. However, attempting to simplify or eliminate certain safety measures and guidelines increases risk of unintended tool loss or pinch-point injuries to suits. The gap S.P.A.D.E addresses is the critical needs for a tool docking system that is user friendly and single fault tolerant. It provides safeguards against human error and mechanical failure, using one-handed, blind installation and requires less than 10 pounds of force from the astronaut.

III. Detailed Overview

To use S.P.A.D.E., the astronaut shall sequentially push the buttons on either side of the device. After pushing the blue button indicated in figure 1 , the astronaut may release the blue button and then press the green button.

Once the blue button is pressed, the parametric spring system retracts the locking component. This allows the bottom spring to move the buckle from Level 1 where the blue button is, to Level 2 of the locking device. This is done by compressing the parametric spring between the locking component and the device wall. Once the green button is pushed, it activates the second locking component, which moves the buckle to the lid in the same manner as the blue button. Since the locking component compresses the parametric spring, the buttons are reset as the spring naturally decompresses, shifting the locking components back into place. Alongside the locking components, the bottom coiled spring will guide the tool all the way up to the silicone lid, where the buckle will be held in place by the friction from the silicone. With minimal force, the astronaut can then pull the tool out of S.P.A.D.E.'s lid. When stowing the tool, the astronaut can use a single hand to replace it in the docking shell, since the funnel at the top of the Lid will guide the buckle into the correct position.

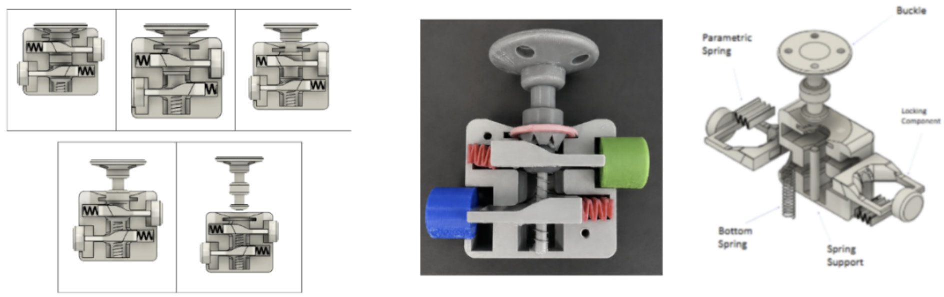

Fig. 1: Expanded View and Device Operation Sequence

IV. Components

A. Shell + Spring Support

To safely enclose various mechanical moving parts and adhere to the 5 x 5 x 5 inch constraint, a compact external housing was required. The Shell is the strong, outer component that houses the Locking Components and the Parametric Springs. Once the dock is actuated and the tool is docked, it ultimately also houses the Buckle. Since the inner mechanisms are housed inside the Outer Shell, the Shell protects the astronaut from any accidental lacerations or entrapment hazards. Furthermore, the Outer Shell is constructed from PET-G, a durable, lightweight plastic that optimizes the docking mechanism and the device's usability during EVA missions. As seen in figure 2, the Spring Support is a long, thin, durable rod that sits in the bottom center of the shell, with the bottom spring wrapped around it.

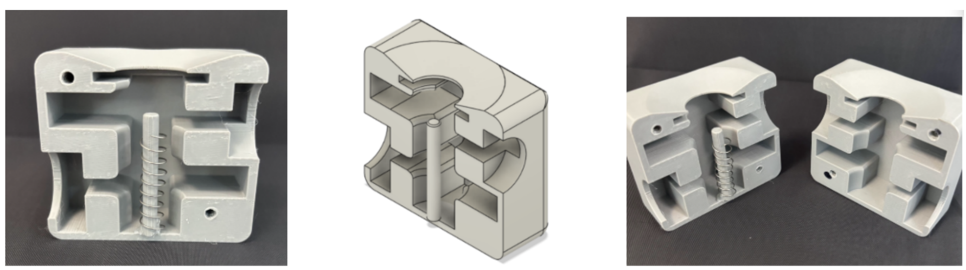

Fig. 2: Shell and Spring Support

It acts as a guide for the buckle and restricts the Buckle's movement while docked, thus preventing any potential snagging within the inner geometry. Its secondary purpose is to ensure that the bottom spring does not tangle when compressed. The height of the Outer Shell is 2.46 inches long, 2.75 inches wide, and 2.0 inches deep. The spring support is 1.15 inches tall and 0.256 inches in diameter.

B. Lid

The Lid is a small flexible disc that acts as a safety mechanism for S.P.A.D.E. It measures 3 inches in diameter and 0.05474 inches in width. It is composed of two very thin rings, measuring 0.00787 inches in width and an inner diameter of 2.9 inches that encase the main silicone body. The purpose of these rings is to increase the Lid's durability and prevent tearing. Figure 3 depicts the eight equal slits in the main body running from the edge of the rings to the center of the Lid.

The main body of the Lid is made of Platinum-Cured Silicone which was poured into a thin rectangular mold and cut into circles each with a diameter of 3 inches. The thin rings were 3D printed with Thermoplastic Polyurethane (TPU). This combination of materials ensures the Lid is flexible enough to allow the buckle to pass through, but strong enough not to rip after prolonged use.

The Lid has several functions. The first is to prevent a pinch point, which is defined as a possible danger zone for entrapment. In other words, every area on S.P.A.D.E. that an astronaut could get caught in or be injured by must be covered, are considered pinch points. The one pinch point on S.P.A.D.E. is the opening at the top of the shell where the buckle is inserted. Figure 4 highlights how this pinch point is impossible to eliminate, so it has been mitigated by covering the opening with the Lid.

Another important function of the Lid is to keep out space debris. If too much debris enters S.P.A.D.E., the mechanism is likely to fail. The Lid covers the opening to prevent this. See the "Debris Testing" section on page six for more information.

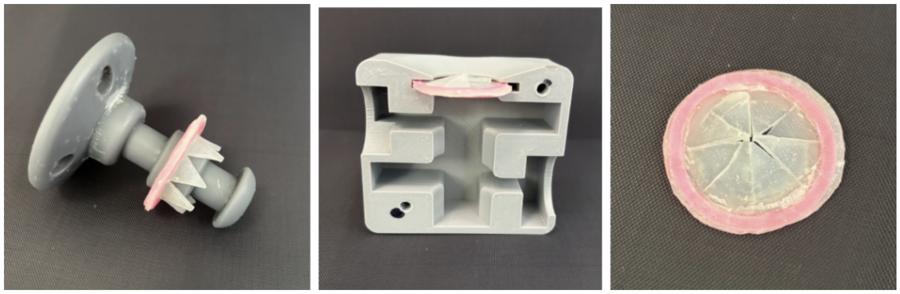

Fig. 3: Lid

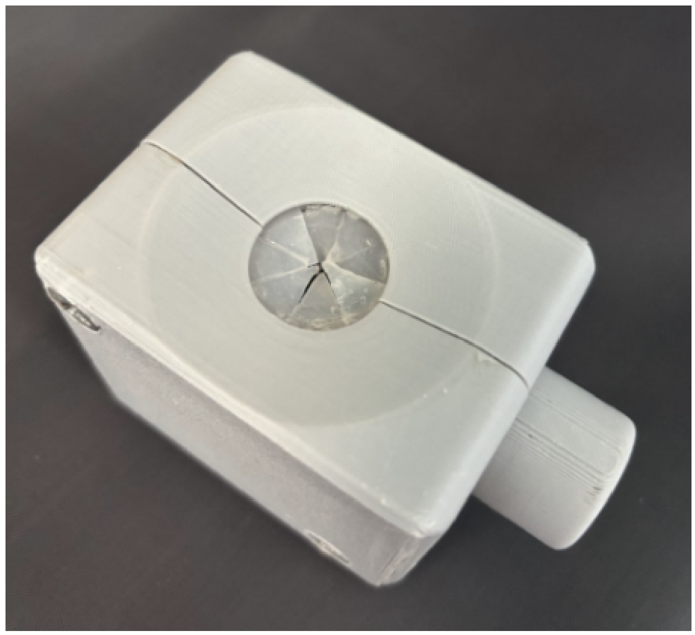

Fig. 4: Lid in Full Assembly

The final function of the Lid is to capture the Buckle as it is released from the Shell. Once both buttons are pressed, the Buckle is pushed up by the spring. The Lid prevents the Buckle and the tool from leaving the Shell fully and free-floating in space. The Lid requires the astronaut to apply a minimal amount of force to remove the Buckle, ensuring the astronaut has complete control over the tool.

C. Locking Components

In order to securely retain a 15-pound EVA tool and meet the single-fault-tolerance requirement, the device required a dual-action internal latching system. This ensures that an accidental bump will not release the tool into space. The Locking Components hold the Buckle in place when inserted. They also allow the Buckle to move out of the device when the corresponding button is actuated. This can be seen in Figure 5. Because these components bear the primary physical stress of securing the heavy tool, they were constructed from PET-G, a highly durable polymer chosen for its rigid structure and high impact resistance. Figure 5 highlights the geometry of the Locking Component as well as the tip of the Buckle that have been designed to ensure that the component does not get stuck during docking and retrieval of tools.

Additionally, the Locking Components avoid contact with screws and other internal systems and are guided by internal support. As the EVA tool is inserted, the Buckle causes the Locking Component to displace by 0.2 in. After the buckle is completely attached, the Locking Component moves back over the ledge of the buckle. When the buttons are pressed, the components are displaced again with the assistance of inner supports.

D. Parametric Spring

To ensure the docking mechanism can be actuated with minimal manual force (under 10 lbf), and to minimize the safety hazards associated with highly compressed stored energy, a specialized spring system was required. The parametric spring is

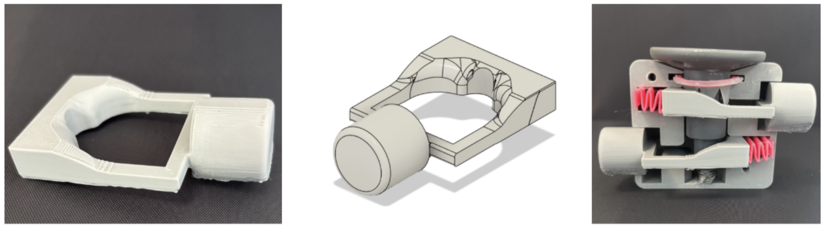

Fig. 5: Locking Component

located inside of S.P.A.D.E. and actuates the locking components over the divots in the buckle once the button is pushed. This spring is approximately 1.13 inches wide and 0.7 inches long. Figure 6 is the spring utilize during testing which was made of TPU; however, the fitting material we decided on for space usage is PEEK (Polyether Ether Ketone).

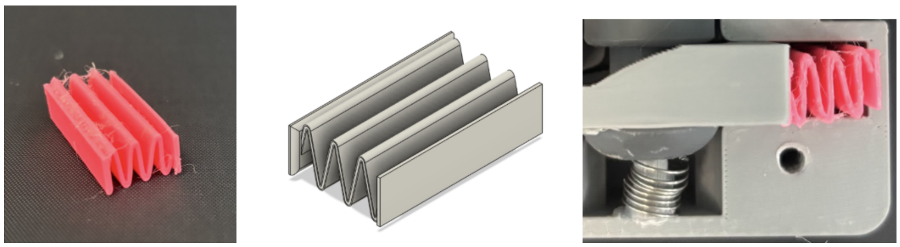

Fig. 6: Parametric Spring

We chose this material due to its ability to withstand extreme temperatures as well as its flexibility.

E. Bottom Spring

To satisfy the strict requirement for one-handed tool retrieval, the docking mechanism requires an active internal force to partially eject the tool once the locking components are disengaged. This prevents the astronaut from needing to use a second hand to manually pull the tool free. The spring at the bottom of the device pushes the buckle up and out past the Locking Components when the buttons are pressed so that the buckle is freed from the device making it available for the astronaut's use.

This spring, unlike the springs used in the locking component system, will be a stainless steel coil spring, as shown in figure 7.

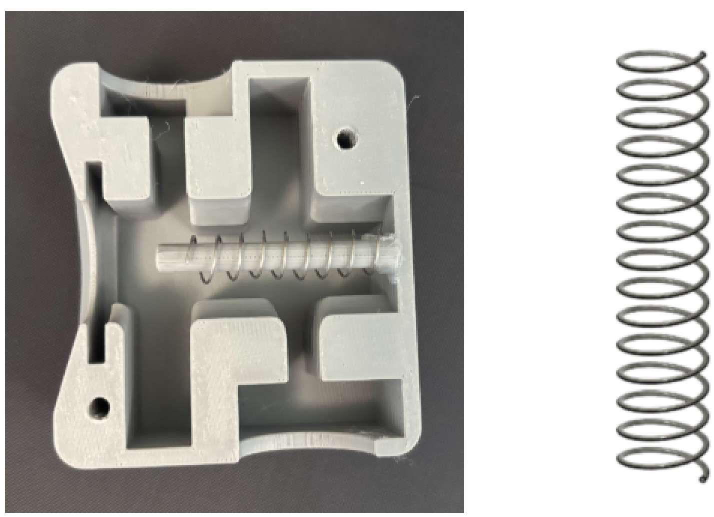

Fig. 7: Bottom Coiled Spring

Additionally, the spring needs to apply a force so that the Buckle can pass each part of the locking mechanism. When the device is attached to the astronaut's belt, the spring will be under compression, holding potential energy that will be partially released as each button is pressed. It will then be restored to its equilibrium position, releasing the buckle and therefore EVA tool.

This spring is smaller than the parametric springs with a larger spring constant due to its application of releasing the EVA tool. Compression springs such as this one are more durable than tension springs; therefore, they are less likely to yield for this purpose [12].

F. *Buckle*

In order to ensure compatibility across a variety of standard EVA tools, a reliable and universal attachment interface was required. The Buckle acts as this critical adapter, bridging the gap between the specialized docking mechanism and the astronaut's equipment. It attaches to the EVA tool and is inserted into the Shell of S.P.A.D.E through the funnel opening at the top. The Buckle was originally printed in Polyethylene Terephthalate Glycol-modified (PET-G) due to the material's ability to withstand high compressive forces without deforming. However, during testing, the PET-G did not consistently support the 15-pound tool and occasionally snapped under the weight. This made the component's functionality inconsistent. Resin is the material used in the final iteration to increase tensile strength, though the Buckle is intended to be made of stainless steel during final manufacture. It is rounded spherically at the tip (as seen in figure 8) to displace the locking components when inserted into S.P.A.D.E.

Fig. 8: Buckle

The Buckle also has a cylindrical opening at its tip, which the spring support enters to keep the Buckle straight as it is lowered into place. The other end of the buckle features four screw holes in a one-by-one-inch square pattern given by NASA's NBL guidelines, which ensures it works for a wide variety of EVA tools.

V. Design Description

A. *Prototyping*

Excluding the main body of the Lid, S.P.A.D.E. is fully 3D printed. The Shell and Locking Components were printed with Polyethylene Terephthalate Glycol, or PET-G, with a 75% infill as per Neutral Buoyancy Laboratory standards [4]. The buckle was printed with photopolymer resin for added durability. The Lid rings were printed in Thermoplastic Polyurethane (TPU) with 75% infill. The main body of the Lid is made of Platinum-Cured silicone. A thin rectangular mold the same width as the lid was 3D printed. From there the Platinum-Cured silicone was poured into the mold and cut into circles 3 inches in diameter.

3D printing should not be used in the final product of S.P.A.D.E. This was for prototyping and testing purposes.

B. ***Bill of Materials***

VI. Calculations

A. *Equation 1*

Equation 1 describes the Moment of Inertia for a rectangular cross section I. The left side contains I, a variable for the solution, whilst the right contains variables such as b (beam width) and t (thickness) which is cubed:

$$I = \frac{bt^3}{12} \tag{1}$$

B. *Equation 2*

$$k_{\text{leg}} = \frac{3EI}{L^3} \tag{2}$$

This step utilizes material, moment of inertia, and length to solve for k, the deflection constant of a single leg of the parametric spring. Equation 2 specifically describes a cantilever beam k:

$$\frac{1}{k_v} = \frac{1}{k_{\text{leg}_1}} + \frac{1}{k_{\text{leg}_2}} \tag{3}$$

TABLE I: Compliance Matrix

Requirement Description	Compliance
Tool installation can be done without looking	The Outer Shell has a funnel that guides the EVA Tool into its slot, making it so the action can be performed blind.
The device shall retain the tool with single fault-tolerance. I.e., the device requires two independent actuations to detach the tool.	The device will retain the tool with single fault tolerance since both buttons must be pushed in sequential order for the tool to be released from the locking mechanism.
Mass of the device shall not exceed 2 lbs in Earth gravity.	The device is approximately 0.37 lbs in earth's gravity.
For a linear-actuating mechanism, the force required to actuate shall not exceed 10 lbf (44.5 N).	The calculated force required to equip the EVA Tool onto the mechanism is 8.53N which is less than the maximum amount of 44.5N.
The device must support a tool that weighs 15 lbs.	The testing proved that S.P.A.D.E. is able to support both a 15 lb and 20 lb tool.
The tool shall require only manual power.	S.P.A.D.E. is spring-based and only requires manual power.
All 3D printed components must be at least 75% infill. This is to help ensure 3D printed parts are strong enough for the application and dense enough to sink in water.	All 3D printed components were printed with a 75% infill density.
There shall be no sharp edges on the device except functional sharp edges.	All sharp edges are inside of the mechanism and are unable to be accessed unless the device is taken apart. The outer shell is filleted to prevent sharp edges.
Uncovered holes or gaps, other than tether points, shall be less than 0.5 in. or greater than 1.4 in. to avoid finger entrapment as per NBL guidelines.	Only one uncovered hole that cannot be eliminated exists, and has been covered with the lid.

TABLE II: Bill of Materials

Components	New Materials	Justification
Locking Components, Buckle, Shell	Stainless Steel 302	Stainless Steel 302 is highly valued in aerospace for its superior heat resistance, high tensile strength, and fatigue resistance [13]. Utilizing this ensures minimal degradation.
Bottom Spring, Screws	Stainless Steel A286	Stainless Steel A286 has exceptionally high tensile strength, oxidation resistance, and structural stability across extreme temperatures [14].
Lid	Platinum-Cured Silicone	Platinum-Cured Silicone provides extreme temperature stability and radiation resistance [15]. Its flexibility allows the buckle to pass easily through the slits.
Shell (external sides)	BALINIT Dylyn Plus	BALINIT Dylyn Plus is a vacuum-friendly, low-friction, corrosion-resistant sealant regarded as an industry standard for stainless steel [16].
Locking Components, Shell (inside), Buckle	Teflon PTFE	Teflon PTFE is an ideal self-lubricating, wear-resistant coating for space mechanisms under harsh radiation and wide temperature swings [17].
Parametric Springs, Lid Support Rings	Polyether Ether Ketone (PEEK)	PEEK sustains UV exposure, ionizing radiation, and atomic oxygen exposure without structural harm [18].

C. Equation 3

This step shows how each leg of the spring can be added to create a deflection variable for a "V" pair instead:

$$\frac{1}{k_{\text{total}}} = \sum_{i=1}^{N} \frac{1}{k_v} = \frac{N}{k_v} \tag{4}$$

D. Equation 4

$$k_{\text{total}} = \frac{k_v}{N} \tag{5}$$

This step, similar to the last, adds all "V" pairs together, specifically 2.5, to find the total deflection constant of the spring.

E. Equation 5

$$F = k_{\text{total}} x = 8.53 \text{ N} \tag{6}$$

Equation 5 finds the force of the parametric spring using Hooke's Law.

F. Equation 6

Coiled bottom spring resistance:

$$k = \frac{d^4 G}{8 D^3 N} = 1500 \frac{\text{N}}{\text{m}} \tag{7}$$

VII. TESTING

A. Pool Testing

S.P.A.D.E. underwent numerous tests to ensure the device's effectiveness and durability. The first test performed was an underwater test of the device to simulate microgravity conditions. Water's buoyant force was leveraged to simulate a microgravity environment where gravitational forces have little to no effect. The goal of this test was to ensure the device would fully lock, actuate, and hold a tool properly in a microgravity environment such as in a space station or on a space walk.

There were two main criteria for determining the success of a test in the simulated microgravity environment. The first criteria was that the device had to fully lock. This means that the buckle must be fully inserted into the device and fully encapsulated by the locking mechanism. Both 15 and 20-pound dumbbells were added to the buckle to simulate a tool utilized during a space mission. The weight was secured to the buckle through its four hole screw pattern utilizing zip ties. Under the weight of both 15 and 20 pounds, S.P.A.D.E was able to completely lock. Additionally, when the tester moved around in an attempt to dislodge the buckle from the main body, they were unsuccessful with both weights.

The next testing criterion was the device's full actuation. This means that when actuated, the device must fully release (ie. pass through both locking components and out of the device) the buckle and tool for the tester's use. This test similarly used 15 and 20-pound dumbbells to simulate a tool. When actuated, the device successfully released the buckle and tool, allowing for easy retrieval and use of the tool within the simulated microgravity environment.

To ensure the validity of their results and to remain as true as possible to an actual microgravity environment, certain aspects of the test subject's movement were constrained to replicate an astronaut's pressurized gloves and restrictive spacesuit. Snorkeling masks were used to restrict peripheral vision. Once it was determined that the tester could easily retrieve and stow the device, their vision was completely restricted, and they were still able to do so easily. The tester also wore large, bulky hockey gloves and several layers of cling-wrap to restrict fine motor function of the fingers, and overall motor function of the shoulder and elbow.

B. Stress Testing

The device requires no more than 5 pounds of force to completely actuate. This allows astronauts to easily retrieve their tools from the dock. To ensure this measure was met, the force required to fully compress the parametric springs that allow the device to be retrieved was measured. This was determined to be 2.9 pounds-force. To ensure the locking component would not deform under significant external pressure, the force required to bend it was measured. The force required to bend the Locking Components (65 pounds-force) while they are not inside the Outer Shell cannot be achieved while the Buckle is inside the Outer Shell, thus there is no risk of the Locking Components deforming in any way due to extreme pressure.

Another component that was tested was the Outer Shell. This component is always exposed and thus carries a risk of damage due to coming in contact with other objects. The Outer Shell was able to withstand over 300 pounds-force of pressure, which is significantly more than any amount could be placed on it, especially in space.

C. Debris Testing

The second test that was carried out was debris testing. Space dust is infamous for getting into small crevices and causing hazards. This is problematic for mechanical systems, electrical systems, magnetic systems, and has caused mission failures. Debris testing ensured that, in the presence of floating space debris, S.P.A.D.E. would still fully actuate and lock. To perform this test, three different materials (flour, sand, and small gravel) with 5, 10, and 15 grams each, were placed on top of S.P.A.D.E.'s Lid. S.P.A.D.E. was then swiftly inverted once and the buckle was pushed through the Lid in an attempt to lock the device. S.P.A.D.E. was successfully locked and actuated with 15 grams of flour, 10 grams of sand, and 10 grams of gravel. When 15 grams of the two larger substances were present, S.P.A.D.E. successfully locked, however was unable to completely actuate due to debris jamming the locking mechanism.

D. Lid Testing

The final test conducted was Lid testing. The Lid is a critical component of the device and is necessary to secure the buckle to the device and to prevent debris from entering S.P.A.D.E., ultimately enhancing S.P.A.D.E. 's durability and structural integrity. Therefore, it is critical that the Lid's structural integrity is ensured during the repetitive actuation of S.P.A.D.E. without degradation. In both dry and wet environments, the buckle was actuated out of S.P.A.D.E. until the team noticed visible deterioration. During dry Lid testing, visible deterioration occurred at the 149th pass when 1 of the Lid's 8 slits tore off. Similar results were found during wet Lid testing. S.P.A.D.E. was submerged in freshwater, and the same method was executed. There was visible deterioration at the 150th pass, with noticeable tearing, and at the 154th pass, 2 of the 8 slits tore off simultaneously.

TABLE III: Table of Dry and Wet Lid Testing

Number of Lid Passes	**Qualitative Observations For Dry Lid Testing**	**Qualitative Observations For Wet Lid Testing**
30	No visible deterioration	No visible deterioration
60	No visible deterioration	No visible deterioration
90	No visible deterioration	No visible deterioration
120	No visible deterioration	No visible deterioration
150	Visible Deterioration	Visible Deterioration
Exact Number	149: 1 of 8 slits on Lid tore off	150: slight tearing 154: 2 of 8 slits on Lid tore off

VIII. Safety

A. Overview

S.P.A.D.E. is a spring-assisted EVA tool dock that employs multiple moving mechanical components to actuate. To ensure astronaut safety, the architecture and functionality of S.P.A.D.E. was designed to minimize all potential risks. S.P.A.D.E. was vigorously tested and iterated upon, changing materials and component design as needed to maximize astronaut safety during extravehicular missions.

All moving mechanical components are enclosed within the two Outer Shells of S.P.A.D.E., with the point of entry being the only opening present. The Lid is placed here to act as a shield between the astronaut and the sole pinch point on S.P.A.D.E. Enclosing the bottom spring, parametric springs, and locking components within the shell ensures that no component is exposed to the outside environment, preventing rapid deterioration and any potential lacerations. Because various environmental factors, such as debris or component fatigue, may lead to the mechanical failure of S.P.A.D.E., all components are housed within the Shell and hence will not be exposed to the astronaut. Additionally, to mitigate the potential of snagging on the astronaut's suit, the entire outer body of S.P.A.D.E. is filleted and sanded down to have a completely smooth surface with no sharp edges or abrasions.

During material selection, filaments and infill for 3D-printed parts were chosen to prioritize device longevity, durability, and the functionality of each component. All 3D-printed components of S.P.A.D.E. are printed with a 75% infill to maximize the lifespan. Flexible polymers such as TPU and Platinum-Cured Silicone were utilized to prototype components that prioritize flexibility as their main functionality. TPU allows the Parametric Springs to flex and successfully engage both the Locking Components and Buttons. The Lid is primarily composed of Platinum-Cured Silicone with TPU rings as support, hence acting as a successful barrier and acting as a form of second fault tolerance. The elasticity and sealing nature of Platinum-Cured Silicone create a safe entry point for the Buckle. PET-G was the primary filament used to print the Shell, Locking Components, and Spring Support. A durable material, PET-G is a rigid structure with high impact resistance, and chemical and heat adhesion. Hence, it serves to withstand potential operational abuse and maximum stress tolerances. Lastly, Resin was used for the Buckle to ensure a tight molecular structure and almost brittle durability so the Buckle can withstand high-impact usage. These materials prevent material degradation and thereby ensure astronaut safety in harsh testing or space environments.

The Bottom and Parametric springs store potential energy, which can lead to uncontrolled tool ejection, compromising astronaut safety and system integrity. To mitigate this, parametric springs are used due to their low stored energy. The bottom spring is a coiled spring, thus decreasing the spring constant and minimizing the risk of unintended release.

To prevent an accidental ejection of the EVA tool, the tool is pushed out a centimeter before being trapped by the Lid. This provides a measure of second-fault tolerance and requires the astronaut to deliberately use a minimal pulling force to fully actuate the EVA tool.

The risk matrix in figure 9 analyzes potential hazards found in S.P.A.D.E. and ranks it based on likelihood and consequence.

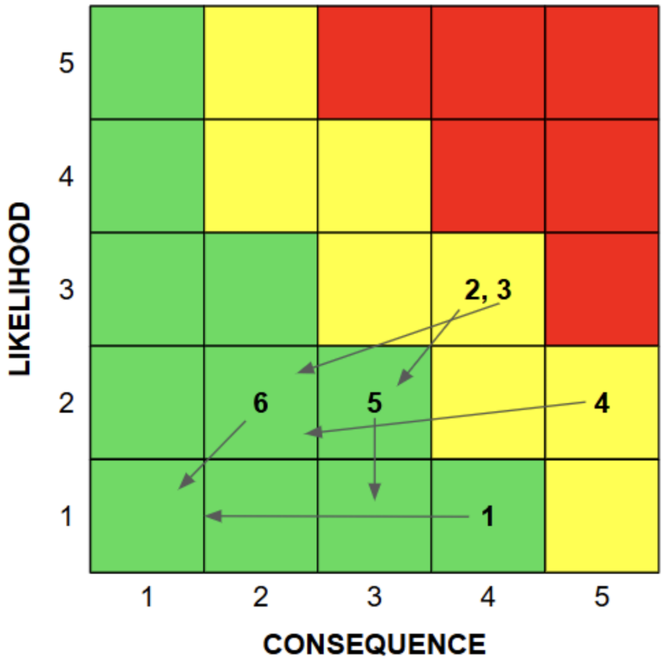

Fig. 9: Risk Matrix for Each Hazard's Likelihood and Consequence

TABLE IV: Explanation of Risk Matrix

ID	Description	Mitigation
1	Degradation	- The Lid is molded out of platinum-cured silicone with TPU supports along the outer ring, ultimately slowing degradation. - The Lid material and thickness of the Lid are altered by utilizing a sealant around the inner mechanisms and outer shell.
2	Environmental Intrusion	- The mechanical components are tightly sealed. - Platinum Cured Silicone and TPU supports prevent debris from entering the device.
3	Structure/Mechanical Failure	- The device is designed to tolerate stronger forces than it should have inflicted upon it.
4	Pinch Points	- The only instance of a pinch point on S.P.A.D.E. is the opening for the Buckle to enter the Outer Shell. The Lid mitigates this.
5	Stored Energy	- The main source of stored energy, parametric springs, are designed to have less stored energy than traditional metal coiled springs.
6	Sharp Edges	- S.P.A.D.E.'s sharp edges were filed down and filleted in the CAD.

TABLE V: Safety Hazard Analysis

No.	Hazard	Cause Scenario	Consequence/Effect	Mitigation	Verification
1	Stored Energy (Spring)	- There may be an unintended release of stored potential energy within the spring. - Due to user or mechanical error, accidental release of buckle.	These scenarios could lead to personnel injury, equipment damage, and lacerations in astronaut's EVA suit.	Decreased spring constant (Bottom Spring: 31.52 N/m, Parametric Springs: 102.27 N/m). Lid serves as a barrier and provides second-fault tolerance.	During water testing, buckle was intentionally ejected and completely contained by the Lid.
2	Pinch Points	S.P.A.D.E.'s sole pinch point is located at the top opening. Improper user training.	Interactions with pinch point could damage suit/equipment or cause injury.	The Lid acts as a barrier between astronaut and tool opening, preventing finger entrapment.	During water testing, tester sustained zero injuries regarding pinch points. No entrapment or lacerations occurred.
3	Environmental Intrusion	Fine particles enter through openings during EVA missions.	Jammed springs leading to buckle jamming and complete mechanical failure.	Silicone Lid covers opening to keep loose debris out. All components enclosed.	Debris testing with 10g sediments verified Lid prevented ingress; device locked and actuated successfully.
4	Structural/Mechanical Failure	Heavy debris impact or user error leading to mechanical failure.	Mechanism damage, equipment loss, and personnel injury.	75% PET-G infill utilized for rigid parts due to robust mechanical properties.	Stress testing proved S.P.A.D.E. maintained integrity under maximum rated loads without deformation.
5	Degradation	Repeated actuation and fine particle intrusion causing friction and wear.	Deterioration of internal components, affecting device longevity.	75% PET-G infill, TPU supports, and dry lubricant coatings applied to minimize fatigue.	Cyclic testing confirmed Lid durability through 150 cycles; internal components protected by sealant.
6	Sharp Edges	Manufacturing and 3D printing defects creating burrs.	Suit lacerations, restricted astronaut movement, or equipment tears.	External edges filleted and sanded smooth; components enclosed within shell.	Water testing confirmed zero punctures or abrasions sustained by the user.

IX. Conclusion

S.P.A.D.E delivers a single-fault-tolerant mechanical docking solution that addresses the concerns operators have during EVA missions. Through simulated microgravity and debris testing, S.P.A.D.E demonstrated its capability to secure heavy equipment with one-handed, blind installation while completely isolating the astronaut from potential hazards. Ultimately, S.P.A.D.E. provides a scalable and reliable blueprint for next-generation tool-docking infrastructure in space. S.P.A.D.E is composed of 7 components each individually manufactured then assembled. This paper details that process. S.P.A.D.E. should be used by engineers and manufacturers as a tool docking mechanism. Its design makes it a safe, easy way to use and store tools at work. While its original purpose was for EVA space missions, it may be used in any situation where a tool requires safe docking and easy retrieval. S.P.A.D.E.'s design makes it ideal for situations where the user has limited mobility or can use only one hand. Examples include roofers and climbers. It is important to note that with the addition of gravity, a heavier tool (an estimated 10 pounds or more) would likely not work in S.P.A.D.E. In space, the device has been thoroughly tested and will function correctly.

Future iterations of S.P.A.D.E. should mainly focus on improving the durability of the Lid, and further increasing the device's resistance to debris. The dimensions, material of construction, or overall design should be redesigned in order to lengthen the lifespan of the Lid. Additionally, implementing more precise tolerances and better methods to seal the shell should also be considered in order to prevent failure due to trapped debris. Future iterations would benefit from these suggestions, as well using more accurate EVA equipment in order to confirm long term durability and ease of operation.

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CAD

This is the link to the CAD of S.P.A.D.E. Fusion. (2026). A360.Co. https://a360.co/4wXIcIZ

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