

College of Engineering, Computer Science, and Technology

Department of Mechanical Engineering

Project 103: Free Flyer Docking System



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Table of Contents

Abstract	3
I. Introduction	4
II. Background / Related Work	4
III. Concept Development and Trade Study	5
Conceptual design phase	5
Inflatable Nose	7
Bayonet Capture	8
Anchor Mechanism	10
Robotic Claw	14
Trade study	15
IV. System Design	16
V. Engineering Analysis	19
VI. Hardware Implementation	22
VII. Testing and Results	23
VIII. Discussion	23
IX. Conclusion	24
References	25

Abstract

Autonomous docking and capture capabilities are becoming increasingly important for satellite servicing, debris mitigation, and the development of on-orbit infrastructure. While standardized docking interfaces exist for crewed spacecraft visiting the International Space Station, most notably the International Docking System Standard (IDSS), these systems are designed for cooperative vehicles and are not widely implemented across the broader satellite population. As a result, many spacecraft lack compatible docking interfaces, limiting the ability to service, repair, or capture both planned and unplanned targets in orbit.

This limitation is especially critical for missions that do not involve human interaction. Spacecraft designed for astronaut servicing often include handrails and other accessible features, but most satellites do not. Therefore, there is a need for autonomous capture systems capable of interfacing with existing structural features such as rings, rails, or exposed components without requiring prior design accommodations. In this work, the proposed docking mechanism is integrated onto an X-Sat Venus class servicing spacecraft, which serves as the host platform for deploying a robotic arm and end-effector system designed to capture and secure client satellites.

This project investigates an alternative capture approach based on robotic manipulation rather than traditional male-female docking interfaces. A trade study was conducted comparing conventional docking mechanisms with robotic capture concepts to identify a system architecture that is mechanically simple, adaptable to varying geometries, and feasible within the constraints of an academic prototype. Based on this evaluation, a tendon-driven anthropomorphic end-effector finger with torsional spring return was selected as the primary capture mechanism.

The present work focuses on the development of a prototype finger mechanism intended to demonstrate grasping capability across a range of target geometries. This prototype serves as a proof-of-concept toward a modular robotic end-effector capable of capturing both cooperative and non-cooperative spacecraft. The results of this work contribute to ongoing research into adaptable capture systems that could complement existing docking technologies and support future satellite servicing missions.

I. Introduction

Many satellites at the end of their operational life remain structurally intact but become non-operational due to power loss, communication failure, or attitude control issues. These non-cooperative spacecraft often drift or tumble in orbit, making traditional servicing operations difficult. A key challenge in on-orbit servicing is the ability to safely capture and stabilize these targets before any repair, refueling, or reactivation can occur.

Existing docking systems are primarily designed for cooperative spacecraft with predefined interfaces, such as those used for crewed missions and International Space Station operations. Systems such as the NASA Docking System rely on precise alignment and standardized interfaces to achieve secure connections between vehicles [1]. However, most satellites in orbit do not include such features, limiting the ability to service a wide range of existing spacecraft.

As interest in satellite servicing and debris mitigation continues to grow, there is an increasing need for capture mechanisms capable of interacting with non-cooperative targets. Research has explored robotic manipulators and adaptable capture systems that can engage with existing spacecraft structures [2].

This project aims to develop a conceptual docking system capable of capturing non-cooperative satellites using a robotic arm and finger-based end-effector. The system targets existing structural features such as launch vehicle adapter rings and truss elements, eliminating the need for dedicated docking interfaces.

II. Background / Related Work

Robotic manipulation has played a critical role in space operations, particularly in servicing, assembly, and maintenance tasks. One of the most well-known examples is the Canadarm2 system installed on the International Space Station (ISS), which has demonstrated the ability to capture visiting spacecraft, reposition large payloads, and assist astronauts during extravehicular activities. The success of Canadarm2 highlights the effectiveness of robotic arms and end-effectors for performing complex tasks in a microgravity environment and serves as a strong foundation for robotic capture systems [1].

Traditional spacecraft docking systems, such as the NASA Docking System (NDS), rely on precisely aligned mechanical interfaces, guide petals, and electromechanical latching systems to establish a rigid connection between two vehicles. These systems are highly reliable and have been successfully used for crewed missions and ISS operations. However, they require both spacecraft to be equipped with compatible docking ports and to maintain controlled relative motion during approach. As a result, these systems are not suitable for non-cooperative targets that lack predefined docking interfaces [1].

To address this limitation, recent research has focused on alternative capture strategies capable of interacting with satellites that were not designed for servicing. NASA and other organizations have investigated a range of capture mechanisms, including mechanical claws, net-based systems, harpoons, and robotic manipulators. These systems aim to safely capture and stabilize target spacecraft while minimizing the risk of damage [2]. Among these approaches, robotic grippers and manipulators have gained significant attention due to their versatility and adaptability. Mechanical claw grippers are widely used in industrial robotics and provide strong, reliable gripping capability through rigid linkages. However, these systems often require precise alignment and can generate high impact forces during contact, which may be undesirable for delicate spacecraft structures.

Compliant and underactuated grippers offer an alternative approach by allowing the fingers to adapt passively to the shape of the target object. Research in robotic manipulation has shown that tendon-driven and compliant finger designs can achieve robust grasping performance while maintaining relatively simple mechanical architectures. The Yale OpenHand project is a notable example, demonstrating low-cost anthropomorphic grippers capable of adapting to a wide range of object geometries using tendon actuation and compliant joints [3]. Another class of capture systems includes granular jamming grippers, which use a flexible membrane filled with granular material that stiffens under vacuum. These systems provide excellent shape conformity and passive adaptability but introduce additional system complexity and challenges in achieving a rigid structural connection.

Overall, existing research indicates that robotic manipulation offers a promising solution for capturing non-cooperative spacecraft. By leveraging compliant mechanisms and adaptable end-effectors, it is possible to interact with existing structural features such as adapter rings, trusses, and support members without requiring dedicated docking interfaces. This capability is critical for enabling future satellite servicing, debris mitigation, and in-space assembly missions.

III. Concept Development and Trade Study

Conceptual design phase

The conceptual design phase will primarily be guided by the list of criteria provided by our client. Before any ideas were developed, the team reviewed the requirements to fully understand the functional expectations, performance goals, and constraints that the final product needed to satisfy. This ensured that all the concept designs aligned with the objective and stayed within the intended scope of the project.

During this phase the team used the criteria provided as a foundation. Each member of the team generated one possible design through individual research and group brainstorming that had a passive and aggressive side, an alignment mechanism, soft latch, hard latch, and allowed for scalability. Rather than focusing on fine details, the emphasis was on exploring different

ways to achieve the requirements effectively. This approach leveraged mechanisms commonly used in industry and existing mechanical systems.

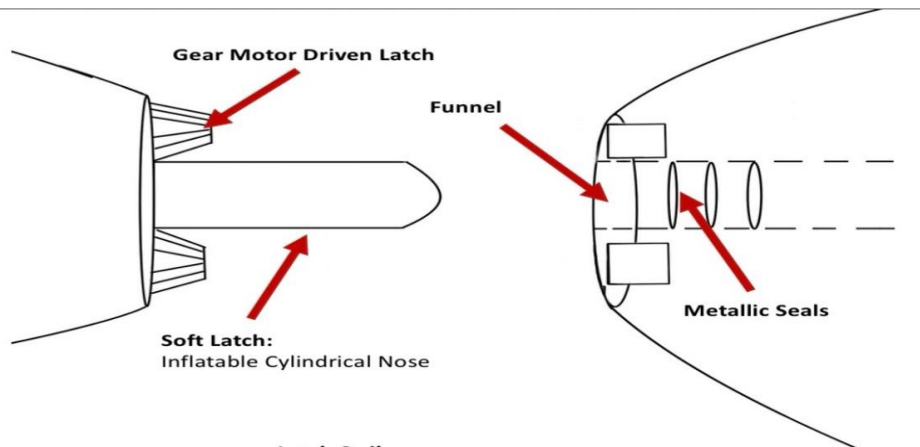
The initial phase generated five distinct concepts, which were evaluated based on a weighted criterion.

1	...	TRL	...	30%
2	...	Complexity	...	20%
3	...	Reliability	...	10%
4	...	Manufacturability	...	20%
5	...	Capture	...	15%
7	...	Separation	...	5%

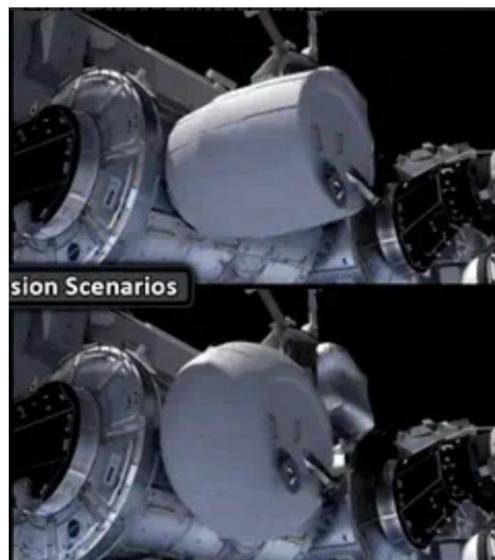
Technology Readiness Level (TRL) evaluated how developed and flight-ready the components are, with designs based on established flight heritage scoring higher. Manufacturability measured the ease of fabrication, assembly, and testing using existing methods, favoring designs compatible with standard machining or Commercial off the Shelf (COTS) components. Complexity assessed the number of parts required for a single action, awarding higher scores to concepts with fewer moving parts and reduced mechanical interfaces. Finally, reliability assessed the likelihood of consistent performance without failure, favoring mechanisms with proven failure rates, redundancy, and simple operation.

The second group of criteria focused on the core functional requirements of the docking system. Capture defined the system's capability to make contact and secure alignment without damage, with systems enabling compliant, forgiving, low-impact engagement scoring higher. The final criterion, Separation, evaluated the ability of the system to cleanly disengage and move apart from the mated vehicle without interference, with predictable, low-force, controlled separation mechanisms scoring higher. This methodology was used to objectively select the two strongest concepts for Phase 2 development.

Inflatable Nose



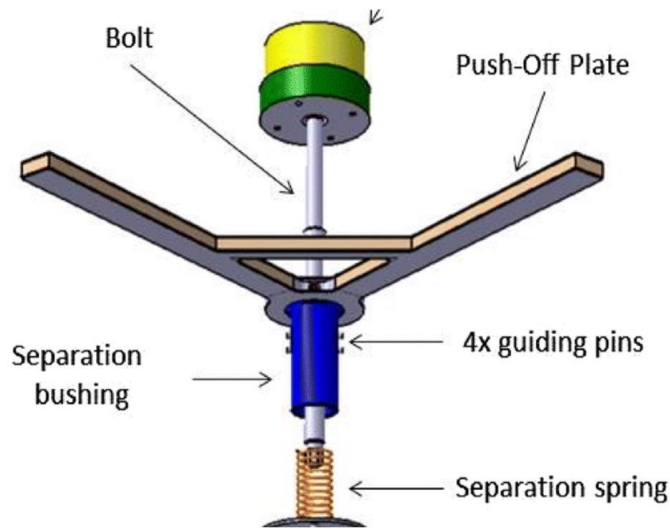
The inflatable nose concept is an active mechanism relying on a controlled and powered change of state due to its inflation and deflation. A similar concept is the Bigelow Expandable Activity Module (BEAM), which is an inflatable habitat on the ISS. The nose is a pressure stabilized structure, where it gets its strength from internal gas pressure. This helps lightweight material handle heavier loads. The inflatable nose would use a strong synthetic fiber such as vectran because it is five times stronger than steel, and it can manage to fold and bend. It would be reinforced with a mylar liner because it is used for a reflective and lightweight material to reflect radiated heat. Nitrogen gas will be used to inflate the cylindrical nose because it is nontoxic and noncondensing in orbit.



Bigelow Expandable Activity Module (BEAM)

The focus of the docking process is safety, precise alignment, soft capture, hard capture, and separation. When making contact, the inflatable nose operates as a safety device, and it stops metal to metal contact by capturing the kinetic energy from the closing velocity. The nose is

going to create a controlled centering torque by using angled funnel walls. The big angular inaccuracy such as 5 degrees will be corrected by the torque. The switch to hard capture starts once the probe is stable and centered. The nitrogen is released into the nose by the nose inflation manifold. The nitrogen gas goes through a secondary connection to the compressor unit, where it's repressurized and stored for later use, instead of being released into space. The nose clears the mating surface as it deflates.



The latch strikers on the passive vehicle port are engaged by the four electrical gears motor latches as they extend their hooks. To eliminate any final remaining angular misalignment, the electrical motors operate in a low power mode to apply a starting tension that pulls the stiff mating rings into parallel flush contact. To slowly reduce the big preload force, the electrical gear motor latches will reverse their torque. The separation process will begin by using springs that will push the two vehicles apart once tension is released. Guiding pins will act as a lock to compress and hold the springs in position. By using a non-explosive actuator as a release mechanism, it is activated during undocking. The restriction is eliminated when the non-explosive actuator releases the bolt. To succeed with the separation velocity, the push off plate is pushed against the other vehicle by the instant release of the stored energy in the separation spring.

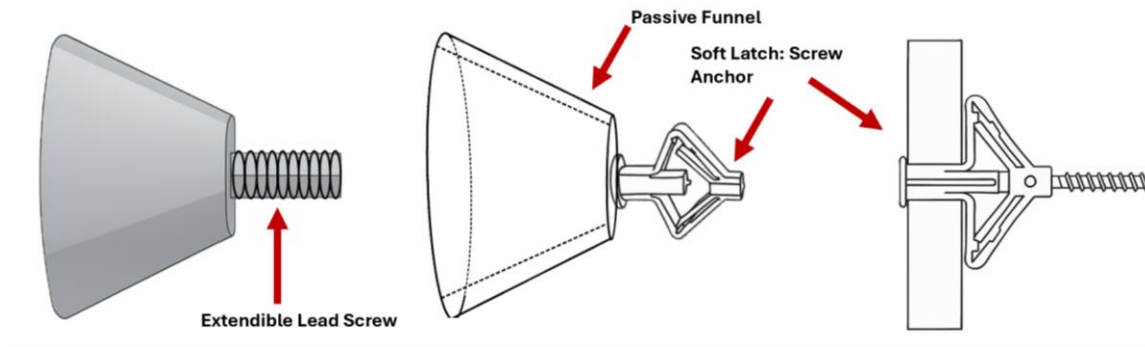
Bayonet Capture

The main goal for the docking mechanism is to create a mechanically simple, primarily passive system capable of aligning, capturing, and rigidly locking to a satellite without the need for ongoing power. This design came from looking at existing docking systems like the IDSS and IBDM. The goal was to make the system simpler and cheaper by replacing expensive motors with tools that help with geometry and locking. The main structure is made up of two interfaces rings, one active and one passive. The rings are meant to fit together using funnel self

alignment features, bayonet style rotating locks, and a compressive spring separation system. This method was chosen because it had to be scalable, manufactured, and used continuously while still being light.

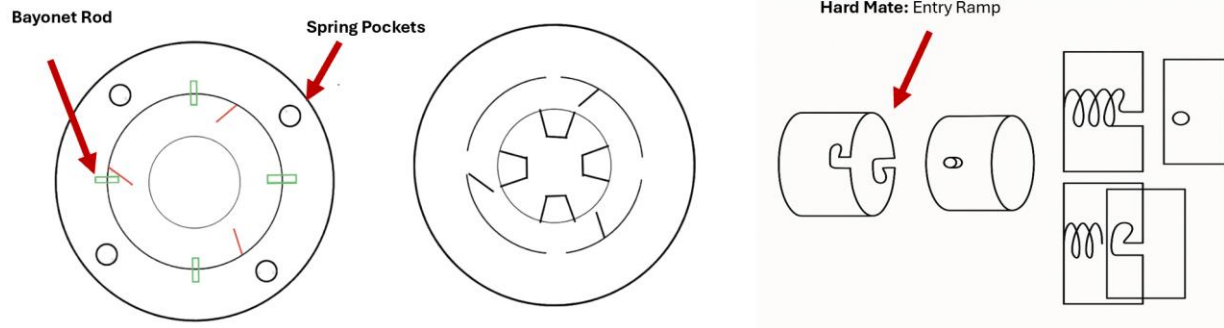
Mechanism for Soft Capture

A cone shaped funnel is attached to the passive side of the soft capture device. Its function is to smoothly guide the active spacecraft into the aligned position and orientation as docking starts. As the active ring moves into the funnel, the connecting geometry lowers the misalignment in length and angle. This helps the system fix small mistakes and translational offsets. The active ring encounters alignment through the funnel throat. This stabilizes the interface before hard capture happens. The soft capture mechanism creates a stable middle position that can handle capture position. This keeps the main locking mechanism from engaging when the components are not lined up correctly.



Mechanism for Hard Capture

The system changes from soft capture to hard capture with the help of a bayonet style rotational lock. In this form, the active side has tabs or lugs that stick out and fit into bayonet slots on the passive ring. When the lugs are properly inserted and lined up, they move back forth a small amount, sliding behind the structural shoulders inside the holes. This rotation makes a mechanical interface that forms a rigid link between the structures that can handle both axial and shear loads. The device locks itself, so it doesn't need to be continuously actuated to keep the preload. The funnel and bayonet system work together to make a two-step docking process. The first step is passive alignment, and the second is a safe, mechanically locked joint.

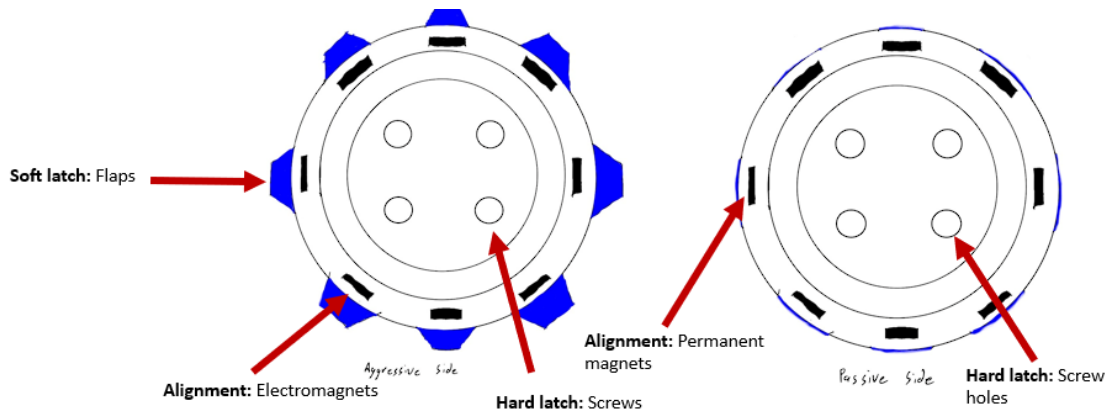


Mechanism for Push Off

The docking system has a spring based push-off mechanism placed behind the passive interface ring so that the two parts can be separated reliably and with precision after hard capture. As the active ring engages and the bayonet mechanism locks during docking, these compression springs are fully loaded. They store potential energy for the servicing action. The bayonet lock is released when a separation order is sent. This lets the springs move freely, creating a predictable axial force that moves the active spacecraft away from the passive side. This passive process gets rid of the need for thruster based separation during the initial departure and makes sure the system meets the goal of a minimum relative speed of 1 ft/s. The push-off mechanism makes the system more reliable and less complicated by using springs that don't need power, sensors, or complicated controls. It also provides a repeatable, low risk way to undock that can be used for many service rounds.

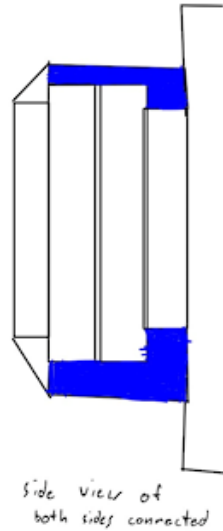
Anchor Mechanism

The Anchor Mechanism is designed as a multi-staged process that combines a magnetic alignment system, soft capture, and hard capture that ensures secure, repeatable, and precisely aligned connections between two mating surfaces. The sequence begins with magnets attracting one another allowing for guidance and fine adjustments that bring the two sides together allowing for proper orientation. Once both sides are aligned, the flaps fold down to allow for a soft capture, stabilizing the interface with a temporary hold that accepts slight remaining discrepancies. Finally, the screws and anchors form a hard latch, securing the connection between the two sides. Together, these phases create a system that allows for ease of engagement with structural reliability.

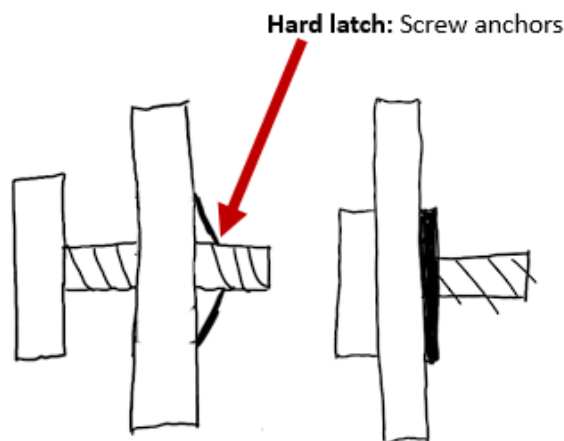


Docking begins with the alignment phase, where the magnetic forces guide the two sides into proper orientation before any mechanical engagement occurs. There are permanent magnets on the passive side that provide a course pull which ensures that the aggressive side is drawn into the correct position. The aggressive side has electromagnets that help refine the self-alignment capabilities. The magnets also allow for a soft capture by holding the two sides together. The alignment phase is critical because it reduces the risk of misalignment that could damage the hardware or compromise the structural integrity of both sides. By combining passive reliability with active control, the alignment phase establishes a precise foundation for the subsequent capture and locking steps.

Once the alignment is completed, the main soft capture phase begins. The soft capture phase engages flaps that fold down from the aggressive side onto the passive side. These flaps fold down and hoop inward onto the passive side creating a hold that stabilizes the connection without requiring too much force. The flaps also allow for any minor bounce or drift during docking. This capture allows for the system to maintain contact while preparing for hard latch, ensuring that the two sides don't separate under and disturbance. The soft capture acts as a transitional safeguard between magnetic alignment and full mechanical locking.



The final stage is hard latching, where the screws and anchors secure the connection into a rigid load-bearing joint. Screws in the aggressive side engage with the help of springs to help catch onto the threads in the passive side. The motors on each screw then activate to begin the threading phase and allowing for the anchors to open inside the passive side. This provides a secure connection that is resistant to vibrational, torque, and environmental stresses. The hard latching phase ensures that the connection can withstand operational loads and repeated use without loosening. By anchoring internally, the hard latch eliminates accidental disengagement and guarantees long-term reliability.

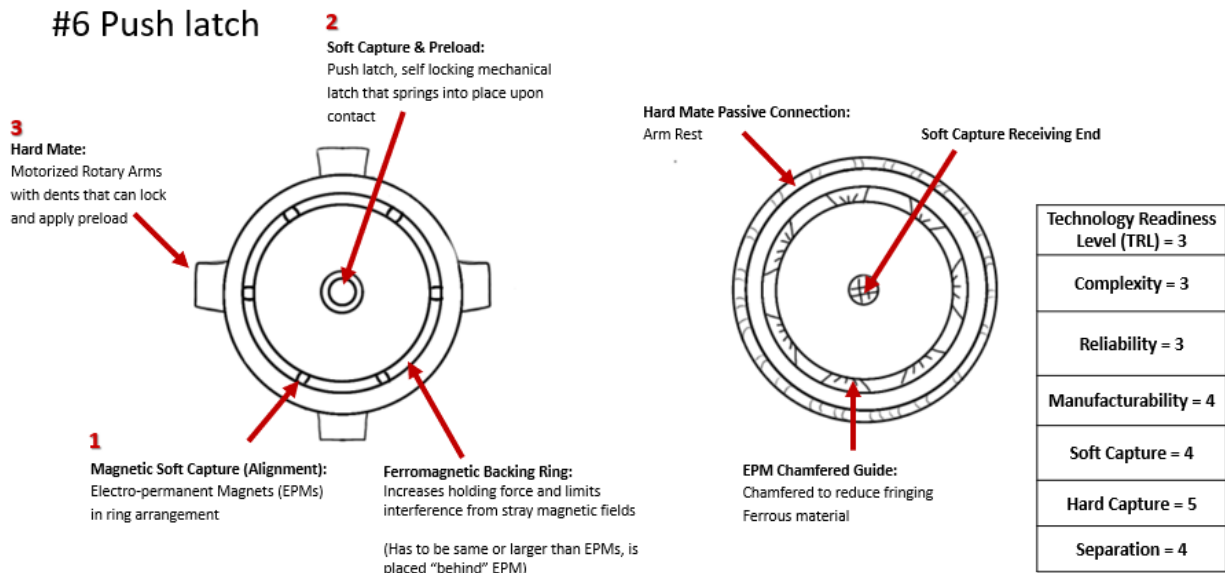


The steps of the separation phase reverse the docking sequence in a controlled manner to ensure safe disengagement. First, the hard latch is released by unscrewing or disengaging the anchors, removing the rigid mechanical bond. Once the structural lock is undone, the soft capture flaps unfold outward, freeing the passive side while still preventing sudden drift.

Finally, the magnetic forces are deactivated-electromagnets switch off, and permanent magnets are overcome by a slight mechanical push or guiding motion-allowing the two sides to cleanly disengage. This staged release precludes shock loads, misalignment damage, or unintended re-capture, and makes the separation process as reliable and repeatable as the docking itself.

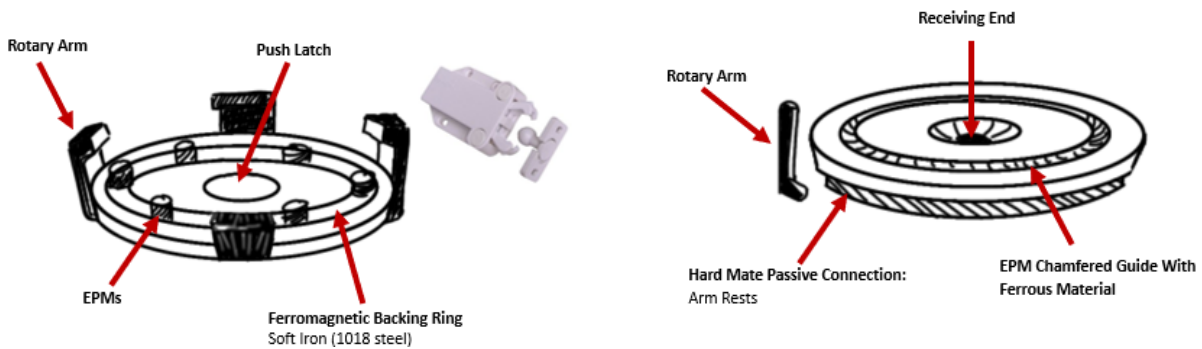
Push Latch

The Push Latch integrates three distinct mechanical and electromagnetic systems to execute the complete docking process in sequence: alignment, soft capture, hard capture, and separation. It is important to note that this is the current design intent, and all performance metrics are yet to be verified through analysis or testing.



The sequence begins with initial alignment using Electro-permanent Magnets (EPMs), a single pulse of current will allow the attraction process to commence, another pulse to switch the poles would be sent after the mission is completed and the system is ready to separate. As the service vehicle approaches the client satellite, the EPMs, arranged in a ring on the active side, are activated. These EPMs interact with the Ferromagnetic Backing Ring, made of a material like soft iron 1018 steel, on the client side. This non-contact magnetic force provides the magnetic soft capture, stabilizing the vehicles, dampening relative motion, and guiding the interface to the center axis. The passive side features an EPM chamfered guide with ferrous material to reduce magnetic fringing and aid the

alignment process.



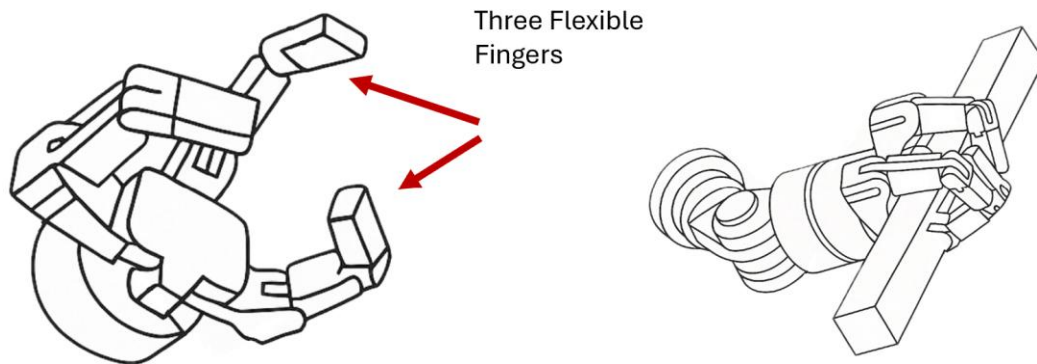
Following magnetic stabilization, the system enters push latch soft capture. This mechanism, located in the center of the interface, is a self-locking mechanical latch that is designed to spring into place upon contact. The push latch provides the initial structural connection and pre-load, managing the transfer from the non-contact magnetic interface to the rigid mechanical phase. Once the push latch engages, the internal sensors will confirm the retention, signaling the control system that the misalignment has been sufficiently corrected and the system is ready for the hard mate. The sequence concludes with motorized rotary arms which engage with the arm rests on the client vehicle's hard mate passive connection. These arms utilize dents to lock and are motorized to precisely draw the interfaces together. This mechanical action is designed to generate a high pre-load, which is essential for achieving a fully rigid structural lock and enabling subsequent on orbit servicing operation.

The final phase is separation. The process is reversed by commanding the motorized rotary arms to release the pre-load and retract. The final separation impulse is intended to be provided by the stored energy of the push latch mechanism or an integrated ejection component. This impulse is critical for achieving a controlled separation velocity of $1 \frac{\text{ft}}{\text{s}}$ and avoiding re-contact.

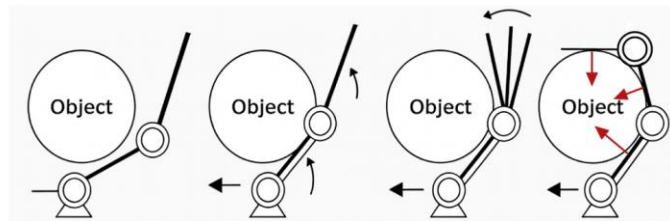
Robotic Claw

In this design for docking, the system relies on a robotic grapppler to make initial contact to anchor the client spacecraft. The robotic grapppler can connect to a variety of external surfaces, this lets it hold satellites with lacking or irregular geometries. The device has an extendable arm with multi fingered or claw like end effector that can fit around edges, structural rails, or flat surfaces. When the grapppler is fully extended, it makes contact with the target satellite, applies controlled gripping force, and stabilizes it by firmly anchoring itself to the chosen surface. This method increases the capture area, so the service vehicle can dock even if the client vehicle isn't aligned correctly or doesn't have a normal docking port. The grapppler is more complex

mechanically than passive concepts, but it is also very flexible, so it can be used for missions that need to service a wide range of spaceships without having to set up specific interfaces.



Self-locking Underactuated Mechanism



Trade study

After each member of the team refined their concept design, we compared them using a trade study. This was formed using a list of criteria that allowed for equal comparison between all the designs. The list of criteria include technology readiness level (TRL), complexity, reliability, manufacturability, capture, and separation. The table below displays what our criterion mean, scoring logic, and how much each criterion is weighted.

Based on our trade study results shown in the table below, the Push latch and the Robotic claw were found to be the best performing concepts, with the Robotic claw coming out on top with a total score of 3.525. These two mechanisms had strong performance based on manufacturability, reliability, and great capture performance which is a key factor for a robust on-orbit capture mechanism. Both the Inflatable nose and Anchor mechanism both showed great performance in some categories but ended up falling behind in others such as separation and reliability. The Bayonet capture and Gecko skin scored lower due to their reliability, manufacturability, or capture effectiveness.

As a team, we ultimately selected the Robotic claw as the design we want to move forward with due to its versatility which allows for it to be used on nearly any surface without a passive side and strong performance across all criteria. The Robotic claw showed great capability in

both soft and hard. Its higher TRL further shows greater technological maturity which reduces the risk of development and increases confidence in its performance during on-orbit operations.

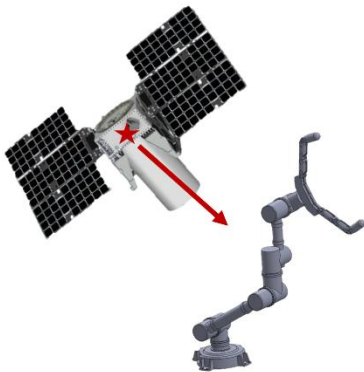
Design	TRL (30%)	Complexity (20%)	Reliability (10%)	Manufacturable (20%)	Capture (15%)	Separation (5%)	Total
Inflatable nose	0.9	0.6	0.3	0.4	0.45	0.15	2.8
Bayonet capture	0.9	0.4	0.2	0.4	0.45	0.25	2.6
Anchor mechanism	1.2	0.4	0.2	0.6	0.6	0.15	3.15
Push latch	0.9	0.6	0.3	0.8	0.675	0.2	3.475
Robotic Claw	1.2	0.6	0.3	0.8	0.525	0.1	3.525
Gecko Skin	0.6	0.8	0.3	0.4	0.375	0.1	2.575

Table 1 Ranked and Weighted Trade Study

Our team ranked each criterion from 1-5, 5 being the best, 1 being the worst. Once ranked we multiplied the weight and summed the values up to get the total value of the overall design.

IV. System Design

System Architecture

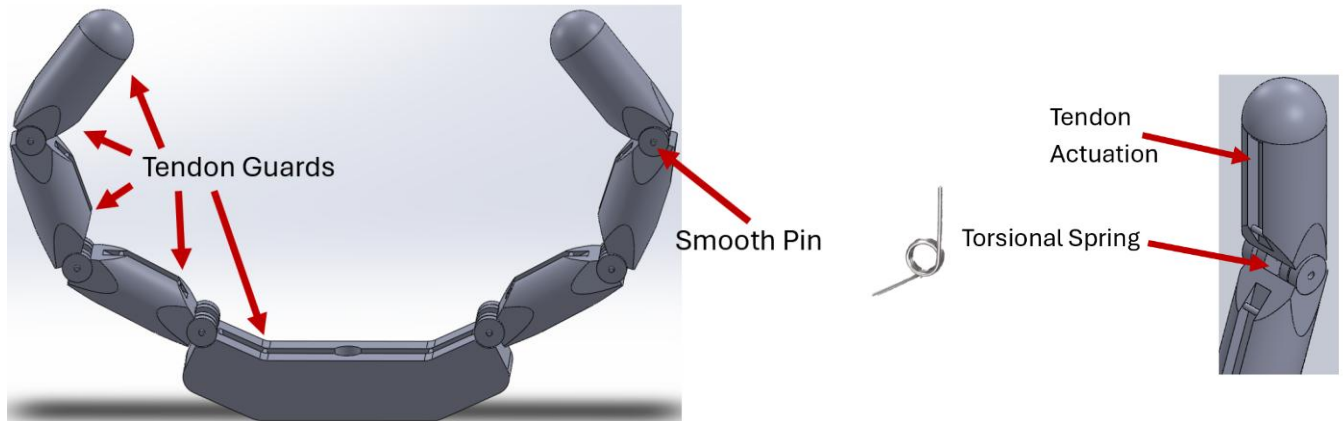


The proposed docking system consists of three primary components: the host spacecraft, a robotic arm, and a finger-based end-effector. The system is designed to be integrated onto a Venus-class X-Sat servicing spacecraft, which provides structural support, power, and control for the docking operation. The servicing spacecraft acts as the active vehicle, while the target satellite represents a non-cooperative client. The robotic arm is mounted to the spacecraft bus and is responsible for positioning the end-effector relative to the target. The arm is designed with 6 degrees of freedom to allow for approach, alignment, and adjustment under uncertain conditions.

The end-effector serves as the primary capture mechanism and is designed to interact with structural features on the target satellite. These features include launch vehicle adapter rings

and truss elements, which are structurally robust and widely available across spacecraft designs.

End-Effector Design

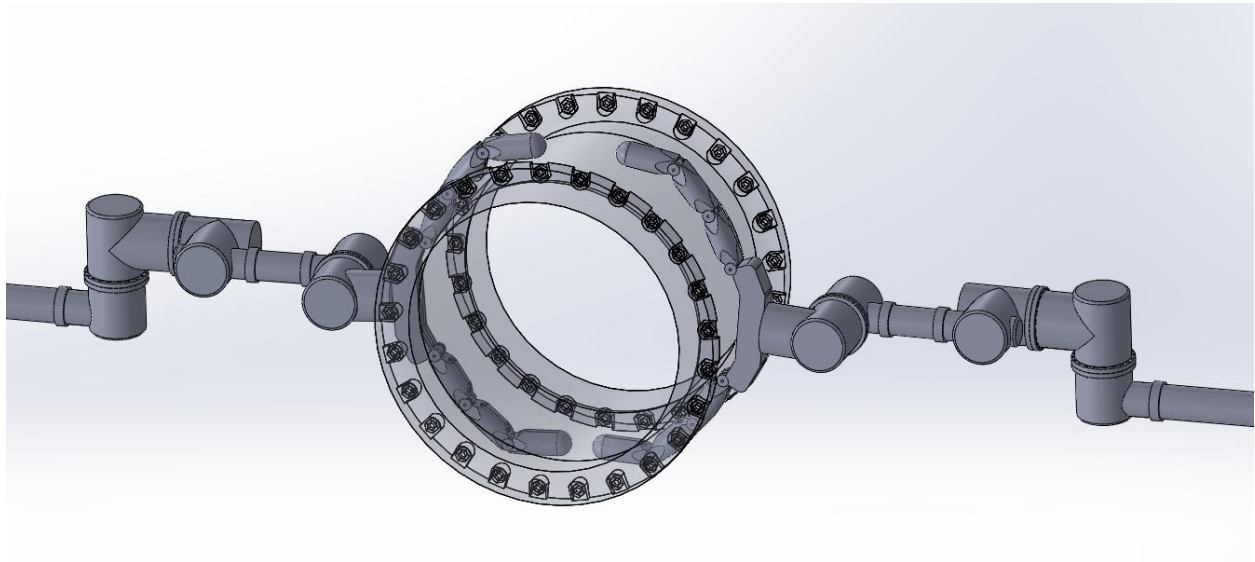


The selected end-effector is a two-finger configuration, where each finger consists of three articulated links connected by revolute joints. The design is inspired by anthropomorphic finger mechanisms and emphasizes adaptability and simplicity. Each finger is actuated using a tendon-driven system, where a cable routed through the finger links is pulled to generate closing motion. This approach allows for compact actuation and simplifies integration with motors located at the base of the finger or within the robotic arm.

Torsion springs are integrated at each joint to provide passive return torque. When tension in the cable is released, the springs cause the finger to reopen, enabling repeatable operation without requiring active extension control. This mechanism reduces control complexity and improves reliability.

The fingertip is designed with a flat contact surface to allow interaction with planar or slightly curved structural elements. To improve grip, the contact surface can incorporate a textured metallic finish or a high-performance polymer insert such as PEEK. A small retention feature, or ledge, is included near the tip to provide mechanical resistance to slip and reduce reliance on friction alone.

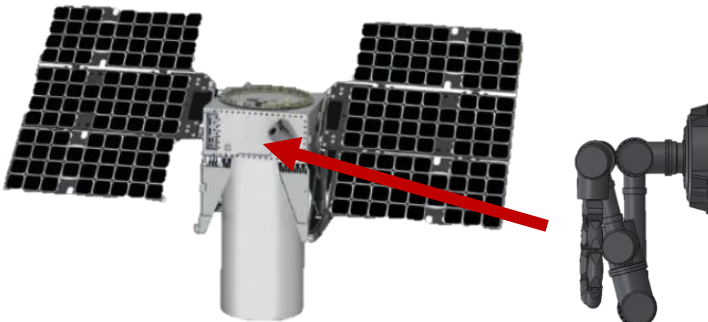
Grasp Strategy



The grasping strategy is based on a compliant capture followed by a rigid hold. During initial contact, the fingers adapt to the geometry of the target feature, allowing for tolerance to misalignment. This compliant behavior reduces impact forces and improves capture success under uncertain conditions.

The primary target for capture is the EELV Secondary Payload Adaptor (ESPA) located at the base of the satellite. This ring provides a continuous, structurally strong interface that can support the forces required for docking. Secondary targets include tubular truss members and structural frame edges, which provide additional capture opportunities in cases where the primary interface is not accessible. Once contact is established, the fingers apply a controlled gripping force to secure the target. The system then transitions to a more rigid configuration, allowing the robotic arm to stabilize and reposition the captured spacecraft.

Deployment and Stowage



To accommodate launch constraints, the robotic arm and end-effector are designed to be stowed in a compact configuration. The arm can be folded against the spacecraft bus and secured using a mechanical launch lock to prevent unwanted motion during launch.

After deployment in orbit, the lock is released, and the arm is extended into its operational configuration. Passive tension in the system and structural constraints help maintain stability during deployment. Future iterations of the design may incorporate active locking mechanisms or damping systems to further improve control and reliability.

V. Engineering Analysis

A first-order engineering analysis was conducted to evaluate the feasibility of the proposed design and to guide component selection. The analysis focuses on grip force, actuator torque, and scalability to representative spacecraft masses.

Grip Force Estimation

The capability of the end-effector to hold the target securely was examined by considering the transitory forces acting during contact initiation. This will provide the maximum force experienced within the compliant joint along with how the forces propagate within the limbs and fingers. These results will determine the structural strength and actuator power necessary for the gripper design.

The collision starts with the relative velocity between the two masses. A velocity of 0.5 ft/s equates to 0.1524 m/s, which provides the initial state for the mass. For an effective mass of 10,000 kg, the impulse is:

$$J = m \times v$$
$$J = 10,000 \text{ kg} \times 0.1524 \frac{\text{m}}{\text{s}} = 1,524 \text{ Ns}$$

This impulse represents the momentum that must be absorbed during the brief contact event. The corresponding kinetic energy is:

$$E_k = \frac{1}{2} \times m \times (v)^2$$
$$E_k = \frac{1}{2} \times 10,000 \text{ kg} \times \left(0.1524 \frac{\text{m}}{\text{s}}\right)^2 = 116.13 \text{ J}$$

This energy is stored elastically in the compliant interface during deformation. For the purposes of design, a maximum allowable compression of 10 mm (0.010 m) was assumed. Applying the spring energy relationship yields an equivalent stiffness of:

$$k = \frac{2 \times E_k}{\delta^2}$$

$$k = 2 \times 116.13 \text{ J}/(0.010)^2 = 2.3 \times 10^6 \text{ N/m}$$

This stiffness governs how rapidly force builds as the interface compresses. Combining the stored energy with the stiffness gives the peak contact force:

$$F_{Contact} = \sqrt{2 \times E_k \times k}$$

$$F_{Contact} = \sqrt{2 \times 116.13 \text{ J} \times 2.3 \times 10^6 \text{ N/m}} = 23,225.76 \text{ N} = 23.2 \text{ kN}$$

This figure corresponds to the highest load transmitted via the fingertips under the worst possible impact scenario.

Since the construction of the end-effector divides this load between two main arms, each arm receives a load of:

$$F_{Arm} = \frac{F_{Contact}}{2}$$

$$F_{Arm} = 23,225.76 \text{ N}/2 = 11,612.88 \text{ N} = 11.6 \text{ kN}$$

Each arm then divides its load between two fingers, resulting in a per-finger design load of:

$$F_{Finger} = \frac{F_{Arm}}{2}$$

$$F_{Finger} = 11,612.88 \text{ N}/2 = 5,806.44 \text{ N} = 5.8 \text{ kN}$$

The forces per arm and finger that come from this are a direct consequence of the peak impact load and describe the internal forces acting from this one event. The effects of friction, gripping, and actuator force have not yet been considered; instead, these values describe the consequences of the impact itself.

Motor Torque Estimation

The torque required to actuate the finger joints can be estimated using a simplified moment relationship:

$$\tau = r \cdot T$$

7. Motor Shaft Torque with Gearbox

The motor torque requirement was estimated by propagating the required fingertip force through the tendon-driven actuation system and accounting for gearbox reduction. The required contact force per finger is:

$$F_{finger} = 5.8 \text{ kN}$$

With a finger length of:

$$L = 0.37 \text{ m}$$

the resulting bending moment at the base of the finger is:

$$M = F \cdot L = 5800 \cdot 0.37 = 2146Nm$$

Assuming an effective tendon pulley radius of:

$$r_p = 0.025 \text{ m}$$

the required tendon tension is:

$$T = \frac{M}{r_p} = \frac{2146}{0.025} = 85,840 \text{ N}$$

With a spool radius of:

$$r_s = 0.020 \text{ m}$$

the required spool torque becomes:

$$\tau_{spool} = T \cdot r_s = 85,840 \cdot 0.020 = 1716.8Nm$$

Using a planetary gear system with gear ratio:

$$G = 100:1$$

and efficiency:

$$\eta = 0.8$$

the required motor shaft torque is:

$$\tau_{motor} = \frac{\tau_{spool}}{G \cdot \eta} = \frac{1716.8}{100 \cdot 0.8} = 21.5 \text{ Nm}$$

Applying a safety factor of:

$$SF = 2$$

the final design motor torque is:

$$\tau_{motor,design} = 43 \text{ Nm}$$

where τ is the required torque, r is the distance from the joint to the point of force application, and F is the force applied at the fingertip.

By estimating the required grip force and the geometry of the finger links, a first-order torque requirement can be calculated for actuator selection. This analysis is sufficient for demonstrating feasibility and ensuring that commercially available motors can meet the system requirements.

Scaling to Spacecraft Mass

The system is designed to capture and stabilize spacecraft with masses up to 15,000 lbm, which is representative of large geostationary communication satellites. In a microgravity environment, the system is not required to support the full weight of the spacecraft but must instead control inertial forces during relative motion.

The required forces are driven by factors such as approach velocity, desired separation velocity, and stabilization requirements. By limiting these velocities, the forces experienced by the end-effector can be kept within manageable limits. This enables the use of relatively compact actuators while still maintaining system functionality.

VI. Hardware Implementation

The finger mechanism was developed through multiple design and fabrication iterations using additive manufacturing. Early prototypes focused on validating basic geometry, joint motion,

and cable routing. Subsequent iterations addressed issues related to friction, structural alignment, and spring integration. Initial designs included features such as extruded cuts and openings for tendon routing. However, these features required refinement to improve reliability and ease of assembly. Adjustments were made to allow proper threading of torsion springs and to reduce interference between moving components.

Later iterations focused on improving joint performance by removing unnecessary material that contributed to friction and binding. Pin diameters were adjusted to achieve smoother motion, and the use of a solid pin was considered to replace printed rods in order to reduce wear and improve consistency.

The integration of torsion springs required redesign of the joint geometry to accommodate spring placement and ensure proper preload. The final configuration allows the springs to provide sufficient return torque while maintaining compact packaging within the finger structure. These iterative improvements resulted in a functional prototype capable of demonstrating the intended motion and grasping behavior of the end-effector.

VII. Testing and Results

The prototype finger mechanism was evaluated through a series of functional tests to assess its performance in grasping and releasing target objects. Testing focused on representative geometries such as cylindrical rods and flat surfaces, which simulate structural features found on satellites.

The tendon-driven actuation system successfully produced controlled closing motion, allowing the finger to conform to the shape of the target. The torsion springs provided consistent return motion, enabling repeatable opening and release of the grasped object.

Grip performance was evaluated qualitatively and through force measurements. Results indicated that the addition of improved contact surfaces and alignment adjustments significantly enhanced grip stability. The inclusion of a retention feature at the fingertip reduced the likelihood of slip during pulling motions.

Overall, the prototype demonstrated the feasibility of the design and validated the core functionality of the tendon-driven, compliant finger mechanism.

VIII. Discussion

The proposed docking system demonstrates several advantages, particularly in its ability to capture non-cooperative spacecraft using existing structural features. The use of a tendon-driven, compliant finger design allows the system to adapt to varying geometries and tolerate misalignment during initial contact.

The simplicity of the mechanism reduces the number of required actuators and minimizes control complexity, making the system well-suited for rapid prototyping and integration. Additionally, the modular nature of the design allows for scalability and adaptation to different mission requirements.

However, the system also presents limitations. The compliant design results in reduced structural stiffness compared to rigid docking mechanisms, which may limit load transfer capability during certain operations. Additionally, the effectiveness of the grip depends on contact conditions, including friction and alignment, which may vary in different scenarios.

Future work should focus on improving the robustness of the grasp through optimized fingertip design, enhanced material selection, and integration with a full robotic arm system. Additional testing under more representative conditions would further validate the system's performance and reliability.

IX. Conclusion

This project presents the conceptual design and prototype development of a robotic docking system capable of capturing non-cooperative spacecraft. The system utilizes a multi-degree-of-freedom robotic arm and a tendon-driven finger-based end-effector to interact with structural features such as adapter rings and truss elements.

A trade study was conducted to evaluate multiple docking concepts, leading to the selection of a compliant robotic claw design based on its adaptability, manufacturability, and performance. The developed prototype demonstrates the feasibility of the approach and validates the core functionality of the end-effector.

The results demonstrate that compliant, tendon-driven robotic capture mechanisms provide a viable alternative to traditional docking systems, particularly for non-cooperative spacecraft. With further development, including refined material selection, actuator sizing, and full-system integration, the proposed design has the potential to support future satellite servicing, debris mitigation, and on-orbit assembly missions.

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