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COSMIC Capstone Challenge: Final Briefing

Wormhole, University of New Hampshire: A Soft-Robotic End-Effector for Orbital Debris Capture

Students: Sabby Clemmons and Sarah Remeis
Advisor: Se Young Yoon, Brad Kinsey
Mentor: Jerry Fuller, MD Shaad Mahmud

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Executive Summary

A Soft-Robotic End-Effector for Orbital Debris Capture

- Problem: Small orbital debris is difficult to capture without creating additional fragments
- Solution: A soft robotic “Wormhole” gripper using SMA (nitinol) actuation
- Key Capability: Gentle, adaptive capture of irregular debris without rigid impact with an instrument that meets low SWaPC requirements
- Why it works: Flexible fingers conform + contract to enclose targets
- Status: Functional prototype + validated actuation + ongoing refinement of curl geometry

Team Overview

A Soft-Robotic End-Effector for Orbital Debris Capture

the students

Sabby Clemmons
Senior EE at UNH

Sarah Remeis
Senior EE at UNH

the advisors

Se Young Yoon (Pablo)
ECE Professor @ UNH
ECE Project Advisor

Brad Kinsey
ME Professor @ UNH
Co-Advisor & C3 Advisor

Jerry Fuller
Senior Engineer @ The Aerospace Corporation
Mentor & Pioneer of AFCs

MD Shaad Mahmud
ECE Professor @ UNH
Unofficial Advisor (on sabbatical)

2.4 Program Management Milestones

Research → Design → Build → Integration → Prototype

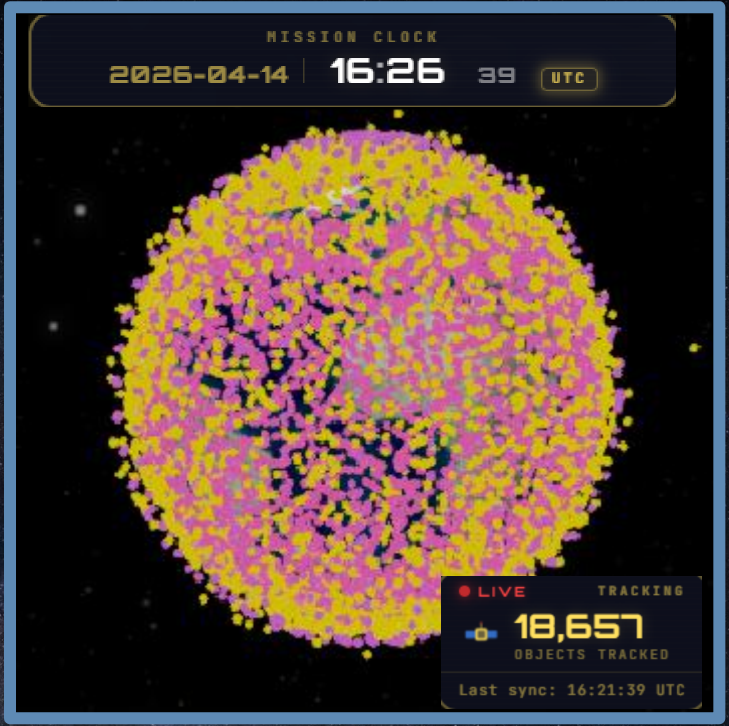
- **July–August 2025:** Learned SMA systems + soft actuation at Aerospace Corporation (mentored by Jerry Fuller)
- **September 2025:**Established UNH connection + received approval to pursue project as senior capstone
- **Fall 2025:** Literature review + concept development Conducted initial trade studies (soft vs rigid, SMA vs motors, finger configurations)
- **December 2025 – January 2026:** Ordered components + began prototyping setup
- **January 2026:** Focused on finger geometry design + nitinol behavior characterization
- **February – March 2026:** System integration + sensor selection and verification
- **April 2026:** Fabricated fixture + assembled full working prototype and developing path to Preliminary Design Review (PDR)

Wormhole

1.1 Impact

Mitigating Orbital Debris to Enable Sustainable and Safe Space Operations

- Low Earth Orbit (LEO) is the most congested orbital region (~160-2000 km)
- 18,000+ tracked objects (and many more untracked) pose collision risks
- Collisions can trigger cascade effects (Kessler Syndrome)
- Existing solutions require high precision and are not scalable



Soft robotic capture enables safe, adaptable debris removal in congested orbits

1.2 Feasibility

Validated Through Prototyping, Material Characterization, and System Integration

- SMA (Nitinol) actuation experimentally validated for repeatable contraction under load
- Finger geometry optimized through iterative design and prototyping
- Low-power operation compatible with small satellite constraints
- Sensor suite integrated and verified (ToF, flex sensor, IMU)
- Supports autonomous servicing functions, including debris capture and object manipulation

A fully integrated prototype demonstrates that soft robotic debris capture is technically feasible for on-orbit servicing

1.3 Innovation

Advancing Autonomous Servicing Through Soft Robotics and Adaptive Gripping

- Soft robotic fingers enable compliant interaction with unknown geometries
- SMA (nitinol) actuation replaces motors → lower mass + complexity
- Passive mechanical compliance reduces control requirements
- Multi-node finger design enables controlled curling behavior
- Sensor-triggered actuation enables adaptive response to proximity/contact

A lightweight, compliant, and adaptive gripping mechanism replaces rigid, precision-dependent systems

1.4 Advancing High Value Missions

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Advancing Autonomous Servicing Through Soft Robotics and Adaptive Gripping

- Enables on-orbit debris capture and removal in LEO Supports ISAM priorities:
  - autonomous servicing
  - robotic manipulation
  - debris mitigation
- Scalable to multi-target debris collection missions
- Compatible with small satellite servicing platforms Enables future on-orbit recycling/manufacturing systems

Wormhole directly supports scalable, autonomous debris removal missions identified by COSMIC

2.1 Animation of Key Operating Sequence

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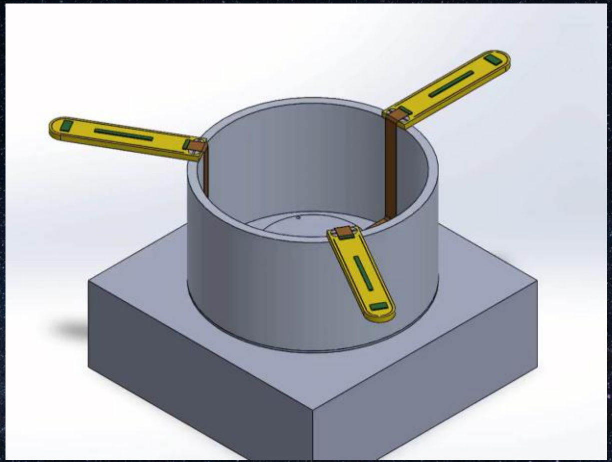
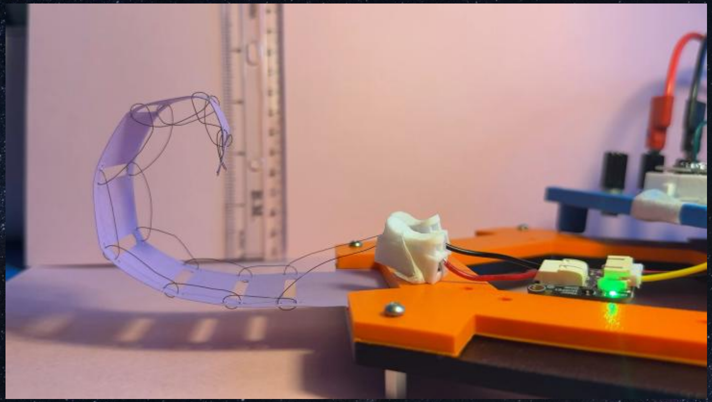
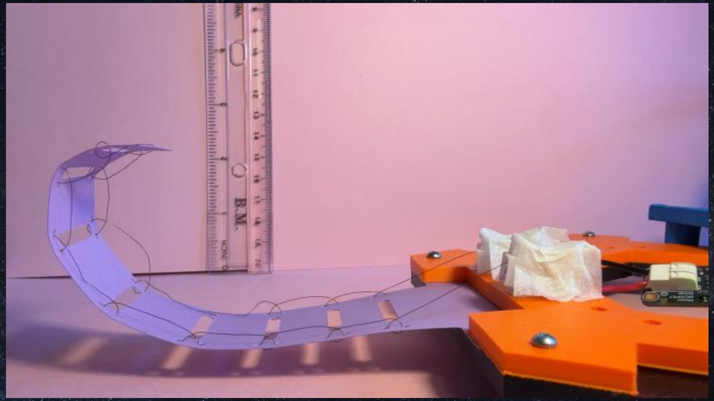
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES



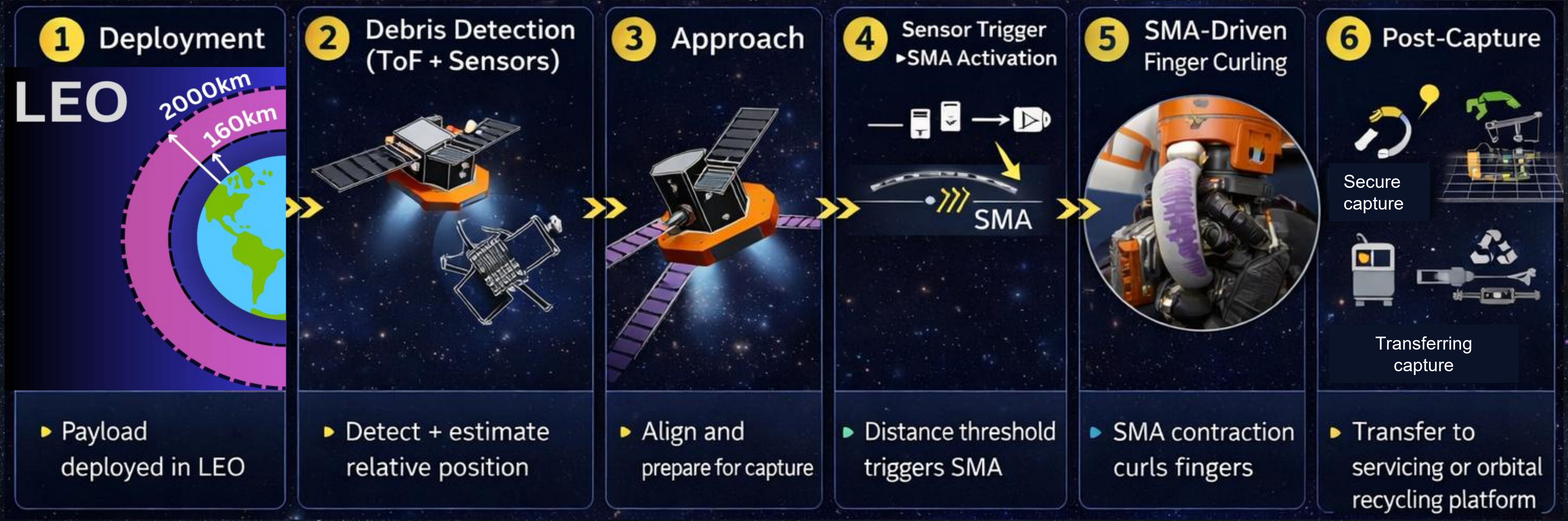




- Detect a free-floating object
- Estimate trajectory + trigger SMA actuation
- Fingers close around a 5-inch balloon

Sho Wormhole

2.2 Storyboard of Complete Operation



3.1 Required Elements

System-Level Required Elements for Autonomous Debris Capture

- **Sensing:**
  - Time-of-Flight (ToF) sensor for proximity detection
  - Flex sensor + IMU for contact and motion feedback
- **Actuation:**
  - SMA (nitinol) wire-based contraction system
  - Electrically driven, low-power actuation
- **Control:**
  - Microcontroller-based logic
  - Autonomous trigger based on distance threshold
- **Structure:**
  - 3-finger soft robotic end-effector
  - Multi-node design for controlled curling
- **Integration:**
  - Low SWaP-compatible payload
  - Interfaces for power, mounting, and communications

3.2 Risks

Risk	Impact	Mitigation
Incomplete Capture / Object Escape	Loss of debris → mission failure	• Optimize finger geometry + node spacing • Multi-finger (3-point) capture redundancy • Increase curl through SMA tuning
SMA Overheating / Material Fatigue	Actuation failure over time	• PWM-controlled current to limit heating • Duty cycling + thermal testing • Select appropriate nitinol diameter
Unpredictable Debris Geometry & Motion	Difficulty achieving secure grasp	• Soft compliant design (core advantage) • Sensor-triggered actuation (ToF threshold) • Passive adaptability reduces need for precision

3.4 Trade Studies and Design Decisions

Comparison	Actuation Trade	End-Effector Trade	Control / Operations Trade
Traditional	Motors: • High precision • High mass + complexity + power	Rigid Gripper: • High force • Requires precise alignment	• Teleoperated: • Requires high bandwidth • Human dependent
Wormhole's Choice	SMA (Selected): • Lightweight and compact • Fewer moving parts	Soft Robotic Gripper (Selected): • Compliant • Adapts to unknown shapes	• Autonomous (Selected): • Low bandwidth • Scalable operation

Design choices prioritize low SWaP, autonomy, and adaptability for space environments

3.3 Data Handling and Comms

Defined Communication Requirements for Autonomous Servicing Operations

- Real-time downlink not required
  → System operates primarily autonomously onboard
- No continuous operator required
  → Human-in-the-loop only for high-level mission oversight
- Event-based communication
  → Data transmitted during key events (capture, status updates)
- Low data rate requirements
  → Telemetry + sensor status (no high-bandwidth video required)
- Estimated bitrate: low (kbps range)
  → Suitable for small satellite communication systems

Autonomous operation minimizes communication needs, enabling low-bandwidth, efficient mission support

4.1 Most Innovative Concepts Considered

8 Finger Gripper *(Not Selected)*

- Initial concept: increase contact points for more secure capture
- Limitation:
  - Increased mechanical complexity and control requirements
  - Higher power demand with additional SMA wires
- Final decision: reduced to 3-finger system for simplicity and reliability

Vision-Based Detection System *(Not Selected)*

- Initial concept: camera-based detection and targeting
- Limitation:
  - Optical sensing challenges in space (lighting, reflectivity, spectrum)
  - Higher processing and data requirements
- Final decision: use ToF sensor for simple, reliable proximity triggering
- SMA-Based Soft Robotic Actuation *(Core Design Choice)*
- Nitinol selected from the beginning for:
  - Lightweight, compact actuation
  - Minimal mechanical complexity
- Enabled development of compliant, adaptive gripping system

4.2 Most Important Technology Gaps

Key Technology Gaps for Future Deployment

• SMA Reliability in Space Environments – Unknown long-term performance under: – thermal cycling – vacuum conditions – Needed for flight validation	• Autonomous Debris Detection & Tracking – Current system uses simple proximity sensing – Future systems require: – vision-based tracking – relative motion estimation	• On-Orbit Debris Processing Infrastructure – Capturing debris is only first step – Need systems for: – storage – recycling – manufacturing reuse

Closing these gaps enables scalable, long-term debris removal missions

4.3 Biggest Challenges Encountered

Key Technical Challenges and Lessons Learned

• Achieving Sufficient Curl with SMA Actuation • Challenge: - Limited contraction length of nitinol - Difficult to generate full enclosure • Solution: - Iterated node spacing and finger geometry - Tuned wire length and placement - Understanding nitinol	• Balancing Power vs Actuation Performance • Challenge: - Higher current → better contraction - But increases heat and power demand • Solution: - PWM control - Optimized wire diameter and voltage	• Designing Controlled, Repeatable Finger Motion • Challenge: - Early designs bent unpredictably • Solution: - Introduced multi-node structure - Adjusted spacing and cut patterns

5.2 Paper

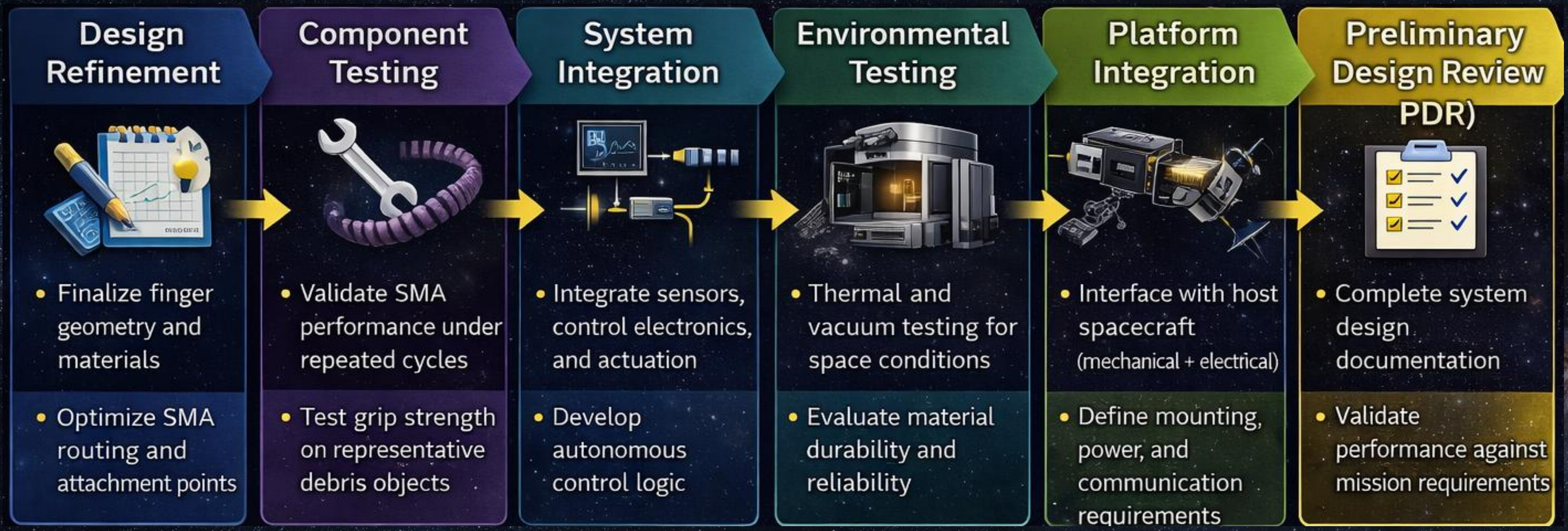
Paper in-progress

- Abstract:

Orbital debris in low Earth orbit (LEO) presents a growing threat to spacecraft due to high-velocity collisions that can result in catastrophic system failure. Existing debris capture methods rely on rigid robotic manipulators or passive capture systems, which require precise alignment and introduce risk when interacting with uncooperative targets. This work proposes *Wormhole*, a soft robotic end-effector designed for compliant capture and stabilization of debris. The system utilizes shape memory alloy (SMA) actuation to induce curvature in flexible polymer fingers, enabling adaptive grasping of irregular geometries. To achieve a low Size, Weight, Power, and Cost (SWaP-C) profile, the design incorporates autodynamic flexible circuits (AFCs), which embed electrical functionality directly into the structure. A proof-of-concept prototype was fabricated and tested using free-moving targets, demonstrating repeatable actuation and partial capture. While full enclosure was not achieved, results validate the feasibility of SMA-driven compliant capture and identify curvature optimization as the dominant design constraint. This work contributes to the development of scalable, modular subsystems aligned with in-space servicing and debris mitigation objectives.

2.3 Path to PDR

Roadmap to a Fully Validated and Integrated Flight-Ready Wormhole System



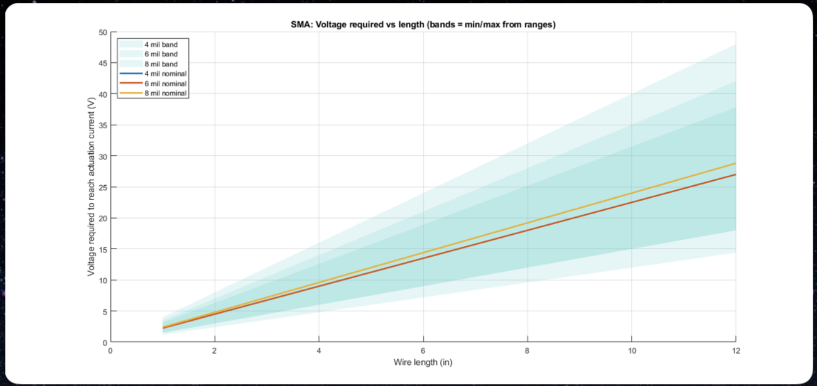
Structured Path from Prototype Validation to Flight-Ready Integration

Summary/ Conclusion/ Highlights

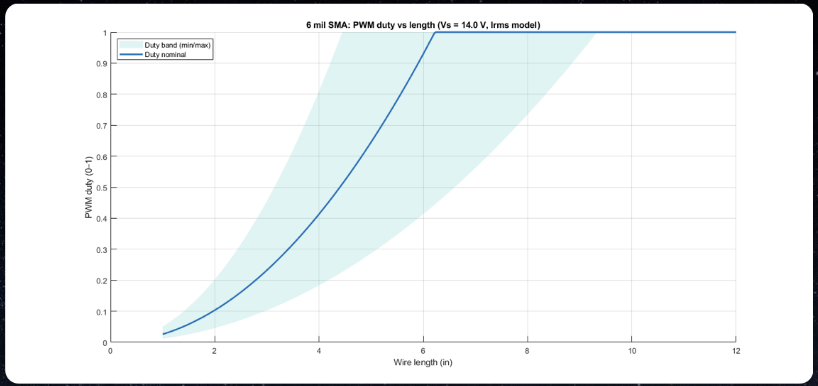
- What We Built
  - Soft robotic end-effector using SMA (nitinol)
  - Functional prototype with adaptive grasping
- Design Approach
  - Prioritized simplicity, reliability, low SWaP
  - Reduced complexity (8 → 3 fingers, no vision system)
- Why It Works
  - Conforms to unknown debris shapes
  - Compact, lightweight, and autonomous
- Next Steps
  - Improve capture reliability
  - Advance toward flight-ready validation

Questions

Questions?



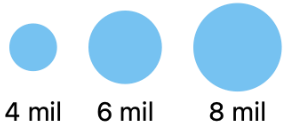
Electrical Feasibility



Control Margin

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

Wire Choice: Nitinol

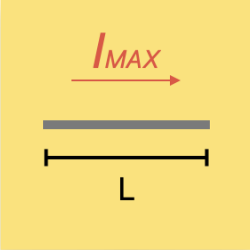


Wire Diameter (mil)	Resistance (Ω/in)	Actuation Current (mA)
4	10–14	150–250
6	5–7	300–450
8	2–4	600

Electrical Model

$R = \rho L$ ρ = ohm/meter

$V_S = I_{MAX} R$



Wormhole

A Soft Robotic SMA-Actuated Capture System for Orbital Debris Mitigation

Video Progress Report 2: Initializing Controls and Early Programming

Sabby Clemmons

Sarah Remeis

Meet the team

the students

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