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THE POWER OF COLLABORATION

COSMIC Capstone Challenge: Final Briefing

# Team PRISM: Penn State Payload for Remote, In-Space Maintenance

4/14/2025


Students: Benjamin Knepper, Ethan Hall, Joe Kozuch, Jonathan Matthews, Sunay Neelimathara, Sanskar Raghuwanshi, Damian Williams

Advisor: Dr. Sara Lego

Mentor: Brian Roberts

PRISM

PennState College of Engineering

# Executive Summary

*Payload for Remote, In-Space Maintenance (PRISM)*

- Problem: 13% of all satellite failures are caused by battery failures
- Capability: Install an external, auxiliary battery to umbilical port
  - Test Case: Neil Gehrels Swift Observatory
- Outcome: Extend’s satellites current lifespan
- Developed CONOPs, design, mass / power / uplink calculations, and CAD model
- Next steps: FEA analysis then develop physical prototype

# Team

*Payload for Remote, In-Space Maintenance (PRISM)*

Joe Kozuch

Sunay Neelimathara

Sanskar Raghuwanshi

Damian Williams

Jonathan Mathews

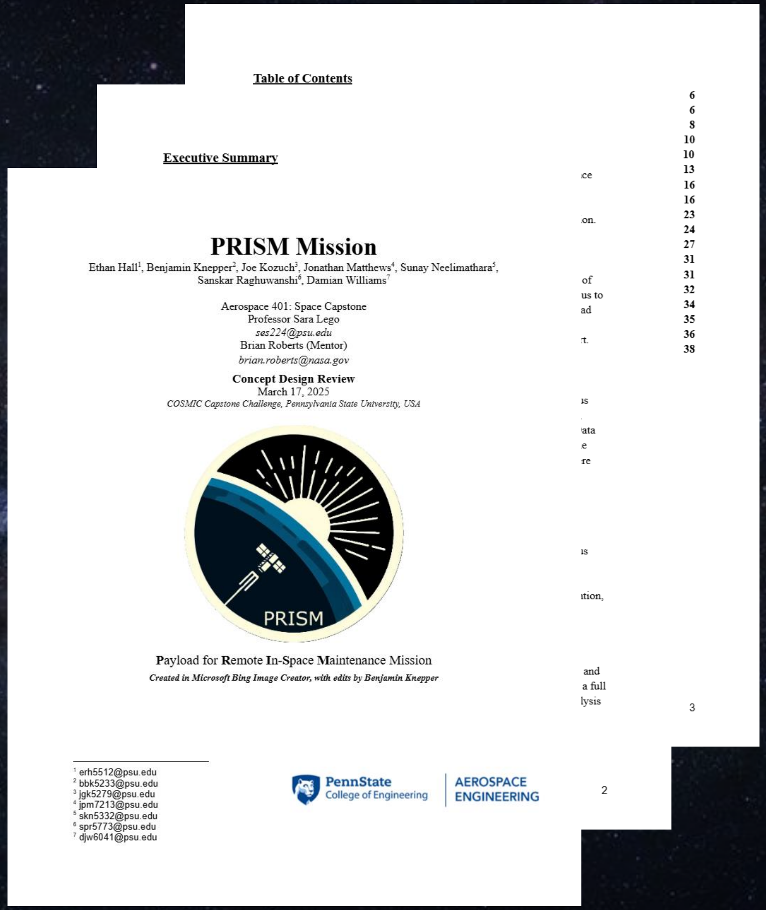
Benjamin Knepper

Ethan Hall

# Systems Engineering Milestones

*Overview of Systems Engineering*

- Program Manager Selection: 9/12/2024
- Selected Operations / Capability: 10/7/2024
- System Requirements Defined: 10/16/2024
- 3 Design Concepts Created: 11/12/2024
- Trade Studies and Final Design: 1/31/2025
- Finalized Conceptual Design: 4/2/2025
- Path to Preliminary Design Review: 4/7/2025



# Overview

*Extending Satellite Lifespan through Autonomous Battery Installation*

- Capability Gap
  - 13% of satellite batteries lead to operational and electrical failures.
- Capability
  - To ensure longer lifespans for aging satellites by installing auxiliary batteries.
- Mission Overview
  - Add supplemental power to Neil Gehrels Swift Observatory as a proof of concept.

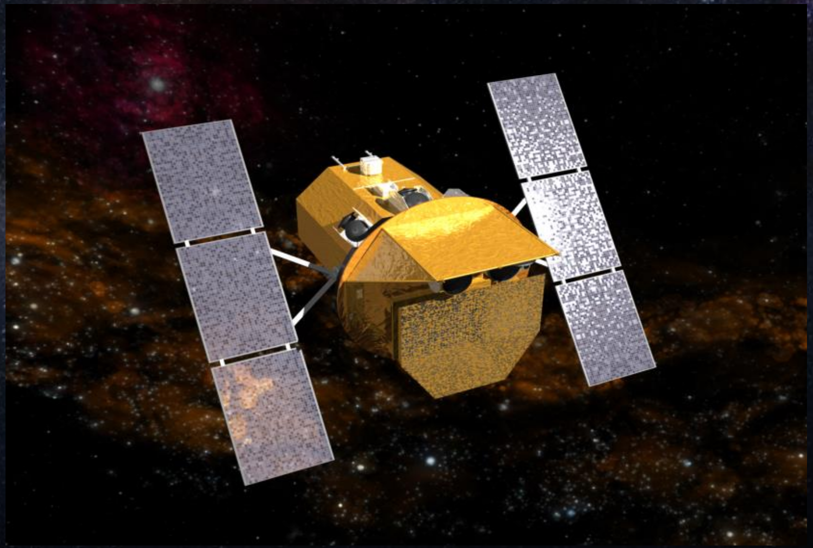
- Mission Operations

1. Dock to Swift
2. Mount Auxiliary Battery
3. Seal Battery

Swift References:

Kevin Cryan - Liaison/POC

John Nousek - Mission Director

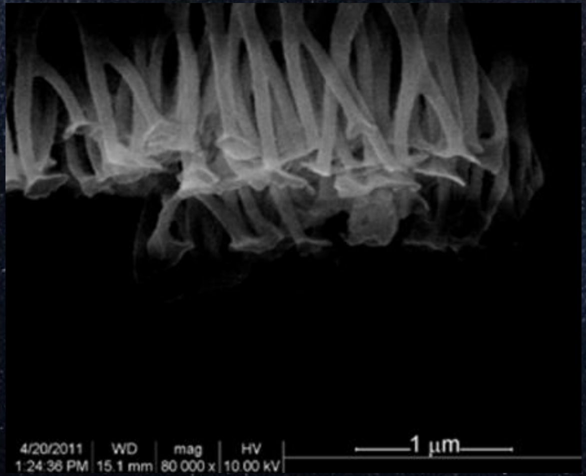


“Neil Gehrels Swift Observatory” Explore-Exoplanets: https://www.explore-exoplanets.eu/resource/swift/

# Innovative Concepts

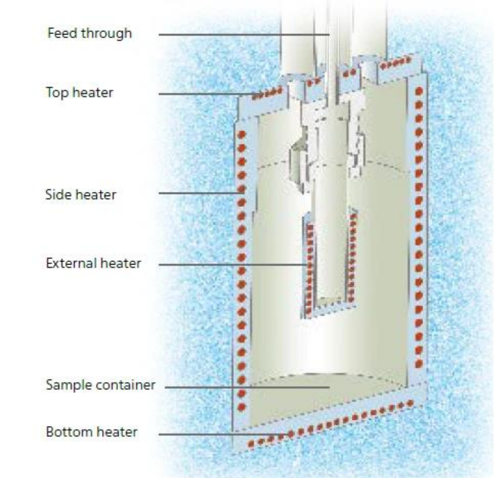
*Most Creative Concepts (Pursued or Not)*

- Gecko feet made of natural setae is employed with our robotic arms to be able attach and detach with objects
- The use of a stud welder was suggested as a form of attachment
- Epoxy to attach auxiliary battery to Swift and curing through heating




1Guo, C., Sun, J., Ge, Y., Wang, W., Wang, D., and Dai, Z., "Biomechanism of adhesion in gecko setae - science China Life Sciences," *SpringerLink* Available: https://link.springer.com/article/10.1007/s11427-012-4286-y.

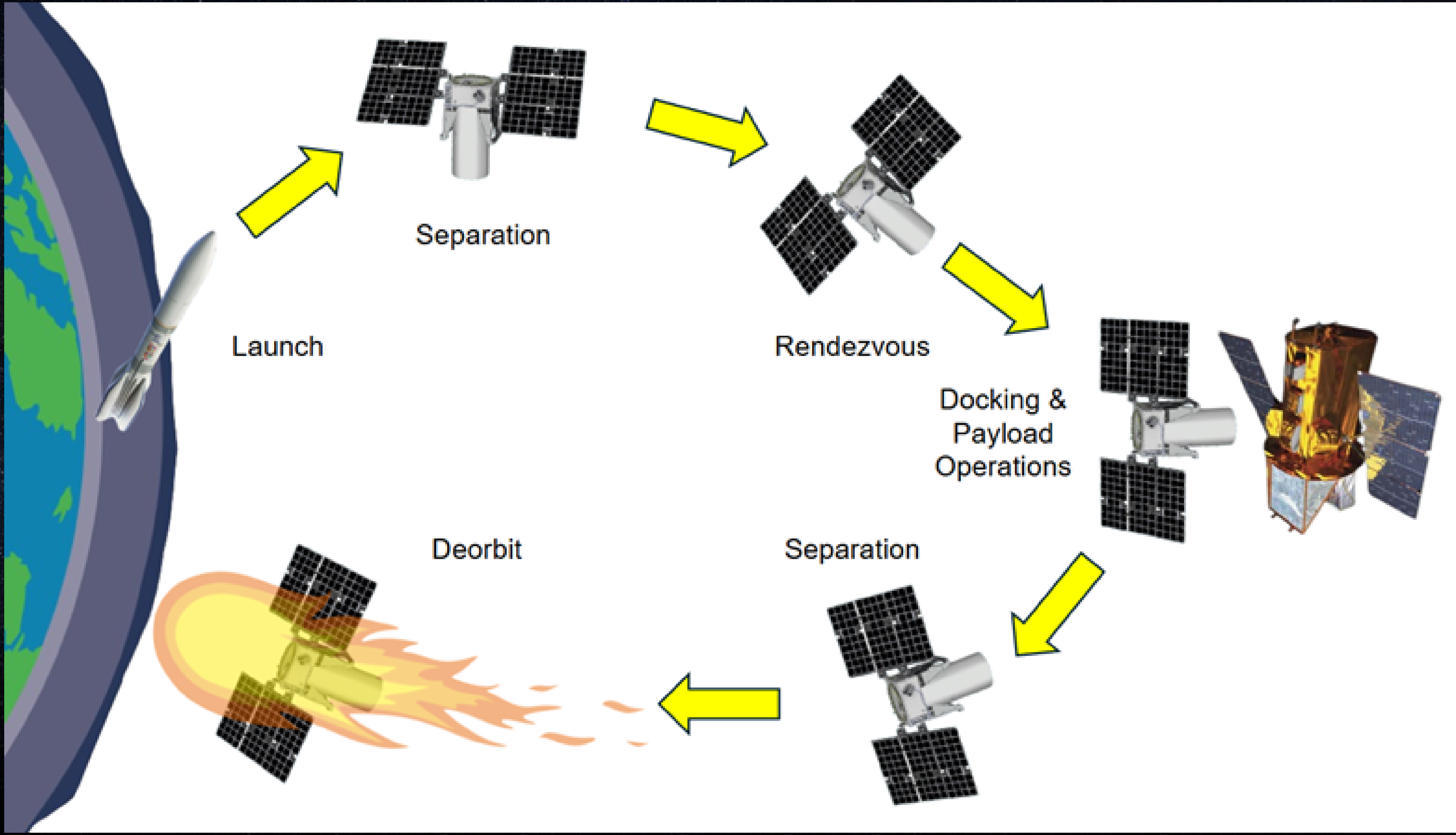
1"RSN-1600HD inverter drawn arc stud Welding Machine," *Huayuan Plasma Cutting Machine Plasma Cutter* Available: https://www.westweld.com/rsn-1600-2500-3150hd-inverter-drawn-arc-stud-welding-machine.html.




1Füglein, Dr. E., "Hazard potential of decomposition reactions using the example of hydrogen peroxide (H2O2)," *NETZSCH* Available: https://analyzing-testing.netzsch.com/en/application-literature/hazard-potential-of-decomposition-reactions-using-the-example-of-hydrogen-peroxide-h2o2.

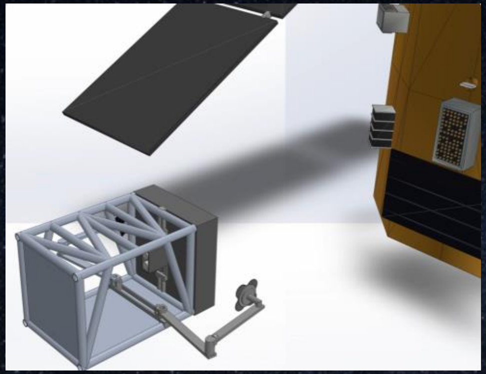
# Storyboard of Macro Operation

*High-Level Overview of the Mission*

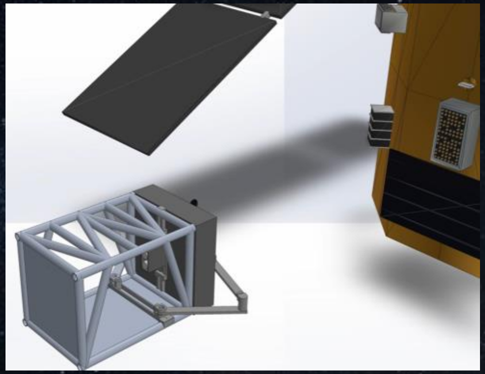


# Storyboard of Micro Operation

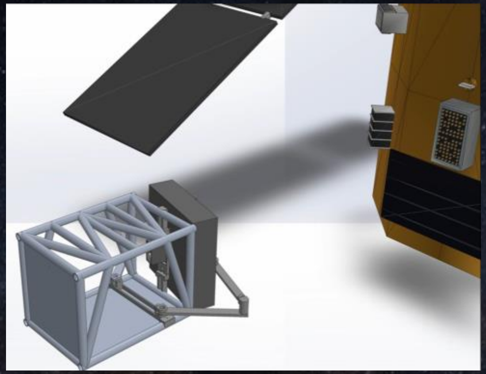
*Overview of Payload Operations*



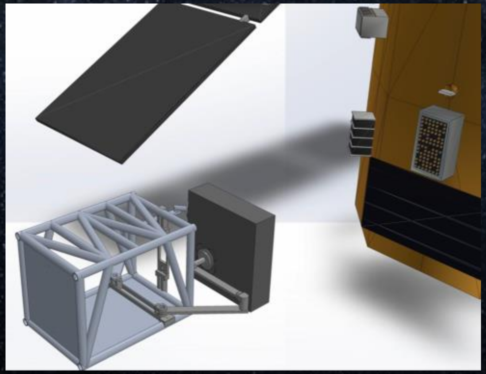
Extend Arms



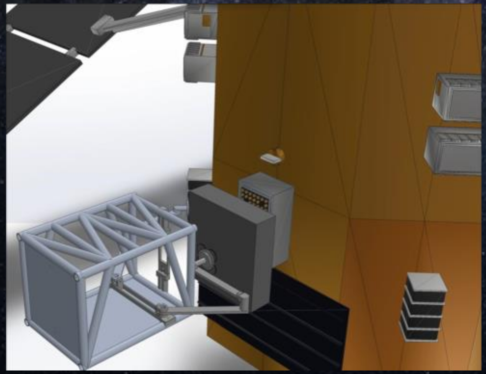
Grab Battery



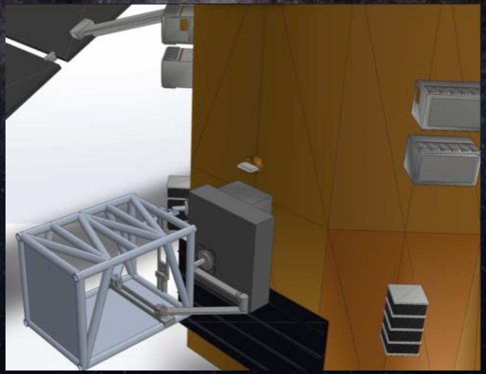
Detach Battery



Orient Battery



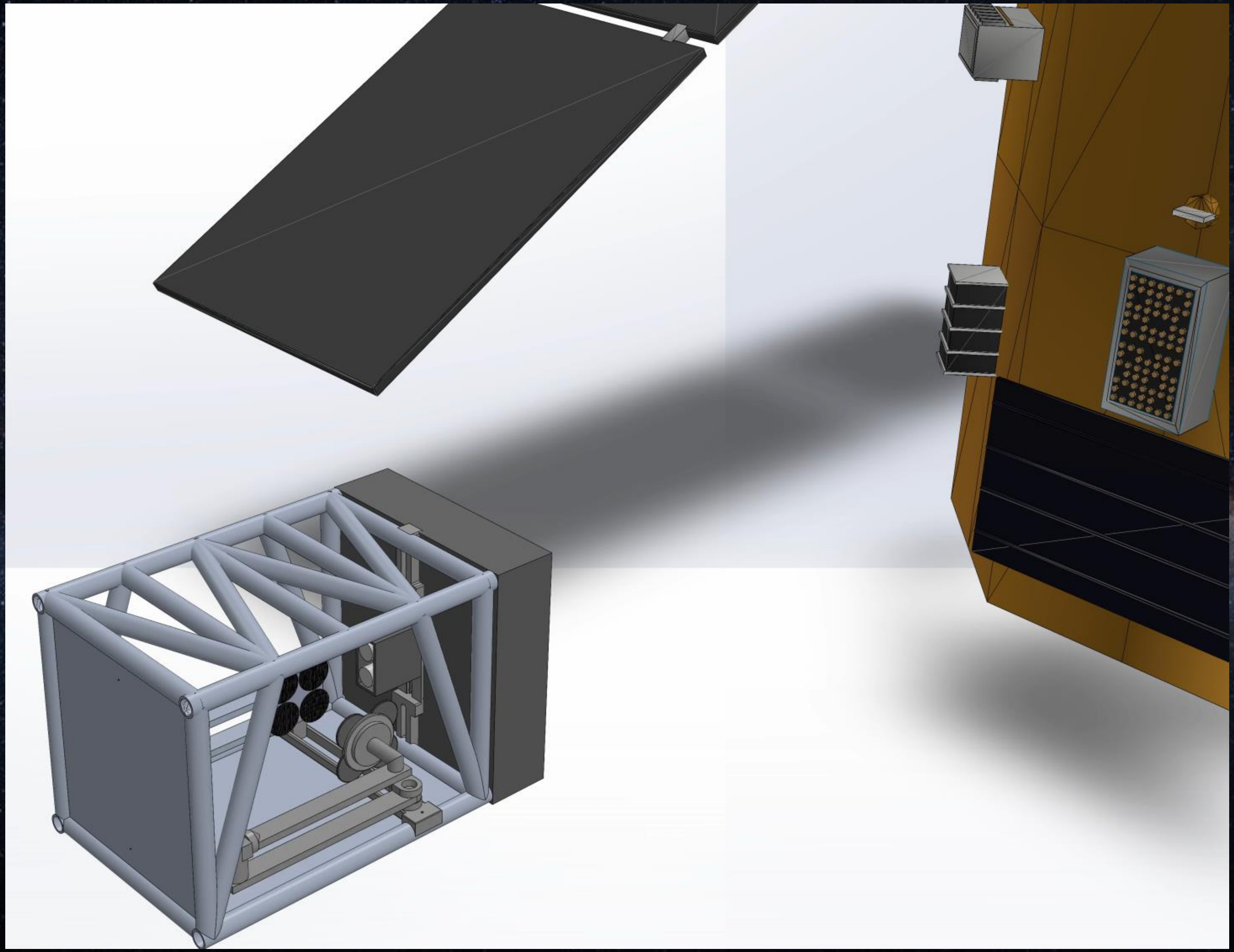
Grab Swift



Attach Battery

# Animation of Key Operating Sequence

*Overview of three mission operations in action*



Remote Maintenance Payload

# Autonomy in Mission Operations

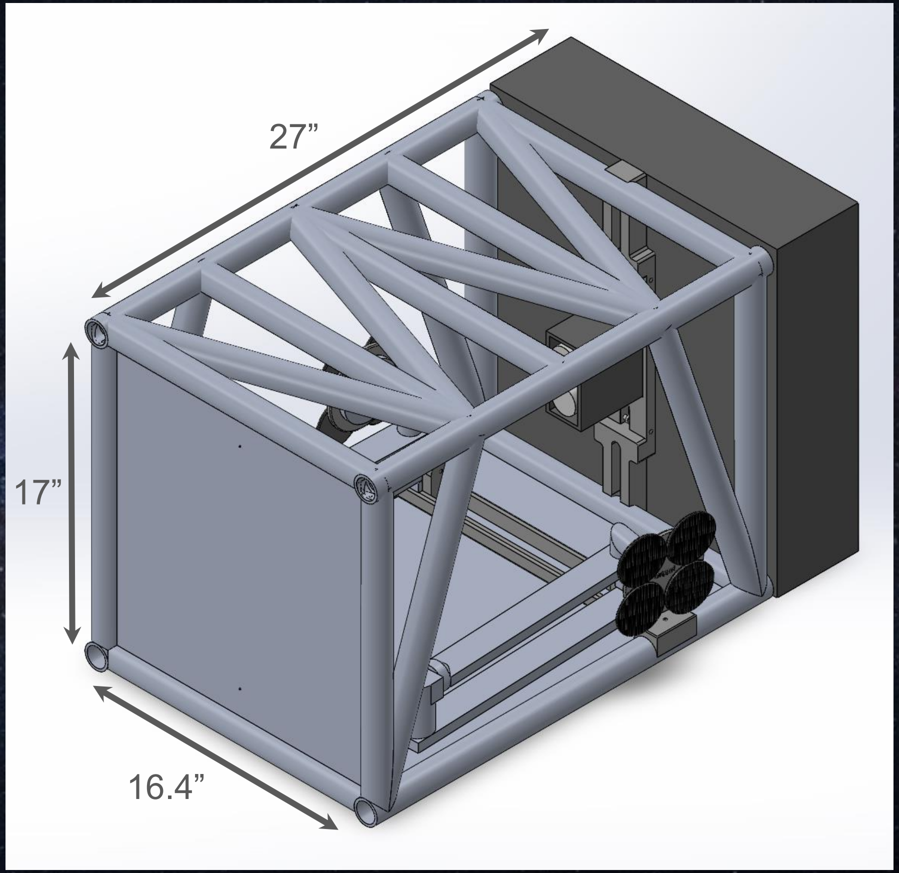
*Core Autonomy Operations*

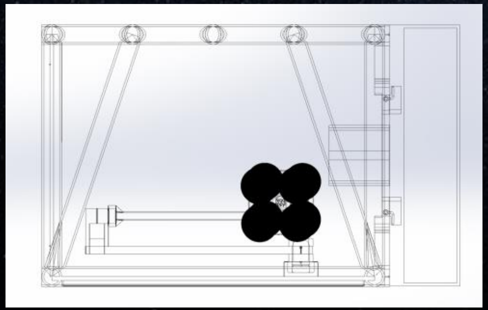
- Autonomous Rendezvous
  - Approach Swift from injection orbit
  - Match orientation of swift
- Autonomous Battery Attachment and Docking
  - 2 cameras on each arm
    - Vision processing to grab battery pack
  - LIDAR system for proximity
- Autonomous Epoxy Curing
  - 4 Heating Coils
  - Temperature Detection & Modulation

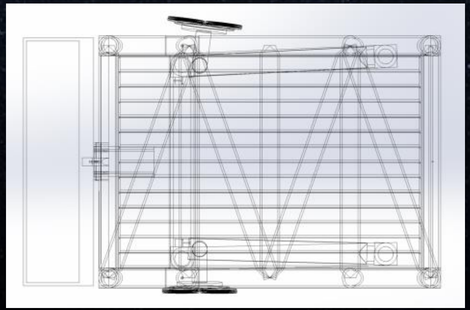
# Payload Overview

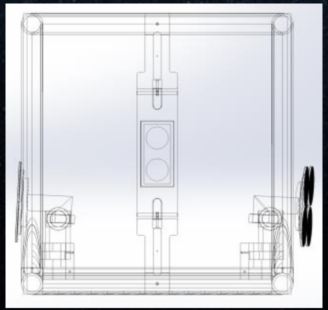
*High-Level Payload Subsystem Breakdown*

- Structure
  - Light, “sturdy”, conforming to volume
- Robotic Arms
  - Strong, maneuverable, within power and mass envelope
- CDH
  - Integrated Lidar, cameras, etc. to control and monitor movement
- Battery Pack
  - Shielded, within mass envelope, capable for Swift, volume envelope







# Payload Overview (cont)

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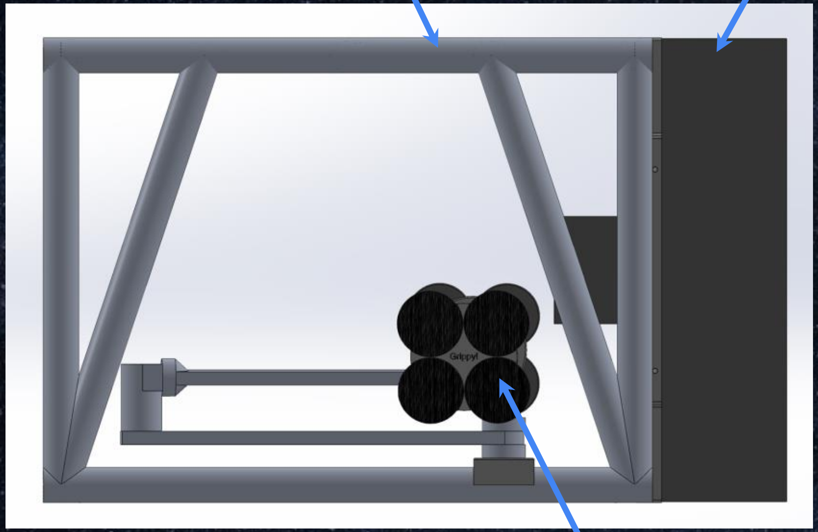
*Side, Top, and Front view of High level payload*

Truss Structure

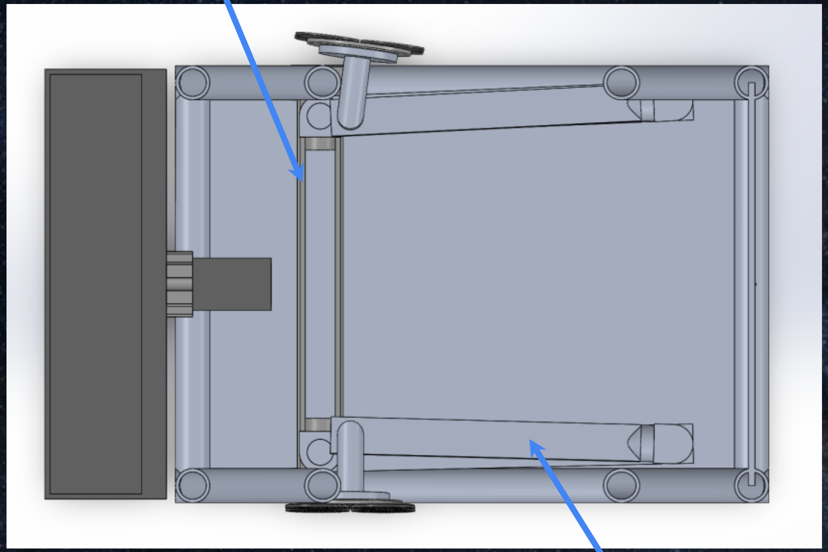
Auxiliary Battery Pack



Side View

2x Gecko Hand

Arm Mount

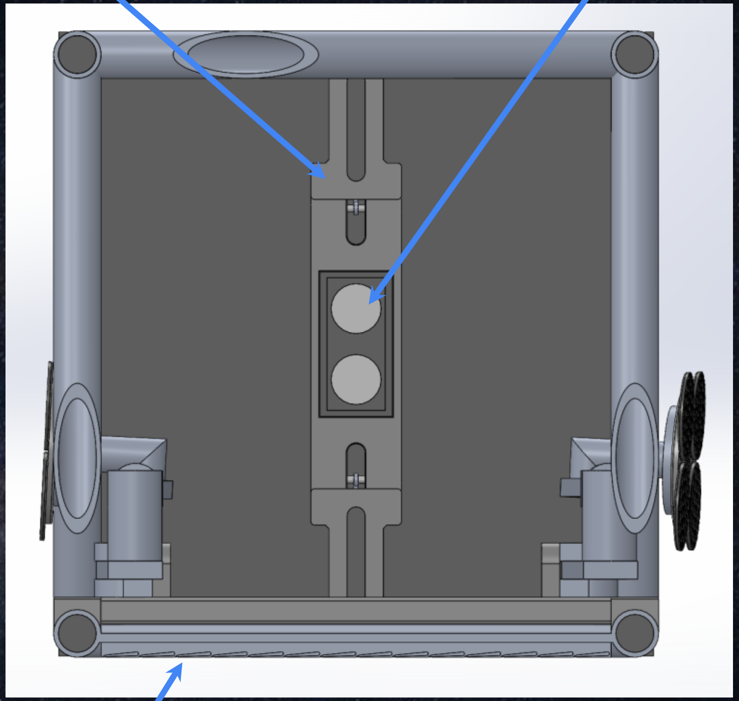


Top View

2x Robotic Arms

Battery Latch Mechanism

Umbilical Port



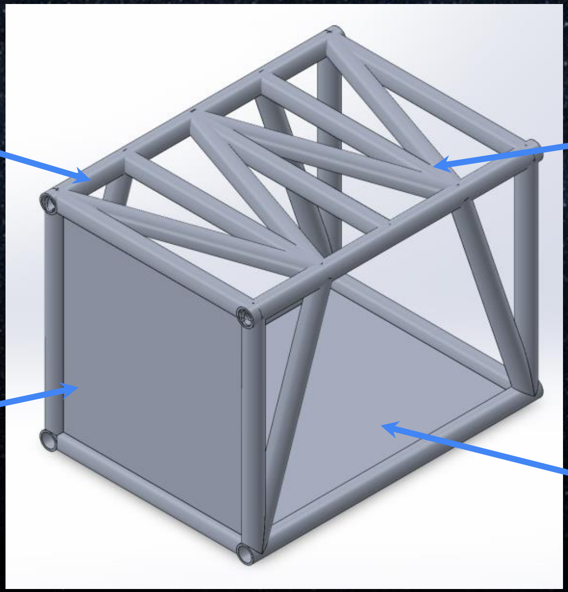
Front View

Thermal Louvers

# Structure

*Strong and Lightweight Beryllium Truss for Payload*

- Structure will have a truss styled layout
  - Top end has truss links for strong structural support at launch
  - Full structure is made of thick hollow pipes for high strength/low weight
- Structure will be composed of beryllium
  - Beryllium consists of high strength while being less dense
  - The material also has a high stiffness which is ideal for handling launch conditions



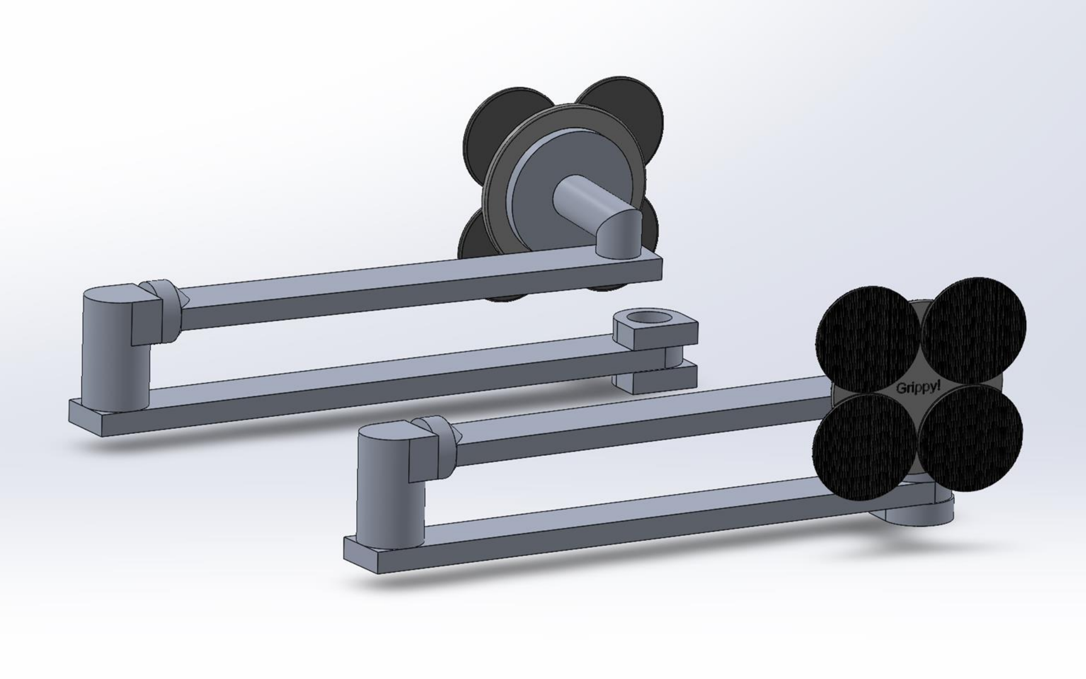

**Material Trade Study for Structure of Payload**

| Criteria | Explanation | Grade | Weight | Magnesium Alloy | Aluminum 6061 Alloy | Beryllium | Stainless Steel |
|---|---|---|---|---|---|---|---|
| Mass Density | Minimize the amount of mass allocated to structure to fit mass budget. | 10 = Best 1 = Worst | 20% | 10 | 7 | 9 | 3 |
| Thermal Conductivity | Material needs to have efficent thermal conductivity to handle the varying temperatures of the space enviorment. | 10 = Best 1 = Worst | 10% | 6 | 7 | 5 | 10 |
| Stiffness | Material needs to have high stiffness so that plastic deformation and failure of the structure is prevented. | 10 = Best 1 = Worst | 20% | 4 | 5 | 9 | 7 |
| Strength to Weigth Ratio | Weight needs to mimimized while strength is maxmimzed to prevent failure of the structure. | 10 = Best 1 = Worst | 25% | 6 | 8 | 10 | 4 |
| Factor of Safety | Factor of safety needs to be high but not to high as the material will be too heavy. Too low of a factor of safety means the structure has a great chance of fracturing | 10 = Best 1 = Worst | 25% | 5 | 7 | 6 | 8 |
| | | TOTALS: | 100% | 61.50% | 68.50% | 81.00% | 60.00% |

# Robotic Arms

*Arm Geometry, Motor Requirements, and Innovative Attachment System*

- Arm Sizing and Placement
  - Dimensions based on Swift's Geometry to ensure it can reach umbilical port
    - ~ 3.5 feet long
  - Sizing achieved using reference images and presskit schematic
- Motors and Force Requirements
  - Kollmorgen AKM1 brushless DC motors
    - Requires 300 W under max load
  - Force required to move battery pack ~ 2N
- Attachment Mechanism
  - Utilizing Gecko grippers to prevent damage to Kapton Film
  - Total 4 rotating pads
  - Effectiveness proven in microgravity by NASA



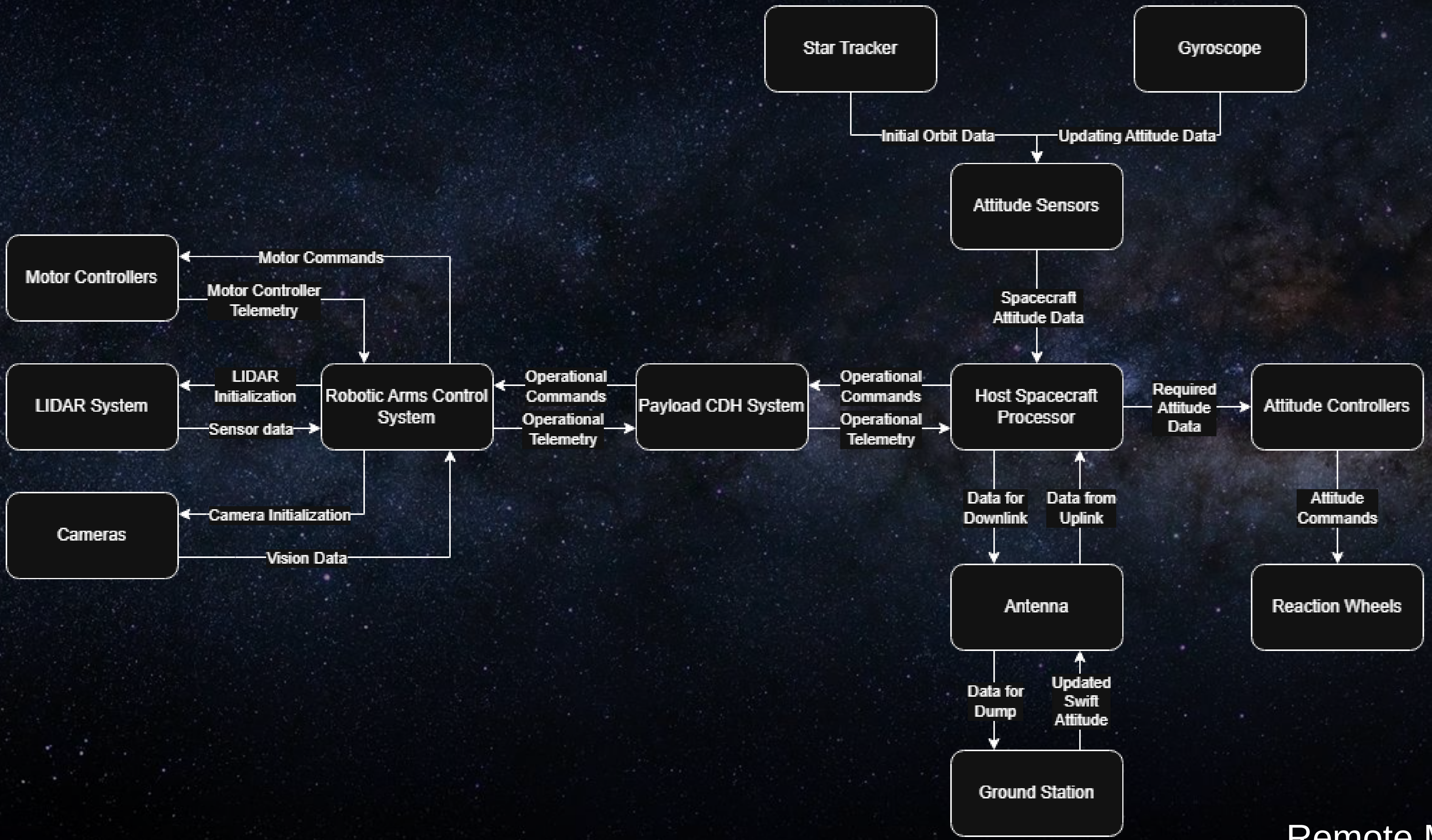
# C&DH

*Overview of Command and Data Handling System*

- Centralized architecture
  - Through the host spacecraft
  - Radiation hardened processor and circuitry
  - Sensor data and commands for subsystems
- PCB for battery bracket
  - Arduino-based
  - Control of epoxy extrusion
  - Control of epoxy curing (temperature control)
- Robotic Arms
  - 2 Cameras on each arm (Crystalspace CAM1U)
    - Vision processing system for battery bracket
  - LIDAR system for distance analysis
    - ASC GSFL-16KS

# C&DH Flowchart

*Overview of Command and Data Handling System*



# External Battery

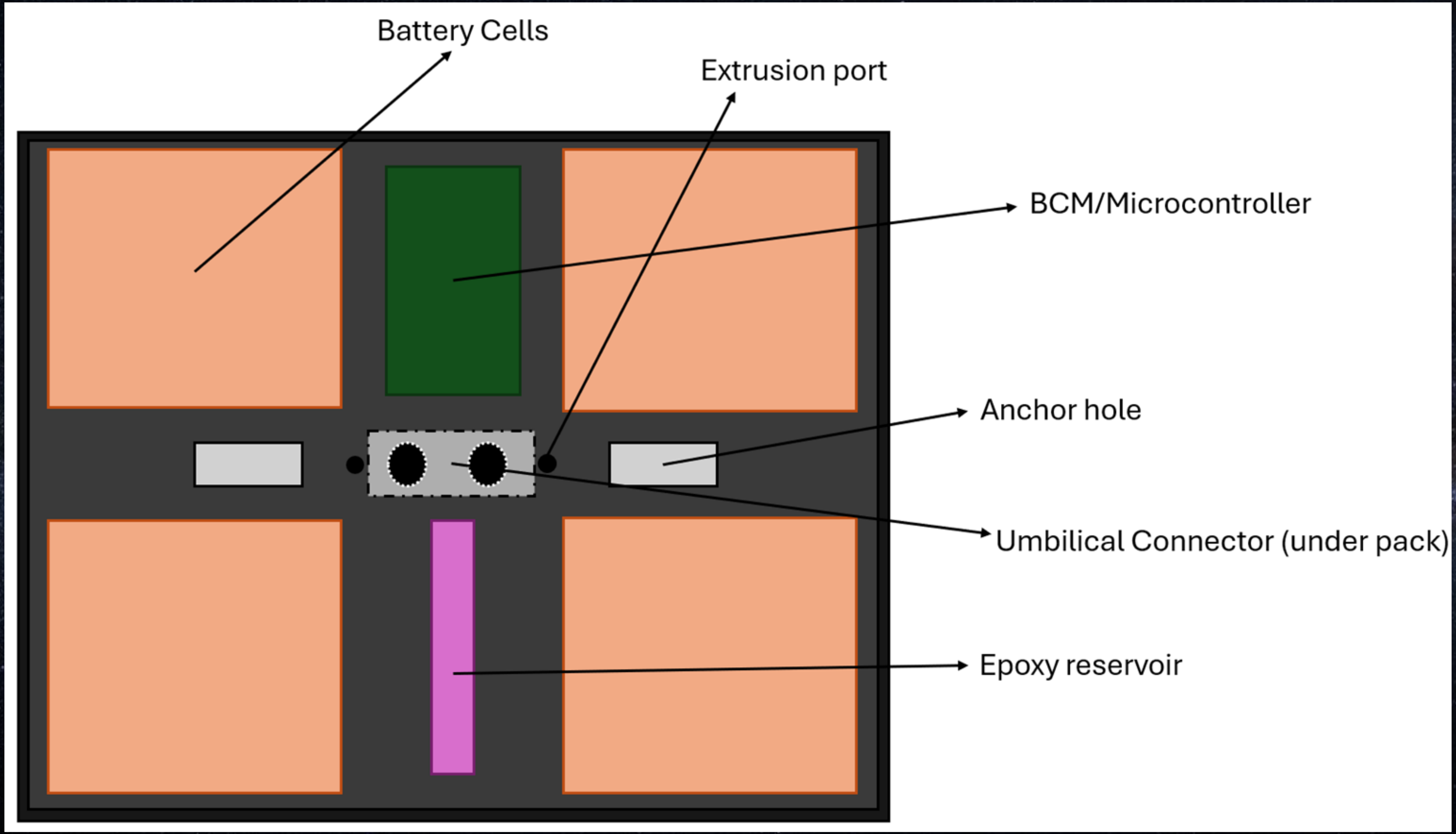
*Battery Selection, Material Considerations, and Monitoring Operation*

- Utilizing four 55 Ah Lithium-Ion cell batteries from Eagle Picher
  - Swift uses 80 Ah Nickel-Hydrogen battery
  - Two for redundancy
- Material Selection
  - Beryllium for structure
  - Pyrogel for thermal insulation
  - Polyethylene for radiation shielding
- Epoxy and Curing
  - Loctite Ea 9690 aero epoxy
  - Heating coils and solenoid-controlled extrusion mechanism
- Battery Monitoring
  - Low-power, radiation-hardened PCB
  - Monitors battery status and temperature wh
    curing

| Lith-Ion Battery | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Criteria** | **Explanation** | **Grade** | **Weight** | **30 Ah Space Cell** | **43 Ah Space Cell** | **60 Ah Space Cell** | **55 Ah Lithium-Ion Cell** |
| **Energy Density** | Maximizes stored energy while keeping mass low, ensuring efficient power use without exceeding payload constraints. | 10 - 1 | 30% | 7 | 9 | 10 | 8 |
| **Mass** | Lower mass reduces launch costs and improves maneuverability, making the spacecraft more efficient. | 10 - 1 | 30% | 9 | 8 | 7 | 7 |
| **Power Storage** | Ensures enough energy for operations during eclipse periods when solar panels aren't generating power. | 10 - 1 | 25% | 5 | 6 | 7 | 10 |
| **Volume** | Space is limited; a high energy density per unit volume ensures more power storage while leaving room for other components. | 10 - 1 | 15% | 9 | 8 | 6 | 6 |
| | | **TOTALS:** | **100%** | **74.00%** | **78.00%** | **77.50%** | **79.00%** |

# Battery Pack Internals

*Payload for Remote, In-Space Maintenance (PRISM)*



# Bill of Materials and Mass Budget

*Bill of Materials List with Calculated Mass*

| Bill of Materials with Mass | | | |
|---|---|---|---|
| **System** | **Item** | **Quantity** | **Mass (kg)** |
| Ext. Battery | 55 Ah Lithium-Ion Cell | 4 | 6.72 |
| Battery Bracket | Bracket (Case) | 1 | 11.70 |
| | Epoxy | 1 | 0.99 |
| | Heating Coils | 2 | 0.75 |
| | Extruders | 2 | 1.00 |
| Thermal | Louver System | N/A | 0.57 |
| Structure | Truss + Mounts | N/A | 11.50 |
| | Bracket Mount Servos | 2 | 0.99 |
| Robotics | "Gecko" Arm Beams | 2 | 6.44 |
| | "Gecko" Arm Motors | 3 | 4.50 |
| | Ext. Bat Arm Beams | 2 | 6.44 |
| | Ext. Bat Arm Motors | 3 | 4.50 |
| Misc. | Margin (15%) | N/A | 10.50 |
| **Payload Total:** | | | **66.60** |

# X-Sat Venus Class Bus Integration

*Overview of Spacecraft Bus Subsystems*

- Thermal
  - Expecting temperatures between 40-80C
- GNC
  - Gyroscopes paired with star trackers selected for precise attitude determination based on trade study results.
  - Reaction wheels chosen for 3-axis stability; sourced from Blue Canyon Technology.
- CDH
  - Centralized architecture implemented for direct data flow into the RAD6000 radiation-hardened processor
- Propulsion
  - Nitrogen cold gas thrusters selected for low power draw and sufficient specific impulse (~60s)
  - Total Δv required for maneuvers calculated at 220 m/s, with an estimated propellant mass of 33 kg.
- Power
  - Chose 444 W array as it was calculated that spacecraft will utilize 337 W of power

# X-Sat Venus Class Bus Integration (cont)

*Power Draw of Payload and Bus Meets the Mission Power Requirements*

## Power

| Day Time | | | Eclipse Time | | |
|---|---|---|---|---|---|
| **Subsystem** | **% Allocated** | **Watts Allocated** | **Subsystem** | **% Allocated** | **Watts Allocated** |
| Thermal Control | 20% | 47.62 | Thermal Control | 40% | 63.62 |
| Attitude Control | 8% | 18.75 | Attitude Control | 5% | 7.95 |
| Power | 2% | 3.75 | Power | 2% | 3.18 |
| CDS | 10% | 24.37 | CDS | 5% | 7.95 |
| Comms | 20% | 48.75 | Comms | 5% | 7.95 |
| Propulsion | 2% | 3.75 | Propulsion | 0% | 0 |
| Mechanisms | 2% | 3.75 | Mechanisms | 0% | 0 |
| Battery Charging | 1% | 1.87 | Battery Charging | 0% | 0 |
| Payload | 28% | 65.62 | Payload | 0% | 0 |
| Error Margin | 20% | 43.65 | Error Margin | 20% | 18.13 |
| Total During Day (W) | | 262 | Total During Eclipse (W) | | 109 |
| Total Power | 372 | Watts | Array Area Req | 0.91 | m^2 |

# Data Handling and Comms (Bus)

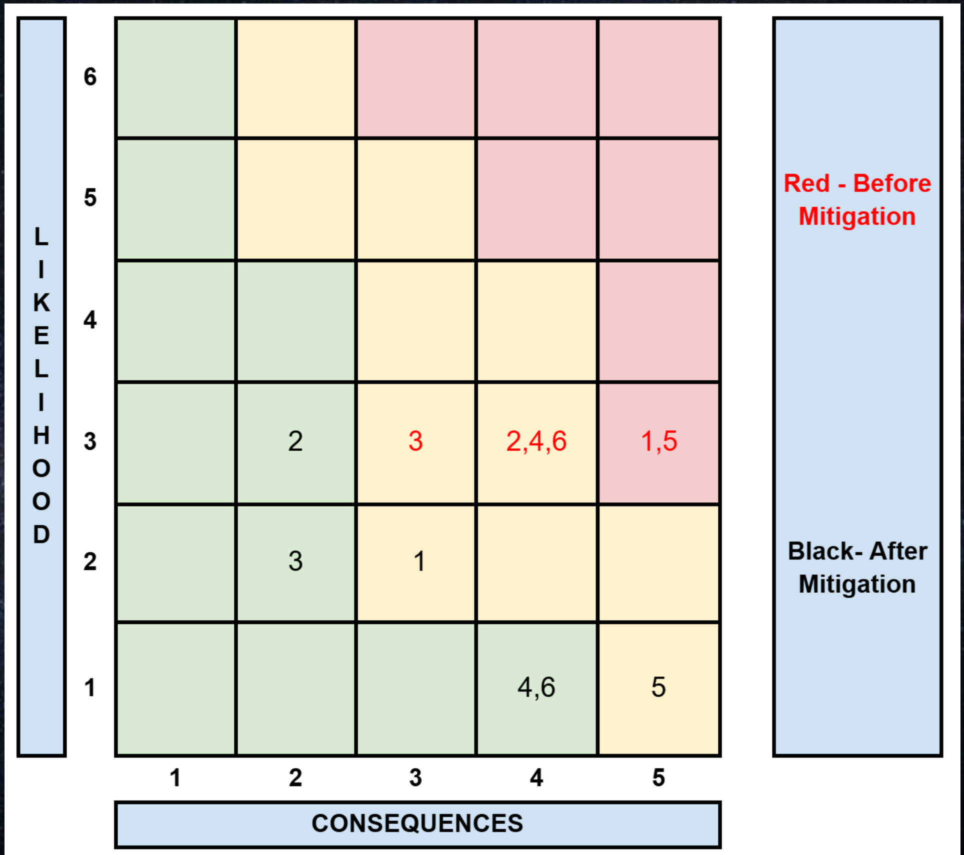
*Station Location and Performance*

- Downlink and Uplink at Malindi Ground Station
  - No real-time downlinks necessary
  - No observer or operator required
- Requirements for Communications System:
  - The communications system must harness S-band communication (Malindi station)
  - 2 links, uplink and downlink
    - Uplink margin: 34.30 dB
    - Downlink margin: 34.58 dB
  - Data rate: 120,000 bps
  - Fits within mass and power constraints

# Risks

*Payload Risk Analysis and Mitigation Strategies*

| ID | Risk Statement | Cause | Mitigation Plan |
|---|---|---|---|
| 1 | One Actuator Stops Working | Momentum Wheel Oversaturation or Failure | - Use the other two momentum wheels in the GNC system of the spacecraft to stabilize and change the attitude. |
| 2 | Camera Failure | Exposure to Radiation, Unforeseen damage from launch / space environment | - Backup cameras are included on the "wrist" of the arm in case of failure of the cameras in the hand of the arms.<br>- Since the cameras are radiation-hardened, only one should fail at a time, if at all. |
| 3 | Improper Data Dump at Link | Data from CDH Subsystem is over the Communication Limit | - The Link Budget for data has a high margin of ~33 dB, which means that there is a lot of room for error regarding data transfer at the downlink. With a data rate of 120,000 bps, there is room for error with the data transfer. This can be monitored.<br>- The data can be attempted to be sent at the next downlink transfer with the ground station. |
| 4 | Bi-metal spring stops working | Vibrational forces from launch | - Add multiple springs |
| 5 | Battery has a puncture | Damage to Aux Battery | - Include redundant battery units, in series |
| 6 | BCM Failure | Bitflip or computational errors arise due to radiation interference | - Redundant BCM on battery |



# Technology Gap Assessment

*Areas for Technology Advancement*

- Battery Energy Density
  - Batteries with higher energy density would allow the mission to use less cells meaning a reduction in weight.
- Standard ports for servicing
  - A standardized port for servicing would allow our payload to work on satellites of all types
- More advanced and lightweight robotic arms
  - More advanced arms would allow for more precise and accurate maneuvers while keeping weight down.

# Biggest Challenges Encountered

*Workplace Changes, Mass Issues, and Battery Attachment*

1. Workplace Fluctuations
   - Redesignate work as a result of losing a member
   - Restructure our work to onboard new teammate

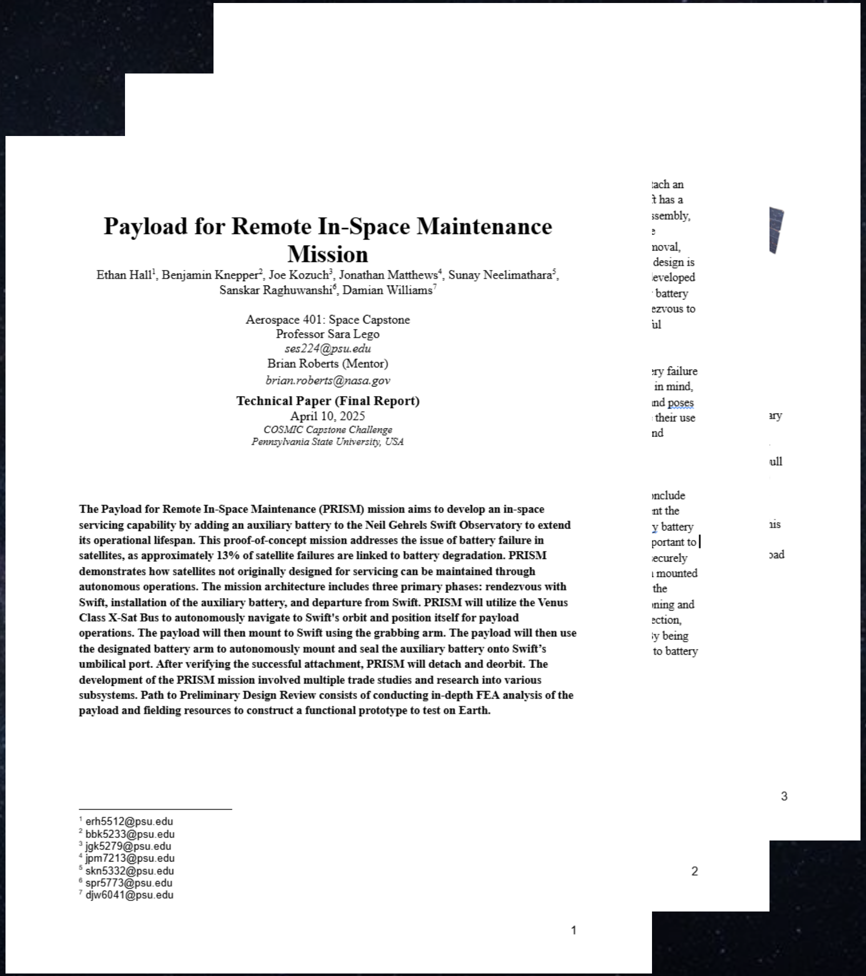
1. The robotic arm, motors, and the auxiliary battery pack had mass issues
   - Materials
     - Initial: Titanium Ti-6Al-4V
     - Revised: Aluminum 6061-T6 with Carbon Fiber Reinforcement
   - Redesigns
     - Reduced auxiliary battery size

1. Attachment of auxiliary battery pack to Swift
   - ensuring sturdy connection and port geometry
   - works well with PRISM’s amount of articulation

# Paper

*Payload for Remote, In-Space Maintenance (PRISM)*

- Key Elements
  - Abstract length: 190 words
  - Paper length: 18 pages
  - Number of references included: 20
  - Potential place to publish: AIAA Journal



**Payload for Remote In-Space Maintenance Mission**

Ethan Hall[1], Benjamin Knepper[2], Joe Kozuch[3], Jonathan Matthews[4], Sunay Neelimathara[5], Sanskar Raghuwanshi[6], Damian Williams[7]

Aerospace 401: Space Capstone
Professor Sara Lego
*ses224@psu.edu*
Brian Roberts (Mentor)
*brian.roberts@nasa.gov*

**Technical Paper (Final Report)**
April 10, 2025
*COSMIC Capstone Challenge*
*Pennsylvania State University, USA*

**The Payload for Remote In-Space Maintenance (PRISM) mission aims to develop an in-space servicing capability by adding an auxiliary battery to the Neil Gehrels Swift Observatory to extend its operational lifespan. This proof-of-concept mission addresses the issue of battery failure in satellites, as approximately 13% of satellite failures are linked to battery degradation. PRISM demonstrates how satellites not originally designed for servicing can be maintained through autonomous operations. The mission architecture includes three primary phases: rendezvous with Swift, installation of the auxiliary battery, and departure from Swift. PRISM will utilize the Venus Class X-Sat Bus to autonomously navigate to Swift's orbit and position itself for payload operations. The payload will then mount to Swift using the grabbing arm. The payload will then use the designated battery arm to autonomously mount and seal the auxiliary battery onto Swift's umbilical port. After verifying the successful attachment, PRISM will detach and deorbit. The development of the PRISM mission involved multiple trade studies and research into various subsystems. Path to Preliminary Design Review consists of conducting in-depth FEA analysis of the payload and fielding resources to construct a functional prototype to test on Earth.**

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# Path to PDR

*X-Sat Venus Class Bus Usage and Next Steps*

- X-Sat Venus Class Bus deals with Communications, Propulsion, and GNC
  - Deals with Uplink / Downlink from ground station
  - Cold gas thrusters for rendezvous
  - Reaction Wheels, Star Trackers, Gyroscope
- Next Steps:
  - Create a FEA and thermal model for analysis
  - Develop a 1:1 prototype for testing
  - Refine design based on testing

# Conclusion

*Payload for Remote, In-Space Maintenance*

- Impact on ISAM:
  - PRISM can expand the lifespan of older satellites while meeting ***all*** requirements stated in the RFP
  - Developed for Swift, easily modifiable for other customers
- Innovations
  - Non-intrusive battery installation
  - Non-destructive docking and grabbing method
- Lessons Learned:
  - Design Process
  - Value of Systems Engineering
  - Collaboration and Teamwork

***PRISM will revolutionize in-orbit servicing and extend satellite's lifespan through innovative external battery attachment!***

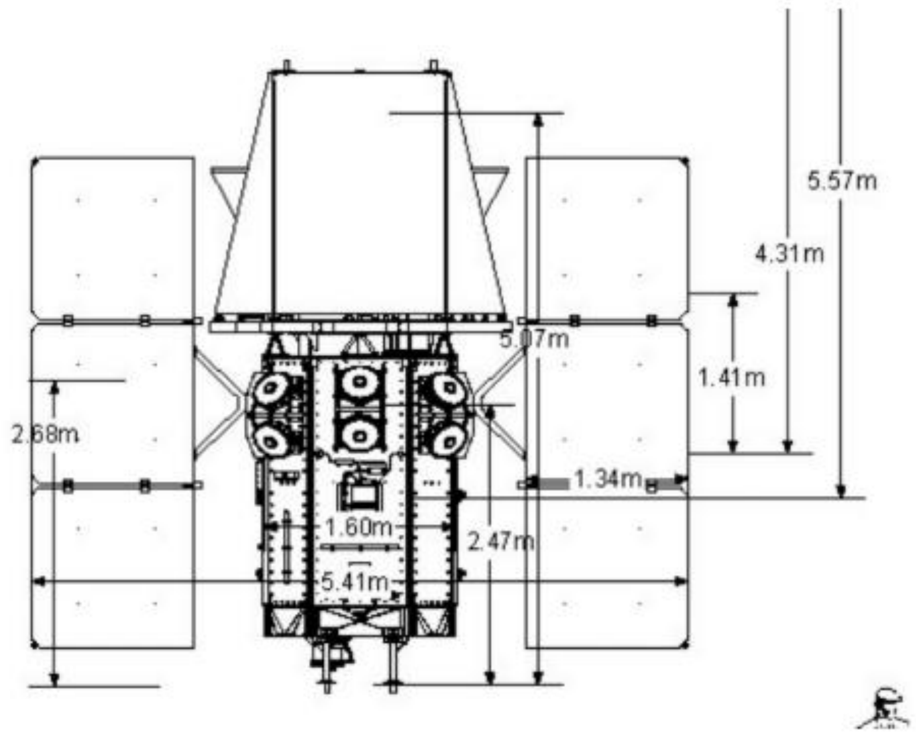
# Questions

*Payload for Remote, In-Space Maintenance*

Questions?

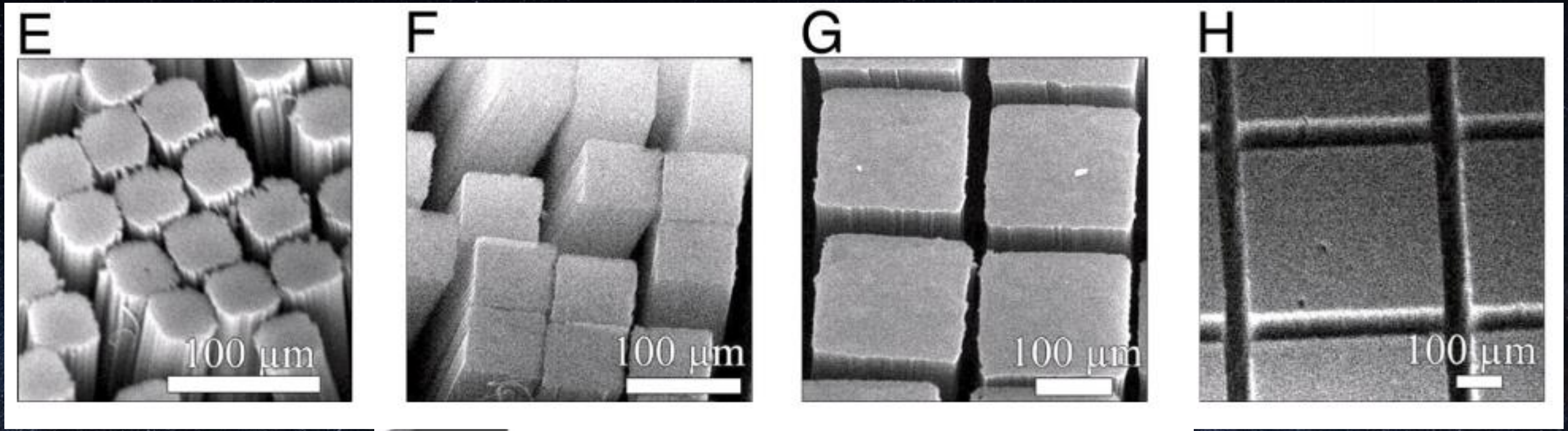
# Backup Slides

# Swift Photos

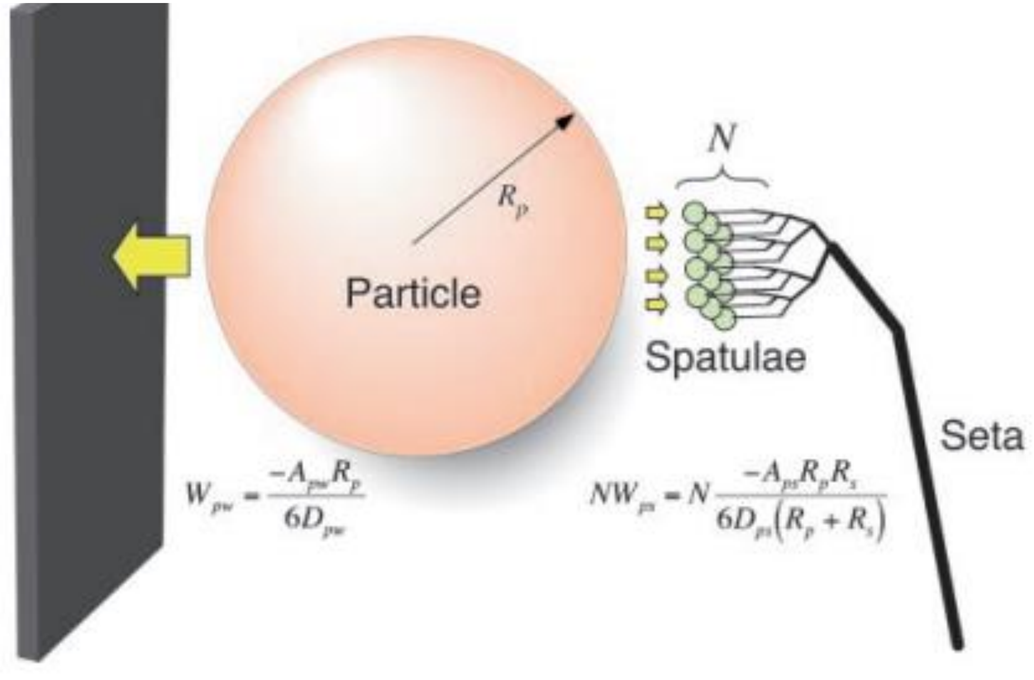



*Public Data

# Gecko Feet



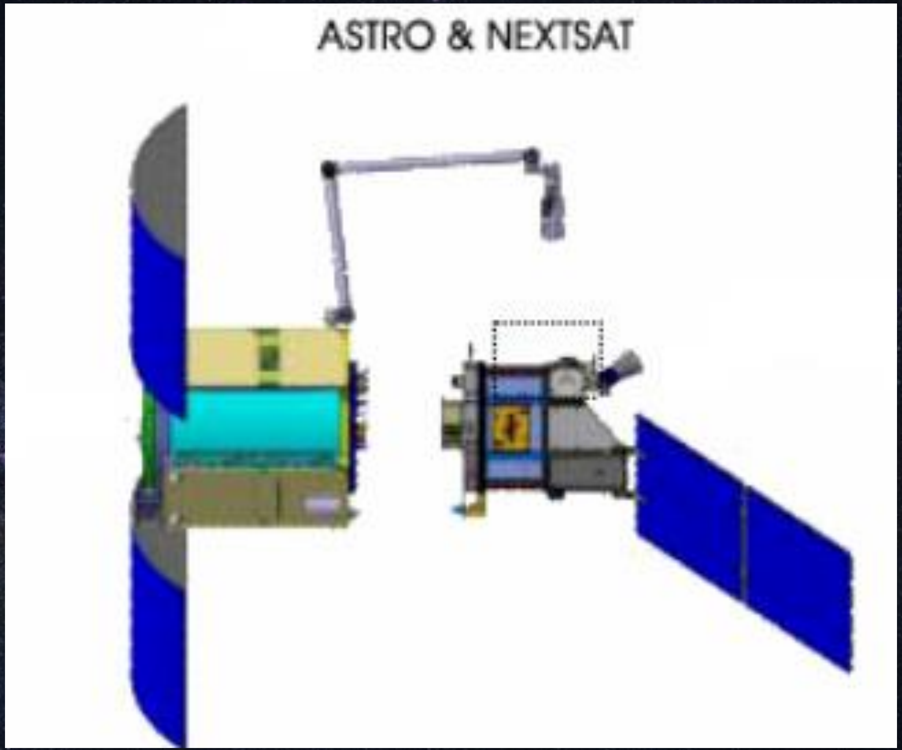

https://www.pnas.org/doi/10.1073/pnas.0703505104




https://www.pnas.org/doi/pdf/10.1073/pnas.0408304102

# Orbital Express

- O. Express comprised of ASTRO and NEXTSAT
  - Both specially made for demonstration
- PRISM is made to work with an already existing platform
  - Platform not designed for servicing
  - Can be easily modified and expanded to work on other platforms




https://en.wikipedia.org/wiki/Orbital_Express