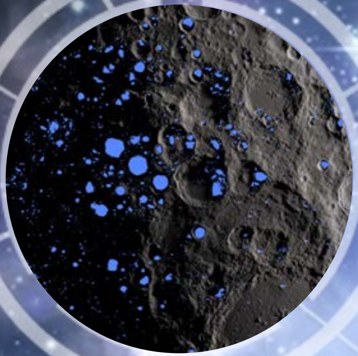
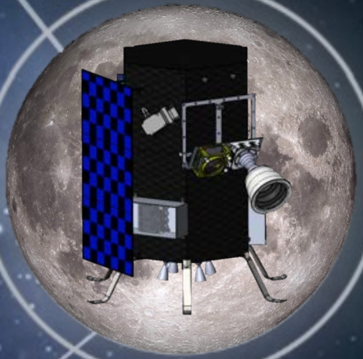
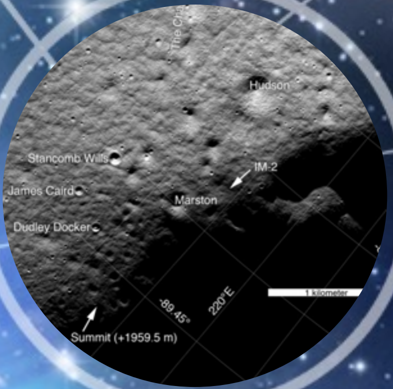
National Aeronautics and Space Administration

NASA







Space Technology Mission Directorate
Game Changing Development Program

Trent Martin | Molly Bannon | FY22 Deployable Hopper Annual Review Presentation | 09.14.22
Name/Email POC: molly.bannon@nasa.gov

Project Overview

- Technology Product Capability
  - Intuitive Machines will develop and demonstrate on the lunar surface a deployable robotic hopper (μNova) which will provide access to extreme environments not reachable by rovers or other technologies. A science payload provided by Arizona State University (ASU) will fly on this first demonstration of μNova.
- Technical Capabilities
  - Operate in Permanently Shadowed Region (60K for 45min)
  - Autonomous flight into and out of the PSR
  - Carry a 1kg payload (2.2lbs)
  - Functional flight range of more than 2.5km (1.5mi)
- Exploration & Science Applicability
  - Enabling for lunar surface science through low-cost secondary payloads on CLPS landers. Platform is flexible to accommodate different payloads on different mission profiles.
  - Increases: science return, lunar terrain accessibility
  - Decreases: mission cost, system complexity and mass, risk to future missions
  - Scheduled to fly in June 2023 on a Nova-C through the CLPS Intuitive Machines-2 (IM-2) mission

IM's Nova-C, the lander that will deliver μNova to the moon.

Team Members / Project Org Slide

Trent Martin
Principal Investigator
VP of Space Systems
Intuitive Machines

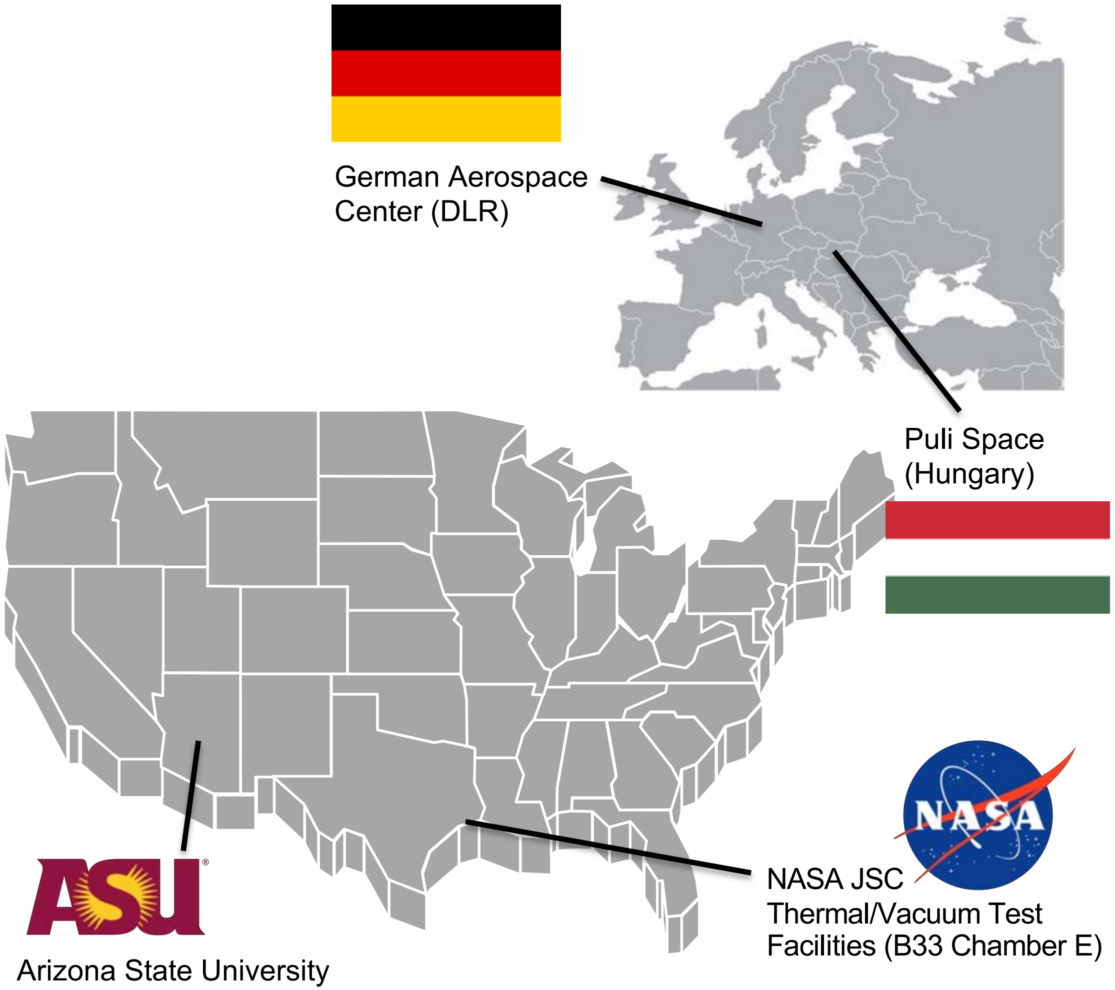
Mark Robinson
Co-Investigator
Arizona State University

Matt Atwell
Project Manager
Intuitive Machines

Molly Bannon
NASA PM/COR

Collaborations & Partnerships

- Arizona State University (Co-Investigator, imaging payload)
- German Aerospace Center (Radiometer Payload Provider)
- Puli Space (Neutron Detector Payload Provider)
- NASA Johnson Space Center (Thermal/Vacuum Test Facility)



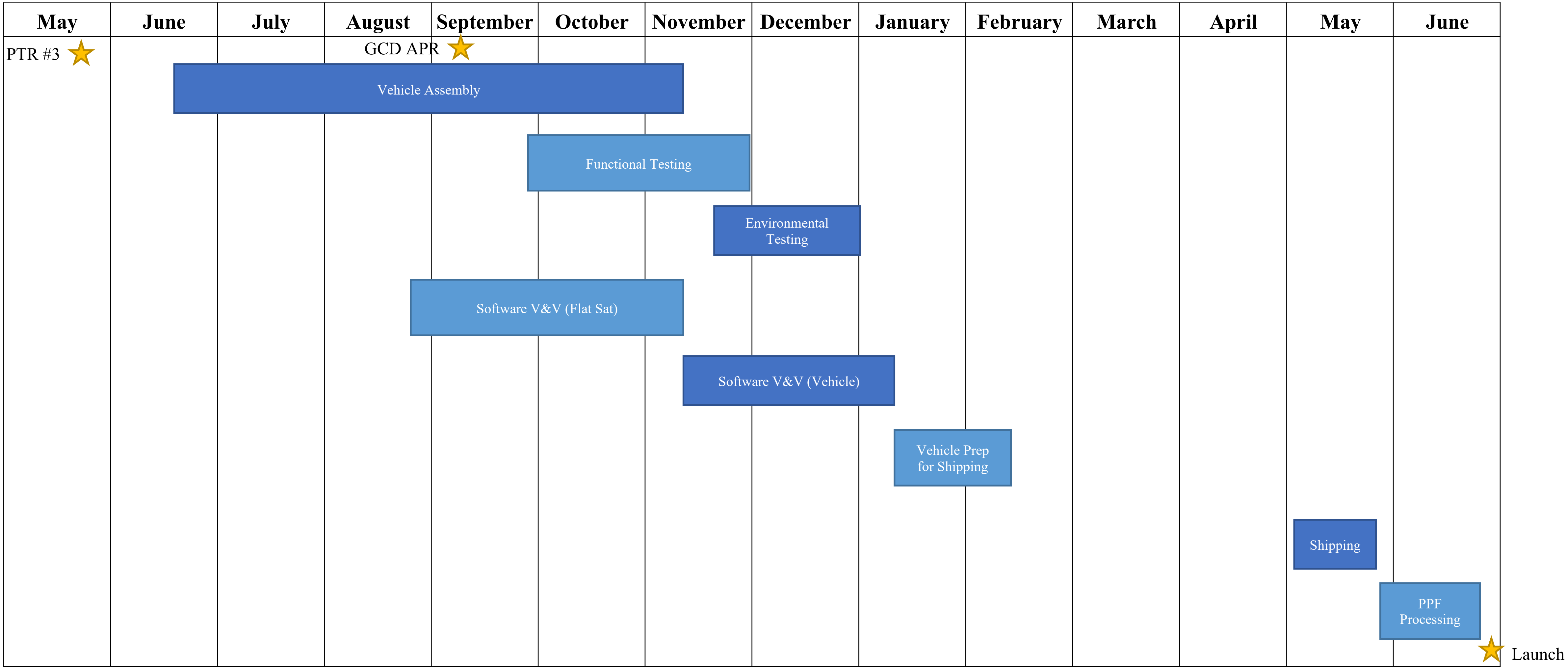
Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

Deployable Lunar Hopper
Technology Goals & Project Objectives

Technology Goals	
Goal #1	Enable robotic access to extreme lunar environments for scientific exploration
Goal #2	Enable regional exploration of wider areas than small rovers or other mobility platforms can cover

Project Objectives	
Objective #1	Design, build, integrate, and test a deployable lunar hopper
Objective #2	Demonstrate the operation of a deployable lunar hopper on the lunar surface, including flight into and out of a permanently shadowed region
Objective #3	Demonstrate the ability of the deployable lunar hopper to gather data for demonstration science payloads and downlink to earth

Deployable Lunar Hopper



Accomplishments

- Completion of detailed technical design through CDR-level
- Execution of all long-lead procurements
- Addition of new German Aerospace Center (DLR) payload (Lunar Radiometer)
- Addition of new Puli Space payload (Puli Lunar Water Snooper), which has been delivered to IM for integration
- EDU LIDI (science lighting system) fabrication and testing completed (at ASU)
- Successful completion of in-house additive pressurant tank development, qualification testing, and flight units
- Successful testing of EDU deployment system
- Stand-up and integration of flight simulation for GN&C team

Accomplishments

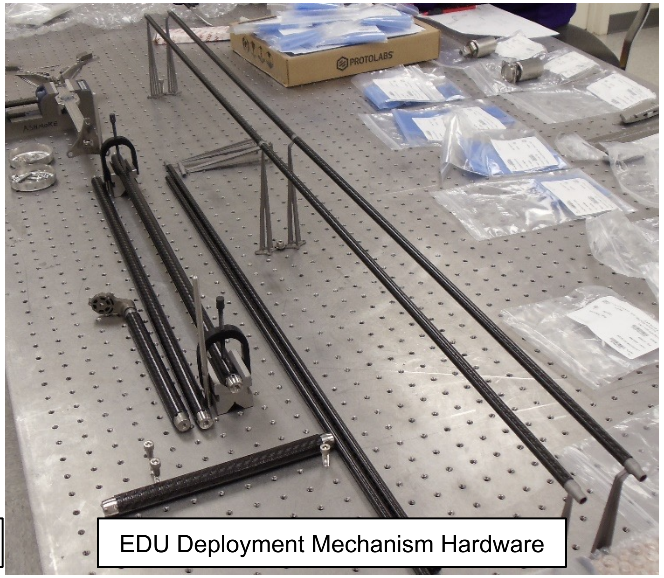
- All EDU controllers through fabrication and testing
  - uTRB (thermocouple routing box)
  - uMECB (multi-purpose controller)
  - uRCSC (thruster controller)
  - HOPSI (power system interface unit)
- EDU back-up UHF radio FlatSat testing round #1 complete
- Successful completion of OBC radiation testing (round #1), with important lessons learned on internal flash storage leading to hardware change
- Successful software integration of all IO apps with new OBC platform
- Successful testing of 4G LTE radio end-to-end RF communication between Nova-C base unit and Hopper User Element
- Successful completion of software integration for control stability testing
- Successful completion of attitude control stability testing

Accomplishments

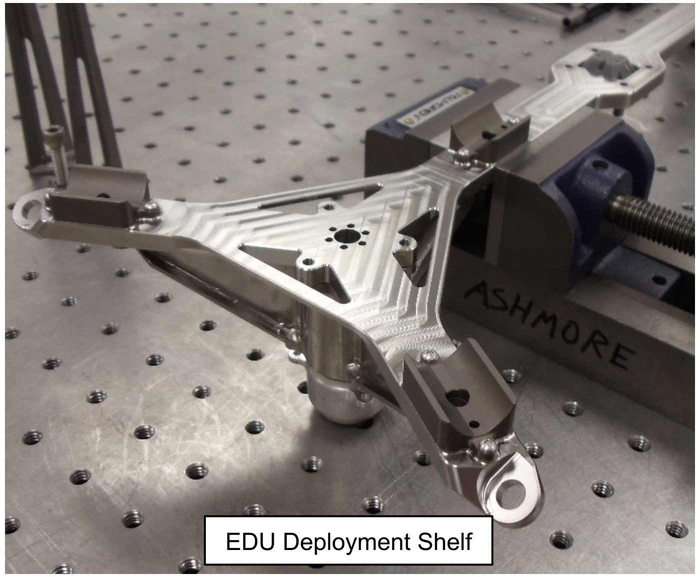
- Successful completion of propulsion cold flow test article testing
- Successful completion of main thruster hot-fire acceptance testing and delivery of units
- Successful completion of RCS thruster development testing, qualification, and assembly of flight units (in response to vendor failure to meet our needs)
- Successful development of all weld schedules for flight propulsion system
- Top deck pathfinder welding completed
- Fabrication of EDU engine deck and top deck completed

Accomplishments

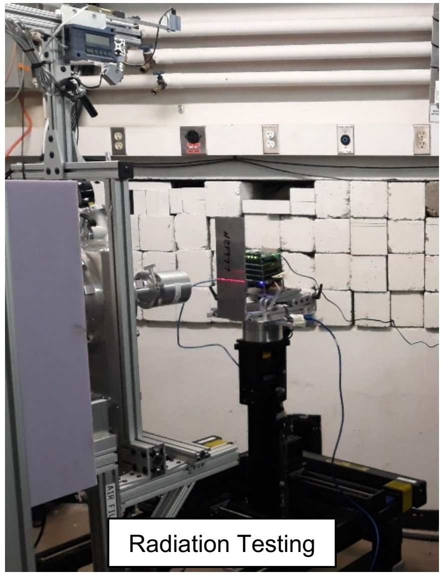

Pressurant Tank Qual Test

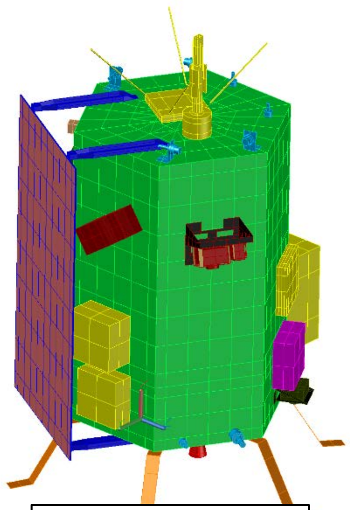


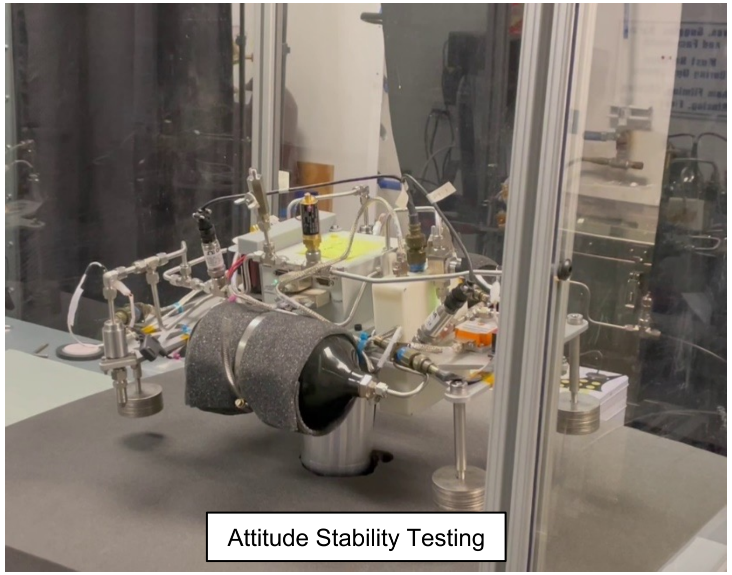
EDU Deployment Mechanism Hardware



EDU Deployment Shelf

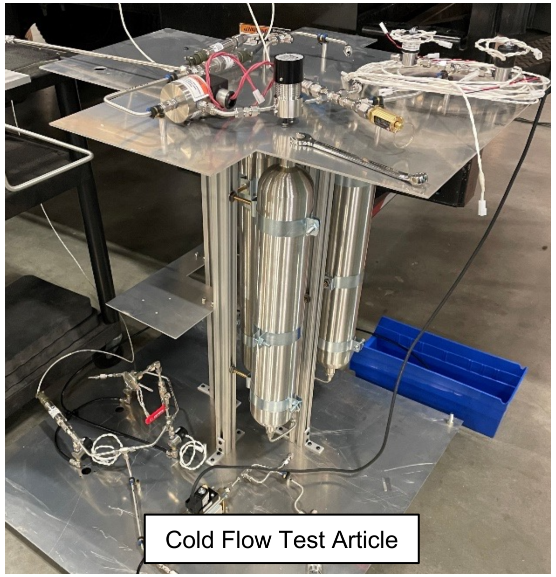

Radiation Testing


Global Thermal Model


Attitude Stability Testing


Landing Gear Fabrication

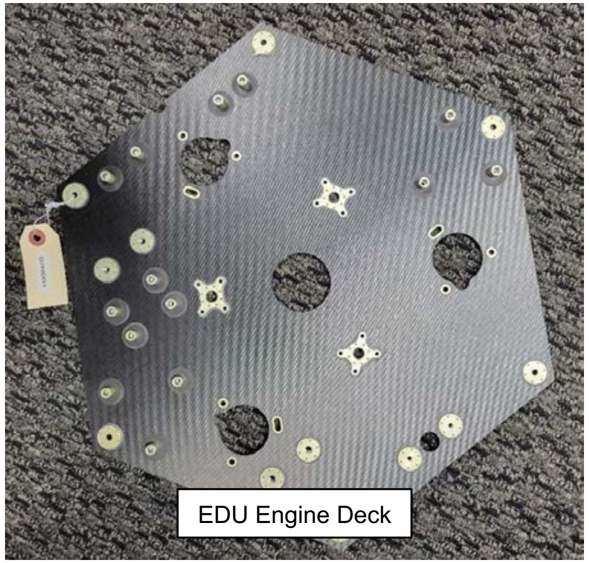

Thruster ATP

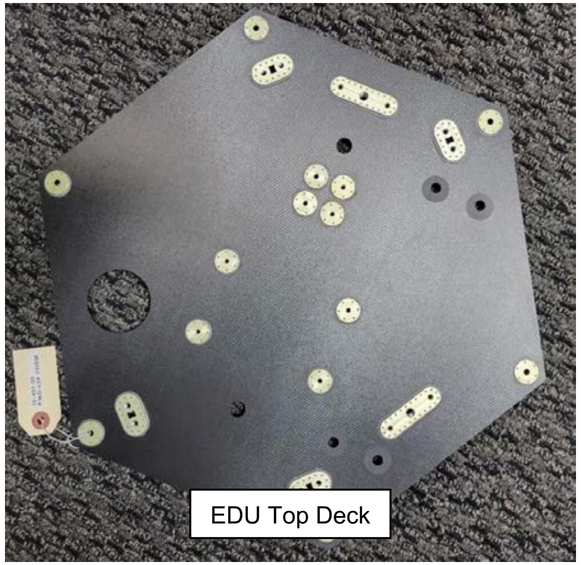

Cold Flow Test Article

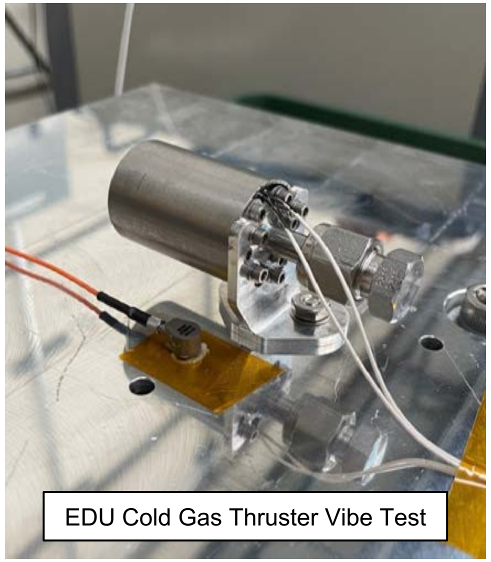

LED Science Lighting System

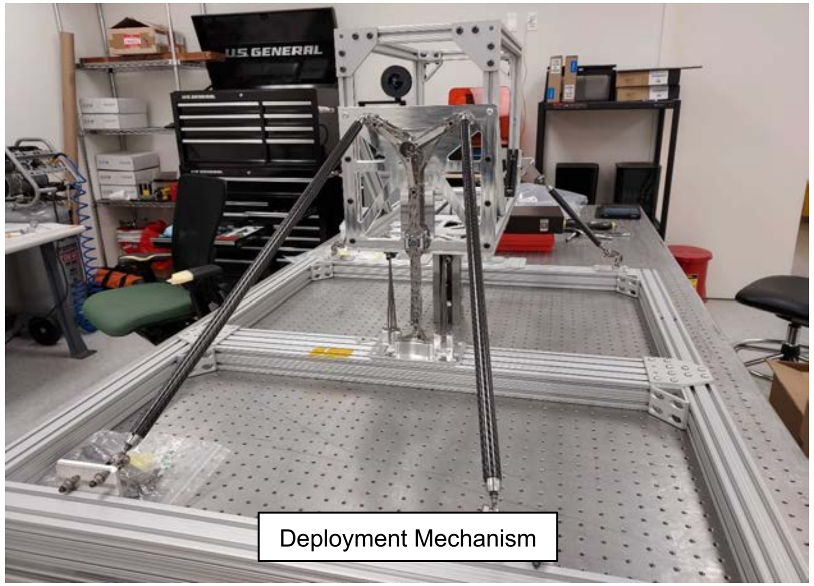
Accomplishments


Propellant Tank


EDU Engine Deck


EDU Top Deck


EDU Cold Gas Thruster Vibe Test



Deployment Mechanism

PLWS Flight Payload

Flight Heaters

Propellant Tank MLI

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year	G	G	G	G	Technical – Cost – Schedule – Programmatic -
Annual	G	Y	G	G	Technical – Cost – Schedule – Multiple, extensive vendor delays for critical systems (all major power system elements, propellant isolation valve) are forcing serial integration steps to move to the right. Programmatic -

Deployable Lunar Hopper

Project description:	Develop and demonstrate a deployable robotic hopper that can provide access to extreme environments and locations on the lunar surface.

Cost:

G	G	G	⇨

Monthly Trend

No cost issues at this time.

Schedule:

G	Y	Y	⬂

Monthly Trend

- Propellant isolation valve material issue (shape-memory alloy) has pushed earliest possible delivery date to early October, with larger delays possible depending on acceptance test results; this component must be integrated serially into the propulsion system before vehicle structure closeout
- Flight PCDU, MPPT, and batteries have all experienced substantial vendor delays due to supply chain issues; these components are not expected until early September, which will delay integrated testing

Technical:

G	G	G	⇨

Monthly Trend

- Current power balance based on latest heater requirements shows reduced margin for battery charging on the surface (power balance is currently at ~120%). We are currently working on a possible 4 solar panel configuration that can easily swap in for the 3-panel configuration in case the power margin cannot be increased, and we determine the uncertainty around available surface power generation is too high. This is a risk reduction step, and right now the mission closes with no change.

Programmatic:

G	G	G	⇨

Monthly Trend

- No programmatic issues at this time.

Mission Infusion & Partnerships

- Infusion/Transition plan
  - Intuitive Machines is actively working with academic partners to develop the science case for various Hopper mission architectures, as well as organize teams to submit proposals to various NASA solicitations (PRISM, Discovery, CLPS) as applicable
  - Intuitive Machines participates in the LSIC mobility technology subgroup and is actively seeking new academic and industry partners via multiple sources
  - Intuitive Machines participates in multiple industry forums and conferences (LPSC, LEAG Annual Meeting, etc.) in order to seek out business opportunities for this platform
  - Intuitive Machines is interested in pursuing additional dialogue with NASA on how Micro-Nova's capabilities would enable an ISRU prospecting mission
  - Candidate missions and applications:
    - ISRU Survey Mission
      - Could play an important role in site selection for an ISRU plant as a part of the Artemis program
    - Mare Tranquilitatis Pit Mission
    - Ina Irregular Mare Patch Exploration Mission
    - South Pole-Aitken Basin Exploration Mission
    - Lunar Terrain Vehicle Payload

Education/Public Outreach

EPO Involvement

- Panelist participation at LSIC Fall Meeting on Nov 4, 2021 (Robotic Flight Demonstrations)
- Poster presentation at LPSC on March 8, 2022
- Poster presentation and abstract submittal to Lunar Exploration and Analysis Group Annual Meeting on August 24, 2022
- Multiple social media posts highlighting the Hopper mission on IM-2
- Other involvement through Nova-C outreach at Daytona 500 (see picture) partnering with Columbia Outerwear

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	
Annual Meeting of the Lunar Exploration Analysis Group	August 23-25

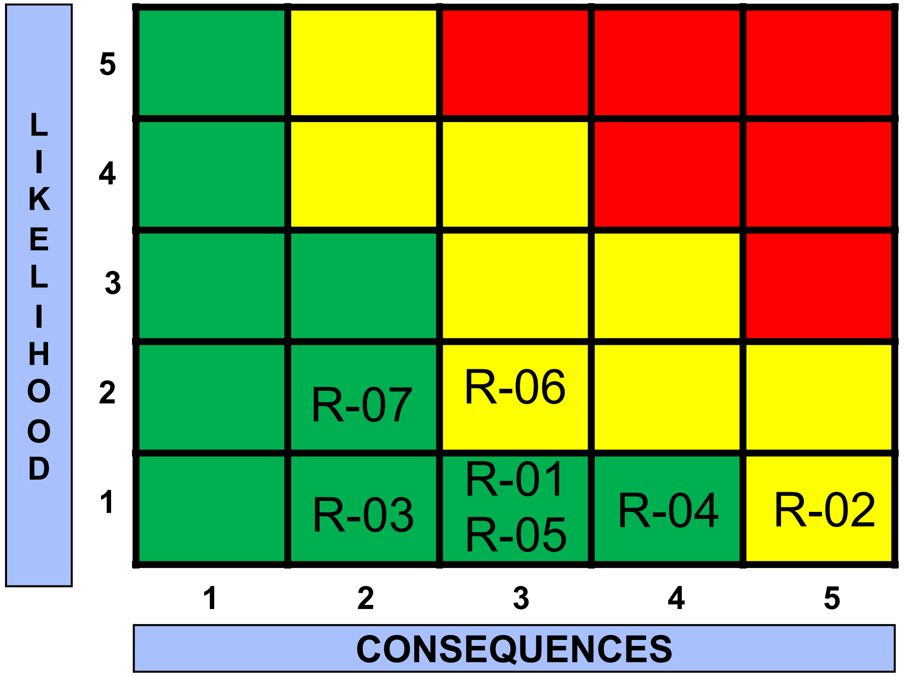
Project Summary

- The Micro-Nova team has conducted a System Integration Readiness Review (PTR #3) and is now fully into the spacecraft integration phase of the project ahead of a mid-2023 launch date
- A number of important test milestones have been achieved this year leading up to readiness for system integration:
  - Deployment mechanisms testing
  - Attitude control stability testing
  - Propulsion system cold flow article testing
  - Integrated OBC testing, including software app development and integration
  - Pressurant tank qualification testing
- The vehicle will be assembled over the next 3 months, with a number of milestones along the way to formal spacecraft delivery:
  - Payload Integration Interface Verification
  - Functional Testing After Assembly Complete
  - Deployment Mechanism Interface Verification
  - Environmental Testing (Vibration, Thermal/Vacuum)
  - Formal Software Verification

Project Plan - Milestone Status

Milestone Title (Mirror Project Plan)	Baseline Date	Planned Date	Variance Explanation
Status of milestones due since last report			
Documentation of deployment mechanism testing and results	3/2022	4/01/2022	Submitted on 3/25
Documentation of initial flight software build release	3/2022	4/15/2022	Submitted on 3/16
Documentation of FlatSat build completion	12/2021	3/23/2022	Submitted on 3/30
Documentation of flight control stability testing completion and simulation validation	2/2022	4/28/2022	Submitted on 4/27
PTR #3 summary package	3/2022	5/20/2022	Submitted on 5/20
Status of milestones due in the next 60+ days			
Documentation of payload integration completion	9/1/2022	9/28/2022	Delays from our PCDU vendor will impact when we can first integrate the Tipping Point payload onto the vehicle with flight equivalent power system. This is likely going to push this milestone to the end of September (still some uncertainty on vendor estimated ship date)
Documentation of checkout test results	10/1/2022	10/28/2022	Delays from our propellant isolation valve vendor will impact when we can finish closeout welding on the propulsion system, which is required before structures integration can be completed (due to access issues).

Risk Summary



Risk ID	Approach	Trend	L x C*	Risk Title
R-01	M	⇨	1 x 3	Mass
R-02	M	⇩	1 x 5	Deployment Crash
R-03	M	⇨	1 x 2	Nova-C Integration
R-04	M	⇩	1 x 4	Control Stability
R-05	M	⇨	1 x 2	Thermal Management
R-06	W	⇧	2 x 3	Schedule
R-07	R	⇨	2 x 2	Dust Mitigation

*Showing L x C score **after** planned mitigation is completed

Criticality
- High
- Med
- Low

L x C Trend
- ⇩ Decreasing (Improving)
- ⇧ Increasing (Worsening)
- ⇨ Unchanged
- ☐ New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: **T**-Technical **C**-Cost **Sc**-Schedule **Sa**-Safety

BACKUP

Deployable Hopper Key Performance Parameter (KPP) Status

Key Performance Parameters								
Parameter	**Units**	**State of the Art (SOA)**	**Threshold Value**	**Project Goal**	**Current Value To Date**	**TBoE for the provided Current Value**	**Expected Exit Value**	**TBoE for the provided Expected Exit Value**
Excursion Data Downlinked[(1)]	GB	N/A	1	3.5	5	Analysis	5	Estimate based on link analysis and Nokia LTE path propagation assessment; also includes available downlink time (shared with other payloads)
Longest Flight Capability	m	N/A	10	100	280	Analysis	280	Flight simulation with processor in the loop
PSR Survival Limits	K, min	N/A	60, 15	60, 45	60, 60	Analysis	60, 60	Global thermal model (to be validated with tvac test)
Landing Capability[(2)]	deg, m/s	N/A	5, 1	10, 2	7[(4)], 2	Analysis	7, 2	Dynamic tip over model
Power Margin[(3)]	%	N/A	15%	30%	21%	Analysis	21%	Power balance model including detailed solar panel degradation model

Notes:
(1) Downlinked to earth
(2) Slope angle, vertical landing velocity
(3) Excess power capacity as a percentage of standby power draw when solar vector is normal to solar panel
(4) Includes lateral and rotational velocity

KPPs are not yet in an approved state.

Deployable Lunar Hopper

Deployment Crash

Risk ID #
R-02

Trend
Decreasing

Criticality

Current L/C
1x5

Affinity Group
Technical

Planned Closure
Completion of control stability testing (May 2022)

Open Date
3/1/2021

Risk Statement :

Approach: Mitigate

Given that the vehicle cannot undergo free-flight deployment testing on earth (gravity), there is a possibility that the deployment flight will encounter unforeseen control issues that cannot be uncovered with the planned stability testing, resulting in the vehicle crashing on the lunar surface.

Context

Attitude control stability testing will be conducted to tune the control system and verify margin over all expected flight regimes. Deployment testing will verify proper separation of the vehicle from Nova-C. But vehicle free-flight testing under the appropriate forces/torques is the only method to truly verify end-to-end deployment, and this must be accomplished on the lunar surface.

Date	Status (Please provide the last 3 status)	LxC (at time change/update)
9/17/2021	Initial GN&C simulations indicate the design approach will close with margin	2 x 5
2/23/2022	Attitude control stability testing underway. Initial results indicate that the test set-up will enable the necessary control system tuning. Initial EDU deployment system assembly underway, with no issues after initial fit-up. Testing scheduled for later in March.	2 x 5
8/23/2022	Attitude control stability testing was completed. Stability was achieved after some tuning of gains and ironing out bugs. The flight simulation was validated against the test results.	1 x 5

Mitigation Steps	Dollars to implement	Trigger/Start date	Schedule UID	Completion Date	Resulting LxC
Deployment mechanism EDU ground testing (including environmental testing, CG offset, etc)					
Deployment mechanism flight unit acceptance testing (including environmental testing with flight vehicle)					
Dynamic tip-over analysis to provide acceptable "box" of landing conditions for Flight Dynamics team					
Drop testing of EDU structural article for validate tip-over analysis					

Deployable Lunar Hopper

Schedule

Risk ID #
R-06

Trend
Increasing

Criticality

Current L/C
2x3

Affinity Group
Schedule

Planned Closure
TBD

Open Date
3/1/2021

Risk Statement :

Approach: Mitigate

If any major project element takes longer than estimated in the baseline schedule, there may not be enough schedule reserve to meet the IM-2 delivery date.

Context

Micro-Nova is only one element of the IM-2 mission, and any delays caused by Hopper could have a major impact on the program's ability to meet obligations to other customers.

Date	Status (Please provide the last 3 status)	LxC (at time change/update)
3/1/2021	Initial risk writing.	2x3
8/23/2022	Spacecraft integration has been delayed due to a number of vendor delays. Significant schedule margin still exists between projected spacecraft completion date and IM-2 launch date.	2x3

Mitigation Steps	Dollars to implement	Trigger/Start date	Schedule UID	Completion Date	Resulting LxC
Early long lead procurements					
Design re-use where possible/practical					
Final integration at the PPF to minimize Nova-C impacts					