SIMULATING ADVANCED LUNAR EXPLORATION ROBOTIC SYSTEMS

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SPEAKER

LUTZ RICHTER

SoftServe Space Projects Consultant

AGENDA

01	Current lunar exploration setting
02	Mobility on and above the Moon
03	SoftServe lunar drone concept
04	Demo showcase: simulation of lunar drone flight through a lunar lava tube
05	Lunar drones way forward
06	Simulation of ground-level work on the Moon: co-simulation and demo showcase
07	Takeaways
08	Q&A

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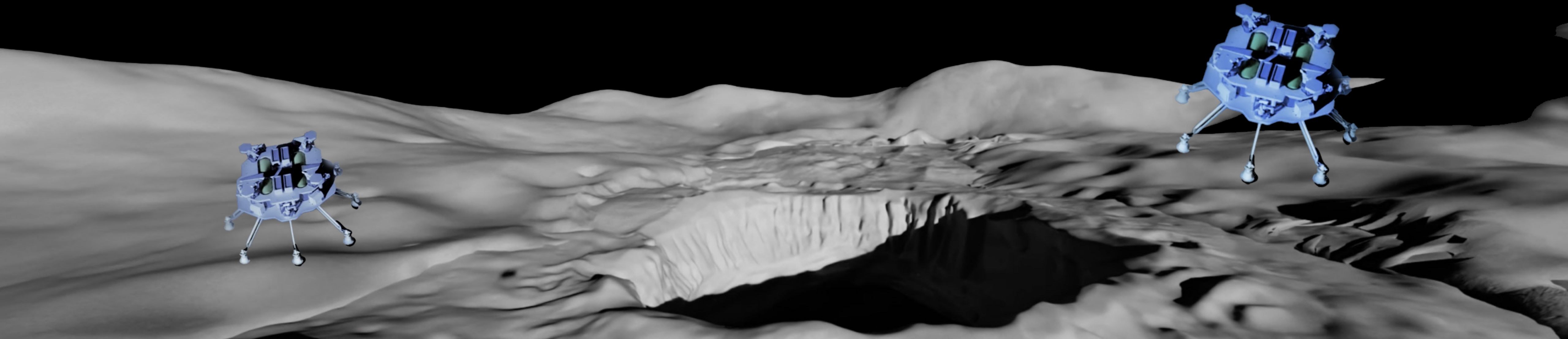
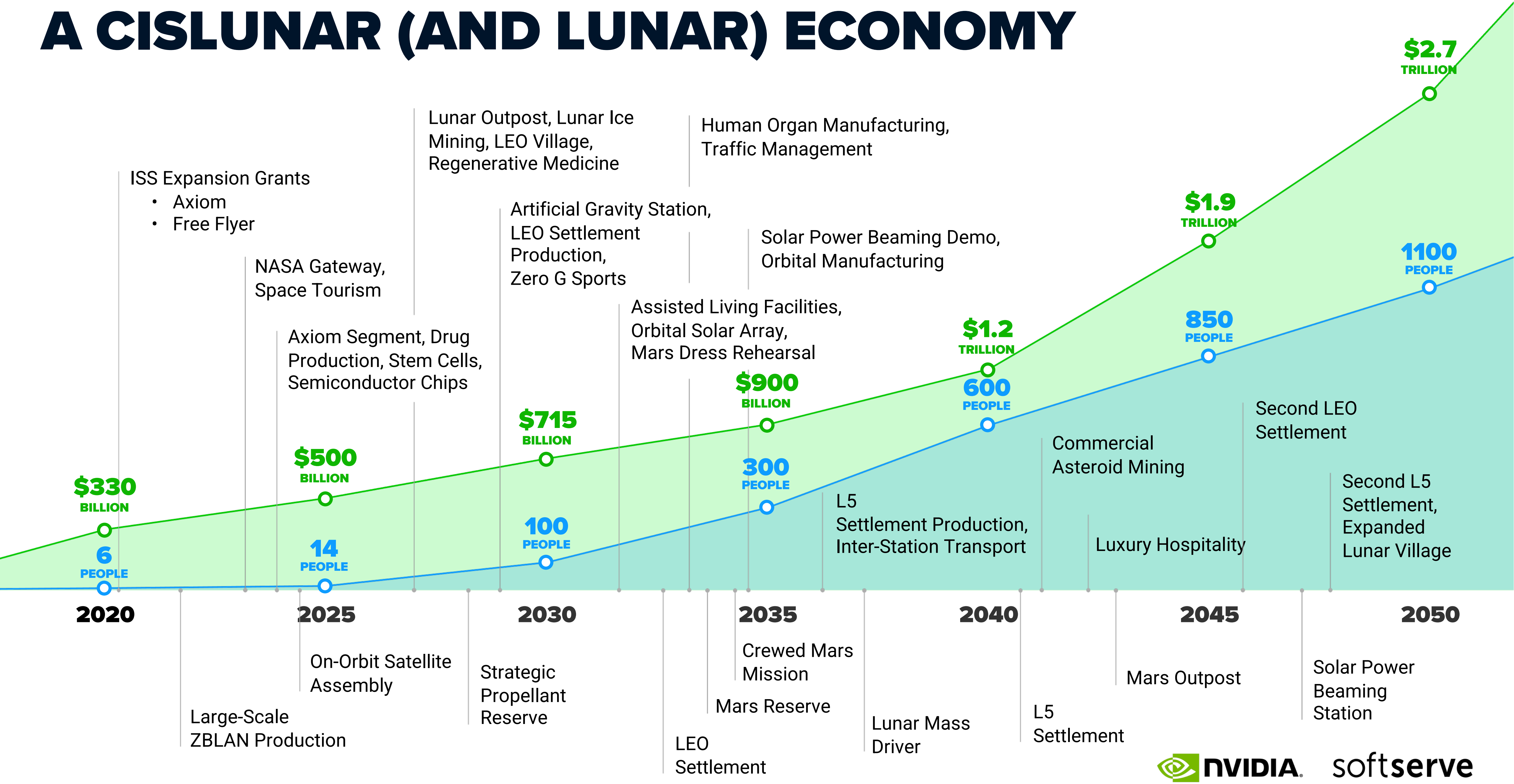
CURRENT LUNAR EXPLORATION SETTING



A CISLUNAR (AND LUNAR) ECONOMY



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LUNAR EXPLORATION: RECENT HIGHLIGHTS

01. New orbiters (1994-now)

Filling knowledge gaps from Apollo: mapping of minerals, chemistry, terrain

02. New uncrewed landers

Chinese Chang'e program: landers, rovers, sample return
ISRO & JAXA landers & rovers
NASA CLPS commercial landers

03. New crewed systems in development

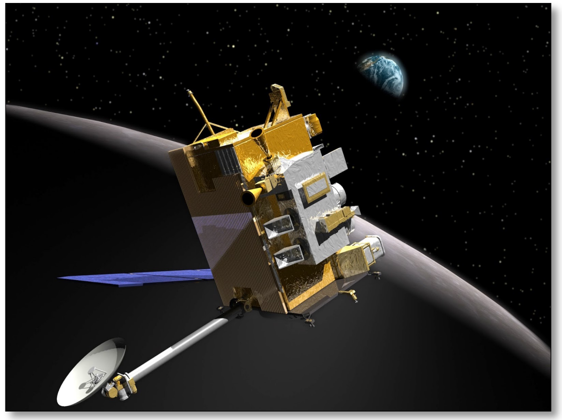
US-led Artemis program, China-led ILRS

04. Plans for sustainable crewed exploration & commercial interests

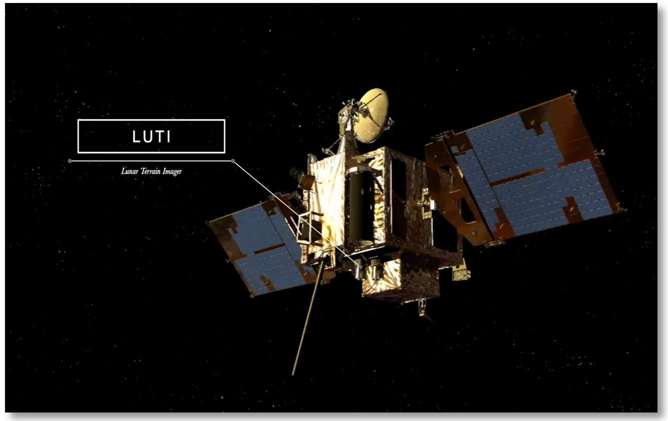
ISRU

Chang'e 3 (2013)

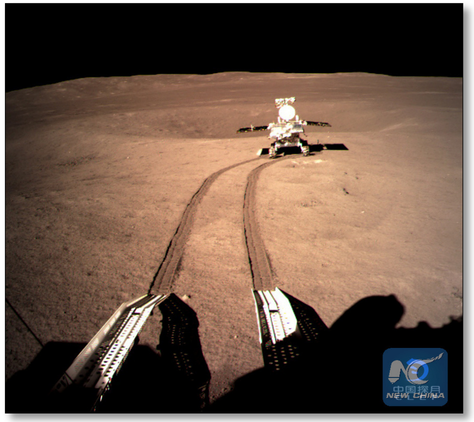
LRO (2009-today)



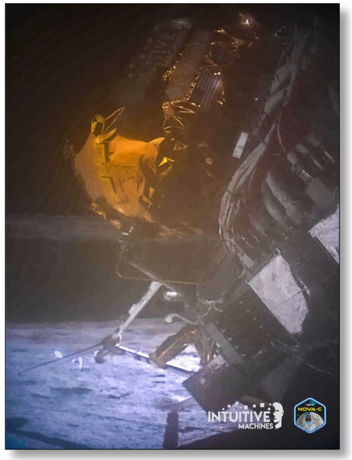
KPLO / Danuri (2022)



YUTU-2 rover Chang'e 4 (lunar farside)



US return to the lunar surface



CHANDRAYAAN-3, SLIM

New actors having scored successful lunar landings: India, Japan!

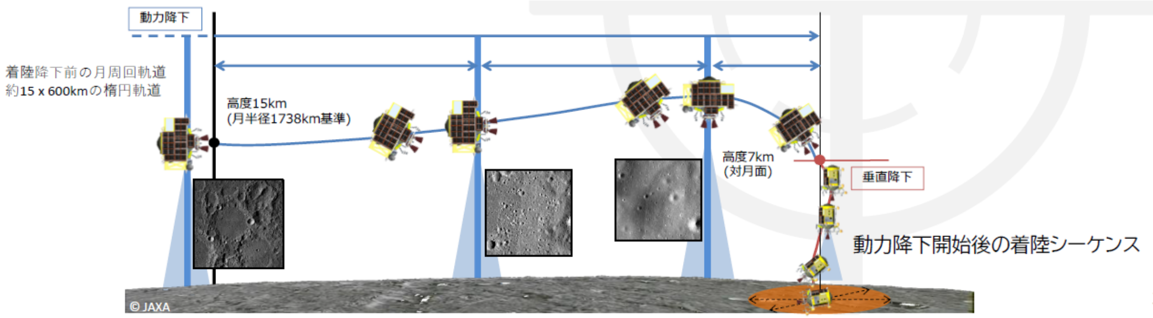
Following the loss of a first attempt in 2019, Chandrayaan-3 (ISRO) landed successfully in August 2023 at 69°S

- Demonstrated a 25 kg rover (precursor to even smaller surface robots)
- Demonstrated presence of sulfur as a volatile element in near-polar soil on the Moon

JAXA (Japan) successfully demonstrated pinpoint landing in January 2024 with SLIM: 55 meters (!) away from pre-designated target -> more precise than the Apollo landings with astronauts

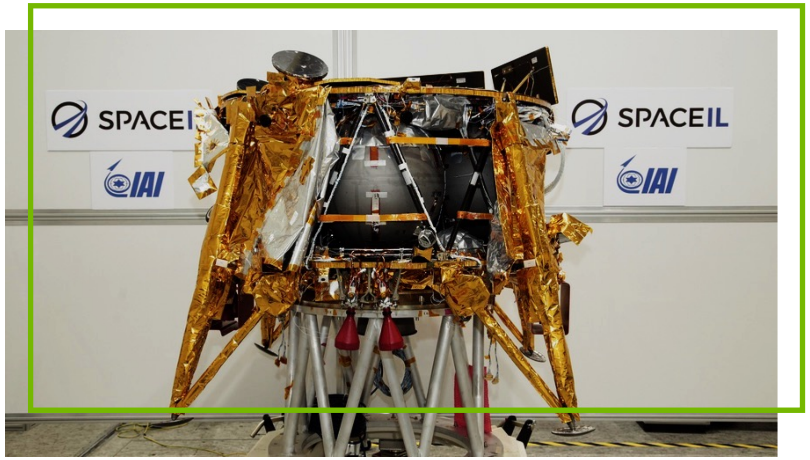
- Also included two novel, tiny surface robots (hopping LEV-1 and 250 g (!) transformable SORA-Q / LEV-2)

India and Japan teaming up for more ambitious future mission to lunar South Pole



SLIM lander as imaged by LEV-2 robot

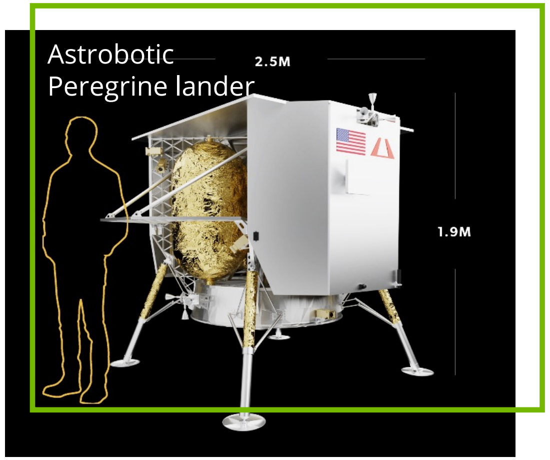
PRIVATE AND COMMERCIAL SMALL LANDERS



Google Lunar X-Prize “survivors”

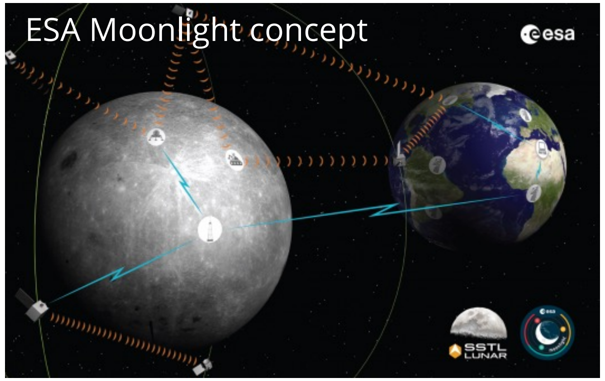
CLPS and other lander service providers

NASA as CLPS customer for start-ups offering small lander missions. ispace (JP) outside CLPS.



Navigation and comms relay satellites

SSTL Lunar Pathfinder, ESA Moonlight, NASA constellation, and private actors



1ST CLPS SUCCESS: IM-1 “ODYSSEUS”

First US lunar surface access since 1972

First CLPS lunar mission by company *Intuitive Machines* for NASA and commercial customers

Lunar landing February 22

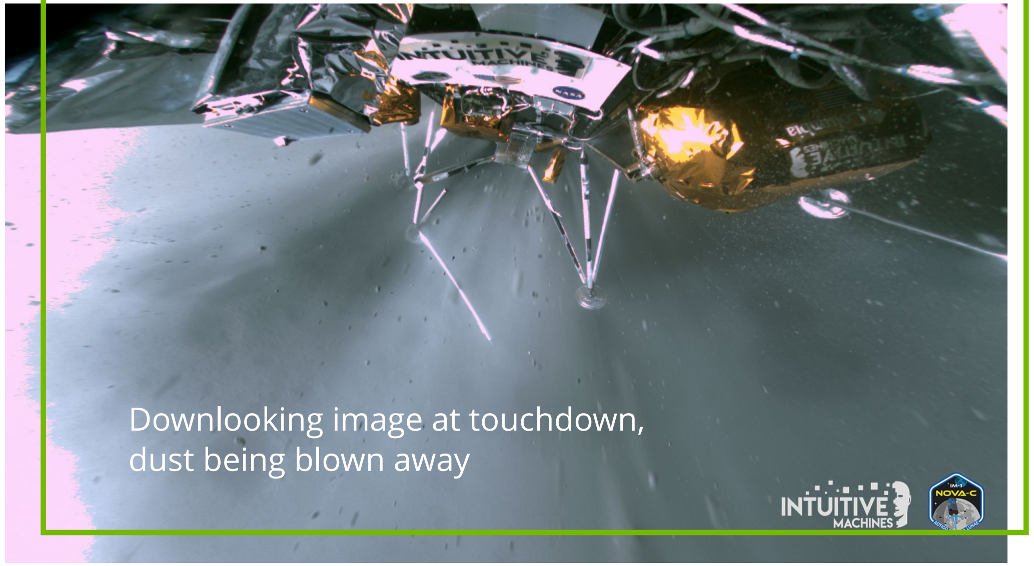
Some challenges but “mission success” data return

Closest landing to lunar South Pole: at 80.1°S

- Novel cryogenic propulsion system worked successfully
- Had to land with backup velocity and altitude sensing and landed “hard”, toppled onto its side

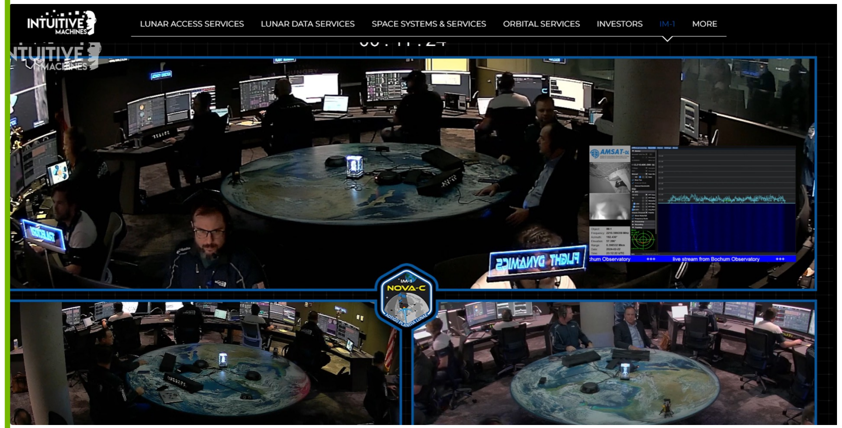
Precursor for fleet of landing missions to lunar South pole region

View during descent



Downlooking image at touchdown, dust being blown away

View from the ground, low sun, dusty lens (and the broken leg)

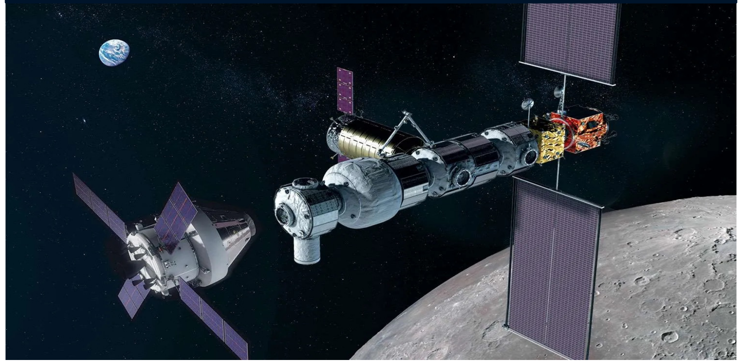


PLANNED CREWED LUNAR PROGRAMS

Space Launch System (SLS) with Orion crewed spacecraft

Chinese crewed spacecraft for lunar missions

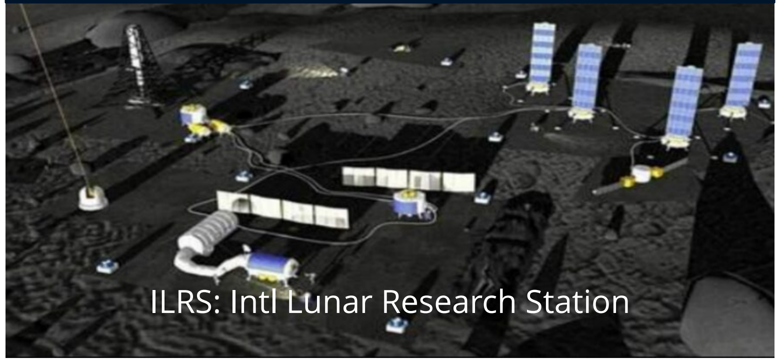
ARTEMIS: Lunar Gateway orbital station



ARTEMIS: crewed landings & outpost near the South Pole

Artemis base camp

ILRS: led by China: outpost near the South Pole



ILRS: Intl Lunar Research Station

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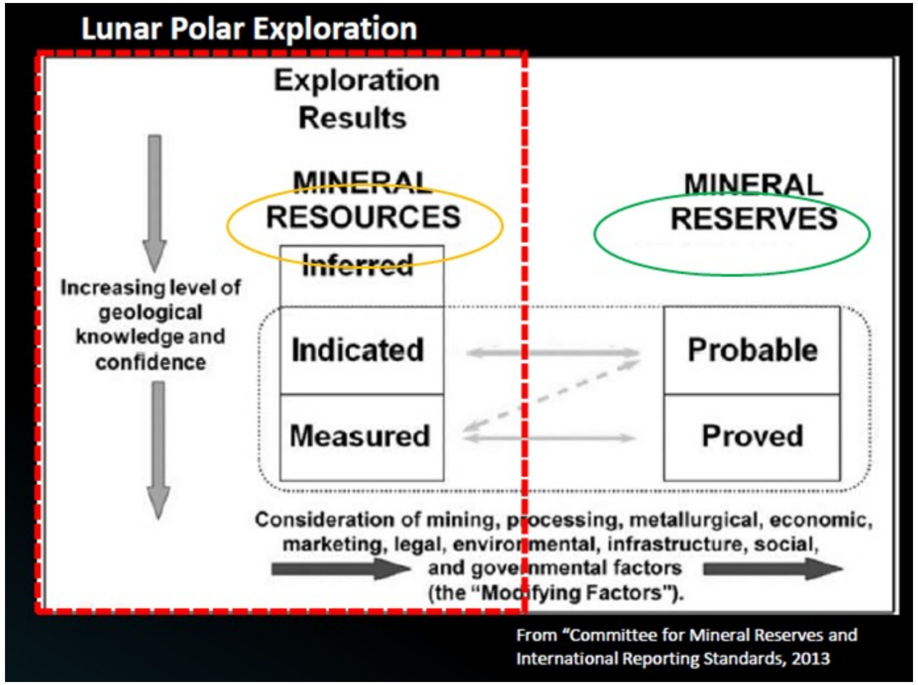
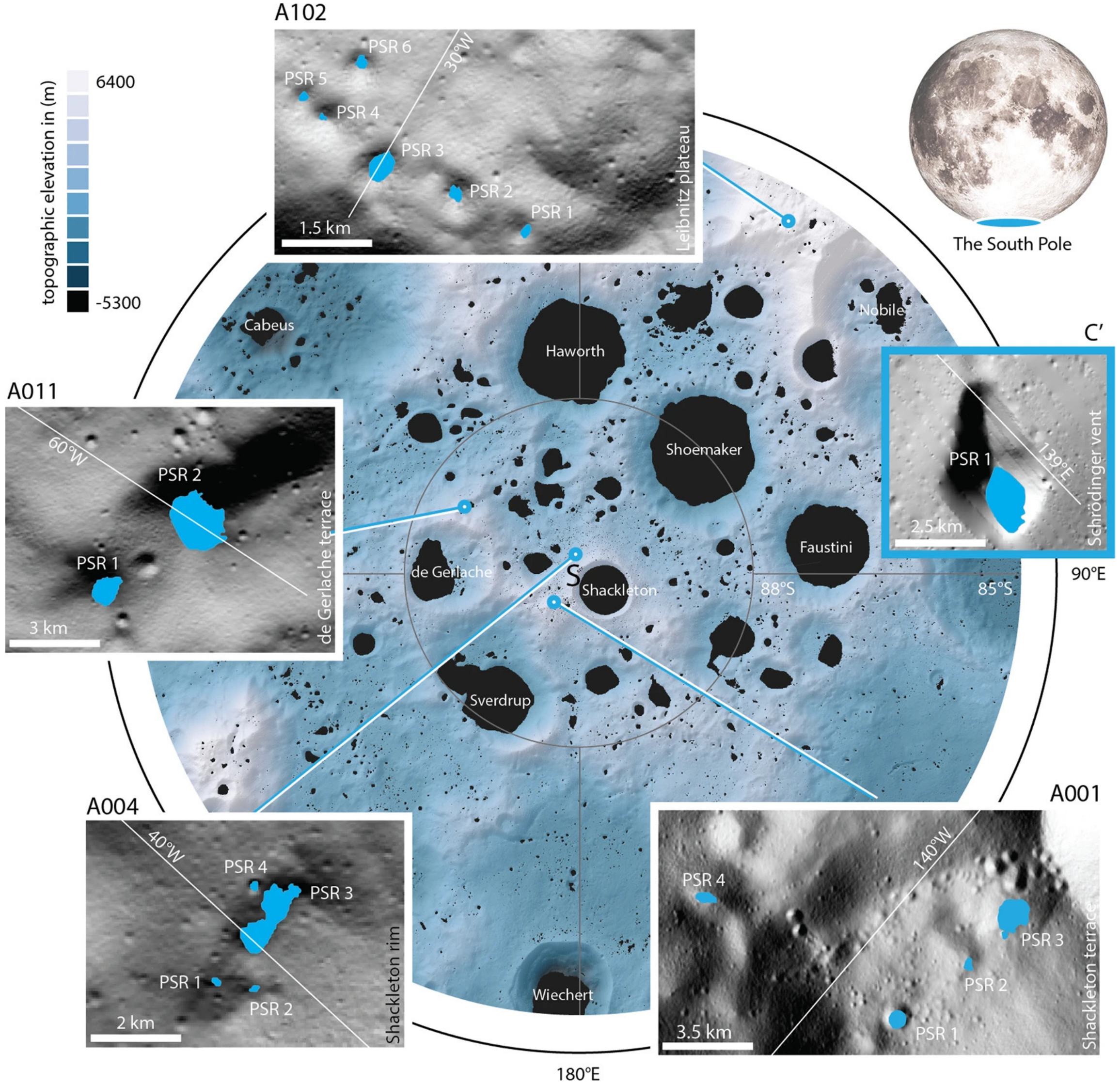
MAKING CREWED LUNAR EXPLORATION SUSTAINABLE: USE OF LUNAR RESOURCES

- Producing in situ ("ISRU"): rocket propellants and breathing gases
- Commercial interest



Key resource of interest: ice in the polar regions



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SIGNIFICANCE OF ROCKET PROPELLANTS MADE FROM LUNAR RESOURCES

“[...] recommending the U.S. government establish reserves in four key locations: low Earth orbit (LEO), near recti-linear halo orbit (NRHO), lunar surface (LS), and Mars orbit (MO)

“Customers of this propellant would begin with NASA crewed lunar missions and lead to commercial activities, for instance construction of on-orbit satellites, LEO and Lagrange 5 (L5) settlements, and solar power beaming stations”

...a Strategic [space-based] Propellant Reserve using lunar-derived propellant [...] will drive the growth of a $3 trillion cislunar economy in the next 30 years.

—

Tory Bruno,
CEO of United Launch Alliance

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MARKETS FOR LUNAR PRODUCED ROCKET PROPELLANTS (DEMAND IN METRIC TONS)

Total USG Demand	Point of Sale	Demand (annual)		
		2020-2030	2030-2040	2040-2050
NSS Mobility	NRHO		32 MT	68 MT
Satellite Manufacturing	LEO		0.5 MT	5 MT
Satellite Servicing	LEO		8 MT	16 MT
NASA Crewed Lunar Lander	LS	25 MT	25 MT	25 MT
Lunar Surface Mobility	LS	10 MT	10 MT	20 MT
Mars Missions	NRHO		70 MT	140 MT
Total		**35 MT**	**145.5 MT**	**274 MT**

USG: U.S. govt
NRHO: nearly rectilinear halo orbit (about the Moon)
LS: lunar surface

Commercial Customer	Point of Sale	Demand (annual cargo)		
		2020-2030	2030-2040	2040-2050
Commercial Lunar Landers	LS		25 MT	100 MT
Satellite Manufacturing	LEO		0.2 MT	2 MT
Solar Power	LEO		1 MT	10 MT
Commercial Launch	LEO		210 MT	210 MT
LEO Settlements	LEO		100 MT	200 MT
L5 Settlements	NRHO			400 MT
Settlement Operations	NRHO/LEO			270 MT
Solar Power Beaming Stations	NRHO			2,000 MT
Asteroid Mining	NRHO			100 MT
Total			**336.2 MT**	**274 MT**

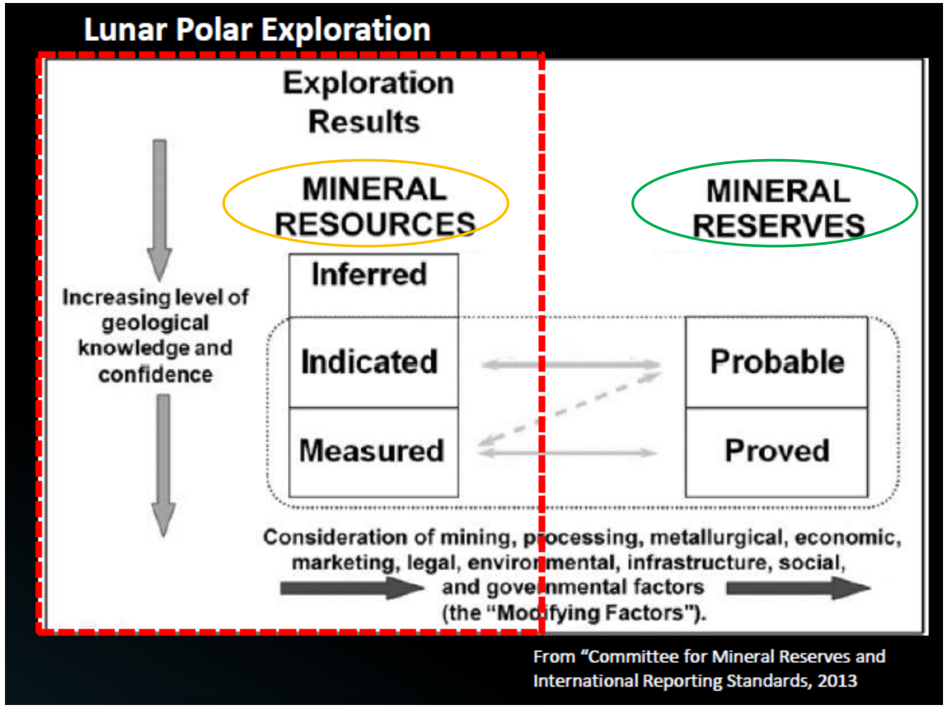
Projected cost of propellant production on the lunar surface is baselined at $500k/MT produced, assuming technology advances in the next 10 years

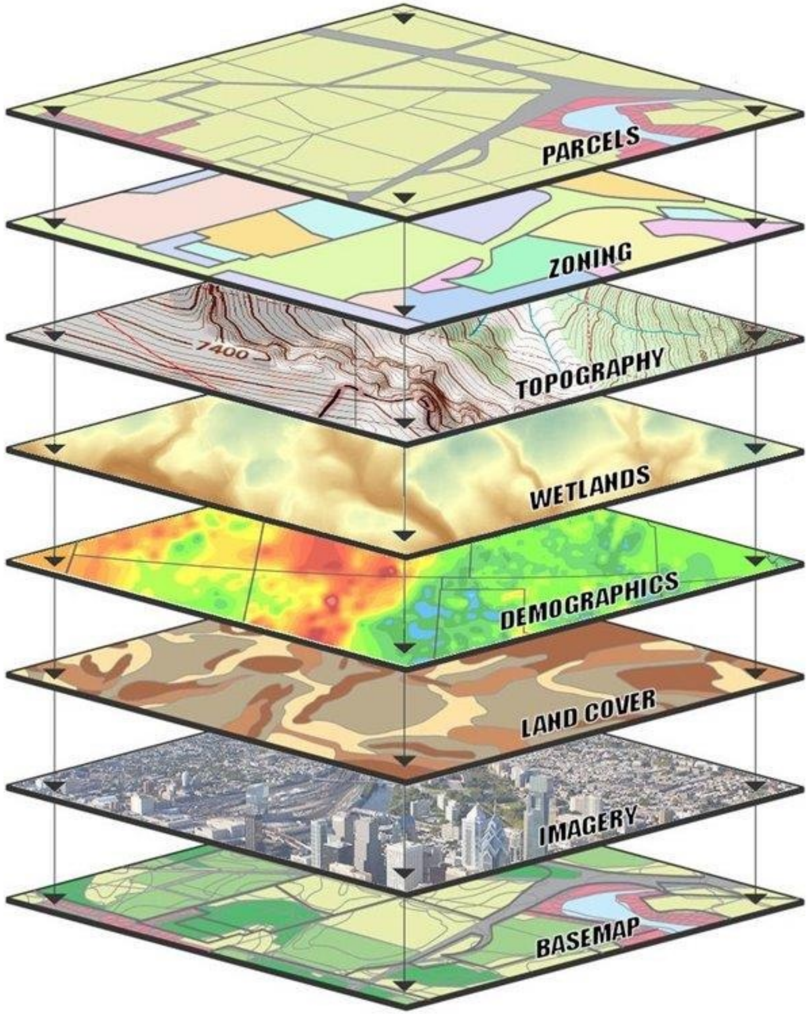
MAPPING & RESOURCE EXPLORATION

Objective is to identify *reserves*: only these would be extractable, consider economic factors and practical constraints

Will need to merge various datasets

Should be made consistent with USGS lunar basemap, its coordinate systems, and the USGS GIS





GIS DATA LAYERS

Many different types of data can be integrated into a GIS and represented as a map layer.

Examples can include: streets, parcels, zoning, flood zones, client locations, competition, shopping centers, office parks, demographics, etc.

When these layers are drawn on top of one another, undetected spatial trends and relationships often emerge. This allows us to gain insight about relevant characteristics of a location.

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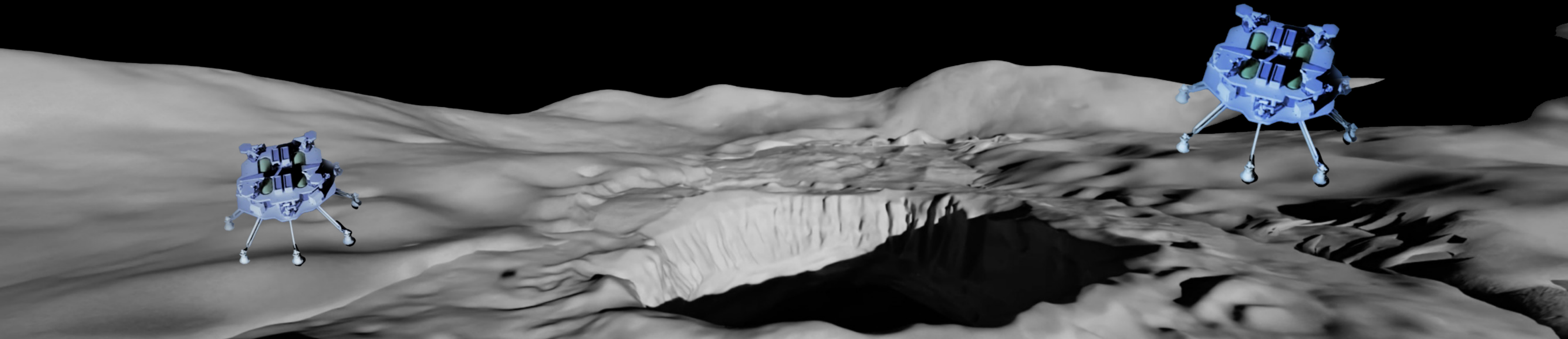
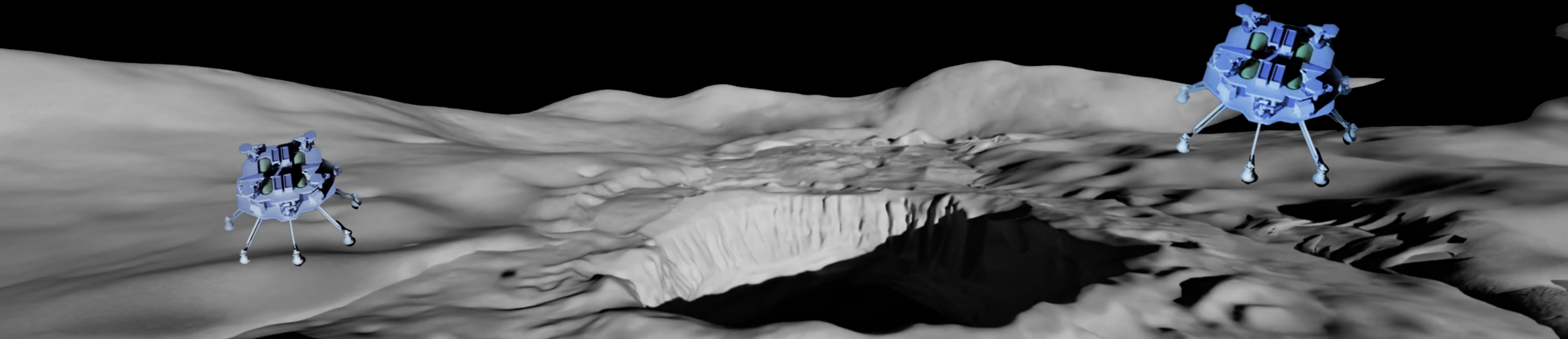
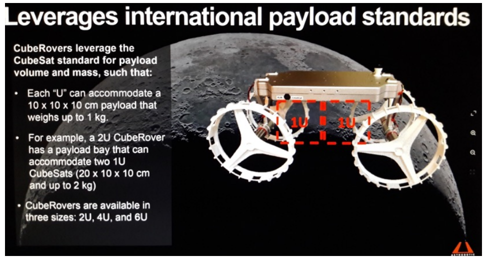
MOBILITY ON AND ABOVE THE MOON



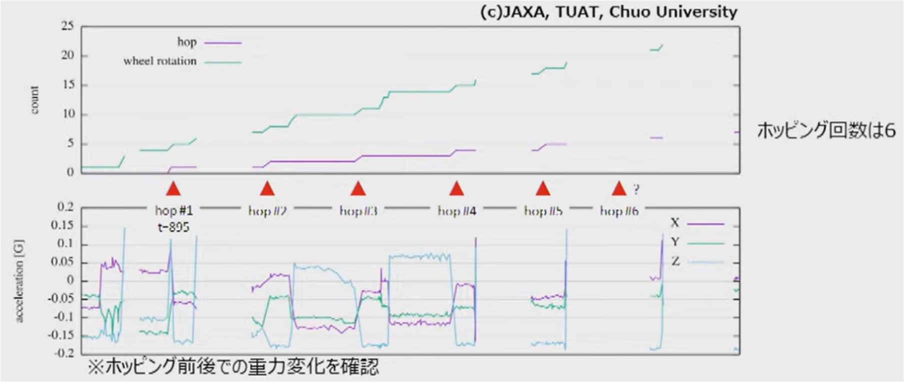
THE NEW LUNAR ERA:
WHAT'S IN IT FOR ROBOTICS?



THE NEW LUNAR ERA



Astrobotic's CubeRover
Tiny rovers



LEV-1 hopping robot of Japanese (JAXA) SLIM lunar lander (January 2024)

SRC / Astronika HOPTER for Moon and Mars mobility (e.g. Wisniewski et al., ESMATS 2017

There will be more lunar rovers

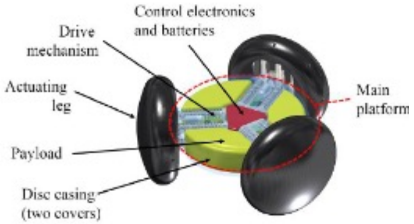
…a lot of actors (commercial and institutional) already doing it; **mostly short-range vehicles (< 100 m)**

Excavation and handling equipment for lunar soil and ice

Very interesting (and demanding) mechatronics applications

Hopping and flying vehicles

Hopping mobile system deployed from lander -> examples: GALAGO (Astronika) for hopping mobility at lunar and Mars gravity (need to release ~50…100 J of energy per jump for a 10 kg robot); Chang'e 7 "leaper" Thruster propelled drones for "last mile access"



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FLYING VEHICLES FOR LUNAR EXPLORATION

Revolutionary: closing capability gap between surface rovers and lunar satellites

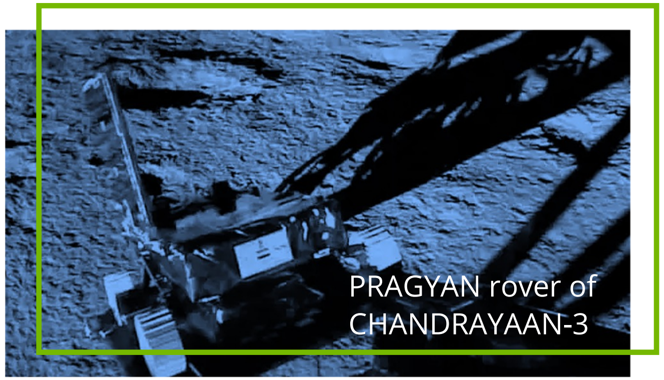
A lunar "drone": propelled by rocket thrusters (no air on the Moon) > can cover **kilometers within minutes, irrespective of terrain**

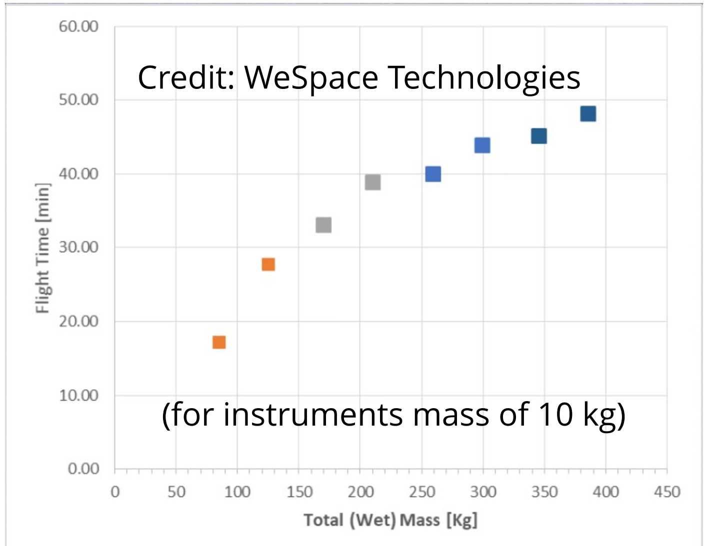
- System designs of 10's of kg mass with propellant are possible
- Can be single flight or multi-land

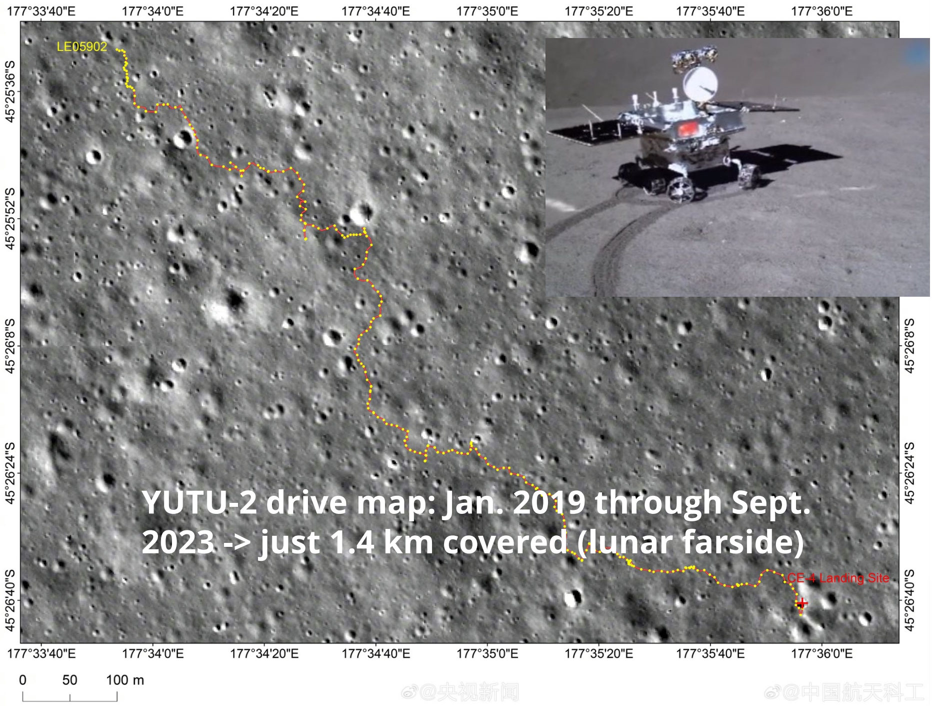
Can control lateral velocity for targeted observations with very high signal-to-noise (superior to that from lunar orbiters)

- The ideal mapping solution over areas of interest

Current limitation: total flight time constrained by fuel load (future: refueling)







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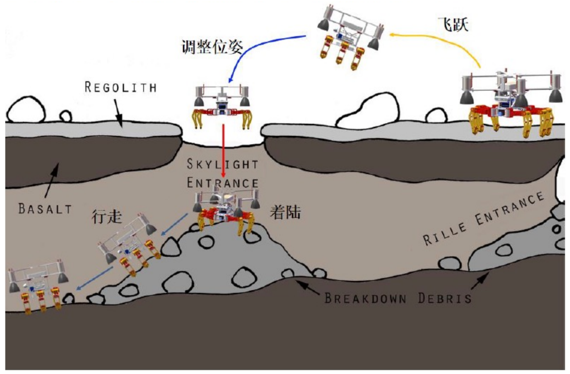
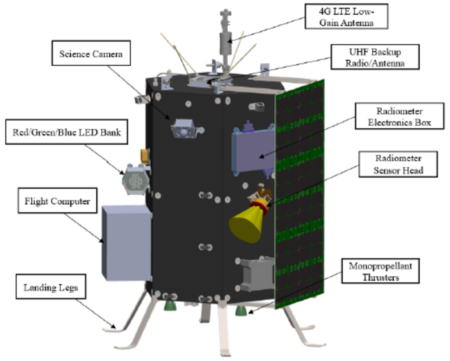
POSSIBLE LUNAR DRONE MISSION SCENARIOS



飞行足式机器人探索月球熔岩管设想

Harbin Institute of Technology

Intuitive Machines "Micro Nova" thruster-driven drone



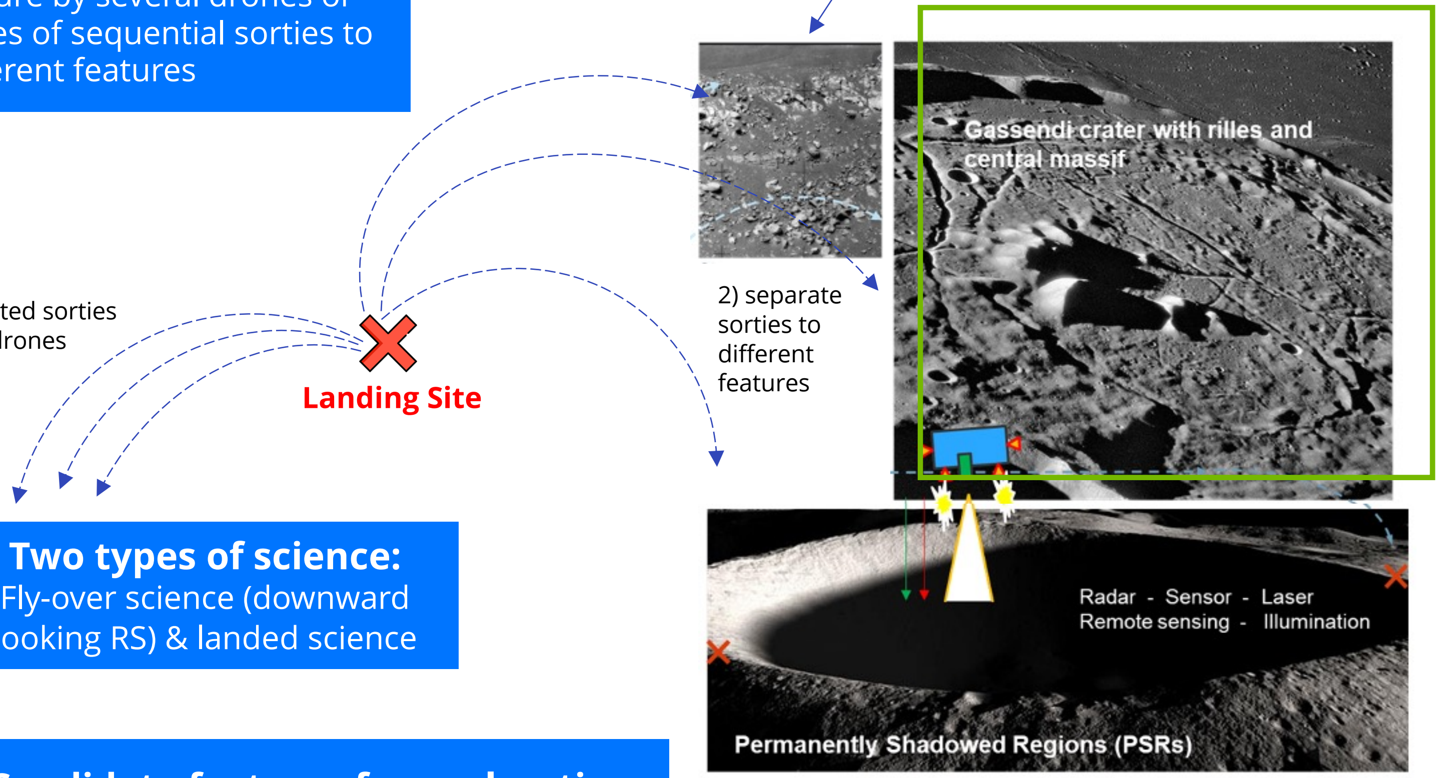
Several scenarios:

1. Joint exploration of the same feature by several drones or
2. series of sequential sorties to different features

Western wall of Hadley rille viewed from the ground (A15)

1) coordinated sorties of several drones

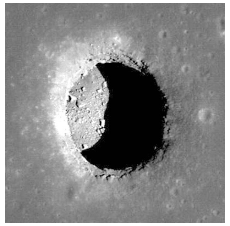
2) separate sorties to different features



Two types of science:
Fly-over science (downward looking RS) & landed science

<u>Candidate instruments include:</u>

- Imagers (for control & navigation, and multispectral for science)
- Radar (to indicate polarizing nature of targets)
- Mass spectrometer (detecting volatile species)
- Laser reflectometer (to pick up exposed ice)
- LIDAR (terrain sensing)



Candidate features for exploration from the drone:
PSR/ skylight or lava tube / exposed bedrock of stratigraphic section (e.g. at a rille)

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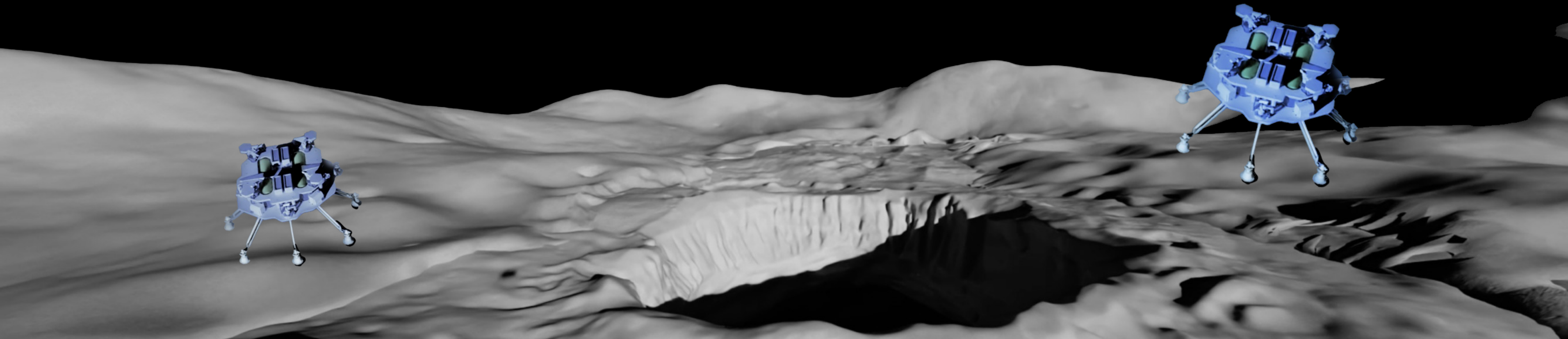
SOFTSERVE LUNAR DRONE CONCEPT



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UNIQUELY QUALIFIED TO HELP CREATE AUTONOMOUS SYSTEMS USING DIGITAL TWINS AND ADVANCED TECHNOLOGIES

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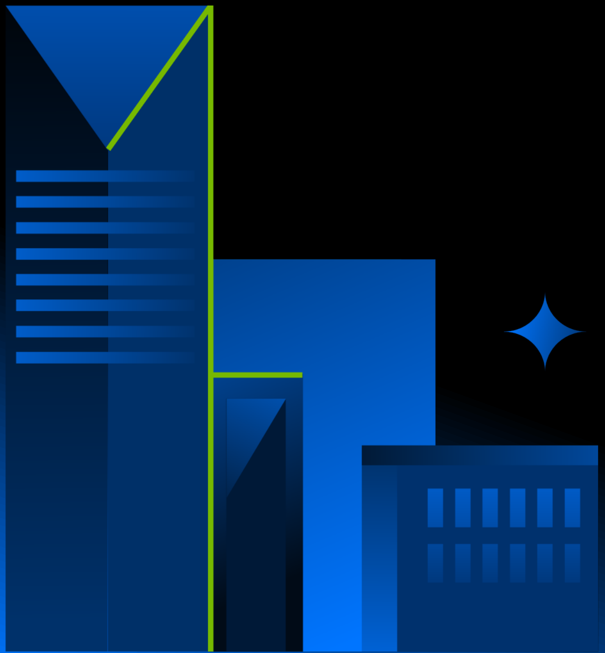

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We have the highest level of partnerships with AWS, GCP, Azure, and VMware.

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Google Cloud Global Partner of the Year Machine Learning 2020

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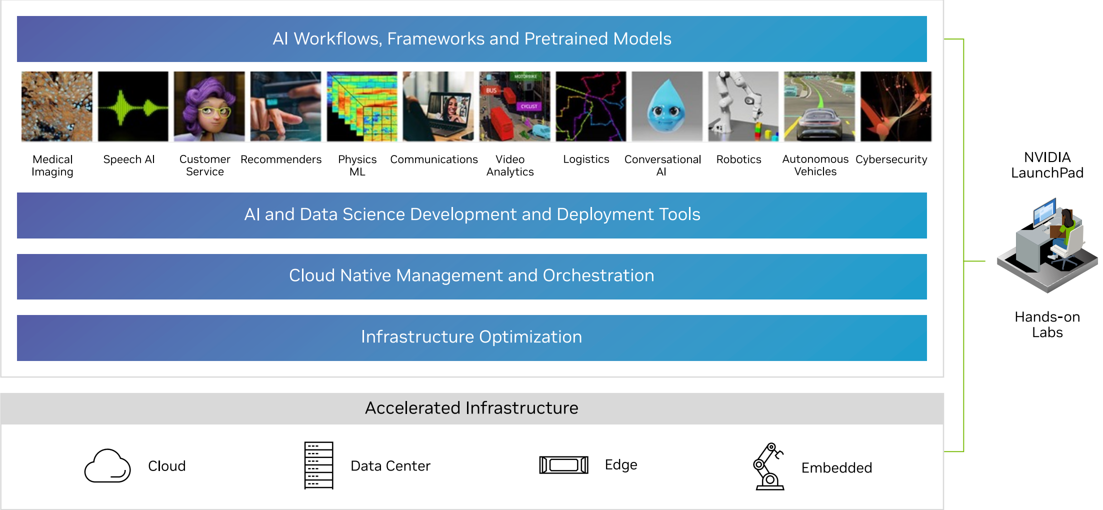
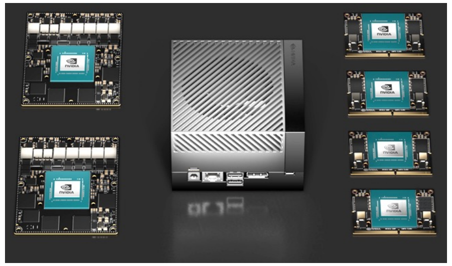


EMBEDDED EDGE COMPETENCY



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WORK BY SOFTSERVE

INTERNAL “ACCELERATOR” PROJECT:

Conceptual design of an on-board guidance system for a ~70 kg wet mass lunar drone for controlled powered flight, landings and take-off

Vision-based navigation with a monocular camera system and an IMU, feeding a SLAM algorithm (Simultaneous Localization and Mapping), performing autonomous navigation to reach pre-assigned targets while generating map via point clouds

- Flight controller: using Linear Kalman Filter for sensor fusion and state prediction

Using ROS (robot operating system) and **NVIDIA Isaac Sim (extensible robotics simulator built on NVIDIA Omniverse development platform for OpenUSD)** to perform the precise execution and validation of guidance, navigation, and control (GNC) algorithms

Notional Design Reference Mission studied and simulated by SoftServe: flight into, through, and out of a lunar lava tube, using a lunar skylight as entry and exit points

- Provided a full visualization of simulated flights

OTHER MISSION TO BE SIMULATED: exploration of a lunar Permanently Shadowed Region (PSR) near the lunar poles

MODELING OF THE LUNAR TERRAIN: LAVA TUBE

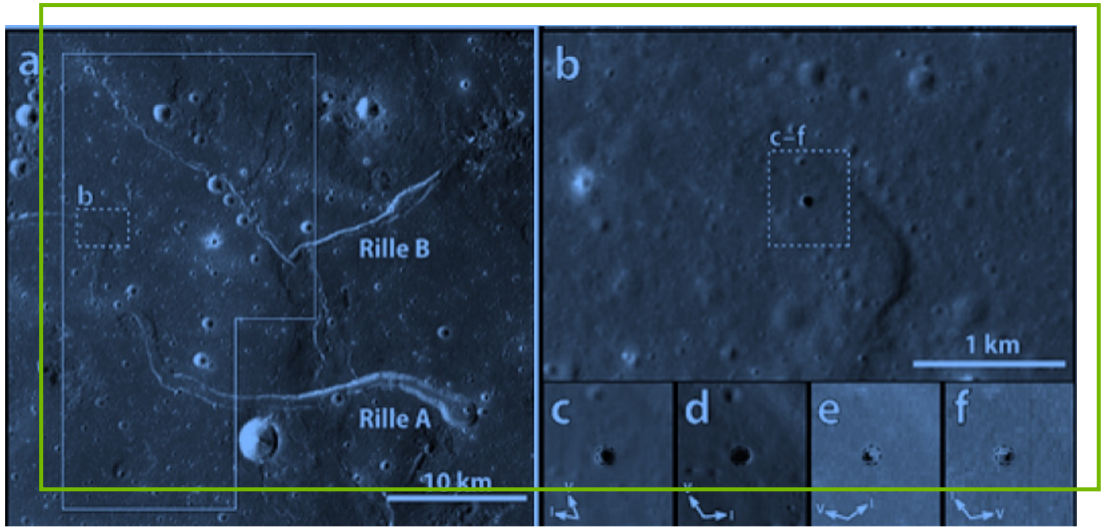
Recreated an example terrain and lava tube model using lunar satellite data and published models on lunar skylights and pits

- Skylights imaged from lunar orbit; presence of lava tubes inferred from orbiting ground penetrating radar measurements (e.g., from KAGUYA lunar orbiter)

Lava tubes: exciting features on the Moon because could be a “safe haven” (protected from thermal extremes and radiation) for future crewed outposts

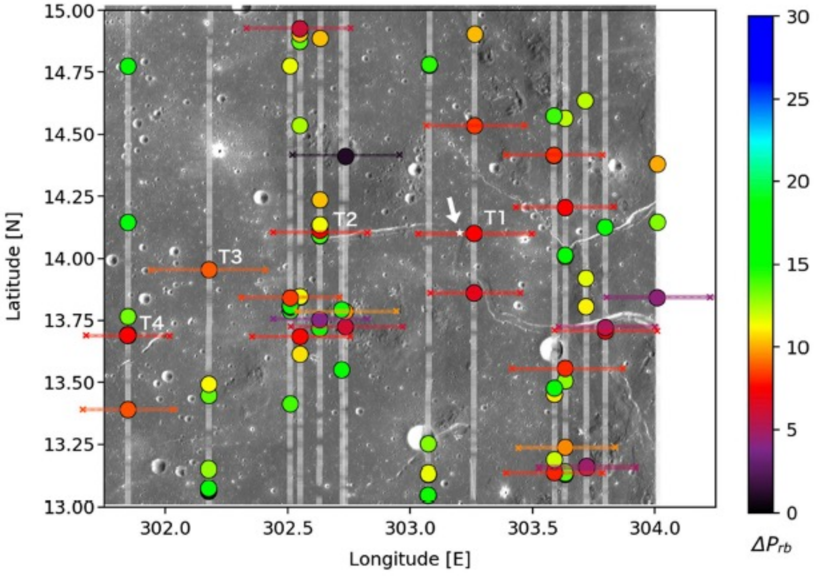
- Moreover, some could be harboring ice (easier to access than in polar shaded regions)

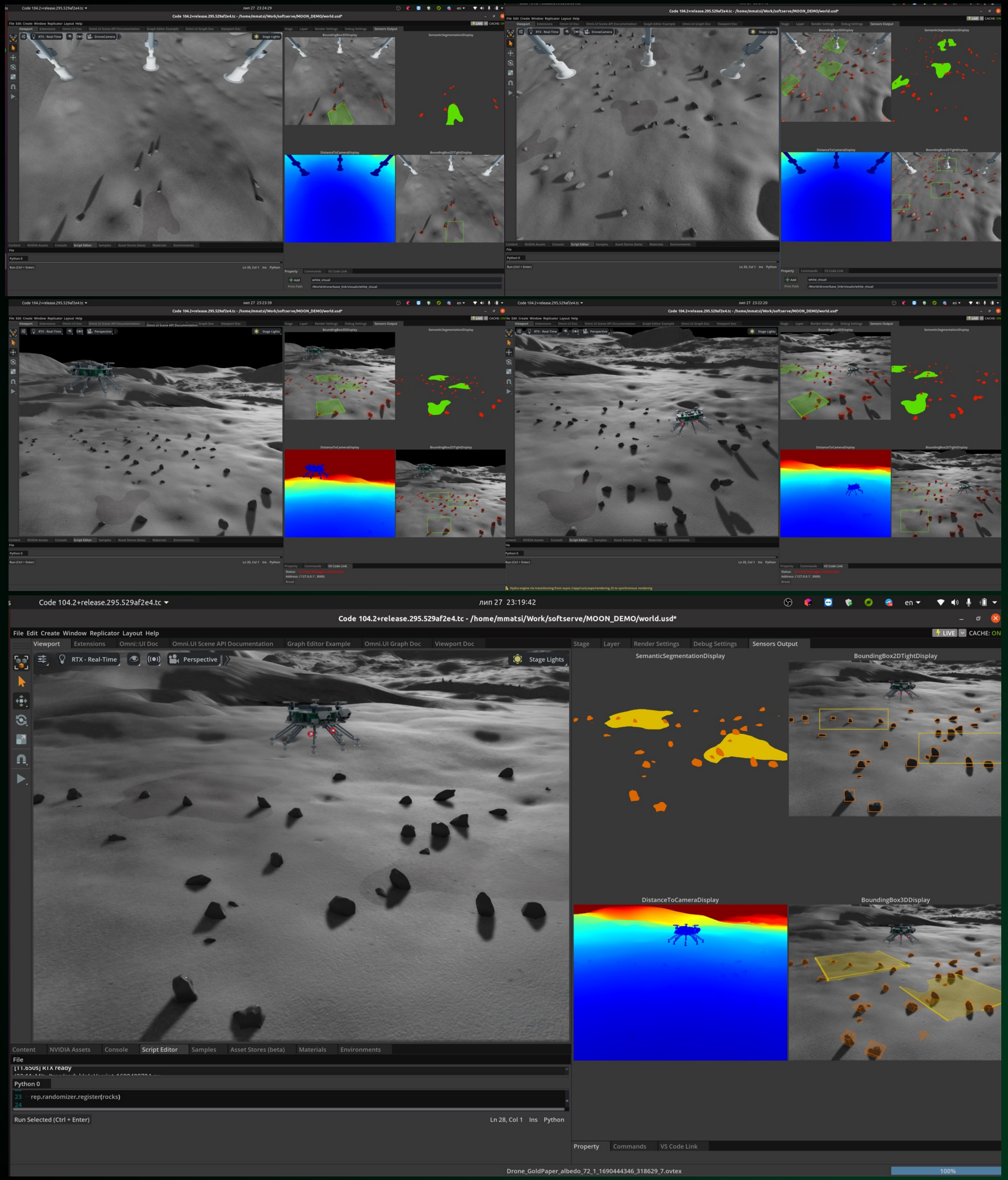
Potential image of a lunar lava tube skylight with a diameter of 65 m in the Marius Hills area. (**a**) Panoramic view of the region, showing the designated area for crater counting marked by a solid white polygon. (**b**) Marius Hills Hole (MHH). (**c**–**f**) Magnified images of the MHH, with arrows indicating the direction of sunlight illumination (I) and camera perspective (V).



(Qiu et al., 2023)

Candidate sites of potential underground caverns in the Marius Hills region. The color of the circles represents the power difference between the first and second echo peaks (DPrb). The lower the DPrb value, the greater the possibility of the existence of underground lava tubes





MODELING OF THE LUNAR TERRAIN: USING NVIDIA REPLICATOR

BUSINESS OVERVIEW

As part of the lunar drone simulation work:

- Reduce implementation time through automatic world modification

SOLUTION

- Utilize **NVIDIA Replicator** and **Isaac Sim** for environment randomization
    - Drone position
    - Stone quantity, shape, and size
- Test the algorithm in various environments
- Fine tune the algorithm based on test results
- Enable obstacles recognition for safe landing

IMPACT

- Increased the quality of the designed mapping algorithm
- Enabled synthetic dataset generation for obstacle recognition
- Decreased the time needed for environment randomization

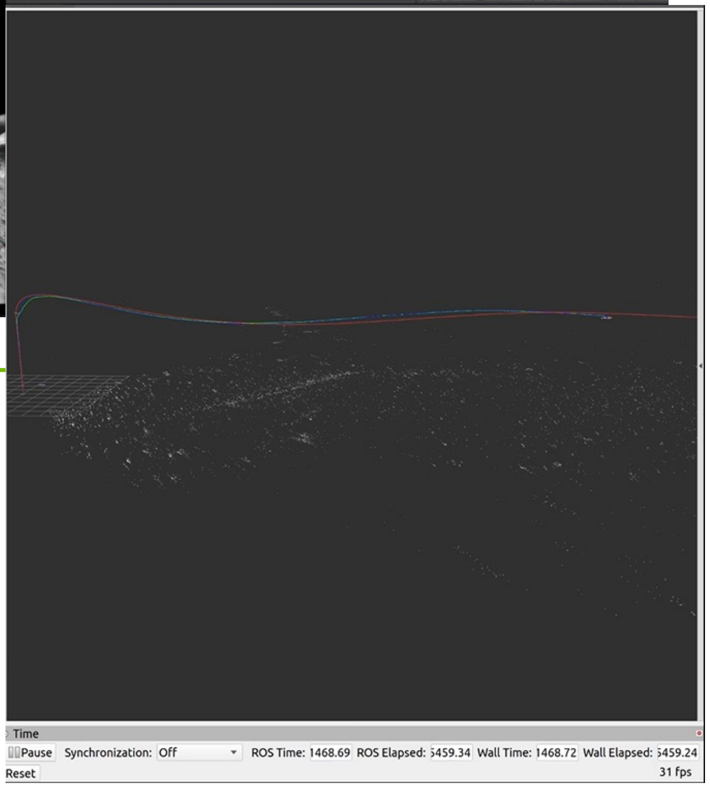
MAPPING APPROACH

- vSLAM: visual simultaneous localization and mapping
- Providing absolute position and attitude (in world frame) for sensor fusion
- Solution used in this software is a modified version of ORB_SLAM3
- ORB SLAM3 provides tracking of keypoints (KP)
- Each keyframe (KF) consist of a set of keypoints. Each map consists of a set of keyframes. The vSLAM package publishes all trackable KFs along with the camera position that was used to capture a given KF

Occupancy map: the drone uses an occupancy map to safely navigate and explore the environment: based on an OctoMap library. OctoMap works by casting rays from the camera to the KPs and marking visited volume (voxels) as:

- Free - volume is known to contain nothing
- Occupied - volume is known to contain an obstacle
- Unknown - volume has not been seen

Behavior tree including a graph-based exploration algorithm1



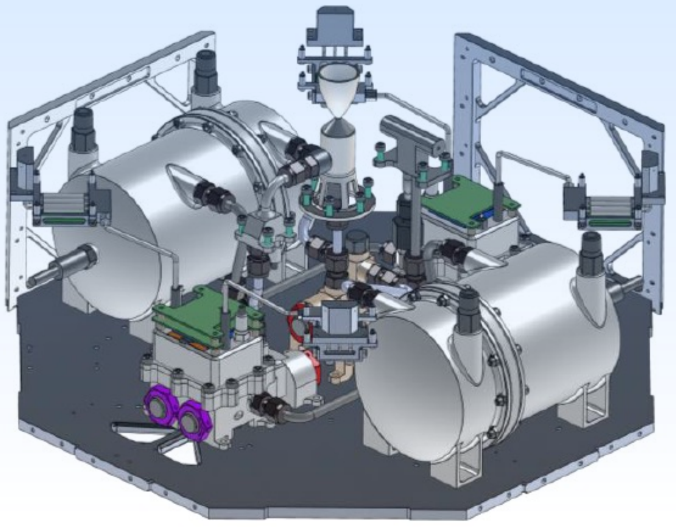
1: The basic idea behind a graph-based exploration algorithm is to represent the environment as a three dimensions occupancy map with nodes representing locations in the environment and edges representing the paths between them. The algorithm then explores the graph by moving from node to node, with the goal of maximizing the *exploration gain*. This gain is given as a function of the distance, path straightness and *volumetric gain*.

LUNAR DRONE: POSSIBLE PROPULSION SYSTEM

SoftServe talking to a potential vendor of a low-cost, “green” propulsion system.

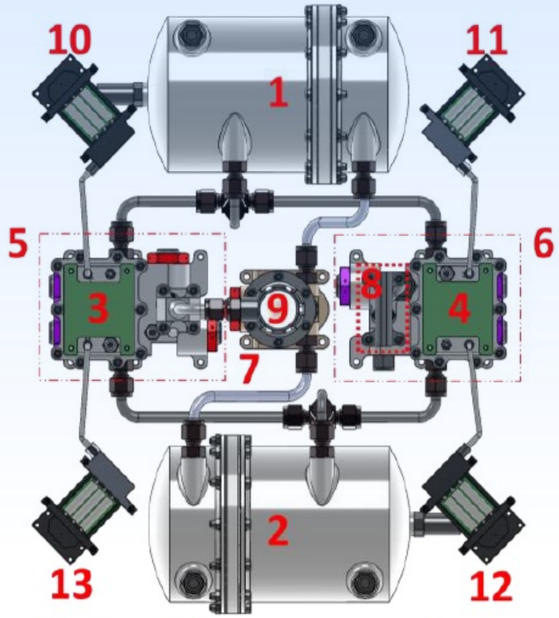
Two working modes:

- Monoprop and bi-prop, working through different thrusters Monoprop: high-purity hydrogen peroxide as propellant (low cost, low toxicity, high density, high specific impulse, and good storability)
- Bi-prop: propane as fuel, hydrogen peroxide as oxidizer, with propane double-acting as system pressurant



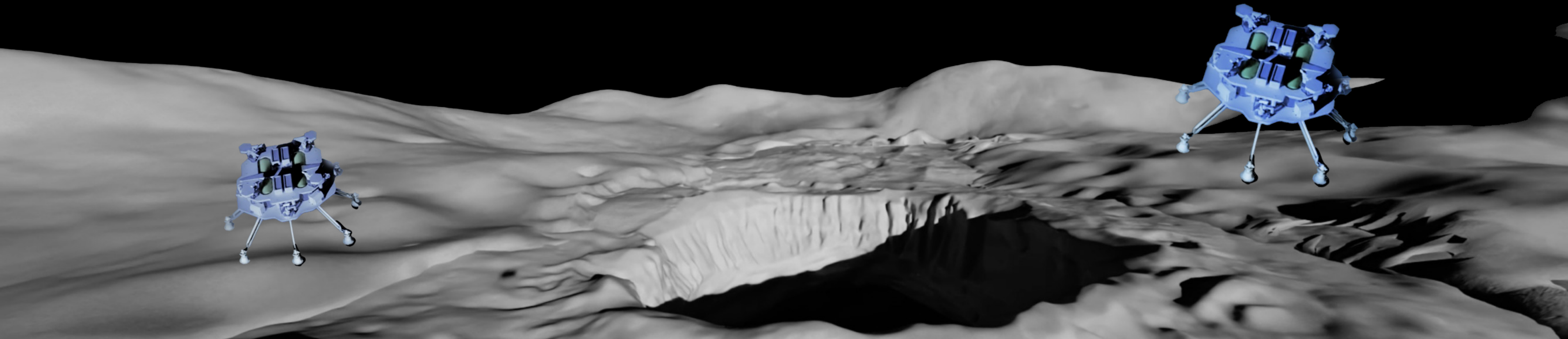
(a) Propulsion system compartment

Drone flight paths can be designed and flown as a series of ballistic arcs interspersed by occasional thruster firings -> mitigating effects of thruster plume impingement onto the terrain below (dust mobilization, effects on ice)



(a) Propulsion system top view

LUNAR DRONES WAY FORWARD



LUNAR DRONE: NEXT STEPS

BUILD A SYSTEM CONSORTIUM

- SoftServe interested in facilitating set up of a team to flight-develop lunar drones
- Several actors in Europe and the U.S. already interested

BUILD A SCIENCE TEAM

- Involving U.S. and European members
- Can build on earlier initiatives in Europe
- Define reference missions for science and ISRU reserves scouting
- Interests already expressed: mass spectrometer for ice detection

ENLIST CUSTOMERS

- Commercial customers
- Lunar landing mission providers (also HLS) benefit from "last mile access" with a drone
- Propose a pathfinder mission to space agencies

STAGE A FIELD DEMO TO GARNER SUPPORT

- Using UAVs along with ground robots
- Caves in Texas
- Lava tubes in Hawai'i (e.g., Hi-SEAS test site)
- Have a strong outreach / STEM component

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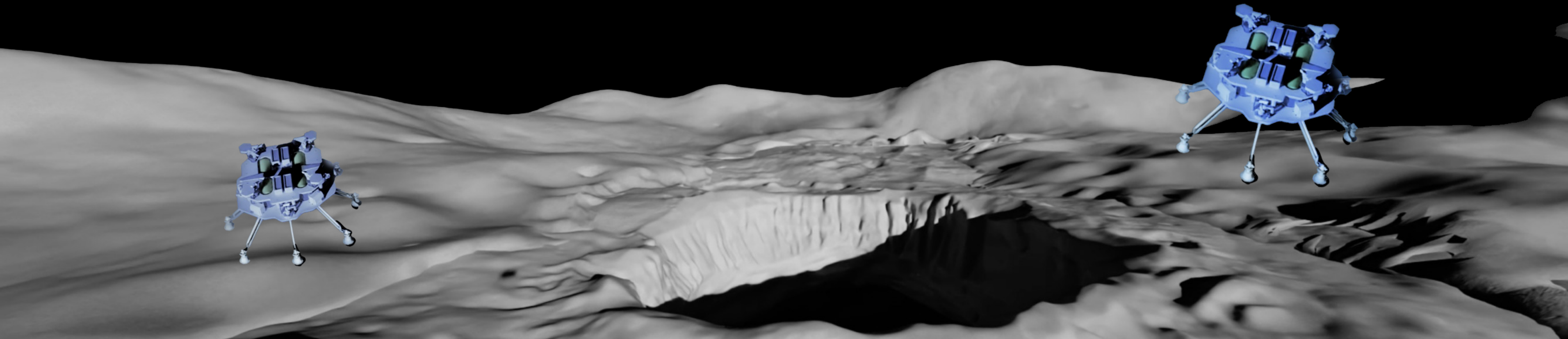
SIMULATION OF GROUND-LEVEL WORK ON THE MOON: CO-SIMULATION & DEMO SHOWCASE



SIMULATION FOR LUNAR PROJECTS

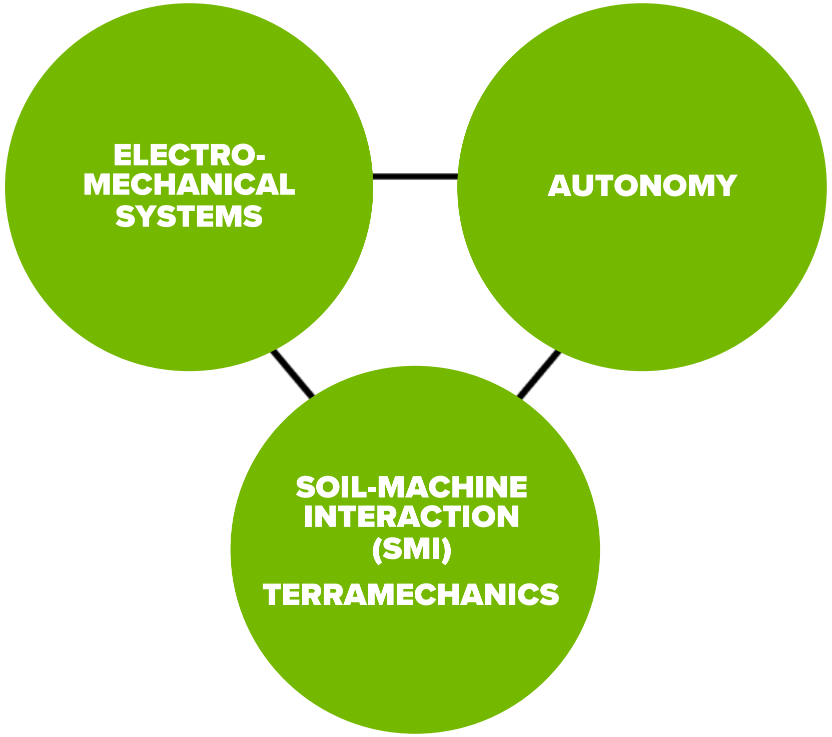
Proper energy consumption on the Moon is an important factor for successful mission accomplishment.

The goal of this project is to ensure optimal regolith excavation while searching for the hidden ice deposits.

Solution utilizes co-simulation to enable combination of high-fidelity model for scoop-regolith (terra-mechanical) interaction modeling with robotics simulation that controls the robotics arm motion.

Mechatronics systems interacting with surface materials include:

- Landing gear
- Rover mobility systems
- Excavation, sampling, and sample handling




SURVEYOR III LUNAR LANDER


APOLLO LM FOOTPAD


MER MARS ROVER WHEEL

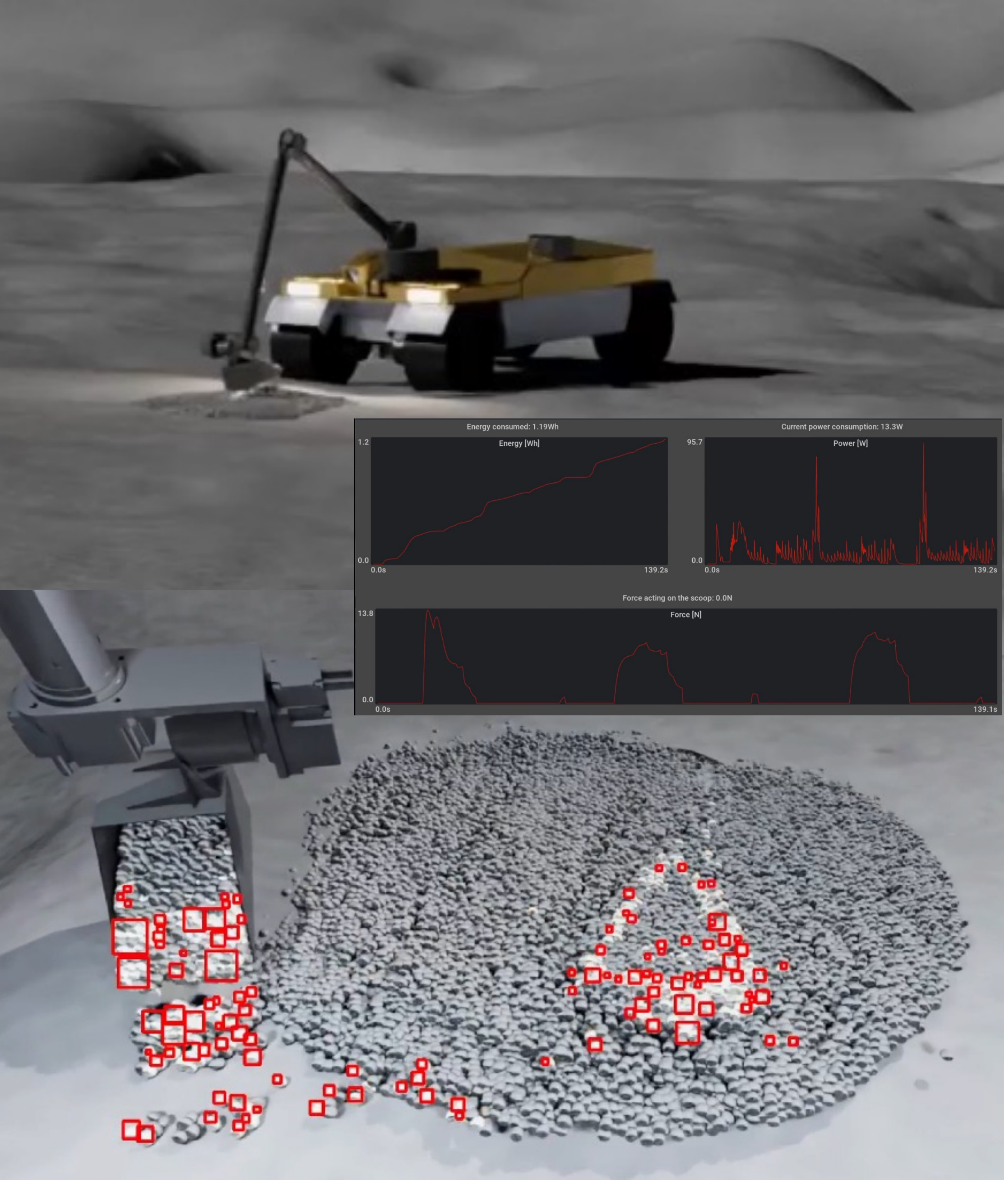

EXOMARS SPDS: SAMPLE METERING STATION

USE CASE: EXCAVATION ON THE MOON

Soil excavation essential for future mining to extract resources

So far: only done at small scales for scientific purposes -> larger scale solutions needed -> simulations required to support concept finding and design

Need to consider lower gravity on the Moon



MOON SCOOPING

POWERED BY
NVIDIA OMNIVERSE

BUSINESS OVERVIEW

SoftServe robotics team developed a solution to a mobile platform equipped with a robotics arm with a scoop and a vibratory mechanism to scoop the regolith searching for ice deposits on the Moon. The solution should include the following features:

- Scoop the Moon regolith for exploration or construction
- Detect ice deposits while scooping
- Enable energy efficient operations

SOLUTION

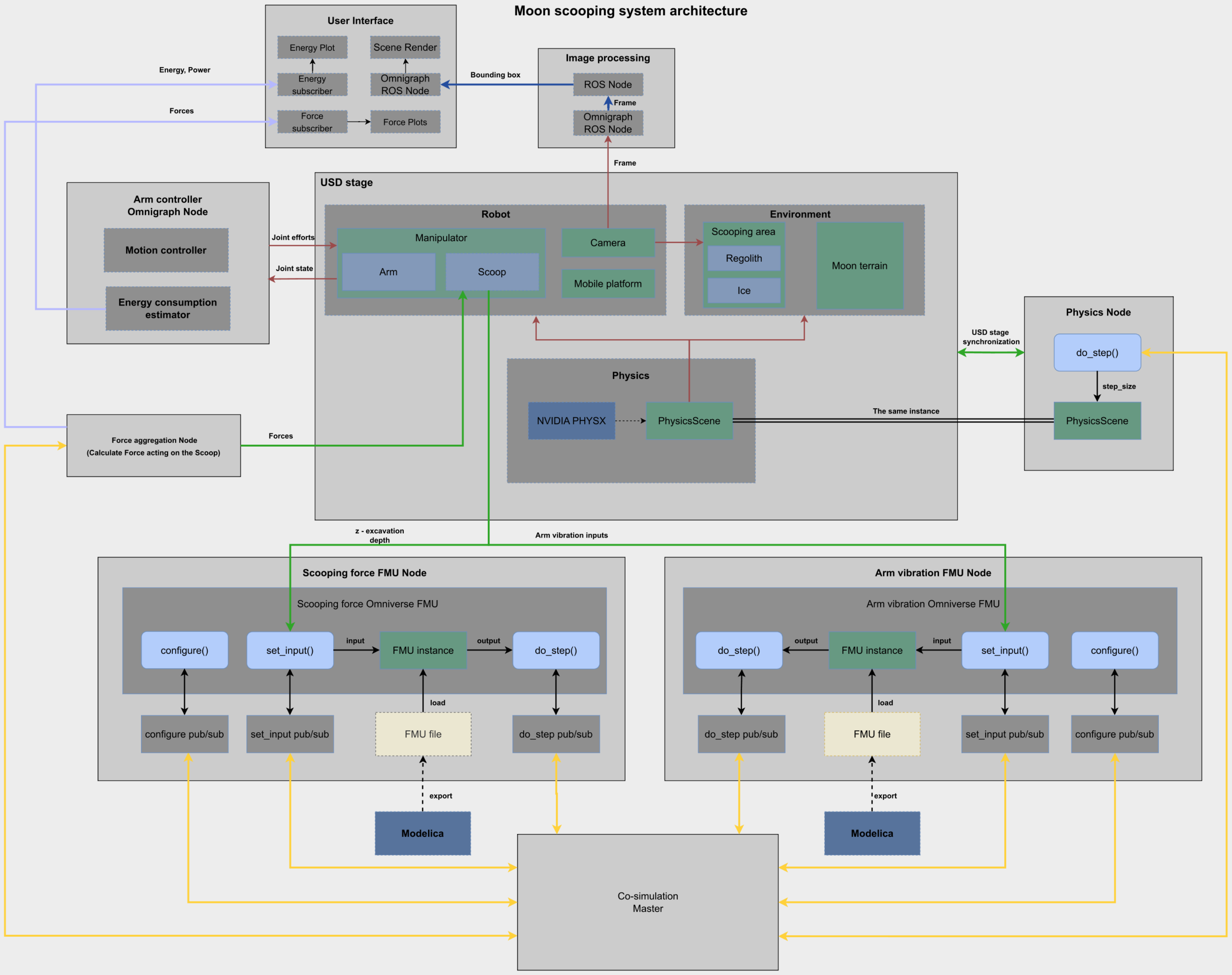
- Provide a conceptual design of hardware components of the robot able to perform scooping on the Moon
- Design a vibratory mechanism to ensure energy effective scooping
- Apply simulation-first approach for efficient scooping
- Utilize robotics perception for ice deposit detection
- Implement high-fidelity terramechanics approach to calculate the forces acting between the scoop and regolith (**NVIDIA WARP**)
- Enable real-time energy consumption tracking to enable energy-efficient mission accomplishment

IMPACT

- Increase mission duration with energy efficient scooping
- Enable real-time ice deposit detection
- Validate complex robotics solution in simulation **using NVIDIA OMNIVERSE**

NVIDIA softserve

MOON SCOOPING SYSTEM ARCHITECTURE



- Live Session
- Omniverse Channels
- Omniverse Events
- ROS topics
- Internal Omniverse Communication
- Internal Python Communication

FEED FORWARD TO PROJECT FOR NASA

DEC 22, 2023

EN

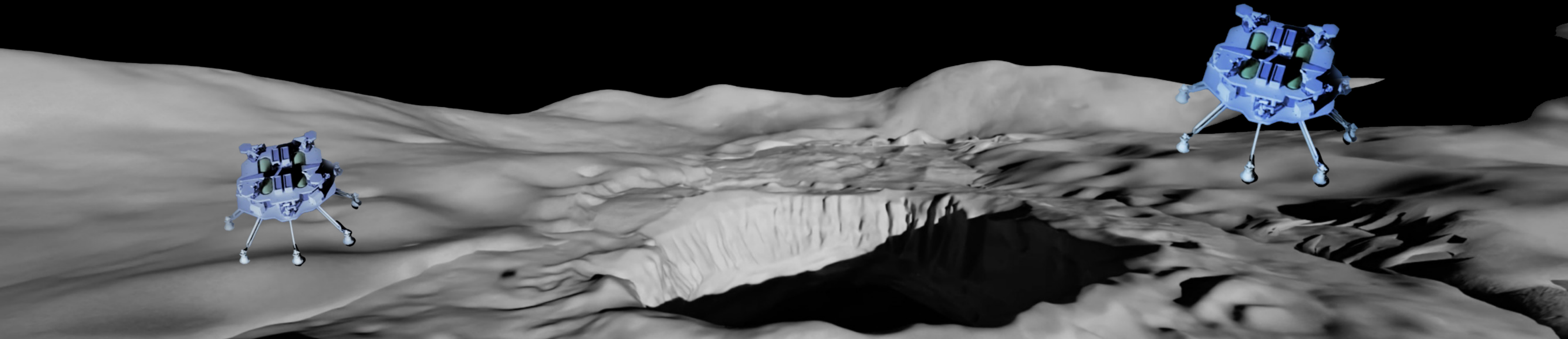
SOFTSERVE JOINS INTERNATIONAL TEAM TO DEVELOP NASA-FUNDED LUNAR LANDING AND LAUNCH PAD TECHNOLOGIES

Companies team up to develop Moon landing and launch pad technology with funding from NASA's STTR 2023 Program

AUSTIN, Texas (Dec. 22, 2023) – SoftServe, a premier IT consulting and digital services provider, today announced plans of joining an international coalition on a NASA-funded project to develop lunar technologies. The project comes after San Antonio-based Astroport Space Technologies won a NASA STTR 2023 Phase II

READ MORE

TAKEAWAYS



SOFTSERVE IN SPACE & IN THE LUNAR ECONOMY

There is a lot going on in space and lunar exploration

There is money to be made: using in-situ resources to make and sell consumables (rocket propellants, breathing air, water, …)

SoftServe is part of this effort: for now, with our "simulation first" approach

We are extensively using the NVIDIA OMNIVERSE tools landscape -> physics engine, various extensions, visualization

NVIDIA OMNIVERSE™

Simulations are great: "no" risk, going concurrently with system design and testing

High-fidelity modeling and simulation of complete spacecraft (digital twinning) including sensors and complex instruments, controllers, data models, agents, robotics systems, interaction with the free space and surface environment

…and we have a lot more on our Space Agenda!

LET'S TALK!

NVIDIA. softserve


FOR
THE
FUTURE
softserve