POLITECNICO DI TORINO
Department of Mechanical and Aerospace Engineering

Jet Propulsion Laboratory
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Space Exploration Robotic Systems
Sample Chain Analysis and Development for Enceladus Surface Acquisition

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Background

- Saturn's moon Enceladus is one of the most promising places in the Solar System that might potentially host life beyond Earth.

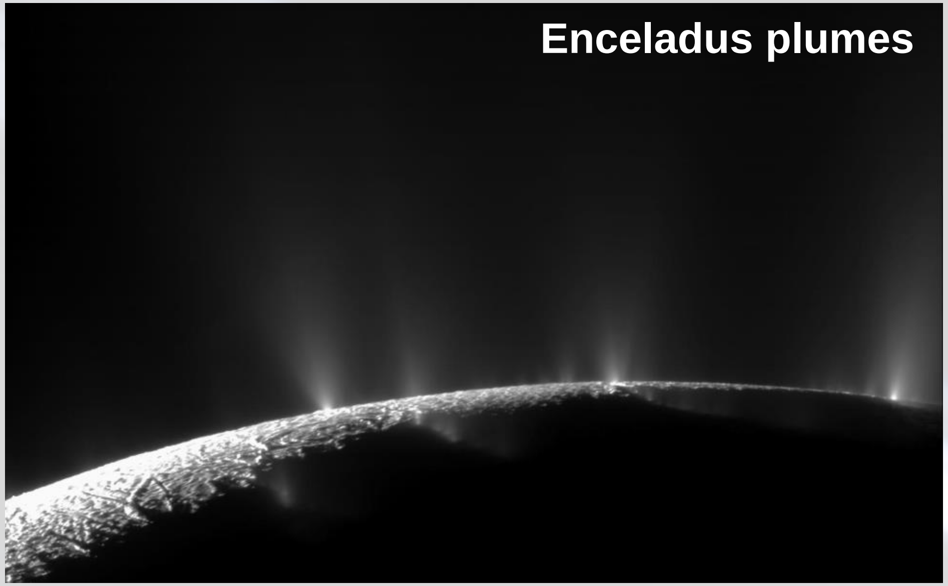
- The Cassini mission observed material from the subsurface habitable ocean being ejected by plumes and then settling on the surface. Ice particles from the plume may hold traces of life and/or biosignatures as well, if they exist.

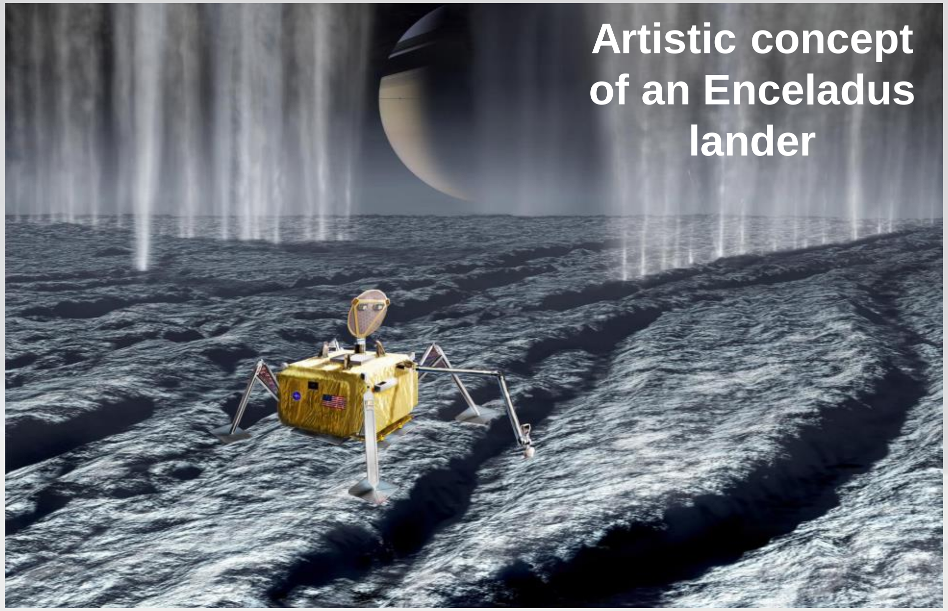
- In addition, the low radiation environment would help preserving the chemical composition of samples deposited on the surface.

- A potential future mission landing on the surface of Enceladus would have the goal to acquire surface samples for in-situ analysis. Such a mission is currently under investigation at NASA Jet Propulsion Laboratory.

- It is desired to acquire 1 cc to 5 cc of surface material that has accumulated in the top 1 cm to ensure acquisition of the least processed material.

A mission to the surface of Saturn's moon Enceladus could determine if life exists beyond Earth since ejected plume material from the subsurface habitable ocean has fallen onto the benign surface.





State-of-the-Art (1/2)

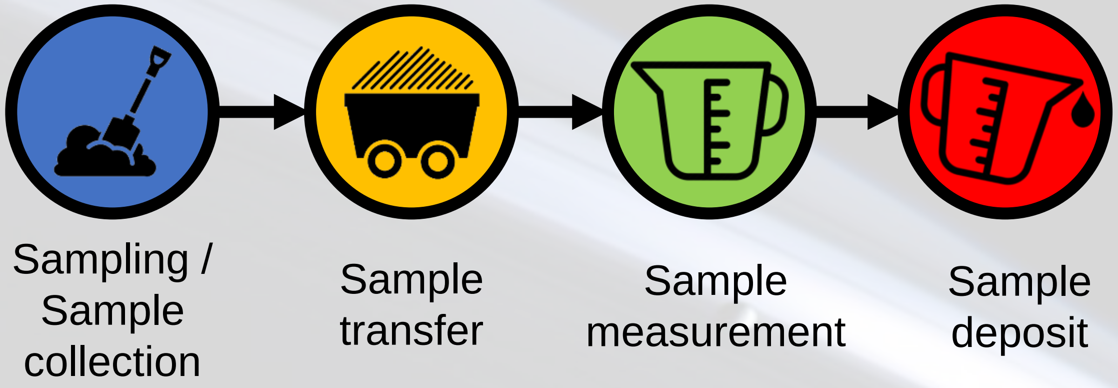
- In addition to cryogenic temperature and vacuum environmental conditions, the low surface gravity of Enceladus (1% of Earth's gravity) represents a new challenge for surface sampling and sample handling throughout the sample chain.

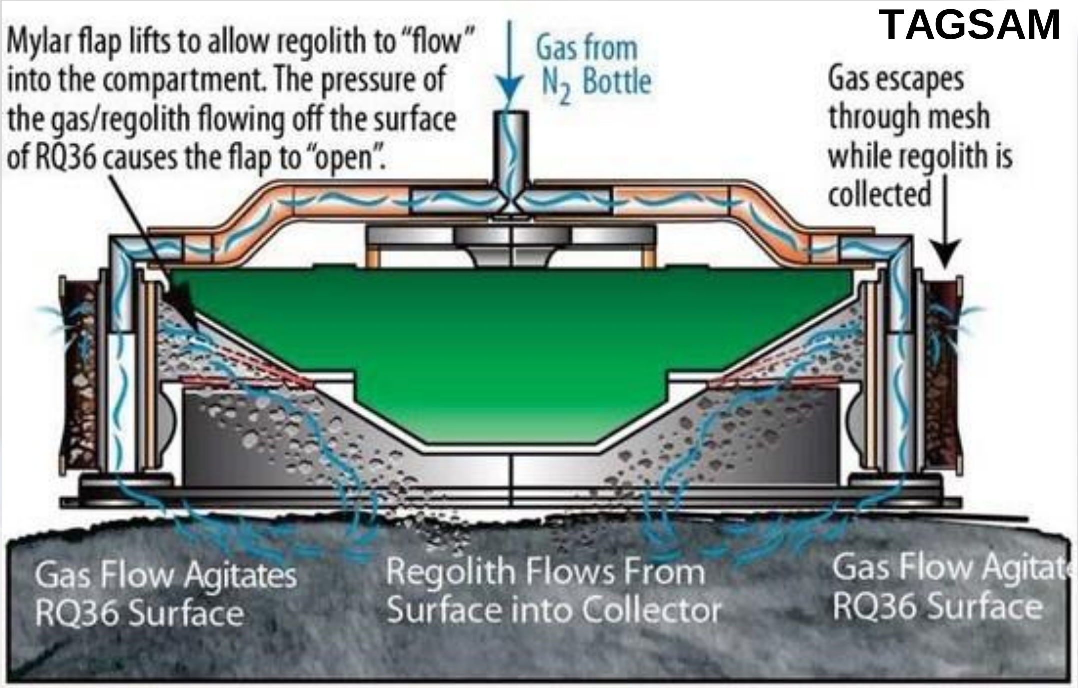
- Main challenges of the Enceladus environment include:
  - A severe limit on the allowable reacted load (< 10 N) from the sampling system to the lander to avoid stability issues.
  - The potential wide range of surface material properties, including 400 kPa to 12 MPa CPT strength and 40-95% porosity.
  - A significant difficulty to perform sample collection and handling in a low gravity environment.

- Sampling systems developed for microgravity (comets and asteroids) or higher gravity (Europa 13%g, Moon 16%g, Mars 38%g) do not meet the unique requirements for Enceladus surface sampling.

- The potentially strong material of 12 MPa precludes use of sampling systems that only work for weak materials such as the TAGSAM sampler of the OSIRIS-Rex mission or the proposed CAESAR comet surface sample return mission sampling system.

Sample chain

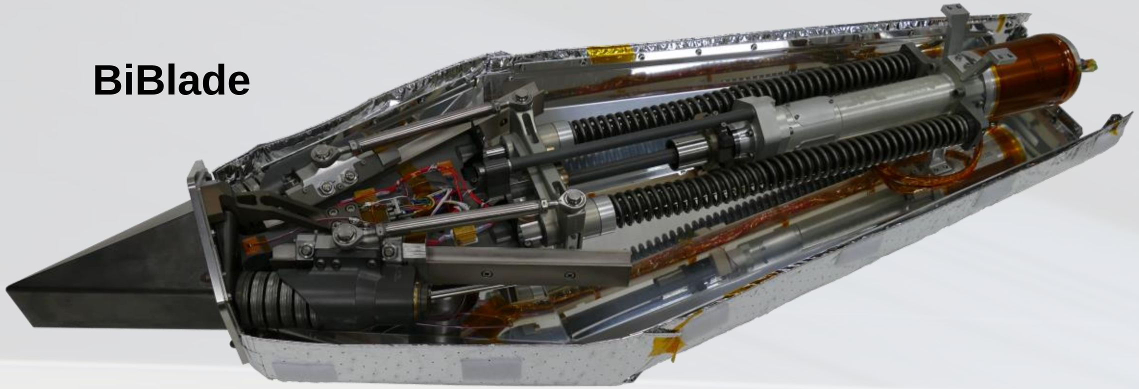




State-of-the-Art (2/2)

MSL powder drill

BiBlade



- The requirement for a low reacted force to the lander precludes use of sampling systems that require high preloads such as the Mars Science Laboratory (MSL) powder drill (~ 300 N), and the proposed Europa Lander mission counter-rotating saws and rasp (~ 50 N).

- The BiBlade developed for comet surface sampling and the Brush Wheel Sampler developed for asteroid surface sampling were designed for the higher reacted loads available in a touch-and-go mission architecture where spacecraft inertia reacts sampling forces (in the order of 1000s N).

- The Rosetta mission Philae lander rotary drill, SD2, would only acquire very weak material, and as a drill, would be poorly suited for collecting surface material.

- The Phobos Grunt mission had the CHOMIK percussive drive tube sampler, but as a drive tube it is designed to primarily collect subsurface samples.

Enceladus surface environment represents a new challenge for surface sampling and sample handling throughout the sample chain. Sampling systems developed for microgravity or higher gravity do not meet the unique requirements for Enceladus surface sampling.

Problem statement and research objectives

Problem statement

To investigate and develop a sample chain for the acquisition of Enceladus surface material for in-situ measurement.

Research objectives

To define the high-level requirements on the sampling system to guarantee the stability of the lander while performing the sampling operation.

To investigate and characterize sample collection and transfer operations in the Enceladus gravity, cryogenic, and vacuum environmental conditions.

To provide sample chain design guidelines to fulfill sampling requirements.

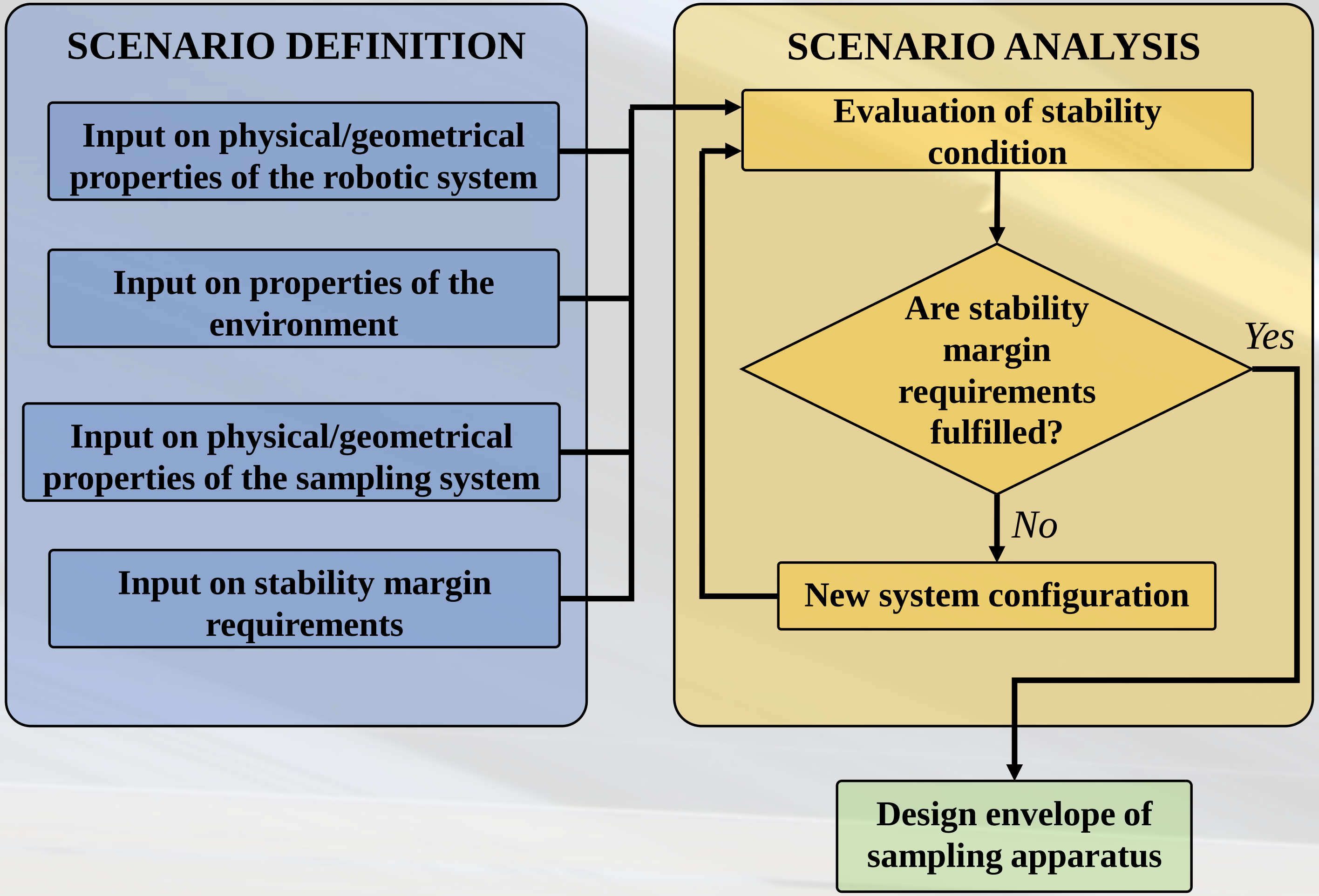
Definition of sampling system requirements (1/2)

- To guarantee a nominal sampling operation, crucial to mission success, it is required that the forces generated by the sampling system do not affect the stability of the lander.

- The traditional approach is to perform ad-hoc analyses on the stability of the lander every time a design parameter, a new sampling system, or a new lander configuration is investigated.

- To make this process more time-effective and reliable, a systematic effort was made to develop **MISTRAL** (MultIdisciplinary deSign Tool for Robotic sAmpLing), a novel **analytical tool** that supports the definition of the high-level requirements of robotic systems involved in sampling operations on planetary bodies.

- MISTRAL is conceived for trade space exploration during early conceptual and preliminary design phases, where a rapid and broad evaluation is required for a high number of configurations and boundary conditions.



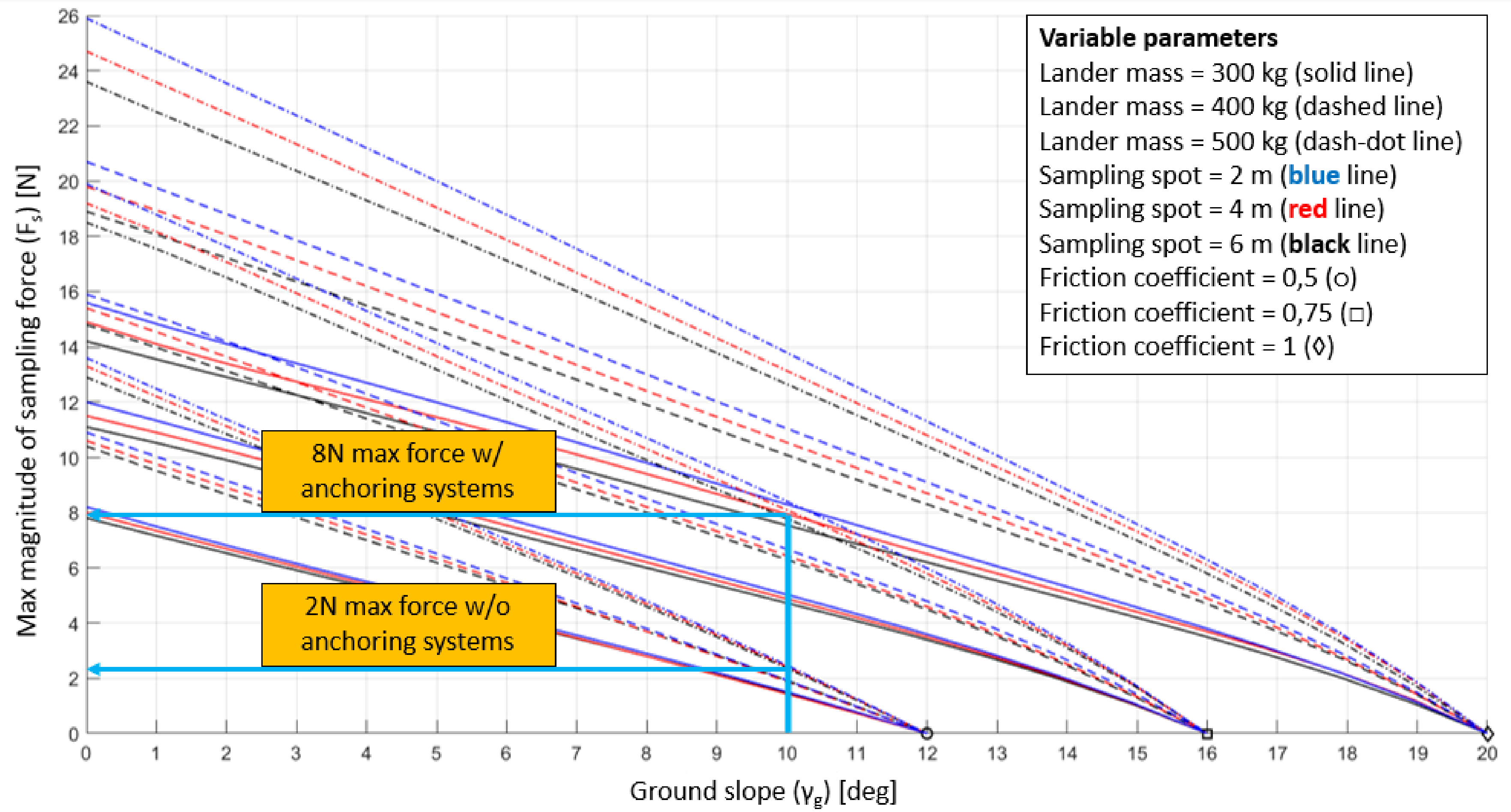
A multidisciplinary design tool for robotic systems involved in sampling operations on planetary bodies, CEAS Space Journal, 2020

Definition of sampling system requirements (2/2)

- Application of the tool to Enceladus lander mission led to the definition of a requirement for both the sampling system (i.e. maximum allowed sampling force of about 8 N) and the lander system (i.e. footpad-to-ground coefficient of friction of about 0.75).

- A higher footpad-to-ground coefficient of friction can be achieved by adding heated pins as anchoring system with the purpose to increase resistance to lander footpad sliding.

Application of MISTRAL to Enceladus lander mission



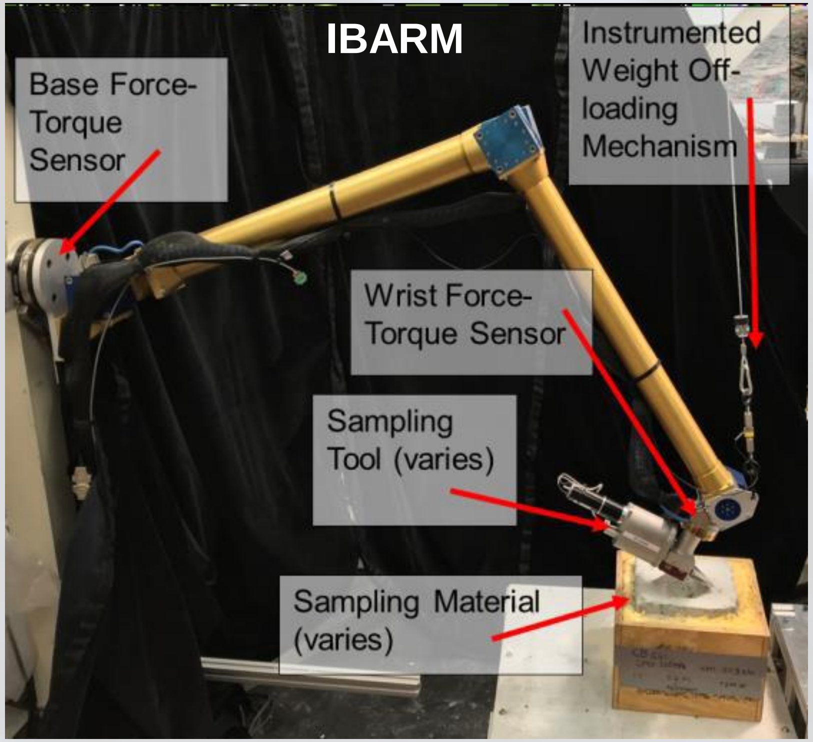
A novel analytical tool was developed to support the definition of the high-level requirements of robotic systems involved in sampling operations on planetary bodies. The tool was applied to both real mission data and to potential future missions, including the the Enceladus lander mission.

Investigation of sampling system concepts (1/2)

- Several sampling system concepts were developed or adapted and then tested in simulated conditions that resemble the Enceladus surface properties.

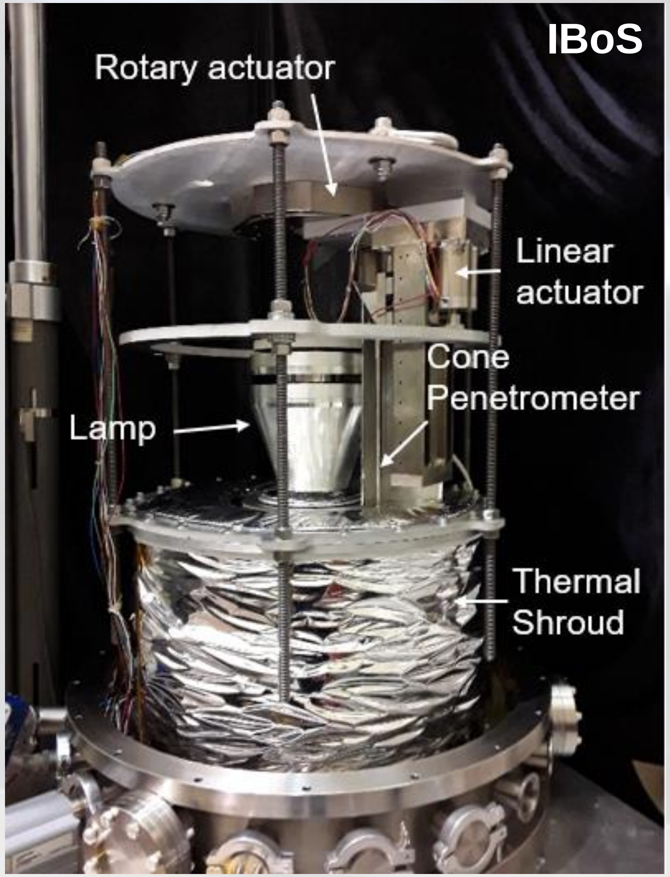
- Investigated sampling systems included a rotary hammer tool equipped with a full-face drill bit, a drive tube, a piezoelectric-actuated ultrasonic scoop, a rasp sampler.

- A 3 DOF robotic arm, named Icy Body ARM (IBARM), was developed and fabricated to evaluate all the sampling system prototypes on the same testbed.



- For early system testing, lab ambient material analogues were developed considering the description of potential Enceladus surface microstructure morphology to obtain the required mechanical strength.

- The Icy Bodies Simulation (IBoS) environmental chamber was designed and fabricated for use in generating and evolving icy body material analogues including to represent the Enceladus surface.



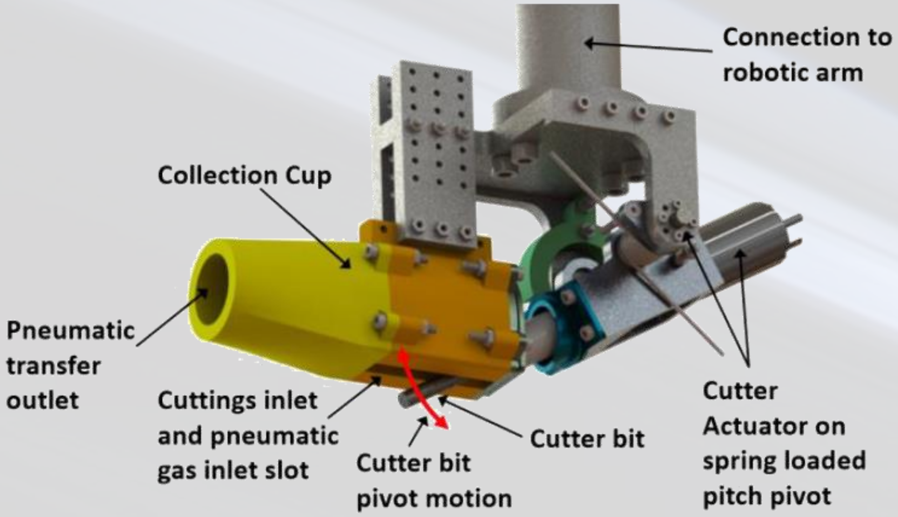
Investigation of sampling system concepts (2/2)

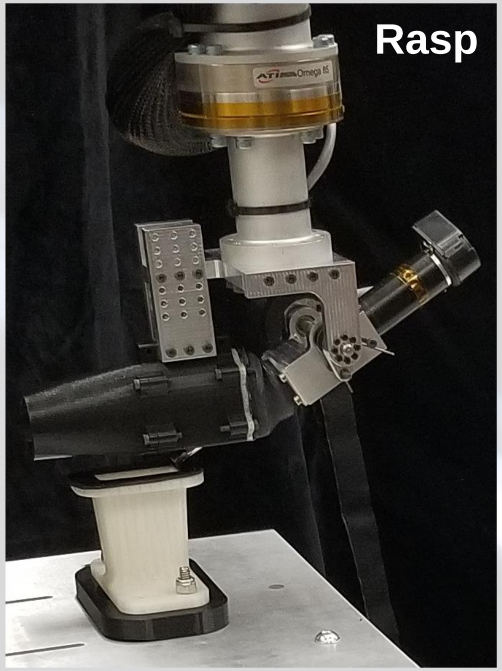
- All investigated sampling systems demonstrated to be able to acquire the desired volume sample from low to mid-strength materials. Concerns were raised about the ability to acquire sample from strongest materials, thus requiring significantly higher preload forces.

- The Rasp sampling system was the only concept capable to acquire sample from weak to strong materials (as utilized in the NASA's Phoenix Mars Lander mission) with average low preload force.

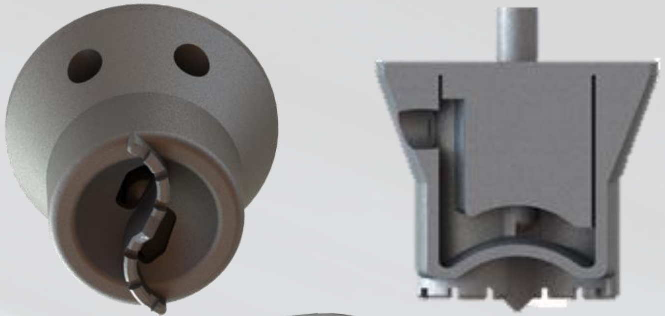
- Further analysis of the Rasp sampler were conducted to adapt the concept to Enceladus environmental conditions, resulting in a novel concept named Dual-Rasp.

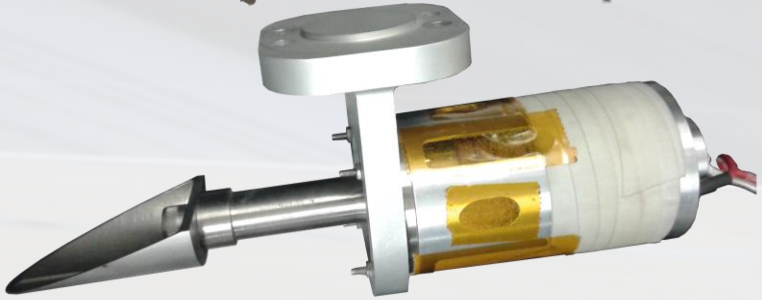
- The Dual-Rasp sampling system exploits a combination of two counter-rotating rasp type cutting heads to remove the surface material and throw it into a controlled path for collection.



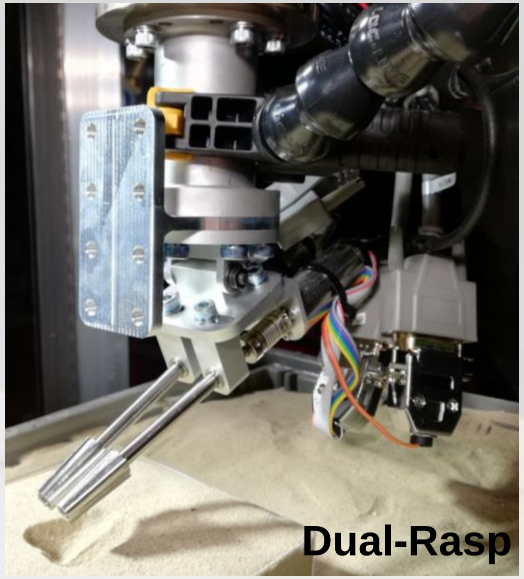


Full-face drill bit





Ultrasonic scoop



Sampling tool concepts for Enceladus lander in-situ analysis, IEEE Aerospace Conference, Big Sky (Montana, USA), 2019
The Dual-Rasp Sampling System for an Enceladus Lander, IEEE Aerospace Conference, Big Sky (Montana, USA), 2020

Investigation of sample collection (1/8)

Introduction

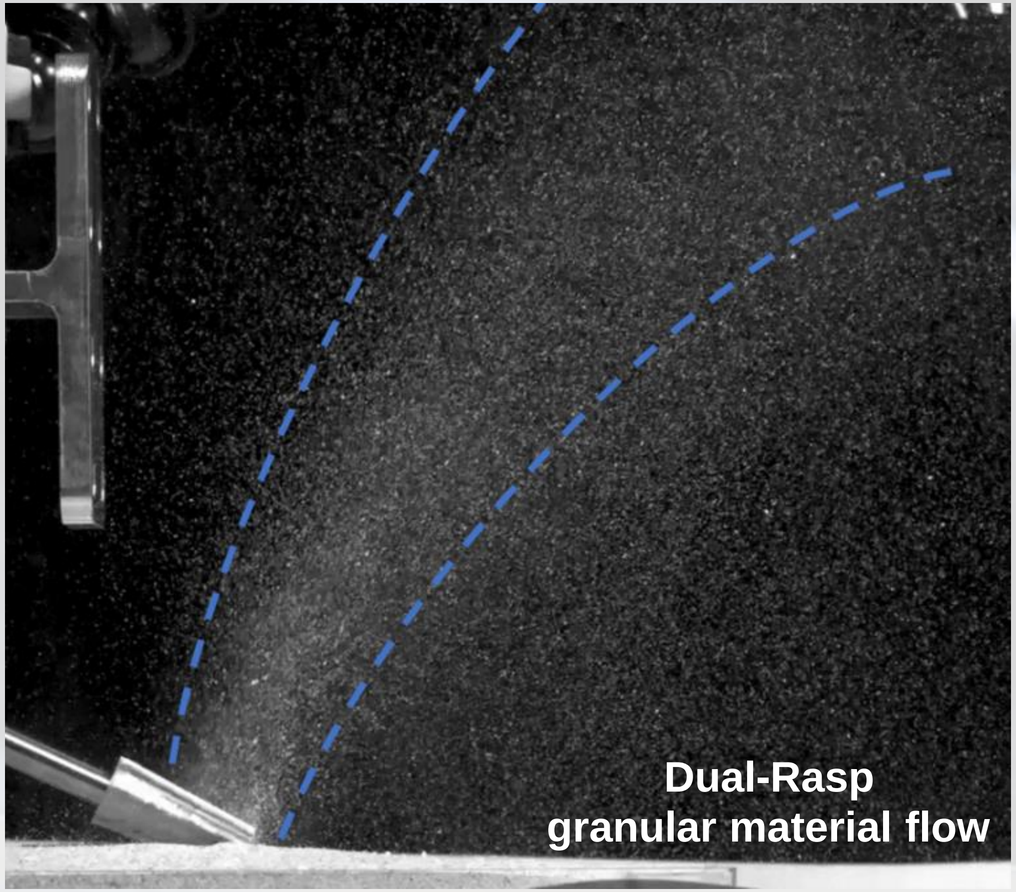
- The Dual-Rasp sampling system was developed to cope with the several challenges of surface sampling on Enceladus, including the wide range of potential surface material strengths, the limit on the allowable reacted load, and the low gravity environment.

- The Dual-Rasp sampling system exploits the counter-rotating motion of its rasp cutting heads to remove the surface material and throw the cuttings into a collection chamber.

- Sample collection is then achieved by transferring momentum from the cutting heads to the cuttings, thus generating a granular material flow.

- The Dual-Rasp ability to generate a granular material flow was observed in laboratory experiments by using high-speed cameras to record the sampling operation.

- To get an insight of this process, it is required to model and quantitatively characterize the granular material flow, in order to make predictions on its behavior in the Enceladus environment. The goal was to support the development of strategies to enable successful sample collection into a chamber.



Granular flow characterization during sampling operation for Enceladus surface acquisition, ASCE Earth & Space Conference, Seattle (Washington, USA), 2021

Investigation of sample collection (2/8)
Numerical model

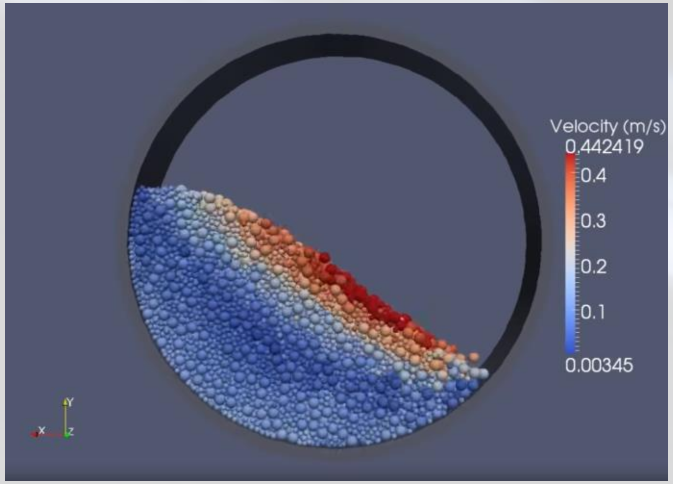
- The Discrete Element Method (DEM) is a numerical method particularly suited to model the complex dynamics of a large assembly of distinct particles.

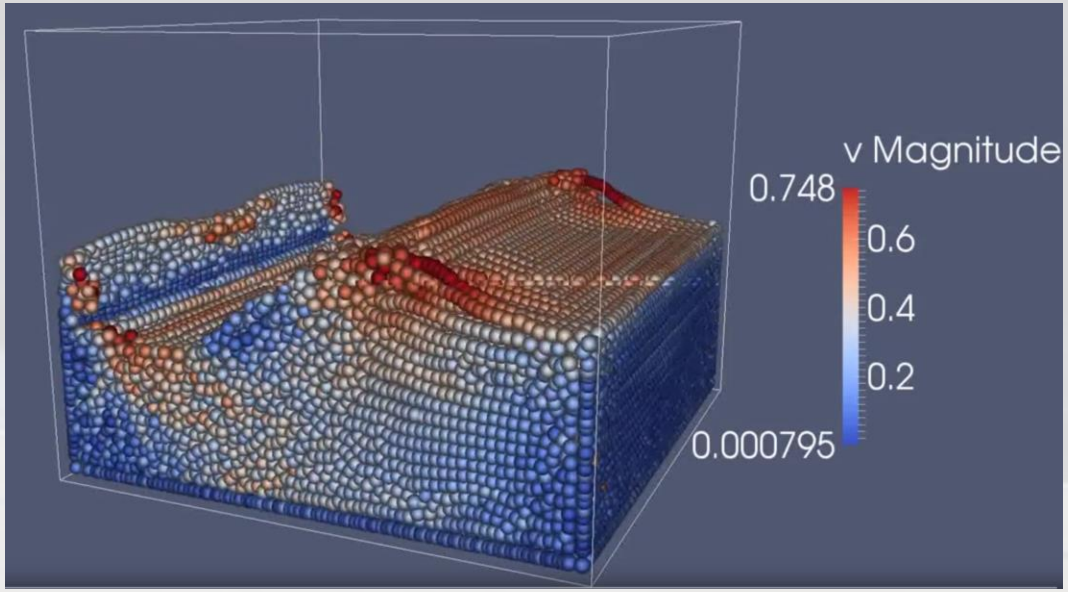
- A model based on DEM was developed to investigate the tool-soil interaction and the resulting granular material flow while performing surface sample acquisition.

- The analysis of tool-soil interaction requires a co-simulation between DEM, simulating particles' assembly, and MBD (Multi-Body Dynamics), simulating the action of the Dual-Rasp sampling system.

- The open source software LIGGGHTS was adopted for the DEM component of the simulation. NASA JPL's in-house-developed software M3TK was adopted for the MBD component of the simulation.

- The DEM model exploits the following contact mechanics models to evaluate forces/torques acting on particles.
  - Hertz-Mindlin model for normal-tangential contact.
  - Elastic-Plastic Spring-Dashpot model for rotational contact.
  - No cohesion is considered.

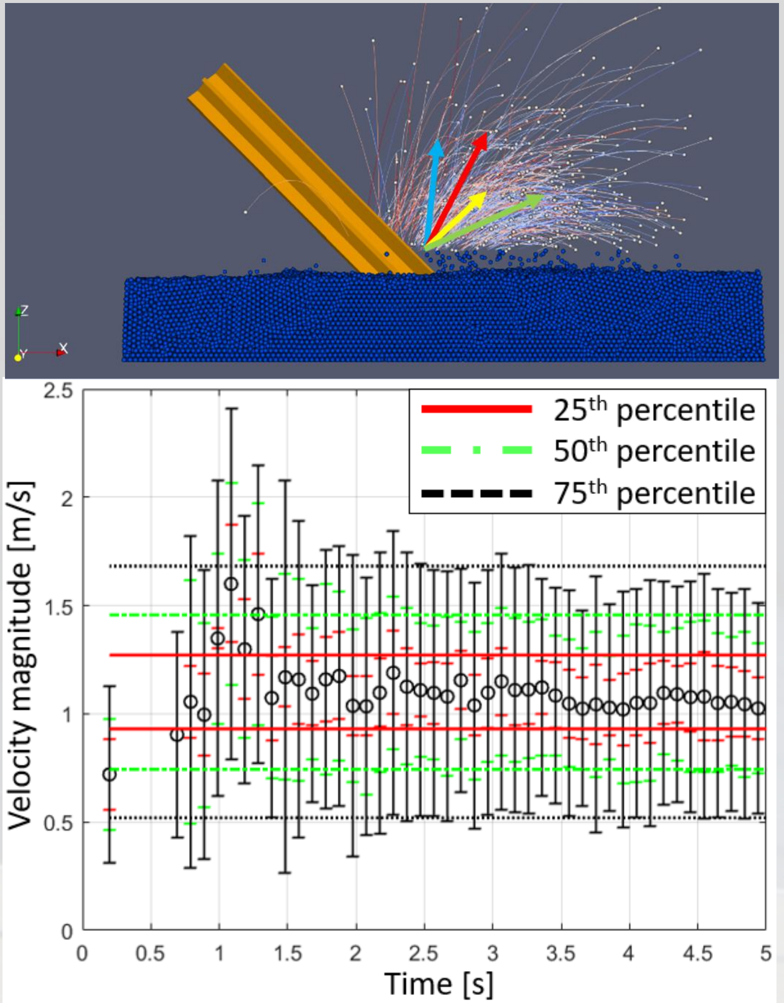




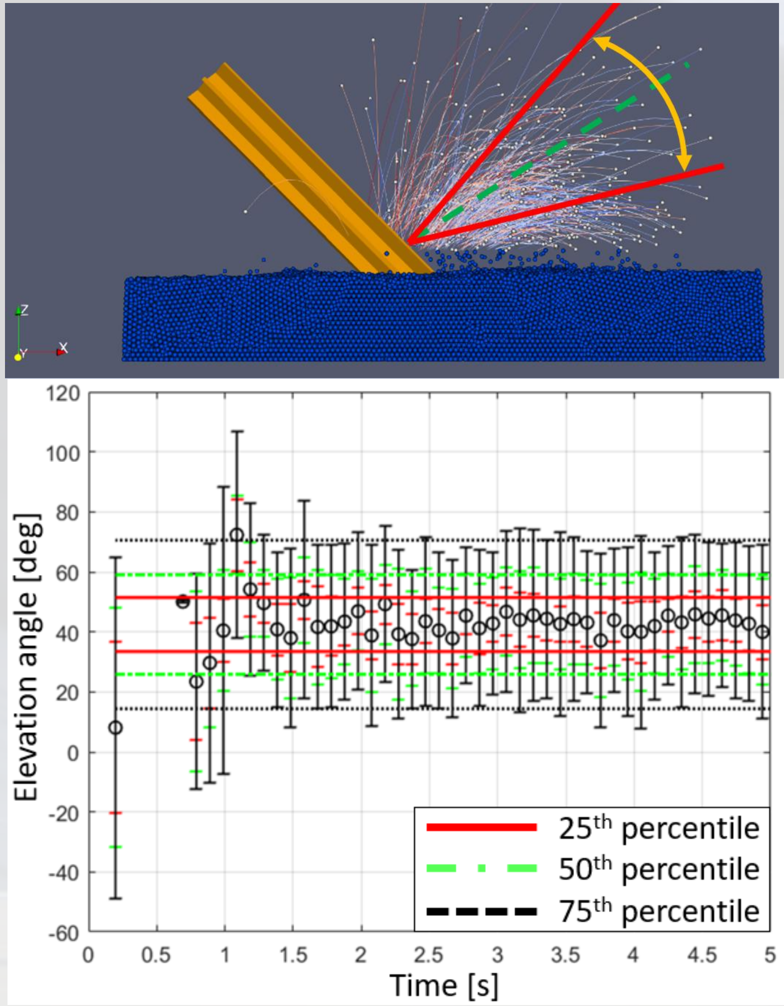
Investigation of sample collection (3/8)

Analysis metrics

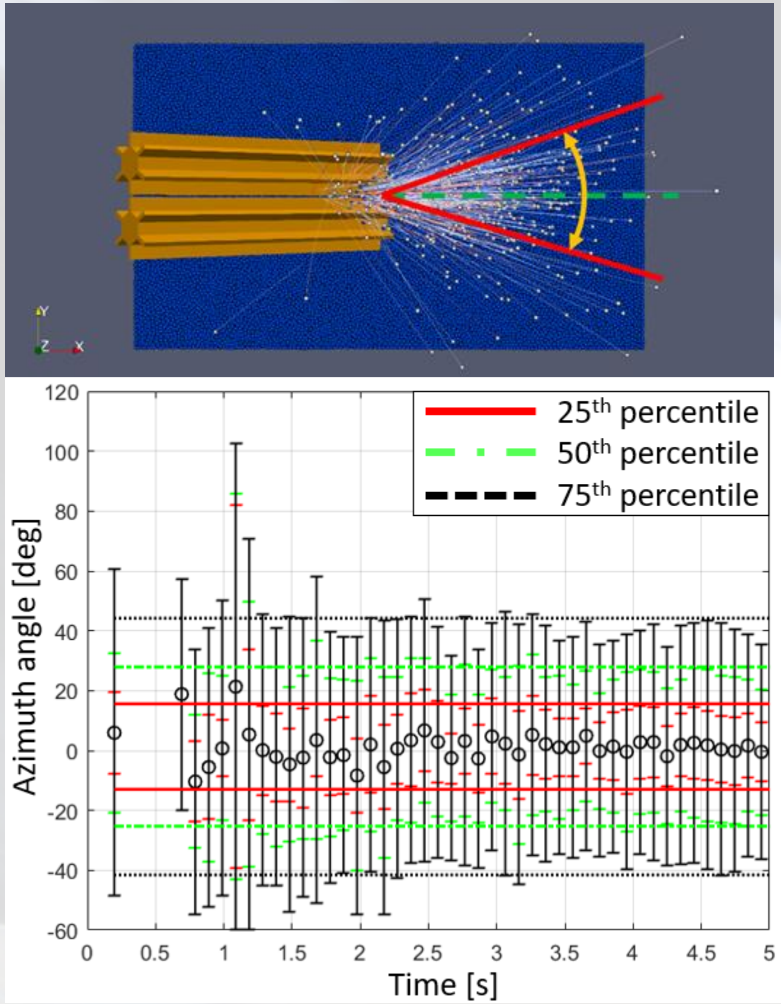
Velocity magnitude



Elevation dispersion angle



Azimuth dispersion angle



A set of metrics was developed to characterize both the simulated and the experimental granular material flow for apples-to-apples comparison.

Investigation of sample collection (4/8)

DEM model validation process

Sensitivity Analysis

To identify *the most sensitive DEM model parameters.*

Measurement

To measure *the most sensitive DEM model parameters.*

Validation

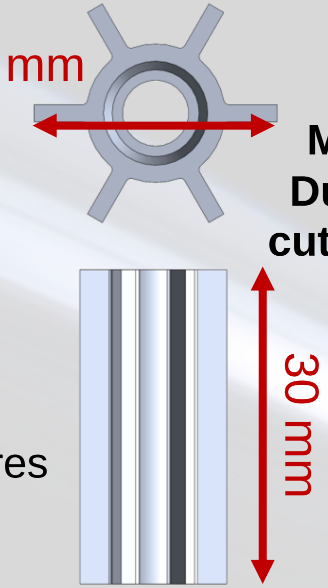
To validate *the DEM model via experimental testing.*

Investigation of sample collection (5/8)

Sensitivity analysis

- Sensitivity analysis process requires:
  - To define a range of values for each parameter
  - To perform simulations by changing parameters' values in the pre-defined range.
  - To evaluate parameters' sensitivity by applying the analysis metrics to simulation results.
  - To identify the most sensitive parameters influencing the granular material flow.

- Simulation setup
  - *Vertical motion velocity*: 2 mm/s
  - *Vertical displacement*: 10 mm
  - *Rotational speed*: 2000 RPM
  - *Cutter's material*: Al 6061-T6
  - *Gravity acceleration*: 1g
  - *Particle size/shape distribution*: monodisperse 1 mm-diameter spheres



Model of Dual-Rasp cutting head

- The sensitivity analysis has the purpose of reducing the dimensionality of the DEM model by determining the most sensitive parameters influencing the granular material flow.

- Particle-tool coefficient of static friction and particle-tool coefficient of restitution were identified as the most sensitive DEM simulation model parameters influencing the granular material flow.

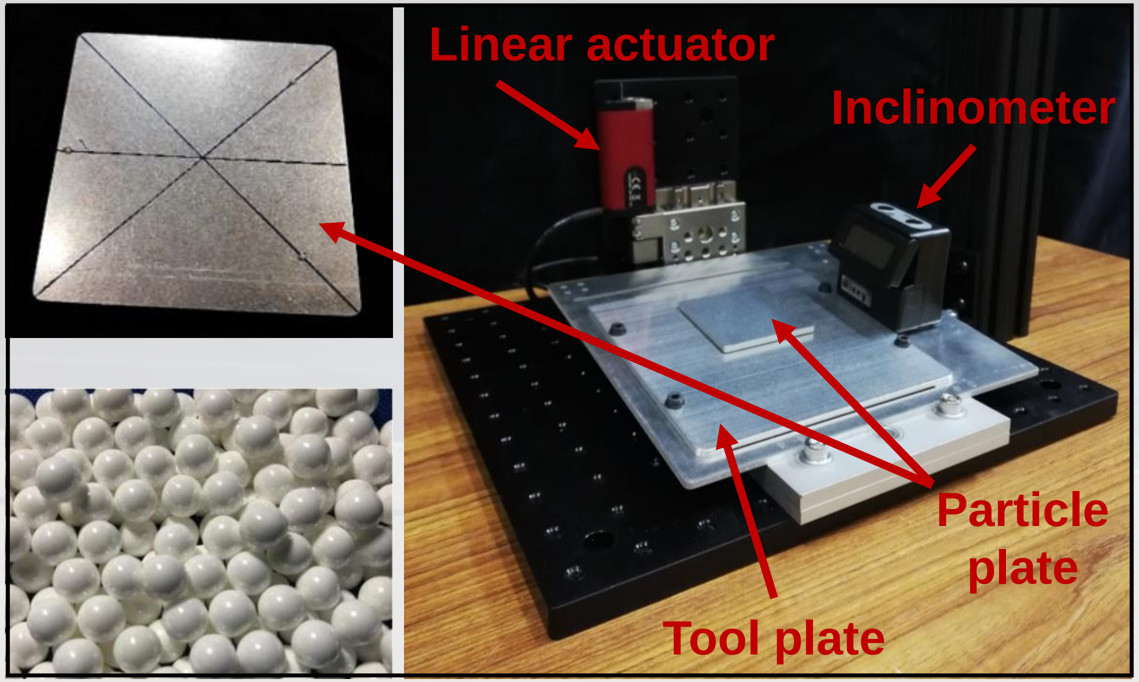
		Analysis Metrics		
		Velocity magnitude	**Azimuth angle**	**Elevation angle**
Model Parameters	Particle Young's modulus	0.50	0.42	0.42
	Particle Poisson's ratio	0.33	0.25	0.25
	Particle density	0.33	0.25	0.25
	Particle-particle coeff. static friction	0.50	0.42	0.42
	Particle-particle coeff. restitution	0.50	0.42	0.42
	Particle-particle coeff. rolling friction	0.33	0.25	0.25
	Particle-tool coeff. static friction	**0.92**	**0.75**	**0.75**
	Particle-tool coeff. restitution	**1.00**	**0.75**	**0.75**
	Particle-tool coeff. rolling friction	0.42	0.42	0.42

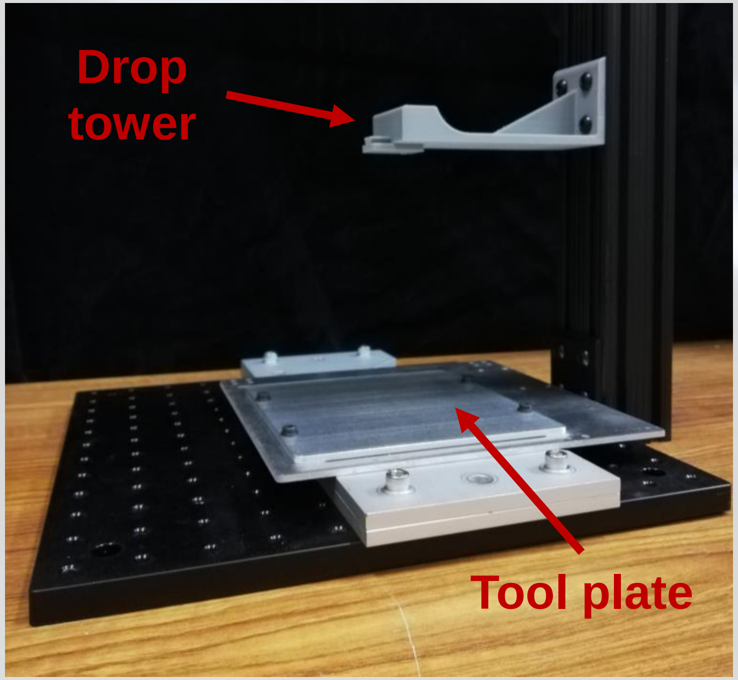
Investigation of sample collection (6/8)

Measurement of most sensitive DEM model parameters

- Most sensitive DEM model parameters influencing the granular material flow were directly measured via independent tests performed by using custom designed apparatus.

- For validation purposes, monodisperse 1 mm-diameter spheres made of zirconia were selected for apples-to-apples comparison between DEM simulations and experimental testing.





- The particle-tool coefficient of static friction was measured by performing an inclined plane test, determining a value of 0.15 ± 0.01

- The particle-tool coefficient of restitution was measured by performing a particle drop test, determining a value of 0.65 ± 0.05

Investigation of sample collection (7/8)

DEM-driven design of sample collection system

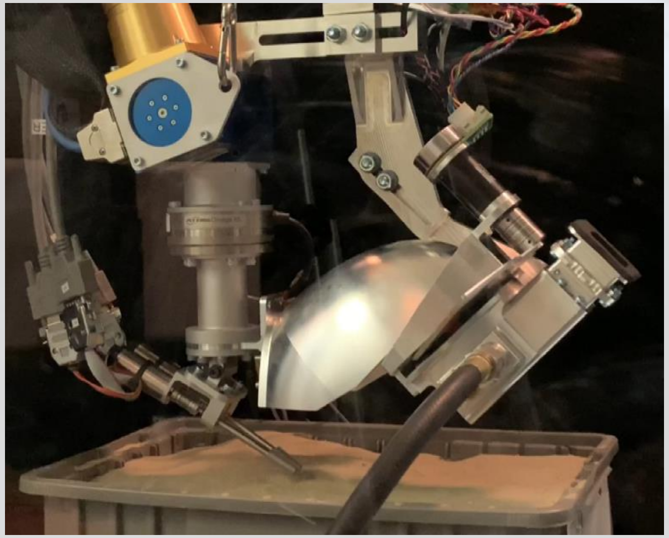
- The DEM model was used to drive the design of sample collection system, including elements named *guide* and *containment system*.

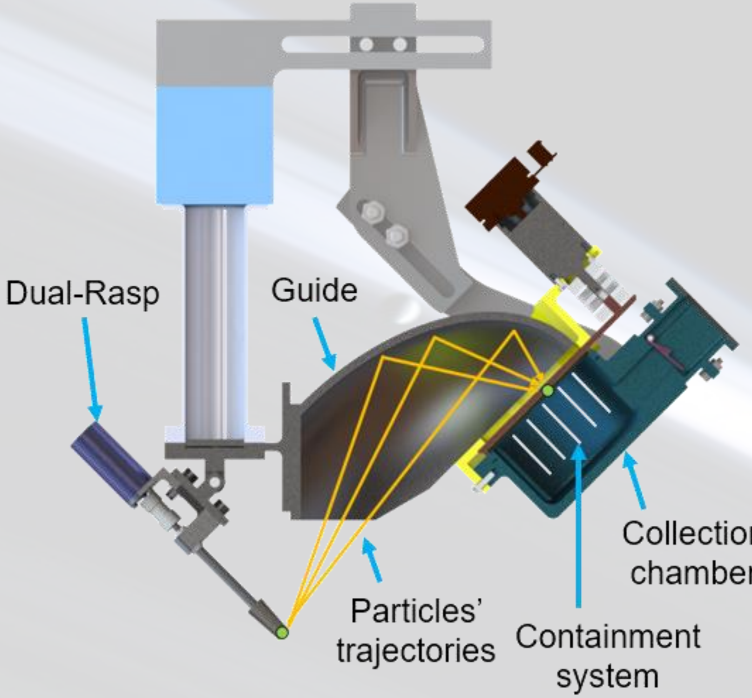
- The *guide* is an ellipsoid-shaped structure designed to direct the granular material flow towards the inlet of the collection chamber by exploiting the geometrical properties of the ellipsoid.

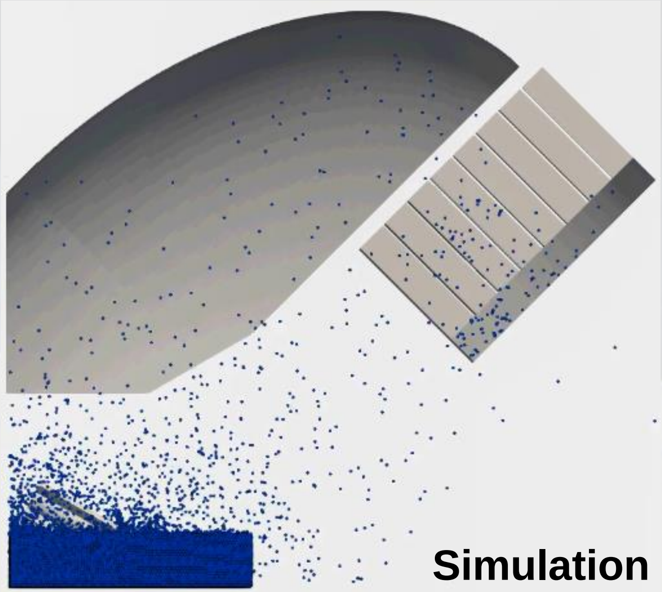
- The *containment system* is a grid-style structure placed inside the collection chamber to aid sample retention in low gravity environment.

- DEM simulations were performed to investigate the granular flow through the guide and into the collection chamber. Simulation results were adopted to provide design guidelines.

- *Guide* and *containment system* were prototyped and verification tests in 1g environment were successfully performed.







Investigation of sample collection (8/8)

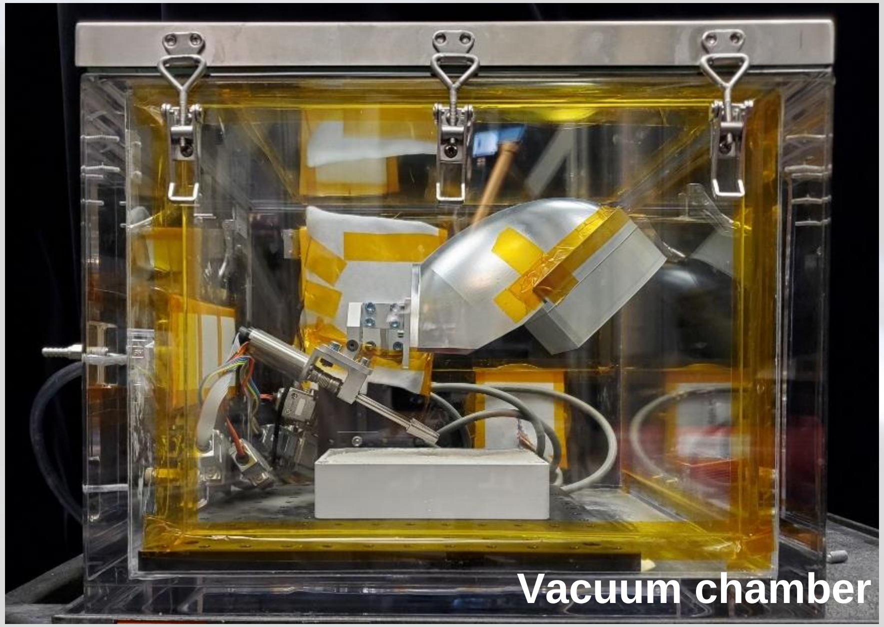
Future work: DEM model validation campaign

- An experimental test campaign of sampling and sample collection operations is planned to be conducted in a custom designed vacuum chamber provided with clear windows and recorded by using high-speed cameras.

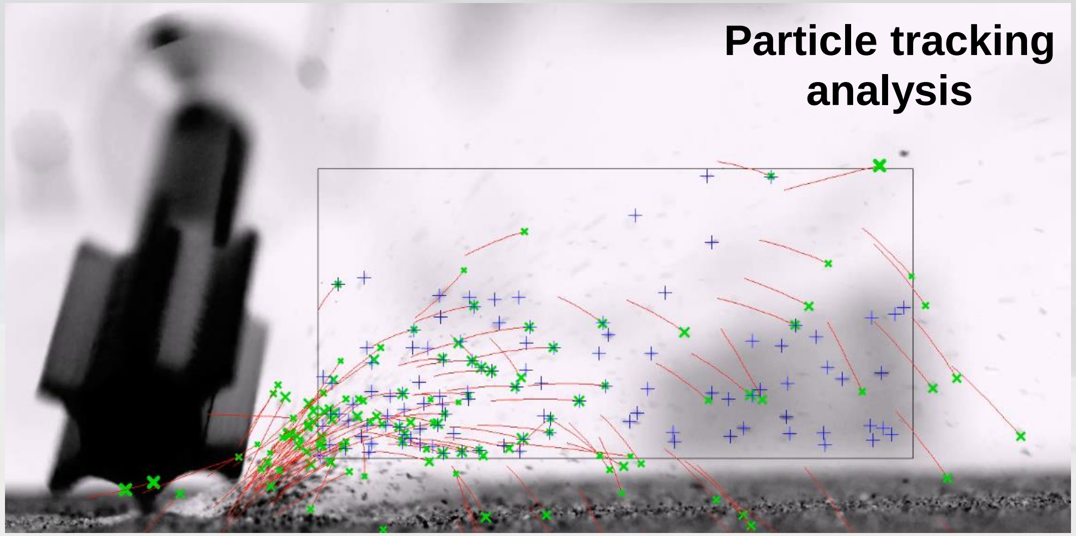
- The experimental test campaign will be conducted in relevant environments, including
  - Vacuum Earth's gravity environment via laboratory testing.
  - Vacuum low gravity environment via a parabolic flight sponsored by NASA.

- The goals of the experimental test campaign are
  - To verify sampling and sample collection operations in a relevant environment, as part of the maturation process to TRL 5.
  - To validate the DEM model predictions.

- A custom developed particle tracker code will be used to characterize the experimental granular material flow and compare it to DEM predictions by using the same analysis metrics, thus providing apples-to-apples comparison and ease of validation.



Vacuum chamber



Particle tracking analysis

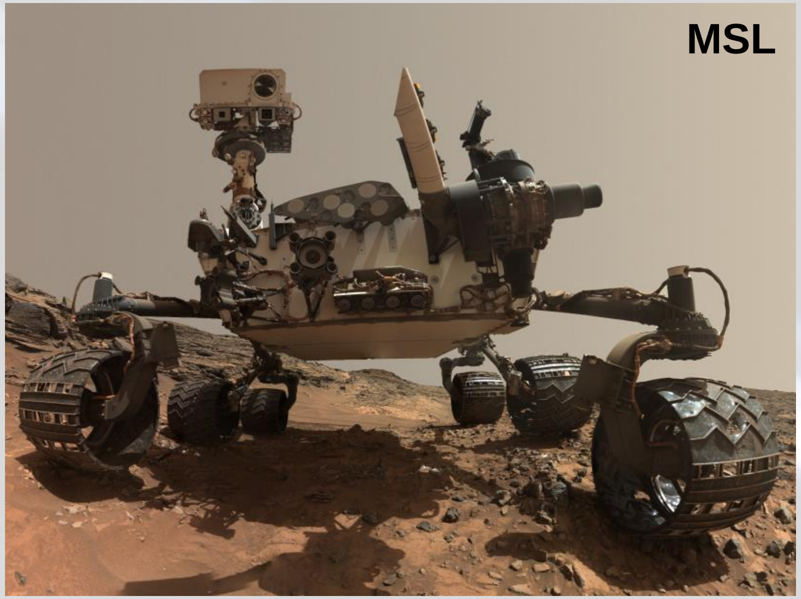
Investigation of sample transfer (1/4)

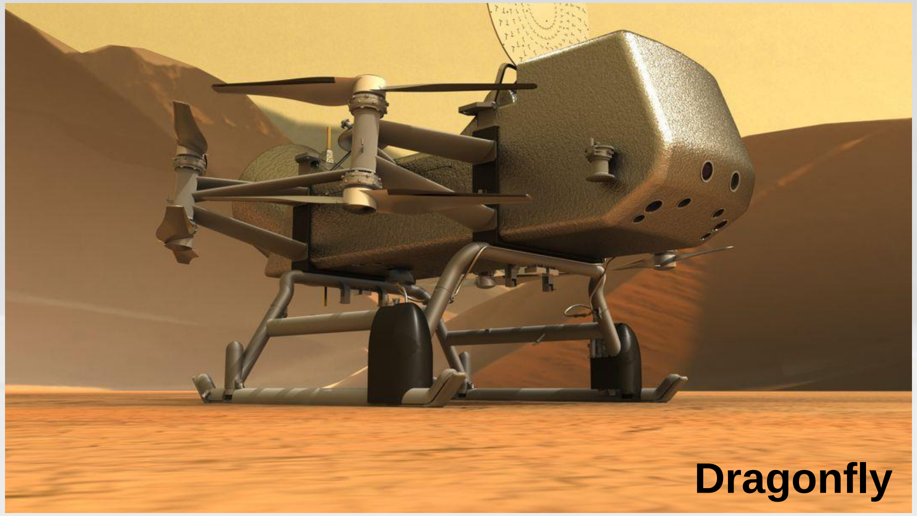
Introduction

- Past missions made use of local gravity for sample handling
  - Mars Science Laboratory (MSL) rover used robotic arm manipulation.
  - Phoenix Mars lander used to pour sample by using a scoop.

- In the low gravity environment of Enceladus it is not possible to rely on gravity for sample handling.

- Pneumatics is an emerging technique that is being adopted by current and future missions, including OSIRIS-Rex to asteroid Bennu and Dragonfly to Saturn's moon Titan.



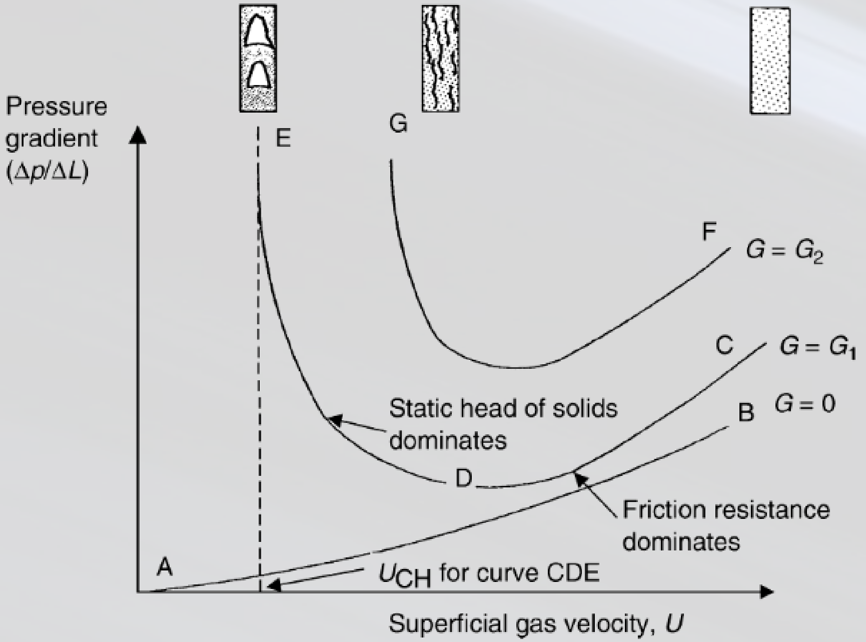


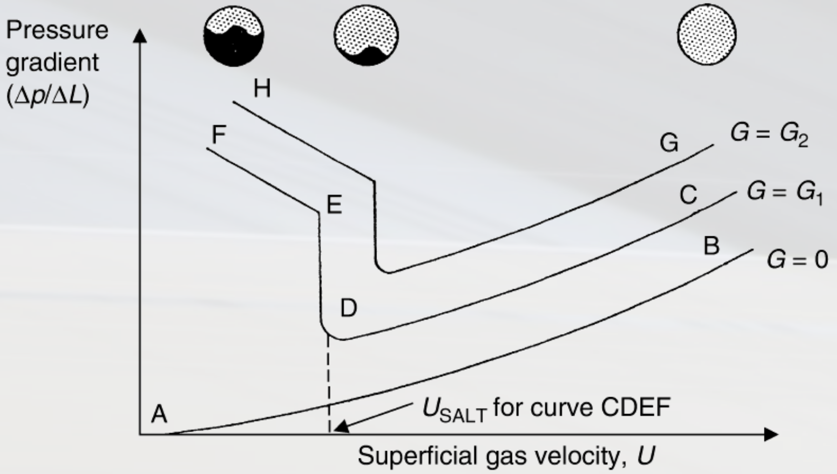
Modelling of pneumatic sample transport systems for Enceladus surface acquisition, 11th IAA Symposium on the Future of Space Exploration, Torino (Italy), 2019
Modelling of low gravity sampling and sample transfer systems for Enceladus surface acquisition, Proceedings of the Turin's Academy of Sciences (In Press)

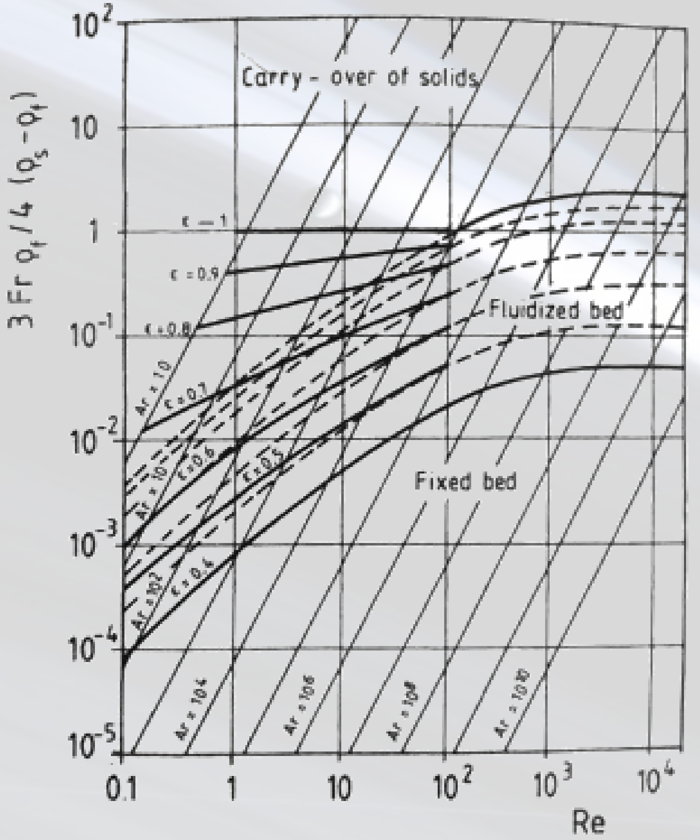
Investigation of sample transfer (2/4)

Analytical model

- An analytical model was developed to investigate the pneumatic transport of particles in a low gravity environment with the aim to provide guidelines for sample chain design.
- Choking and saltation velocities were used to define the boundary between dilute phase and dense phase transport in vertical and horizontal pipelines, respectively.
- Moreover, non-dimensional groups were also used to determine the flow regimes.
- These information can be used to derive the gas velocity required to achieve a specific flow regime.
- The fundamental relationships governing the flow of gas and solids in a pipe were used to determine flow rates and pressure drops.



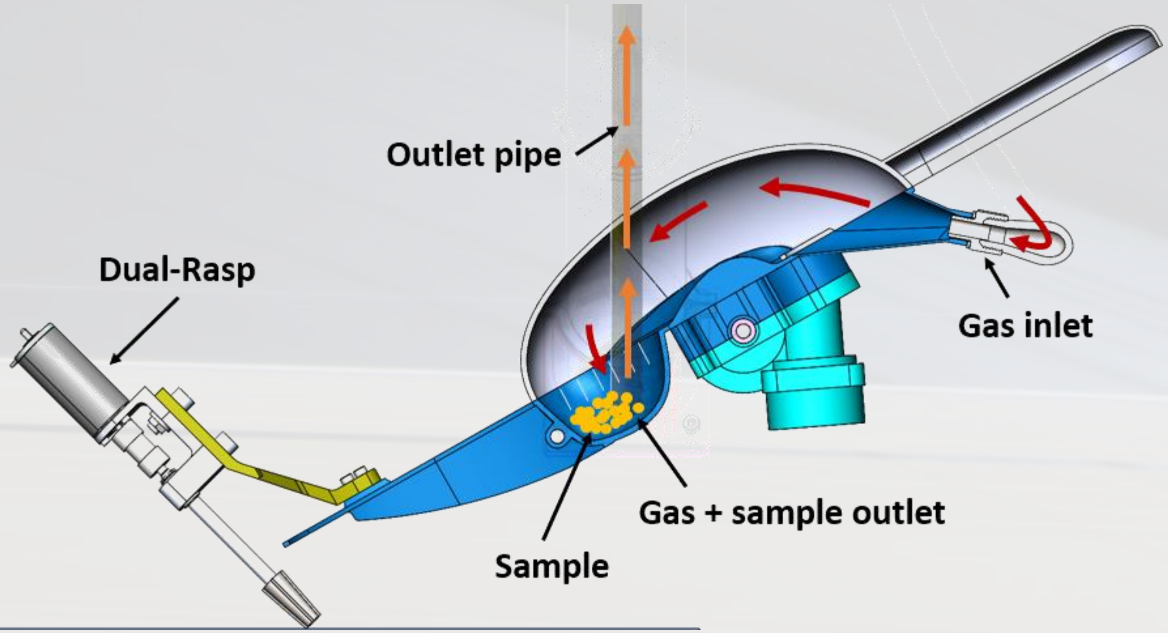


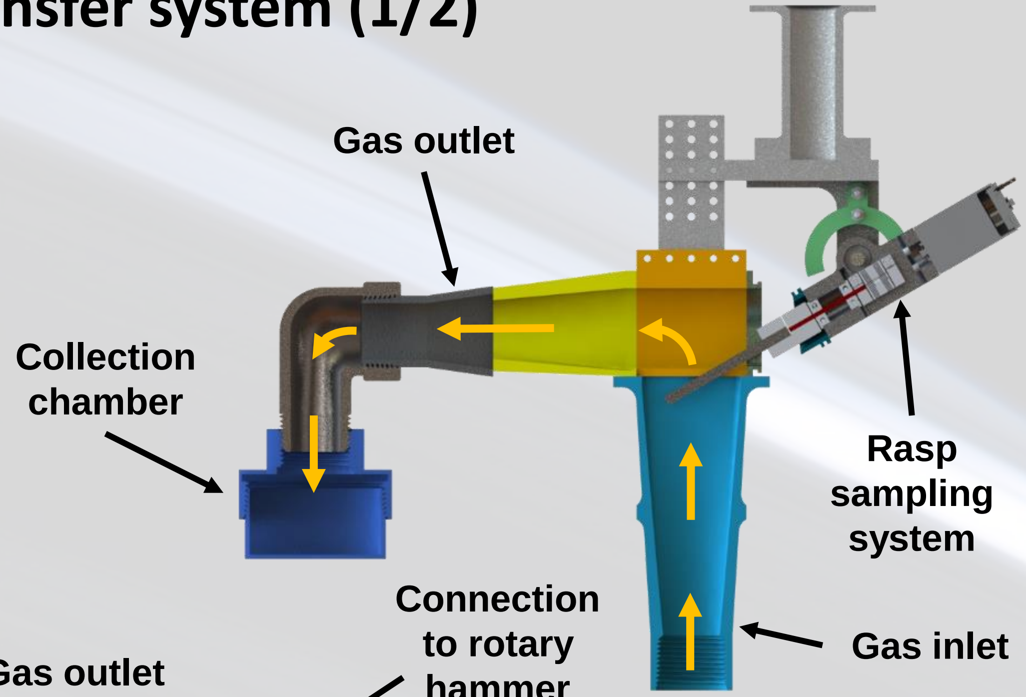


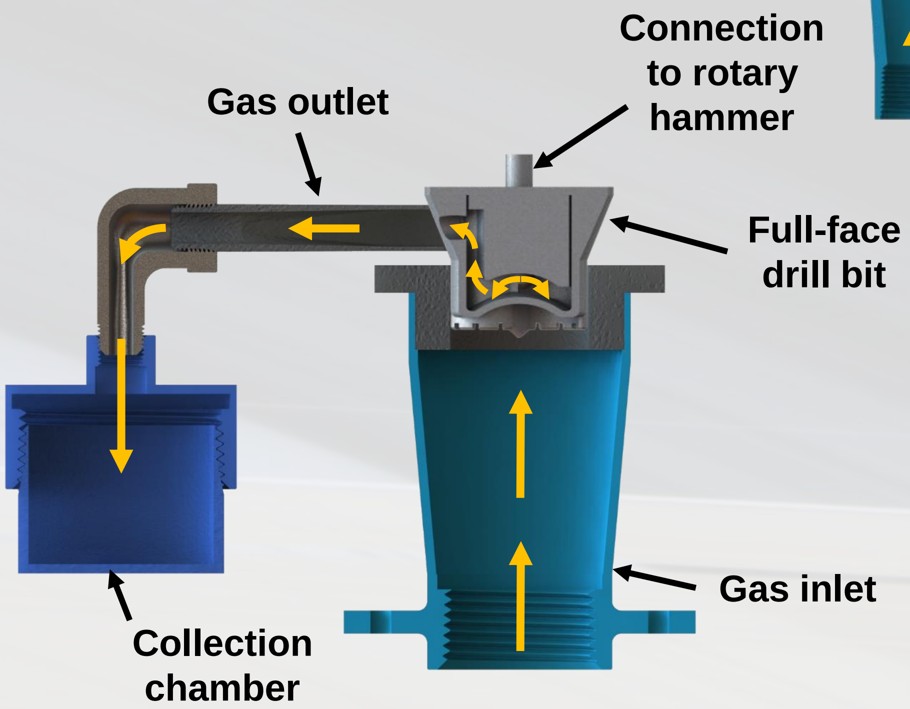
Investigation of sample transfer (3/4)

Model-driven design of sample transfer system (1/2)

- The analytical model was used to drive the design of various prototypes of pneumatic sample transfer system with the goal to mature this technology to TRL 5.
- Some of the sampling system concepts evaluated were designed with an integrated pneumatic sample transfer system with the purpose of performing preliminary test of end-to-end sample chain operations.
- A pneumatic sample transfer system was also designed and fully integrated in the Dual-Rasp sample chain.



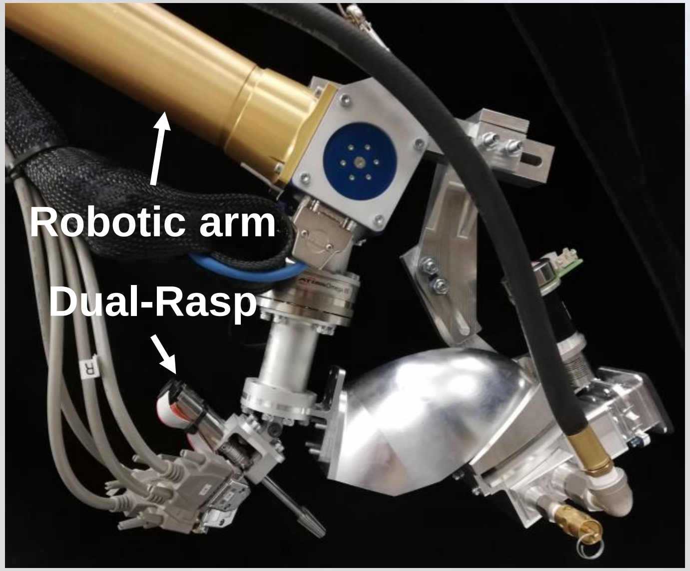


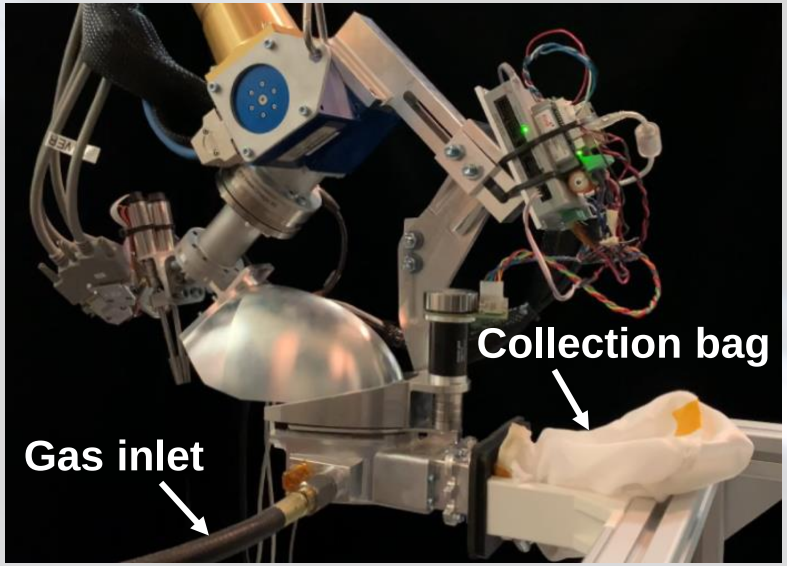


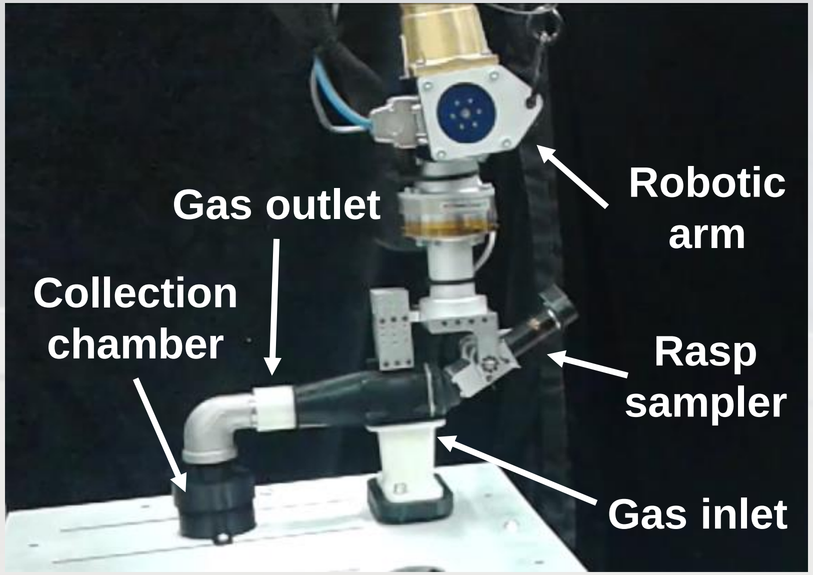
Investigation of sample transfer (4/4)

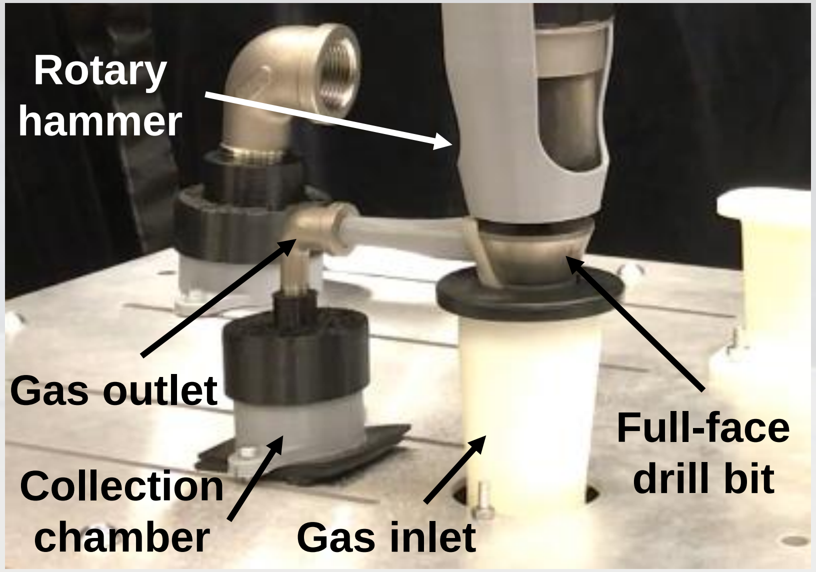
Model-driven design of sample transfer system (2/2)

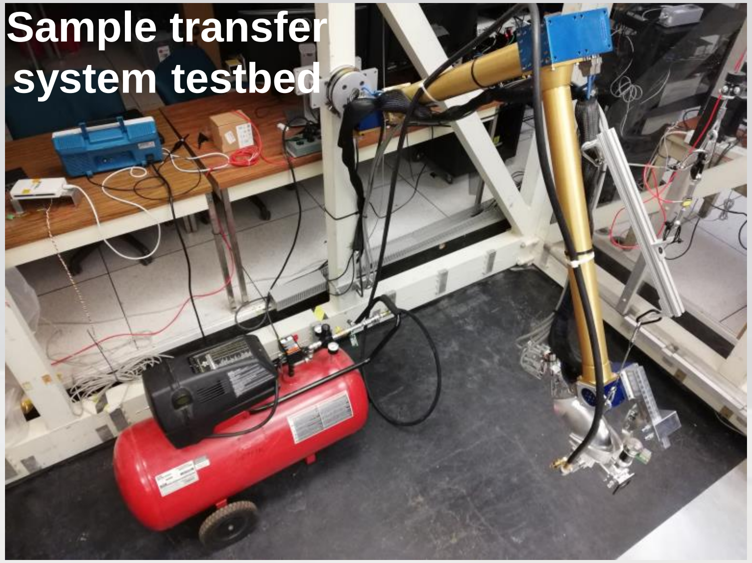
- All pneumatic sample transfer systems were prototyped and integrated.
- End-to-end sample chain verification in 1g lab ambient environment was successfully performed for the Full-face drill bit, the Rasp sampler, and the Dual-Rasp sampler.
- End-to-end Dual-Rasp sample chain verification in 1g thermal vacuum environment is planned.











Conclusions

- A mission to the surface of Saturn's moon Enceladus could determine if life exists beyond Earth. Such a mission is currently under investigation at NASA Jet Propulsion Laboratory (JPL).

- The objective of JPL's task is to investigate and develop a sample chain for the acquisition of Enceladus surface material for in-situ measurement.

- The Ph.D. research supported JPL's task by pursuing the following objectives.
  - To define the high-level requirements on the sampling system.
  - To investigate and characterize sample collection and transfer operations.
  - To provide sample chain design guidelines to fulfill sampling requirements.

- Ph.D. research objectives were pursued by performing the following tasks
  - A novel analytical tool was developed to support the definition of the high-level requirements on both the sampling system and the lander system to guarantee successful sampling operations.
  - A numerical model based on DEM was developed to investigate sample collection
    - ✓ DEM-driven design, prototyping, and verification of sample collection system were successfully conducted.
    - ✓ DEM model validation campaign in 1g vacuum and low-g vacuum environments is planned.
  - An analytical model was developed to investigate pneumatic sample transport
    - ✓ Model-driven design, prototyping, and verification of sample transfer system were successfully conducted.
    - ✓ End-to-end sample chain verification in 1g thermal vacuum environment is planned.

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Thank you for the attention!

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