Doctoral Program in Mechanical Engineering (33th Cycle)

Space Exploration Robotic Systems

Sample chain analysis and development for Enceladus surface acquisition

By

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Doctoral Dissertation Abstract

Saturn's moon Enceladus is among the most promising candidates in the Solar System to host life beyond Earth. Observations from the *Cassini* mission suggest that Enceladus contains a global ocean beneath its thick ice shell. Moreover, *Cassini* directly observed active cryovolcanism since material from the subsurface ocean is ejected through surface fractures in the South polar region. Enceladus' plume consists of vapor and particles that are deposited on the surface. The presence of complex organic materials, and the abundant geothermal energy from the interior and within the South polar terrain provide evidence for habitability and the prospect that life may have emerged and still be present on Enceladus.

A potential future lander mission to Enceladus is currently under investigation at NASA Jet Propulsion Laboratory (JPL). The research presented in this dissertation is part of a NASA JPL Strategic Research and Technology Development (RTD) effort to develop and mature a sample chain for Enceladus surface acquisition for in-situ measurements to Technology Readiness Level (TRL) 5. In this context, it is desirable to develop a sample chain to provide 1 cc to 5 cc volume samples to science instruments from the very shallow surface material in the top 1 cm, in order to acquire the freshest material deposited on surface from plume fallback.

Ph.D. research presented in this dissertation supported JPL's RTD activity by pursuing the following 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 sample acquisition requirements.

The definition of high-level requirements was driven by a novel analytical design tool conceived and developed for trade space exploration during early conceptual and preliminary design phases, where a rapid and broad evaluation is required for a very high number of configurations and boundary conditions. The tool rapidly determines the preliminary design envelope of a sampling apparatus to guarantee the stability condition of the lander. The tool also provides the capability to infer high-level requirements concerning other elements of the lander critical to its stability, such as the footpads.

The investigation and characterization of sample transport and collection is achieved by developing a model based on the Discrete Element Method (DEM). DEM is a numerical simulation technique for computing the motion and effect of a large number of particles. A set of analysis metrics is developed to characterize the granular material flow generated during the sampling operation. The analysis metrics are devised to be used for both numerical analysis and experimental testing, providing a framework for apples-to-apples comparison. Most sensitive model parameters are determined through a sensitivity analysis and then directly measured via independent tests performed by using custom designed apparatus.

The investigation and characterization of sample transfer is achieved by developing analytical tools to study the flow of particles dispersed into a gas with the aim to pneumatically transfer the sample to the scientific instrument. The exploration of design space is performed to determine the optimal design parameters to achieve a dilute phase transport of the sample.

Results of previously described investigations were adopted to drive the design of sample chain elements that were subsequently prototyped and subject to verification testing and maturation to TRL 4.

A test campaign is planned for DEM model validation and Dual-Rasp sampling system and sample collection verification to achieve TRL 5 via parabolic flights in 1%g Earth's gravity and vacuum conditions.

Finally, a two DOF RA was designed and developed with integrated sampling system, sample collection, and pneumatic sample transfer systems to a notional science instrument chamber with the aim to perform end-to-end sample chain verification in 1g Earth's gravity and Enceladus-like thermal vacuum environment to achieve TRL 5.