**Advancing Dust Tolerant Mechanisms for a Sustained Exploration of the Moon.** J. I. Núñez1,2, M. E. Perry1,2, S. Hasnain1,2, R. S. Miller1,2, L. R. Tolis1,2, B. A. Clyde1,2, A. M. Fritz3, A. J. Sanchez4,5, and K. K. John3,4, 1Johns Hopkins University Applied Physics Laboratory; 2Lunar Surface Innovation Consortium; 3NASA Johnson Space Center; 4NASA STMD, 5Stellar Solutions, Inc. (Contact: jorge.nunez@jhuapl.edu)

**Introduction:** “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.”– Gene Cernan, Apollo 17 Technical Debrief

The Apollo missions revealed the impact of lunar dust on mechanisms. Lunar dust particles are jagged and electrostatically charged, giving them the ability to bind or damage mechanisms and alter thermal properties. Reports documented clogged equipment and jammed mechanisms in every mission, regardless of surface duration, as well as clogged mechanisms in the Extravehicular Mobility Suit (EMS), including zippers, wrist and hose locks, faceplates, and sunshades [1-2]. Several astronauts remarked they could not have sustained surface activity much longer because clogged joints would have frozen up completely [2]. Effective dust mitigation strategies are needed to support longer duration stays on the lunar surface [3-4].

**State of the Art:** Technology for mechanisms able to operate in dusty enviroments is advancing rapidly due to the needs of both Mars rovers and the Artemis program. Vacuum-tight connectors are essential for spacesuits and habitats, and their performance can be dependent on cleaning technologies, which have proven difficult on the lunar surface. Several TRL 3-5 technologies are undergoing tests with the expectation to reach TRL 6 within 1-2 years. Some mechanisms will be infused and tested on the VIPER (Volatiles Investigating Polar Exploration Rover) mission planned for mid-2020s.

**NASA Funded Efforts:** NASA has recognized the need for dust tolerant mechanisms, and has partnered with industry to advance the state-of-the-art. At NASA GRC, KSC, and JSC, the Dust Tolerant Mechanisms Project is working to develop advanced actuator seals for rotary joints and rotary bearing technologies for long-term sustained operation in lunar dust environments. Another NASA project at NASA GRC, partnered with GSFC, JPL, and KSC is Motors for Dusty & Extreme Cold Environments (MDECE). MDECE is developing an unheated magnetically-geared motor that can operate continuously for a long duration at an ambient temperature of -243 ºC (33 K). NASA GRC has the capability to characterize the effects of dust on seals, mechanisms, and other mating surfaces and components under lunar conditions [5].

Through the SBIR/STTR program, NASA has funded several companies to advance dust tolerant mechanisms via the Dust Tolerant Mechanisms sub-topic with applications in surface mobility, spacesuits, connectors, joints, and more.

**LSIC and Community Efforts:** The Lunar Surface Innovation Consortium (LSIC) Dust Mitigation focus group has fostered collaborations across NASA, industry, and academia to develop solutions that minimizes the impact of lunar dust on robotic and human systems. Community efforts have included topical meetings on dust tolerant mechanisms, featured technology presentations, and feedback to NASA on potential gaps and needs.

**Testing:** In 2021, NASA released NASA-STD-1008 [6]. This NASA Technical Standard establishes minimum requirements and provides guidance for testing systems and hardware to be exposed to dust in planetary environments. The standard has specific sections dedicated to Mechanisms Testing (e.g. bearings, gears) as well as Seals and Mating Surfaces Testing (e.g. hatches, docking systems).

**Gaps and Needs:** NASA is tracking dust tolerant mechanisms as a gap in a cross-directorate analysis of capability areas needed to enable future human space-flight architectures. Two high-priority gap areas include additional facilities for testing mechanisms in lunar-surface conditions, and a better understanding of vulnerabilities to the smallest, nanometer-scale dust particles.

**Conclusion:** Understanding and mitigating lunar dust is critical to successful, sustained operations on the lunar surface – whether autonomous or otherwise. This presentation will discuss both the state-of-the-art and open needs in lunar dust tolerant mechanisms, technology impacts, mitigation approaches, testing, LSIC community efforts, and more.

**References:** [1] Gaier, J. R. (2020). The Impact of Dust on Lunar Surface Equipment During Apollo. Lunar Dust 2020. [2] GRC, & Gaier, J. R. (2005). The Effects of Lunar Dust on EVA Systems During the Apollo Missions. [3] Johansen, M. R. (2020). An Update on NASA’s Lunar Dust Mitigation Strategy. Lunar Dust 2020. [4] ASI, CSA, ESA, JAXA, & NASA. (2016). Dust Mitigation Gap Assessment Report. [5] Jimenez, N. et al (2022), LPSC Abstract 2572. [6] NASA-STD-1008, 2021.