Sole Morphing Astronaut Boots (SMAB) For Lunar Dust Mitigation. S. Lanctot[1], L. Figueroa[2], J. Cooke[1], B. Phipps[3], S. Trujillo[1], T. Bjorkman[1], E. Nunez[1], N. Badgett[1], J. Bertrand[1], C. O'Malley[4], and M. Hassanalian[4], [1]Undergraduate student, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA, [2]Undergraduate student, Department of Engineering, Sacramento City College, Sacramento, CA 95822, USA, [3]Graduate student, Department of Astronautical Engineering, University of Southern California, Los Angeles, CA 90007, USA, [4]Assistant Professor, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.

Introduction: Lunar dust was a significant challenge during the Apollo missions due to its strong adhesive and abrasive nature. The dust is known to erode through equipment and be tracked back into the cabin, breathed in by the astronauts, and with prolonged exposure, lead to long-term health consequences. In order to mitigate the amount of dust that adheres to the astronauts' suits and maintain the cleanliness of the lander and cabin, our team proposes a new design to the boots originally used in the Apollo missions.

Our over boot design, the Sole Morphing Astronaut Boots (SMAB), hopes to accomplish two primary goals. The first is to minimize surface area contact with the Moon's surface by elevating the astronaut on an extended cleat like design to reduce the amount of dust kicked off the ground.

The second goal will focus on improving the stability and enhancing the sense of foot feel for the astronauts. Tests will also include determining how a person with limited senses and motion, much like what the Apollo astronauts had to deal with, reacts to different surface conditions while wearing the boots, and testing the effectiveness of the SMAB prototype in comparison to previous lunar mission boots both in regards to dust kick-up and overall traction. A large part of our proposed verification testing will be the development of the piezoelectric-haptic-system. While the haptic system is already being researched for use in gloves of EVA suits of astronauts aboard the ISS, this concept has not yet been transferred to the boots of the astronauts to improve gait and balance.

Figure 1: CAD design of sole morphing astronaut overboot.

Surface Contact Layer: The SMAB's incorporates an adaptive design with replaceable studs to allow for maintenance and to reduce the general problem of "gouging" out dust from the lunar surface. The SMAB's incorporates an adaptive design with replaceable studs to allow for maintenance and to reduce the general problem of "gouging" out dust from the lunar surface. The Apollo boot had its fair share of issues in the dust. The dust is clingy and clogged up the treads of the boots. Astronauts commented on how slippery the boots would get, especially on the ladder. Furthermore, the abrasive nature of lunar regolith acting on a standard soled shoe was able to wear through the sole within a single day's worth of activity on the lunar surface.

A simple experiment utilizing different shoes found that by decreasing the amount of surface area, the shoe has contact with the ground and decreased the size and density of a dust cloud. This experiment focused on using the heel to kick fine dirt, easily found anywhere in New Mexico, and studying the splatter made by the shoe.

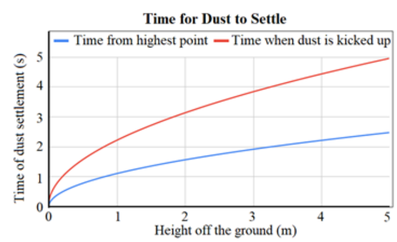

Figure 2: Comparison of time of dust settlement vs. height off the ground.

Sole Morphing Layer: The second layer of the SMAB overshoe accounts for a majority of the mechanical mechanisms. This layer provides the mechanism by which the studs may conform to the terrain and arranges them like a cleat in evenly distributed and strategically placed positions on the sole of the boot to provide stability, grip, and balance. Each stud has an integrated spring system called the shock-absorption mechanism (SAM) which is similar to a shock absorber found in an automobile. This mechanism is intended to make the studs both shock absorbent and surface conforming for two reasons. First, when landing with springs the impulse will be better absorbed by the springs rather than the dusty surface or the rigid astronauts, reducing dust clouds and aiding the astronauts with Moon walks. Second, while the astronauts are walking over the uneven lunar surface, littered with rocks and small craters, an adaptable and surface conforming contact arrangement is necessary to stabilize the astronauts as it will prevent an unstable single point of contact and instead allow

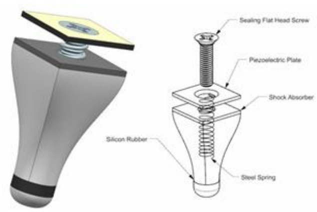

Figure 3: View of stud CAD modeling and components.

for a greater distribution of force.

Each shock-absorption mechanism is composed of a silicone rubber outer sheath that contains a springed based shock absorber to prevent unnecessary motion. This ensures that while the astronaut is walking the studs will not bend and only retract directly along the spring. A group of four studs will work in conjunction with the PHS-system and the force will be directly applied to a basal piezoelectric pressure sensor.

The sole of the shoe will contain thirteen studs located where the foot holds the most weight: the heel and balls of the feet (see Figure 4). A gap will be left at the front of the arch of the foot for ladder climbing. Additionally, the front studs will be angled slightly to help the astronauts start and break their loping gait, similar to how figure skates have a jagged edge at the front for breaking. The studs will be attached to a rigid but lightweight plate forming the structure which the astronauts will stand on. This plate is meant to give the boots rigidity and ensure nothing breaks through to the PAG Boot. Beneath this plate is a secondary layer that forms around the studs made out of a silicon rubber that is meant to morph to obstructions that fully compress the studs while still functioning in the low temperatures of the Moon. The silicon rubber provides additional insulation from hazardous charge builds-up due to the triboelectric effect.

Piezoelectric-Haptic-Sensory Layer:

The piezoelectric-haptic-sensory (PHS) layer, also known as the piezoelectric-haptic-sensory system, is the last layer of the boot and is the layer closest to the foot. It is also the first layer to incorporate electrical components. The boots use a proven piezoelectric technology that works as a sensor in conjunction with haptic feedback. The insole, located inside the SMAB, will contain four piezoelectric ceramic disks that are placed strategically in the posterior metatarsal, heel (hind foot), great ball and little ball of the foot, these are common pressure points of the human foot. These will be integrated in the sole morphing layer which will be triggered by the studs when adjusting to a surface. The electrical signals are proportional to the

Figure 4: The right shows the placement of the stubs on the foot. The left foot indicates the corresponding placements of the piezoelectric ceramic sensors.

pressure applied to the sensor meaning that the touch will be represented non-binarily, as in the astronauts will have a range of tactile information which allows them to know how hard they are stepping on something. The haptic sock consists of about six vibrational motors each housed in a memory foam padding. The memory foam padding has a gradient of small flat-headed aluminum pins across the posterior metatarsal, heel (hind foot), great ball and little ball of the foot. These aluminum pins, when vibrated by the motors, provide the user with simulated tactile sensory information for the user. These tactile sensations will send information directly to the central nervous system by stimulating the impulses of the nerves located on the foot such as the lateral plantar nerve, medial plantar nerve and the medial calcaneal branches. The heightened stimulation of the plantar nerves causes signals to be sent to the small muscles of the foot that constantly adjust to the various pressure differences sensed by our feet and adjust posture, balance, and overall prevent one from falling.

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