LUNAR AND PLANETARY EXCAVATION SYSTEMS: LESSONS LEARNED AT THE COLORADO SCHOOL OF MINES. P. J. van Susante [1] and C. B. Dreyer[2], [1]Center for Space Resources, Colorado School of Mines, 1310 Maple street, Golden, CO 80401; PH (720)-272-8892; email:paulvans@mines.edu, [2]Center for Space Resources, Colorado School of Mines, 1310 Maple street, Golden, CO 80401; PH (303)-273-3890; email: cdreyer@mines.edu.

Introduction: The feasibility of a sustainable and affordable solar system wide exploration program is improved by in situ resource utilization (ISRU). For ISRU to be successful a range of new technologies needs to be developed and improvements need to be made to existing technologies. The Colorado School of Mines (CSM) at the Center for Space Resources has been working for the past decade in developing techniques and prototype systems for lunar surface activities. This abstract discusses lessons learned from prototype development and experimental tests done at CSM.

Lunar Excavation Activities: Lunar surface activities may include a variety of excavation tasks depending on the mode of exploration. In an aggressive program of manned exploration there would likely be an initial robotic phase followed by a robotic lunar outpost construction phase, and finally a manned outpost construction and permanent human presence phase. Lunar surface equipment will have to be able to perform functions related to all these phases and work on several goals including in situ resource utilization, civil engineering and science activities. The robots will most likely be remotely controlled, or locally controlled by astronauts due to the short (several seconds) signal delay from the Earth to the Moon. In less aggressive manned exploration modes or purely robotic modes there still exists a need for ISRU and excavation systems. No matter the mode of exploration, additional research is needed in excavation systems.

Excavation Systems at CSM: The excavation systems developed at CSM have been built by several funded NASA projects and as senior design projects. All excavation systems at CSM are scaled for small robotic platforms (50-100 kg).

Figure 1: The CSM bucketwheel excavator.

The first systems were initiated by Michael B. Duke using a bucketwheel excavator [1], [2] (Fig. 1). Following this, most work shifted to bucket ladder designs [3], [4] (Fig. 2). A CSM bucketladder excavator was entered in the 2008 and 2009 NASA Centennial Challenge competition but was not successful in either bid due to control system issues. A CSM bucketladder excavator has been entered in the ESMD Lunar Regolith Excavation Competition which was held in May 2010 (Fig. 3).

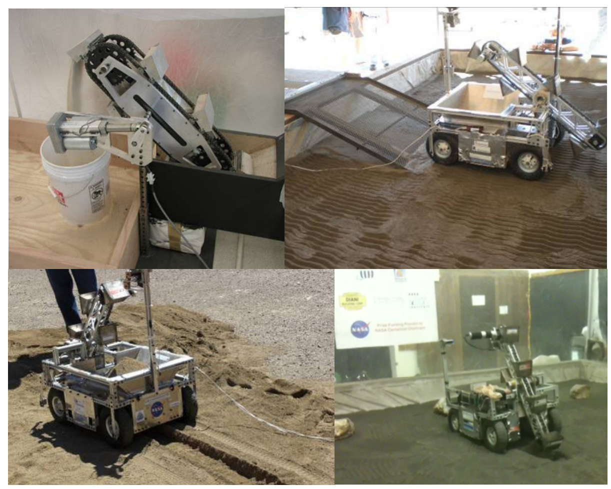

Figure 2: Bucketladder prototype and continuous feed setup to measure excavation rate and power use [3] (top left). CSM bucketladder NASA Centennial Challenge excavation rover [4] (top right, bottom).

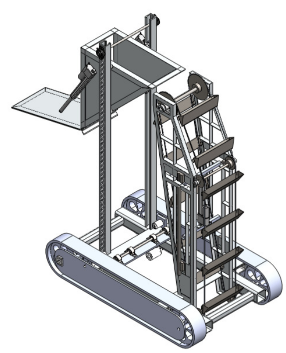

Figure 3: CSM ESMD Lunar Regolith Excavation Competition rover model.

The CSM excavation rover prototypes are relatively low mass (<80kg) and require relatively low power (150 Watts), yet can excavate at 1000-1500 kg/hr. The bucketladder has become the preferred

Figure 4: CSM Lunar Backhoe designs and Trommel Sorter which can be integrated with CSM Centennial Challenge Rover, bucket end effector (left), gripping claw end effector (center), Trommel Regolith Sorter.

method of regolith excavation at CSM as it combines low force excavation and material transport in the same unit. A bucketladder also can support small scale and large scale excavation requirements for science, civil engineering and ISRU operations.

More specialized excavation systems have also been developed at CSM (Fig. 4). The lunar backhoe is compatible with the CSM rover using a type of universal coupling and enables unique excavation possibilities. The trommel sorter is capable of sorting >2mm rock fragments from regolith (<8% of lunar regolith). Rock fragments are undesirable in gas production ISRU but may be useful for civil engineering tasks, and may have important scientific value.

Lessons Learned: The long history of CSM excavation systems enables us to derive several lessons learned. There are many lessons learned that are true of any engineering system, but we focus here on lessons that are unique to lunar excavation systems.

- Testing testing testing, of the whole system, every component and subsystem/assembly.
- Situational awareness of the excavator itself and its surroundings is crucial.
- Noise control in the electronics is very important in an ungrounded system. Perhaps more important with lunar dust due to tribo charging.
- A system integration approach is important, the earlier the better.
- Lots of thin cuts work well for fast excavation.
- Dumping regolith simulant works well with smooth steep sides.
- Wheels are vulnerable to losing traction; tracks are more reliable and versatile.
- It is very difficult to design a high production, low power, robust, working excavator.

Conclusions: The nearly decade long history of excavation system development at the Colorado School of Mines has led to a variety of hardware systems being built. A bucketwheel, two bucketladders and a backhoe system are operational and have been tested using a variety of sands and lunar simulants. Separate material transportation devices have also been developed including augers, inverse augers and a trommel. The power required to operate these robot mobile excavation systems is in the order of 100-200 Watt and they can excavate between 50-1500 kg/hr for a variety of purposes. More field testing is planned to better understand and address the needs of ISRU, civil engineering and science operations.

References: [1] Muff, T., M.S. Thesis, Colorado School of Mines, 2003. [2] Johnson, L.L., M.S. Thesis, Colorado School of Mines, 2005. [3] Johnson, L.L. and van Susante, P. J, SRR VIII, Golden, 2006. [4] van Susante, P. et al., 2009 Southeast Region Space Grant Meeting, Puerto Rico, Jan. 2009.