A Review of Lunar Regolith Excavation Robotic Device Prototypes

Robert P. Mueller[1]
Surface Systems Office , M/S: NE-S, National Aeronautics & Space Administration (NASA), John F. Kennedy Space Center, Florida 32899, USA

Paul J. Van Susante[2]
Colorado School of Mines, Division of Engineering, Golden, Colorado 8040, USA

The excavation of lunar regolith is desirable for use as a feedstock for oxygen production processes as well as civil engineering purposes and for the fabrication of parts and structures. This is known as In-Situ Resource Utilization (ISRU). More recently, there has been mounting evidence that water ice exists at the poles of the Moon, buried in the regolith where thermally stable conditions exist. This means that regolith excavation will be required to mine the water ice which is believed to be mixed in with the regolith, or bonded to it. The mined water ice can then be electrolyzed to produce hydrogen and oxygen propellants which could form the basis of a cis-lunar transportation system using in-situ derived propellants.

In 2007, the National Aeronautics & Space Administration (NASA) sponsored a Lunar Regolith Excavation Competition as part of its Centennial Challenges program. The competition was not won and it was held again in 2008 and 2009, when it was won by a university team. A $500,000 prize was awarded to the winning team by NASA.

In 2010, NASA continued the competition as a spinoff of the Centennial Challenges, which is restricted to university participation only. This competition is known as the "Lunabotics Mining Competition" and is hosted by NASA at Kennedy Space Center. Twenty three American university teams competed in the 2010 Lunabotics Mining Competition. The competition was held again in May 2011 with over 60 teams registered, including international participation. The competition will be held again in May 2012 at Kennedy Space Center in Florida.

This paper contains a thorough review of the various regolith excavation robotic device prototypes that competed in these NASA competitions, and will classify the machines and their methods of excavation to document the variety of ideas that were spawned and built to compete at these events. It is hoped that documentation of these robots will serve to help future robotic excavation designers and provide a historical reference for future lunar mining machine endeavors.

[1] Chief, Surface Systems Office, M/S: NE-S, AIAA Senior Member
[2] Adjunct Professor, Division of Engineering

I. Introduction

IN 2005 the United States of America congress funded a program of contests to stimulate innovation and competition in technical areas of interest to NASA. This program consists of the NASA Centennial Challenges, a collection of public contests designed to stimulate technological innovation in areas that benefit space exploration. The intent was to build on historic and current prize experience. As early as the 18th century, the British government offered the Longitude Prize, a competition for a navigational solution to the accurate determination of longitude on the high seas. At the time the prize was set, it was assumed that the solution laid in using star maps as navigational aides and that the winner would be an astronomer. The solution was actually achieved by a London clockmaker and his invention, the marine chronometer [Steidel, 2004]. Another historic prize was the $25,000 Orteig Prize which was offered in 1919 by a prominent New York businessman, Raymond Orteig, for the first non-stop flight from New York to Paris. It was won in May, 1927 by Charles Lindbergh and is widely credited with stimulating public interest in commercial passenger flights and bolstered confidence in airplane safety. More recently the Ansari X PRIZE was a space competition in which the X PRIZE Foundation offered a US$10,000,000 prize for the first non-government organization to launch a reusable manned spacecraft into space twice within two weeks. The prize was won on October 4, 2004, the 47th anniversary of the Sputnik 1 launch, by a project designed by Burt Rutan and financed by Microsoft co-founder Paul Allen, using the experimental spaceplane SpaceShipOne. $10 million was awarded to the winner, but more than $100 million was invested in new technologies in pursuit of the prize.

II. NASA Centennial Challenges: Regolith Excavation

Prize competitions have been used throughout history to accelerate the development of many different technologies. The desire for new or better technologies have often come from unmet needs in various sectors of society, including commerce, industry, military, public safety, public health, and adventure/tourism.

The history of successful prize competitions has shown the potential for break-through developments and the accomplishment of feats thought to be "impossible." In most cases, the detrimental effects are negligible for a competition when the prize is not won, because there was little cost and no resulting purse payment.

Although the U.S. government has a long history of awarding medals to individuals of merit (a.k.a. 'recognition prizes'), it has only recently begun experimenting with inducement prizes to spur technology developments in selected areas. Centennial Challenges is a program recently initiated at the National Aeronautics and Space Administration. In the case of NASA contracts and grants, the government will pay 100% of the cost proposed by the contract winner. In some cases, the government will pay more than 100% of the contract cost due to any number of factors or circumstances. In the case of prizes, the prize purse is generally some fraction of what a contract would be worth to achieve the same results. Also, the government only makes a payment after somebody wins the competition by meeting all requirements as described in the rules. [Davidian, 2005]

A. Regolith Excavation Challenge: 2007

The first NASA competition related to excavating lunar regolith simulant was organized by the California Space Education and Workforce Institute (CSEWI) and the California Space Authority (CSA) as partner organizations to NASA (Everingham, 2008). This event was held in Santa Maria, California from May 11-12, 2007, with a prize of $250,000 offered to the competitor that excavated the most simulated lunar regolith and deposited it in a collection box. The lunar regolith simulant used was 8 tons of JSC-1a, which is widely used for NASA lunar research activities. In this challenge, teams designed and built robotic machines to excavate simulated lunar soil (regolith). Excavating regolith will be an important part of any construction projects or processing of natural resources on the Moon (Mueller, 2007). The robots were tested in a box containing eight tons of simulated lunar regolith that is about 4 meters square and about one-half meter deep. In order to qualify for a prize, a robot had to dig up and then dump at least 150 kg of regolith into a container in 30 minutes. The teams with the robots that moved the most regolith could claim the three cash prizes. NASA is looking for new ideas for excavation techniques that do not require excessively heavy machines or large amounts of power. The competition required autonomous robots with a simulated wireless signal time delay of several seconds simulating lunar communications. There were four teams of engineers competing to be the first to build a robot capable of collecting at least 150 kg of lunar soil in less than 30 minutes. Machines also could use only 30 watts of power , which was provided by a "house" tether and had to weigh less than 40 kg as they excavated the simulated lunar regolith defeated the competitors. Two other teams dropped out before even landing at the competition (Santa Maria Times, 2007). Three of the four teams had excavators that

shut down due to mechanical or electrical challenges from digging. The "Technology Ranch" team, however, was the exception drawing 65.25
kilograms within the half hour requirement—a clear accomplishment but still far below the 150 kilograms needed to win.

Teams from Rancho Palos Verdes, Calif., Livermore, Calif., Berkeley, Calif., Fulks Run, Va., Rolla, Mo., Berkley, Mich., Milwaukee, and Vancouver, British Columbia, have registered to participate in the challenge. The teams that actually competed were:

- Technology Ranch, Pismo Beach – 65.25 kg
- The Lunar Miners, University of Missouri-Rolla -Broke down while digging.
- Duplex Engineering, Michigan, Geoffrey Pulk - Broke down while digging.
- Todd Mendenhall, Mendenhall BFD excavator - Broke down while digging.

B. Regolith Excavation Challenge: 2008

The 2008 Regolith Excavation Challenge was held on Aug. 2 and 3 on the campus of the California Polytechnic State University in San Luis Obispo, CA. The 2008 prize purse was $750,000, and the rules were not changed significantly from 2007, but mass allowed was increased to 70 kg and the available tethered power was increased to 150 watts. In addition a 20 degree inclination (from horizontal) ramp was provided to all the teams. Twenty-five teams registered for the competition. Sixteen teams came to San Luis Obispo, at the Cal Poly Campus, to compete and although no team was able to win the prize, the competition was very spirited. The challenge was significantly more difficult than the 2007 event. To autonomously navigate through randomly placed rocks and to reach a collection box at the top of a ramp proved to be a taxing technical challenge for all of the entrants. The task required expert integration of multiple systems and thorough testing of complex operational scenarios. Following the competition phase of the event, many of the teams did demonstrate their excavators under less demanding conditions and some were able to deliver loads of regolith to the collection box. No cash prizes were awarded but the judges selected three teams for recognition. Tech Ranch, Slobotics, and Team Waldbaum were designated for first, second and third prize, respectively. The competitors included several universities, small businesses and a few individuals. NASA engineers from six different field centers plus Headquarters witnessed the event. During a break, Astronaut Jim Newman addressed the assembled competitors and spectators.type (NASA, 2008). Eight teams actually put their inventions to the test during the competition at Cal Poly, but none met the challenge of digging 150 Kg of simulated moon dirt, called regolith, putting it into a collector and completing the task within 30 minutes. In total 25 teams registered for the event, but only 16 traveled to the Central Coast. Half of those ended up dropping out due to mechanical or logistical problems. Two teams from San Luis Obispo County competed along with others from elsewhere in California, Texas, Washington, Colorado and Michigan (Santa Maria Times, 2008). The final teams to compete were:

- Waldbaum, Sunnyvale, CA
- Next Step, Houston, TX
- Tech Ranch, Arroyo Grande, CA
- LuneOreDiggers, Denver, CO
- Cal Poly Slobotics, San Luis Obispo, CA
- Team of One, Detroit, MI
- Toy Garden, Friday Harbor, WA
- Boppers, Huntington Beach, CA

C. Regolith Excavation Challenge 2009

For the 2009 challenge, two significant changes were made to the rules. First, teams were allowed to teleoperate their robots instead of requiring them to be fully autonomous as in previous years. The team's drivers were isolated in a room separate from the robot and field and had to control their robot through a competition-provided two-second delay on the sending and receiving of commands. This was designed to simulate delayed communication to the moon. Teams were limited to 1000 kbs communication bandwidth averaged over their 30-minute run. Second, competitors were required to provide their own onboard power. In previous competitions, robots were tethered to a competition power source that limited them to 30 watts in 2007 and 150 watts in 2008. To account for the onboard power requirement, the weight limit was increased from 70 kg to 80 kg. Optional ramps were allowed but had to be provided by the teams.

Twenty-three teams registered for the challenge and traveled from across the country to compete. Of the 23 teams, only 19 competed, one was disqualified as a result of specification violations and the rest withdrew on their own due to last-minute mechanical or logistical problems. These teams pushed their robotic competitors to the limit and three teams claimed a total of $750,000 in NASA prizes for their hard work and innovation at this year's Regolith Excavation Challenge held at NASA's Ames Research Center on Moffett Field. After two days of intense competitive drama, organizers conferred Paul's Robotics of Worcester, MA, with the first place title, second went to Terra Engineering of Gardena, CA, and Team Braundo of Rancho Palos Verde, CA, took home third. This was the first time in the competition's three-year history that any teams qualified for a cash prize, the largest NASA had ever given at that time.

The winning excavator lifted 437 kg of regolith material in the allotted time. Runners up excavated 270 kg and 263 kg, respectively. Special mention was given to Team E-REX and Eric Jones of Little Rock, AR for transferring the most regolith, 75 kg, in a single deposit of simulated lunar substance into the official collector bin. Competitors were required to use mobile, robotic digging machines capable of excavating up to at least 150 kg of regolith and depositing it into a container in 30 minutes or less. The rules require the remote controlled vehicles to contain their own power sources and weigh no more than 80 kg (CSEWI, 2009).

III. NASA Lunabotics Mining Competition

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations.

The competition is conducted by NASA at the Kennedy Space Center Visitor Complex. The teams that can use telerobotic or autonomous operation to excavate lunar regolith simulant, called Black Point-1 or BP-1, and score the most points wins the Joe Kosmo Award for Excellence. The team will receive the Joe Kosmo Award for Excellence trophy, KSC launch invitations, team certificates for each member, a $5,000 team scholarship, and up to $1,000 travel expenses for each team member and one faculty advisor to participate at one of NASA's remote research and technology tests. Awards for other categories include monetary team scholarships, a school trophy or plaque, team and individual certificates, and KSC launch invitations.

Undergraduate and graduate student teams enrolled in a U.S. or international college or university are eligible to enter NASA's Lunabotics Mining Competition. Design teams must include: at least one faculty with a college or university and at least two undergraduate or graduate students. NASA has not set an upper limit on team members. A team should have a sufficient number of members to successfully operate their Lunabot. Teams will compete in up to five major competition categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, teams can earn bonus points for mined and deposited BP-1 in the competition attempts, having multidisciplinary teams, and collaborating between a majority institution and a U.S. minority serving institution. All documents must be submitted in English (NASA, 2011).

For more information, visit NASA's Lunabotics Mining Competition on the Web at www.nasa.gov/Lunabotics; on Facebook at www.facebook.com/Lunabotics; on YouTube at http://www.youtube.com/user/Lunabotics; and follow Lunabotics on Twitter at http://twitter.com/#!/Lunabotics

D. Lunabotics Mining Competition: 2010

The Lunabotics Mining Competition (LMC) was held on May 27 & 28, 2010 at the U.S. Astronaut Hall of Fame near Kennedy Space Center, FL. Twenty-two teams competed for the grand prize of winning the Joe Kosmo Award for Excellence. A total of 181 students participated in the competition, but only USA University teams were allowed to enter in 2010.

The excavation robot was designated a "Lunabot" and the mass limit was 80 Kg. An allowable average data rate of 5 Mb/s over 15 minutes of competition time was required. Each team was required to dig at least 10 kg of regolith simulant to qualify for the on-site mining prize attempt. The excavation hardware was required to be contained within 1.5m width x .75m length x 2m height. The hardware could deploy beyond the 1.5 m x .75 m footprint after the start of the competition attempt, but was not allowed to exceed a 2 meter height. There was no communications signal time delay and the lunabot was tele-operated from a remote control center where the operators could only see the arena through onboard or one facility camera.

The following 22 University teams competed:

Table 1: Lunabotics 2010 Competitors

University	Team Name
University of Akron	PiRATE (Piloted Robotic All-Terrain Excavator)
University of Alabama	Roll Tide Robots
University of Arkansas	Razorvators
Auburn University	Team Pumpernickel
University of Bridgeport	UB Excavator
Carnegie Mellon University/ Hampton University	Moon Rediggers
Colorado School of Mines	Colorado School of Mines Lunabotics
Embry Riddle Aeronautical University – Daytona Campus	TEAM AETHER
Florida Institute of Technology	The Invading Huns
Florida State University/ Florida A & M University	The ARTEMIS Project
Iowa State University	Team LunaCY
John Brown University	Eagles
Milwaukee School of Engineering	Luna Baggers
Montana State University	Montana M.U.L.E.
University of North Carolina-Charlotte	UNC Charlotte NASA Robotics Team
University of North Dakota School of Engineering & Mines	Team Raptor
Prairie View A & M University	X-CAVATOR
South Dakota School of Mines and Technology	SDSMT Moonrockers
University of Southern Indiana	iDigU
Temple University	Temple Robotics
Virginia Tech	Virginia Tech Lunabotics
Western Kentucky University	A.R.T.E.M.I.S.

The following teams were awarded prizes:

Table 2: Lunabotics 2010 Prizes

Category	University	Prizes
Lunabotics Mining in the Lunarena	Montana State University	1st Place $5,000 and VIP launch invitations
	Auburn University	1st Place Honorable Mention $2,500 and VIP launch invitations
	University of Southern Indiana	2nd Place Honorable Mention $1,000 and VIP launch invitations
Systems Engineering Paper	Auburn University	$500
Outreach to Informal Education or K-12 Education	Embry Riddle Aeronautical University – Daytona Campus	$500
Slide Presentation	Western Kentucky University	$500
Team Spirit Competition	University of Southern Indiana	$500
Joe Kosmo Award for Excellence	Montana State University	Trophy, KSC VIP launch invitations, and up to $1,500 travel for each team member & advisor to attend NASA Desert RATS

1st place in the "On-Site Mining" category with a total mass of 21.6 kg, was awarded to Montana MULE from Montana State University – Bozeman. Since there were no other teams that excavated the required minimum of 10 kg, the judges decided to award honorable mentions to the following teams. The 1st and 2nd place honorable mentions received the prize money and VIP launch invitations.

Honorable Mentions:
1st place with a total mass of 6.6 kg, was awarded to Team Pumpernickle from Auburn University
2nd place with a total mass of 2.4 kg, was awarded iDigU from University of Southern Indiana
3rd place with a total mass of 2.2 kg, was awarded to Moonrockers from South Dakota School of Mines and Technology
4th place with a total mass of 0.8 kg, was awarded to Luna Baggers from Milwaukee School of Engineering
5th place with a total mass of 0.6 kg, was awarded to PiRATE from the University of Akron

E. Lunabotics Mining Competition: 2011
In 2011, the rules were unchanged except that international participation was allowed. This created a burst of additional interest with 62 universities registering and 36 actually competing at Kennedy Space Center. Of these 14 teams were able to excavate regolith and dump it in the collection bin. There were 36 teams from 23 states and 4 foreign countries (India, Bangladesh, Colombia and Canada) represented.

The 2011 "On-site Mining " category results were:

Table 3: Lunabotics 2011 "On-Site Mining" Results

1) Laurentian University	237.4 kg
2) University of North Dakota	172.2 kg
3) West Virginia University	106.4 kg
4) Embry Riddle U. – Prescott	85.4 kg
5) Auburn University	80.0 kg
6) Virginia Tech	79.0 kg
7) Colorado School of Mines	72.0 kg
8) University of Alabama	63.2 kg
9) John Brown	50.0 kg
10) Southern Indiana	37.6 kg
11) South Dakota School of Mines	34.0 kg
12) Temple University	33.6 kg
13) University of Akron	32.0 kg

Other teams were not able to excavate more than 10 kg of regolith simulant.

The 2011 Winners by Category were:

The Joe Kosmo Award for Excellence (to the school with the best overall results from all categories): *North Dakota University*

On Site Regolith Collection Award Winners
1st Place - *Laurentian University,* Ontario, Canada - 237.4 kilograms
2nd Place - *North Dakota University* - 172.2 kilograms
3rd Place - *West Virginia University* - 106.4 kilogram

Judges Innovation Design Award to *Embry Riddle Aeronautical University, Prescott, Arizona Campus*

Communications Efficiency Award to *Laurentian University*

Team Spirit Award - University of Alabama Honorable Mention - *North Dakota University, Embry Riddle Daytona Campus & West Virginia University*

Slide Presentation Award - *Embry Riddle Daytona*

Outreach Project Award - *Montana School of Mines*

Systems Engineering Paper Award- *John Brown University, Arkansas*

F. Lunabotics Mining Competition: 2012

In 2010/2011 Lunabotics Mining Competition rules & specifications were based on Constellation program requirements. NASA has revised the rules for 2012 to reflect new NASA requirements. In addition, last year's winner would have placed 14th in 2011, also necessitating changes to make the competition more challenging.

IV. Classification of Regolith Excavation Prototypes

All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and two Lunabotics Mining Competitions (2010 and 2011) can be grouped in several categories. Categories can be distinguished for several subsystems including regolith excavation mechanisms, regolith transfer mechanisms, regolith storage mechanisms, regolith dumping mechanisms, robot mobility mechanism.

A. Regolith Excavation Mechanisms

In the competitions, the many robots can be subdivided in approximately 15 types. Bucket ladder type excavation mechanisms were by far the most common type used. This type consists of chains (most commonly two, but in some cases one or four were used) with excavation buckets attached to the chains that rotate at high speed and thus digging the regolith simulant one small bite at a time. This approach requires relatively little power, results in relatively low excavation forces and has a high excavation capacity. All winners of the competitions can be classified as bucket ladders. Bucket belts, bulldozers and scrapers were the next most common types, followed by other less commonly used mechanisms. Table 4 shows all classifications used.

Table 4: Identification of types of regolith excavation mechanisms

Regolith Excavation Mechanism	# of machines employing excavation mechanism
Bucket ladder (two chains)	29
Bucket belt	10
Bulldozer	10
Scraper	8
Auger plus conveyor belt / impeller	4
Backhoe	4
Bucket ladder (one chain)	4
Bucket wheel	4
Bucket drum	3
Claw / gripper scoop	2
Drums with metal plates (street sweeper)	2
Bucket ladder (four chains)	1
Magnetic wheels with scraper	1
Rotating tube entrance	1
Vertical auger	1

B. Regolith Transfer Mechanisms

Several regolith transfer mechanisms can be identified. Some excavation mechanisms are required to use a separate system to transfer regolith once it is excavated, others combine the excavation and transfer mechanism in one. The bucket ladder excavation mechanism combines the functions of excavation and material transfer in one device and does not require a separate mechanism. The second most popular transfer mechanism is a conveyor belt followed by less popular methods of material transfer. Table 5 lists the identified transfer mechanisms that were used during the competitions.

Table 5: Identification of types of regolith transfer mechanisms

Regolith Transfer Mechanism	# of machines employing transfer mechanism
Bucket ladder	34
Conveyor belt	13
Impeller	3
Raising scraper with chute	3
Bucket belt	2
Bucket chain	2
Raising whole robot or main body	2
Auger	1
Catch bin with auger	1
Rotating tube (auger like)	1

C. Regolith Storage Mechanism

Very few different varieties of regolith storage mechanisms were used. To minimize trips back and forth to the collection bin and to save time, the robots used a storage bin or hopper to store the excavated regolith simulant. The hopper could store many scoops of regolith so that maximum time could be spent excavating and as much regolith simulant as possible could be stored and deposited each trip. This led to the hopper being the most popular storage mechanism. The second most popular storage mechanism was the excavation scoop itself because some teams chose to use one large scoop to take one large scoop of regolith and then traverse back to dump so that those robots did not need a separate storage system. Table 6 shows the different options used.

Table 6: Identification of types of regolith storage mechanisms

Regolith Storage Mechanism	# of machines employing storage mechanism
Hopper	56
Scoop	14
Scraper	3
Backhoe scoop	1
Bucket drum	1
Bulldozer	1
Inside tube body	1

D. Regolith Dumping Mechanism

The dumping mechanisms showed many varieties which can be seen in table 7. Since the hopper was by far the most popular storage mechanism, most teams chose to raise and tilt the hopper to empty it. However, since many teams had stationary hoppers, they needed to develop a system to empty the hopper. Some teams stored the material high which lead to top-heavy robot designs and then used a chute or conveyor belt at the bottom of the hopper to dump the material. Others chose a mechanism to excavate the regolith stored in the hopper and transport it to the dumping point, effectively excavating the material twice.

Table 7: Identification of types of regolith dumping mechanisms

Regolith Dumping Mechanism	# of machines employing dumping mechanism
32 raising / tilting hopper	32
Tilting / raising scoop	9
Conveyor belt (with attachments)	8
Chute	5
Raising hopper with back chute	5
Bucket ladder	3
Ramp plus rotating valve bottom	3
Angled auger	2
Angled vibrating hopper (stationary)	2
Cable pulling up bottom of hopper	2
Horizontal belt / back opens	2
Separate lifting ramp/storage bin	2
Tilting / raising scoop with overhead dump	2
Raising whole robot on second robot, then tilting hopper with chute	2
Swivel of backhoe arm, rotating scoop	2
Raising bucket drum, counter rotate	1
Rotating scoop (overhead)	1
Clamshell scoop opening	1

E. Robot Mobility Method

One of the most crucial systems for a robot is its mobility method. Without mobility the robot cannot traverse the obstacle zone (containing two craters and three rocks for Lunabotics, or just rocks for the Centennial Challenge) into the excavation zone and back to the dumping zone. Many different shapes, sizes, materials were used for the systems listed in table 8, even within a category. Some wheel based systems worked great while others dug themselves in and got stuck. Wheeled systems were in the majority and only one of the winners used tracks. However, tracked vehicles overall had better mobility than wheeled vehicles of which the majority had problems.

Table 8: Identification of types of regolith dumping mechanisms

Robot Mobility Method	# of machines employing mobility method
Two tracks	26
Four fixed wheels	24
Four fixed wheels with grousers	12
Stationary with swivel	5
Four individually steerable wheels	4
Four fixed wheels with super profile	2
Six fixed wheels	2
Four individual steerable tracks	1
Four steerable wheels with grousers	1
Four wheels with grousers and suspension	1
Six fixed wheels with grousers	1
Stationary	1
Three wheels (one steerable)	1
Two tracks and two wheels (half track)	1
Two very wide tracks	1
Four fixed tracks	1

F. Robot Control Software

Two approaches could be distinguished between teams for the control software. Some teams chose to program their micro-controllers directly but more and more teams chose to program in higher level programs such as National Instruments LabView. This is partly due to the experience team members have from FIRST robotics. Both methods work, however, with the standards used for the communications and the drivers available for other subsystems it is faster (but more expensive) to get a robust control system when using LabView or similar commercially available systems.

G. Wireless Data Communication

Most robots used on on-board wireless hub to connect web cameras for visuals and to communicate with the control system. During the last Lunabotics competition it was decided to allow contestants to bring their own wireless router and thus minimize communication system issues when interfacing with the NASA provided secure network that caused problems during the previous competitions. It also allowed for testing at the university in the actual configuration used during the competition using industry standard wifi equipment.

V. Lunar Operations Feasibility, Problems Encountered and Lessons Learned

None of the robots competing in the competitions would be considered space ready hardware. The robots were designed to meet the competition goals and conditions which required the use of only physical principles that would be possible on the lunar surface. Many of the robots would not survive the vibration and loading conditions during launch towards the moon and hence would not be operational when arriving. Some of the robots could be adapted by using space qualified hardware in their design and would be robust enough to survive the launch conditions and space requirements, but those were far and few between. The teams learned a tremendous amount and returning teams showed enormous improvement. Some lessons learned from a participant's perspective can be found in van Susante and Dreyer (2010).

H. Regolith Excavation Challenge: 2007

The first competition was a learning experience for everyone including organizers. The observations include that teams were not well prepared because machines were not robust and broke down. This was partially due to not knowing how to operate in JSC-1A which was caused by that simulant not being available (and affordable) for teams to test their robots with. Teams that tested with other substances such as play sand or cement learned that those materials behaved very differently than JSC-1A did. The low power (30 Watt) and required autonomy proved very challenging leading to all designs being stationary designs and using anchoring methods. In addition, many machines were too spindly and structurally unstable which contributed to their failure because most teams under estimated the excavation forces required.

I. Regolith Excavation Challenge: 2008

The second competition had many more promising designs but due to a random draw of starting position and orientation all robots had to start in a corner of the competition sand box. This starting position meant there were two walls (one in front and one to the side) and the ramp forming the three sides with the fourth side of the starting square being formed by a rock. The orientation of the robot pointed the front to one of the walls and the rock was to the back of the rover. This made autonomy extremely challenging and only two teams were able to move out of the corner but got stuck before being able to dump any JSC-1A in the box. Many of the structures and systems designed to function as beacons and help the robot orient itself with regards to the box were dubious in quality and robustness. None of the teams managed to dump any regolith. Demo's were run afterwards, mostly tele-robotically, and some had good results dumping significant amounts of regolith. Two bucket ladders and a bucket wheel performed well during the demo runs.

J. Regolith Excavation Challenge 2009

The third and last Centennial Excavation Challenge was dominated by bucket ladders but also saw some very exotic designs such as one with magnetic wheels designed to pick up the regolith containing iron. First and second place were bucket ladders and the third was a bucket wheel. Most machines in this competition were very tall and had a high center of gravity. All competitors were focusing on gathering maximum amounts of regolith because there were no other judging criteria. Most of the robots generated copious amounts of dust when excavating leading to extremely poor visibility and a breathing hazard for people in the enclosure. One solution was to put brightly colored LED lights on the robot so the position of the robot was still clear despite the poor visibility and contrast.

All machines were tele-operated where the operators were isolated visually and auditory from the arena. The built-in time delay caused some teams problem in their control. In addition there were many communication problems because teams had not been able to test with the required use of the provided NASA network. Some teams lost video for instance but could still control their robot.

K. Lunabotics Mining Competition: 2010

Only a few university teams (including the 2009 winner) participated in the Centennial Excavation Challenges but the Lunabotics Mining Competition was open ONLY to university teams. That meant a lot of fresh teams who had never participated before. This lead to many mechanical failures (some spectacularly breaking in half or burning out a drive motor with flames coming out of it). Also there were many communication issues and many hours were spent in fixing the operation and compatibility with the required use of the provided secure WiFi NASA network. Many teams were not ready to compete and had no time to test their robots thoroughly. Integration of the subsystems to create a fully functional robot was a challenge and many teams had to work through the night to fix things. Some only got things running for the first time ever just before the competition. The majority of the teams had no access to lunar simulants and thus were surprised by the behavior of it in the box when trying to excavate it. This included the natural presence of small rocks that caused some systems to jam.

L. Lunabotics Mining Competition: 2011

The second Lunabotics competition showed a very strong field of teams with many now being veterans. 62 teams registered and 36 made it to the Kennedy Space Center Visitor Center. Out of the 36 teams, 14 managed to deposit BP-1 simulant in the collection bin. All teams showed great improvement from 2010. This year was the first year that international participation was possible. The international teams provided some very innovative ideas but some showed great similarity with the big spindly designs of earlier competitions. Due to the travel requirements they had to design their robot to fit in several suitcases which also meant that a lot of their time was spent in putting the robots together instead of testing. The level of the competition was much higher than in 2010 which can be seen from the fact that the 2010 winner would be placed 14th in 2011. One of the important facts is that transfer of lessons learned from one year to the next greatly improves next years' teams performance.

VI. Good Practices for Lunabotics Mining Robot Design

One of the goals of the Lunabotics competition is to create designs and prototypes of Lunabot excavation machines that could plausibly function on the moon if developed further with space qualified components and other enhancements such as thermal control systems. Since the first step in deploying to the moon is to launch on a rocket which experiences up to 5 G's of acceleration vertically, these lunabots must be compact and strong enough to withstand the launch loads and constrained shroud volume. Then the lunabot must deploy to the lunar surface and unpackage itself, leading to further challenges. At this point the lunabot can start mining regolith and delivering it to the lunar end user. To successfully execute these critical events, good design and operations practices must be used. The alternative is to have a mission fail at a great cost and embarrassment.

M. Lunabot Inspections

All Lunabots will be inspected to ensure safe operations and compliance with the rules. An emergency stop button must be present so that judges can disable the lunabot in the event of a fire or other mis-hap.

The mass and stowed dimensions will also be verified. A communications check will be performed to ensure that the rules are being met and that there is no radio frequency interference with other communications systems in the area. All teams are advised to be prepared for these checks by doing an internal audit before arriving at the competition. This will expedite the inspections and will avoid unnecessary disqualification.

N. Regolith Simulants & Mining

The regolith simulant used in Lunabotics is a geotechnical bulk simulant that has a particle size distribution very similar to actual lunar regolith as measured from Apollo Mare samples, and it is made of crushed basalt from the Black Point lave flow in Arizona which is very similar to the lunar mare mineralogy. Black Point-1 (BP-1) – A crushed lava aggregate with a natural particle size distribution similar to that of lunar soil. The aggregate will have a particle size and distribution similar to the lunar regolith as stated in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. Teams are encouraged to develop or procure simulants based on lunar type of minerals and lunar regolith particle size, shape, and distribution.

Many teams have used sand and other commonly available granular materials only to find that the cohesive behavior of BP-1 is completely different when compacted to the correct bulk density as found on the moon. Teams are advised to use granular materials that are cohesive, or can be compacted or altered (e.g. wet sand) to make it more cohesive.

O. Wireless Communications Bandwidth

Space Exploration does not always afford a high bandwidth capability- so the lunabot should attempt to minimize the bandwidth used at all times. Using sub- routines that reside on board may mitigate high communications rates and using just the house camera is another way to reduce communications data rate needs.

All communications devices should be thoroughly tested at the University prior to competing, since previous competitions indicate that this is an area which has high potential for creating problems for the lunabot operation.

P. Lunabot Mass

Since launch costs vary between $4,000 to $10,000 per pound to Low Earth Orbit, and more to transport it to the Moon (as high as $100,000 per pound) it is highly desirable to minimize the mass of the Lunabot. This creates difficulties since a low mass in 1/6 th G means that there will be a very low reaction force to counteract the digging forces. This means that ingenuity and clever design will have to be employed to keep the lunabot both light and effective for excavation. Innovative uses of lightweight materials, efficient structural design and packaging will help to minimize mass.

Q. Energy Consumed by the Lunabot

Since energy must be stored on board the robot, the mass and complexity of the energy storage device will drastically affect the lunabot mass and operations ability. If batteries are used then capacity and re-charging time will play a major role in the capability of the lunabot. For this reason it is required to minimize the energy consumed by the lunabot. Each team is asked to devise a way to measure the energy consumed by the lunabot during the competition run, so that awareness of this critical variable will be a part of the lunabot design and operation.

R. Dust Tolerant Design and Minimum Dust During Operations

Many lunar excavation robot designs have been generated and built in the last five years for the sole purpose of winning a competition based on maximizing regolith excavated in a set time period. However, on the moon, many of these machines would break down after a short period of operating time, because the sharp, electrostatically charged, abrasive dust will intrude and clog mechanisms and moving parts if they are exposed and not sealed. In order to be most lunar like all teams should strive to protect all mechanisms, joints, sensors and other vulnerable sub systems from dust intrusion and damage.

S. Autonomy while Driving through the Obstacle Area

Autonomy is difficult and relies on sophisticated sensor perception systems and on board real time data processing. A partial level of autonomy is an option, where the lunabot can be made semi-autonomous. In this mode it just navigates the obstacle area autonomously and the rest of the time it is tele-operated.

T. Fully Autonomous Lunabot

A fully autonomous robot will be very useful for areas and planets where line of sight communications or communications delays make it impossible to directly tele-operate the robot. If a lunabot has full autonomy, then this demonstrates a mastery of robotics technology and will be highly rewarded in the competition. No tele-operation is allowed in this mode, and it is highly advised to do extensive check out testing prior to the competition. A tele-operated back-up mode is also a good way to recover from potential failures during the competition.

VII. Conclusion

Various competitions during the last five years have demonstrated that STEM inspiration is possible and successful with lunar regolith excavation competitions. Students are drawn to the real nature of the task, and industrial partners have expressed a high degree of interest in employing engineers with the mechatronic skills needed to build a lunabot system.

The future is bright for these types of competitions and the Lunabotics Mining Competition is planned to be held annually to meet this demand for exciting challenges, that result in superior engineering solutions and personal growth. NASA and the nation will benefit by having a better workforce and a plethora of clever ideas to investigate for future space exploration missions.

Appendix

This appendix contains an example of the scoring matrix used for the Lunabotics Mining Competition "On-Sit Mining" category. The full set of rules for the NASA 2012 Lunabotics Mining Competition. Regular updates will be documented ine the "Frequently Asked Questions (FAQ)" section of the official NASA Lunabotics Mining Competition internet web site: www.nasa.gov/lunabotics/.

In each of the two official competition attempts, the teams will score cumulative LunaPoints. See Table 1 for the Mining Category Scoring Example. The teams' ranking LunaPoints will be the average of their two competition attempts.

A) Each team will be awarded 1000 LunaPoints after passing the safety inspection and communications check.

B) During each competition attempt, the team will earn +2 LunaPoints for each kilogram in excess of 10 kg of BP-1 deposited in the LunaBin. (For example, 110 kg of BP-1 mined will earn +200 points.)

C) During each competition attempt, the team will earn -1 LunaPoints for each 50 KB/sec of average data used throughout each competition attempt. A minimum of 10 kg of BP-1 must be mined and deposited in the LunaBin during each competition attempt to receive these points. (For example, 5000 Kb/sec will earn -100 points.)

D) During each competition attempt, the team will earn -10 LunaPoints for each kilogram of total Lunabot mass. (For example, a Lunabot that weighs 80 kg will earn -800 points.)

E) During each competition attempt, the team will earn +100 LunaPoints if the amount of energy consumed by the Lunabot during the competition attempt is reported to the judges after each attempt. The amount of energy consumed will not be used for scoring; a team must only provide a legitimate method of measuring the energy consumed and be able to explain the method to the judges.

F) During each competition attempt, the judges will award the team 0 to +200 LunaPoints for regolith dust tolerant design features on the Lunabot and regolith dust free operation. If the Lunabot has exposed mechanisms where dust could accumulate during a lunar mission and degrade the performance or lifetime of the mechanisms, then fewer points will be awarded in this category. If the Lunabot raises a substantial amount of airborne dust or projects it due to its operations, then fewer points will be awarded. Ideally, the Lunabot will operate in a clean manner without dust projection, and all mechanisms and moving parts will be protected from dust intrusion. The Lunabot will not be penalized for airborne dust while dumping into the LunaBin. All decisions by the judges regarding dust tolerance and dust projection are final.

G) During each competition attempt, the team will earn +250 LunaPoints if the Lunabot is able to drive autonomously (no teleoperation), through the obstacle area only. The Lunabot may be teleoperated in the mining area and LunaBin/starting area. A minimum of 10 kg of BP-1 must be mined and deposited in the LunaBin during each competition attempt to receive these points.

H) During each competition attempt, the team will earn +500 LunaPoints if full autonomy is achieved and a minimum of 10 kg of BP-1 is mined and deposited in the LunaBin. No teleoperation is allowed to achieve full autonomy status.

Table 9: Example of On Site Mining Points for Lunabotics

Mining Category Elements	Specific Points	Actual	Units	LunaPoints
Pass Inspections				1000
Regolith over 10 kg	+2/kg	110	kg	+200
Average Bandwidth	-1/50kb/sec	5000	kb/sec	-100
Lunabot Mass	-10 /kg	80	kg	-800
Report Energy Consumed	+100	1	1= Achieved 0= Not Achieved	+100
Dust Tolerant Design & Dust Free Operation	0 to +200	150	Judges' Decision	+150
Autonomy through Obstacles	+250	0	1= Achieved 0= Not Achieved	0
Full Autonomy	+500	0	1= Achieved 0= Not Achieved	0
Total				550

Acknowledgments

The authors would like to acknowledge the support and funding for the Lunabotics Mining Competition from the NASA HQ Exploration Missions System Directorate (ESMD) Education organization and in particular the Education Lead, Mr. Jerry Hartman who has been instrumental to the success of these competitions in 2010 and 2011. Mr. Robert Cabana, Center Director of KSC was highly supportive of hosting this competition and provided inspiration to hundreds of students. In addition, outstanding project management was provided by Ms. Gloria Murphy, at NASA KSC who is the ESMD Space Grant Manager & Lunabotics Mining Competition Project Manager. Ms. Susan Sawyer provided coordination for all aspects of the events and served as the interface between the student teams and NASA and is highly commended for the dedication and efficiency provided in planning and daily operations.

The Centennial Challenges Lunar Excavation Competition was managed by Mr. Ken Davidian and Mr. Andrew Petro in the Innovative Partnerships Program (IPP) office at NASA HQ and brought to a successful conclusion with a $500,000 prize awarded in 2009.

We would also like to thank our industrial sponsors for the NASA Lunabotics Mining Competition as listed below:

- **Delaware North, Kennedy Space Center Visitor's Center**
- **Caterpillar inc.**
- **Newmont Mining**
- **Harris Corp.**
- **Honeybee Robotics SpaceCraft Mechanisms**

The following professional organizations provided their endorsement:

- **American Institute of Aeronautics and Astronautics (AIAA) Space Resources Technical Committee**
- **American Society of Civil Engineers (ASCE) Regolith Operations, Mobility and Robotics Technical Committee**

Last but not least, each and every individual, company, student and faculty member that competed is deeply thanked for the extreme effort and ingenuity displayed in designing, building and competing these lunar mining prototype robots. Their efforts show that there is a bright future for humanity assisted by robots in outer space.

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