# NASA Lunabotics Robotic Mining Competition
# 10th Anniversary (2010-2019): Taxonomy and Technology Review

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## ABSTRACT

Space Mining for resources such as water ice, and regolith, which contain many elements in the form of metals, minerals, volatiles and other compounds, is a necessary step for In-Situ Space Resource Utilization (ISRU). One of the primary goals is to extract propellants from the regolith and water ice, such as oxygen and hydrogen which could then be used for in-space transportation. In addition, the space mining system can be used for various construction tasks that can benefit human and robotic exploration as well as scientific investigations based on excavated exposed topography, such as the side walls of trenches.

The National Aeronautics & Space Administration (NASA) “Lunabotics” Robotic Mining Competition (RMC) is a university-level competition designed to engage and retain students in science, technology, engineering and mathematics (STEM). NASA has directly benefited from the competition by encouraging the development of innovative lunar excavation concepts from universities which has resulted in clever ideas and solutions which could be applied to an actual lunar excavation device or payload. The challenge is for students to design and build a remote controlled or autonomous excavator, called a “lunabot”, which can collect and deposit a minimum of 10 kilograms of lunar simulant within 15 minutes. In recent years the goal has been changed to excavate a minimum of 1 kg of simulated icy regolith which is found under an overburden of regolith simulant. The complexities of the challenge include the abrasive characteristics of the lunar regolith simulant, the weight and size limitations of the lunabot, and the ability to control the lunabot from a remote-control center or operate it autonomously.

This paper will present the results of the ten Lunabotics Robotic Mining Competitions held between May 2010 and May 2019. Each year over 50 university teams have attended, resulting in over 500 lunabot designs and subsequent prototypes. Over 6,000 university students have been part of the on-site competition at KSC. Even more students and the public were engaged via internet broadcasting and social networking media. The various designs have been

cataloged and categorized here to provide information to future Lunabotics RMC mining robot designers and competitors. Categories will focus on both the mechanical design as well as the autonomy architecture/design. It is also expected to be of value for actual future space missions, as knowledge is gained from testing many innovative prototypes in simulated lunar regolith. A taxonomy of robotic excavator designs has been presented. In addition, the paper will discuss changes in learning paradigms occurring in the current generation of students, and how this competition leverages those changes to challenge students to develop skills in graduate level concepts and apply them. Examples of how this translates to hiring opportunities for commercial sponsors has also been discussed.

## INTRODUCTION

In 2010 the NASA Lunabotics Robotic Mining Competition (RMC) for universities and colleges was initiated by NASA Kennedy Space Center, as a “spin off” from the successful NASA Centennial Challenge: “Regolith Excavation Challenge” which was held from 2007-2009. The history and more background information has been previously published by the authors (Mueller & van Susante 2011). Since then, the competition has evolved to reflect the policies of the United States (US) government and NASA priorities while still remaining true to its original goal of providing a positive learning experience for university students with benefits for NASA. Compelling and mounting evidence of water buried in the regolith on Mars and the Moon have strengthened the case for the competition and the overwhelming commitment to attendance by over fifty university teams for ten successive years attests to its relevance to academic university programs. These programs include undergraduate and graduate student participation, often for course credit in a senior design capstone project, involving extensive systems engineering education, as well as “hands-on” engineering, computer programming and fabrication skills development.

The competition has provided many examples of creative and clever design solutions in response to the requirements documented in the competition rules. While these designs have been documented in the systems engineering reports provided to NASA as a competition deliverable by each team, the aggregated performance and detailed engineering data have not been previously documented or published. Due to the large data set from over five hundred entries over ten years, the data collection and processing have been challenging. However, a large part of the value of the competition for NASA lies in applying the lessons learned from observing the competitor’s performance to actual lunar or martian excavator designs. Since a terrestrial test over two short fifteen-minute periods does not provide an adequately relevant environment, the designs are not directly applicable to space flight hardware, but nevertheless, trends in design and performance have been observed which allow the authors to draw conclusions which help to predict future successful design and operations attributes.

## LUNABOTICS ROBOTIC MINING COMPETITION

> “NASA is called to land American astronauts, including the first woman and the next man, on the Moon by 2024. We’re committed to achieving this bold goal. Through the Artemis program, we will go to the Moon in a way we have never gone before – with innovative new partnerships, technologies and systems to explore more of the lunar surface than ever before. Then we will use what we learn on the Moon to take the next giant leap – sending astronauts to Mars.” -NASA Administrator Jim Bridenstine-

NASA has led the charge in space exploration for more than six decades, and through the Artemis program (https://www.nasa.gov/what-is-artemis ) NASA will pave the way to the Moon and on to Mars. The Artemis program is the next step in human exploration. It will enable the USA to land the first woman and next man on the Moon by 2024, and establish sustainable exploration with commercial and international partners by 2028. Artemis will secure America's preeminence in space exploration and establish a strategic presence at the Moon. A lunar investment is also an investment in our future: it will create new jobs, help improve life here on Earth, and inspire a new generation and encourage careers in Science, Technology, Engineering and Mathematics (STEM). Furthermore, Artemis is a part of NASA's broader Moon to Mars exploration approach, through which we will quickly and sustainably explore the Moon and enable humanity's next giant leap, human exploration of Mars. On the Lunar surface we will demonstrate technologies, expand commercial opportunities needed for deeper space exploration, and test methods to obtain water from ice and other natural resources to further our journey. The presence of water at the lunar poles was detected by NASAs Mini Synthetic Aperture Radar (Mini-SAR) on the Indian Chandrayaan-1 lunar orbiting mission and confirmed by the NASA Lunar Crater Observation and Sensing Satellite (LCROSS) space probe. Capturing this water is the key to allow humans to "live off the land", or in scientific terms: In-Situ Resource Utilization (ISRU). The water can be used for human consumption, hygiene, growing plants, providing radiation shielding, industrial processes, construction materials and making rocket propellant for the journey home. NASA's Lunabotics RMC is a multi-semester university-level event that supports our Moon to Mars trajectory by requiring teams to participate in four events: (1) present their robot and their design philosophy at the competition; (2) submit a Systems Engineering Paper explaining the methodology used in developing their robot; (3) perform public outreach targeting the under-served, under-represented grade K-12 students in their communities and; (4) design, build and compete a robot to simulate an off-world mining mission. The complexities of the challenge include the abrasive characteristics of the Black Point-1 (BP-1), regolith simulant (Suescun-Florez 2014) and icy-regolith simulant, the weight and size limitations of the mining robot and the ability to tele-operate it, or operate autonomously, from a remote Mission Control Center. Points from all the events determine the winner of the "Joe Kosmo Award for Excellence". NASA evaluates over fifty proof-of-concept mining robots every year from the competition. These innovative robotic concepts may result in unique or clever solutions that may be applied to an actual excavation device and/or payload on an ISRU mission. Additionally, the United States of America (USA) will need a future work force that has the skills for developing autonomous robotic mining on Earth, the Moon and other off-world locations. Advances in off-world mining have the potential to contribute to our nation's space vision and NASA's space exploration operations. The USA will benefit by being leaders in a new space-based economy. In addition, the systems engineering skills are valuable in other high technology industries that will add to the economic strength of the USA. The rest of the world will benefit as well through the introduction and development of new technologies and methods to harness the vast resources and energy available in our solar system and beyond. The competition has shown that the next generation are well prepared through extensive and excellent education and inter-disciplinary collaboration. The top universities in this competition are shown in Table 1.

**Table 1. "Joe Kosmo Prize", On-Site Mining and Systems Engineering Winners: 2010-2019**

| Year | Joe Kosmo Prize | Robotic On-Site Mining | Systems Engineering Report |
|---|---|---|---|
| **2010** | Montana State University | Montana State University | Auburn University |
| **2011** | University of North Dakota | Laurentian University | John Brown University |
| **2012** | The University of Alabama in collaboration with Shelton State Community College | Iowa State University in collaboration with Wartburg College | Montana State University - Bozeman |
| **2013** | Iowa State University | Iowa State University | The University of Alabama |
| **2014** | The University of Alabama | Iowa State University | Milwaukee School of Engineering |
| **2015** | The University of Alabama | The University of Alabama | University of Illinois Urbana-Champaign |
| **2016** | The University of Alabama | The University of Alabama | University of Illinois Urbana-Champaign |
| **2017** | The University of Alabama | The University of Alabama | Case Western Reserve University |
| **2018** | The University of Alabama | The University of Alabama | The University of Alabama |
| **2019** | The University of Alabama | NA* | The University of Alabama |

*Government shutdown (Alternative competition held by competitors and Caterpillar Inc.), NA= Not Available, U= University

## Lunabotics Robotic Mining Competition - Autonomy

In 2013, Caterpillar Inc. worked with NASA to make autonomy part of the scoring structure for On-Site Mining and established the "Caterpillar Autonomy Award". Previously, the robots were tele-operated directly with an operator in the loop. As can be seen in Table 2, several development cycles (2 years in this case), were required by the competitor base to adapt to the new challenge of autonomy. After this initial adaptation period there was growth in the number of teams with the ability to execute autonomy in the competition. The addition of autonomy increased the level of difficulty substantially, and has resulted in graduate research level work being performed for the competition, while demonstrating the possibilities to NASA for consideration during planning and execution of excavation for In-Situ Resource Utilization.

**Table 2. Caterpillar Autonomy Award Winners: 2013-2019**

| Year | Caterpillar Autonomy Award | Year | Caterpillar Autonomy Award |
|---|---|---|---|
| **2013** | None | **2017** | 1st – University of Alabama<br>2nd - University of Illinois at Chicago<br>3rd - University of North Carolina at Charlotte |
| **2014** | None | | |
| **2015** | 1st – University of Alabama | | |
| **2016** | 1st – University of Alabama<br>2nd - South Dakota School of Mines | **2018** | 1st – University of Alabama<br>2nd - North Dakota State University<br>3rd - North Carolina at Charlotte |
| **2017** | 1st – University of Alabama<br>2nd - University of Illinois at Chicago<br>3rd - University of North Carolina at Charlotte | **2019** | 1st – University of Alabama<br>2nd – North Dakota State University<br>3rd – Colorado State University<br>4th – Case Western Reserve University |

Pursuit of the Caterpillar Autonomy Award has stretched undergraduate students to research, develop insight, and implement graduate level robotic concepts. The current generation of students have grown up in the information age with ubiquitous internet access. As a result, there is a trend among these students to pursue learning outside the classroom and not wait for formal instruction. In doing so, they investigate and leverage open source communities, on line tutorials and other sources of information to be able to implement the necessary capabilities to achieve the objectives of the competition in the area of autonomy. The results are students with higher levels of marketable skills as they enter the work force. Caterpillar, Inc. has been able to effectively recruit top talent with these skills from its engagement in the competition. This proves that the competition is a valuable development tool with positive results for all stakeholders: the student, the universities, NASA and the industrial sponsors as well as benefiting the US economy as the workforce of highly knowledgeable individuals increases the technology base and increases the value of the human capital.

The impressive concepts and approaches pursued by competitors are described in detail below, in the Autonomy Architecture and Design section in this paper.

## TAXONOMY OF REGOLITH EXCAVATION PROTOTYPES

### Classification of Competition Prototypes

The robot designs and approaches to meet the competition requirements are numerous. Over 300 competition entries have been reviewed (2007-2016 currently, 2017-2019 to be done). Their mechanical functionality can be divided up in an excavation mechanism, transportation mechanism, storage mechanism, dumping mechanism and movement mechanism. Tables 3, 4 and 5 list the top 20 most commonly used mechanisms in each category.

## Table 3: Most popular excavation and regolith transportation mechanisms

| | regolith | | regolith |
|---|---|---|---|
| # sys | **excavation mechanism** | # sys | **transportation mechanism** |
| 101 | bucket ladder | 103 | bucketladder |
| 37 | front end loader | 40 | in scoop |
| 29 | bucket belt | 22 | conveyor belt |
| 27 | bucketwheel | 21 | bucketbelt |
| 17 | bucket drum | 15 | auger |
| 15 | snow blower (auger or brush) | 11 | Over shoulder dump into hopper |
| 12 | auger | 8 | chute for guiding regolith |
| 8 | backhoe | 7 | bucketdrum |
| 8 | bulldozer | 7 | drum |
| 8 | scraper | 6 | bucketwheel |
| 7 | large single scoop | 6 | impeller |
| 4 | dual auger | 4 | bucket rim |
| 4 | dual bucket wheel | 4 | bucketwheel discharge through bottom |
| 4 | rotating brush | 4 | in bucket |
| 3 | excavating wheels | 4 | rotate scoop to slide simulant in hopper |
| 2 | claw/gripper scoop | 3 | throw from impeller |
| 2 | dual bucketladder | 2 | bucketwheel with side discharge |
| 2 | dual counter rotating bucketdrums | 2 | paddle conveyor |
| 2 | large bulldozer scoop | 2 | raising scraper with chute |
| 2 | paddle conveyor | 2 | thrown from brush up ramp |

## Table 4: Most popular regolith storage and regolith dumping mechanisms

| | regolith | | regolith |
|---|---|---|---|
| # sys | **storage mechanism** | # sys | **dumping mechanism** |
| 213 | hopper | 111 | rotating tilting hopper |
| 41 | in scoop | 36 | conveyor belt as bottom and inclined side o |
| 10 | drum | 30 | scoop tilting |
| 6 | bucketdrum | 7 | auger |
| 6 | on conveyor belt | 6 | counter rotate buckedrum |
| 4 | auger | 6 | raising/tilting hopper/ scissor lift |
| 3 | scraper | 5 | conveyor belt |
| 2 | in bucket | 5 | fixed rotating hopper |
| 1 | bucketdrums | 4 | raising hopper with back chute |
| 1 | bucketladder | 4 | rotate and lift scoop to slide off back into co |
| 1 | bulldozer | 4 | scissor lift and tilting hopper |
| 1 | drums | 4 | tilted raised drum |
| 1 | in auger pipe | 3 | bucketladder |
| 1 | in clamshell | 3 | raising counterrotating drum |
| 1 | inside tube body | 3 | raising hopper with bottom conveyor belt |
| 1 | large conveyor belt with crazy carpet | 3 | tilting raising scoop |
| 1 | saddle hopper (two sides) | 3 | tilting scoop |
| 1 | scraper scoop | 2 | angled vibrating hopper |
| 1 | side hopper | 2 | chute |
| 1 | slide | 2 | horizontal conveyor belt |

**Table 5: Most popular robot movement mechanisms**

| # sys | robot movement mechanism |
|---|---|
| 173 | 4 fixed wheels |
| 73 | tracks |
| 21 | 6 fixed wheels |
| 10 | 4 steerable wheels with custom profile |
| 6 | two auger drums to propel |
| 5 | stationary with swivel |
| 4 | 4 fixed track wheels |
| 3 | 4 digging wheels |
| 2 | 3 wheels (2 driven, one steering) |
| 2 | 4 six-legged wheels |
| 2 | 4 wheels with suspension |
| 2 | each of two robots hase 4 fixed wheels with grousers |
| 2 | four individual steerable tracks |
| 2 | three robots working together, two transport, one excavator, each with 4 fixed wheels |
| 1 | 3 fixed wheels (front wheel swivels freely) |
| 1 | 3 large wheels (2 with grousers, third with scoops) |
| 1 | 4 medium and 2 large front wheels |
| 1 | 4 wheels (two steerable coupled) with grousers |
| 1 | 4 wheels with grousers, two of which have buckets to fill with regolith to increase counterweight |
| 1 | 4 wheels, of which 2 steerable rear wheels |

## AUTONOMY ARCHITECTURE AND DESIGN

The approaches that the competitive teams take to implement autonomy can be grouped into the primary on-board sub-systems of autonomy:

Localization – fusing and interpreting data from various sensor inputs to determine the location and orientation of the robot in its environment.

Perception – fusing and interpreting data from various sensor inputs to perceive (terrain mapping, object detection, object classification, and object tracking) the environment around the robot.

Mission Planning – utilizing perception and localization knowledge to determine the planned actions to execute the mission or task the robot has been assigned. In this competition this would include navigation planning to traverse the arena, and excavation & dump (unloading) planning for regolith extraction and deposition.

The competitors have demonstrated a range of approaches to autonomy architecture. These approaches are discussed here, classified by autonomy sub-systems.

Localization

The competitors define a local arena coordinate system for their robot. This most typically designates the regolith simulant collection bin as the origin of the coordinate system. The architectures can then be defined by two high level approaches. See Table 6.

1. Determining position and orientation of the robot only.
2. Determining position and orientation and relative change in position and orientation of the robot. In this case the team propagates the solution in between updates of the position and orientation based on the relative change. This propagation or prediction of the change in position and orientation have been seen to be based on inertial measurement units (IMUs), powertrain encoders (also known as odometry), visual odometry based on perception sensors or combinations of these inputs. This approach allows the teams to produce an overall more accurate and smooth localization solution. The approach is most typically implemented through some form of Kalman filter.

Both architecture approaches require determination of position and orientation of the robot. Two approaches have been seen within the competition.

1. Fiducials – Physical markers placed in arena environment (at the collection bin and/or on the robot) that can be "seen" by camera or Light Detection and Ranging (LIDAR) sensors. The most prevalent use of fiducials are "AprilTags". AprilTags are a camera-based approach that can leverage targets that can be created from an ordinary printer. It is a visual fiducial system, useful for a wide variety of tasks including augmented reality, robotics, and camera calibration. The associated open source software allows computation of 3D position, orientation, and indent of the tags relative to the camera.

Triangulation with ranging radios - This approach leverages ranging information from Time of Flight (TOF) radio beacons. Radio beacons place on the robot and the collection bins at specific known distances at each location allow triangulation methods to be used to determine position and orientation of the robot.

**Table 6. Localization Algorithm / Architecture Approaches (2019 results)***

| **Localization Algorithm / Architecture Approaches** | **# of machines employing Algorithm / Architecture Approaches types** | **Sensors** | |
|---|---|---|---|
| | Position & Orientation | Position & Orientation | Relative Change in Position & Orientation |
| Position & Orientation – Only (6) | | | |
| Fiducials (5) | AprilTags (4) | Mono Camera | NA |
| | Pixel sizing objects at known distance apart (1) | Mono Camera | NA |
| Ranging Radio Beacons (1) | Simple Triangulation (1) | DecaWave TOF radios | NA |
| | Position & Orientation | Fusion Method | |
| Position & Orientation – w/ fusion of relative change in position/orientation (5) | | | |
| Fiducials (4) | April Tags (3) | Stereo Camera | IMU 6 DOF, Encoders |
| | | Stereo Camera | Encoders |
| | | Stereo Camera | Stereo Camera – Visual odometry |
| | Specialized fiducials for LIDAR (1) | LIDAR | IMU 6 DOF, Encoders |
| Ranging Radio Beacons (1) | Simple Triangulation (1) | DecaWave TOF radios, | IMU (3axis gyros), Encoders |

*Numbers in parentheses show how many teams used this approach.

**Perception**

The perception systems developed by the teams are defined by three approaches. See Table 7

- Object extraction based on ground state estimation – in this approach 3D point cloud data from either stereo cameras or LIDAR sensors are processed to determine the ground plane. The system then looks for data in the point cloud that is above the ground plane and assigns them as objects.
- Object extraction based on normal vectors to the terrain – in this approach the 3D point cloud is grouped into triangular blocks. The normal vector to the triangular blocks is then calculated and normal vectors at a pre-defined threshold from vertical are then flag as location of obstacles.
- Object identification and extraction based on utilizing artificial intelligence and trained convolutional neural networks. In one case the team created their own training set specifically for the competition.
- "Fly Blind" – the teams elected to have no active perception and relied on the physical design of their platform to be able to handle obstacles or craters in the arena field.

**Table 7. Perception Algorithm / Architecture Approaches (2019 results)**

| Perception Algorithm / Architecture Approaches | # of machines employing Algorithm / Architecture Approaches types | Sensors |
|---|---|---|
| | | |
| Object extraction based on Ground State Estimation | 6 | Stereo Camera (4)<br>LIDAR (2) |
| Object extraction based on Normal Vectors to terrain | 1 | Stereo Camera |
| Object extraction based on Artificial Intelligence – Convolutional Neural Network | 2 | Mono Camera (1)<br>Stereo Camera (1) |
| Fly Blind | 2 | NA |

In all cases, except for "fly blind", the defined objects where then referenced to the arena coordinate system as defined in the localization section (Table A1) and an occupancy grid created.

**Mission Planning**

Mission planning for this competition is comprised of two focal areas:

1. Navigational Planning – How to traverse the competition arena while avoiding obstacles. There are two primary location destinations within the arena – the mining area and the collection bin. As can be seen in Table 8, the most prevalent approach is the use of the

"A* algorithm". This algorithm is an informed search algorithm that leverages weighted information about the environment – obstacles, targeted destinations, etc.) to determine a best path to traverse the environment. A variant of the A* algorithm is the "D* algorithm", which has also been used in the competition.

2. Excavation Planning – The general approaches have been to monitor and control the excavation implement based on velocity, torque, position, or a combination of these parameters.

**Table 8: Algorithm / Architecture Approaches (2019 results)**

| Mission Planning Algorithm / Architecture Approaches | # of machines employing Algorithm / Architecture Approaches types |
|---|---|
| Navigation Planning | |
| A* based on occupancy grid | 5 |
| D* based on occupancy grid | 1 |
| Rapidly explored Random Trees (RRT) w/ Modified Dynamic Window | 1 |
| Predefined plan | 4 |
| Excavation Planning | |
| Velocity Control | 1 |
| Torque Control | 2 |
| Position Control | 2 |
| Velocity & Torque Control | 3 |
| Position & Torque Control | 1 |

## LUNAR OPERATIONS FEASIBILITY, PROBLEMS ENCOUNTERED AND LESSONS LEARNED

Robots are rated by the judges on a scale of "1 through 5" on drivability, where 1 means the robot is completely unable to drive and 5 means the robot has complete command of the regolith and evidences driving competence such that there is no detectable risk of getting stuck. The in-between grades are as follows: 2 = the robot can drive with difficulty but is always on the cusp of getting stuck due to continual wheel slippage, ground clearance, wheel dragging, or other problems; 3 = the robot can drive adequately but has repeated moments of slippage or other indicator of risk; 4 = the robot can drive competently but care must still be used to avoid "initiating events" like striking rocks and driving through a crater because the robot does not evidence complete command of all driving situations. In earlier years of the competition, very few robots were able to drive well. About half the robots that drove at all would get stuck, resulting in many scores of 1 or 2. A common problem was that one or two wheels begin spinning, which fluffs the soil under that wheel causing it to lose shear strength. Then, that wheel is unable to transmit any traction from the ground to the vehicle. Unless the vehicle is able to pull forward on the remaining wheels, it is stuck. Vehicles that are designed to drive on fewer remaining wheels are thus able to avoid this state. The competition judges have kept data on the robots for all ten years of the competition and have analyzed statistically what correlates to a robot scoring higher. Factors that have been correlated to good driving are: tall wheels; wide wheels; higher torque; higher gear ratio; aspect ratio of the wheel base closer to unity; adequate ground clearance; active steering; and some form of wheel suspension. However, none of these factors individually correlate to good driving, which was a surprising result and makes it difficult to choose parameters for a robot to keep it from getting stuck. The correlations are discovered only when combinations of robot parameters are analyzed. Over the years, teams pass on knowledge to their successor teams within the school, and as teams, they copy and share ideas between other university teams by observation and informal interaction. Remarkably, although no teams have access to the data that the judges have collected, and although no individual robot parameter correlates to better driving, the teams have evolved their robots to higher competence every year. This year, the average drivability score was 3.92 so approximately half the robots were in the upper echelon of excellent or outstanding driving. The histogram of scores is shown in Figure 1.

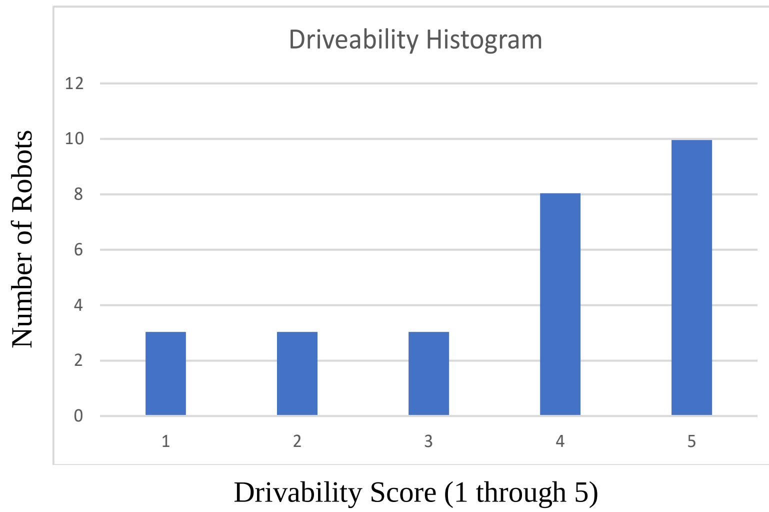


**Figure 1. Number of Robots at each Drivability Score.**

Very few teams in recent years had problems with communications or electronics that prevented the robots from operating. In early years approximately 50 to 75% of teams had such problems, but this has continually decreased. In 2019 only three teams had those problems.

Regolith handling continues to be a challenge. The regolith has extremely high cohesion and friction so it does not pour or flow well. One team had a robot that was unable to pour the regolith from its digging implement into its internal transport hopper, but during the competition modified the robot to add low-adhesion coating and to increase the mechanical vibration of the implement, and this solved the problem.

Soil cutting is also a challenge. Although the shearing action of wheels is able to transition the regolith into a very loose state with little cohesion or friction, making the robot vulnerable to getting stuck, the soil is also capable of being highly compacted with extremely high cohesion and friction. Therefore, the soil can be difficult to excavate, requiring very high torque and innovative digging mechanisms. Teams used a variety of innovative methods to dig including four-bar digging implements to increase leverage, small but fast buckets to reduce the cutting force into smaller parcels, and augers to localize the force. In 2019, the only mining points were awarded for simulated “ice chunks” represented by larger rocks, which were buried at depth, so teams implemented innovative methods to reject fine material and keep only the rocks. This included porous digging implements with vibration to encourage discharge of the fines as slag. These were moderately successful in general but created problems with dust dispersal onto the robot mechanisms, so more innovation is needed. This is the benefit of continuing to evolve the competition rules, because it continually accesses new challenges for the teams to overcome.

## CHANGES IN LEARNING PARADIGMS

To participate in this competition, the students have to go above and beyond the traditional coursework taught at universities. Some coursework applies directly, such as mechanics of materials or material science, other coursework may or may not be offered at some universities such as a course on robotics and controls or is only offered at the graduate level. This implies that students will have to do a lot of independent learning and discovery (perhaps under faculty supervision) about topics that they may not have had any coursework on or that is beyond the current level of knowledge gained from such courses. A good example is the autonomy component in which very few undergraduate students can take any coursework. The students find online and other sources to learn about and implement solutions to these challenges which fosters life-long learning skills and invaluable experience for them. This experiential learning fostered by self-motivated students to achieve a goal set by the competition allows the students to learn much more than if they only would go to traditional courses without such a competition or hands-on experience. This observation is in line with experiences with new class room teaching methods: the so-called ‘flipped classroom’ in which students read assigned material or watch on-line material, perhaps do some small assignment before coming to class, where they then actively apply the prepared material in the form of practice problems in an active manner. Various methods exist to achieve this active class room. It is time consuming to implement and to prepare the educational material, and it is challenging to perform active class participation activities in large lecture hall style rooms, but it is possible. The flipped class room style and active learning methods result in better mastery of the subject material.

## TALENT ACQUISITION FOR COMMERCIAL SPONSORS

### Caterpillar inc. Case Study

Graduates of the science, technology, engineering and mathematics (STEM) fields are a critical piece of the Caterpillar talent pipeline. Caterpillar has more than 10,000 engineers and technologists developing innovative solutions for our customers. Continuing this pace of innovation requires a sustainable pipeline of technical talent. However, the number of STEM graduates has steadily declined since 2003 and highly-skilled jobs in these fields continue to go unfilled in the United States - a major concern for Caterpillar.

Caterpillar supports various STEM competition outreach initiatives as part of our overall talent pipeline process:

- For Inspiration and Recognition in Science and Technology (FIRST
- The American Society of Agricultural and Biological Engineers (ASABE) International 1/4 Scale Tractor Design Competition
- Society of Automotive Engineers (SAE) Baja competition
- NASA Robotic Mining Competition

One of the key technology areas of focus for Caterpillar is "Automation and Autonomy". This technology area ranges from operator assist and remote control to full autonomy and provides key value drivers of improved safety, reduced variability, and increased productivity for our customer base. Pursuit of the Caterpillar Award for autonomy as part of the NASA Robotic Mining Competition has created a pool of top talent in the automation and autonomy technology area from which Caterpillar has successfully recruited. The nature of the competition produces students with advanced skills sets in the area of automation and autonomy and the right balance of academic knowledge, technical skills and critical thinking skills to keep up with the rapid changes in this technology area.

Over the last 10 years, Caterpillar has been sponsoring the RMC and testing the hypothesis that competitions attract a high caliber of senior students who are eager to find jobs immediately after the RMC which occurs in May of each year just as they are graduating. Caterpillar has been able to recruit talent by hiring some of these students, who have subsequently performed very well at Caterpillar, proving that sponsorship of the RMC has been beneficial for both industry and academia. NASA benefits through effective inspiration of the next generation and a strengthening of the US economy and technical workforce, as the STEM skills become available in industry. Some competitors have been hired by NASA contractors and are actively contributing to the space program.

## CONCLUSION

This paper has presented the results of ten Lunabotics Robotic Mining Competitions (RMC) held between May 2010 and May 2019. Each year over 50 university teams have attended, resulting in over 500 excavation robot designs and subsequent prototypes. Over 6,000 university students have been part of the on-site competition at KSC. Even more students and the public were engaged via internet broadcasting and social networking media. The various designs have been cataloged and categorized here to provide information to future Lunabotics RMC mining robot designers and competitors. In addition, the paper discussed changes in learning paradigms occurring in the current generation of students, and how this competition leverages those changes to challenge students to develop skills in graduate level concepts and apply them. Examples of how this translates to hiring opportunities for commercial sponsors has also been discussed.

Overall, the RMC continues to be a success after ten years of annual competitions. The rules have evolved over the years to reflect the growing body of knowledge about water ice ore on the Moon and at Mars, which is buried under an overburden of regolith that provides an insulating layer. The students have benefited by gaining a very good education through "hands on" engineering design, computer programming and fabrication, culminating in a mission to NASA, KSC in Cape Canaveral, Florida, where they can test their skills and robot designs against peers at other colleges and universities. NASA has benefited by getting unique insights into the design and operation of tele-operated and autonomous regolith excavation robots.

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