Badger Robotic Mining Team 2015-2016 Technical Report[1]

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Abstract
This report entails the first-year Badger Robotic Mining Team's involvement in NASA's annual Robotic Mining Competition and design choices in constructing our Badger Lunar Excavating Robot (BLER). The team was split into three groups: mechanical, electrical, and software sub teams. The mechanical team explored several mining methods for BLER and settled on a scraper design. All three sub teams worked together to create a functioning robot that successfully met competition qualifications. Members learned valuable engineering skills such as machining on heavy equipment, computer-aided design, electrical system design, and code. The team will return for NASA's subsequent mining competition in May 2017 learning from their experiences from the 2016/2017 academic year.

Background

The Badger Robotic Mining Team competed for its first year in NASA's annual Robotic Mining Competition. The team is comprised of members from the student organizations, Badger Ballistics and Wisconsin Robotics. The team built a miner named the Badger Lunar Excavating Robot, or BLER. The primary objective of the competition is to construct a robot that can mine large amounts of lunar soil simulant and deposit it into a bin quickly. The majority of points are awarded for autonomy, optimizing load and capacity, lowering robot power consumption and bandwidth usage. The inspiration behind the competition stems from the abundance of Helium-3 found in the moon's ground level, which is an efficient fuel for nuclear fusion experiments but is only found in trace quantities on Earth.

The University of Wisconsin-Madison Fusion Technology Institute has an ongoing program researching how to make fusion energy production feasible. One of these aspects is fuel production for such reactions. Much attention is focused on Helium-3. A group of graduate students from the University of Wisconsin has developed a prototype system called the Helium Extraction and Acquisition Testbed (HEAT). The purpose of HEAT is to separate Helium-3 from the lunar soil.

[1] Thank you to Fred Best and the Wisconsin Space Grant Consortium for your generous donations making our experience possible

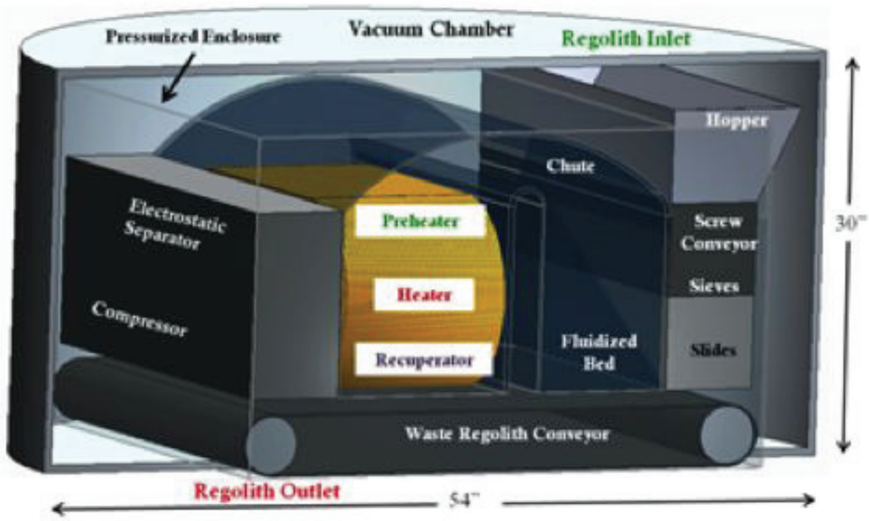

Fig. 1: Diagram of HEAT

BLER is intended to both serve the Badger Robotic Mining Team's needs as part of competition as well as to serve as testing for HEAT's integration with a mining system.

Team history. Badger Ballistics and Wisconsin Robotics have seen limited interaction before academic year 2015-2016. Badger Ballistics president Tashi Atruktsang assembled a team of members from both student organizations for competition. Mechanical, embedded, and software sub teams were created. More experienced students lead these groups. A three credit course supervised by professor Aaron Nimityongskul was created in conjunction with the competition team to support recruitment.

System Design

The mechanical, electrical, and computational design aspects of BLER are discussed individually in this section.

Driving mechanism. Several iterations of the driving mechanism were assessed. The first design consisted of four wheels of PVC and aluminum webbing. Prototype PVC wheel tests, however, failed to produce necessary levels of traction.

A proposed modification was to use a 'tweel.' A tweel is a rubber tire with no gas filling that conforms to the surface it rests upon. Tweels are ideal for uneven terrain.

The main disadvantage of a tweel is their weight:traction ratio. SolidWorks was utilized to model different tweel geometries and their respective responses to varying loads. The Mechanical team determined the weight of an average tweel to be in excess of 10 pounds. With the tested traction of the typical tweel design, the team determined this to be unacceptable. The tweel design was abandoned.

Treads were the next drivetrain system that was reviewed. The tread system of interest provided more traction with a contact patch that exceeded the tweel by a factor of + 10; however, weight would increase as well. The deciding benefits are that treads are able to distribute weight more evenly. This reduces risk of sinking into the ground. The primary disadvantage is increasing weight, but the increase in traction allows a heavier robot to remain functional and the trade-off was deemed acceptable. The team found a track system manufactured by SuperDroid Robots.

Chain drive was selected to couple motors to their drive wheels. Calculations taken from our final assembly shown below include 1.2 ft/s maximum robot velocity and 88 lbf of driving force. The system exerts a maximum of 367 lbf if robot is stationary. This system is optimized for higher torque and driving force.

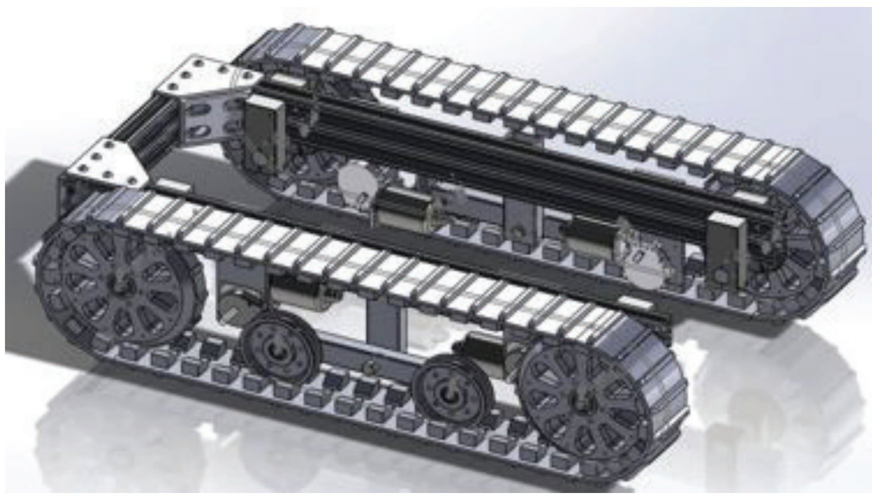

Fig. 2: Final Assembly of BLER's powertrain

The motor shaft is composed of a 33 mm steel shaft build into the motor assembly. A #35 ANSI chain steel sprocket with 11 hardened teeth to fixed to the shaft by two set screws. A second #35 ANSI chain aluminum sprocket with 30 teeth is fixed to each drive wheel. Each drive wheel and sprocket coupling is fixed to a 0.625 in aluminum shaft that rotates relative to the robot frame. A 11:30 gear ratio allows the motors to deliver a 11.7 Nm torque to a wheel with a rotation rate of 29.2 rpm.

Each driving wheel is comprised of two UHMW Polyethylene plates with a central cleated circular rubber plate that grips a tread. Each tread is made of rubber with internal reinforcement and has a width of 4 in.

Four total idler wheels were machined by team members from polyethylene blocks. Idler wheels are free spinning wheels positioned adjacent to the treads to restrict any undesirable tread movement. Each idler wheel is vertically offset a sixteenth of an inch below the main wheels to improve the robot's ability to turn without sacrificing significant traction.

Mining System. The team's primary goal in developing a mining system was to design one that could collect large volumes of gravel. This choice did not change as the academic year progressed.

However, development of the system went through several phases with changes being made as tests were completed assessing feasibility of each prototype. There were three main phases: first an auger mechanism, then a bucket wheel digger, and finally a scraper which was ultimately made the mining system for BLER.

The team's first prototype was intended to mine beyond one foot deep into the competition arena. There are two separate layers of simulant in the test area. The top one foot is composed of Black Point 1 which is similar to flour. A second gravel layer, if collected, was worth five times per mass more points than the top layer.

The team determined a system using an auger would be the most effective in reaching deeper layers of simulant. A SolidWorks model of this first design is shown in figure 3. The model was later deemed unfeasible for several reasons. Power calculations indicated that stresses from lifting an auger rooted into the ground were high enough to damage the robot, and a mounting system that met our weight requirements and provided enough structural support was not devised. Furthermore, as the auger dug deeper a solution for preventing the robot from spinning above ground around a rooted stationary auger could not be found. The team decided to scrap this idea in light of these issues.

The second prototype featured a bucket wheel. This design used a rotating circular mechanism to continuously collect small amounts of material from rigidly attached buckets. This idea was abandoned for two main disadvantages. First, the team still had the desire to reach below the one foot depth and the bucket wheel, through testing, was deemed unable to reach below a few inches for significant results. Second, a solution for dumping the material from the bucket wheel once collected could not be found. No CAD models of the conveyor system were completed with machinable linkages.

Fig. 3: BLER's first mining system prototype used an auger

Fig. 4: BLER's second mining system prototype used a bucket wheel

The final scraper design was established according to two major advantages.

i) the scraper was predicted to be the simplest design to create in SolidWorks that had the target load capacity needed to surpass the 2015 winning load

ii) the scraper was designed to streamline the fabrication process. At this time the team decided to stress the time allowed for embedded to test the driving and mining software and optimize the code.

The team's scraper consisted of a bin that was lowered to ground level and filling using work from the robot's own powertrain to collect material like a shovel. This design also benefited from BLER's heavier weight necessary to push through larger sums of BP-1 without stalling. The scraper was also researched to be a hydrofoil; the bottom surface acts as a foil that creates a pressure difference as it moves across material. The pressure difference creates an upward force on the material against the scraper which theoretically pushes material into the bin, similar to an airfoil moving through the atmosphere.

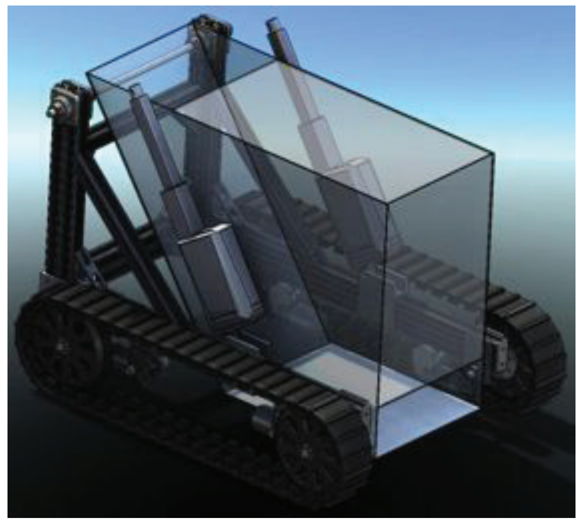
Fig.5: BLER's final scraper mining system

At this point, the team also abandoned the design goal of digging deeper to reach gravel.

Estimated material collection values were optimistic.
As much as 65 kg of material could be collected for each mining pass. One pass was defined by the team as driving the scraper mechanism over 90% of the competition floor, which was estimated to take about two minutes to perform.

The power consumption of the scraper design is calculated using the following assumptions. All motors and linear actuators will be considered in operation at peak load. This assumption should vastly over-exaggerate our power consumption. Drive motors operate at 50% CCW (forward) at 50 W [2] and 50% CW (backward) at 55 W [2]. The bin linear actuators operate at 24V and 10A [3]. Time calculation is estimated using distance traveled divided by actuator operation speed. The door actuator operates at 12V and 3A [4]. Time calculation is estimated using distance traveled divided by actuator operation speed. Computer system and associated electronics are not included in the calculation.

The total estimated power consumption is 65.34 W-hr for a single 10 minute competition run. The four drive motors come to a total of 35 W-hr, the two bin actuators come to a total of 29.86 W-hr, and the door comes to 0.48 W-hr.

Framework. Given the ease of obtainment, use, modularity, and strength to weight ratio, 80-20 aluminum extrusions [10] were selected to construct the framework for the chassis of the robot. Due to the widespread application of 80-20 it is trivial to find dedicated fasteners and bolts designed specifically for attaching pieces of it together. The team took advantage of this to create a design that is extremely simple to assemble and disassemble as needs arise and modifications occur. Assembling the framework was completed via the plethora of fastening methods available to the versatile 80-20 slotting. Additionally, 80-20 is made of 6105-T5 aluminum alloys, a lightweight material with a high moment of inertia and relatively strong yield strength for its weight. FEA stress analysis software, ANSYS, was utilized to determine the deflection of the structure to ensure that the frame design would be able to withstand the forces exerted upon it during operational loading. The simulation determined that there would be minimal deformation in the 80-20 beams under a compressive force three times the competition weight limit.

Chassis. The machine's chassis is designed to be in a "U"-shape (parallel to the ground) allowing for maximized excavating area and an opened front end accommodating of many mining methods. Extrusions selected are double the length in the vertical direction (3 in) than in the horizontal direction (1.5 in) yielding a higher area moment of inertia in relation to the major bending axis. This helps prevent excessive flexure of our chassis in the vertical direction without being unreasonably stiff which enables durability yet each continuous track mechanism has semi-independent suspension. Fastening the chassis consisted of extreme corner linkage by a multitude of premade aluminum connectors as a requirement of the extreme forces on said connections due to the cantilever design of the chassis. The attachment of external devices to the chassis was mainly by means of tailored 1/4 in thick aluminum plate mounts and premade 80-20 connectors. Finally, stress analysis was performed using a finite element analysis package, ANSYS, to determine the deflection and failure of the structure to ensure optimal reliability and design. The simulation determined that there would be minimal deformation in the 80-20 beams under a compressive force three times the competition weight limit.

Tool Framing. Derived from the modularity of the chassis a variety of excavating tools are designed. Framing of the excavating tools is performed by slew of different 80-20 extrusions. Main vertical mounts are completed utilizing 3 in by 1.5 in beams to suppress flexure and compression problems. Support connections are constructed from 1.5 in by 1.5 in extrusions and exist as cross-linkages and angled supports greatly increasing stiffness and permanency of the frame. Finally, connections of the frame are subsisting by a myriad of standard prefabricated connectors.

Operation. The operation of the scraper design is extremely simple. After crossing the obstacle area, the robot will lower the scraper to ground level using linear actuators. As the robot begins to move forward, the linear actuators retract, forcing the blade two inches into the BP-1 terrain. The robot will drive the length of the mining area until it reaches the far wall. At this point, a door on the front wall of the bin will extend downwards, closing the collection area. Then the robot will extend the linear actuators to lift up the bin and reverse to the where it initially started digging. At this point, depending on how full the collection bin is, the robot will repeat the process, opening the front collection door, and retracting the actuators into the terrain another two inches. Once the bin is full, the robot will reverse to the collection bin wall and extend the actuators to collection height, and begin the deposition process. To expedite the process, a dry material vibrator is attached to the back of the bin. Once the material is deposited, the robot will repeat the collection process.

Construction. Throughout the design process we had to keep feasibility of fabrication in mind, meaning the team had to be certain that our designs could realistically be constructed within a reasonable timeframe. This key distinction caused the team to reconsider several early solutions in favor of more easily constructible options. For example, despite having a custom tread drive system design, the team elected to purchase a manufactured set for ease of fabrication and time. Additionally, whether it be due to lack of resources, abilities, or knowledge portions of the fabrication process were identified that would best be outsourced, such as welding. This allowed for a more streamlined fabrication process in which the team constructed a majority of the components using techniques we were comfortable and experienced with. The team was able to acquire many of our own tools and machines specifically for constructing the robot. This was in addition to having access to a student shop on campus. Together, this allowed the team to simultaneously fabricate several components.

Embedded. The technical challenges of the Robotic Mining Competition required that a certain degree of creativity be employed to solve them.

The power system is composed of two 24V lithium iron phosphate batteries operating on separate power rails. The reasoning for using two batteries is the incredibly high amount of current the rover is expected to draw at peak; while the batteries are capable of sustaining 40A of continuous current at 24V, calculations indicate that when the rover is fully loaded with BP-1 the current draw may exceed these maximums. The first battery powers the drive motors, the main computes, and associated periphery while the second battery drives the collection bin dry material vibrator, the collection bin gate, and collection bin lifting mechanism. A separate COTS power logger exists for each power rail.

One of the core design philosophies employed was reliability. To reduce uncertainty in our implementation, the team selected the Talon SRX to drive all motors on the robot. Controlled by a PWM signal, the Talons are cost-effective and reliable speed controllers capable of driving large loads. Additionally, a quadrature encoder has been placed on each motor drive shaft, allowing for precise positional control of BLER. The Talons will be driven by an Atmel XMEGA microcontroller board running FreeRTOS. A real-time operating system ensures that operations will execute with some amount of temporal determinism.

The main computer that runs the software control stack is an Intel Core i3 NUC running Windows 10. The system and OS were selected due to the already existing software stack the Wisconsin Robotics software team had developed.

Software. Software for BLER is composed of the onboard system control software and the remote control software used to drive the robot. In addition, various libraries were created to support operations such as sensor data acquisition and networked communication.

BadgerJAUS. Due to Wisconsin Robotics' history at the Intelligent Ground Vehicle Competition, the team possesses a library that implements the SAE Joint Autonomous Unmanned Systems specification. This library has underpinned the last three robots developed by Wisconsin Robotics, with BLER being the fourth. The primary advantage of BadgerJAUS is to allow significant reuse of code for controlling entirely different robots and also allowing for the use of a single remote control program instead of custom solutions tied to each robot.

Badger Control System. The Badger Control System is a graphical user interface application that Wisconsin Robotics developed to remotely control all of its robots. BCS takes advantage of the BadgerJAUS library to be able to connect and allow for operation of any robot that is JAUS compliant, even those not using BadgerJAUS. The application supports a variety of command messages, ranging from simple drive commands to manipulation of actuators.

Lunar Autonomous Mining Excavator. The LAME system control software is the heart of the software stack designed for BLER, capable of both autonomous and remotely controlled operation. Remote control is handled by the BadgerJAUS library described above, utilizing code that is common across all of Wisconsin Robotics' current systems. The autonomous navigation software was however specifically written against the requirements of the NASA Robotics Mining Competition.

Autonomous Operation Design. In order to autonomously control the robot, in both navigation and also the actual mining and retrieval of payloads, BLER must know where it is relative to the collection bin. As the competition rules do not permit the usage of range finding against the arena walls or even the collection bin to derive distance information, options were limited for how the robot was to determine its location. The team ultimately elected to employ computer vision techniques to help the robot orient itself relative to the collection bin.

The solution the team ultimately settled on was to use the AprilTags library, a computer vision library that utilizes simplified QR codes to determine the angle and distance of the viewer relative to the each AprilTag. The code to analyze an image to detect AprilTags is open-source. When given an image, the AprilTags API returns the pixel-coordinate location of each AprilTag's exact center and four corners, as well as a homography matrix representing each AprilTag's 3-dimensional rotation. To find the location of an AprilTag relative to the camera, we compare the pixel-unit size of the tag in the image to its known actual size.

The majority of the calculations done by the software compensates for distortions in the AprilTag in the image due to rotation in 3-dimensional space. It is impossible to directly obtain the pixel-unit side length of each tag from the pixel-coordinate location of the four corners of the tag, since the tag in the image is a distorted projection of a real tag that has 3-dimensional rotation. Edges closer to the camera have a longer pixel-length than edges further from the camera, even though they have the same real world length. While it is possible to flatten the underlying homography matrix provided by the AprilTags library, it was determined that it would be easier to simply obtain the pixel-lengths for a flattened projection geometrically through the following algorithm.

A single possible projection of the AprilTag into camera space is displayed in the figure to the left. The AprilTag size in pixels must be determined in order to complete the scaling factor from pixels to physical distance.

To determine the robot's position and orientation, three AprilTags are placed along the top of the collection bin to serve as reference points. From these points the robot can determine whether it has traveled far enough to begin mining or is close enough to deposit its payload. In theory one tag would be sufficient, but three provide redundancy in case one or more tags goes out of the camera's field of view.

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