Design and Implementation of a Rocker-Bogie Suspension for a Mining Robot

Wesley B. Williams and Eric J. Schaus
University of North Carolina at Charlotte/Georgia Institute of Technology

Abstract

As their capstone senior design experience, students from the William States Lee College of Engineering at UNC Charlotte participated in the 5th Annual NASA Robotic Mining Competition, where they competed with a six-wheeled robot that employed a rocker bogie suspension to traverse the simulated Martian terrain. The 170 pound robot was designed to be teleoperated during a 10 minute competition run where it was tasked with travelling to a designated mining area, mining regolith simulant from that area, and returning to the starting area to deposit the regolith. Travel across the mining arena is complicated by the properties of the basaltic regolith simulant (Black Point-1 or BP1) as well as the intentional presence of both rocks and depressions in the surface. The students were tasked with employing either a torsion bar suspension or rocker-bogie suspension, and ultimately settled on the rocker-bogie approach. In order to maximize their maneuverability during the competition, the students set a design criteria of being able to traverse any of the prescribed obstacles in the mining arena. Students progressed toward the final design by using: kinematic analysis, SolidWorks Motion simulations, prototyping, and literature reviews. After the relative motions were defined, the design focus shifted to the stresses calculations and manufacturability, where a combination of hand calculations and finite element analysis (FEA) were used to make material, sizing, and hardware selections. The resulting design was fabricated and tested to ensure both range of motion and stiffness during static loading. After modifications to increase the stiffness in key areas, the design was tested under dynamic conditions to mimic the arena obstacles and found to meet or exceed the desired performance. This performance was repeated at Kennedy Space Center, where the suspension allowed the operators to navigate the arena with confidence during both testing and competition.

Keywords

Robotics, FEA, Design, Capstone

Introduction

The NASA Robotic Mining Competition (RMC) engages university students in designing, building, and competing with robots in a simulated Lunar or Martian terrain (depending on the year). The goals of the program include introducing these students to some of the real challenges of robotics, teleoperation, and automation, while also tapping into their creativity for innovative ideas or strategies that could be applied to NASA missions[1]. At the University of North Carolina at Charlotte, participation in this competition also serves to fulfill the capstone senior year design experience requirement for engineering undergraduates.

The senior design experience for engineering students at UNC Charlotte spans two semesters, with the first being dedicated to understanding the problem, exploring the design space, and arriving at a detailed design. The second semester is dedicated to the fabrication, assembly, and testing of the design. The multidisciplinary teams for each project are filled based on preference surveys given to the entire pool of students in senior design and some direct placements based on prior experience. While most senior design teams consist of four or five students, the NASA RMC team was assigned a total of ten students, based on the scope and complexity of the competition. The students came from the departments of Mechanical Engineering, Electrical and Computer Engineering, Electrical Engineering Technology, Mechanical Engineering Technology, and Systems Engineering. For the 2014 team, one Mechanical Engineering student, and two Mechanical Engineering Technology students were preassigned to the project based on prior experience (informal work with the previous year's team). The remaining students were assigned to the project as a result of the project preference survey administer in the capstone senior design lecture course. The RMC students receive faculty support from 2-3 faculty mentors and a grader at regular meetings throughout the semester, with three main design reviews each semester constituting the majority of their grade in the course.

The students were tasked with meeting all of the NASA requirements for competition, while satisfying the requirements for senior design, and meeting any additional design requirements established by the faculty mentors. For the 2013-2014 RMC competition, the faculty mentors specified that the robot design must include either a torsion-bar suspension system or rocker bogie suspension system. The design was also to focus on the automation and drive systems, leaving the excavation system from the prior year untouched, as it had performed reasonably well in the competition.

Design Approach

The team naturally divided into an automation subgroup and drive subgroup, with the drive subgroup (particularly the student technical lead for the drive subgroup) taking ownership of the suspension design. The drive students began with an initial interview of the faculty mentors to understand why they mandated the inclusion of either a rocker bogie or torsion bar suspension. The students then went through a preliminary selection process to determine whether to proceed with a rocker bogie or torsion bar concept, ultimately deciding to pursue the rocker bogie concept. Following that decision, they performed a literature review to identify best practices for implementing a rocker bogie, performed a kinematic analysis to establish the required geometry, and finally performing a finite element analysis (FEA) to size the suspension components.

A rocker bogie suspension consists of linkages on either side of the base that pivot (or rock) in response to terrain features and bogie, which is a linkage with drive wheels at both ends. The left side and right side linkages are connected through a differential, which accounts for variation in the terrain traversed by the left side and right side suspension. The rocker bogie aims to meet several design goals including: keeping all six wheels in contact with the terrain, minimizing the vertical travel of the rover body, and increasing the severity of the terrain that can be traversed without risking tipping.

NASA patented the concept of what came to be known as a rocker bogie suspension in 1989. Recent robotic exploration of Mars has showcased the rocker bogie design in the Mars

Pathfinder, Spirit, Opportunity, and Curiosity rovers. These rovers vary in terms of scale and geometry, but the suspension concept remains throughout. In testing (on Earth) as shown in Figure 1 below and actual missions on Mars, the suspension has met the design objectives of allowing maneuverability over obstacles, with minimal tilt or displacement of the robot frame.

Figure 1. NASA's next Mars rover, Curiosity, drives up a ramp during a test at NASA's Jet Propulsion Laboratory, Pasadena, Calif., on Sept. 10, 2010[2]

The suspension was analyzed initially for the kinematics, using both the largest rock and largest depressions expected in the competition arena, based on NASA RMC published specifications[3]. The orientation of the linkages were assessed with a combination of hand calculations initially and later, by inspection of SolidWorks assemblies. An example of a simplified kinematic model used in the analysis is shown in Figure 2 below.

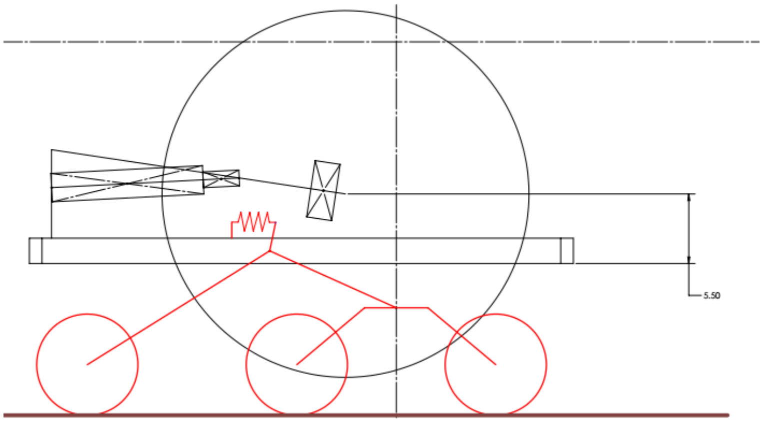
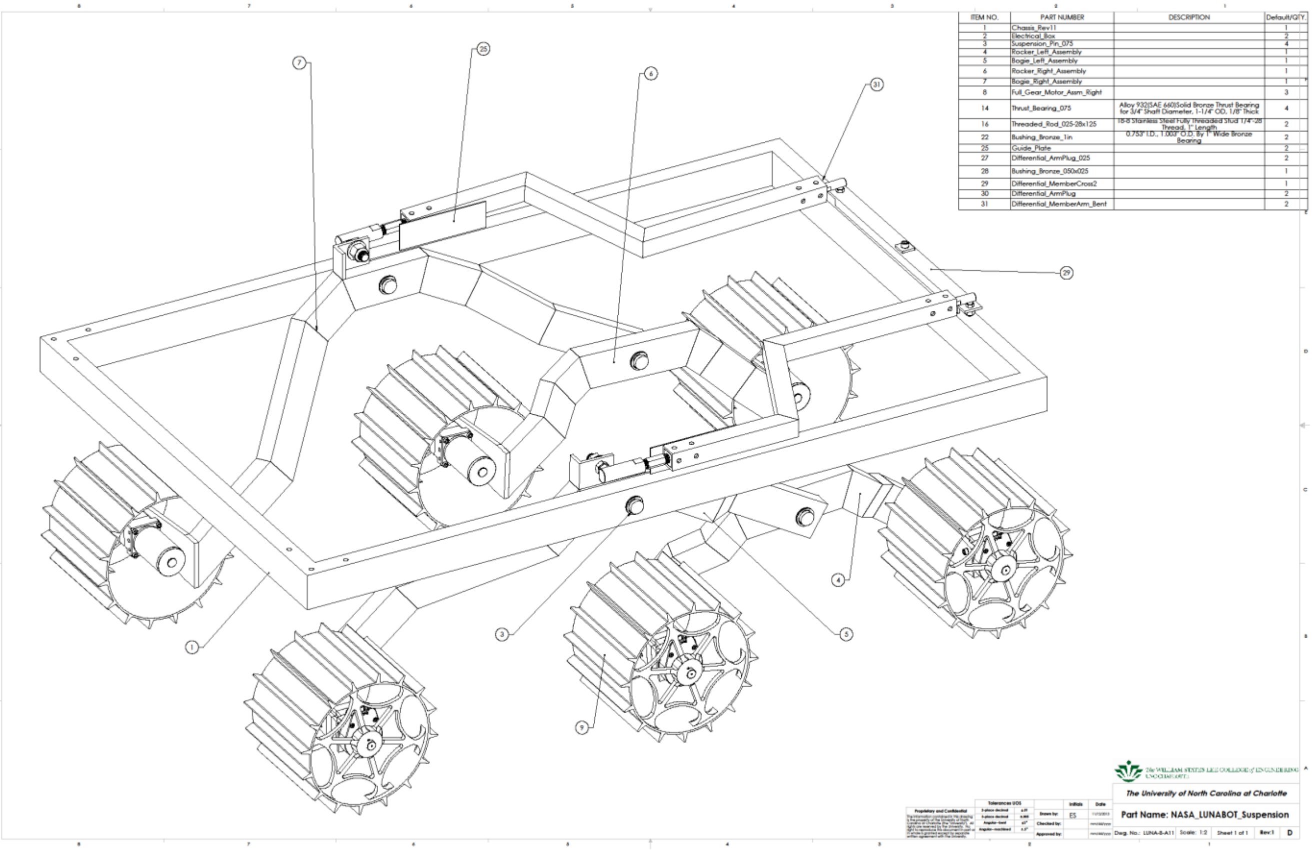


Figure 2. Simplified kinematic analysis geometry of a spring balanced rocker bogie suspension.

The SolidWorks assemblies were comprised of part models that were connected with relations that reflected the types of joints and associated degrees of freedom. Elements of the assembly could then be ‘dragged’ into an appropriate orientation for the model terrain, and the rest of the assembly would move accordingly. In addition to the standard rocker bogie design task of verifying the appropriate motion of the linkages when encountering an obstacle, the student designers also had to avoid any excursions into the interior of the frame, as that would interfere with the operation of the bucket wheel excavation system.

This represented a significant challenge of the design, making it markedly different from simply designing a rocker bogie suspension for a robot or even designing an excavating robot from scratch that employed a rocker bogie suspension. This element of the design was the result of deliberate decisions by the faculty mentors, based on both educational outcomes and competitiveness. From an educational point of view, the mentors wanted to constrain the design space somewhat based on their prior experiences and conversations with other RMC mentors at competition that suggested that starting with a completely new build each year was too daunting of a task. Carrying over the excavation design from previous the year helped to reduce the scope to be more manageable, but also gave students experience with designing around preexisting geometry as constraints, which is more probable for an early career engineer than being given ‘a blank sheet of paper’ and complete latitude with a design. From a competitiveness perspective, it salvaged the most encouraging system from the prior year, allowing the students to focus on drive and automation systems, both of which had fallen short of expectations in prior years. As previously mentioned, inheriting the excavation system meant the design challenge of designing around that volume and those ranges of motion. A prime example of this is the bent and offset geometry for the differential linkages that had to be designed around two enclosures mounted on the frame (to house drive and control electronics). An assembly drawing of the suspension is shown in Figure 3 below, detailing the various components and notably leaving the interior of the robot chassis empty to allow for the excavation system.



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
1	Chassis_Rev11		1
2	Electrical_Box		2
3	Suspension_Pin_075		4
4	Rocker_Left_Assembly		1
5	Bogie_Left_Assembly		1
6	Rocker_Right_Assembly		1
7	Bogie_Right_Assembly		1
8	Full_Gear_Motor_Assm_Right		3
14	Thrust_Bearing_075	Alloy 932(SAE 660)Solid Bronze Thrust Bearing for 3/4" Shaft Diameter, 1-1/4" OD, 1/8" Thick	4
16	Threaded_Rod_025-28x125	18-8 Stainless Steel Fully Threaded Stud 1/4"-28 Thread, 1" Length	2
22	Bushing_Bronze_1in	0.753" I.D., 1.003" O.D. By 1" Wide Bronze Bearing	2
25	Guide_Plate		2
27	Differential_ArmPlug_025		2
28	Bushing_Bronze_050x025		1
29	Differential_MemberCross2		1
30	Differential_ArmPlug		2
31	Differential_MemberArm_Bent		2

Figure 3. Assembly view of the rocker bogie suspension (excavation and control systems removed for clarity)

With the kinematics and relative motion of the linkages understood, it was important to then verify that the suspension would not fail due to high stresses or deflections in the components. To minimize weight while maintaining stiffness in the suspension components, aluminum 6061 box tubing was considered a prime candidate based on experience from prior years, with the required wall thickness being determined by the resulting finite element analysis. Static loads were applied to individual elements of the suspension, based on the results from free body diagrams. Key areas of concern were the rocker and bogie linkages themselves, the pins supporting the left side and right side linkages, and the differential bar. An example of the FEA results are shown below in Figure 4, which details the von Mises stresses in the rocker linkage under static loading.

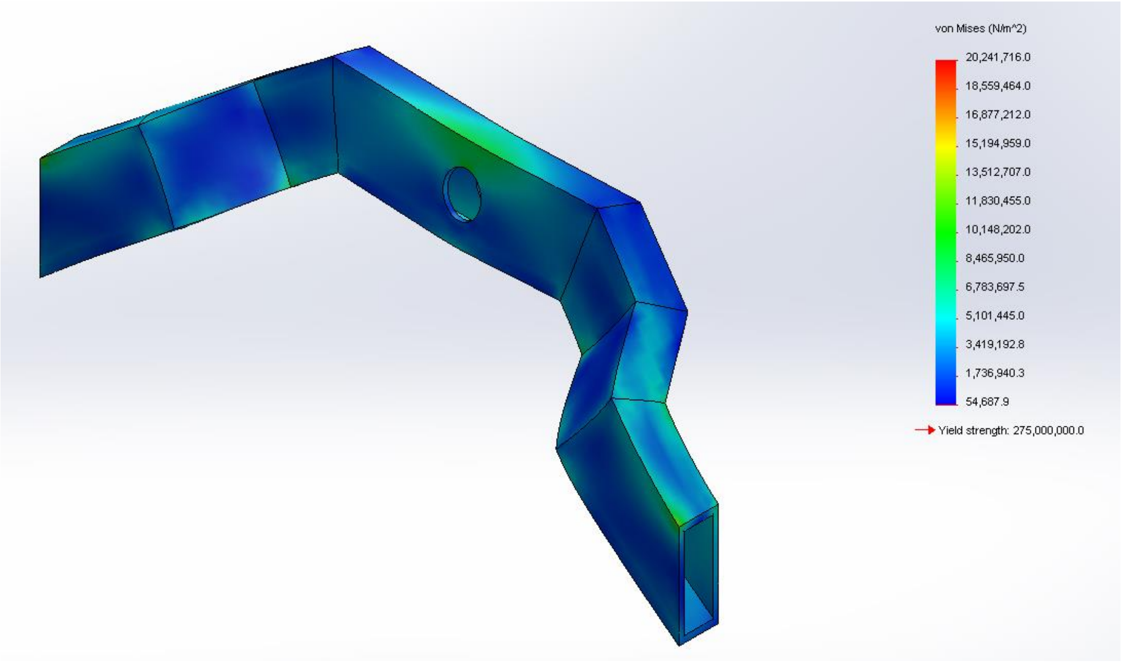


Figure 4. SolidWorks Simulation FEA static load results for the rocker linkage, showing von Mises stresses.

The kinematics and FEA went through several iterations, with candidate 2D geometry from the kinematic analysis being given a cross section and material that enabled the FEA to assess the stresses and deflections. Once the stresses and deflections were acceptable, the kinematics of the 3D model was examined to identify any potential interferences or collisions. Ultimately, the student designers selected aluminum 6061-T6 1.5” × 1” box tubing for the suspension components and 1” × 1” square tubing for the differential components.

The pinned connections between the rocker and chassis, and rocker and bogie were designed using a 0.75 inch steel shaft supported in bronze bushings. The steel shaft is held in place by two retaining rings on either side of the pinned locations. The maximum PV value seen by the bushings was expected to be less than 6.91, which for the specified bushings should mean an indefinite lifespan. The maximum allowable thrust load for the retaining rings was 5180 pounds force and the maximum expected thrust load was less than 400 pounds. With these expected values, the selected retaining rings were not anticipated to fail under normal operating conditions

Fabrication

To assemble the suspension, students cut the individual sections out of 6061 aluminum box tubing. In addition to the requisite angles to build up the linkage geometry, the edges of the section were also slightly beveled in preparation for welding the sections together to form the linkage. Prior to welding, the holes for press fitting the bushings were drilled into the relevant sections. These sections which housed the pivot had a High Density Polyethylene (HDPE) insert pressed into the interior prior to pressing in the bushings. There was concern that the thin wall at the bushing location would be prone to deflections during the bushing insertion or any side loading and the decision was made to include these inserts to reinforce this critical area. Once the HDPE inserts and bushings were pressed into the pivoting sections, a student welded up the sections to complete the linkage element.

The aluminum sections at the end of the differential linkages were fitted with threaded inserts to house the hardware connecting the differential arms to the rocker and the differential arms to the differential bar. In the base of the differential bar, that connection was a pivoted joint to allow for left the left side wheels to travel over an obstacle at the same time the right side wheels were travelling through a depression, without the robot experiencing significant roll. The differential to rocker arm connection included a turnbuckle style threaded rod, which allowed for adjustments to the linkage lengths. These linkage adjustments enabled balancing the suspension once the robot was completely assembled and all the component weights were included in the system.

Testing and Performance

Once fabricated, the suspension was tested in several environments prior to competition, including laboratory obstacles, sand in a volleyball court, and in the actual competition arena. Testing in the laboratory involved tethering a controller to the robot and having the operators walk alongside as they had it traverse obstacles such as 2”×4” pieces of lumber on the floor. While the robot was able to traverse these obstacles, the transition off of the right angles of the lumber provide a significant jar to the robot. A contributing factor in the jarring was also the speed of the robot when traversing the obstacles. The actual Mars rovers move at much slower speeds (<0.05 mph), which mitigates if not eliminates much of the prospect of jarring when coming off of obstacles. Fortunately, there was minimal damage to the suspension as a result of the jarring drop off of the obstacle, with a plastic deformation in the differential bar being the only significant damage.

In order to remain competitive, it was not feasible to lower the speed of the robot during competition, so it was important to understand the nature of similar impacts that might occur during competition. The laboratory impacts involved falling onto a hard, thinly carpeted, floor which increased the shock loading experienced by the suspension. Events in the arena would be less severe because a) the obstacles in the arena are less likely to include immediate drops and b) the compressibility of the regolith would help to attenuate any impact from any falls after losing contact with an obstacle.

Despite these mitigating factors, the team did make plans for reinforcing the perceived weak points in the design. Given the plastic deformation that occurred in the differential bar, the 1”×1” square aluminum tubing was replaced with 1.5”×1” box tubing to increase the stiffness. While there were no signs of failure during the initial testing, there were concerns about the differential arm assemblies because a) they used the same 1”×1” square tubing and b) the zig zag geometry created stress concentrations in the model. Replacing these sections with the 1.5”×1” box was not feasible due to space constraints and weight constraints (as the robot was already approaching the 176 pound weight limit), so the students designed gusset plates that could be welded into the corners of the differential arm if later testing determined that they were needed.

The assumptions about the mitigating effects of the regolith on impacts were put to the test when the robot was first tested in a sand volleyball court. The robot was able to readily traverse both mounds that were built up and depressions that were dug into the sand. These obstacles were roughly the same height/depth as the wheel diameter, which was smaller than the largest obstacles that calculations suggested it should be able to traverse[4]. Despite repeatedly traversing these obstacles in the sand court tests, the suspension did not show any signs of damage. Considering both the lack of damage and the penalty assessed in the competition for each kilogram of mass, the students made the decision not to include the reinforcing gussets to the differential arm.

As the properties of the simulated regolith are very different from common sand, the first practice round in the competition arena posed maneuverability challenges for the robot, but these were due not to suspension, but the wheels. Once the wheels were modified, the students were able to navigate the arena with confidence and successfully mine and deposit 17.9 and 42.7 kg of regolith in their first and second runs respectively, as shown in Figure 5 below. A key element in the operators being willing to drive the robot more aggressively in their second bout was additional stress testing of the robot in a sand practice field between the matches. In the practice field, the students built obstacles (mounds and depressions) that approached twice the wheel diameter in size. Seeing that the robot was able to traverse these oversized obstacles, as was predicted in their literature search, they felt confident in pushing the robot in the final competition run. This aggressiveness led the students to an 8th place finish in terms of points and a 7th place finish in terms of regolith mined.

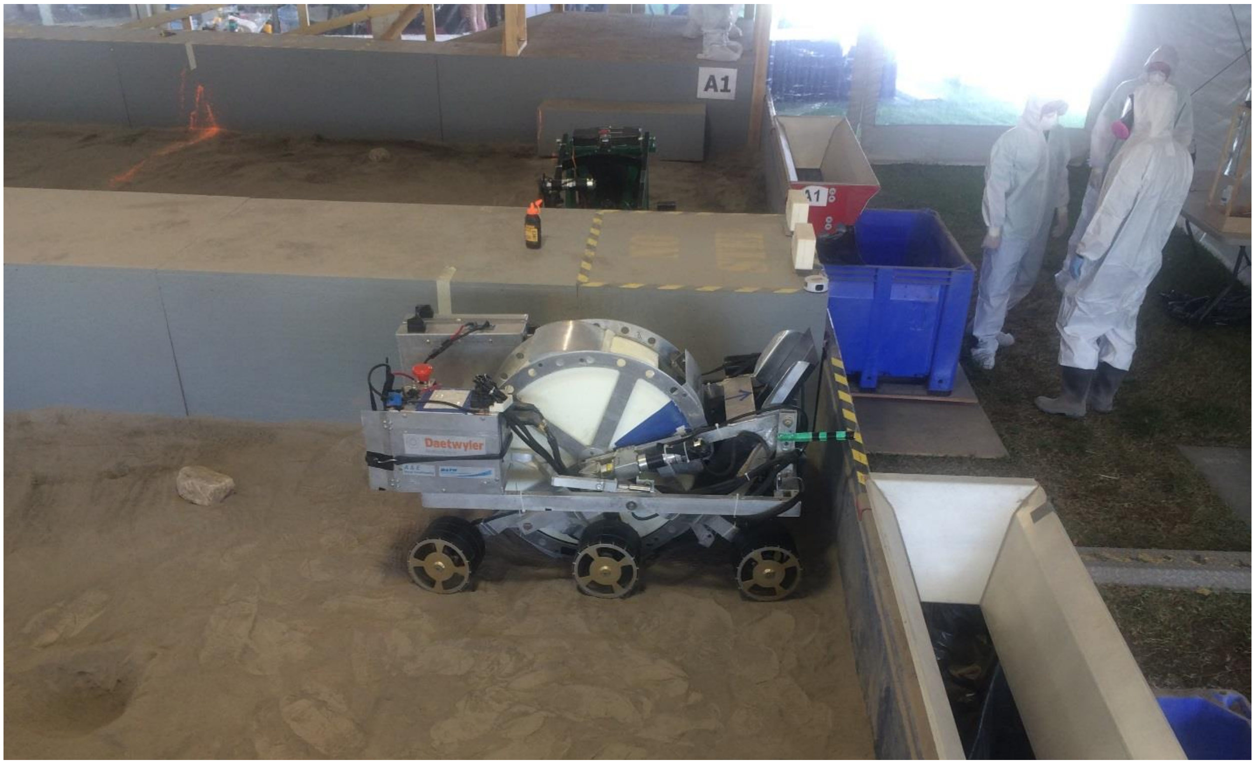


Figure 5. The UNC Charlotte RMC robot during a competition round at Kennedy Space Center in the Martian regolith simulant.

Conclusion

The students were successful in designing, building, testing, and implementing a rocker bogie suspension on a competitive robot in the 2013-2014 NASA Robotic Mining Competition. The design portion progressed through logical steps of a literature review, kinematic analysis, finite element analysis, and clearance and interference checks. Similarly, the build progressed through component fabrication, verification, assembly, testing, and refinement. It was particularly satisfying for the students involved in the design to see the suspension successfully tackle the larger obstacles that were presented before it in testing. While the design calculations had been checked and double checked, the tension in the assembled students was apparent as the robot navigated those extreme mounds and depressions. The cheers and congratulations that ensued once it successfully cleared the obstacle were the equivalent of many sporting events or FIRST Robotics competition. In addition to being a success for the team, it was a success for the approach as the performance predicted in the design process was realized in the final product.

In addition to the countless hours that the students put into this competition, the team also benefited from several other key sources of support. Participation in the competition would not have been possible without a Senior Design Project and Team Competition grant from the NC Space Grant. Travel funds from the UNC Charlotte Student Government Association and matching funds from the UNC Charlotte Senior Design committee were critical as well. Finally, the team benefit from strong corporate support with companies providing financial support, access to manufacturing equipment, and materials to build a scaled competition arena for testing.

References

1 http://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html
2 http://www.jpl.nasa.gov/news/news.php?feature=2732
3 http://www.nasa.gov/sites/default/files/robotics_mining_competition_rules_2014_1.pdf
4 Ullrich, Franziska, Goktogan Ali, and Sukkarieh Salah . Australian Centre for Field Robotics, "Design Optimization of a Mars Rover's Rocker-Bogie Mechanism using Genetic Algorithms." Accessed December 7, 2013. http://db.acfr.usyd.edu.au/download.php/Ullrich_GoktoganASSCDesignOptimization.pdf?id=2409.

Wesley B. Williams

Wesley Williams is an assistant professor in the Department of Engineering Technology and Construction Management in the William States Lee College of Engineering at UNC Charlotte. His research interests include additive manufacturing, loose abrasive finishing, and magnetic gearing. He teaches courses in the areas of instrumentation and controls, technical programming, and strength of materials. In addition to mentoring UNC Charlotte's NASA RMC team, Dr. Williams has mentored several other capstone design teams and volunteers as a lead robot inspector at FIRST Robotics competitions.

Eric J. Schaus

Eric Schaus is a doctoral student in the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. He graduated from the William States Lee College of Engineering at UNC Charlotte, with a bachelor's degree in mechanical engineering. While at UNC Charlotte, he served as the student technical lead for the drive systems on UNC Charlotte's 2013-2014 NASA Robotic Mining Competition team, which placed 8th overall at the national competition.