Proceedings of The National Conference
On Undergraduate Research (NCUR) 2019
Kennesaw State University
Kennesaw, Georgia
April 11-13, 2019

Using Rocker-Bogie Suspension System to Build R-BEAR: Rocker Bogie Earth explorAtion Rover

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Abstract

Do you remember the Mars rover, 'Sojourner'? It was the first Mars exploration robot developed by Jet Propulsion Laboratory (JPL). One of the engineering accomplishments of JPL's engineers was the rover's wheel mount system that is referred to as the rocker-bogie suspension. The main objective of this research is to apply the rocker-bogie system to the Rocker-Bogie Earth explorAtion Rover (R-BEAR). The rocker-bogie system consists of six wheels, has no spring or axles for each wheel, and can climb obstacles higher than its wheel size. This work discusses various aspects of design, analysis, and applied physics concepts used in building and testing R-BEAR. R-BEAR was remotely controlled, its motion was studied, and relevant experimental data were obtained on test tracks with varying environmental conditions that included artificial obstacle courses and diverse outdoor terrains. A detailed analysis was performed to determine R-BEAR's optimal build-structure, composition, and functionality based on the collected structural and motion-based observations.

Keywords: Rocker-Bogie Suspension, Mars Rover, Differential

1. Introduction

R-BEAR, Rocker-Bogie Earth explorAtion rover, is a robot that uses a rocker-bogie suspension that was modeled after NASA's first rocker-bogie rover *Sojourner*, from its 1993 *Pathfinder* mission [1, 7]. The rocker-bogie suspension is a six-wheel mount system designed with the purpose of traversing rough terrain by maximizing adaptive balance and ground contacts in order to prevent immobilization. This reliable stability is critical for exploration robots as they must travel alone; it is crucial that an exploration rover does not topple while scaling unknown terrain [16]. If an exploration rover loses its balance, the expedition for that rover is essentially over as it is most likely in a rough environment and a very remote location. This type of suspension is not just useful for outer space exploration; it is useful for accessing many different types of environments in which humans cannot easily access. This suspension design allows robots to travel through areas affected by natural and man-made disasters [13].

This balancing ability is specifically due to several different components that make up the rocker-bogie suspension. One such component is the differential [12, 14] between the two sides of the robot so that while one side is elevated higher than the other, the opposite side can still adjust to maintain contact with the ground. As the name suggests, the other two components are the rocker and the bogie. The rocker part is the larger "arm" of the suspension that is connected to the differential and balances the vertical displacement between either side of the main body. Figure 1 shows the rocker portion (shown in blue) of the suspension along with the bogie (shown in red) and the differential (shown in green) components of the suspension system. The bogie part is the smaller "arm" that rotates around the axis where the rocker and bogie arms meet. These two arms are on either side of the rover and are able to pivot independently of each other to provide a highly adaptive and balanced maneuvering ability [11, 12]. This paper focuses on the designing, assembling, and testing of R-BEAR.

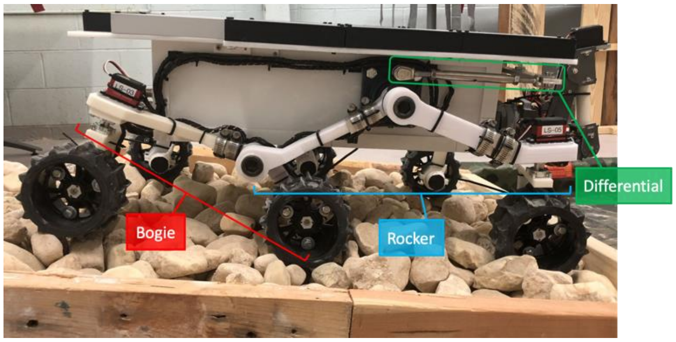

Figure 1. Diagram of R-BEAR's lateral view showing the differential and the rocker and bogie arms.

2. Methodology

2.1 Mechanical Design

One predicted issue that NASA had encountered and responded to with the development of Curiosity compared to Sojourner is that the front two wheels tend to drift inwards when the rover moves with its bogie wheels in front. A remedy to this was recommended by NASA by employing a front-facing rocker wheel configuration [2]. Therefore, R-BEAR, similar to Sojourner, moves forward with its bogie arms in front. In spite of having several advantages of rocker-bogie suspension compared to a regular four-wheeled suspension, the biggest disadvantage of this type of wheel system is that it is slow-moving and is more complicated than the ubiquitously found differential-based four-wheel system due to its extra pair of wheels. At high speeds, the rocker-bogie suspension is generally much more unstable than regular four-wheeled suspensions [10, 14].

All main 3D printed parts in R-BEAR were made of ABS (acrylonitrile-butadiene-styrene) filament and were modeled in Design Spark Mechanical and Fusion 360 software. All the custom designed parts were printed using the Qidi Print 3D printer. Figure 2 shows a collage of the 3D design for R-BEAR in Fusion 360 software. The ABS printed bogie arms were designed using two approaches. The left side had six small 0.8mm holes and pins to hold the pieces together while the right side had only two 2mm square holes and pins to hold the printed arms together. Initially it seemed that this difference would be no problem, and that the smaller pins would be stronger than the two larger pins, but the opposite proved to be true as the outer walls of filament surrounding the joints were too thin. The left side bogie arm started to fracture after the third test run.

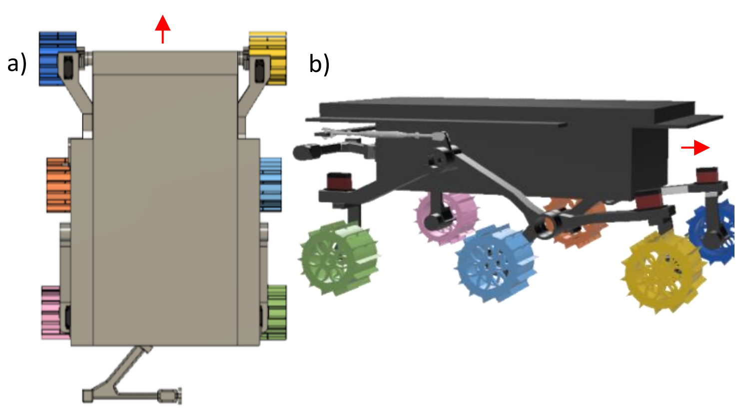

Figure 2. Top view with front facing up (a) and side view with front facing right (b) of R-BEAR 3D model generated in Fusion 360 CAD software. The wheel colors correspond to the entries in Figure 7.

The temporary remedy for this was the installation of two metal clamps on each of the three joint connections to both sides. The future remedy with be replacing the printed arms with the experimentally strongest joint connection type.

The enclosure wall of R-BEAR's central body was cut from ¼" and ½" thick HDPE (High-density polyethylene) boards. The dimension of the central compartment was chosen to be closely resembling that of Sojourner rover. The central compartment was made by assembling two rectangular HDPE pieces of dimensions 19" x 5" with two rectangular HDPE pieces of dimensions 11" x 5". Assembly of R-BEAR successfully allowed demonstration of the basic requirement for rocker-bogie suspensions: the ability of the rocker and bogie components to pivot independently of each other. Below is a table of the other components used to assemble R-BEAR.

Table 1. Table of the main components in R-BEAR

Part name	**Quantity**	**Description**
¼" and ½" thick HDPE plastic sheets	1 each	The ¼" thick sheet was cut to be used as the walls and roof for the main body of R-BEAR. The ½" thick sheet was cut to be used as the bottom of the main body of R-BEAR.
Rubber tires	6	The tire height measured 5". The tires were mounted on plastic wheels (rims) and bolted to DC motors with connector hubs.
DC geared drive motors 12V	6	These motors were used as the drive motors for forward and backward movement of the rubber tires.
Digital servo motors 6.6V	4	These servo motors were placed on the front and back wheels of R-BEAR in order to rotate R-BEAR's wheels.
20W Solar Panel	1	Measures 12.6" x 6.3" x 1" and charges the main Pb battery when in sunlight to allow independent recharging in remote and/or inaccessible areas.
Lead-acid (Pb) battery 12V	1	Main battery used to power the motor controller and drive motors.
Flysky RC (radio-controlled) transmitter and receiver	1	Radio-control (RC) set used to wirelessly control R-BEAR's drive and servo motors. Came with a 4.8V NiMh battery to power the RC receiver.
Lithium polymer (LiPo) battery 7.4V	1	Additional power for the servo motors after field testing proved not enough power was supplied to the servo motors.
Roboclaw 2x60A motor controller	1	Motor controller that controls the DC drive motors
SainSmart Environmental Robotic Arm (E.R.A)	1	9.5" x 8.8" x 4.6" and 1102 grams. Not yet programmed for sample collection but attached to R-BEAR.

2.2 Electrical Design

R-BEAR is powered by three batteries: a main 12V Pb battery, a servo-powering 7.4V LiPo battery, and a 4.8V RC receiver-powering battery. Initially, the main Pb battery was a larger and heavier but was replaced with the lighter 12V Pb battery. The six drive motors are controlled by one dual motor controller, while the four servo motors connect to an RC receiver and transmitter. Initially, the power provided to each servo was not high enough to fully rotate the servo to the intended position. This was corrected through installation of a separate dedicated 7.4V LiPo battery to power the servo motors. However, the installation of this LiPo battery also caused a large increase in high-frequency interference between the motor signals and the servo signals. Every time isolated drive motor input was given, the S4 and S6 servo motors rotated 90° along with twitching from all other servo motors. The installation of multiple ferrite beads and isolation of signal wires from power wires significantly decreased servo motor twitching. However, further permanent wire separation is required in order to minimize levels of noise interference.

The 20W solar panel connects to the main 12V Pb battery for additional charging in outdoor environments with access to sunlight. The outer wires from the servo and drive motors were wrapped in black a plastic coil for organization and protection. The wires from the outer components (drive and servo motors) were connected to the inside of the body through a plugging and unplugging soldered bushing (Figure 3) connection to closely resemble Sojourner. The wires were soldered onto metal bushings as shown in the image below:

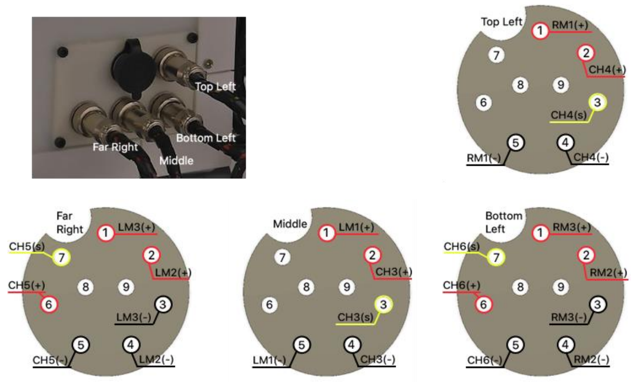

Figure 3: Bushings of wire connections for R-BEAR

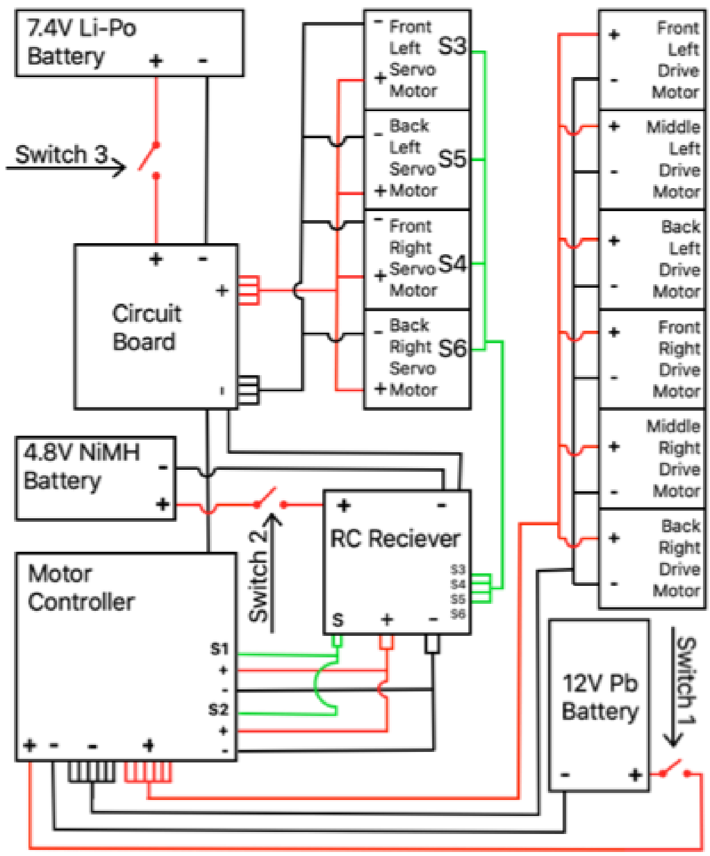

Figure 4: A wiring diagram of R-BEAR

Figure 4 shows the wiring for the main components of R-BEAR. All components in the diagram except for the servo motors, drive motors, and switches are contained within the main body of R-BEAR. The positive power wires are colored in red, while the negative/ground power wires are colored in black, and the signal wires are colored in green. The circuit board component was added to help simplify connections between the many components as well as provide more ground access. The motor controller only connects signals for the left and right sides of the drive motors to the RC receiver, while signal for the servo motors directly connect to the RC receiver.

3. Data

After design and assembly of R-BEAR, several different tests and experiments were performed in order to measure R-BEAR's performance and functionality. The data section below is separated into two main parts: experimental design and experimental results. Definitions and descriptions of the experiments performed are found in the experimental design section. Data collected and analysis of said data are found in the experimental results section.

3.1 Experimental design

Table 2: Identification of the experiments used to test the functionality of R-BEAR

Test name	Test Description
Hill tests *3.2.1*	R-BEAR was tested for its capability of traversing three custom made hill topographies that were composed of different material: brick, rock, and sand. These hill tests help to assess R-BEAR's potential for traveling in an unknown outdoor environment by testing first in an indoor controlled environment [7, 8].
GGC Local Terrain Tests *3.2.2*	In this test, R-BEAR's mobility was tested on several types of terrains found on Georgia Gwinnett College (GGC) campus. For each of the local terrain, the rover was tested for 35 minutes each in order to determine whether or not R-BEAR was capable of traversing locally found terrain. The terrains we found on GGC campus were carpet, linoleum, grass, asphalt/pavement, concrete, and gravel.
Incline tests *3.2.3*	Incline tests were performed on R-BEAR in order to measure the coefficient of friction [8] between the surface of R-BEAR's tires and test surfaces. For this test, R-BEAR's wheels were zip-tied (to prevent rolling) and placed on an oriented strand board (OSB) with one end gradually lifted to create an incline. The degree of the inclination was recorded at the moment R-BEAR began to slide down the incline. Additionally, this test was performed by placing layers of bricks and rocks on top of the OSB to create desired test surfaces.
Mass distribution tests *3.2.4*	The mass distribution tests measured the weight recorded under each wheel as R-BEAR was tilted in the increments of 2°, starting with a 4° tilt until a maximum of 10° tilt. The weight under each wheel was recorded by placing weight scales under each wheel. To increase the tilt of R-BEAR, bricks were placed under the balances on one either (left or right) side. At any time, all wheels on one side of R-BEAR were elevated by the same height. Side-tilting of the wheels essentially moved R-BEAR's center of gravity.
Obstacle tests *3.2.5*	The obstacle tests measured R-BEAR's ability to overcome obstacles at least 1.5 times its wheel diameter of 5", or obstacles of at least 7.5" tall [9]. Theoretically, this suspension should be able to overcome obstacles more than half of its wheel radius [12].
Minimum tipping angle tests *3.2.6*	R-BEAR was placed on an OSB board with a ledge at the bottom end to stop it from rolling. The tipping angle was measured twice, with the rear of R-BEAR facing towards the ledge (Forward) as well as away from the ledge (Backward) as it was inclined. The inclination angle of the board was measured at the point where R-BEAR began to tip over.
Differential motion dampening tests *3.2.7*	R-BEAR was placed on a flat, level surface to determine its resting orientation. An OSB board placed under one of the rocker-bogies was tilted so that the front wheel was higher than the rear wheels. The inclination angles of the board and the main body of the rover were measured to determine if the differential [14] was effective at reducing the amount the body tilts when passing over terrain with different slopes on each rocker-bogie.

3.2 Experimental Results

3.2.1 hill tests: brick, rock, and sand

The brick hill measured 33 ½" long with a peak height of 9", and an angle of incline of 19.02°. The rock hill measured 30" long with a 6" peak height, and 16.16° angle of incline. The sand hill measured 20" long with an 8" peak height, and 13.83° angle of incline. The standard deviation (2.5997) between the angle of these three tests is small enough (less than 1/3rd of the mean: 16.34) for the results to be comparable.

For all the hill tests, performance during translation motion was considered good if R-BEAR was able to climb the hill if it consistently maintained a constant velocity. Any significant changes in this constant velocity of 8 cm/s, such as skidding, demonstrated a poor performance. Failure to perform the climbing task was defined as R-BEAR being unable to climb over the hill.

For the rock hill test, R-BEAR's performance was considered poor due to its drive motors rubbing against the rocks as it climbed the rock hill. This is because there is not enough clearance, which is partially due to the placement of the motor where the body of the motor is closer to the ground than to the body of the rover. To remedy this, the drive motors must be rotated so that the main body (Figure 5) is facing upwards instead of downwards to minimize contact with the ground.

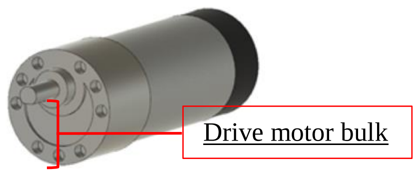

Figure 5: Fusion 360-generated 3D model of drive motor used in R-BEAR. The drive motors were installed with the bulk of the main body facing down towards the ground but must be rotated 180° to improve clearance.

For the sand hill test, R-BEAR failed as it could not climb over the peak of the hill. This is because there is not enough traction within the sand, which causes the forward movement of R-BEAR's wheels to dig into the sand and become stuck. The design of R-BEAR's wheels must be more specific to achieve higher traction on sand in order to successfully climb over this sand hill.

3.2.2 GGC local terrain tests

R-BEAR was tested outdoors on carpet, linoleum, grass, pavement, and gravel successfully. Initially, the servos could not turn fully on surfaces with too much friction such as carpet and grass, as the main power supplied to the servo motors was shared from the RC receiver's 4.8V battery. This was corrected with the installation of a dedicated 7.4V LiPo battery to provide maximum power to the servo motors.

3.2.3 incline tests: brick, OSB, and rock

The coefficients of static friction were calculated by using the coefficient of friction (C.O.F.) equation (1) while driving on bricks, OSB, and rocks. For the C.O.F. equation (1), $\boldsymbol{\mu}$ is the C.O.F. and $\boldsymbol{\theta}$ is the degree of the slope just before R-BEAR begins to slide on each surface tested (also known as the angle of static friction). As shown in Figure 6, during the incline testing, the bogie of R-BEAR tipped upwards off of the surface at angles of incline around 30° but this did not occur every time nor at the same angle of inclination. This indicated that the center of mass of R-BEAR is closer to the back end (bogie end). This finding was supported by the installations of large mass battery packs at the bogie end of R-BEAR. In order to remedy this, weights inside the main compartment must be evenly distributed, specifically added to the front of R-BEAR in this situation. The results shown in Table 3 indicate that R-BEAR performs the best on the brick surface as it has the highest C.O.F., meaning that it can maintain contact with the brick surface at higher angles of incline without skidding as compared to the wood and rock surfaces.

$$\boldsymbol{\mu} = \mathbf{tan}(\boldsymbol{\theta}) \tag{1}$$

Table 3: Results from calculating the coefficient of static friction using θ.

Surface Media	Concrete Brick	OSB	Rock
Angle (degrees)	37	33	33
μ (C.O.F.)	0.75	0.65	0.65

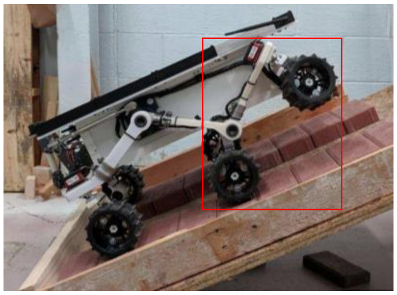

Figure 6: Brick incline test where the front part of R-BEAR's bogie (in red) tilted up off of the brick surface.

3.2.4 mass distribution tests

The mass distribution test was done in duplicates, with the averages of the masses recorded being used to create the graph below:

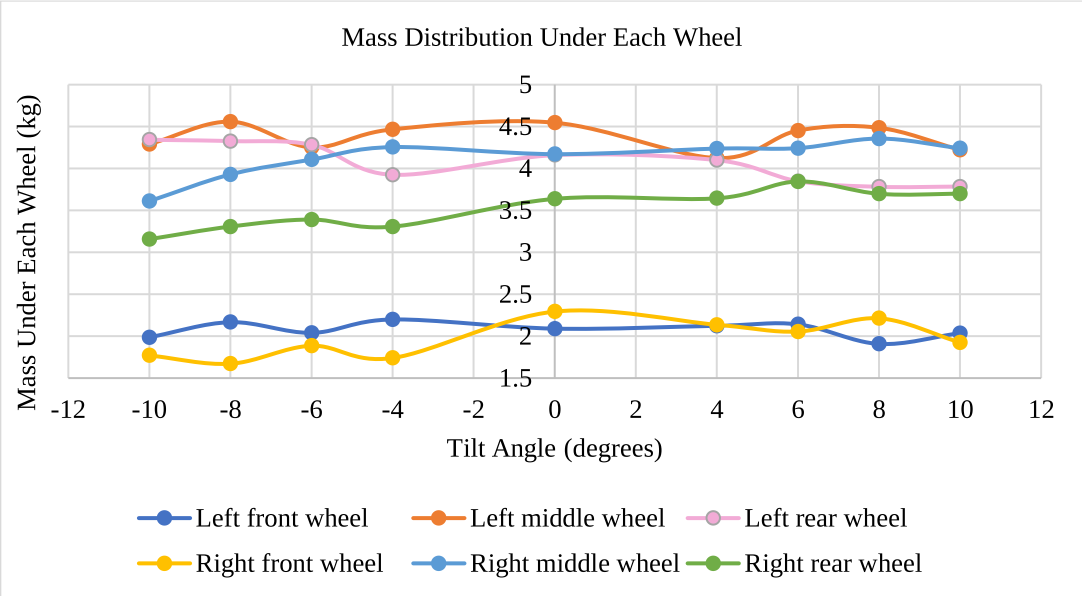

Figure 7: This graph summarizes data from the mass distribution tests and uses averaged data from two trails. The negative x-values indicate that the rover was tilted towards its left side. The positive x-values indicate that the rover was tilted towards its right side. The wheel entry colors correspond to the wheel colors in Figure 2.

Ideally, mass distribution should be evenly spread out among the six wheels [9, 11]. The results from Figure 7 show that the downward force on each wheel converges as the rover tilts from left to right, however, the convergence is minimal. This indicates that the center of mass is very stable because the weights on each wheel would fluctuate significantly more as R-BEAR's tilt angle changes. If R-BEAR has a low center of mass, it is highly stable and successfully demonstrates the stability of its rocker-bogie suspension.

3.2.5 obstacle tests

R-BEAR was tested to overcome stacked brick obstacles of heights 3.75", 5.875", and 7.125". It must be able to overcome at least 1.5x its wheel diameter of 5"; it must be able to overcome an obstacle of at least 7.5" tall [9]. The rover was tested to overcome incremental obstacle height with the average input speed of about 8 cm/s. The height of the obstacle was increased gradually until sliding occurred. The results below show that R-BEAR failed to exceed an obstacle height past 7.125", which is less than the target minimum obstacle height of 7.5" (Figure 8). However, from these results, R-BEAR is capable of overcoming a brick obstacle (5.875" tall) 1.175x larger than its wheel height of 5" or more than twice (2.35x) the wheel radius of 2.5". This is considered more capable than a four-wheeled rover, as they are found unable to climb over obstacles taller than the rover's wheel radius [11].

Table 4: This is a table of the results from the obstacle tests. The test is determined successful if it can fully climb over the obstacle. R-BEAR's performance is considered better the less time it takes and worse for the longer it takes to overcome the obstacle while traveling an average of 8 cm/s.

Obstacle height (inches)	Time for completion (s)	Max body angle displacement	Description
3.75	6	13°	Built with 2 layers of stacked red bricks. Successful; best recorded performance with least amount of time
5.875	7	24.5°	Built with 3 layers of stacked red bricks. Successful; decent recorded performance taking one second longer than previous obstacle
7.125	N/A	N/A	Built with 3 layers of stacked red bricks plus one layer of grey bricks. Failure; the plastic around the rocker/bogie joint gets caught on the brick obstacle and lifts the brick in a way which impedes any forward motion. Future projects should be mindful to reduce protrusions which could catch on obstacles.

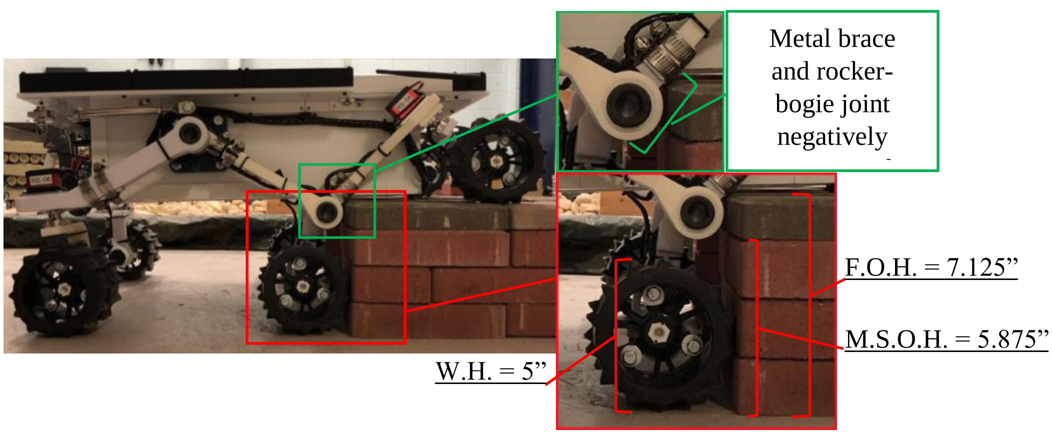

Figure 8: Analysis of R-BEAR's side view during failed obstacle height (F.O.H.) test of 7.125". The wheel height (W.H.) is shown to be 5" while the maximum successful obstacle height (abbreviated M.S.O.H.) is shown to be 5.875" (1.175x of the wheel height).

In Figure 8, the cause of failure for the F.O.H. is shown to be due to both the metal clamp and rocker-bogie joint rubbing against the obstacle. Solutions to this failure are to modify the bogie shape to allow more room for clearance, as well as rotate the drive motor shaft so that the bulk of the drive motor is facing away from the ground.

3.2.6 minimum tipping angle tests

Table 5: A small table showcasing the results of the minimum tipping angle tests.

Tilt Direction	Backward	Forward
Tipping Degree	50°	55°

These results indicate that the front of R-BEAR is more stable than its rear as the results, from the mass distribution tests (Figure 7), show that the center of mass is concentrated in the middle and rear of R-BEAR. R-BEAR will tip over sooner the sooner its center of mass is effected, so if the rear (where the center of mass is located) is tipped, the entire rover will begin to tip over sooner than if the front of the rover was tipped as the front of the rover is farther away from its center of mass. This is considered beneficial as the front of R-BEAR is tipped first when climbing obstacles, and so tipping over is minimized when the center of mass is placed farthest away from the first part of the rover that begins to tip [10].

3.2.7 differential motion dampening tests

R-BEAR was placed on a flat, level surface to determine its resting body angle of 2.88° tilted forward. Then the rocker-bogie was inclined to 30° uphill on the right side while the left side was kept level. The new body angle was found to be 9.11° tilted backward, so the total change in body tilt was 11.99°. This was repeated except with the left side raised instead of the right. The body angle from the left side rocker-bogie tilt was 11.52° backward, so the total change was 14.40°.

Rocker-bogie suspension systems with a differential must reduce the change of body angle to at most 50% of the angle between the rocker-bogies on each side, or the differential is faulty [11, 12, 15]. Since the body angles are less than half of the 30° rocker-bogie angles, this shows that R-BEAR's differential functions at least as well as minimum requirement.

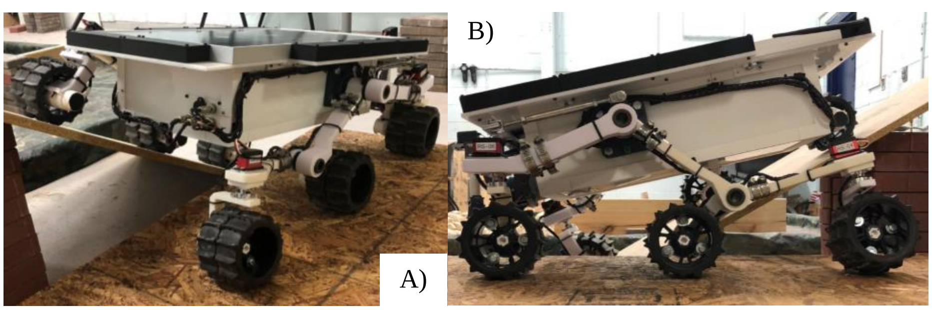

Figure 9: A) Front-view of R-BEAR with 30° uphill incline on its right side. B) Side-view of R-BEAR with 30° uphill incline on its left side.

4. Conclusion

A rocker-bogie suspension rover was successfully designed and assembled using custom 3D printed ABS plastic arms. The mechanical and electrical design was inspired by JPL's Sojourner [1], but with the purpose of Earth exploration rather than Mars exploration. The results of the experiments and tests conducted demonstrate R-BEAR's high level of stability as well as the differences in its performance over various terrain.

Both terrain tests (*3.2.1* and *3.2.2*) as well as the friction tests (*3.2.3*) show that R-BEAR performs the best when traversing terrain that is hard and static (provides more traction), such as brick and rock, and worst when traversing terrain that is softer and more fluid/dynamic such as sand and grass, which provide less traction.

R-BEAR proved to have a low center of mass (and therefore high stability) as the mass distribution (*3.2.4*) changed little throughout the change in the angle of the side-incline. The obstacle tests demonstrated R-BEAR's ability to traverse terrain with obstacles taller than its wheel height (*3.2.5*) while maintaining stability [9]. Minimum tipping angles (*3.2.6*) were found to be 50°, which is the exact target tipping minimum of theoretical rocker-bogie suspensions of high stability [12]. Finally, R-BEAR demonstrated its ability to minimize changes in the angle of the main body through the action of its differential (*3.2.7*). R-BEAR was found to have main body angle changes by less than half of the angle change (half is the theoretical minimum for high stability of rocker-bogie suspensions [11, 12, 15]) for the rocker-bogie suspension. The results of these experiments prove R-BEAR to be a successful model of the rocker-bogie suspension with opportunities or optimization.

Analysis of the experimental results show that the main goal of designing and assembling a rocker-bogie suspended Earth rover was successfully achieved. Future goals for this research are more electrically focused, while also improving upon mechanical limitations uncovered by the experimental results. The implementation of highly precise turning wheel configurations, ROS, Gazebo simulation software, installation and data analysis of environmental sensors, and programming of the E.R.A. are planned for future electrical study of R-BEAR. Further environmental testing, precise adjusting of the center of mass, and optimal-strength 3D printed arms are also planned for future mechanical study of R-BEAR.

6. Acknowledgements

Funding was provided by Georgia Gwinnett College's Undergraduate research program.

7. References

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