Field validation of Nomad's robotic locomotion

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ABSTRACT

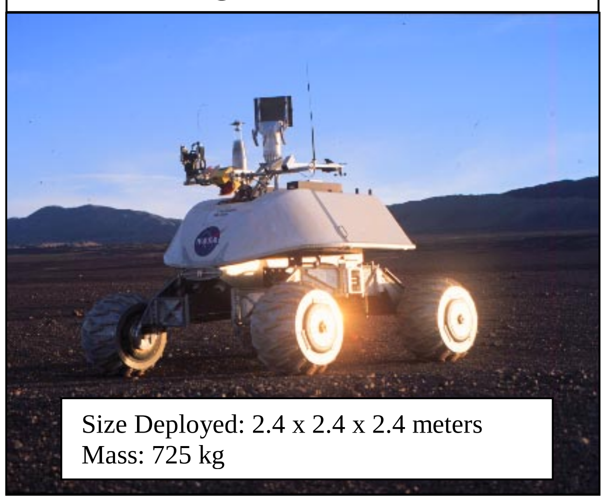
During June and July of 1997, a mobile robot named Nomad traversed 223km in the Atacama Desert of southern Chile via transcontinental teleoperation. This unprecedented accomplishment is primarily attributed to Nomad's innovative locomotion design which features four-wheel/all-wheel drive locomotion, a reconfigurable chassis, electronically coordinated steering, pivot-arm suspension, and body motion averaging. Nomad's locomotion was configured through systematic analysis and simulations of the robot's predicted performance in a variety of terrain negotiation scenarios. Experimental work with a single wheel apparatus was used to determine the effect of repeated traffic and tread pattern on power draw. Field tests before and during the Atacama traverse demonstrated Nomad's substantial terrainability and autonomous navigation capabilities, and validated theoretical performance projections made during its geometric configuration. Most recently, the augmentation of the internal monitoring system with a variety of sensors has enabled a much more comprehensive characterization of Nomad's terrain performance. Because of Nomad's unique steering design a comparison of skid and explicit steering was performed by monitoring wheel torque and power during steady state turns. This paper summarizes the process and metrics of Nomad's mobility configuration, and reports on experimental data gathered during locomotion testing.

Keywords: Nomad locomotion, robotic locomotion, robot performance, Atacama

1. INTRODUCTION

Nomad, a prototype mobile robot, was developed to traverse planetary analogous terrain. During June and July of 1997 Nomad traversed 223km in the Atacama Desert of southern Chile[2]. The primary goal of the trek was to demonstrate teleoperation of a wheeled vehicle over long distance and duration. Several technologies were demonstrated including: imaging, communication, position estimation, safeguarded teleoperation, remote science, and locomotion. Nomad carried a panospheric camera that was used to generate rich imagery with an ultra wide field of view. High band width communication (up to 1.5 Mbps) over long distances (up to 11km) was achieved by the use of an actively pointed antenna. Safeguarded teleoperation gave remote operators direct steering control of Nomad as long as the commanded direction was deemed safe by the robot's onboard sensors. Remote science gave geologists the ability to study rocks from information provided by high resolution stereo cameras, an eddy current sensor, and two 3-axis magnetometers. In order to allow scientists and other remote drivers the ability to traverse a wide variety of unknown landscapes Nomad was designed with a highly capable locomoter.

Figure 1: Nomad



Size Deployed: 2.4 x 2.4 x 2.4 meters
Mass: 725 kg

The configuration design of Nomad was accomplished by using mobility equations to optimize the size and type of locomotion components to satisfy size and performance requirements. In order to detail the performance and validate wheel components a single wheel test-bed was constructed. The test-bed allowed a single wheel to travel in a circle for long

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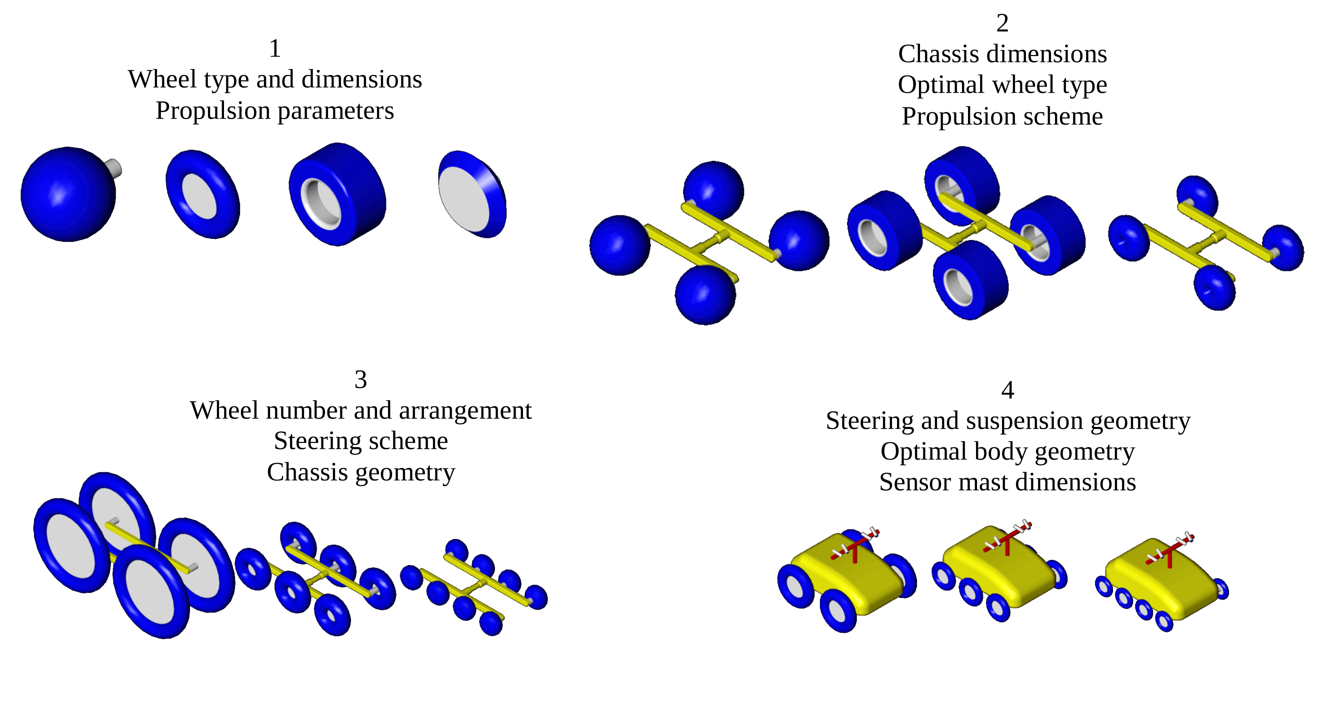
distances. Power draw was monitored as a performance metric while the effects of repeated traffic and tread pattern were studied.

Once Nomad was completed the vehicle served as a unique test-bed in order to compare skid and explicit steering on one vehicle. Explicit steering was accomplished by the transforming chassis, which also served to change the heading of the wheels, in a double Ackerman fashion. Because Nomad has individual drive units in each wheel, a differential velocity between inner and outer wheels can be commanded in order to cause Nomad to change heading. The experiments covered explicit and skid steering over a range of turning radii. For each case an infinite radius (equivalent to straight driving), 12, 8, 4, and a 0 meter (equivalent to point turning) radius was studied at a vehicle velocity of 15 cm/s. Measurements of wheel velocity as well as current and voltage values were used to compute torque and power for each in wheel drive unit.

2. NOMAD MOBILITY CONFIGURATION

The configuration of Nomad's locomotion followed the implementation of a systematic framework for synthesizing robot geometries through simulation and optimization of analytical models of vehicle-terrain interaction, all-terrain traversability, and the physics of interaction of locomotion with sensing and autonomous navigation. Nomad's configuration progressed from determining the geometry of the wheel to sizing the chassis and identifying the appropriate propulsion, steering, and suspension schemes. The primary concepts considered and analyses performed are depicted in Figure 2.

Figure 2: Configuration Progression



To account for the uncertainty associated with a priori knowledge of terrain's characteristics (e.g. soil parameters, statistical distribution of rocks, etc.), configuration studies were performed in a parametric fashion and a range of possible locomotion values was computed. Parametric analysis allowed for a deeper evaluation of the relative merits of multi-wheel concepts and a variety of motion actuation schemes.
Analysis of robot mobility, such as computation of sinkage, motion resistance, and drawbar pull led to the selection of wheel dimensions and geometry. Further evaluation of the robot's ability to negotiate sloped terrain and surmount ground obstacles using models of terrainability yielded estimates of gross locomotion dimensions, wheel spacing, and disposition around the main body frame. It was determined that a four-wheel configuration with sufficiently large wheels (more than 25 inches in diameter) and symmetric wheel placement over a square footprint would be ideal for traverses over desert-like terrains, such as those in the Atacama.

Additional considerations of performance, such as maximization of the robot's predicted positioning accuracy facilitated by an in-wheel independent drive system. To minimize body excursions and in turn maximize terrain-sensor performance, a rocker bogie suspension averaging system was selected. Finally, analysis of steering activity in desert terrain and response to stop and emergency maneuvers when driving in a fully autonomous mode justified the selection of all-wheel explicit steering with electronic coordination and point-turn capability.

Configuration decisions were implemented in the design and physical production of Nomad. The detailed sizing of locomotion's subsystems was bound by overall dimensions and geometric arrangement determined through the configuration process.

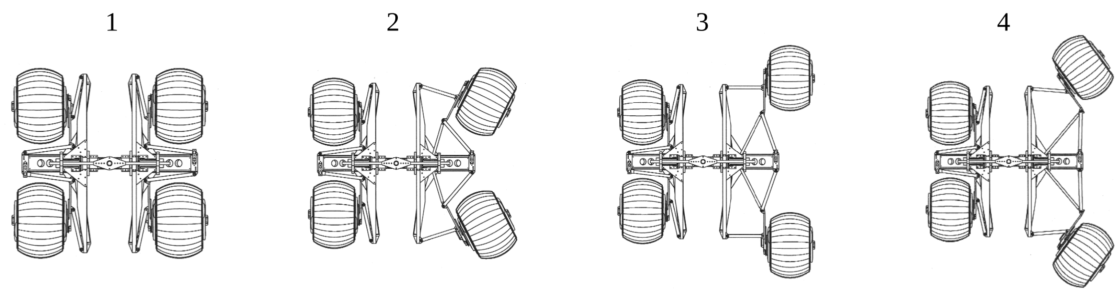
3. NOMAD ELECTROMECHANISM

The results of the implementation of Nomad's configuration are described bellow. The design specifics of Nomad also calibrate the experimental results described in section four.

3.1. Transforming Chassis

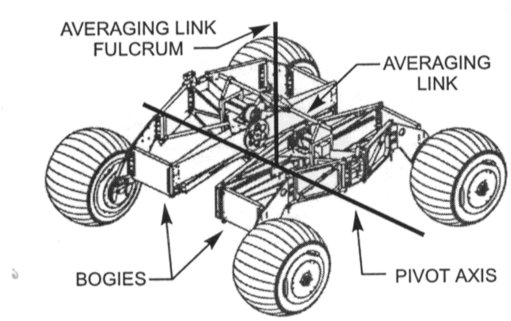
Nomad features a transforming chassis that can expand or compact by driving two pairs of four-bar linkages with two electric motors, one on each side of the robot. This transforming action leads to a significant increase in vehicle footprint and enables

Figure 3: Transforming Chassis - Range of Motion for One Side



steering by differential actuation of the two deployment motors. Due to packaging constraints the outer dimensions of Nomad were limited to fit inside of a 1.8 meter cube. Nomad's transforming chassis enables increased stability by deploying the wheels beyond packaging dimensions once the robot has been deployed. The transforming chassis also allows explicit steering by using the same two actuators used to deploy the wheels to cause changes in wheel heading. The transforming chassis is based on the motion of four bar linkages connected to each wheel. The wheels are actuated in pairs such that the two right wheels move synchronously (as do the two left wheels) to achieve double Ackerman steering. A detailed description of the transforming chassis including a kinematic analysis can be found in the work by Rollins[3].

Figure 4:Averaging Mechanism



3.2. Internal Body Averaging

In order to distribute the normal forces on the wheels, Nomad has two floating side frames (called bogies). Each bogie is a structure that supports and deploys two wheels (left or right). By allowing the side frames to pivot on a central axle, the wheels can conform to uneven terrain and maintain even ground pressure. In order to stabilize the sensors mounted to the body, the two side frames are connected by means of a passive mechanical mechanism, enclosed in the chassis above the central axle. The averaging mechanism consists of a linkage attached to the middle of each of the side bogies. The central pivot of the averaging mechanism has a degree of freedom in the vertical direction, which is needed to allow the link to follow the bogies through a maximum wheel excursion of 50 cm. Body averaging of pitch and roll allows Nomad to have greater mobility while maintaining a high level of stability for accurate sensor readings.

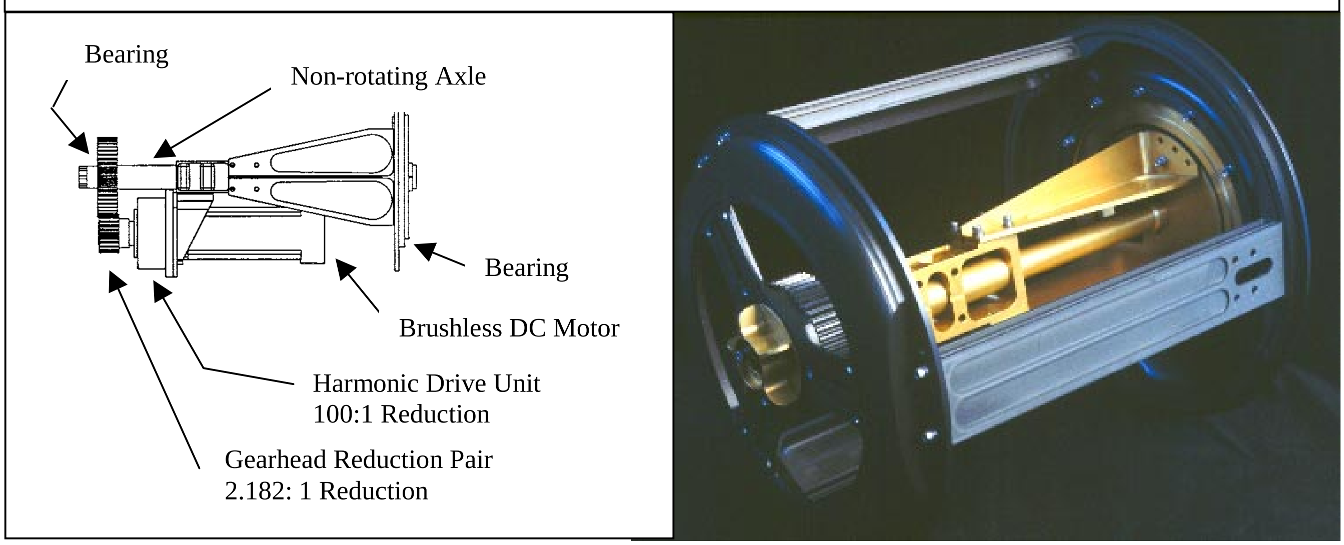
3.3. In Wheel Propulsion

Nomad features individual propulsion drive units that reside inside the wheel. This is unlike typical all-terrain vehicles, which have a central drive unit that distributes power to each of the wheels. The advantages of in-wheel propulsion include: sealed drive units, identical drive components, simplicity, and improved motion control.

The in-wheel propulsion unit is independent of the steering and suspension systems; no geometric or operational interferences occur between the systems. No electromechanical components are needed for propulsion beyond those enclosed in the wheel (with the exception of the motor wires, which are routed to the body fuselage through the deployment/steering linkages). This allows the drive components to be sealed within the wheel.

The motor and drivetrain assembly is at an offset distance below the wheel axle, which lowers the center of gravity of the wheel and simplifies its structural design and bearing selection. Triangular brackets suspend the drive assembly from the stationary axle. The motor is accessible for ease of removal and replacement if necessary. In the drive unit a brushless DC motor transmits torque and power to the wheel hub through a harmonic drive and a single stage gearing reduction. The output gear is mounted on the inside face of the outward facing wheel hub.

Figure 5: In Wheel Drive Unit



Eliminating mechanical transmission components and coupling assemblies encourages simplicity (and thus reliability). Only two bearings are needed to decouple the stationary wheel parts from the moving parts. Furthermore, the simplicity of the propulsion system imposes fewer constraints on the design of the chassis and the steering mechanism.

3.4. Tire Design

The tire provides the surface area needed for traction and weight distribution. Typically the tire soil interaction provides the deformation that absorbs shock loading and diminishes suspension lift. Conventional tires succeed by using flexible elastomerics and pneumatic inflation to conform to terrain. However, in order to be space relevant the tires must be able to function effectively in an environment with a vacuum and temperature variations up to 100 degrees. The risk of deflation and decomposition of elastomers in such an environment prevents the use of the conventional approach.

Nomad relies on all-metal wheels to generate traction and negotiate terrain. The tire, which is the outmost portion of the wheel, is constructed of a thin aluminum shell manufactured to the shape of a wide-profile pneumatic tire. The compound curved shell provides maximum strength and resilience for minimum mass. The rigid tire is composed of thirty strips of

6061-T6 Aluminum. The wheel diameter of 0.71 m reduces sinkage, and in turn motion resistance due to soil compaction and bulldozing. Despite the negative impact of a wider tire on steering resistance, the selected diameter to width ratio improves vehicle flotation and reduces ground contact pressure with positive effects on mobility in loose sand. The tire contact profile allows for uniform load distribution over the contact patch and gradual soil compaction.

Grousers are attached to the tire to increase traction. A pattern similar to that used on tractors and other earth moving equipment is used. Each grouser is 7.6 cm long and 1.9 cm square. The shape and orientation of the cleats limits steering resistance on the tires as the chassis expands or contracts but increases traction for normal driving.

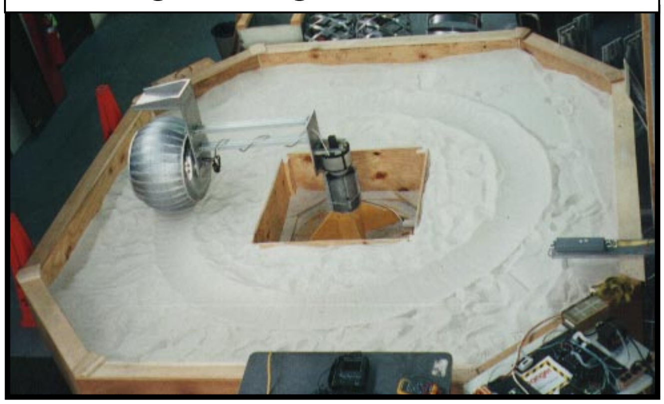
4. NOMAD LOCOMOTION TESTING

The culmination of Nomad's performance was demonstrated during the Atacama Desert Trek. Nomad traversed over 200km of off road terrain[2]. This demonstration was proceeded by component testing. Two major testing initiatives are described here. The first being experimental evaluation of a single wheel drive unit in a sandbox. The second being testing of the rolling chassis in an outdoor testing ground to compare explicit and skid steering[4].

4.1. Single Wheel Testing

A single wheel testbed was created to allow one wheel to travel long distances before the entire vehicle was completed. Experiments determined the reliability of the wheel drive mechanism and the necessary traction requirements. The testbed was also used to evaluate the effect of repeated traffic and tread pattern.

Figure 6:Single Wheel Testbed



The test bed was a polygonal sandbox filled with fine grained sand 0.5 meters deep. The wheel traveled in an 8.3 meter diameter circle. At the center of the testbed was a slip ring, which provided power and control signals to the wheel. The wheel was supported from the slip ring by two parallel linkages.

In order to determine the effects of repeated traffic the wheel without grousers was run at a constant velocity for 600 laps. Mean power readings were recorded at 10, 200, 400 and 600 laps. The results are shown in table 1 with the average power decreasing 37% from lap 10 to lap 600.

Table 1: Effect of Repeated Traffic on Power Draw

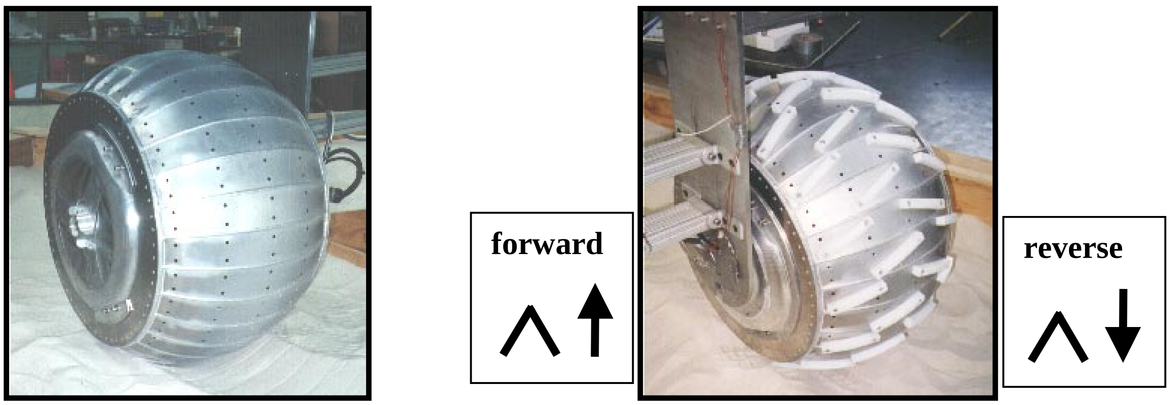
	Mean Power [Watts]
After 10 Laps	93
After 200 Laps	65
After 400 Laps	61
After 600 Laps	59

Testing was performed to determine the effect of the treads attached to the tire. The wheel was run at 4 velocities and the power draw was monitored. The results in table 2 show how the tread pattern has an increasingly significant affect as the velocity increases. The single wheel testbed not only provided quantitative results but also gave confidence in the drive mechanism. By the end of the single wheel testing the wheel traveled over 125km without any mechanical failures.

Table 2: Effect of Treads on Power Draw

	No Treads	*Treads Forward*	*Treads Reverse*
Velocity [m/s]	*Mean Power [Watts]*	*Mean Power [Watts]*	*Mean Power [Watts]*
0.27	74	84	112
0.36	95	120	153
0.45	113	157	193

Figure 7: Wheel With and Without Treads



4.2. Nomad Field Trials: Skid and Explicit Steering

Experiments were performed using Nomad as a vehicle that can exhibit both skid and explicit steering while driving steady state circles[4]. Skid steering was accomplished by creating a differential velocity between the inner and outer wheels. Explicit steering was accomplished by changing the heading of the wheels to cause a change in heading of the vehicle. Experimental results were gathered to provide information regarding power draw and individual wheel torque.

Power and torque for skid and explicit turning degenerate to equal values at infinite radius (or straight driving). As the turn radius decreases from straight driving to a point turn, greater power and torque are required because a greater side-slip angle is encountered. For all turns skid steering requires greater power and torque than for explicit turning. This is because side-slip angles are greater in all cases. In the limiting case of a point turn, the power for skid steering is approximately double that for an explicit point turn. Figure 9 shows the experimental results of the power draw for skid and explicit steering while driving on gravel terrain at 15 cm/s over turn radii from zero to twelve meters. For straight driving, or infinite radius, Nomad required 248 watts to power the four drive motors.

Figure 8: Skid and Explicit Steering for Nomad

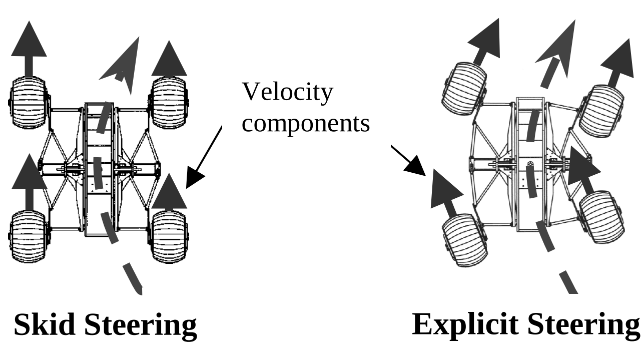
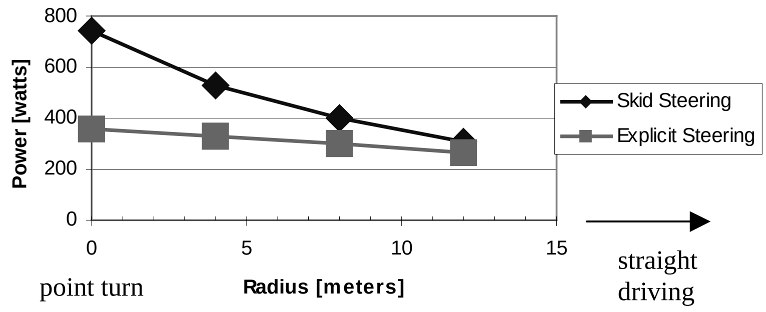


Figure 9: Radius vs. Power for Skid and Explicit Steering



4.3. Nomad Trials: Steering Torque

By monitoring the current of the drive motor amplifiers the torque used to propel each wheel was estimated. The torque constant for the drive motors was given as 0.56 Nm/A. Using the gear reduction of 218, wheel torque was determined. Figure 10 shows the torque values for explicit steering from 0 to 12 meter radii. The markers show the actual data points of 0, 4, 8, and 12 meter radii. The values from 4 to 12 meter radii are grouped well showing that by changing the heading of the wheels the torque is evenly distributed. The point turn shows an interesting phenomenon where the front inner and rear outer wheels are carrying approximately 75 Nm more torque than the front outer and rear inner wheels.

Figure 10: Radius vs. Torque for Explicit Steering

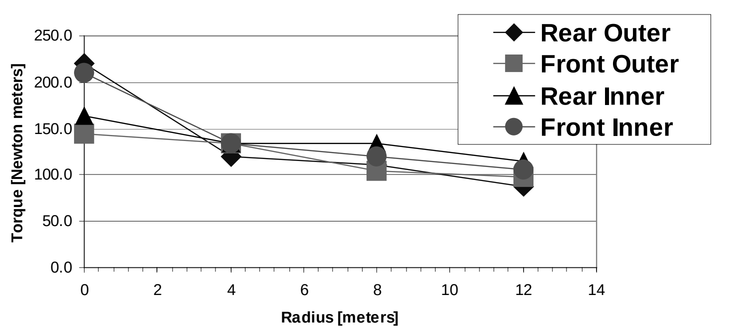
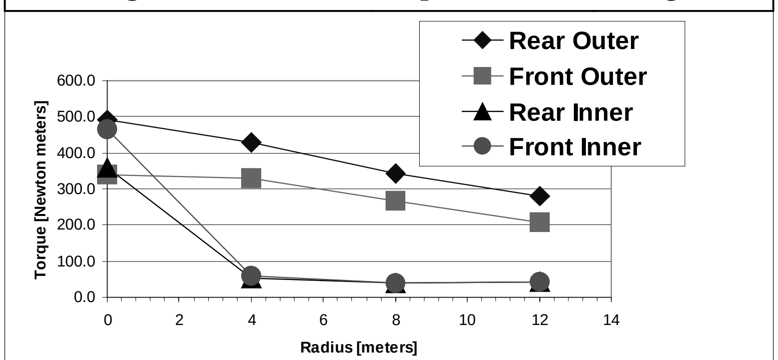


Figure 11 shows the torque values for skid steering. The skid steer point turn showed the same trend as the explicit point turn. Again, the torques were split in the same diagonal fashion with the rear outer and front inner carrying 150 Nm more than the front outer and rear inner wheels. As the radius increased the rear outer wheel consistently carried between 75 and 100 Nm more than the front outer wheel. For skid steering it was expected for the outer wheels to carry a higher torque value because the outer wheels were running at a higher velocity to cause the turn. However, the front outer and rear outer wheels should have identical torque values. In order to determine if the rear outer wheel consistently carried more torque than the other wheels, the direction of turn was modified for the 4m radius skid steer turn. A counterclockwise and a reverse clockwise turn were performed, as shown in Figure 12. The results show that, independent of turn

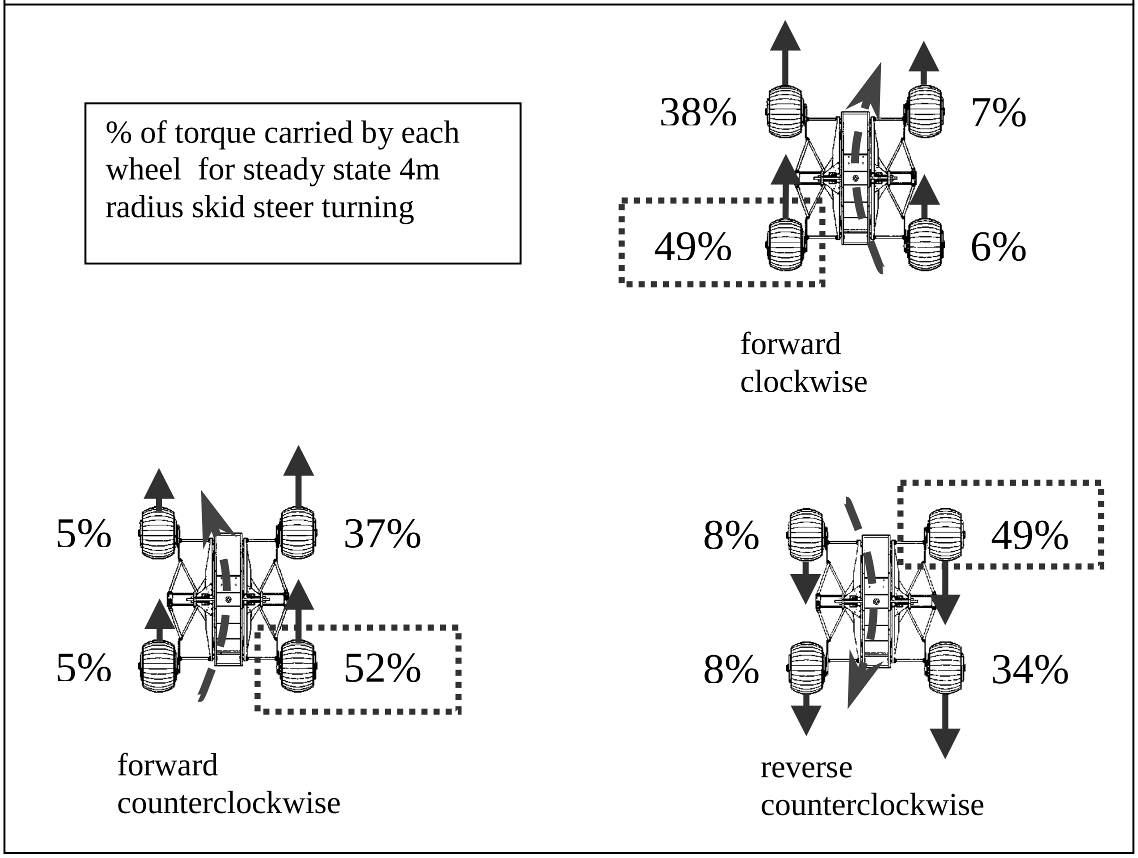
Figure 11:Radius vs. Torque for Skid Steering



direction, the rear outer wheel had a consistently higher torque value than the other wheels.

One observation that can be made about the higher torque in the rear outer wheel is that the phenomenon occurred only when the lateral resistance force was pushing from the outside of the wheel. This observation is consistent with the torque values of the point turn, in which the wheels with lateral forces stemming from outside the wheel required higher torque. The lateral resistance pushing from the outside of the wheel could be affecting the forces on the drive gears (which are located on the outside of the wheel). The drive gears are cantilevered from the inner wheel linkage. If the lateral forces on the outside of the wheel were producing a deflection of the gear support structure, increased torque would be needed to turn the wheel. However, further investigation is needed to prove if such deflection is occurring.

Figure 12: Torque Distribution



5. CONCLUSION

The configuration of Nomad as a planetary analogous wheeled rover was accomplished by a systematic configuration progression. The highest level validation of the configuration, design, and construction of Nomad is held by the long distance traverse of 223km made in the Atacama Desert.

The single wheel test bed showed that repeated traffic on fine sand terrain has a dramatic effect on power draw. As the sand was compacted a 37% decrease in power draw was observed. The treads attached to the rigid tire showed an increase in power draw over the smooth tire as the velocity was increased. The single wheel test bed not only provided performance information in terms of power draw of a single wheel on sandy terrain but also endurance testing on the wheel drive mechanism.

The quantification of power and torque values for a range of turn radii for both explicit and skid steering for Nomad sets a data point to be compared with other wheeled rovers. Skid steering a point turn required 746 watts while an explicit point turn required only 355 watts, which is approximately half the power of the skid steer point turn. Both skid and explicit steering degenerated to a value of 248 watts for straight driving. This work has relevance to the optimization of rover designs in light of steering performance requirements. By quantifying the amount of power used for both explicit and skid steering, educated decisions can be made about the most appropriate steering configuration for a specific application. Further testing on a varied set of terrains will generalize the results for a rover of Nomad's scale and mass. As data points of rover performance are published future designs can be compared and optimized to reach new levels of mobility.

6. ACKNOWLEDGEMENTS

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