Effect of Tire Design and Steering Mode on Robotic Mobility in Barren Terrain

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***ABSTRACT*–Robotic tasks call for a range of steering activity: one extreme is highway driving with negligible turning for hundreds of kilometers; another is forklift handling, which calls for agile turning. Steady state turning of a wheeled vehicle on natural terrain with slow but capable locomotors characteristic of planetary robotic vehicles is the scope of this research.**

Two tire designs were developed, implemented and evaluated aboard the Nomad robot, enabling a comparative study of their effect on mobility and steering. Rigid tires, utilized on desert terrain, are relevant to planetary exploration where elastomeric tires are inappropriate. Pneumatic tires, specialized for Antarctic terrain, achieved performance advantages on ice. The research presented here investigates the collateral issues of steering and mobility for the two tire designs.

Experiments involve a single robot that can exhibit both skid and explicit steering while driving in steady state circles on gravel terrain. Skid steering is accomplished through the creation of a differential velocity between the inner and outer wheels. In explicit steering, a change in the heading of the wheels causes a modification to the vehicle heading. Power draw, individual wheel torque, and position data have been gathered for the purpose of quantifying performance.

The experimental results show that power and torque for skid and explicit turning degenerate to equal values at infinite radius (straight driving). As the turn radius decreases from that of straight driving to that of a point turn, greater power and torque are necessary as larger slip angles are induced.

In the limiting case of a point turn, with both rigid and pneumatic tires, the power for skid steering is on the order of double that of an explicit point turn. For explicit steering, with turns greater than a radius of 4 m, the pneumatic tires exhibit a lower power draw than rigid tires.

Keywords: Nomad locomotion, robotic locomotion, robot performance, steering performance, skid steering

1. INTRODUCTION

Quantification of the power used for both explicit and skid steering is necessary for the generation of educated decisions about appropriate steering configurations for specific robotic applications. Mission planning is used to determine the actions of a robot to perform a goal. The plan can be optimized over many criteria, such as energy consumption or distance traveled. For extreme tasks such as planetary exploration or work in hazardous environments, a complete understanding of the energy consumed for different maneuvers can affect the amount of work that the robot accomplishes. Depending on the configuration of the robot, a longer path with a large turn radius may be more efficient than a point turn. The empirical study of real systems allows increased understanding of different mobility configurations including the optimization of steering mode and tire design.

Figure 1. Nomad with Pneumatic Tires

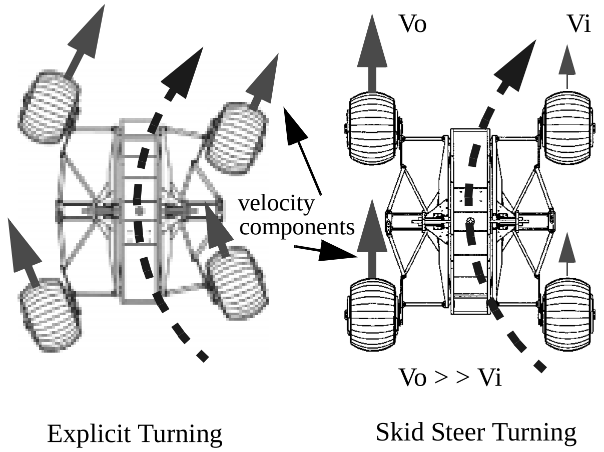
size:2.4 x 2.4 x 2.4 meters mass: 725 kg

The four-wheeled Nomad [2] served as a unique testbed for the comparison of two steering configurations [4](skid and explicit) and of traction elements (using rigid and pneumatic tires) on one vehicle. Explicit steering was accomplished by the transforming chassis, which also served to change the heading of the wheels. Each wheel heading is synchronized to drive the vehicle in a double Ackerman fashion with the wheels on each side of the vehicle steered by one actuator. Because Nomad has individual drive units in each wheel, a differential velocity between inner and outer wheels can be set in order to cause Nomad to change heading. The experiments covered explicit and skid steering with rigid and pneumatic tires over a range of turning radii. The steering radii studied include an infinite radius (equivalent to straight driving), 12, 8, 4, and a 0 (equivalent to that of point turning) meter radius all 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. STEERING MODES

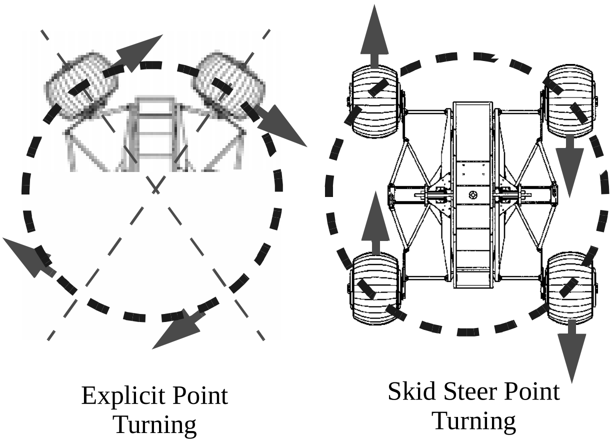
Skid steering can be compact, light, require few parts, and exhibit agility from point turning to line driving using only the motions, components, and swept volume needed for straight driving. One drawback is that skidding causes unpredictable power requirements. Skid steering also fails to achieve the most aggressive steering possible, which can be achieved with explicit steering. Skid steering during travel up a slope will be inhibited before explicit steering is inhibited. Explicit steering points the wheels in the direction of travel so that skidding is minimized. In general the advantage of explicit steering is more aggressive steering with better dead reckoning and lower power consumption. On the other hand, explicit steering requires a higher actuator count, part count, as well as the necessary volume sweep.

Figure 2. Explicit and Skid Steer Configurations for Nomad



Another significant difference between skid and explicit steering is the transmission of torque. For skid steering, the motion of the wheels is limited to rotation around one axis. Therefore, a centralized drive can pass the drive torques directly to each wheel. In the case of explicit steering, because the wheels move around two axes, torque transmission is more difficult. If a centralized drive is used, the torque must pass through universal joints and drive shafts that are inefficient. Another approach to explicit steering is to use individual drive motors inside of each wheel with the necessary gearing. Although the transmission of drive torque for explicit steering is complex, the lateral forces observed in skid steering are significantly higher than those of explicit steering. Therefore, the structure supporting the wheels must be stronger than that used for explicit steering. The merits of steering depend both on the task and the terrain. For example, steering efficiency and aggression are unimportant for driving on a straight, flat road. Alternately, torturous agility might require excessive turning. Examples include reversals and three-point turns.

Figure 3. Point Turn Configurations for Nomad



3. 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 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 begins a traverse. 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. Figure 2 and Figure 3 show the range of motion for explicit steering from large radii to a point turn. A detailed description of the transforming chassis including a kinematic analysis appears in the work by Rollins [3].

4. TIRES

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 through the use of flexible elastomerics and pneumatic inflation that facilitates conformity to the 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 of 100's of degrees. The risks of deflation and decomposition of elastomers in such an environment prevents the use of conventional tires. Traction element performance is a function of terrain, vehicle size, and mobility requirements. A fundamental distinction between classes of wheeled vehicles is whether they use rigid or pneumatic tires.

The tractive performance of rigid and pneumatic tires can be compared on the basis of the soil compaction resistance. In a comparison of tires having equal proportion and tread, the low pressure pneumatic tire will have lower compaction resistance [5]. The pneumatic tire must be operating in the elastic mode, such that the part of the tire in contact with the terrain is flat resulting in a decrease of ground pressure.

5. TIRE SPECIFICATION

Nomad's rigid traction elements rely on all-metal tires for generation of traction and negotiation of terrain. The tires, which are the outmost portion of the wheels, are 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 was sized and validated with experiments for soft and hard soils [1]. 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 which produces positive effects on mobility in loose sand. The tire contact profile allows for uniform load distribution over the contact patch and for gradual soil compaction.

Grousers that are 2 cm high are attached to the tire for increased traction. A pattern similar to that used on tractors and other earth moving equipment is used. The shape and orientation of the grousers limits steering resistance on the tires as the chassis expands or contracts but increases traction for normal driving.

Pneumatic tires were chosen to increase traction on the terrain of ice and snow that makes up the Antarctic landscape. Analytical studies of wheel and soil/ice interaction were used to size the wheel dimensions, shape, and inflation pressure. Criteria of sinkage, ground pressure, and drawbar pull were used for comparison. Available snow tires with the desired dimensions were modified to fit custom rims (Figure 5). The tires have an aggressive rubber tread pattern as well as metal studs imbedded in the rubber treads. An inner tube maintains a tire pressure of 3 to 5 psi.

6. 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: individual traction control, greater control flexibility, and sealed drive units.

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). 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. This allows the drive components to be sealed within the wheel.

Figure 4. Rigid Tire Dimensions

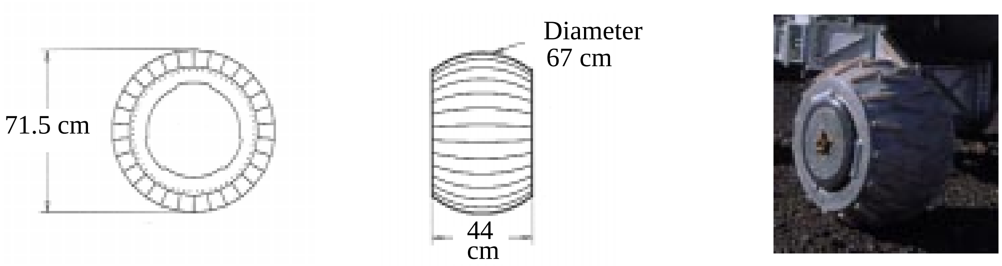
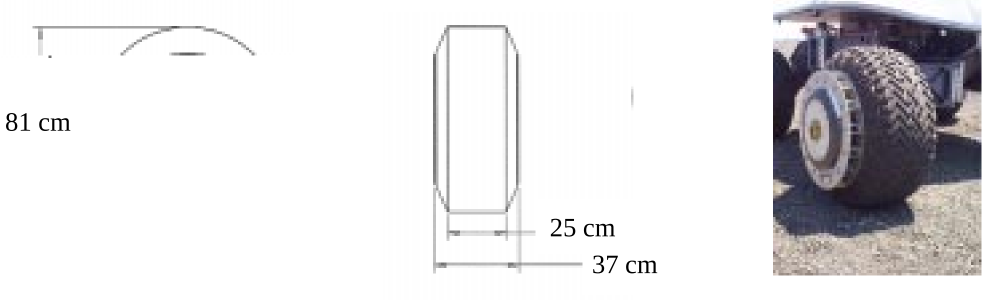


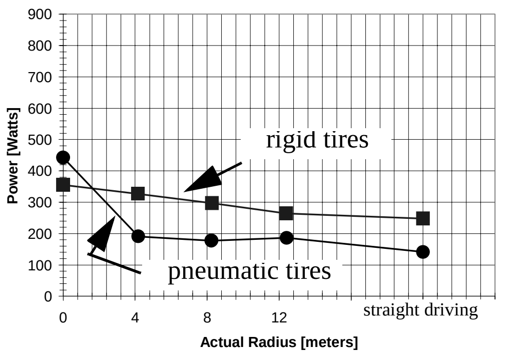
Figure 5. Pneumatic Tire Dimensions



7. EXPERIMENTATION METHOD

To compare explicit and skid steering as well as rigid and pneumatic tires, empirical performance was derived from experimental data. The data were gathered using a vehicle that can change its wheel heading for explicit steering and lock the wheel heading for skid steering. GPS was used as a measure of independent absolute position. The GPS data from steady state turning were post processed to determine the radius of each turn. Using measurements of wheel velocity as well as current and voltage values, torque and power were computed for each in wheel drive unit.

Figure 6. Explicit Steering - Radius vs. Power



The experiments consider steady state turning which does not include the transition from driving straight into a turning condition. All experiments were performed on flat gravel terrain in an outdoor environment. The terrain is naturally flat and without obstacles. However, locally varying slopes up to +/-2 degrees and terrain inconsistencies were encountered.

The experiments cover explicit and skid turning over a range of turning radii with rigid and pneumatic tires. For each case an infinite radius (equivalent to straight driving), 12, 8, 4, and a 0 meter or point turn was studied at a vehicle velocity of 15 cm/s. The velocity studied is representative of the state-of-art speed for autonomous driving of planetary robots.

For each test data signals were recorded including vehicle position, wheel motor current, voltage and velocity at 60 Hz. The PID controller used on the velocity loop for the drive motors did not change during any of the experiments. The nominal direction of turn studied was clockwise. However, the 4m-radius turn was studied in both the clockwise and counterclockwise direction to examine inconsistencies with respect to turn direction.

During the experiments, Nomad was teleoperated from a command station in view of all maneuvers. Velocity commands were given for each wheel as well as a steering command. During the skid steer experiments the steering motors hold the linkages in the position for straight driving.

Individual wheel velocities for skid steering were based on the kinematic model of the vehicle. Due to the inaccuracies of the kinematic model the wheel velocities were modified experimentally until Nomad traversed the desired radius while holding a vehicle velocity of 15 cm/s.

8. POWER: EXPLICIT STEERING

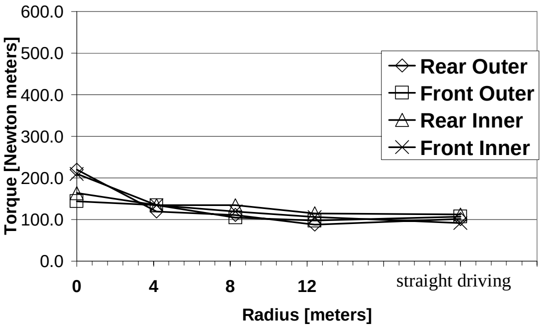
Power for explicit steering degenerates to a minimum value at infinite radius (or straight driving) for both rigid and pneumatic tires. Figure 6 shows that greater power was required as the turn radius decreases from straight driving to a point turn. This can be attributed to an increase in the wheel slip angle. The slip angle is the difference between the thrust vector provided by the wheel and the actual direction of travel of the wheel.

The rigid tires show a smooth reduction of power as the radius increases with the max power differential of 100 Watts occurring between the point turn and straight driving. However, the pneumatic tires show a notably high power draw for a point turn then a flat profile for the 4, 8, and 12 meter radii and a minimum value for straight driving. This suggests that for very tight turn radii (less than 4 meters), power is consumed in the lateral deformation of the pneumatic tire.

The reduced power draw of the pneumatic tire versus the rigid tire is due to several factors. The larger diameter of the pneumatic tire as well as the elastic nature of the tire result in an increased contact patch area between the tire and the ground. The larger contact patch reduces the ground pressure which lowers motion resistance and thus reduces power draw for each wheel.

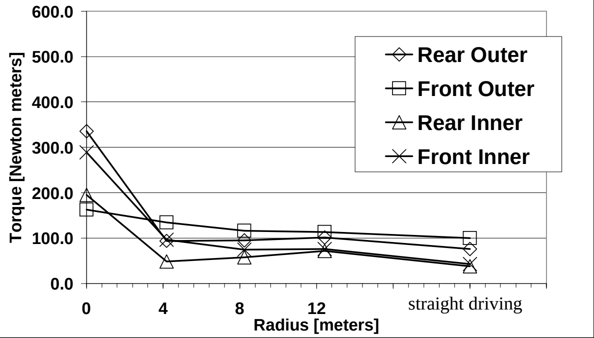
Explicit Steering

Figure 7. Rigid Tires - Radius vs. Torque



Explicit Steering

Figure 8. Pneumatic Tires - Radius vs. Torque



The fact that the pneumatic tire shows a flat profile between 4 and 12 meter radii suggests that there is little twisting of the tire carcass to cause increased power at smaller radii. The flat profile also suggests that the slip angle is constant between 4 and 12 meter radii, unlike the rigid tire profile where the slip angle, and thus the power draw, increases at the same rate as the radius decreases.

9. TORQUE: EXPLICIT STEERING

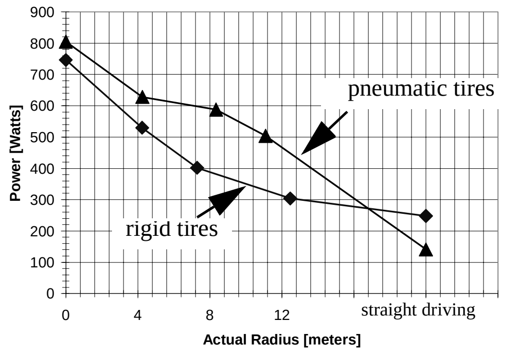
By monitoring the current of the drive motor amplifiers the torque used to propel each wheel was estimated. The torque constant for the drive motors was given as 0.56 Nm/Amp from the motor manufacturer. Using the gear reduction of 218, wheel torque was determined. Figure 7 and Figure 8 show the torque values for explicit steering with rigid and pneumatic tires. The markers show the actual data points of 0, 4, 8, 12 and infinite (straight driving) meter radii. For both rigid and pneumatic tires the values from 4 to 12 meter radii are grouped well showing that by explicitly changing the heading of the wheels the torque is evenly distributed for each wheel. The point turn exhibits an interesting phenomenon where the front inner and rear outer wheels are carrying approximately 75 Nm more torque for the rigid tires and approximately 100 Nm more for the pneumatic tires than the front outer and rear inner wheels.

10. POWER: SKID STEERING

Due to the significant lateral forces that occur during skid steering the power draw is expected to be higher than that observed for explicit steering regardless of tire design. Figure 9 shows that skid steering with pneumatic tires requires more power than with the rigid tires. For pneumatic tires the lateral forces act to deform the tire carcass, thus requiring increased power for forward propulsion.

The dramatic increase in power draw (350 Watts) from straight driving to a 12 meter radii for the pneumatic tires shows the effect of small lateral forces on elastic material. While the rigid tires require an higher power draw than the pneumatic tires for straight driving, the further increase of power draw as the radius decreases is much smoother than that for pneumatic tires.

Figure 9. Skid Steering - Radius vs. Power

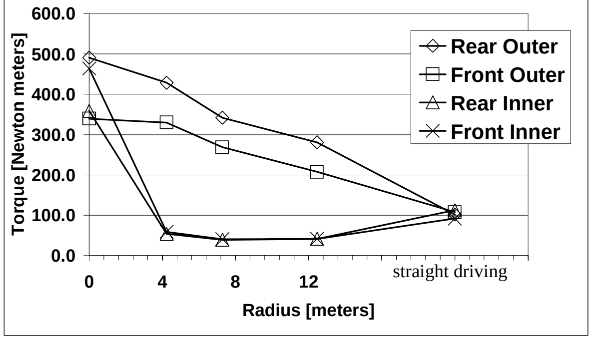


11. TORQUE: SKID STEERING

Figure 10 and Figure 11 show the torque values for skid steering. It is interesting to note the difference between the inner wheel torque of the rigid and pneumatic tires. With rigid tires at radii of 4, 8, and 12 meters the inner wheels require almost half the torque required during straight driving. However, in all of the trials using pneumatic tires the minimum torque for any individual wheel occurs in the straight driving condition.

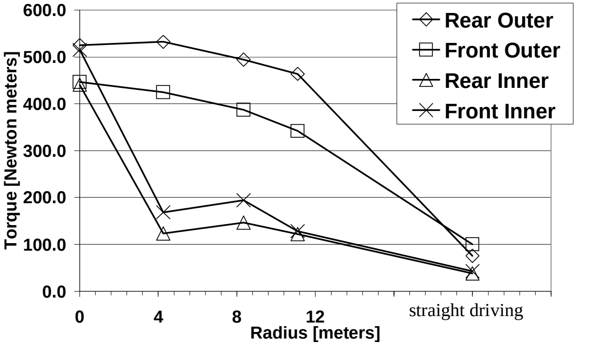
Skid Steering

Figure 10. Rigid Tires - Radius vs. Torque



Skid Steering

Figure 11. Pneumatic Tires - Radius vs. Torque



Regarding wheel torque, the skid steer point turn showed the same trend as the explicit point turn for both types of tires. The torques were split in the same diagonal fashion with the rear outer and front inner carrying 125 Nm more than the front outer and rear inner wheels for both rigid and pneumatic tires. 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 outer wheels should have identical torque values. 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. Counterclockwise and reverse clockwise turns were performed with both tire types. The results show that, independent of turn direction, the rear outer wheel had a consistently higher torque value than the other wheels for both rigid and pneumatic tires.

The phenomenon of increased rear outer wheel torque 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.

12. ASSUMPTIONS AND CALIBRATION OF DATA

In this comparison of rigid and pneumatic tires for skid and explicit steering several assumptions need to be highlighted. First, no correction or normalization was made to the data even though the tires are of different diameters and width, which does affect power draw and torque measurements. Second, the state of the vehicle has changed slightly between the time that the tests were performed with rigid and pneumatic tires. The torque of individual wheels for straight driving is evenly distributed for the rigid tires (Figure 10) while there is a discrepancy of wheel torque for the pneumatic tires (Figure 11). The testing for the pneumatic tires occurred almost one year after testing was completed with the rigid tires at the same testing site. Variations of mechanical wear for the in wheel drive units could be the source of the discrepancy.

13. CONCLUSION

From the quantification of power and torque for explicit and skid steering with rigid and pneumatic tires general trends applicable to design and mission planning can be extracted. In all cases studied here skid steering required higher power than explicit steering. For skid steering the power and torque for the outer wheels was notably higher than the inner wheels.

Skid steering with pneumatic tires required more power and torque than skid steering with rigid tires. Even at a 12 meter radius the power draw for pneumatic tires was 1.5 times that of the same turn with rigid tires.

Notably higher power and torque was observed for the explicit point turn (75 Watts more than with rigid tires). This could be attributed to significant tire distortion or slip angle for tight turning. However, explicit steering with pneumatic tires at a radius greater than 4 meters required the minimum power and torque. Straight driving with pneumatic tires required 100 Watts less than that required for straight driving with rigid tires.

With rigid tires skid steering a point turn required 750 Watts while an explicit point turn required only 350 Watts, which is approximately half the power of the skid steer point turn. Both skid and explicit steering degenerated to a value of 250 Watts for straight driving. For the radii 4, 8, and 12 meters skid steering required on the order of 1.5 times more power than explicit steering.

Skid steering required 805 Watts for a point turn while an explicit steered point turn required only 440 Watts. Both skid and explicit steering degenerated to a value of 140 Watts for straight driving. For the radii 4, 8, and 12 meters skid steering required on the order of 3 times more power than explicit steering.

The significance of this comparative analysis from field data is multifold. First, it provides a quantitative assessment of the terrain performance of two generic tire classes and two steering modalities used by the vast majority of off-road and planetary robots. The results of this work provide insight into the preliminary evaluation of variant rover configuration designs.

Second, the summarization of torque and power profiles for a wide range of steering angles, enables a first order appreciation of the complexity of power management and control for such a robot. A smoother steering response to heading changes has a positive effect to power management and control, especially for rough terrain robotic mobility.

Third, this work lays the foundation for more advanced concepts of traction control in which a priori knowledge of steering performance could be used to tune the parameters of an adaptive scheme to optimize smoothness of motion, power utilization, and dynamic performance. For instance, the observation of consistent discrepancies in power draw by individual wheels during skid steering could be taken into account by a centralized mobility planner, allowing effective tuning of control gains when executing a specific maneuver.

14. ACKNOWLEDGMENTS

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