Midsize Lunar Rover Development and Testing

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Abstract

The Canadian Space Agency has been funding the design and development of numerous rover prototypes since 2008. A credible candidate for a Canadian lunar flight-program is an evolving class of rovers (known internally at Ontario Drive & Gear as "J-class rovers", which includes the Juno 1, Juno II, and Artemis Jr. rovers.

Compared to previous or in-service Mars rovers, J-class rovers also share common design attributes which include increased ruggedness, reduced parts-count and an emphasis in reducing the effort expelled to integrate payloads, sensors and thermal subsystems. Since 2010, J-class rovers have undergone significant laboratory and analogue field testing and subsequent continued development of several key rover sub-systems such as the chassis, drivetrain, suspension and traction subsystems. This effort culminated in the development of a new mid-sized utility rover, known as the J5, a vehicle designed to address key requirements expected from lunar, planetary or terrestrial activities.

1 Introduction

Lunar and planetary exploration is expected to continue in the near-term with the launch of ExoMars, Resource Prospector Mission (RPM) and Mars 2020 missions. These activities are increasingly likely to be complemented with missions conducted by private enterprises and emerging economies. The inevitable shift in mission goals, from exploration to utilization of in-situ resources, will require the deployment of more rugged and capable mid-sized utility rovers.

This paper will present a review of salient design attributes as they pertain to mid-size rover development for application in planetary and lunar missions. This discussion will be illustrated by examples and experiences drawn from the development and testing of the Ontario Drive & Gear (ODG) J-class rovers.

2 Design and Development

Mid-size utility rovers associated with in-situ resource utilization (ISRU), must have the ability to climb steep slopes and traverse rough terrain, whilst transporting large payloads or native material. The rovers must also be able to operate for extended periods of time while exposed to the native environmental extremes. In recent times of fiscal restraint and cross-border collaboration, it is also imperative that a mid-size utility rover be adaptable and highly reliable, ultimately to achieve mission success and maintain public engagement.

Arguably, one method to meet these mission goals and that exemplified by the J-class mid-size utility rovers, involves initially marrying terrestrial design convergence and simplicity, with material science and processes to meet extreme terrestrial environments. The design should then be rigorously tested at analogue lunar or planetary test sites to validate the overall system and supporting architecture. If successful at the test sites, the inherent modularity of the base design should facilitate any changes necessary to meet changing payload demands and the expanded environmental requirements required for successful thermal-vacuum chamber testing and later space-flight.

The J-class mid-size rovers have been developed in accordance with the previously outlined design philosophy, culminating in several successful lunar analogue field deployments. Without coincidence, the J-class rovers are all skid-steered, an important characteristic of numerous terrestrial ground-working vehicles. Although skid-steered vehicles consume more power than Ackerman-steer vehicles when turning, this effect may be minimized in low gravity by performing proper path planning and wheel design. In comparison to Ackerman-steer vehicles, J-class rovers are also mechanically very simple, robust and light-weight due to the reduction in pivots, joints and actuators.

The effort to reduce complexity and build-upon proven field-tested technology is a hallmark of all J-class rovers. The most recent addition to the J-class rovers is the J5 variant shown in Figure 1, a vehicle that has application in the terrestrial and space industries due to its entirely environmentally sealed structure, amphibiousness, superior terrain-ability, ruggedness and class-leading payload-to-mass ratio.

Figure 1. J5 rover

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2.1 Chassis

The chassis is a key component in a mid-size utility rover. Whether or not a monocoque, ladder-frame or Super-leggera style frame is used, the chassis interfaces with almost all aspects of the rover.

Unlike Mars-style rovers that utilize a boxed central chassis with instruments fastened around the periphery, the utility rover performing ISRU tasks must carry large and heavy payloads. The J-class rovers are examples of mid-size utility ISRU rovers, consisting of a U-shaped frame that wraps around a large central payload. This arrangement protects the payload whilst placing the center of mass well within the stability footprint of the rover. Whereas the frame for the Juno rover [3] is formed from commercially available standard sized rectangular tube, the Juno II and Artemis Jr rovers are formed from thin-walled high strength aluminum alloy (7075-T6) sheet and extrusions. In all instances, this high-strength, lightweight design provides a large volume for sensitive components such as batteries and electronics. With strategically located access panels, the entire volume is easily protected from dust or thermal extreme.

The J5 rover shown in Figure 1 is the latest evolution of mid-size utility rover developed by ODG. The chassis along with the drive-units (see 2.2) are environmentally sealed and buoyant, eliminating the need to water-proof and dust-protect when operating in terrestrial or space-environments respectively.

The chassis and drive-units are fabricated from aluminum alloy (6061-T6) which has an excellent mechanical strength-to-mass ratio, relatively low thermal emissivity and is often used in many cryogenic applications. In one particular configuration, the modular J5 chassis may provide up to 220 litres of environmentally sealed and unrestricted volume for incorporating avionics or batteries. This design provision has several additional advantages. Firstly, installed avionics are only required to survive a reduced subset of environmental conditions similar to the Mars rover warm-electronic box (WEB) configuration; secondly, the unrestricted volume eases avionics and payload integration, providing cost benefits and risk reduction when various groups are developing componentry in parallel. Lastly, integration of an appropriate thermal system will be mechanically and thermally more efficient due to the consolidation of payload and avionics into a ‘bulk’ zone.

2.2 Drivetrain

Each variant of J-class rover consists of two separate drivetrains or rather ‘drive-units’. Each drive-unit consists of a pair of wheels mounted to a walking beam and powered by a single, centrally-mounted drive motor from which an enclosed chain drive transfers power to the drive wheels. Unlike the Mars rovers that use a hub-motor placed in each of the six rover wheels, the J-class rover design consists of a motor located centrally with respect to the wheels, therefore enabling it to be protected within an environmentally sealed volume. This feature increases motor reliability and decreases complexity associated with protecting the motor from contamination and thermal extremes.

The most recent rover drive-unit shown in Figure 2 was developed to improve the environmental and impact protection of the centrally located motor. The solution involved leveraging the thin-walled high-strength designs characterized in early J-class rovers, by forming a sheet-metal volume around the motor. Formed from aluminum alloy 6061-T6, this new environmentally sealed volume is connected to the adjacent main chassis volume for wiring and thermal system interfacing considerations.

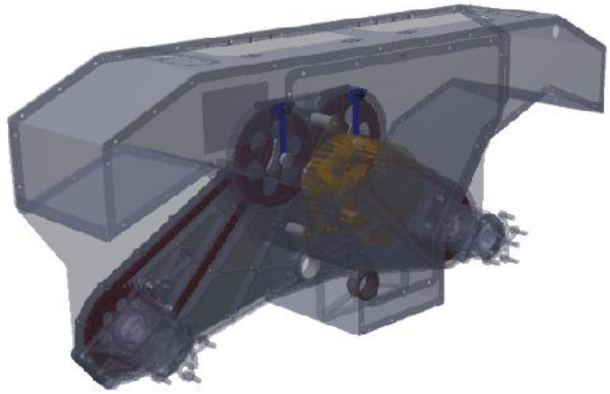

Figure 2. J5 drive-unit

Since no steering actuators are required unlike Mars-style rovers, the J-class rovers require only two traction motors to provide torque to four wheels. The development costs and mass savings realized by eliminating the additional Mars-style drive motors and steering actuators, along with the associated wiring, sensors, controllers, heaters, etc. is very significant. In short, up to ten traction/steering motors can be replaced by a pair of robust and thermally protected motors similar to that used in the J5 configuration.

A reduction in design complexity should improve or as a minimum, maintain overall reliability predictions. Reliability of a J-class rover with two traction motors can be shown to exceed that of a Mars-style rover with multiple mobility motors. Review of the 2006 Spirit rover motor failure indicated that although the rover lost one-sixth of its tractive force, dragging of the wheel inevitably exacerbated the net traction loss, likely close to half of the original value. In contrast, although a J-class rover would also lose half of its traction as a result of the same motor failure case, effectively preventing mobility, a great deal of mass margin is made available to increase the robustness and protection of the traction motors. This would reduce the failure probability while still realizing a net mass saving.

2.3 Suspension

Lunar and planetary rovers are unmanned and operate at low speed carrying a wide variety of payloads. Terrestrial suspension designs incorporating springs and hydraulic dampers are not only unnecessary but unfeasible for use in such rovers. The extreme temperature range found on the lunar or planetary surface would make a hydraulic damper a difficult proposition. Besides the large temperature induced variance in the viscosity of the damping fluid, rubber seals and springs would likely not survive the harsh environment. Without appropriate damping, a spring-based suspension would also be unpredictable and unstable.

A lunar rover will be required to operate properly over a wide range of gross vehicle weights. A geometric suspension similar to that installed in all J-class rovers is considered more appropriate. The differential link walking beam suspension incorporated upon the Juno, Juno 2 and Artemis Jr rovers was designed to fit along the perimeter of the U-shaped frame, thereby ensuring the suspension did not compromise the contiguous payload mounting volume. In the case of the Juno 2 and Artemis Jr. rovers, the suspension was also upgraded to include an active element, permitting the rover chassis to essentially pitch up or down. Although it is true that the addition of an actuation element would result in a small mass and complexity penalty, the feature would have several major operational benefits. The first benefit would be realized when the rover traversed steep slopes. By levelling the chassis (pitching chassis away from slope asymptote), the rover center-of-gravity would ‘move up’ the slope increasing the stability and biasing load towards the front wheels for additional traction. Solar collection efficiency would also benefit from the rover pitch-ability. For example, if the rover was stationary and performing analysis for a period of time, the rover could perform slight pitch adjustments to maintain an optimum panel-to-sun collection angle.

Figure 3. Juno II suspension-arm in ‘vertical’ articulation

Similar to previous J-class rovers, the J5 rover is fitted with a geometric suspension. However, the J5 rover suspension arm operates in a different plane compared to previous versions. Whereas the Juno and Juno 2 rover suspension-arms articulated in a vertical sense as shown in Figure 3, the J5 rover operates in the horizontal plane, shown in Figure 4. This has a significant advantage in that the useable payload volume in the J5 rover now extends beyond the ends of the rover providing a true unrestricted flat-deck design, a feature often touted by terrestrial utility vehicle providers.

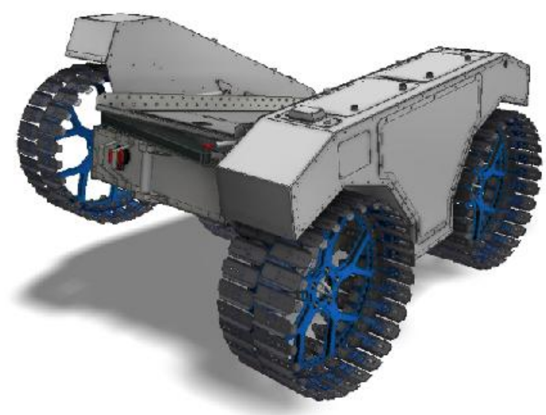

Figure 4. J5 suspension-arm in 'horizontal articulation'

2.4 Traction

In terrestrial applications, high traction vehicles use either large rubber tires or tracks. The majority of agricultural vehicles use large diameter rubber pneumatic tires. These tires are typically run at very low air pressure (2-3 bar) to provide high traction while remaining highly efficient. Terrestrial earth-moving applications, in which traction and flotation are a priority, employ caterpillar-style tracks almost exclusively.

ODG developed a metallic track system for use with the Juno mid-size utility rover. The track system shares characteristics of both the high performance, lightweight rubber track used more commonly in the power-sports industry and that of the heavy-duty steel segmented track used in an earth-moving application. In addition to traction characteristics, consideration was given to durability and efficiency over various terrains. Initial test results demonstrated that the metal track tractive performance eclipsed that of the baseline low-pressure rubber tire. Constructed largely from titanium and stainless steel, the entire track system had a mass of 100 kg. By comparison, a set of rubber tires for the same J1 rover weighed approximately 55-65 kg depending on size.

At this time, comparison of mass-to-traction ratios for tracks versus wheels does not favor track systems until lower launch costs can be realized. Instead, adequate traction for a mid-size utility rover can be achieved by developing non-rubber wheels. The desiderata [2] for a lunar or planetary wheel should include a balance between strength, weight, durability and traction. It is also important to tailor the wheel design to the steering and suspension methods employed upon the rover.

Figure 5. TIRELESS GEN2 metallic wheels (patent pending)

ODG have used the techniques and technologies that arose during the prior track development, in the development of a lightweight metallic wheel. Several iterations of wheel have been produced, with each version intended to be lighter and more durable than the previous version. The most recent generation shown in Figure 5 is a 1g analogue wheel, weighing 14 kg and measuring 60 cm in diameter. This wheel develops traction comparable to a pneumatic wheel of similar size, but is fabricated entirely from metals such as titanium, aluminum and spring steel. The design comprises of individual tread-plates with integrated grousers to provide grip and add rigidity. Each tread-plate is connected to the periphery of the central aluminum-alloy hub via leaf-springs. The springs are designed such that the distal end of the leaf-spring (connected to the traction plate) deflects without the spring being overstressed, a feature enforced when the spring contacts the central hub rim. A stainless steel cable is also fastened to each tread-plate to provide pre-load to each traction plate and maintain an appropriate wheel shape.

In addition to achieving comparable traction to a similar sized pneumatic tire, the semi-compliant TIRELESS GEN2 wheel has been shown to be very durable (tested without mission critical failure for over 80 km) and more importantly not as susceptible to point-loading or punctures, a condition appearing to plague the Curiosity rover non-compliant wheels as shown in Figure 6, after traversing only a five kilometers.

Although the Curiosity wheel damage may have been prevented by using substantially thicker material, the weight penalty affecting all six wheels would have likely been unacceptable for launch.

Figure 6. Curiosity wheel damage (credit NASA)

3 Testing and Deployments

The main purpose for rover laboratory testing and analogue deployments is to progress the Technology Readiness Level (TRL) [1]. Analogue testing is typically required of all systems in order to graduate from a TRL 4 to TRL 5. A system that is demonstrated and tested in a laboratory setting can achieve TRL 4, however, achieving a higher TRL requires progressively more thorough testing in a relevant environment. While it is unfeasible to combine natural terrain with the thermal extremes and vacuum of the lunar surface, it is well accepted that mobility testing on earth is a valid method to prepare for driving on the surface of the moon or Mars.

Since 2008, NASA and the CSA have been working together on a series of analogue deployments with various ISRU objectives. The majority of these analogue tests utilized J-class mid-size rovers and a Canadian drill combined with NASA-developed instruments. The goal of these missions was to locate, extract and measure lunar volatiles including water.

In 2008, NASA and CSA arranged the first of several lunar analogue deployments at a location in Mauna Kea, Hawaii. This deployment included a NASA RESOLVE payload mated to a CSA provided drill. Part of this package was carried by a NASA rover. ODG provided an off-road vehicle and trailer capable of transporting ground support equipment for the RESOLVE payload. In addition, ODG and University of Toronto conducted numerous instrumented tests traversing a wide variety of natural terrain types, from Mars-like rocky terrain to more lunar-like craters. The result from this tested aided ODG in the development of the Juno rover, the first J-class mid-size utility rover.

Following the 2008 deployment, plans were made to return to Hawaii in 2010 to conduct a higher fidelity demonstration featuring the RESOLVE payload. In 2009, ODG along with a number of other companies visited an aggregate production facility near Sudbury Ontario, to prepare for the imminent Hawaii deployment. Five Juno rovers were operated and used to perform a number of ISRU tasks including carrying the RESOLVE payload. The site provided an excellent opportunity to perform a dress rehearsal for all of the equipment before it was shipped to a higher fidelity analogue site.

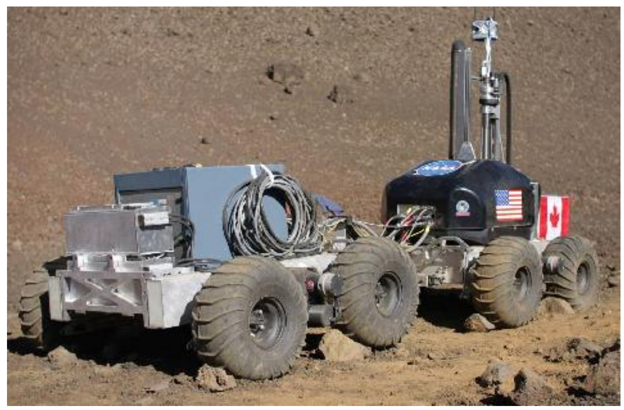

Figure 7. CSA / NASA RESOLVE

In February 2010, a fleet of six Juno rovers returned to Mauna Kea, Hawaii. The bulk of rover activity occurred in the bottom of the Pu'u Hawaihini Valley. Additional mobility tests were conducted within the adjacent volcanic crater including on a nearby sandy slope. A variety of ISRU-related tasks were demonstrated using the rovers and various payloads. One particular test shown in Figure 7 involved two Juno rovers connected in tandem used to carry the NASA RESOLVE payload and CSA provided drill. With regards to mobility alone, the tests were highly successful and raised several issues in the mobility design. Although the rovers demonstrated excellent controllability, maneuverability and climbing ability across rocky and sandy terrain, one major short coming was identified. This issue was related to the traction motor selection. The single motor used on each drive-unit was undersized and when used in combination with the chosen gear ratio, was not operating within an efficient speed range. The consequence was that battery life was shortened and the motor overheated.

The motor and batteries for this rover have since been upgraded and has now proven to be a highly reliable vehicle with no additional failures.

In 2012, NASA and the CSA conducted a further ISRU analogue field test, exclusively utilizing J-class mid-size utility rovers, Juno II and Artemis Jr. The analogue tests consisted of two main mission simulations, the evaluation of the RESOLVE payload and the Moon Mars Analogue Mission Activity (MMAMA). The RESOLVE payload testing [4] was conducted using an Artemis Jr. rover with the objectives to first verify the presence of water by direct ground truth measurements. Once water was discovered, a physical characterization of the regolith and a water/volatile measurement was carried out to support design of subsequent resource extraction systems. At another location, MMAMA mission objective was to perform a geological survey and validation of a Mars analogue valley using the Juno II rover.

During the 6 mission days of RESOLVE testing, the Artemis Jr rover shown in Figure 8 successfully demonstrated tele-operation and autonomous navigation for 1 km and 200 m respectively. The navigation system allowed the mission team to track the rover position within a world coordinate frame by feeding information into a NASA-developed operations tool. This provided the team with the ability to find and then characterize the water 'hotspots'. With regards to mobility, the rover fitted with TIRELESS GEN2 metallic wheels performed nominally. Admittedly, the terrain was not considered particularly challenging for the rover, since the maximum slope reached 11 deg with few rock-strewn areas.

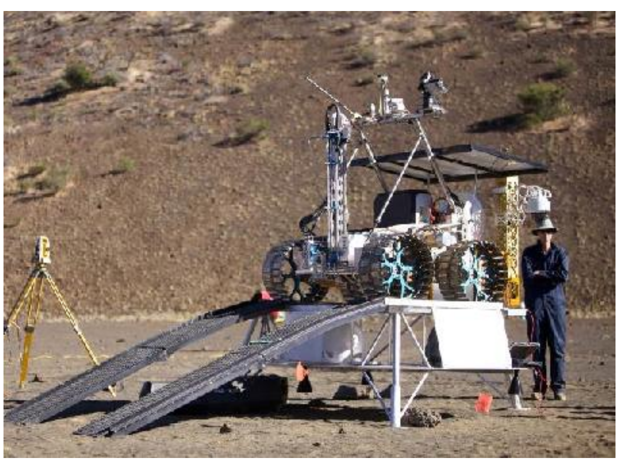

Figure 8. CSA Artemis Jr & NASA Resolve in Hawaii

In the case of the MMAMA mission [5], a Juno II class rover fitted with metallic wheels conducted testing in an area known as Apollo Valley. The rover shown in Figure 9 was powered by 5kW-hr lithium ion batteries and driven by a pair of sealed brushless DC motors using a radio-frequency transmitter. A Ground Penetrating Radar, Bartington Magnetic Susceptibility Meter, Lucy camera and associated communications equipment was fitted to the rover. Due to its difficult accessibility, Apollo Valley presented several unique challenges placing greater significance on the reliability and power economy of the rover mobility platform. The valley is almost entirely comprised of jagged volcanic rock providing a challenge to the durability and agility of the rover. The rover successfully achieved its test objectives, providing a mobility platform for the NASA payloads. In total 10.3 km were traversed in three days at the Apollo Valley test-site, with another 15 km accumulated at various other locations. Notably, this test was performed on terrain with 26 deg grades and significantly higher rock distribution than expected on the lunar or Mars surfaces. The test could also be considered to be a form of highly accelerated life testing for the rover and wheels, a test which the Juno II completed with only minor scratches to the underside of the rover and wheels. Importantly, no repairs where performed during the testing, nor found necessary post-mission.

Figure 9. MMAMA Apollo Valley site

Following completion of the MMAMA mission objectives, the Juno II rover fitted with metallic wheels was tested across a pre-planned repeatable route shown in Figure 10. The objective for this test was to perform further durability testing of the metallic wheels and rover, along with characterizing energy consumption of the rover mobility system alone. An on-board data logger was used to collect the necessary data for post-mission processing. Using the logged data, total energy consumption was determined using the product of average motor-current and battery state-of-charge integrated across the test time. Vehicle odometry was also derived using motor encoder logged data. The testing was performed using the TIRELESS GEN2 metallic wheels and the CSA owned iRings. The iRing test was cut short to protect the motors from overheating as a result of the significant energy required to operate the iRings. The Juno II fitted with TIRELESS GEN2 was tested for a further 13 km beyond the 10.3 km previously traversed during the MMAMA testing. In total, including traverses to and from the test sites, the Juno II and TIRELESS GEN2 metallic wheels were tested for 23 km without failure.

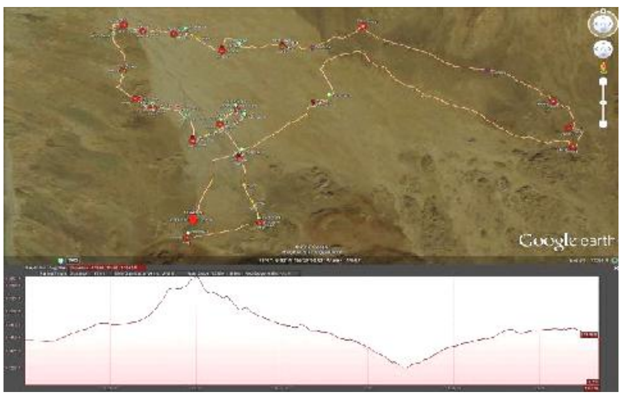

Figure 10. ODG mobility testing, Hawaii

Under the auspices of an agreement with NASA, ODG have continued testing and characterization of the TIRELESS GEN2 metallic wheels. In 2013, testing was completed at the NASA Glenn Simulated Lunar Operations (SLOPE) facility located in Cleveland Ohio. The primary use for the facility is to perform traction testing of vehicles and their components for use on the lunar surface. The facility shown in Figure 11 is filled with GRC-1 simulant which is essentially a blend of sands, formulated at NASA Glenn to mimic the lunar regolith particle size distribution. The blend was formulated to replicate the penetrometer gradient measurements obtained by the Apollo missions, resulting in a blend that is arguably a conservative representation of lunar soil at lower density or looser conditions.

Figure 11. ODG J4 rover at GRC SLOPE facility

Draw-bar pull and efficiency tests were performed at the SLOPE facility using a J4 rover (physically similar to Artemis Jr) fitted with various test wheels, including the TIRELESS GEN2 metallic wheel. Draw-bar pull testing was performed using the NASA GRC test-rig and in accordance with their standard practices and techniques to obtain the universal slip curves for each wheel test case. Slip curves were generated as shown in Figure 12 by plotting the traction coefficient against the slip rate, where the traction coefficient is the average load normalized by vehicle load, and slip rate is the reduction in vehicle ground speed, due to wheel slippage.

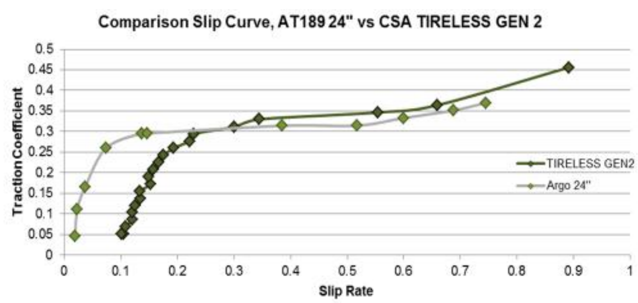

Figure 12. Universal Slip Curve

Draw-bar pull data was found to be extremely repeatable and highlighted both shortcomings and advantages for each tested wheel. In summary, the TIRELESS GEN 2 wheel was found to be very comparable to a similar sized pneumatic tire, in-fact displayed superior ultimate traction but at slightly higher slip rates.

Efficiency tests were also conducted at the SLOPE facility to determine energy consumption both in a straight line and during a skid-steering maneuver. In a straight-line, the power consumed is used to overcome motor inefficiency, driveline losses (gears, chains, bearing, seals), as well as energy required to roll the wheel. This also includes a small amount of bulldozing and any hysteresis in the wheel. Performing a skid-steer includes all of the inefficiency present in straight-line driving with added traction losses from slipping and sliding in a sideways manner. Although the energy data is important to evaluate the performance of various wheels or the effect of design changes made to the wheels, the collected energy consumption data can in its basic form be used to aid various design studies and activities, including mission planning, motor-sizing and power storage/collection definition.

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5 Conclusions

Development of the J-class mid-size utility rovers exemplify TRL progression, with each rover variant tested in laboratory conditions and refined through analogue deployments. The latest J-class rover, known as the J5 retains the mechanical simplicity of previous variants and consists of an architecture that can be efficiently modified to support space-flight componentry, materials, processes and subsequent testing.

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