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iRings — development of a wheel prototype concept for lunar mobility

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Abstract. Development of a metal compliant wheel for lunar mobility was initiated following President Kennedy's challenge of sending man to the Moon. A number of conceptual wheels were investigated culminating with the Apollo lunar rover wheel. In a separate venture, the Russians also developed a successful spoke wheel design. More recent efforts have led to the composite wheel design based on the Michelin Tweel, as well as the revisit of the Apollo wheel design through an 800-spring wheel developed by GoodYear. This study had three objectives: to review the facilities being developed to support wheel development at McGill University, to summarize the wheel design concepts being explored, and to present an overview of some of the preliminary performance measures of one of the concept wheel designs dubbed "iRings". The iRings wheel is a reduced scale 12.7 cm diameter particulate-filled chainmail wheel that conforms to rock surfaces and demonstrates traction performance similar to that found for a benchmark rubber wheel.

Résumé. Le développement d'une roue souple en métal pour assurer la mobilité sur le sol lunaire a débuté suite au défi lancé par le président Kennedy d'aller sur la Lune. Un certain nombre de modèles conceptuels de roues ont été examinés culminant avec la roue de l'astromobile (rover) lunaire d'Apollo. Dans le contexte d'une autre initiative, les Russes ont également développé un modèle de roue à moyeu. Des efforts plus récents ont mené au modèle de roue composite basé sur le Tweel de Michelin de même qu'à une mise à jour du concept de la roue d'Apollo par le biais de la roue à 800 ressorts entrelacés et porteurs développée par GoodYear. Dans cet article, on vise trois objectifs : on fait un survol des installations en cours de développement à l'Université McGill en soutien au développement de roues, on décrit les concepts de roues en cours d'exploration et on présente un résumé de certaines mesures préliminaires de performance obtenues pour un des modèles de roue baptisé "iRings". La roue iRings testée est un modèle à échelle réduite de 12,7 cm de diamètre d'une roue à cotte de mailles remplie de particules granulaires qui s'adapte aux surfaces de la roche et qui affiche une performance de traction semblable à celle d'une roue de caoutchouc de référence.

Introduction

Development of a metal compliant wheel was initiated following President Kennedy's challenge of sending man to the Moon. Much of this development has been summarized in a number of studies (Young, 2007; Asnani et al., 2009). Some of these activities led to the development of the Apollo lunar rover wheel, while others, in the Soviet Union, developed the Lunokhod wheel. Recent efforts have led to wheels developed by Michelin (Stowe et al., 2008; Heverly et al., 2010) (**Figure 1a**) and GoodYear (Cooney, 2010) (**Figure 1b**), as well as ExoMars wheel investigations (Patel et al., 2010) (**Figure 1c**).

The Canadian Space Agency initiated studies on the development of concepts, technologies, and know-how in support of the development of lunar mobility systems. One of these studies, led by Neptec Design Group and a number of associated organizations (Jones et al., 2010), aimed to investigate, conceptually design, and test a lunar mobility system. The proposed rover design was dubbed JUNO (**Figure 2**).

The main feature of the JUNO rover is the walking beam suspension with skid-steer directional control that is attached to a U-shaped chassis. This chassis shape provides increased adaptability to different payload interfaces.

In the frame of such a partnership, McGill University in Montréal, Que., was invited to participate and focus on the definition, development, and validation of a compliant wheel design methodology that would be used to evaluate and compare the feasibility of different wheel configurations, steering and suspension strategies, and traction designs. The McGill project aimed to address the following objectives:

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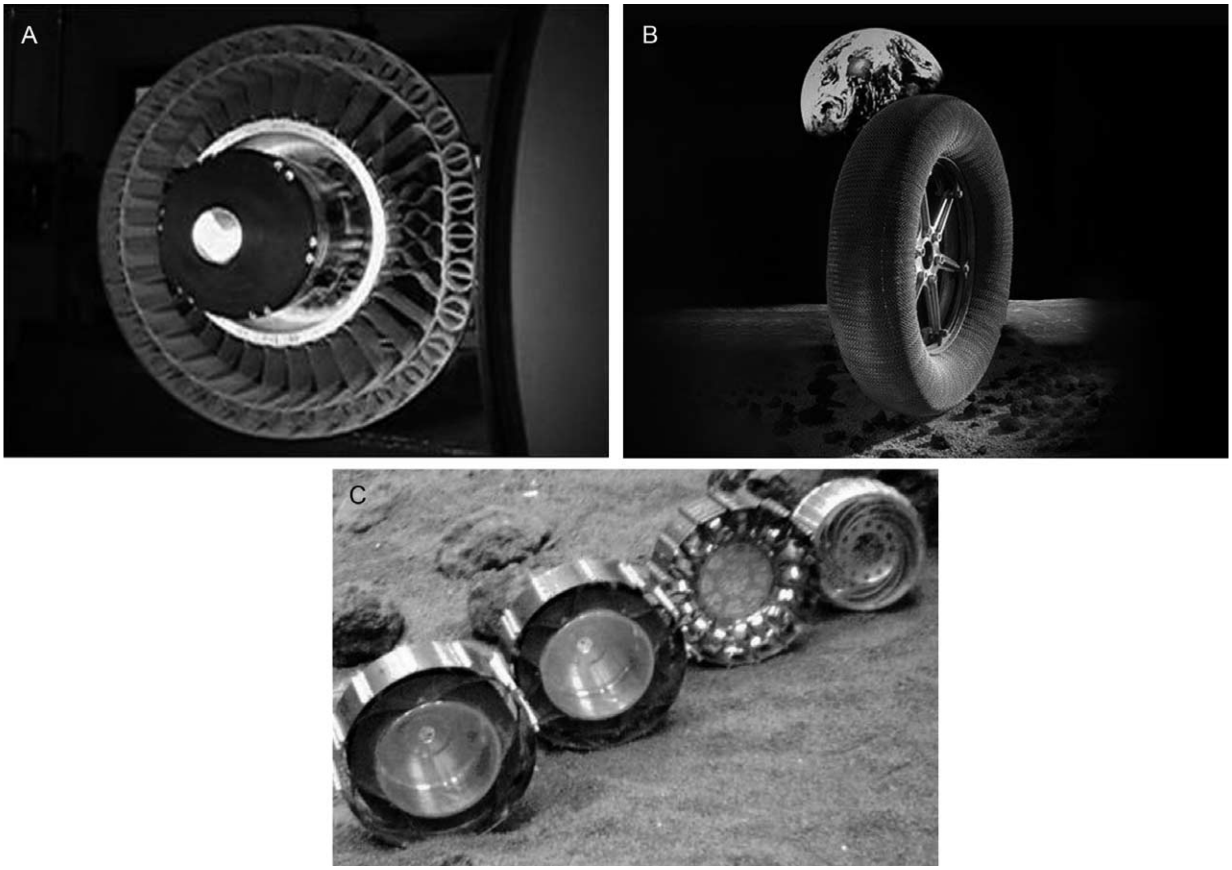

Figure 1. Recent planetary wheel designs, (a) NASA Michelin prototype, (b) GoodYear spring wheel, and (c) ExoMars wheel prototypes.

(*i*) determine the optimum wheel size, shape, and design given the expected range of rover activities, payloads, and lunar surface types;
(*ii*) evaluate and compare a subset of wheel configurations through a combination of simulation and prototype testing on a representative rover vehicle operating in a lunar analog environment; and
(*iii*) investigate the effects of operating one or more of the recommended mobility systems in the presence of the fine, abrasive dust on the lunar surface and identify strategies to mitigate dust infiltration and component wear.

Figure 2. The JUNO rover.

It should be noted that an unstated objective of this project was to create a dynamic between graduate and undergraduate students leveraging both groups' talents and enthusiasm.

This study briefly outlines the facilities being developed at McGill to support wheel development, summarizes the wheel design concepts being explored, and presents the development of one of the concept wheels dubbed "iRings" along with an overview of some of its preliminary performance measures.

Facilities

Virtual and physical facilities are being developed in support of this traction systems project.

Some of the virtual facilities have been outlined by Briend et al. (2010), Gharib and Radziszewski (2010), and Faragalli (2010). These studies addressed wheel-ground interaction through the use of 3-D discrete element models (**Figure 3**), wear (**Figure 4**), and dust mitigation (**Figure 5**), respectively. Modelling and simulation used discrete element models and strategies that combined multiobjective optimization

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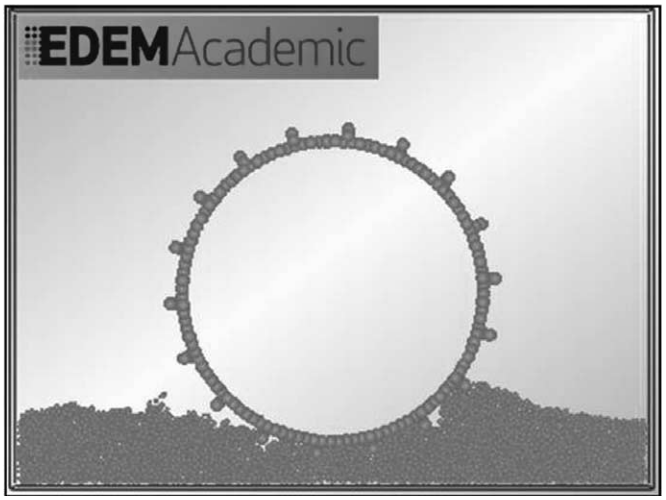

Figure 3. 3-D DEM model of wheel thin section on lunar regolith.

and multidisciplinary design optimization. Our study initiated work using ADAMS to simulate lunar mobility system dynamics as well as integrated lunar topology with powertrain performance modelling to predict wheel and vehicle power consumption over any particular path. Additionally, we initiated a study on electric motor design and performance prediction for lunar mobility using the electromagnetic modelling and simulation facilities at the Department of Electrical Engineering, McGill University.

However, the results from virtual facilities are only as good as the confidence that one has in them. To this end, a number of different physical facilities were developed that allow the simulated results to be validated experimentally. These physical facilities include geotechnical test facilities to measure cohesion and internal angle of friction for different soils as well as the angle of repose. Tests by Briend et al (2010) were modelled and repeated in numerical order to calibrate the discrete element parameters for realistic wheel–ground simulations.

A single-wheel testbed was designed and manufactured to test different wheel designs on different sand soils and to determine parameters, such as sinkage and slip, for different wheels and power consumption. A twin roll-wheel dynamometer was constructed for endurance testing. A circular test track was set-up to test different wheel types on sand or rocking soil using a wheel motor.

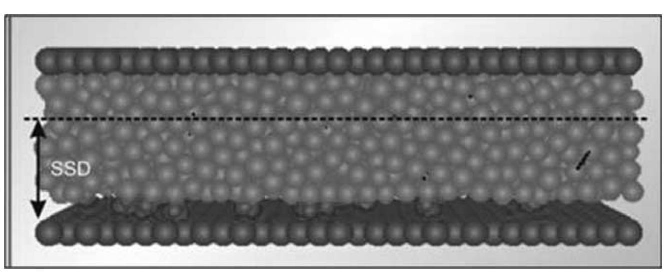

Figure 4. DEM model of abrasive wear in the presence of a hard abrasive.

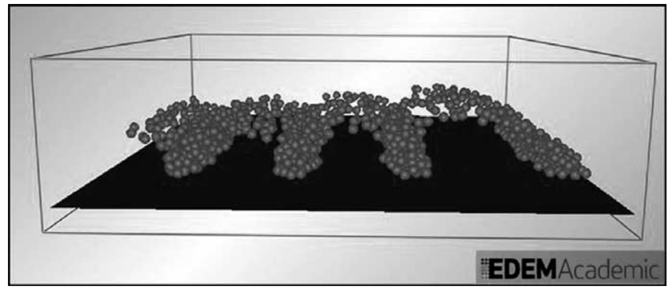

Figure 5. DEM model of an electrostatic regolith protection current.

Two reduced-scale mobility testbeds were purchased for reduced-scale testing of 12.7 cm diameter (**Figure 6**) and 20.3 cm diameter wheels.

It is important to note that the physical facilities were, and are, developed in support and validation of the development of virtual facilities. The ultimate validation will be completed on a full-scale four-wheeled test bed at Neptec (Jones et al., 2010).

A rubber wheel is considered as the benchmark with which to compare all wheel prototypes. Depending on the scale of the vehicle testbed, the diameter of the rubber wheel benchmark will be similar to the prototype wheel being tested. It is also important to note traction and rolling efficiency tests will be accomplished on both the rubber wheel benchmark as well as any prototype wheels.

Wheel concepts

As mentioned, this project was designed to leverage the talents and enthusiasm of both graduate and undergraduate students, with a number of undergraduate students initiating the first design iteration. This led to the development of three 55.9 cm diameter wheel prototypes (**Figures 7–9**). Two of these prototypes (Chu et al., 2009; Gabrielli et al., 2009)

Figure 6. Reduced scale rover test bed for 12.7 cm diameter wheels.

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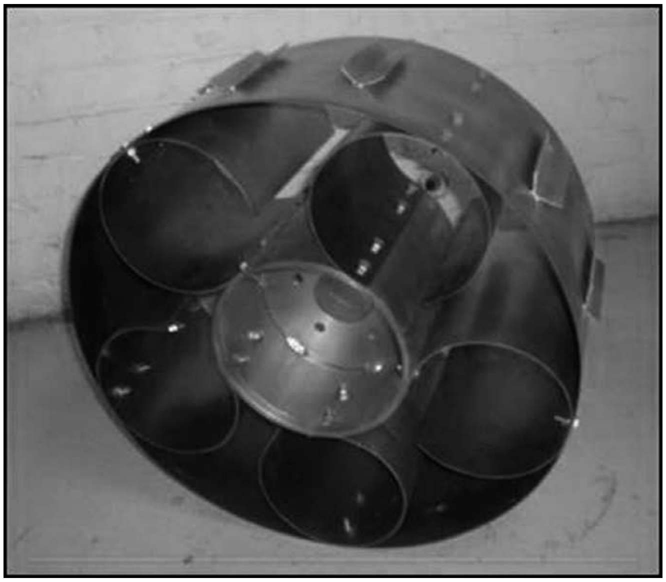

Figure 7. Compliant wheel 1.

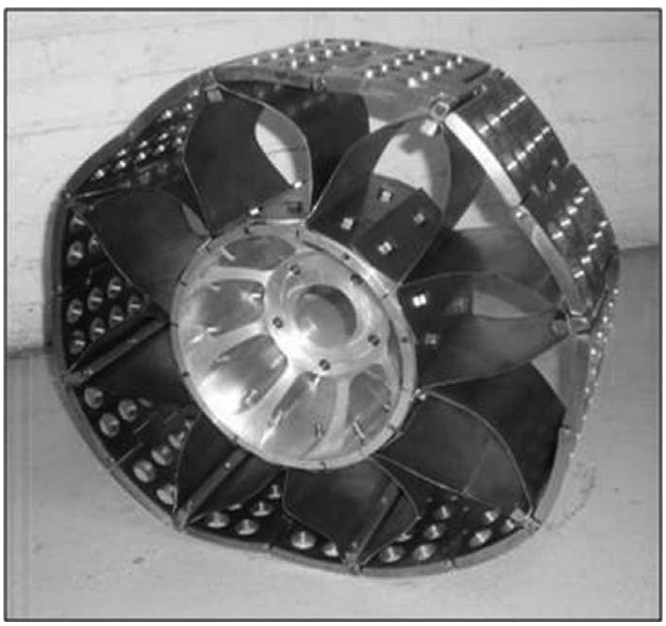

Figure 8. Compliant wheel 2 [16].

addressed the design and fabrication of the compliant wheel, while the third (Engelberg et al., 2009) addressed the design of a compliant hub. All prototypes were characterized by elastic compliance. Overloading the elastic designed capacity of a particular wheel concept resulted in plastic failure. All of these wheels, from the Apollo-era wheels to those more recently developed, essentially define a class of wheels that are predominantly illustrated by elastic compliance.

These observations raised a few questions:

- What are the effects of dampening, energy dissipation, or plastic compliance on the wheels?

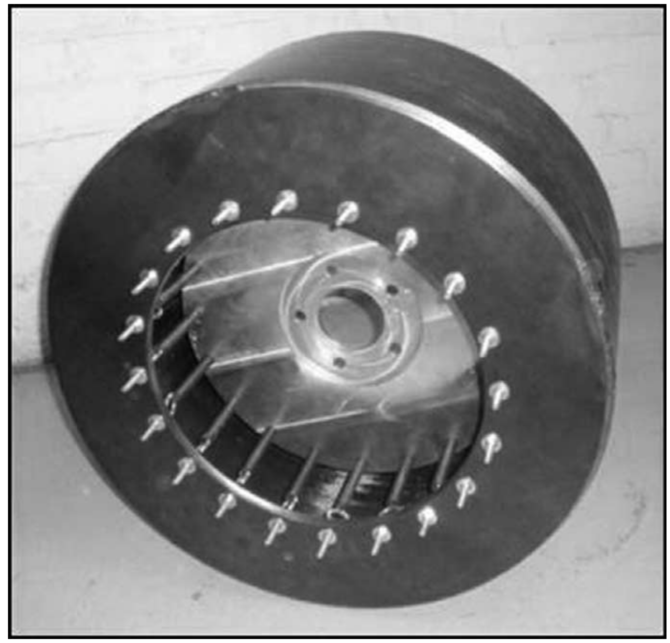

Figure 9. Compliant hub.

- Would the inclusion of some energy dissipation in a wheel be of benefit in lunar mobility either by decreasing the amount of shock transmitted to the vehicle or by allowing higher vehicle speeds?
- Would energy dissipation contribute to simplifying suspension system design?

These questions led us to revisit the typical pneumatic wheel system. Essentially, a pneumatic wheel system is composed of a rigid rim, a rubber tire, and an air filling. The rigid rim transmits vehicle load to the inflated rubber tire. The rubber tire acts like a balloon where the air filling carries the load while the rubber acts in tension by containing the compressed air. The previously mentioned lunar wheels substitute a more complex, elastically compliant structural system for the three-component pneumatic wheel system, which led us to the following questions:

- What if the rubber tire was substituted with another type of fabric, such as chainmail, that would only work in tension?
- What if the compressed air was substituted by a random particulate system of multiple load-bearing elements?

The wheel concept was characterized by the granular flow of the particulate fill contained between a hub and a flexible chainmail tire, which was inspired by the experience of modelling and simulating the charge motion of tumbling mills that are typically found in the mining industry (Radziszewski and Morrell, 1998). The particulate can be any pebble-like material such as ceramic or plastic balls; ultimately, it can be potentially screened regolith pebbles or sintered or molded regolith beads. This particulate-filled

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chainmail wheel concept (Radziszewski and Martins, 2009) was dubbed "iron rings" or "iRings".

It should be noted that in tumbling mills, the mill charge, which is composed of rocks and grinding media, is continually lifted in a rotating drum. This behavior is similar to the expected dynamics of the particulates in this wheel concept. Just as in the tumbling mill, the particulates centrifuge at a specific rotation speed, which is a function of the wheel radius and the gravitational pull. This rotation speed in mineral processing is called the critical speed (ω (rad/s)) and is defined by Equation (1).

$$\omega = \sqrt{\frac{g}{R}} \tag{1}$$

where g is the gravitational acceleration, and R is the diameter of the wheel.

For a particulate-filled chainmail wheel concept, it is possible to modify this equation such that the critical speed can be expressed as the vehicle speed (in km/h) at which centrifuging occurs (**Figure 10**):

$$v = 3.6\sqrt{\frac{Dg}{2}} \tag{2}$$

For a 12.7 cm diameter wheel, the critical speed on Earth would be just under 3 km/h, while on the Moon this wheel would centrifuge at just over 1 km/h.

This critical speed is significant because it can be used to describe two mobility regimes for such a wheel. Below this critical speed, one would expect a larger ground contact area and therefore greater traction. This would be typical of slower mobility applications such as grading, pulling loads, and climbing slopes. Above this speed, a particulate-filled chainmail wheel would be expected to stiffen with increased speed due to the increased centrifugal forces exerted by the particulate. One can speculate that at greater speeds, this stiffening leads to a wheel behavior closer to a rigid wheel. In this regime, the wheel would presumably exhibit a decreased rolling resistance, rendering it more efficient with increased speeds mainly because the ground contact area will decrease. However, in a braking situation, one can speculate that the charge would fall into the first regime; a loose system that quickly increases the ground contact area and therefore increases the stopping force in braking.

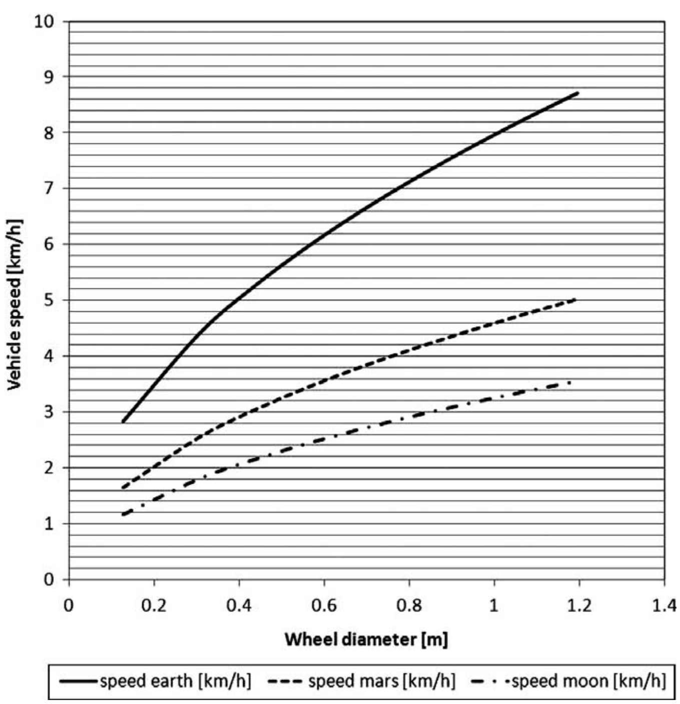

Figure 10. Critical speed of a rover as a function of wheel diameter.

Having defined a possible avenue for further wheel development, it was necessary to illustrate how the major components to this wheel concept would work together. This was accomplished through the construction of three mock-up models of the wheel concept using nonmetallic fabric. The first of these mock-up models (**Figure 11**), assembled a compressible hub and a fabric tire filled with styrofoam media where the two hub disks could be compressed together to decrease the volume of the tire and increase the tire's rigidity. The second mock-up model was a sewn fabric tire constructed to fit a beadlock rim (**Figure 12**). The third mock-up model provided insights into the construction of a metal fabric or chainmail tire, as well as its interfacing with a reduced scale beadlock wheel rim (**Figure 13**). This mock-up model also provided the first vehicle demonstration results, which indicated that the particulate-filled wheel concept would indeed work (**Figure 14**).

iRings wheel prototyping

Chainmail, which can be described as a network of metal rings, was first used in the Middle Ages by individuals for protection from arrows and swords (Lamontagne, 2001; Hanel, 2008). A number of chainmail patterns were developed in that era and can be identified by geographic regions (Robinson, 1995): Europe, Persia, and the Orient. Apart from replica fabrication of medieval chainmail garments, chainmail today is mainly found in protective clothing for industries requiring protection from sharp equipment. This form of chainmail is typically welded 4-in-1 chainmail, which can be made from metals such as stainless steel, titanium, brass, and copper. Welded chainmail is produced using an automated process, where the welds are produced using resistance welding or electrical spot welding.

The first challenge was to fabricate a chainmail tire. As chainmail is a fabric, the fabrication process required defining the fabric sections, producing those sections, and then stitching those sections together. The iRings tire required two different pieces. The first piece, was called the tread section and was defined by the width of the wheel and

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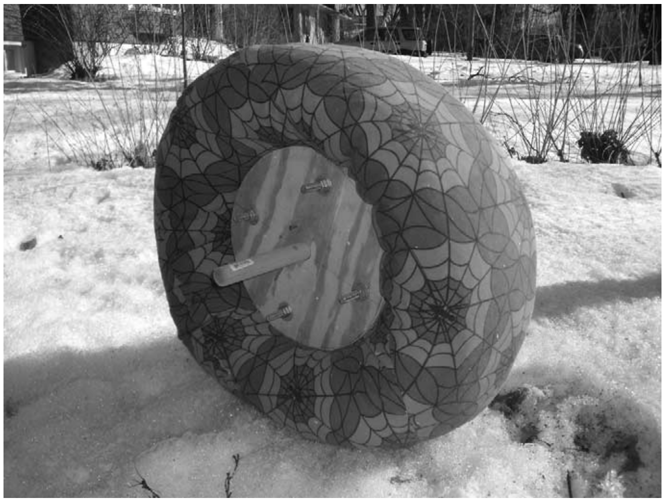

Figure 11. First wheel mock-up model.

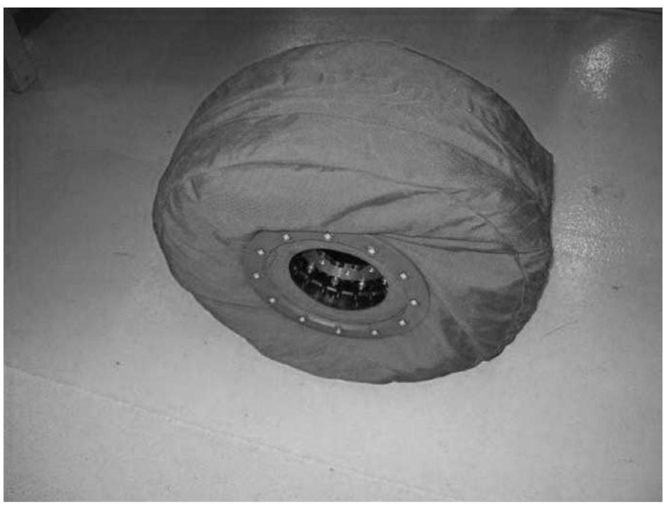

Figure 12. Second wheel mock-up model.

its circumference. The second piece was called the sidewall and was defined by the wheel and inner rim diameter as well as the number of radial pie-shaped sections. Each of these pie-shaped sections were stitched together to form a dough-nut sidewall. Two such sidewalls were required. The outer edge of the sidewall was then stitched to one edge of the tread section by the chainmail manufacturer (Daniels, 2010).

The interface between the rim and the chainmail tire was made using a beadlock rim. This required cutting a few rings out of the chainmail tire to bolt the beadlock ring to the rim, which sandwiched and bound the chainmail between two hard surfaces.

The iRings wheels were filled to about 80% of the available volume with an available particulate before the second beadlock ring was bolted in place. The first set of four 12.7 cm diameter wheels were filled with 6 mm diameter Delrin balls (**Figure 15**).

Figure 13. Third wheel mock-up model.

Figure 14. First vehicle demonstration.

iRings initial performance results

With the completed set of iRings wheels, it was possible to proceed with a demonstration. **Figure 16** shows the 12.7 cm diameter set of chainmail wheels installed on a rover test bed similar to the dimension of the rubber wheel benchmark. Visual inspection of 1 m drops of the rover with both rubber and iRings wheels illustrated that the iRings wheel dissipated energy quite well. With the testbed rover equipped with iRings wheels, drop impact with the ground was described as critically damped where no visible bounce is seen. It gave the impression that the testbed rover

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Figure 15. First 12.7 cm diameter iRings wheels set.

Figure 16. 12.7 cm diameter iRings wheels on reduced scale rover.

literally stuck to the impact surface. For the testbed rover with rubber wheels, the impact was underdamped where clearly the testbed rover bounced with a rapidly decaying rebound amplitude. It should be noted that at this scale the rubber wheel benchmark (**Figure 6**) was not filled with air, and its elastic properties were related exclusively to the rubber used in the wheel. Further visual inspection showed that the compliant nature of the chainmail and particulate combination tended to hug rock surfaces when riding over them (**Figure 17**). Initial traction tests on two hard (concrete and wood) surfaces indicated that the iRings wheel had greater drawbar pull at 100% slip than a rubber wheel benchmark.

Subsequently, traction performance tests were completed on dry sand on this set of wheels and compared with those obtained for the rubber wheel benchmark. The two wheel widths were different, with the rubber wheel being initially about twice the width of the iRings prototype. However, the wheel widths increased with increased load as illustrated in **Figure 18**. It is interesting to note that the width of the rubber wheels tended to increase linearly with increased load. However, for the iRings wheels the width increased with load to some limit and then tended to become independent of the load. One explanation is that with the iRings, once any slack between chainmail links was taken up the chainmail did not expand much, resulting in a constant wheel width.

Figure 17. Example of iRings compliance on rock surface.

With the variation in wheel width, the traction values were compared on a per unit wheel width. Furthermore, traction was determined using a load cell fish-hook set-up where traction or drawbar pull was determined for 100% slip. **Figure 19** shows that for a unit wheel width the traction of one iRings wheel is greater than the rubber wheel benchmark.

This wheel concept dissipates energy as opposed to storing it and releasing it in an elastically compliant structure, thus it can be expected that the rolling resistance of this wheel would be greater than that of the benchmark wheel. A number of tests were completed to determine and compare the energy consumed by the rover testbed with the rubber benchmark wheel and the iRings wheel as a function of load (**Figure 20**). In both cases, energy consumption increased with increased vehicle load as expected. It is clear that the power consumption of the iRings is greater than that of the rubber wheels.

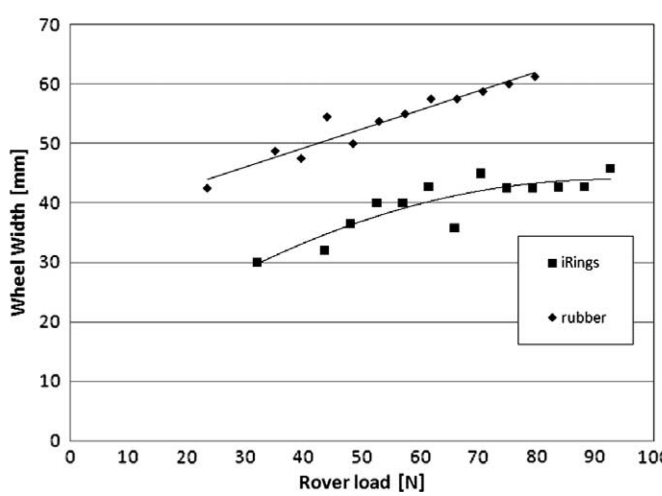

Figure 18. Wheel width as a function of rover load.

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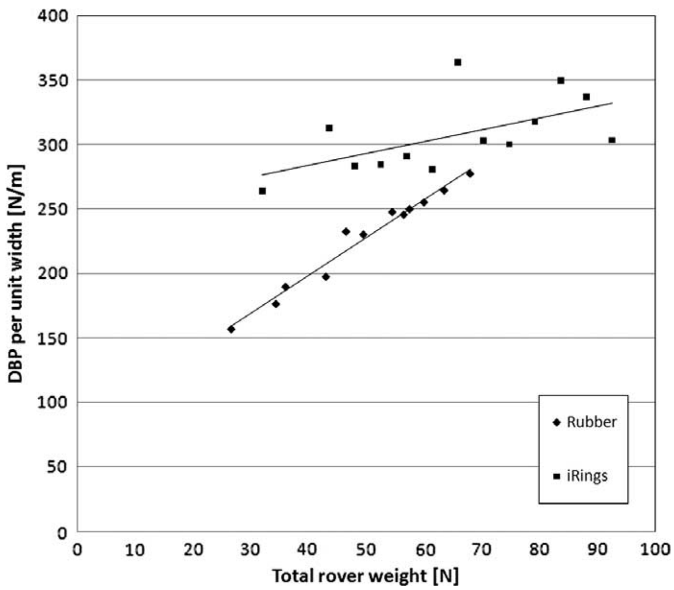

Figure 19. Ratio of drawbar pull/unit wheel width for 100% slip.

All tests on this 12.7 cm diameter wheel were completed at speeds less than the critical speed, which would be just under 3 km/h. Subsequent tests will look at increasing the speed of the this rover test bed to 7 km/h and investigating whether the wheel power consumption improves with greater speed.

Comparison with traction predictions

For the conditions tested, wheel slip was 100%. In this case, the Bekker traction relationships can be reduced to the following:

$$F_{\mathrm{ti}} = n_{\mathrm{ti}}[C_{\mathrm{o}} b_{\mathrm{ti}} L_{\mathrm{ti}} + (W/n_{\mathrm{ti}}) \tan \phi] \quad (3)$$

where F_{ti} is the traction or drawbar pull, n_{ti} is the number of wheels, b_{ti} is the width of the wheels, L_{ti} is the wheel contact length, W is the rover load, C_{o} is the soil cohesion, and ϕ is the internal friction angle of the soil.

Soil cohesion and internal friction angle were determined for the dry sand soil used in the testing. Cohesion was found to be 0, and the internal friction angle was found to be 43.5°.

A rigid wheel model was used to approximate wheel contact length while the previously measured wheel width was used for the wheel width input.

As shown in **Figure 21**, the traction prediction at 100% slip is higher than that measured for the iRings wheel. It should be noted that no other traction losses, such as bulldozing or soil compaction, were estimated in the preparation of the drawbar pull estimate in **Figure 21**. Such traction losses would reduce the Bekker drawbar pull estimate. Further analysis is necessary.

Avenues to future research and development

Although the results presented here are limited to the 12.7 cm diameter iRings wheel, it is important to note that on such a wheel scale the traction results are applicable to small exploratory rovers. In this case, the results presented can be used to predict rover traction and energy consumption. However, further research and development is needed in order to provide a viable implementation of the iRings wheel concept to larger scale rovers. Scalability, particulate characteristics, metal fabric design, wheel aspect ratio, rim design, media filling mechanisms, fabric replacement, wheel stiffening, grouser, and track addition are all issues that need to be addressed to provide such a viable implementation. Some possible avenues to address these issues are described below.

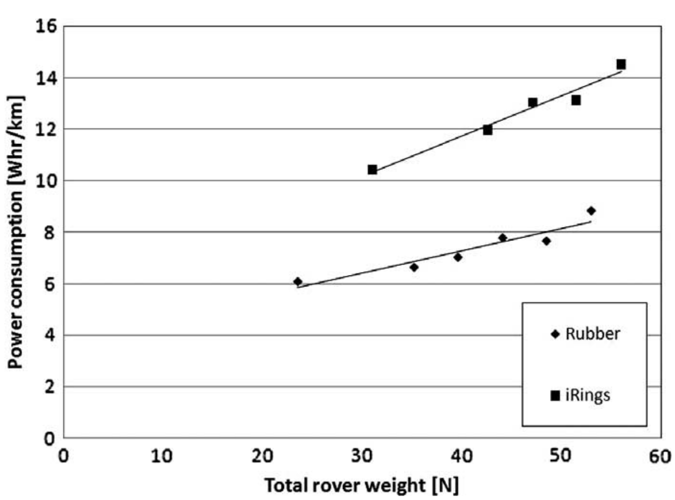

Figure 20. Power consumption for 5 in wheels.

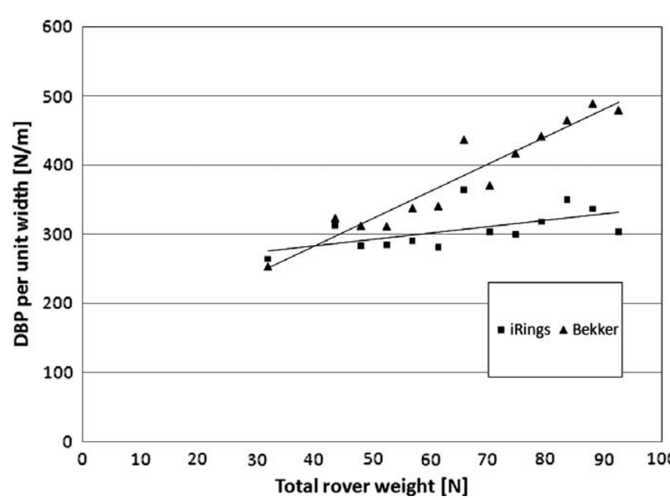

Figure 21. Drawbar pull comparison between predicted and measured.

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Scalability

The particulate-filled chainmail wheel is fairly simple in concept and structure and can be easily scaled for larger wheel sizes using geometric similarity. This was validated by prototyping wheels of different sizes (20.3 and 55.9 cm diameter; **Figure 22**).

Particulate characteristics

There are a number of characteristics to describe any particulate filling that can be used in the iRings wheels. Some of these characteristics affect the flow of this media, the power consumed by the wheel, and how that energy is dissipated, while other characteristics affect the load capacity of the wheel and the rate at which the particulate wears as a function of load.

It is known from studies of tumbling mills that smaller media contribute to a lower riding mill charge and, therefore, lower power consumption. Angular media tend to increase the friction between media components leading to a higher riding mill charge and, consequently, higher power consumption. More charge leads typically to greater power consumption while lower media density reduces mill power consumption. It is expected that these tendencies will similarly affect power consumption, media flow, and energy dissipation in the iRings wheel, especially if the speeds of the rover are below the critical speed of the wheel as indicated previously (**Figure 10**).

Load capacity and particulate wear rate would be determined partially by the mechanical and abrasive wear characteristics of a given particulate, which in turn would be defined by its composition.

The initial iRings concept aimed to have the iRings filled with regolith pebbles screened to a target size fraction that minimized the mass and reduced the packaging of the wheels to be sent to the Moon. Subsequently, this concept evolved to a manufactured regolith marble media, where the regolith was melted using microwave energy and formed into regolith smooth pebbles. Sintering regolith was proposed by Taylor and Meek (2005) in the construction of either roads on the Moon surface or thermal masses for night time heating of rover infrastructure.

However, at the prototype development stage, the particulate included dried peas and chickpeas (used for their cost and expediency) as well as polypropylene and Delrin balls. It would be expected that in a flight-ready wheel, the composition could be limited to space-certified plastics such as Delrin or PEEK, with densities around 1.4 specific gravity (SG) or, for greater wear, resistance hollow metal balls with potential bulk densities of 0.6 SG.

Metal fabric design

The iRings wheel was developed using a chainmail fabric. The chainmail fabric is a 4-in-1 welded chainmail design. As noted, there are a number of chainmail weaves. It is expected that each weave and each material used in the weave have different mechanical strengths and wear characteristics. Consequently, it can be expected that the maximum loading of an iRings wheel composed of different chainmail will be different.

Wheel aspect ratio

The mass of this particulate-filled metal fabric wheel is currently greater than the benchmark rubber wheel systems investigated. One avenue to reduce the mass of the wheel system is to select or design the particulate filler to have a low density while maintaining excellent abrasion properties. However, another way to reduce the mass of the wheel system is to reduce the amount of particulate needed. This can be accomplished by investigating the effect of wheel, or rather tire, aspect ratio on traction, energy efficiency, and shock absorption as a function of rover speed and payload mass. For pneumatic wheels, this aspect ratio is defined as

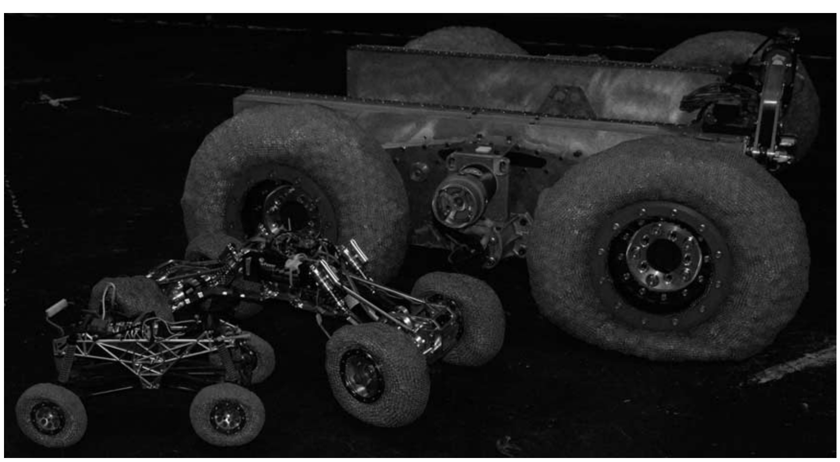

Figure 22. The suite of iRings prototype wheels – 12.7 cm, 20.3 cm and 55.9 cm diameter.

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the ratio between the tire side-wall height to the wheel width. In the iRings wheels, such an investigation would need to be completed in conjunction with the study of the effect of particulate filling size distribution.

Rim design

In previous iRings wheels prototyping investigations, the rims used were very rigid. No effort has been made to redesign these rims to either increase elastic compliance or reduce the rim mass. However, using a number of previously designed lunar wheels with rigid or elastically compliant rims, it can be conceptually determined if the iRings wheel system can be interfaced with these rim designs. Referring to Asnani et el (2009), it seems that the Gromov, spiral spring Markow, the hoop spring Bendix, elliptical and hubless Markov wheels can be used as rims to which the iRings chainmail tire can be attached. The current Michelin lunar wheel design (Heverly et al., 2010) can also be interfaced with the iRings wheel concept. To model this, desired elastic characteristics for a given set of mobility scenarios as well as the desired shock absorption characteristics can be determined. Then, the elastic characteristics of a rim and the shock absorbing, energy dissipating characteristics of the iRings system must be engineered.

Media filling mechanism

Depending on the particulate media used to fill the iRings wheels, the abrasion resistance characteristics vary. However, in all cases, the particulate media wear away and reduce the filling of the iRings wheel, effectively "deflating" the wheel. If the mission scenarios limit the effective useful life of lunar wheels to a few hundred kilometres, then abrasive wear of the particulate media might be considered negligible. However, if the mission scenarios aim for thousands of kilometres of useful wheel life, then wear becomes an issue and the ability to "refill" the iRings wheel becomes a requirement. Future studies will need to address this requirement.

Metal fabric replacement

Abrasive wear not only affects the longevity of the particulate media but also the metal fabric. When using a chainmail metal fabric, the chainmail wheel can be engineered so that the chainmail in contact with the ground is thicker than the chainmail in the wheel sidewalls. The increased thickness increases the effective life of the iRings wheel. However, at some point, the metal fabric needs to be replaced to reduce the risk of chainmail breakage, the wheel needs to be replaced with a completely new wheel, or a new wheel needs to be constructed in proper facilities.

To replace the metal fabric, a "retread" approach, similar to that used with rubber tires, can be developed and a second chainmail envelope can be affixed to a worn iRings wheel.

Wheel real-time stiffening

The iRings wheel is initially filled with a finite amount of particulate media, which is about 75% of the available volume between the rim and the chainmail tire envelope. Increased filling produces a stiffer or more rigid and heavier wheel. Increased wheel rigidity undoubtedly affects wheel traction, most likely increases efficiency, and reduces shock absorbing characteristics. Depending on the mission scenario, such changes might be required. If the mission scenario requires high traction, for either bulldozing regolith or climbing, a lower filling would increase the ground contact area and increase traction. This could be done by using a particulate filling mechanism. However, this would require stopping the rover next to a particulate "filling" station or burdening the rover with a particulate filling mechanism. Further, transitioning to a "deflated" state might pose other problems.

On the other hand, long traverses over predriven tracks or roads might require lower traction, higher efficiency, and nominal shock absorption. In this case, a stiffer iRings wheel might meet these requirements. This could be addressed by developing a real-time stiffening mechanism.

Grouser addition

The iRings wheel traction characteristics can be augmented by the addition of grousers, which can take the form of typical "chains".

Potential track addition

The iRings wheel design can possiibly further augment the nominal traction characteristics through the linking together of the chains, thus creating a track.

Conclusion

The goal of this study was to provide a brief overview of the facilities being developed to support wheel development, to summarize the wheel design concepts being explored, and to present an overview of some of the preliminary performance measures of one of the concept wheel designs dubbed "iRings".

The physical facilities being developed are typical of any research undertaking addressing lunar wheel design and development. Our virtual facilities are addressing new avenues to modelling ground and wheel interaction, wear and dust mitigation (particularly the coupling between electromagnetic fields and regolith-induced movement), multidisciplinary design optimization, and powertrain modelling as a function of terrain topology. The added physical

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facilities provide the opportunity to verify and validate the modelling being developed.

The wheel design space is being explored and future activities will explore other potential wheel structures.

In the exploration of this wheel design space, a new class of particulate filled wheels has been defined. One possible manifestation of this new class of energy dissipating wheels was dubbed the "iRings" wheel. It was prototyped and is currently being tested. Initial results illustrate that for the 12.7 cm diameter wheel increased traction (on a per unit width basis) can be achieved at the expense increased energy consumption during locomotion. However, the wheel also holds the promise of increased shock absorption and potentially allows for increased vehicle speed on the lunar surface. Further tests will look at, among other things, the performance of larger wheel diameters. The 12.7 cm iRings wheels tested can be used for small exploratory rover implementation.

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This project aimed to leverage the talent and enthusiasm of both graduate and undergraduate students. There are 3 MEng and 5 PhD students addressing different dimensions to this project. A further 20 undergraduate students completed capstone projects on problems related to this project in 2008–2009 and another 33 undergraduate students completed projects on problems related to this project in the 2009–2010 academic year.

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