iRINGS – DEVELOPMENT OF A WHEEL PROTOTYPE CONCEPT FOR LUNAR MOBILITY

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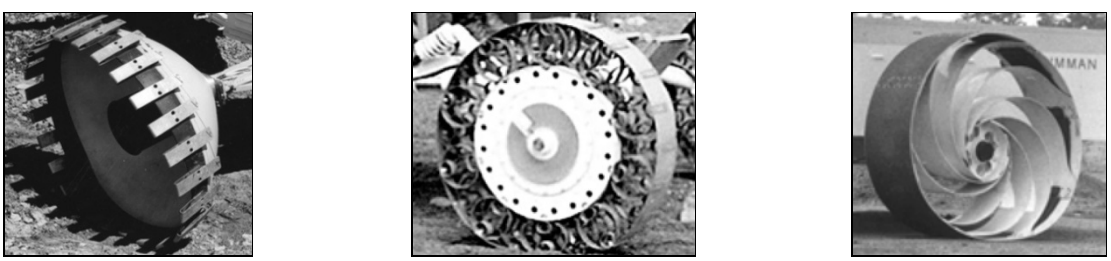
Abstract

Development of a metal compliant wheel for lunar mobility was initiated following the President Kennedy challenge of going 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. In the present paper, we will address three objectives: review the facilities being developed to support wheel development at McGill, summarize the wheel design concepts being explored, and present an overview of some of the preliminary performance measures of one of the concept wheel designs dubbed "iRings".

Introduction

Development of a metal compliant wheel was initiated following the Kennedy challenge to go to the moon. Some of this development is summarized in [1] and illustrated in Figure 2. These activities led to the development of the Apollo Lunar Rover Wheel [2-4] (see Figure 3). In a separate venture, the Soviet Union also designed a successful spoke wheel design illustrated in Figure 4 [1, 5, 6]. Subsequent work on the Michelin Tweel [7] (see Figure 5) also inspired some reflection on a metal compliant wheel design.



a) Grumman wheel 1 *b) Bendix wheel* *c) Grumman wheel 2*

Figure 2 Some wheel concepts [1]

Figure 3 Apollo wheel [2, 3, 4]

Figure 4 Lunokhod wheel [5]

Figure 5 NASA Michelin prototype [7]

With the Canadian Space Agency initiating studies on the development of concepts, technologies and know-how in support of the development of lunar mobility systems, a study led by Neptec Design Group and a number of associated organizations [8], aimed to investigate, conceptually design and test a lunar mobility system. In the frame of such a partnership, McGill University was invited to participate and focus on the definition, development and validation of a compliant wheel design methodology which would be used to evaluate and compare the feasibility of different wheel configurations, steering and suspension strategies, and traction designs. The defined project aims to address the following objectives:

1 Determine the optimum wheel size, shape and design given the expected range of rover activities, payloads and lunar surface types.
2 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.
3 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.

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

The present paper aims to review the facilities being developed at McGill to support wheel development, summarize the wheel design concepts being explored and present an overview of some of the preliminary performance measures of one of the concept wheel designs dubbed “iRings”.

Facilities

Two types of facilities were developed or are in the process of being developed. These are virtual and physical facilities.

In the case of virtual facilities, some of these have been outlined by Briend [9], Gharib [10] and Faragalli [11]. Specifically and respectively, these address wheel-ground interaction through the use of 3D discrete element models (see Figure 7), wear (see Figure 8) and dust mitigation (see Figure 9) modelling and simulation using again discrete element models and strategies combining multi-objective optimization (MOO) and multi-disciplinary design optimization (MDO). In addition to this, we have initiated work using ADAMS (see Figure 10) [12] 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 (see Figure 11). Lastly, we initiated a study on electric motor design and performance prediction for lunar mobility using electromagnetic modelling and simulation facilities in electric engineering (see Figure 12).

Figure 7 3D DEM model of wheel thin section on lunar regolith

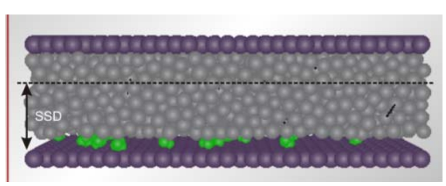


Figure 8 DEM model of abrasive wear in the presence of a hard abrasive

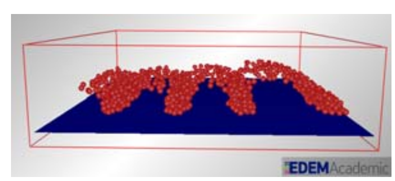


Figure 9 DEM model of an electro-static regolith protection current

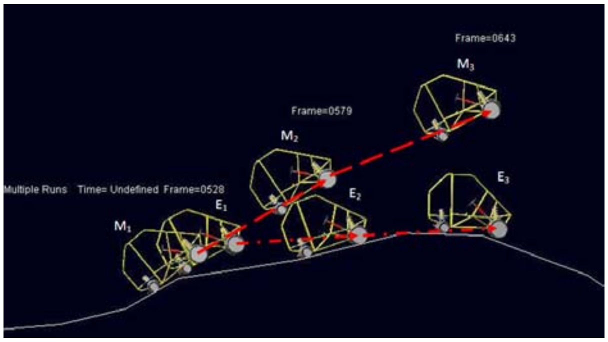


Figure 10 ADAMS model of a rover under both terrestrial and lunar gravity [12]
M_1, M_2, M_3: trajectory of rover on moon
E_1, E_2, E_3: trajectory of rover on earth

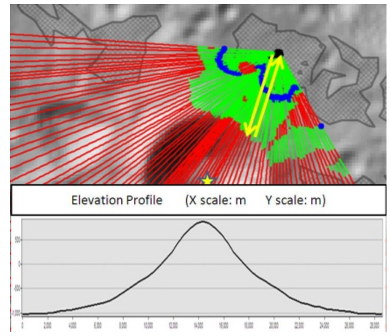


Figure 11 Estimating power consumption as a function of lunar topology

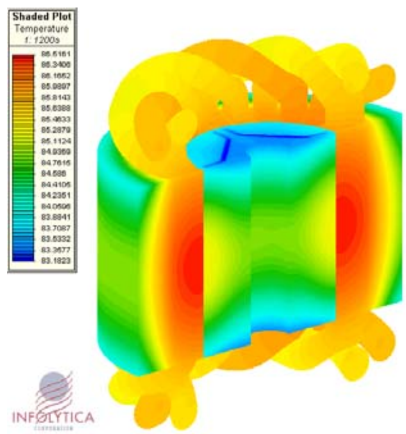


Figure 12 Simulation of temperature gradients induced by electromagnetic field in an brushless DC motor

However, virtual facilities are only as good as the confidence we have in them. To this end, we developed and are in the process of developing different physical facilities that will allow us to validate simulation results. Here we include geotechnical test facilities for the measurement of cohesion and internal angle of friction for different soils as well as angle of repose. As illustrated in [9], these tests were modeled and simulated in order to determine the appropriate simulation parameters for wheel-ground simulations.

A single wheel testbed (see Figure 13) was designed and manufactured to test different wheel designs on different sand soils and determine parameters such as sinkage and slip for different wheels and power consumption. Furthermore, a twin roll wheel dyno was constructed in order to provide an endurance test (see Figure 14). Finally, a circular test track was set-up to test different wheels types on a sand/rocking soil using a wheel motor (see Figure 15).

Also, two reduced scale mobility testbeds were purchased to allow reduce scale testing of wheel designs. These testbeds allow the testing of 5 inch diameter and 8 inch diameter wheels (see Figure 16a, b).

It is important to underline that the physical facilities were and are being developed in support and validation of the development of virtual facilities. The ultimate validation will be completed on a full scale four wheeled testbed at Neptec [8].

Figure 13 Single wheel testbed

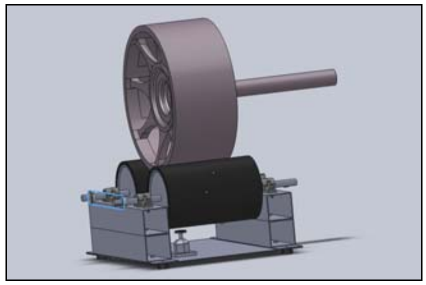


Figure 14 Drawing of twin roll wheel dyno [13]

Figure 15 Circular sand track [14]

a) testbed for 5" wheels

b) testbed for 8" wheels

Figure 16 Reduced scale rover testbeds

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 22 inch wheel prototypes (see Figures 17 to 19). Two of these prototypes [15, 16] address the design and fabrication of the compliant wheel, while the third [17] addressed the design of a compliant hub. In examining these prototypes, it was found that all of them were characterized by elastic compliance. Plastic failure was the result of overloading the elastic designed capacity of a particular wheel concept. Referring back to the Apollo era wheels as well as those more recently developed, all of these wheels essentially define a class of wheels that are predominantly illustrated by elastic compliance.

Figure 17 Compliant wheel 1 [15]

Figure 18 Compliant wheel 2 [16]

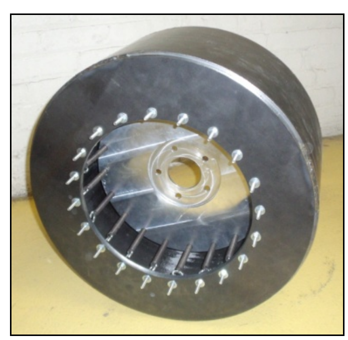


Figure 19 Compliant hub [17]

This raises the questions:

- What about dampening or energy dissipation or plastic compliance?
- 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 it contribute to simplifying suspension system design?

These types of questions led to exploring other wheel concepts of which one can be described as a particulate filled chainmail wheel [18] concept. Inspired by the experience of modelling and simulating charge motion of tumbling mills typically found in the mining industry, this wheel concept is characterized by the granular flow of a particulate fill contained between a hub and a flexible chainmail tire. The particulate can be any hard pebble like material and ultimately, the particulate can be potentially screened regolith pebbles or sintered/molded regolith beads which would make this wheel concept into an In-Situ Resources Utilisation (ISRU) activity. As in the case of tumbling mills, the interactions between the wheel particulate filling (mill charge) would dissipate energy of movement through friction between particles.

It should be noted that in the case of tumbling mills, the mill charge, composed of rocks and balls, is continually lifted in a rotating drum similar to the expected dynamic of the particulate in this wheel concept. Just as in the tumbling mill case, the particulate will centrifuge at a specific rotation speed which is a function of the wheel radius and the gravitational pull. This rotation speed in the grinding field is called the critical speed (ω [rad/s]) and is defined by Equation (1).

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

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

For this particulate filled chainmail wheel concept, it is possible to express the critical speed as the speed at which the vehicle will travel when centrifuging occurs (see Figure 20). For a 5 inch diameter wheel, the critical speed on earth would be just under 3km/hr while on the moon this wheel would centrifuge just over 1km/hr.

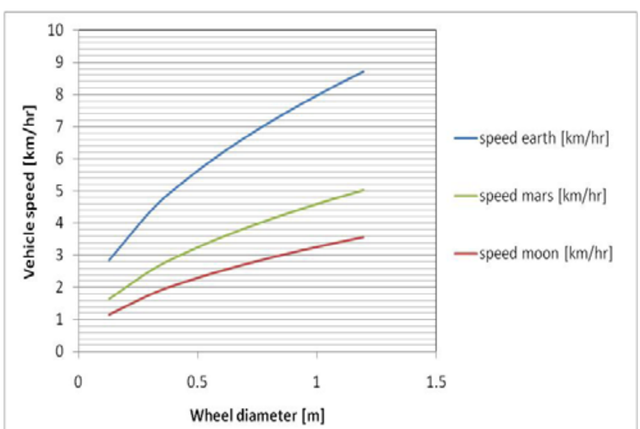


Figure 20 Critical driving speeds for iRings wheel with respect to wheel diameter

This critical speed is significant because above this speed a particulate filled chainmail wheel will stiffen with increased speed due to the increased centrifugal forces exerted by the particulate. One can therefore speculate that at greater speeds this stiffening will lead to a wheel behavior closer to a rigid wheel which would presumably exhibit decreased rolling resistance of the wheel rendering it more efficient with increased speed mainly because the ground contact area will decrease. However, in a breaking situation, one can speculate that the charge would fall into a loose system that will quickly increase the ground contact area and therefore increase the stopping force in braking.

As this wheel concept dubbed “iRings” for its coincidental description of the “iron rings” chainmail structure and recognition of a Canadian engineering tradition, dissipates energy as opposed to storing it and releasing it in an elastically compliant structure, it might be considered as defining a new class of wheels that are predominantly illustrated by energy dissipation or plastic compliance.

iRings Initial Performance Results

The investigation into the viability of this concept wheel started with a mock-up and then proceeded with a fabric 22in wood filled wheel on beadlock rim. Sub-sequent prototypes included a set of dried pea filled felt and duct tape 5in diameter wheels on a beadlock rims and a set of 5in diameter delrin filled chainmail wheels on similar beadlock rims. Figure 21 illustrates the 5in diameter set of chainmail wheels as installed on a rover testbed. Visual inspection of 1m drops of both the rover with rubber and iRings wheels illustrate that the “iRings” wheel dissipates energy quite well. In the case of the iRings wheels, impact with the ground can described as critical damping while that for the rubber wheels under damping. Further visual inspection shows that the compliant nature of the chainmail and particulate combination tends to hug rock surfaces when riding over them (see fig 22). An 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.

Figure 21 5” iRings wheels on reduced scale rover

Figure 22 Example of iRings compliance on rock surface

Subsequently, traction performance tests were completed 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 twice the width of the “iRings” prototype. As such, the traction values were compared on a per unit wheel width. Further, traction was determined using a load cell fish-hook set-up where traction or drawbar pull was determined for 100% slip. Figure 23 shows that for a unit wheel width the traction of the “iRings” wheels were greater than the rubber wheel benckmark.

Noting that this wheel concept dissipates energy as opposed to storing it and releasing it in an elastically compliant structure, it can be expected that the rolling resistance of this wheel would be greater than the benchmark wheel. To this end, 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 (see Figure 24). In both cases, energy consumption increased with increase vehicle load as it would be expected. It is clear that for the "iRings" case, the power consumed is greater than that consumed by the rubber wheels.

It should be noted that all tests on this 5 in diameter wheel were completed at speed less than the critical speed which would be just under 3 km/hr. Subsequent tests will look at increasing the speed of the this rover testbed to 7 km/hr and investigating if indeed the wheel power consumption improves with greater speed.

It should be noted that current research aims to determine the performance of the "iRings" wheel concept on both the 8 inch wheel platform as well as on 22 inch wheel platform JUNO (see Figures 25).

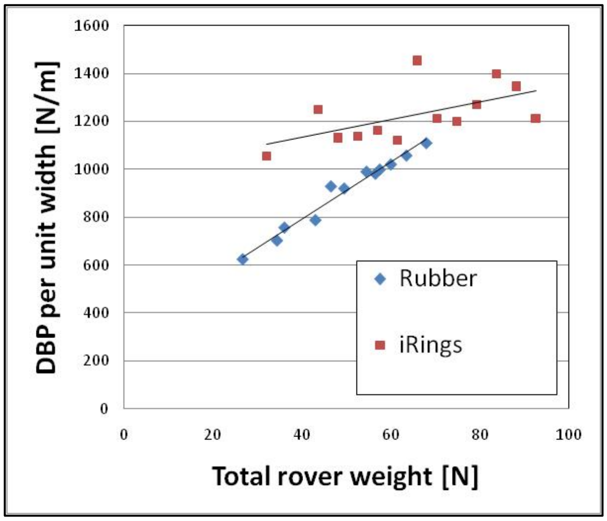


Figure 23 Ratio of drawbar pull / unit wheel width for 100% slip

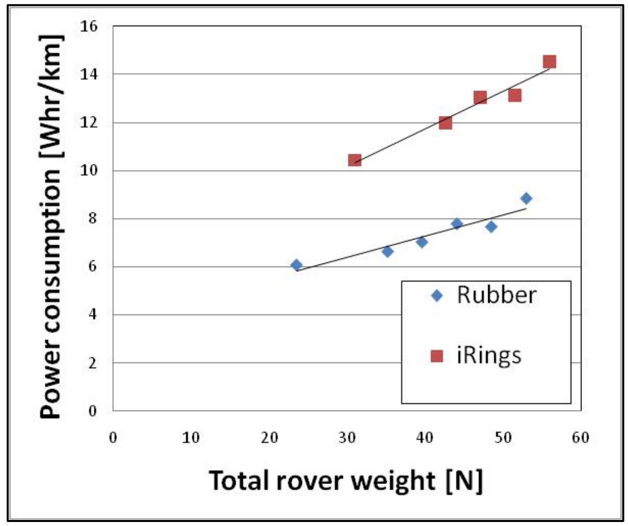


Figure 24 Power consumption for 5in wheels

Figure 25 The suite of "iRings" prototype wheels – 5inch, 8 inch and 22 inch diameter

Conclusion

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

In terms of physical facilities being developed, they are typical of any research undertaking addressing lunar wheel design and development. In terms of virtual facilities, we are addressing new avenues to modelling ground/wheel interaction, wear and dust mitigation (particularly regarding the coupling between electromagnetic fields and regolith induced movement), multi-disciplinary design optimization and powertrain modelling as a function of terrain topology. Here the added physical facilities provides the opportunity to verify and validate the modelling being developed.

In terms of wheel concepts, the wheel design space is being explored and future activities will undoubtedly 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 and it was prototyped and is currently being tested. Initial results illustrate that for the 5 inch diameter wheel increased traction (on a per unit width basis) can be achieved at the expense increase energy consumption during locomotion. However, the wheel also holds the promise of increased shock absorption and potentially allowing for increased vehicle speed on the lunar surface. Further, tests will look at, amongst other things, the performance of larger wheel diameters.

Finally, this project aimed at leveraging the talent and enthusiasm of both graduate and undergraduate students. To date, 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 the year 2008-2009 and another 33 undergraduate students are currently completing projects on problems related to this project in the 2009-2010 academic year.

Acknowledgements

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