



Study on mobility of planetary rovers- A review

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Abstract—The current paper presents a review of recent advancements in the study of mobility of planetary rovers in terms of size parameter(for plain wheels or wheels with lugs) from various research works. In designing a planetary rover, it is necessary to evaluate the effect of model size parameters such as weight, diameter/width and grousers of a wheel on its travelling performance. This travelling performance depends on the wheel mechanism/track mechanism with no effect from change in rover weight, for tracked mechanism. However, for the wheeled mechanism the travelling performance decreases as the rover weight increases. The wheel diameter rather than wheel width, improves travelling performance. The provision of lugs improves travelling performance. The paper describes the analytical method for predicting the stress distribution beneath the wheel when it interacts with the soil. The salient observations and inferences from pertinent research works, pertaining to the travelling performance of planetary rovers are also outlined.

Keywords—mobility; travelling performance; rovers; slip ratio; drawbar pull; models;

I. INTRODUCTION

Rovers are light weight, unmanned vehicles that explore the surface of difficult terrain of the Martian planet and lunar surface, negotiating steep slopes and rough terrain. Hence, a study on their tractive performance becomes essential. Small projections on the rim of the wheel, known as lugs or grousers are provided and the performance of the lugged wheel are studied. This paper highlights the impact of various size parameters such as wheel weight, diameter of wheel,width of wheel, wheel surface pattern (grouser's), grouser height. Recent advancements in the study of wheel-soil interaction are presented. Various methods for the analysis of wheel-soil interaction are presented. For the evaluation and improvement of wheel performance onvarious types of soils, it is necessary to know the stress distribution in the deformation of soil and wheel. An analytical method for predicting the stress distribution generated beneath the wheel when it interacted with the soil has been studied and noted.

II. STRESS DISTRIBUTION MODELS OF A RIGID WHEEL

A.IMPORTANT TERMS

1. Slip Ratio

The rovers tend to slip and the slippage is measured in terms of slip ratio and the drawbar pull. The wheels of the rover may be rigid or flexible. For rigid wheel, the following conditions apply.

Slip ratio is calculated as per equation1(Wong et al.,2001) and as per equation 2(Ding et.al, 2011) as follows.

s = (v\_d - v) / v\_d ..... (1)

where, v\_d = circumferential velocity; v = actual travelling velocity of the wheel.

s = (r\*omega - v) / r\*omega ..... (2)

where, omega = angular velocity of the wheel; r= radius of the wheel; v = actual travelling velocity of the wheel.

Slip ratio ranges between 0 and 1. If, slip ratio is zero, it indicates that the wheel is moving forward without any slippage, whereas slip ratio of one indicates that the wheel cannot move forward because of slippage. Therefore,lower slip ratio is an indication of high travelling performance on a slope.

2. Drawbar Pull(DP)

The drawbar pull is the difference between the total thrust and the total external resistance of the vehicle. It is the force required for a wheel for its movement, on slope. At the same time, vertical force is required to prevent its sinkage into the soil. The traveling performance is evaluated based on the relationship between drawbar pull and vertical force.

The driving performance of wheel is analyzed using absolute performance indices such as drawbar pull, driving torque, and wheel sinkage which depends on normal stress and shear stress distributions. The stress distribution models can be used for such a purpose.

**B. Stress Distribution Models**

A rigid wheel soil interaction model is used to evaluate the tangential/normal stress distribution under the wheel-soil interface. Shear deformation modulus, cohesion and angle of internal friction of soil are derived from direct shear tests. Prediction of wheel performance, by analysis of normal (equation 3,4 as per Wong and Reece, 1967) and shear stress (equation 5, as per Wong and Reece, 1967) distributions under wheel soil interaction are as indicated.

Normal stress [4], [19]

$$\sigma = (k_1 + k_2 b_w) \left[ \frac{r_w}{b_w} (\cos \theta - \cos \theta_0) \right]^n \text{ when } \theta_m \leq \theta \leq \theta_0, \text{ forward zone} \dots \dots \dots (3) \quad \sigma = (k_1 +$$

$$k_2 b_w) \left[ \frac{r_w}{b_w} \left( \cos \left[ \theta_0 - \frac{\theta}{\theta_m} (\theta_0 - \theta_m) \right] - \cos \theta_0 \right) \right]^n \text{ when } 0 \leq \theta \leq \theta_m, \text{ rearward zone} \dots \dots \dots (4)$$

Shear stress [4], [19]

$$\tau_s = (c + \sigma \tan \phi) \left( 1 - e^{-\frac{r_w}{k_s} [(\theta_0 - \theta) - (1-l)(\sin \theta_0 - \sin \theta)]} \right) \dots \dots \dots (5)$$

In order to evaluate DP and the vertical force, normal stress and shear stress need to be calculated. For a wheel travelling on loose soil, the maximum normal stress occurs in the transition zone between the forward and rearward portions (Fig.1,Wong, 2001)

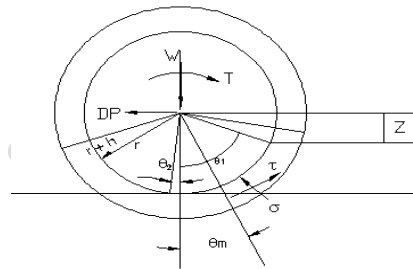


Fig 1: Wheel-soil interaction diagram

where, 'c' indicates cohesion, 'phi' is the internal friction angle of the soil, 'k\_s' is the shear deformation parameter [19].

As per Ishigami (2007), maximum normal stress can be arrived at from the given normal stress calculated from equation 6.

$$\sigma(\theta) = \sigma_{max} [\cos \theta - \cos \theta_f] \theta_m \leq \theta \leq \theta_f \dots \dots \dots (6)$$

$$\sigma_{max} = (ck_c + \rho k_\phi b) \left( \frac{r}{b} \right)^n \dots \dots \dots (7)$$

k\_c and k\_phi are the pressure-sinkage constants, corresponding to the shear parameters, cohesion and friction angle, n denotes soil exponent, c and rho are cohesion and bulk density of the soil, respectively.

The entry angle, theta\_1 and the exit angle theta\_2 of the wheel (for determining DP and vertical stress), depend on lambda, the sinkage ratio of the wheel, the ratio of front sinkage to rear sinkage of the wheel, as well as the lug size parameters, height h and radius r.

$$\theta_1 = \cos^{-1} (1 - h/r) \dots \dots \dots (8)$$

$$\theta_2 = \cos^{-1} (1 - \lambda h/r) \dots \dots \dots (9)$$



For a wheel travelling on loose soil, the maximum shear stress is obtained by modifying Mohr's relationship to include the radius of the wheel 'b', shear deformation parameter 'k<sub>s</sub>', shear parameters, c and φ and the slip 'i' (equation 10).

$$\text{Slip } i = \frac{\omega r - v}{\omega r} \dots\dots\dots (10)$$

where 'ω' is angular velocity of wheel, 'r' is radius of wheel and 'v' is the travel velocity of wheel.

Shear stress is calculated as per equation 11 (Wong, 2001),

$$\tau_s = (c + \sigma \tan \phi) (1 - e^{-\frac{\tau}{k_s}[(\theta_1 - \theta) - (1-i)(\sin \theta_1 - \sin \theta)]}) \dots\dots\dots (11)$$

Ishigami (2007), simplified the shear stress equation by introducing the shear deformation modulus 'k<sub>s</sub>' and the soil deformation modulus, 'j<sub>s</sub>', dependent on the wheel angle θ as in equation 12.

$$j_s(\theta) = r[\theta_1 - \theta - (1-i)(\sin \theta_1 - \sin \theta)] \dots\dots\dots (12)$$

Hence the modified shear stress equation 13 becomes,

$$\tau_s = (c + \sigma(\theta) \tan \phi) [1 - e^{-j_s(\theta)/k_s}] \dots\dots\dots (13)$$

### III. EFFECT OF WHEEL SIZE PARAMETERS ON TRAVELLING PERFORMANCE

#### A. Literature Review

The wheel size parameters are 1. wheel diameter, 2. wheel width, 3. Lugged wheel diameter, 4. Lug height

**Grandet et al. (2002)** carried out optimization of locomotion performance of vehicles for planetary explorations and designed a reconfigurable mini-rover. Velocity based algorithm improving both the global traction as well as stability performance of a rover was considered. Sensors like inclinometers for pitch and the roll measurements and position sensors for detecting lug mechanism are provided.

**Dimitrios Apostolopoulos et al. (2003)** conducted 50 experiments on various terrain conditions and geometries, including discrete orthogonal and combined steps, and slopes to characterize inflatable wheel mobility as a function of tire construction, loading and inflation. The wear resistance of the inflatable tire was tested over 50 km of endurance traverses in a closed test course and was quantified.

**Yoshida et al. (2003)** uses slip based traction control of a planetary rover over a rough terrain. Experiments were conducted on a test bed, to understand tire-soil interaction. The slip ratio ranges from 0.1 to nearly 1.0 and hence limits excessive tire velocity or force.

**Benoit et al. (2005)** carried out sinkage tests with circular plates on four soils chosen to represent the mechanical properties of a range of soils: a sand for frictional soils, a silt for cohesive soils and a silty sand and a sandy loam for cohesive frictional soils. The vehicle motion resistance on tilled soil was related to its sinkage which was one of the components of the mobility models allowing calculation of the motion resistance related to the running gear sinkage into the soil. This modelling of the pressure-sinkage curves for the tilled soils must operationally allow estimation of the sinkage with an acceptable precision.

**Bauer et al. (2005)** reported good agreement between experimental and simulation results, for, wheel sinkage as a function of slip ratio. Dry sandy soil was used. When 18 lugs were provided on the wheel, approximately 30% increase in drawbar pull was observed from that of a 9 lugged wheel, with relatively little effect on sinkage, AESCO Soft Soil Tire Model (AS<sup>2</sup>TM) capturing the sinkage versus slip ratio relationship accurately, for both single and multi pass cases.

**Giulio Reina et al. (2006)** establish methods for wheel slippage and sinkage detection aiming to improve vehicle mobility in soft sandy terrain. Slip detection is obtained based on observing different onboard sensor modalities and by defining deterministic conditions that indicate vehicle slippage. The limitation of this approach is that slippage along longitudinal direction of motion is considered neglecting lateral slippage. An innovative vision based algorithm for wheel sinkage estimate is discussed based on edge detection strategy. It gives information about vehicle -terrain interaction.

**Wong et al. (2006)** evaluated the travelling performance of wheeled vehicle and tracked vehicle. Two computer simulation models, one for wheeled vehicles, NWVPM and other for tracked vehicles, NTVPM are used. Shearing characteristics of the



terrain thrust on a wheeled and tracked vehicle are explained. The thrust from both wheeled vehicle and tracked vehicle are compared. For the tracked vehicle, total contact area is usually much larger than that of wheeled vehicle. Hence the traction of a tracked vehicle on cohesive soil is more than the traction of wheeled vehicles.

**Michaud et al (2006)** carried out optimization of wheel design on a particular soil using Rover Chassis Evaluation Tool (RCET) tool. The travelling performance is given in terms of trafficability and terrainability. Trafficability characteristics include static stability and slope gradeability; Terrainability includes obstacle climbing ability and ground clearance. The optimal rover design is achieved considering the soil properties and wheel load range.

**Liu J. et al (2008)** results show that grouser height and slip influence the motion performance compared to grouser spacing and thickness. The grouser parameters obtained through experimental results by evaluating tractive and steering performance are 15° grouser spacing, 10 mm grouser height, 1.5 mm grouser thickness, optimal value of slip is 13%.

**Liu J. et al. (2008)** conducted experiments on small rigid wheel traversing on a soil bin of loose sand. They analyzed the effect of straight lugs on the wheel performance and optimized the wheel configuration of planetary rovers. Experiments were carried out using single-wheel test bed at a free wheel sinkage and 0 to 60% slip. Six transducers, displacement transducer, and torque sensor, towing motor, driving motor and steering motor were used. Motion Performance was evaluated by its drawbar pull (DP) and driving torque (DT). Two wheels were considered – one with a diameter of 135 mm and width of 95 mm and another with diameter as 167 mm and width of 105 mm. Based on the study, the optimum lug spacing was 15°, optimum height was 10 mm and thickness was 1.5 mm. The lug height and slip produced had major effect rather than lug thickness and spacing.

**Sutoh M. et al. (2010)** conducted experiments with two-wheeled rover. Numerical simulations were also carried out. Increase in the wheel width, from 50 mm to 150 mm, results in a decrease in the slip ratio to 0.3 (maximum change at slope angle equal to 17°). Hence, the wheel diameter was increased keeping the width constant, contrary to general belief, as wheel diameter increases, the slip ratio decreases leading to better travelling performance. But, the weight of the wheel is not explicitly mentioned. The above result becomes a possibility if for the same wheel weight and the same width, the diameter alone is increased. In the simulations, as the wheel width increased, the slip ratio decreases as in the case of experiments. The drawbar pull increases. However, in the simulation as width increased, the slip ratio also increased. The effect of variation of diameter was not felt in the simulations carried out.

**Ding et al. (2011)** conducted experiments using single-wheel test bed for wheels. The parameters varied include wheel diameter width, lug number, lug heights, and lug inclination angles. Influence of vertical load and moving velocity on wheel driving performance were also studied. Wheel driving performance in terms of performance indices and relative indices are provided. Increase in radius and width results in increase in wheel driving performance; Lug height affects the wheel driving performance more than increase in radius. Optimum number of lugs, were arrived at, to achieve maximum tractive performance. Minimum inclination of lug angle was also determined.

**Ishigami et al. (2011)** describes a comprehensive model for the traction performance of flexible/rigid wheels driving on deformable terrain calculates wheel deflection as well as wheel sinkage. Simulation results gives the optimal wheel pressure based on wheel load, wheel dimension and terrain stiffness.

**Lizuka et al. (2011)** carried out investigations on the shape of lugs. Experiments were carried out using single-wheel test bed, to measure slip ratio over various slopes and different shapes of lugs. The ratio between radius of the wheel and lug length is considered. When the lug length is more, the wheel performs better. There is limit on traversing slope on loose soil if the length of lugs, become longer. Wheels with larger radius will have better performance than those with small radius.

**Sutoh M et al. (2011)** conducted experiments using lightweight two-wheeled rover. The number of lugs, lug heights was varied; in a sand-box, the influence of lugs on the travelling performance of planetary rovers was assessed. From experimental results, it was found that although lugs have some effect on the travelling performance over gentle slopes (for slopes less than 8°); they have more effect on the travelling performance over steep slopes (slopes more than 8°). On gentle slopes, when the number of lugs are less, increase in lug height (from 5 mm to 15 mm) results in decreasing travelling performance whereas an increase in the no of lugs with an increase in lug height results in increase in traveling performance. On the other hand, increase in lug height and increase in no of lugs contributes high travelling performance of wheels over steep slopes. Wheels with lugs have higher travelling performance than wheels with diameter.

**Meng Li et al. (2012)** selected the key parameters of the system between lunar soil and rover wheel and the terramechanical model of the system under lunar gravity was formulated based on similarity theorem. The feasibility of model experiment

approach was discussed. The drawbar pull and tractive torque obtained from models from experiment were 6 times the corresponding values under prototype condition. Hence, the proposed method can be used to study a lunar rover's tractive performance.

**Sutoh M et al. (2012)** conducted experiments using a mono-track rover and a four-wheeled rover with different rover weights in order to evaluate its travelling performance, based on the influence of rover weights, wheel diameter/width (diameters considered are 116 mm, 202 mm, 327 mm and widths are 50 mm, 100 mm, 150 mm). Numerical simulation and comparisons with experimental results are carried out. For tracked mechanism, there is no effect due to increase in rover weight; in wheeled mechanism, decrease in travelling performance occurred with increase in rover weight. Wheel diameter (327 mm) rather than wheel width (150 mm), contributes to better travelling performance. The increase in the number of lugs will improve the travelling performance than having large diameter.

**Gareth Meirion-Griffith et al. (2012)** presented a comprehensive pressure-sinkage model for small diameter wheels on soils by including the effect of wheel width on a previously proposed diameter-dependent pressure-sinkage model. The effect of wheel width on the pressure-sinkage relationship was similar to that of a change in wheel diameter. Experimental results indicated that the proposed model offers better predictive capabilities than its predecessors in both laboratory and field tests

**Skonieczny K.M. et al. (2012)** proposed an expression for determining appropriate lug (grouser) spacing for rigid wheels. Experiments were conducted using test bed with different no of lugs on wheel and with various heights of grousers resulting in an increase in grousers beyond the minimum number do not improve performance. The proposed expression relates the geometric wheel parameters (such as wheel radius, lug height and spacing) and operating parameters (such as slip and sinkage), and predicts the maximum allowable lug spacing which is given in below.

$$\phi < \frac{1}{(1-i)} (\sqrt{((1+h)^2 - (1-z)^2)} - \sqrt{1 - (1-z)^2})$$

Where  $\phi$  is angular grouser spacing,  $h$  is grouser height,  $z$  is wheel sinkage and  $i$  is wheel slip.  $i = 1 - \frac{v}{r\omega}$ ; where  $v$  is wheel linear velocity,  $\omega$  is wheel angular velocity and  $r$  is radius of the wheel.

**Ding et al. (2012)** carried out studies on slip ratio of a lugged wheel. Wheel-soil interaction experiments were carried out varying wheel diameter, lug height. Sensors are used to determine drawbar pull, torque and wheel sinkage. If the slip ratio is zero, the soil can cause little resistance force on the smooth wheel. It also results, wheels with different lug heights to verify this, the driving torques were also same if the slip ratio was zero.

**Sutoh et al. (2013)** provided a fundamental guideline for determining the lug interval on a wheel. Linear travelling speed model is proposed for wheeled vehicle first and, to verify this model, travelling tests were performed using two-wheeled rover with wheels of different lug intervals and with different lug heights. Maximum allowed lug interval can be determined for a given wheel using the angle derived from static sinkage of wheel. From experimental results it was found that, for a wheel to have high travelling performance there should be more than two lugs between the vertical and the surface of the soil on a wheel.

**Sreenivasulu and S.Jayalekshmi(2014)** provide a comprehensive review of the terramechanics on lunar soil mechanics.

**Sreenivasulu(2014)** prepared a lunar soil simulant: TRI-1(Tiruchirappalli -1) and characterization of the same and wheel-soil interaction studies were carried out on TRI – 1.

**Yamamoto et al. (2014)** examine about influence of lug motion, the soil reaction forces acting on a single actuated lug (without wheel) in various motion scenarios. The parameters of lug motion, such as inclination angle, moving velocity and sinkage length of the lug were assessed. Both the bulldozing force and vertical force are independent of horizontal moving velocity of the lug. Bulldozing force achieved its maximum value around  $120^\circ$  whereas vertical force achieved its maximum value around  $130^\circ$ .

**ShTahesi et al. (2015)** conducted technical survey on Terramechanics models, for tire-terrain interaction of wheeled vehicles. Model validation has been effected by comparison of experimental results with simulation results. The models were categorized into three groups-empirical model, physics-based model and semi-empirical model. Features of all models are reviewed and compared in order to get efficient tire models for performing vehicle simulations.



**B. Summary**

The interaction of wheel on loose soil has been well investigated in the field of terramechanics. Terramechanics is the study of soil properties, specifically the interaction of wheeled or tracked vehicles on various surfaces. The principle of wheel soil interaction mechanics and the empirical models of stress distribution beneath the wheel have been studied. Using the relationship between normal and shear stresses beneath a rigid wheel on loose soil, calculation method for a net traction force, drawbar pull, and vertical force acting on the wheel are studied.

**C. Conclusion and Future Scope**

This paper presents a review on the mobility of planetary rovers. It is inferred from the review. Ample scope exists for wheel soil interaction studies. A comprehensive summary on the experimental investigations carried out on wheel-soil interaction is presented. The analytical and numerical study on terramechanism on lunar soil simulants is addressed. A major scope on further research on wheel soil interaction is revealed through this review.

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**References**

- [1] Bauer R, Leung W and Barfoot T, "Experimental and simulation results of wheel-soil interaction for planetary rovers", in proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems. Edmonton, Alberta, Canada, pp. 586-591, 2005.
- [2] Benoit O and Gotteland Ph., "Modelling of sinkage tests in tilled soils for mobility study", Soil & Tillage Research, Vol. 80, pp. 215-231, 2005.
- [3] Dimitrios Apostolopoulos, Michael D. Wagner, Stuart Heys and James Teza, "Results of the Inflatable Robotic Rover Testbed", Robotics Institute Carnegie Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213 June, 2003.
- [4] Ding L, Gao H, Deng Z, Nagatani K and Yoshida K, "Experimental Study and analysis on driving wheels, performance for planetary exploration rovers moving in deformable soil," Journal of Terramechanics, 48(1): 27-45, 2011.
- [5] Ding L, Gao H, Deng Z, Yoshida K and Nagatani K, "Slip ratio for lugged wheel of planetary rover in Deformable soil: Definition and Estimation". Pages: 3343-3348, 2012.
- [6] Gareth Meirion-Griffith and Matthew Spenko, "A pressure-sinkage model for small-diameter wheels on compactive, deformable terrain," Journal of Terramechanics, ISSN 0022-4898, 2012.
- [7] Giulio Reina, Lauro Ojeda, Annalisa Milella and Johann Borenstein, Wheel Slippage and Sinkage Detection for Planetary Rovers. IEEE/ASME Transactions on Mechatronics, Vol. 11, No. 2, April 2006.
- [8] Grand C, Ben Amar, Plumet F and Bidaud, "Stability control of a wheel-lugged mini-rover". University de Paris VI, 2002.
- [9] Ishigami G, Otsuki M, Kubota T and Iagnemma K, "Modeling of flexible and rigid wheels for exploration rover on rough terrain". 28th International Symposium on Space Technology and Science, Okinawa, Japan, 5-12 June, 2011.
- [10] Liu J, Gao H and Deng Z, "Effect of straight grousers parameters on motion performance of small rigid wheel on loose sand." Information Technology Journal, 7(8):1125-1132, 2008.
- [11] Lizuka K, Yoshida T and Kubota T, Effect of tractive given by grousers mounted on wheels for lunar rovers on loose soil. 37<sup>th</sup> annual conference of the IEEE industrial electronics society, Melbourne, Australia. Page: 110-115, 2011.
- [12] Meng Li, Feng Gao and Peng Sun, "Prediction Method of Lunar Rover's Tractive Performance Based on Similitude Methodology," Fifth International Conference on Intelligent Computation Technology and Automation, 978-0-7695-4637-7/12, 2012 © IEEE DOI 0.1109/ICICTA.2012.177..
- [13] Skonieczny K, Moreland S.J and Wettergreen D.S, "A grouser spacing equation for determining appropriate geometry of planetary rover wheels." CMURI, pittsburg, PA 15217 USA, 2012.
- [14] Sreenivasulu S and Jayalekshmi S, "Terramechanics on Lunar Soil Simulants- A Review". Int.J.Struct. & Civil Engg. Res. Vol.3, No 2, 2014.
- [15] Sutoh M, Nagaoka K, Nagatani K and Yoshida K, Design of wheels with grousers for planetary rovers travelling over loose soil. Journal of Terramechanics.vol no: 50, page no: 345-353, 2013.
- [16] Sutoh M, Nagatani K and Yoshida K, Analysis of the travelling performance of planetary rovers with wheels equipped with lugs over loose soil. Earth and space 2012: pp. 1-10, 2012.
- [17] Sutoh M, Yoshida K and Nagatani K, "Evaluation of influence of surface shape of wheel on Travelling Performance of planetary rovers over slope". Proceedings of 17<sup>th</sup> ISTVS International Conference, Blacksburg VA, USA, 2011.
- [18] Sutoh M, Yusa J, Nagatani K and Yoshida K, Travelling Performance Evaluation of Planetary rovers on weak soil. Journal of Field Robotics. Sapporo, Japan, 2010.
- [19] Sh Taheri, C. Sandu, E. Pinto, D. Gorsich, A technical survey on Terramechanics models for tire-terrain interaction used in modeling and simulation of wheeled vehicles, Journal of Terramechanics, volume 57, pages 1-22, February 2015.
- [20] Wong J.Y and Huang W, Wheel vs Tracks – A fundamental evaluation from the traction perspective. Journal of Terramechanics, 43(1):27-42, 2006.



- [21] Wong J.Y, and Reece A, “Prediction on Rigid Wheel performance based on the analysis of soil-wheel Stresses: Part 1. Performance of driven rigid wheels,” Journal of Terramechanics. 4(1): 81-98, 1967.
- [22] Wong J.Y., Theory of ground vehicles, 3<sup>rd</sup> ed. New York: Wiley – Interscience; 2001.
- [23] Yamamoto R, Yang Y, Sun Y and Ma S, “Influences of lug motion on lug-soil reaction forces in sandy soil”. International conference on Automation Science and Engineering, Aug 18-22, 2014.
- [24] Yoshida K, Nagatani K, Miwa and Ishigami G, “Terramechanics based model for steering Maneuver of planetary exploration rovers on loose soil”. J. Field Robotics, vol.24, no.3, pp. 233-250, 2007.

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