Current Status and Prospects of Terramechanics-based Simulation Techniques for Planetary Rover Locomotion

T. Kobayashi*, G. Ishigami**, S. Ozaki***, M. Sutoh****

*Department of Architecture and Civil Engineering, University of Fukui, Japan
e-mail: tkoba@u-fukui.ac.jp

**Department of Mechanical Engineering, Keio University, Japan
e-mail: ishigami@mech.keio.ac.jp

***Faculty of Engineering, Yokohama National University, Japan
e-mail: s-ozaki@ynu.ac.jp

****JAXA Space Exploration Center, Japan Aerospace Exploration Agency, Japan
e-mail: sutoh.masataku@jaxa.jp

Abstract

Current computer simulation techniques for lunar/planetary rover locomotion will play important roles in future extraterrestrial exploration missions. The mechanism of vehicle-terrain interaction (Terramechanics) is extremely complicated, especially when the vehicle travels on soft and uneven terrain. Hence, it remains difficult to accurately predict the traverse path and/or mobility characteristics of a rover. In this paper, the current status of simulation techniques for planetary rover locomotion was summarized and unresolved problems were pointed out. We first describe the general calculational flow of rover simulation techniques with the use of multi-body dynamics (MBD). We then revisited the applicability of the Bekker and Wong–Reece models, which form the basis of the MBD simulations. In this way, we clarified the problems and limitations of applying classical terramechanics models to the MBD simulations. Moreover, we reviewed three examples of current innovative simulation techniques that implement possible solutions for solving these problems.

1 Introduction

Simulation technologies for lunar/planetary rover locomotion play important roles in the research and development phase of mechanical design optimization and in the exploration phase of real-time path planning/navigation support. The mechanism of vehicle-terrain interaction (terramechanics) is extremely complicated, especially when the vehicle travels on soft and uneven terrain. Therefore, the processes of developing simulation techniques and improving their accuracy are constantly in operation. Although the accuracy needed depends on the purpose of the simulation, rational evaluation of wheel-soil interaction behavior is always essential.

In this paper, we briefly describe the general calculational flow of rover simulation techniques, and then revisit the classical models of terramechanics, namely the Bekker [1] and Wong–Reece models [2], which form the basis for predicting the behavior of wheel-soil interactions. These models, which are two of the long-established theories of terramechanics, are still frequently implemented in up-to-date rover simulation packages. We also clarify the problems and limitations of the classical models when they are applied to MBD simulations. Moreover, we review three examples of current innovative simulation techniques that implement potential solutions for overcoming these problems.

2 Calculational Flow of Lunar and Planetary Rover Simulation

In a mobility simulation for a multi-wheeled vehicle system, the calculated positions and forces at each wheel must be kinetically compatible with the vehicle motion. In other words, the motions of each wheel are mutually associated with the system-wide motion of the vehicle. To predict the dynamic motion of such a multi-body system, multi-body dynamics (MBD) analysis by using a computer is a promising tool.

Given that a driving force to move the vehicle forward is generated at the soil-wheel interface of each wheel, we prepare a soil-wheel contact model to solve

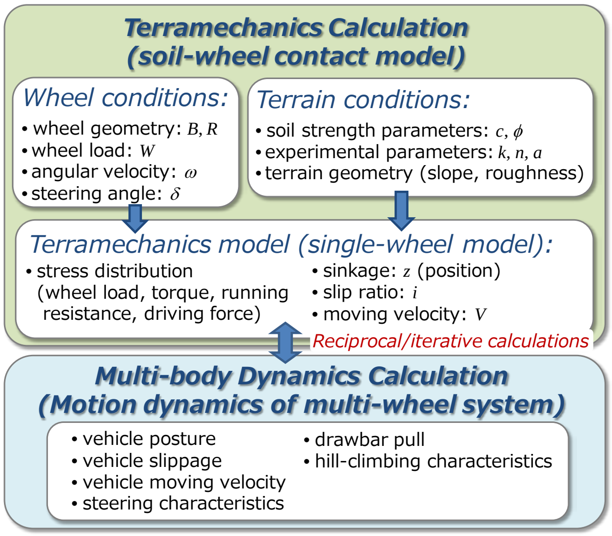
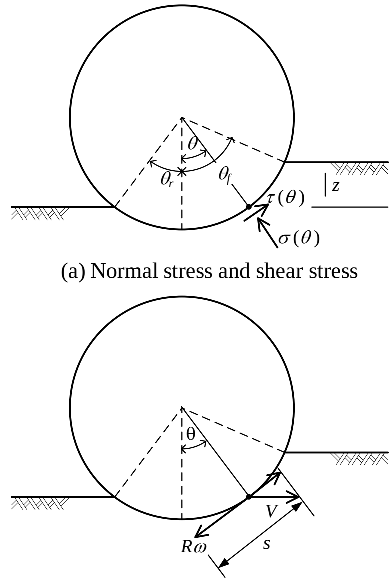


Figure 1 Calculational flow of rover simulation



(a) Normal stress and shear stress

(b) Moving velocity and slip velocity

Figure 2 Schematic diagram of soil-wheel interaction

the soil-wheel interaction at each wheel, and then incorporate the solutions into the MBD calculations. Figure 1 shows the typical calculational flow of existing rover simulations. The calculation is executed by solving a coupled problem between a soil-wheel system (terramechanics problem) and a multi-wheeled vehicle system (multi-body dynamics problem). The soil-wheel contact model (terramechanics model) provides solutions including those for wheel load, running resistance, driving force, slip ratio, and sinkage at each wheel; this information is then communicated to each wheel joint. The motion of the rover is then determined by the MBD calculation. The terramechanics and MBD calculations are reciprocally performed until both solutions are mutually consistent.

3 Classical Terramechanics Models

3.1 The Bekker and Wong–Reece models

Most existing rover simulations use terramechanics models that were originally established by Bekker [1] and by Wong and Reece [2]. These theories are outlined below.

When a rigid wheel having a radius of R is traveling at a speed of V with an angular velocity of ω, the slip ratio i is defined as:

$$i = 1 - \frac{V}{R\omega} \quad (1)$$

Figure 2 illustrates a schematic diagram of a soil-wheel interaction. Figure 2(a) shows the normal stress $\sigma(\theta)$ and shear stress $\sigma(\theta)$ acting at an arbitrary point with depth z. Figure 2(b) shows the relationship between moving velocity V and slip velocity s, where s is the amount of relative slippage generated in a unit time at the arbitrary point of the wheel. From the geometric relationships shown in Figure 2, z and s can be expressed as:

$$z = R\left(\cos\theta - \cos\theta_f\right) \quad (2)$$

$$s = R\omega\left[1 - (1 - i)\cos\theta\right] \quad (3)$$

where θ is the central angle of the arbitrary point and θ_f is the front contact angle. The accumulated amount of slippage j at the arbitrary point is given by integrating s from the beginning of contact to an arbitrary time, and is consequently expressed as:

$$j = R\left\{(\theta_f - \theta) - (1 - i)(\sin\theta_f - \sin\theta)\right\} \quad (4)$$

Bekker [1] established a method for determining the contact pressure $\sigma(z)$ acting along the wheel. He assumed that $\sigma(z)$ at an arbitrary point with depth z is expressed as:

$$\begin{aligned}\sigma(z) &= k_1 z^n \\ &= k_1 R^n \left(\cos\theta - \cos\theta_f\right)^n\end{aligned} \quad (5)$$

where k_1 and n are empirical parameters obtained by conducting a plate loading test, etc. Equation (5) provides a normal stress at depth *z*; consequently, the stress distribution along the soil-wheel interface is obtained. Note that in Bekker's approach, the stress distribution is independent of slip (he did not consider slippage at the time). He then proposed an equation for calculating the running resistance on the assumption that the soil compressed by the wheel rim moves only vertically and the work dissipated by soil compaction is equal to the work required to make the wheel move forward.

Subsequently, Wong and Reece [2] revealed that the stress distribution depends on the slip ratio when a wheel is traveling with slippage. They first determined that the normal stress becomes maximal at the point where the central angle is θ_m and suggested the following empirical equation to express θ_m:

$$\theta_m = (\alpha_1 + \alpha_2 i)\theta_f \qquad (6)$$

where α_1 and α_2 are empirical coefficients. Equation (6) indicates that θ_m increases with increasing *i*. By introducing Equation (6) into the pressure-sinkage relationship (5), they derived the following equations that provide a slip-dependent normal stress distribution.

For $\theta_m \le \theta < \theta_f$

$$\sigma(\theta) = k_1 R^n (\cos\theta - \sin\theta_f)^n \qquad (7)$$

For $\theta_r < \theta \le \theta_m$

$$\sigma(\theta) = k_1 R^n \left[\cos\left\{\theta_f - \frac{\theta - \theta_r}{\theta_m - \theta_r}(\theta_f - \theta_m)\right\} - \cos\theta_f \right]^n \qquad (8)$$

where θ_r is the rear contact angle. Moreover, they also determined an equation for calculating the shear stress $\tau(\theta)$ by applying Equation (4) to the Coulomb's failure criteria: $\tau = \sigma \tan\phi + c$. The proposed equation is also known as the Janosi–Hanamoto formula [3] and expressed as:

$$\begin{aligned} \tau(\theta) &= \{\sigma(\theta) tam\phi + c\}\left\{1 - \exp\left(-\frac{j}{k_2}\right)\right\} \\ &= \{\sigma(\theta) tam\phi + c\} \\ &\times \left[1 - \exp\left\{-\frac{R}{k_2}\left[(\theta_f - \theta) - (1-i)(\sin\theta_f - \sin\theta)\right]\right\}\right] \end{aligned} \qquad (9)$$

where ϕ and *c* are the internal friction angle and cohesion of soil, respectively, and k_2 is an empirical parameter obtained from a soil shear test.

Then, integrations of the vertical, tangential, and horizontal components of the stress distributions expressed by Equations (7), (8), and (9) yield the wheel load *W*, torque *Q*, and driving force *F*, respectively. These are given by the following equations:

$$W = RB\int_{-\theta_r}^{\theta_f} \{\sigma(\theta)\cos\theta + \tau(\theta)\sin\theta\} d\theta \qquad (10)$$

$$Q = R^2 B\int_{-\theta_r}^{\theta_f} \tau(\theta) d\theta \qquad (11)$$

$$F = RB\int_{-\theta_r}^{\theta_f} \{\tau(\theta)\cos\theta - \sigma(\theta)\sin\theta\} d\theta \qquad (12)$$

where *B* is the width of the wheel.

Except for θ_f, θ_r, and *i*, the parameters shown in the above-mentioned equations are all known or empirically definable values. Wong and Reece then proposed an algorithm to predict the sinkage *z*, torque *Q*, and driving force *F*. Numerical iterations with respect to θ_f, θ_r, and *i* are first performed by using Equation (10) until the calculated output of *W* matches the real value. Once θ_f, θ_r, and *i* are determined, *Q* and *F* are easily obtained from Equations (11) and (12).

3.2 Limitations of classical models

As described above, the classical terramechanics models are well-established in that they provide information including sinkage (position), slip ratio (moving velocity), and forces (torque and driving force) at each wheel, which are required to perform the MBD analysis. The Wong–Reece model in particular has frequently been incorporated into rover simulations because it takes into account the influence of slippage. However, we think that the classical terramechanics models will not suffice for appropriate rover simulations. When incorporating the classical models into the MBD analysis, attention should be given to the fact that the models have the following intrinsic limitations:

(a) Three-dimensional (3D) geometric shapes of the wheel and roughness/slope of the terrain surface cannot be directly taken into account.
(b) The pressure-sinkage relationships given by Equations (5), (7), and (8) are inadequate for slipping wheels.
(c) The slip-induced mobility change cannot be evaluated.
(d) In-situ experimental tests are needed to determine the model-governing parameters.
(e) The steering motion of the rover cannot be predicted.

Among the five issues listed above, we regard (a), (b), and (c) in particular as important. The details are as follows:

(a) 3D characteristics of the wheel and terrain surface

The classical models assume plane-strain conditions. Accordingly, 3D soil flows and the lateral inclination of the terrain surface cannot be directly taken into account. Stresses acting on a wheel rim will be distributed not only in the circumferential direction but also in the direction parallel to the wheel rotation axis, even when the wheel is on even ground. Existing models are incapable of considering such lateral stress distributions.

Numerical methods such as the Finite Element Method (FEM) and the Discrete Element Method (DEM) allow us to minutely analyze the 3D behavior of the soil-wheel interaction. However, the coupled FEM-MBD/DEM-MBD simulation has not yet been put to practical use, presumably because of the high computational cost. Notably, Holz et al. [4] attempted a novel numerical approach via multi-scale modeling. Their approach assumes that the soil deformation field is divided into two domains: micro-scale domains that show complex soil flows, and the macro-scale domain. Subsequently, the DEM was applied to the micro-scale domains to simulate complex soil behaviors. The major advantage of multi-scale modeling is that it keeps the computational cost feasible.

When the numerical approach comes to be used in practice, the terramechanics model (soil-wheel interaction model) will no longer be required and the problems/limitations of the models may be eliminated. However, this is likely to take some time. Hence, for the time being, modifying or newly establishing terramechanics models will be feasible solutions.

(b) Pressure-sinkage relationship

The pressure-sinkage relationship (5) is an empirical equation originally derived for the case when the soil is loose and compressed vertically by the passing wheel. When the wheel undergoes slippage, the equation may no longer be able to approximate the actual stress distribution accurately. Also, the parameters k_1 and n in equations (5), (7), and (8) are experimentally determined by performing an in-situ plate loading test, etc. Note that the pressure obtained is the area-averaged contact pressure acting in the vertical direction. Wong and Reece assumed in Equations (7) and (8) that the stress component perpendicular to the wheel rim can be expressed by the vertical contact pressure of the plate. Unfortunately, no logical necessity can be found in this assumption. We emphasize again that the normal stress distribution given by Equations (5), (7), and (8) is no more than an assumption or approximation without logical necessity.

(c) Change in motion over time

When a wheel undergoes slippage, the wheel sinkage will depend on the slip ratio and wheel load because the soil beneath the wheel will be more or less swept out rearward by the effects of the shear stress. This implies that the mobility at one moment influences that at the next moment; that is, unsteadiness is inherent in the soil-wheel interaction. Although a change in motion over time might be seen even in existing simulations, this may be attributed simply to the effect of unevenness of the terrain surface. Note that time-dependent changes of the soil-wheel interaction, including for example, the increase in slip-induced sinkage over time, is not considered in the classical models: the Wong–Reece model considers only stress and/or force relationships and is viable only on the condition of static equilibrium of force of wheel load W. For the unsteadiness and continuity over time to be reflected in the simulation, an additional equation that governs soil deformation in addition to existing stress/force equations may be required.

4 Innovative Approaches

Recently, numerous investigators have conducted studies on rover simulators. Some have proposed innovative techniques towards solving the aforementioned problems. In this section, we review three examples of noteworthy approaches presented by Ishigami et al. [5, 6] (Tohoku University model), Krenn et al. [7-9] (DLR soil contact model), and Azimi et al. [10-12] (Vortex dynamics model).

4.1 Tohoku University model

A group at Tohoku University (Ishigami et al.) [5, 6] has developed a simulation technique for a four-wheeled rover. Most importantly, they succeeded in steering the simulation by incorporating additional equations to calculate the side forces acting along the lateral direction of a wheel. In this model (Figure 3), 3D force information, including the side force F_y and steering torque T_z, can be evaluated.

The group also performed experiments by using a real model rover to assess the validity of the simulator (Figure 4). Moreover, they demonstrated path planning and performance evaluation by applying the simulation technology (Figure 5). This model, which was the first to deal with steering maneuvers, is now widely used in other simulators.

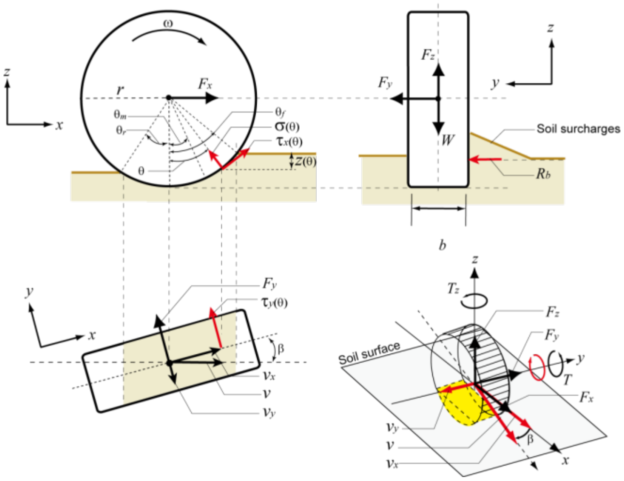


Figure 3 Wheel-soil contact model developed at Tohoku University[5,6]

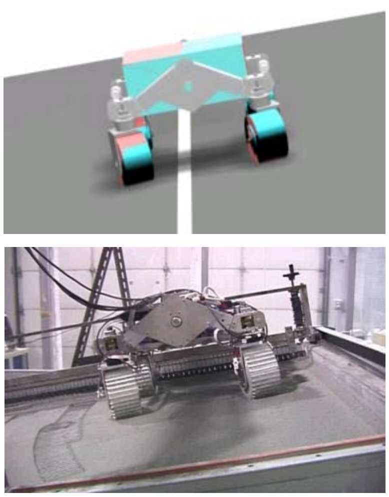


Figure 4 Experimental validation [5, 6]

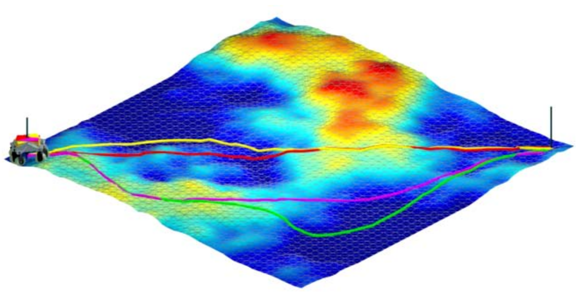


Figure 5 Path planning and performance evaluation [6]

4.2 DLR soil contact model

Krenn et al. [7-9] at the German Aerospace Center (DLR) have developed a simulator implementing a 3D soil-wheel contact model, so that not only the 3D characteristics of the terrain surface but also the 3D wheel structure can be taken into account.

In this model, the 3D terrain surface is expressed as a digital elevation grid (Figure 6) that provides height information. In addition, the wheel is described as polygonal mesh grid (Figure 7) so that the soil-wheel contact region can be detected computationally. Then, the local contact pressure at each contact node is given by Bekker's sinkage-pressure equation (5). Interestingly, they applied a weighting function to the pressure calculation so that the 3D pressure distribution beneath a wheel could be computed. Moreover, they proposed a unique algorithm regarding soil deformation, in which soil displacement was divided into two modes—lateral flow and downward compression—by determining the direction of the relative velocity vector at each contact node. Thus, the footprint and ground heave around the wheel can both be represented (Figure 8). This procedure may lead to the solution of problems (a), (b), and (c) described in Section 3. 2.

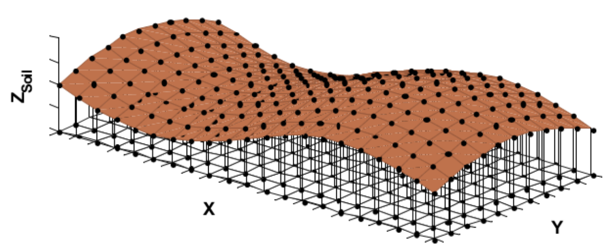


Figure 6 Soil surface elevation grid [8, 9]

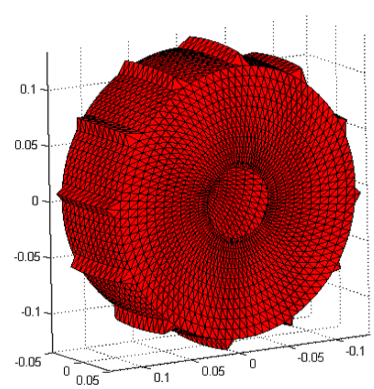


Figure 7 Polygonal surface of contact object [7-9]

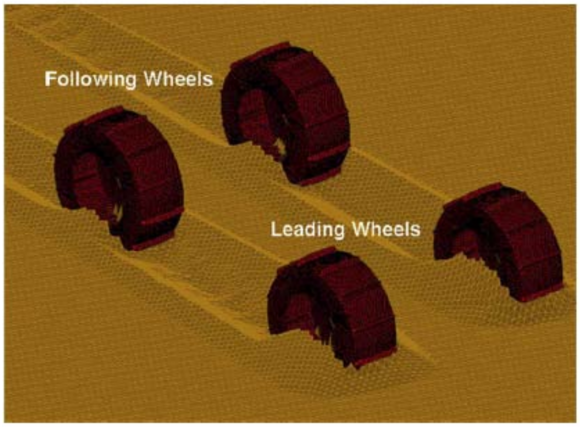


Figure 8 SCM simulation in soft terrain [7]

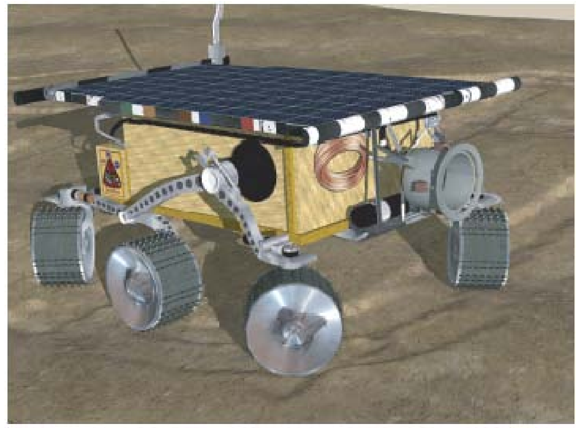


Figure 9 Sojourner rover simulation in Vortex [10]

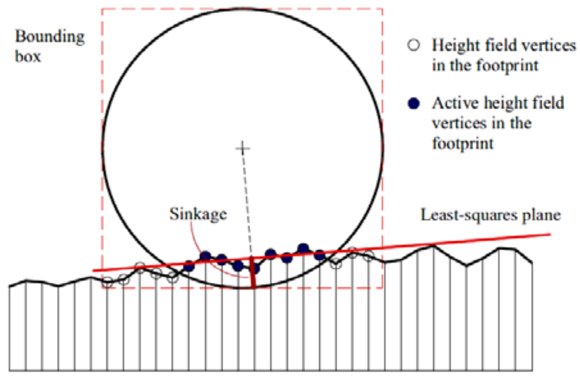


Figure 10 Schematic of height-field and wheel interaction [10]

4.3 Vortex dynamics model

CMLab Simulation Inc. provides a commercial simulator engine called Vortex Dynamics that calculates rigid body dynamics, collision detection, contact determination, etc. Azimi et al. [10-11] have developed a lunar/planetary rover simulator by using the Vortex engine (Figure 9).

The features of their technique are as follows. First, an equation for calculating lateral force (side force) is introduced to simulate steering maneuvers. Second, the simulator is equipped with an algorithm for soil-wheel contact detection. In their model, a high-resolution height-field is used to detect the intersections between a wheel and an uneven terrain surface, after which a pseudo terrain surface (least squares plane) is calculated from the cloud of intersections (Figure 10). This calculation process enables considerations regarding soil compaction by a passing wheel as well as irregularities and/or inclination of the terrain surface.

Azimi et al. [12] have also proposed a unique model for taking the soil compressibility into account. In their model, a stress-strain constitutive relationship (the Drucker–Prager constitutive equation with cap hardening) is used to express the soil behavior. Notably, this approach proposed a procedure for calculating stress and strain fields in the vicinity of the contact area on the assumption that the velocity of soil deformation is exponentially attenuated in the radial direction. This may lead to an approach that enables simulations capable of considering unsteadiness and/or continuity over time.

5 Conclusions

In this paper, we reviewed the classical terramechanics models (the Bekker and Wong–Reece models) that are frequently implemented in MBD simulations for planetary rover locomotion. We showed that the classical models are not sufficient for simulating mobility on uneven terrain or behaviors of soil compression and flow, etc. To facilitate progress in rover simulation techniques, it will be especially necessary to: 1) consider the 3D characteristics of the wheel/terrain, 2) establish a alternative method to estimate the stress distributions at the soil-wheel interface, and 3) implement an equation that can express the soil deformation so that the unsteadiness and/or continuity over time can be reflected in the simulation. Interestingly, some researchers have proposed innovative techniques that may lead to solutions of the issues mentioned above. We hope this review will be of assistance to accelerate progress in rover simulation techniques.

Acknowledgment

This work was supported by Grand-in-Aid Scientific

Research: Grant Number 24760376 from Japan Society for the Promotion of Science (JSPS). The authors gratefully acknowledge the support.

References

[1] M. G. Bekker, “Theory of Land Locomotion: The Mechanics of Vehicle Mobility”, The University of Michigan Press, Ann Arbor, MI, USA, 1956.

[2] J. Y. Wong, and A. Reece, “Prediction of Rigid Wheel Performance based on the Analysis of Soil-Wheel Stresses, Part I, Performance of Driven Rigid Wheels”, Journal of Terramechanics, 4(1), 1967, pp. 81-98.

[3] Z. Janosi, and Z. Hanamoto, “The Analytical Determination of Drawbar Pull as a Function of Slip for Tracked Vehicle”, Proc. of the 1st Int. Conf. on Terrain-Vehicle Systems, 1961.

[4] D. Holz, T. Beer, and T. Kuhlen, “Soil deformation Models for Real-time Simulation: a Hybrid Approach”, Proc. of the 6th Workshop on Virtual Reality Interactions and Physical Simulation, 2009, pp. 21-30.

[5] e. g., G. Ishigami, A. Miwa, K. Nagatani, and K. Yoshida, “Terramechanics-Based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil”, Journal of Field Robotics, 24(3), 2007, pp. 233-250.

[6] G. Ishigami, Terramechanics-based Analysis and Control for Lunar/Planetary Exploration Robots, Doctoral Thesis of Tohoku University, 2008.

[7] R. Krenn, A. Gibbesch, and G. Hirzinger, “Contact Dynamics Simulation of Rover Locomotion”, Proc. of the 9th Int. Symposium on Artificial Intelligence, Robotics and Automation in Space, 2007, on CD-ROM.

[8] R. Krenn, and G. Hirzinger, “Simulation of Rover Locomotion on Sandy Terrain-modeling, Verification and Validation”, Proc. of the 10th Workshop on Advanced Space Technologies for Robotics and Automation, ESTEC, 2008.

[9] R. Krenn, and A. Gibbesch, “Soft Soil Contact Modeling Technique for Multi-Body System Simulation”, Trends in Computational Contact Mechanics, 58, 2011, pp. 135-155.

[10] A. Azimi, D. Holz, J. Kovecses, J. Angeles, and M. Teichmann, “Efficient Dynamics Modeling for Rover Simulation on Soft Terrain”, Proc. of the 50th AIAA Aerospace Science Meeting, 2012.

[11] A. Azimi, M. Hirschkorn, B. Ghotbi, J. Kovecses, J. Angeles, P. Radziszewski, M. Teichmann, M. Courchesne, and Y. Gonthier, “Terrain modelling in Simulation-based Performance Evaluation of Rovers”, Canadian Aeronautics and Space Journal, 57(1), 2011, pp. 24-33.

[12] A. Azimi, J. Kovecses, and J. Angeles, “Wheel-Soil Interaction model for Rover Simulation Based on Plasticity Theory”, Proc. of Int. Conf. on Intelligent Robots and Systems, 2011, pp. 280-285.