PROGRESS TOWARDS ROBUST MOBILITY ANALYSIS FOR A LEGGED PLANETARY FETCH ROVER

Brian Yeomans and Chakravathi M. Saaj
Surrey Space Centre, University of Surrey, Guildford, United Kingdom
Email: B.Yeomans@surrey.ac.uk, C.Saaj@surrey.ac.uk

ABSTRACT

Legged rovers offer a potentially superior alternative to wheeled locomotion for the exploration of challenging planetary terrains. Compared with a wheeled vehicle, a walking rover will have improved agility, slope climbing and rough terrain capability. However, when it comes to the analysis of the interaction with deformable terrain, surprisingly little study has been made of the terramechanics applicable to the type of micro-legged vehicle that might be deployed on a future mission.

This paper describes progress towards a robust mobility model of legged vehicle performance on sands and other deformable terrains, applicable to a diverse range of vehicle and soil combinations. Software tools are described which aid analysis of terrain interaction, assist with optimisation of the vehicle design, and generate vehicle controller inputs enabling more reliable go/no go decisions to be made, optimisation of path planning, and management of vehicle gait and foot positioning.

Key words: walking rover, terrain, trafficability, terramechanics, control.

1. STATE OF THE ART

Whilst the NASA Mars Exploration Rover (MER) missions [1] demonstrated that wheeled rovers can prove very successful for planetary exploration, wheels suffer from a number of potential problems which mean that they may not be the ideal locomotion system to reach sample or data collection sites in particularly challenging locations. A wheeled rover cannot climb very steep slopes or traverse extremely rugged regions, and it may encounter such severe problems traversing sandy terrain that the mission is at risk of complete failure [2].

Walking rovers offer an alternative to wheels which may be more effective across difficult landscapes. The capabilities of these vehicles on steep, rocky terrain has been studied on a number of occasions, and impressive results have been achieved using reflexive behaviours to negotiate unstructured environments - for example, the ‘Big Dog’ project [3]. Combining the long distance capabilities and energy efficiency of a wheeled rover with the agility of a walking rover has been explored in [4] which utilised the German Research Center for Artificial Intelligence’s (DFKI) SCORPION eight legged vehicle as a scout adjunct to a wheeled rover. DFKI are also developing ‘SpaceClimber’ [5], see Fig. 1, a lunar crater exploration rover constructed from space qualified components.

Figure 1. DFKI SpaceClimber [5] - image courtesy DFKI

Although a walking rover’s superior agility may not be in doubt, performance over non-rigid terrain, and particularly the soft deformable areas which have proved such a hazard on Mars, has not been well studied. There are examples of designs which have been shown to perform particularly well in soft terrain; the CESAR robot, also developed by DFKI, won the European Space Agency Lunar Robotics Challenge in October 2008 [6], with a hybrid legged-wheel design with five feet per wheel, which managed to climb into and out of a lunar-like crater on the island of Tenerife, collecting and delivering a 100g soil sample without the aid of external illumination.

The work presented in this paper extends the understanding of how a walking vehicle will perform over deformable terrain. The theoretical basis of a detailed an-
alytical model of leg / terrain interaction for a walking vehicle is presented in Section 2. Discussion and analysis of the Model Predictions are presented in Section 3, and Conclusions and Planned Future Work are set out in Section 4.

2. THE LPTPT TOOL

2.1. Introduction

The Legged Performance and Traction Prediction Tool (LPTPT) comprises a comprehensive model of the interaction between deformable terrain and the legs of a walking rover [7] [8].

LPTPT uses the MATLAB computation engine for its calculations and can produce both numerical and graphical output as required. The model contains a database of reference vehicles and physical data on a range of planetary soil types, both real and simulated; currently interactions between ten vehicle and twenty five soil types can be assessed. The model analyses the forces arising between the vehicle and soil, and predicts the trafficability performance. Leg loading, and the effect of gait modification can be varied. The model’s force predictions have been validated by experiment using a test rig comprising a manipulator arm moving a representative leg / foot assembly through simulated planetary soils.

It should be noted that in very loosely packed granular materials and / or with increase in limb velocities, “walking” behaviours can very rapidly transition to a completely different form of locomotion resembling slow swimming through the granular material [9]. The analysis presented here is confined purely to walking behaviours.

2.2. LPTPT Model - Primary Components

The diagram in Fig. 2 illustrates the forces arising on a leg stepping into soil with a stepping angle $\alpha$. Four force types are described and quantified by LPTPT:

(i) **Soil Force** $H_o$, is the shear force acting on the foot / soil interface, providing forward traction.

The soil force at the foot / soil shear interface is based on the Mohr - Coulomb equation [10]. The maximum shear stress $\tau_{\text{max}}$ arising is:

$$\tau_{\text{max}} = C_o + \sigma \tan \phi,$$

where $C_o$ and $\phi$ are the soil physical properties of cohesion and friction angle, and $\sigma$ is the normal stress on the soil / foot interface.

(ii) **Draught Force** $F_d$, is the force between the soil and the leg / foot assembly cutting through the soil. This force provides additional traction for the vehicle unless the leg is stepping “forward” into the soil, in which case it will act to resist forward motion.

The draught force derivation in LPTPT is based on the application of tillage theory, the study of the mechanics of tool / soil interaction [11]. Terzaghi’s Universal Earthmoving Equation [12] as further developed by Reece [13] is used, and is expressed as follows:

$$F = \gamma g z^3 N_c + C_\alpha z^2 N_q + q z^2 N_a + C_a z^2 N_{ca}$$

where $\gamma$ = unit weight of soil, $g$ is acceleration due to gravity, $z$ is the sinkage, $N_c, q, a, ca$ are Terzaghi’s four dimensionless soil bearing capacity factors, $q$ is the soil surcharge pressure, and $C_a$ is soil adhesion.

(iii) **Active Force** $F_a$, which arises as soil falls back into the trench created by the leg as it moves through the soil. This force acts to assist the leg moving through the soil and so reduces traction.

The active force derivation is also based on Terzaghi’s analysis [12]. It is not described in detail here as at low to moderate levels of sinkage, active force has a negligible effect on the total forces arising.

(iv) **Frictional Force** $F_f$, the effect of friction between the soil and the foot / leg. Where the stepping angle $\alpha$ is high ($\alpha \approx 90^\circ$), this force will provide further resistance to the leg moving back through the soil and so provides additional forward traction.

Frictional force is modelled in LPTPT following the same principles applied to determining the shear force at the foot / soil interface. At high values of stepping angle ($\alpha \approx 90^\circ$), friction derives principally from the sides of the leg / foot assembly and depends on soil cohesion, the geometry of the leg / foot, and the sinkage depth.

(v) **Other Factors** The model also addresses other relevant factors such as the effect of gravity, and
changes to leg loading that can arise during the stepping cycle in more complex gait patterns.

The forces derived by the model are illustrated in Fig. 3. This scenario is based on a 20kg hexapod walking in a low density lunar-type granular soil. This is similar to the DFKI SpaceClimber vehicle shown in Fig. 1, and represents the type of walking rover which could well be deployed on a future Lunar mission, for example to explore the polar regions.

The plot shows the horizontal components of each of the forces arising, plotted against sinkage. The figure highlights a number of significant features:

(i) All forces other than the Active Force increase thrust per leg as they increase.

(ii) All forces other than the soil Thrust increase as sinkage increases; in the case of Draught Force, markedly so.

It can be seen that a degree of sinkage, provided this is not so large as to overwhelm the vehicle, is of assistance to a legged vehicle as the force available to generate forward movement is increased. This is the opposite of the position for a wheeled rover, where sinkage is a negative factor as it increases compaction and other resistances [14].

2.3. LPTPT Model - Further Development

The model described above derives the basic force analysis and computes the maximum horizontal force available from all sources at the soil interface, given a known level of sinkage. Whilst this information enables a view to be formed of the potential of the rover/terrain combination to deliver thrust, it does not describe the impact of slip at the soil interface, and the consequent effect on sinkage and the forces generated.

LPTPT has therefore been developed further to incorporate slip and sinkage modelling, to enable it to directly show the effect on forces as these parameters vary. Additionally, sinkage and slip are vehicle operational parameters that can be measured or estimated, enabling terrain interaction predictions to be directly linked with vehicle performance.

Sands deform under stress in a characteristic manner; the stress/shear relationship can typically be characterised by one of two types of exponential function [15]. The shear stress tends to a constant residual level, and in the case of compacted rather than loose sands [15], the curve shows a pronounced peak. Given that the degree of compaction of the sand may not be known, and to avoid overstating the forces available at the soil interface, LPTPT models the stress/shear relationship using the curve without a peak, as follows [16]:

\[
\tau = \tau_{\text{max}} \left(1 - e^{-j/K}\right),
\]

where \( j \) is the shear displacement at the relevant point in the interface, and \( K \) is the shear deformation parameter. To determine \( K \), LPTPT adopts a model proposed by Godbole and Alcock [17] to compute \( K \) derived from known laboratory reference values using the relative contact patch area, which was found to be well supported by experimental results:

\[
\frac{K_1}{K_2} = \sqrt{\frac{A_1}{A_2}},
\]

where the ratio of the value of \( K \) sought to the reference value equals the square root of the ratio of actual \( A_1 \) and laboratory \( A_2 \) contact patch areas.

It can be seen from equation (3) that any stress applied to the soil interface gives rise to some shear; the shear
results in movement of the soil material resulting in slip of the leg against the soil. Slip can be quantified by means of the Slip Ratio; this measures the extent to which the forward traction theoretically available at the leg / soil interface fails to be converted to actual forward motion. The slip ratio \( i \) can be defined as \[15\]:
\[
i = 1 - \frac{V}{V_t},
\]
where \( V \) is the actual forward speed and \( V_t \) is the theoretical forward speed with perfect traction.

The force developed at the foot / soil interface, and its dependence on \( i \) is computed by substituting the Mohr-Coulomb relation from equation (1) for \( \tau_{\text{max}} \) and integrating the resulting stress values over the contact patch area. In the simple case of a flat, rectangular foot, of width \( b \), length \( l \) and area \( A \), the shear displacement \( j \) at a point under the foot is related to the slip ratio \( i \) and the distance from the front of the foot \( x \) as \( j = ix \) \[15\], and the force can be derived analytically as:
\[
F = b \int_0^l \left( C_0 + \frac{W}{b} \tan \phi \right) \left( 1 - e^{-ix/K} \right) dx
\]
\[
F = (AC_0 + W\tan\phi) \left[ 1 - \frac{K}{il} \left( 1 - e^{-il/K} \right) \right]
\]

Static sinkage is modelled using the Bernstein-Bekker methodology relating pressure \( p \) and sinkage \( z \) \[10\]:
\[
p = \left( \frac{k_c}{b} + k_\phi \right) z^n
\]
where \( k_c \) is the cohesive modulus of soil deformation, \( k_\phi \) the frictional modulus of soil deformation, \( n \) is an experimentally determined exponent (typically between 0.7 and 1.3), and \( b \) is the smaller dimension of the contact patch (the radius, in the case of a circular contact area).

With respect to slip sinkage, a number of methodologies have been developed \[10\] \[18\] \[19\], which depend on slip, static sinkage \( z_0 \) and, in some cases, grouser height. LPTPT implements the following relationship, which has been verified against experimental results \[20\].
\[
z_{\text{total}} = K_{ss}z_0
\]
where
\[
K_{ss} = 1 + i \left( \frac{1}{1 - 0.5i} \right)
\]
Each of the methodologies considered gives a similar result at low to moderate slip levels, but results diverge at high slip ratios. The approach chosen was selected because:

(i) Sinkage does not tend to infinity at high slip levels unlike some of the other available methodologies;
(ii) Grousers may or may not be fitted, depending on the foot design, and this model does not depend on grouser height;
(iii) It is non linear, in accordance with observed results, and accords well with observed data.

2.4. Model Testing

The basic force relations in LPTPT have been extensively tested using a lower leg segment moved through soil by a robotic arm manipulator. The difficulty with this arrangement however when it comes to verifying the slip dependency relations is that the kinematics are substantially different from those applicable to the actual vehicle, principally because the manipulator base and the soil are fixed relative to each other. This makes it difficult to replicate certain of the kinematic features of a moving leg in soil, and in particular means that only zero or 100% slip ratios can be achieved. This issue is addressed using a specially developed single leg testbed, comprising a suspended carriage to which the test leg is attached. A schematic of the testbed is shown in Figure 4.

(i) The carriage height above the soil can be adjusted, to allow for a wide variety of leg sizes and designs.
(ii) The carriage moves on horizontally aligned linear bearings, either freely, driven or braked, to simulate various scenarios that might arise from walking on the level or up and down slopes.
(iii) The loading of the leg / soil interface is adjusted directly using the leg actuators and controlled by measuring the leg load using a sprung telescopic leg and linear potentiometer sensing.
(iv) The leg / foot assembly is equipped with multi-axis force sensors to directly measure forces arising.
(v) An infra red camera based motion capture system is used to capture and analyse sinkage, and the kinematics of the motion at the soil interface.
(vi) The design of the testbed has been developed initially using CAD tools and then simulated using a
LPTPT enables the Forces / Slip relation to be plotted, giving insights into the dynamics of legged vehicle mobility.

The plot in Fig. 5 demonstrates how total force available at the soil interface increases strongly with slip ratio. Unlike a wheeled rover, available traction will increase with slip provided sinkage is not so large as to overwhelm the rover.

The mass and geometry of the rover will have a significant effect on both the force available at the soil interface, and the force necessary to produce adequate forward traction, particularly where slope climbing is required.

To illustrate the effect of mass variation, total force per leg available at the soil interface as a function of both slip ratio and mass of the rover is shown in the plot in Fig 6. The effect of mass changes on the dimensions is based on the same illustrative 20kg hexapod described in Section 2.2 with critical dimensions scaled proportional to the cube root of the ratio of actual mass to the mass of the example rover; thus assuming, for comparability purposes, a constant density for the rover construction materials.

These data could, for example, be used to compare the effect of changes in rover mass for a particular application, factoring in the effect of mass change on force required from the soil interface for slope climbing and to overcome other resistances.

Understanding the range of predicted performance across a class of terrain materials could be extremely useful, as in many cases information on the material’s precise in situ physical properties will not be available.

One of the objectives of LPTPT development has been to explicitly derive the relation between force, slip, and sinkage, so that these relationships can be directly utilised by the vehicle controller.

This could be deployed by implementing an LPTPT derived model of terrain interaction in the vehicle controller. The rover would employ on-line estimation of slip and sinkage and compare predicted (by the model) slip and sinkage with that actually observed. This comparison could then be used to refine the model parameters on an on-line basis, indirectly deriving the characteristics of the actual terrain, and enabling greater confidence in understanding vehicle - terrain interaction to be achieved and better vehicle performance realised.

3.1. Wheeled Rover Drawbar Pull Comparison

Drawbar Pull (DP) for Sojourner, the 11.5kg vehicle used in the Mars Pathfinder mission, was estimated by Ellery at 6.88N [14]. In contrast, LPTPT computes DP of a 11.5kg hexapod rover, walking with a wave gait in soil typical of the Mars Viking Lander 2 site soil [22], as 31.5N, a very substantial increase.

This comparison gives an indication of how significant are the resistances encountered by a wheeled rover; whilst in this example the force available for thrust at the soil interface in both cases is of a similar amount, the resistances to motion of a legged rover typically do not act to impede forward motion as it can simply pick up its
legs and step across intervening obstacles. Additionally the principal forces given a high ($\approx 90^\circ$) stepping angle reinforce rather than degrade $DP$, as described in Section 2.2.

The effect of gait variations can also be analysed. For this analysis, to show the applicability to different rover classes, a much smaller vehicle has been chosen; the sub-1kg nanorover SAFER-1 shown in Fig. 8. Using the LPTPT tool, the predicted performance of SAFER-1 is computed under Mars gravity assuming a 90$^\circ$ stepping angle on soils with the characteristics of those seen at the Viking 1 and 2 (VL1 and VL2) Mars lander sites [22].

The potential impact of gait changes was evaluated by assessing two gait scenarios; the wave gait, a highly stable gait under which only one leg is lifted at any one time, and the tripod gait, where three legs are lifted at any time, and which represents the maximum number of legs lifted consistent with a statically stable gait. Although highly stable, the disadvantage of the wave gait is that it is quite a bit slower than the tripod gait. The plot in Figure 9 shows the individual and combined forces on the leg for a range of sinkage amounts. The active force $F_a$ is negligible and has been omitted for the sake of clarity.

Predicted static sinkage for this configuration using the Bernstein-Bekker formula is 6.5mm, and in practice sinkage will somewhat increase once leg slip occurs due to slip sinkage. At what might be considered a typical sinkage level of 10mm, the draught force $F_d$ as the leg pushes through the soil is the dominant force providing forward thrust, followed by soil friction and the shear force at the soil interface which are approximately equal.
Table 1 summarises outputs from LPTPT showing the force components and calculating the DP available for this vehicle on both VL1 and VL2 soils, using wave and tripod gaits, at an estimated sinkage of 10mm.

The results demonstrate that whilst varying the gait has some effect on DP per leg, this is modest given the limited contribution the soil interface shear force (the element primarily affected by the gait pattern) has on the total DP.

Total DP is therefore maximised by using the slower wave gait option as more legs are in ground contact at any time. Where high thrust is needed, such as for slope climbing, a wave gait scheme is likely to be required. It can also be seen that total DP of SAFER-1 (7.05N, mass 850g) compares favourably with that of a much larger wheeled vehicle such as Sojourner (6.88N, mass 11.5 kg) [14], despite the low mass.

### 4. CONCLUSIONS AND FUTURE WORK

LPTPT is presented as a comprehensive tool to predict, analyse and quantify the forces available at the leg / soil interface of a walking rover. It enables performance predictions to be made of a wide variety of vehicles operating on many soil types, and suggests that a legged rover, in addition to demonstrating superior agility over rough, rocky terrain, can also be an effective vehicle to traverse soft sands and other types of deformable materials.

Incorporation of Slip / Sinkage analysis enables the dynamics of the Force / Slip relationship to be modelled, and shows that slip and associated sinkage, rather than being a disadvantage, can positively aid legged vehicle traction.

LPTPT can reduce the risk that incorrect “stop / go” decisions are made in challenging terrain scenarios, by increasing confidence that a traverse is feasible despite incomplete information on terrain physical characteristics.

It is planned to develop the model further to incorporate LPTPT in the vehicle controller, working with an online estimator of slip and sinkage parameters to reduce the uncertainty arising from unknown terrain parameters and enable improved performance to be achieved.


