MODELLING LEG / TERRAIN INTERACTION FOR A LEGGED PLANETARY MICRO-ROVER

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ABSTRACT

The superior ability of a walking rover to negotiate rugged or steep terrain means that this type of vehicle has the potential to significantly enhance the effectiveness of future planetary exploration missions through the ability to reach otherwise inaccessible locations. However, improved prediction of the forces arising between the vehicle and the dry, granular and often loose regolith that covers much of the surface of the Moon and Mars is required, together with the implications for vehicle mobility, before such a mission could become a practical reality. The work described here focuses on predicting leg /terrain forces applicable to the type of lightweight hexapod rover vehicle which might well be utilised in a future exploration mission, perhaps as a scout adjunct to the mother rover. It concentrates on the interaction of the leg / foot assembly with loose granular materials as this is the type of terrain likely to present the greatest challenge to adequate mobility. Prior work in this field is based on a semi-empirical terramechanics based approach to modelling the interaction. However, here a different approach is adopted based on granular physics theory. It is demonstrated that whilst a terramechanics based model results in unreliable force prediction, this approach is shown to not only give greater accuracy and reliability but is relatively simple to apply. Validation of the proposed model is achieved through the construction and operation of a new design of test bed, the Single Leg Test Bed. This facility provides a kinematically accurate representation of the leg motion of a walking vehicle, and overcomes a number of concerns with prior approaches to measuring leg / soil forces. Use of the facility is described to derive test results which will validate the modelling approach adopted.

1. STATE OF THE ART

Interest in and development of walking vehicles like the example shown in Fig. 1 remains strong. These rovers find both terrestrial uses, for example in hazardous environments [1] and space use, for example for planetary exploration [2, 3]. These vehicles, for example [4, 5, 6] are becoming more successful in emulating the abilities of animals which are themselves successful locomotors on natural terrains such as [7], and are being increasingly deployed on terrains such as sands which move in response to the passage of the vehicle. In a planetary exploration context, a small walking rover used as a scout is particularly interesting as it could supplement the main rover's capabilities and be used to reach otherwise inaccessible locations on the planet's surface for improved science return [3, 8].

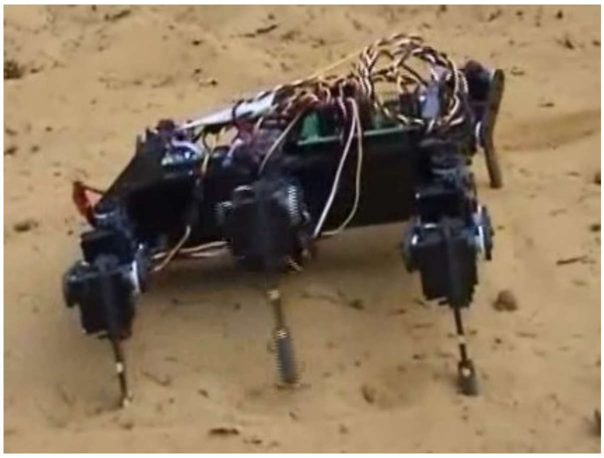

Figure 1. Walking Hexapod on loose sand

The performance of walking rovers is clearly enhanced by the improving sophistication of their control systems, however they typically proceed across deformable terrain such as sands without any prior knowledge or model of the properties of the vehicle / terrain interface. In contrast, modelling of this interface for wheeled vehicles using semi - empirical terramechanics principles is well established for both terrestrial and space applications [9, 10, 11, 12]. Although the approach of Bekker, Reece, Wong and others has been used successfully to model the trac tive performance of large, heavy vehicles, several of its assumptions are not met for small vehicles and therefore doubts have been expressed regarding the accuracy of this approach for small rovers [13]. Semi - empirical models of leg / terrain interaction have been described in [14, 15, 16].

A key property of granular materials is that they can exhibit both solid - like and fluid - like properties [17]. The transition between the two states can be rapid, as was demonstrated in [6]. Therefore a logical alternative approach to modelling vehicle / terrain forces is based on modelling of the granular material as a flow; the fluid - like behaviour is instigated by the interaction with the vehicle, giving rise to “granular drag” as the vehicle moves.

Albert *et al* [18] found that the drag force on a vertical cylinder inserted in a rotating container of glass spheres was linearly dependent on the cylinder diameter, quadratically dependent on the depth of insertion, and independent of velocity. In addition, despite variation of the cylinder / soil friction coefficient by a factor of ≈ 2.5 by changing the cylinder material, the average drag remained within 5%, strongly suggesting that in a granular flow, the properties of the intruder / soil interface have little effect on the overall forces arising. An analytical model using the q model of Coppersmith *et al* [19] was developed which predicted the force as:

$$F_{\mathrm{d}} = \eta g \rho h_i^2 d_{\mathrm{c}} \tag{1}$$

where h_i is the depth of insertion, d_{c} the cross-sectional dimension, ρ the density of the individual particles, g gravitational acceleration and the coefficient η is related to the surface properties, morphology, and packing of the grains. A physics derived model of leg / terrain interaction based on similar principles and using the linear superposition of calculated resistive forces on the leg elements is described in [20]. However, accurate modelling of leg / terrain forces for a walking rover remains relatively undeveloped and will need to make substantial progress if these capable and versatile vehicles are actually to be deployed for planetary exploration.

2. LEG AND WHEEL TERRAIN INTERACTION - A COMPARISON

There are some differences between legged and wheeled vehicle behaviour on deformable terrain. For a wheeled vehicle, forward traction is achieved primarily by means of the shear force developed between the wheel and soil; sinkage of the vehicle into the terrain is a major problem as it has the effect of creating an obstacle forward of the moving wheel which tends to obstruct its progress. In contrast, legged vehicle interaction is more complex. Sinkage can be a positive feature as the effect is to create a wall of terrain material behind the leg which adds to the reaction force received from the soil, increasing traction, and so the drawbar pull achieved by a walking rover is derived both from the shear force acting on the foot and from this reaction resistance derived from the leg / foot assembly. Consequently sinkage per se is typically not a major concern for a walking rover, provided it is not so large as to ground the body, as the vehicle legs can simply be lifted out of the terrain material and re - placed to make forward progress.

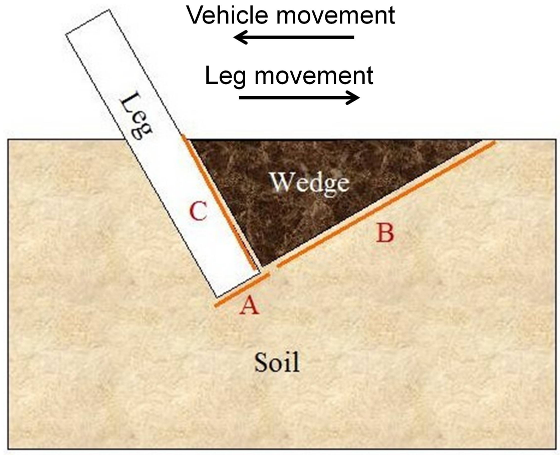

Figure 2. Leg Terrain analysis based on soil wedge

Semi - empirical terramechanics theory is based on an idealisation of the vehicle / terrain contact behaviour. The contact zone is simplified as a flat plate (as a wheel analogue) or as an intruder object of simple form (in tillage theory as applied to leg / terrain interaction). Soil behaviour is idealised as consisting of strain taking place in well defined shear zones, where the soil contacts the intruder object and along well defined in - soil surfaces forming a prismatic “wedge” shape. Fig. 2 illustrates these surfaces as they might be modelled for a vehicle leg [21]. The analysis proceeds by modelling the behaviour of these interfaces, typically using simple models of soil failure behaviour such as Mohr-Coulomb [22] combined with an analysis of the geometry of the soil / object relationship. It should be stressed that an analysis of this type uses force balance principles and makes the assumption that the soil and vehicle objects that interface at these idealised boundaries are in quasi static equilibrium.

3. PREDICTING LEG DRAG

Terramechanics theory has its origins in the study of large, heavy vehicles and agricultural equipment [9] for which these geometrical simplifications and assumption of quasi static equilibrium may well be perfectly valid. For lightweight vehicles such as those suitable to be carried as a subsidiary scout rover of, say, 20 - 25 kg mass [2, 3] it would seem less clear that these assumptions still hold good; indeed simple observation of the progress of a small walking rover will confirm that dy-

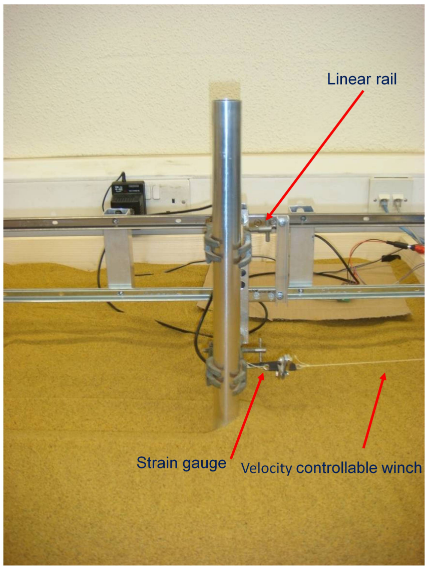

Figure 3. Test Apparatus [21]

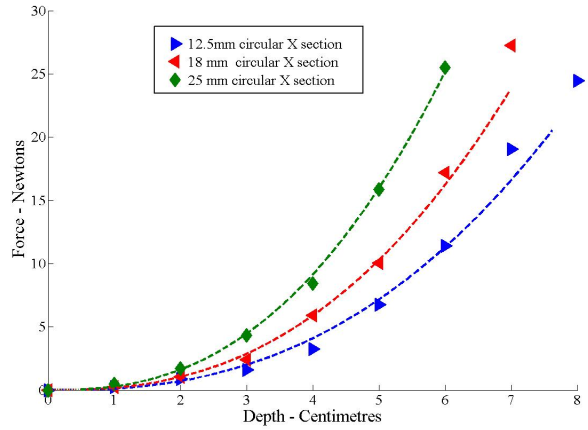

Figure 4. Coarse Quartz sand - drag results

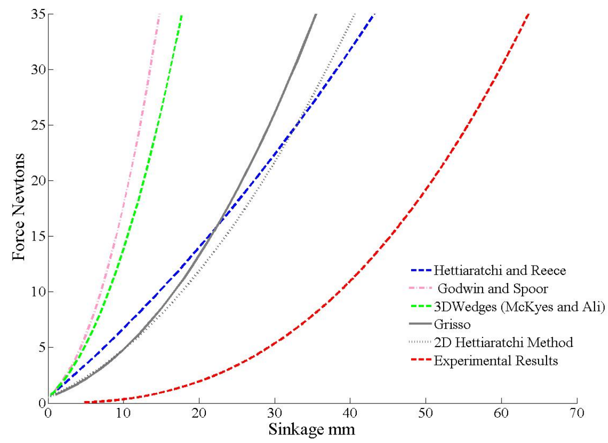

Figure 5. Wedge Theory Comparison - Results

namic characteristics such as soil material flow are much in evidence.

It was therefore concluded that a comparison would be made between experimental results, and the predictions of models under alternatively a semi - empirical or granular drag based approach to modelling leg / terrain interaction.

The apparatus used to derive the drag data is shown in Fig. 3. It comprises a carriage to which rods of various cross-sectional shapes and dimensions appropriate to those of a walking rover leg can be clamped vertically, at a pre-determined depth of insertion in the soil.

The carriage is free to move along a rail with one degree of freedom over a soil bed, and is driven by a speed controlled DC motor and geartrain. The motor winds a cord attached to a strain gauge which is in turn attached to the carriage, and the output of the strain gauge is captured and digitised.

Fig. 4 plots the drag arising using circular cross section rods in a range of cross sections.

Fig. 5 shows a sample of the results compared with the predictions of several alternative wedge theory models.

Full details of the test apparatus, procedures, soil material properties and results analysis are set out in [21].

It was concluded that the semi - empirical models were unable to reliably predict the drag arising on the inserted leg section. In addition, whilst variations in the frictional properties of the leg section inserted, achieved using materials such as PTFE and low - friction ceramics, were found to have had little effect on the experimental results, the semi - empirical models, which assume interface effects dominate, predicted a major change to the results

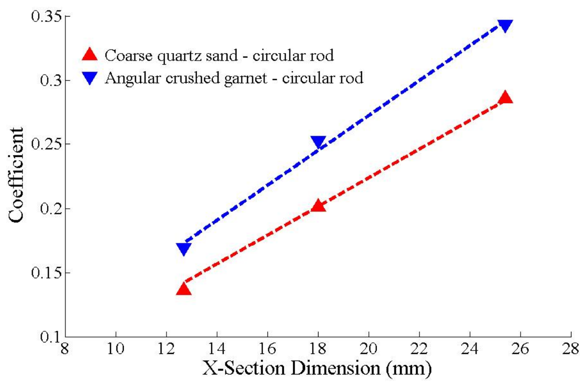

Figure 6. Coarse Quartz sand - drag coefficient

(not shown here). This strongly suggested that one of the key assumptions in the semi - empirical models - that forces arise primarily at the interfaces - is flawed, in these loose, low stress conditions.

In contrast, a granular drag model based on equation 1 was found to give an accurate and reliable prediction of leg / terrain forces, with the exception that the dependence of force on depth of insertion, when applied to actual sands rather than idealised, spherical glass beads, was found to be based on $h_i^{2.5}$ rather than $h_i^{2.0}$.

Fig. 6 plots the coefficient A in the equation $F_d = Ah_i^{2.5}$, which can be seen to have a linear relationship with the cross sectional dimension d_c, suggesting that the force can be expressed as $F_d = A'd_c h_i^{2.5}$ where A' is a constant which is a characteristic of the soil material. Precise determination of forces will require either experimental testing of the actual material (impractical in a planetary exploration context) or a deeper understanding of the soil physical properties which give rise to the coefficient value. However the testing undertaken so far arrives at a reassuring conclusion; despite the considerable differences in physical properties between the two materials tested here, the values of A' are quite similar, suggesting that drag can be estimated with reasonable accuracy even in the absence of detailed knowledge of soil physical properties.

The dependence on $h_i^{2.5}$ rather than $h_i^{2.0}$ is consistent with earlier experimental work described in [23] and the work with natural sands which is described in [20]. It is likely that this somewhat increased drag dependence on depth of insertion, when compared with predictions based on idealised, perfectly spherical materials, is a consequence of the less than perfectly round grains in real sands being somewhat more resistant to the rolling required to reorganise them [20]. Micro - scale variations in the force response of the experimental materials was also found to be completely consistent with a granular flow model under which drag arises as a result of force chain disruption and re - formation in the body of the material rather than at the interfaces.

A further advantage of this modelling approach is that despite the underlying complexity of the processes occuring in the body of the granular material as it flows, the resulting model of the large scale behaviour is a simple one.

4. MODELLING SINKAGE

The power law dependence on depth of insertion described above means that a model of forces arising based on depth of insertion only provides a partial answer to the challenge of developing an accurate leg / terrain interface model; in addition, an accurate sinkage model is required. For wheeled rovers, sinkage comprises both a static component, which is conventionally estimated using semi - empirically derived Bekker parameters [9], and a dynamic component referred to as “slip sinkage”for which a variety of methods for estimation based on empirical observation have been developed [24].

For a lightweight walking rover, static sinkage also arises. As this relationship is explicitly based on a quasi static equilibrium, the semi - empirical approach based on Bekker theory may well be sufficiently accurate with some provisos; care is needed when applying the Bekker sinkage model in lightweight, low stress scenarios. Without adjustment it is likely to be inaccurate [13], probably linked to the differences in soil failure mode at low stress as compared with that developed as stress increases, as described in [25, 26].

Dynamic sinkage effects also arise for walking rovers. These are more complex than those applicable in the wheeled scenario as the motion of the walking rover leg is itself more complex; for example, the kinematics of a typical three degree of freedom hexapod leg force it to rotate around the vertical axis as it moves through the vehicle stepping cycle. The loaded foot rotates in the soil, changing the soil stress environment and resulting in additional sinkage. Self evidently this is a dynamic process and so is in principle not susceptible to quasi static equilibrium analysis.

Work is continuing on both static and dynamic sinkage behaviour in order to develop an accurate prediction of sinkage applicable to a lightweight walking rover.

5. THE SINGLE LEG TEST BED - SLTB

The experimentation described so far takes place in somewhat idealised circumstances, using a vertically positioned section representing the vehicle leg. Given the dynamic nature of the processes involved, it was considered essential to develop a test environment which much more closely replicated the actual kinematics and dynamics of walking rover operation. This led to the development of the SLTB shown in Fig. 7.

The SLTB comprises a number of integrated subsystems:

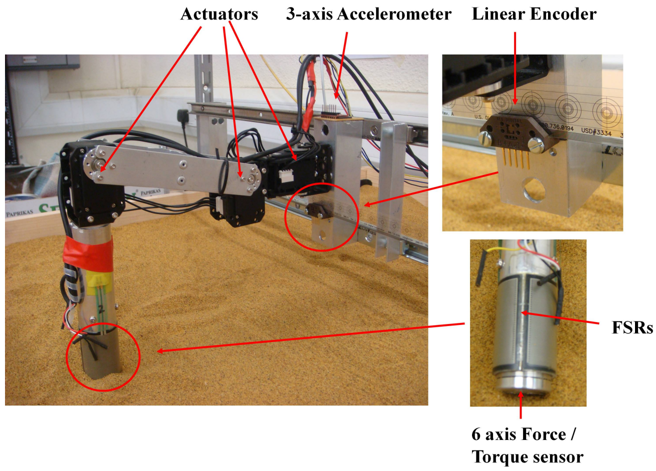

Figure 7. SLTB facility

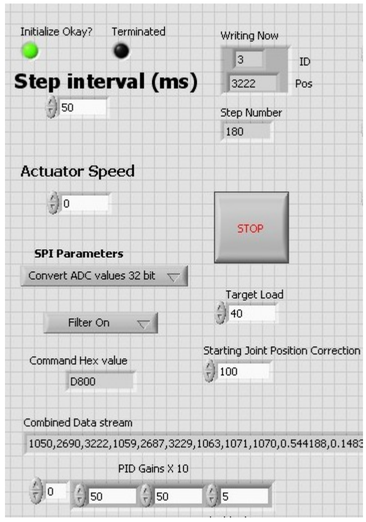

Figure 8. LabVIEW Front Panel - section

1. Mechanical system - the SLTB comprises a carriage constrained so it can move in one degree of freedom only, horizontally along a linear rail assembly very similar to that described in Section 3, which is suspended over a soil bed. A system of cords and pulleys balance the carriage to compensate for residual friction and so that the carriage can be braked or accelerated as required.

2. Drawbar Pull and position sensing - in series with the cord system is a strain gauge, amplifier and digitising microcontroller so that drawbar pull on the carriage can be directly measured and recorded. Carriage position is sensed and digitised using a linear encoder and associated microcontroller. Additional information on carriage movement is provided using an attached accelerometer.

3. Leg Mechanical System - a complete three degree of freedom leg is attached to the carriage, comprising commercially sourced actuators [27], off the shelf and custom made brackets and links. The intention is that a wide variety of rover systems can be tested by installation of an actual leg from the proposed design.

4. Leg actuation and control - the commercial devices used provide both actuation and feedback of joint position, velocity and torque.

5. Soil Force sensing - this is achieved using a combination of a miniature six axis Force / Torque sensor forming the foot of the single leg, and two Force Sensing Resistors (FSRs) wrapped around the lower leg section, giving eight channels of force data in all.

6. Sensor - Microcontroller (SM) Subsystem - an important aspect of the design is to achieve realistic loadings of the foot / soil interface, enabling a range of potential vehicle designs and masses to be emulated. The loading is achieved via real time feedback to the leg actuators, based on information from the force sensors. To achieve this in the required time frame plus achieve a desirable reduction in system noise via averaging of sensor results requires some quite complex data processing; consequently the SM subsystem was developed around a dedicated 32 bit microcontroller board [28]. This is capable of a number of tasks in real time including initialisation of the sensors, noise reduction via a 40 tap moving average calculation, and generation of 32 bit floating point force and torque readings.

7. Integration of the control and data generation for the SLTB takes place in the LabVIEW environment [29]. A section of the front screen display is shown in Fig. 8. Leg control utilises a modified position system - the gait and target step pattern are pre - generated in MATLAB and read by the labVIEW routine, so that a wide variety of gait styles can be tested. The leg proceeds through its cycle, with LabVIEW applying a PID algorithm to the joint actuator commands based on the Z axis load readings, to maintain a foot loading equivalent to that of the emulated system.

8. LabVIEW coordinates the various sub systems using its multi - threading facilities and generates an integrated comma separated value (.csv) file of results, using the microcontroller clocks to timestamp each data collection cycle.

9. Digital video data of the foot movement is also sourced and synchronised with the other data collected, to provide additional video based evidence of dynamic sinkage behaviour.

The result is a comprehensive data set covering the whole leg stepping cycle, which is then analysed and post processed in MATLAB. Work continues on data gathering, however some initial results are shown as follows:

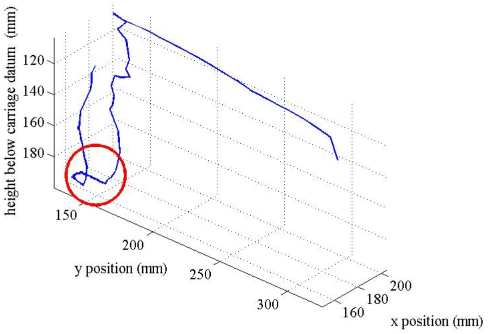

Figure 9. 3D plot of foot movement

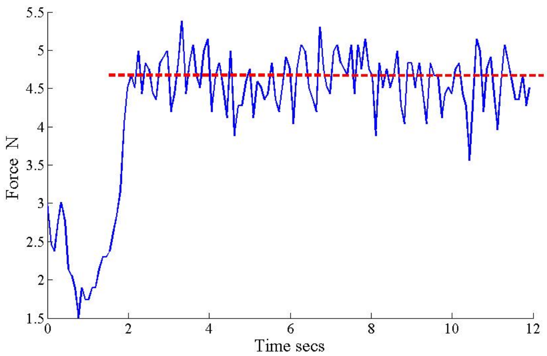

Figure 10. Drawbar Pull values

Fig. 9 shows a plot in Cartesian space of the foot movement; the zone where the foot is in contact with the soil bed is circled in red. This is computed based on joint and carriage position data.

Fig. 10 shows a plot of Drawbar Pull, derived by calibrating the data from the in series strain gauge.

6. CONCLUSIONS AND FUTURE WORK

The primary area of work required to complete this granular drag based model for walking rover leg / terrain interaction is the development of an accurate sinkage prediction. Once this is completed, it is expected that much more accurate modelling of leg / soil interaction will be achieved.

The SLTB will be used hand in hand with the model development to validate the predictions. However, it is expected that the SLTB will find a number of additional uses, including the investigation of the effect of foot design variation on walking behaviour and drawbar pull. The SLTB will also be able to directly investigate the effect on vehicle locomotion of the potentially abrupt change between "solid like" and "fluid like" behaviour of the soil material. The ability of the SLTB to emulate a wide range of vehicle / terrain interaction scenarios lends itself to investigation of this aspect, and may highlight regions of operation where particular care is required to control applied forces to avoid excessive fluidisation of soil material and consequent loss of traction.

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