Mobility Assessment of Wheeled Robots Operating on Soft Terrain

Bahareh Ghotbi, Francisco González, József Kövecses, and Jorge Angeles

Abstract Optimizing the vehicle mobility is an important goal in the design and operation of wheeled robots intended to perform on soft, unstructured terrain. In the case of vehicles operating on soft soil, mobility is not only a kinematic concept, but it is related to the traction developed at the wheel-ground interface and cannot be separated from terramechanics. Poor mobility may result in the entrapment of the vehicle or limited manoeuvring capabilities. This paper discusses the effect of normal load distribution among the wheels of an exploration rover and proposes strategies to modify this distribution in a convenient way to enhance the vehicle ability to generate traction. The reconfiguration of the suspension and the introduction of actuation on previously passive joints were the strategies explored in this research. The effect of these actions on vehicle mobility was assessed with numerical simulations and sets of experiments, conducted on a six-wheeled rover prototype. Results confirmed that modifying the normal load distribution is a suitable technique to improve the vehicle behaviour in certain manoeuvres such as slope climbing.

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1 Introduction

Defining robust and reliable operational strategies for wheeled robots operating on soft terrain is a challenging task. An example of this are planetary exploration rovers, one of the most demanding applications of wheeled robotics. Besides tackling the usual problems derived from operating on irregular terrain, rovers must often deal with an incomplete knowledge of the soil properties. Moreover, most missions must be accomplished in an autonomous or semi-autonomous fashion.

Optimizing the vehicle mobility is an important goal in the design and operation of wheeled robots on soft soil. In the case of wheeled robots that operate on rigid ground, mobility is a kinematic concept which can be defined based on the assumption that each wheel in the robot rolls without slipping. However, when the same robots operate on soft terrain the above mentioned assumptions are generally no longer valid. Mobility can be understood in the sense of the ability to move from a certain configuration, or to move with maximum speed. This definition is close to the *trafficability* concept introduced in [1], which points to the capacity of the vehicle to overcome terrain resistance and generate traction.

Reduction of the slip at the wheel-terrain contact area has been proposed as a way to enhance the mobility of wheeled robots operating on unstructured terrain [11, 14]. In these papers, the wheel-terrain interface is modelled using the assumption of Coulomb friction while the ratio of tangential to normal forces at the wheel-ground contact is minimized with the goal of reducing the risk of developing slip. While not directly dealing with soft soil modeling, these papers highlight the need for keeping wheel slip under control in order to improve mobility.

Some publications in the literature point out that a uniform distribution of normal forces among the vehicle wheels may have a positive effect on the mobility. In [9], the authors state that balancing the normal loads helps the vehicle to develop a higher value of the overall traction force. Along the same lines, it is suggested in [4] that uniformly distributing the weight of the rover among the wheels is a valid strategy to achieve better mobility, when not enough information about contact forces is available. A similar conclusion was also reported in [13]: the load distribution among the wheels has to be even on flat ground to achieve the best performance. In [15] an alternative strategy was chosen to reduce the likelihood of developing wheel slip that relies on the minimization of the virtual friction coefficient $\mu^* = F_T/F_N$ where F_T is the traction and F_N the normal force at each contact. In [10] the normal load and the motor torque applied to each wheel are computed as a solution of an optimization problem to enhance mobility for quasi-static motion of the rover on rough terrain.

The authors of this paper reported an experimental confirmation of the above research for a particular rover design in [7] and [6]. They also introduced the normal force dispersion as performance indicator to quantify the proximity of the load distribution to ideal operation conditions [8]. This distribution can be changed by means of reconfiguration or by introducing actuation on the suspension elements. As a consequence, in some cases it is possible to obtain a more favourable load distribution that would increase the mobility for a given manoeuvre. This paper dis-

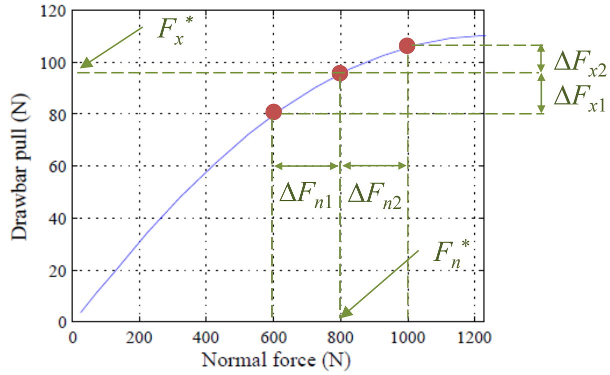

Fig. 1 Effect of a non-uniform normal force distribution on the total available drawbar pull for a three-axle vehicle

cusses the effect of two of these strategies during slope climbing and drawbar pull tests. The first one consists of relocating the vehicle centre of mass (CoM), while the second introduces redundant actuation between suspension elements.

2 Normal Force Dispersion as Mobility Indicator

The mobility of a wheeled robot depends on its ability to generate a required amount of drawbar pull while keeping the slip ratio low. Terramechanics theory [16] points out that the normal force F_n at each wheel of a robot affects the tangential force and the net drawbar pull F_x it develops. This consequently affects the total drawbar pull the vehicle provides. The sum of all the normal forces must balance the weight of the vehicle and every other vertical load applied to the vehicle. Therefore, when the robot moves on a terrain with a uniform, constant slope, if dynamic effects are not considered, the total normal force is constant. However, the distribution of the normal forces among the wheels can result into different values of the drawbar pull developed by the vehicle.

The effect of normal force distribution can be studied using the F_x-vs.-F_n curve. An example for a planar three-axle system in 2-D motion is shown in Fig. 1. If the three axles are moving with the same angular speed, and the terrain under the vehicle is homogeneous, then the same curve can be used for all the wheels. In this case, an even distribution of normal forces would be the one in which $F_{n1} = F_{n2} = F_{n3} = F_n^*$. A transference of normal load between the first and second axles of the robot ($\Delta F_{n1} = -\Delta F_{n2}$) will result in changes ΔF_{x1} and ΔF_{x2} in the drawbar pull at these wheels. The slope of the F_x-vs.-F_n curve is consistently decreasing, for the range of soil parameters commonly encountered in real applications. Then $\Delta F_{x2} < \Delta F_{x1}$, and this will yield a lower total available drawbar pull for the same level of slip of the vehicle. In other words, in the unbalanced configuration the slip should become higher in order to achieve the same traction delivered by its balanced counterpart, where the normal forces are uniformly distributed among the wheels.

For the case of a wheeled robot operating on homogeneous terrain, the F_x-vs.-F_n relation will be the same for all the wheels if they are identical and develop the same slip. These assumptions can be considered close enough to reality for a broad range of operating conditions, including slope climbing.

The *Normal Force Dispersion* η was introduced in [8] as a measure of the uniformity of the normal load distribution. This performance indicator is the standard deviation of the normal forces F_n at the wheel-terrain contact interfaces, namely,

$$\eta\left(F_{n1},\dots F_{np}\right)=\sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(F_{ni}-\mu\right)^{2}} \tag{1}$$

where p is the number of wheels of the vehicle and μ is the average normal force:

$$\mu=\frac{1}{p}\sum_{i=1}^{p}F_{ni} \tag{2}$$

An even distribution of normal forces ($F_{n1}=F_{n2}=\ldots=F_{np}$) would result in $\eta=0$. In this study, operation on non-homogenous terrain or multi-pass effect are not considered. Therefore, all the wheels are assumed to move on the same type of soil. In such a case, information on the normal load of each wheel is not required. Quantifying the unevenness of the load distribution via η facilitates the comparison of different rover configurations in terms of their mobility.

As a conclusion, it can be stated that making the normal force distribution more uniform will have a noticeable effect on the net traction when the F_x-vs.-F_n curve shows a highly nonlinear relationship. This is the case of operation conditions where high slip values are expected to develop, such as slope climbing, or in the presence of loose terrain with little cohesion.

2.1 Case study: the RCP rover

The normal force dispersion η was used to study the mobility of the Rover Chassis Prototype (RCP), shown in Fig. 2. The RCP is a six-wheel prototype developed by MDA Space Missions. The total mass of the RCP is about 125 kg. The rover main body is attached to three bogies (starboard, port, and rear), each one connected to two wheels. Every wheel can be independently steered and actuated.

A model of the rover was built using the Generic Multibody Dynamics Library, a multibody software tool developed by the authors [5], implemented in MATLAB. This library includes functions to evaluate the wheel-terrain interaction forces according to the terramechanics semi-empirical relations introduced in [16] and [2]. Among many features of this library having access to all dynamic terms and choice

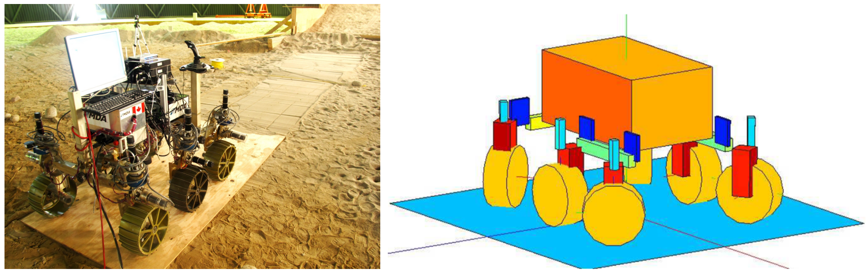

Fig. 2 The RCP rover (left) and its multibody model (right)

of various multibody dynamics formulations and integrators make it suitable for rover analysis in complex environments. RCAST is an alternative dynamic simulation tool which has been reported to model the same rover [3].

First, the climbing manoeuvre of the RCP on a 10° slope with the terrain properties listed in Table 1 was simulated. The wheels of the rover were commanded to move with a constant angular speed $\omega = 0.4$ rad/s. In order to obtain different load distributions among the wheels of the RCP, a 22.5 kg (50 lb) payload was added as a movable mass element to the rover model. The simulation was repeated for different locations of the payload along the longitudinal axis of the vehicle. This resulted in variations of the position of the centre of mass (COM) of the rover, which in turn produced different values of η during the climbing manoeuvre.

Table 1 Soil properties used in the simulation of the slope climbing manoeuvres

n -	c [N/m^2]	ϕ [deg]	k_c [N/m^{n+1}]	k_ϕ [kN/m^{n+2}]	K_d [m]
1	220	33.1	1400	2000	0.015

Figure 3 shows that lower values of η resulted in less wheel slip required to complete the climbing manoeuvre.

Alternatively, it is possible to consider the effect of achieving a low η on the maximum slope that the vehicle can negotiate. The climbing manoeuvre was simulated for a variable slope with the soil properties summarized in Table 1. In this study the rover is considered unable to climb a slope if the required slip ratio becomes higher than 90%. A similar slip threshold was used in slope climbing tests with the Dynamic Test Model of the Mars Exploration Rover in [12]. The slope angle was increased until the rover was unable to complete the manoeuvre without exceeding the maximum admissible slip. Fig. 4 shows that a correlation exists between the value of η and the maximum slope the vehicle can successfully climb.

Lower values of the force dispersion resulted into the RCP being able to travel on steeper terrain. The increase in the steepness of the slope that the rover is able to

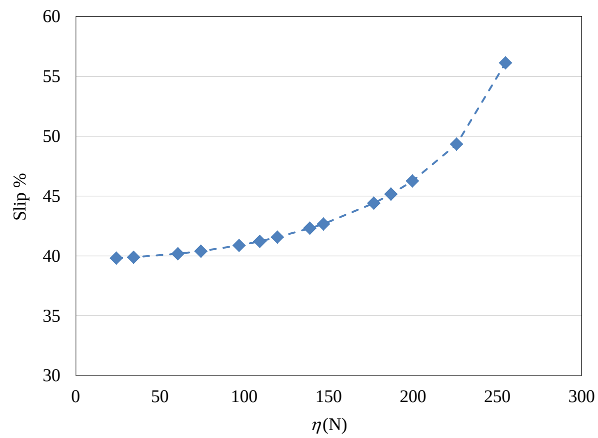

Fig. 3 Values of the slip-vs.-η index obtained in the simulation of a 10° slope climbing manoeuvre with the RCP carrying a 22.5 kg payload

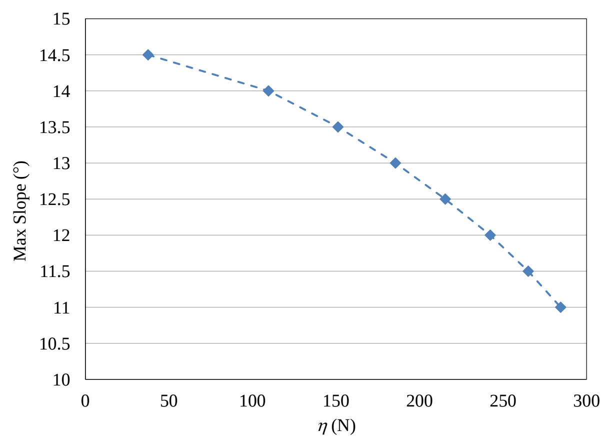

Fig. 4 Correlation between the maximum slope angle that the RCP can climb with a 90% slip and the η index

climb is a result of the improvement of its ability to develop a greater drawbar pull for the same slip ratio.

3 Modification of the Normal Load Distribution

Two strategies to decrease the normal force dispersion η were designed and tested on the real prototype of RCP: displacing the centre of mass of the vehicle and introducing actuation torques between the suspension components. In this work, the

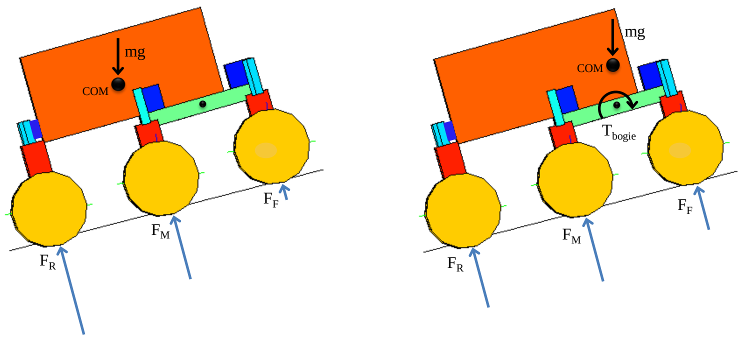

Fig. 5 Uneven load distribution during climbing manoeuvre with the original configuration of the RCP (left); improved load distribution after displacing the CoM and introducing a torque between the chassis and the side bogies to reduce η (right)

latter is refereed to *redundant actuation* which allows for altering the system internal forces via applying actuation forces and torques on the suspension components.

Movable mass elements were mounted on the rover chassis to obtain different sets of normal force distributions during experiments. These mass elements consisted of two weights of 22.5 kg (50 lb). Two attachment positions for the weights were designated on the rover body, one at the front end of the chassis and another one on the connection to the rear bogie. Three load configurations were defined: extra mass at the front location, extra mass at the rear location, and evenly distributed extra mass. An even distribution of the normal loads, however, could not be achieved only via displacement of the CoM of the vehicle. There were limitations in terms of the placement of the movable elements and their mass. For example, the weight of these elements cannot exceed certain limits and their location must be within certain boundaries. Therefore the CoM cannot be arbitrarily displaced.

In the case of some rover designs such as the RCP, the presence of passive joints between the bogies and the chassis frame does not allow one to fully control the load distribution among all the wheels. By repositioning the CoM of the rover one can only control the load distribution between the rear wheels and the side bogies. The way in which the load of each side bogie is distributed between front and middle wheels depends on the orientation of the bogie with respect to the rover main body. Since this joint is not active, in principle the angle between the body and the bogies cannot be controlled. It is possible, however, to actuate this joint by introducing a torque between the chassis and the side bogies.

Figure 5 illustrates the effect of these two strategies on load dispersion. The left part of the figure represents the default configuration of RCP. In the right diagram, the CoM is displaced towards the front of the rover and a torque (60 N.m in this example) is introduced between the chassis and the side bogies. In these figures the lengths of the arrows that represent the reactions at the wheel-terrain interface are proportional to the magnitudes of the normal forces obtained from simulation. In

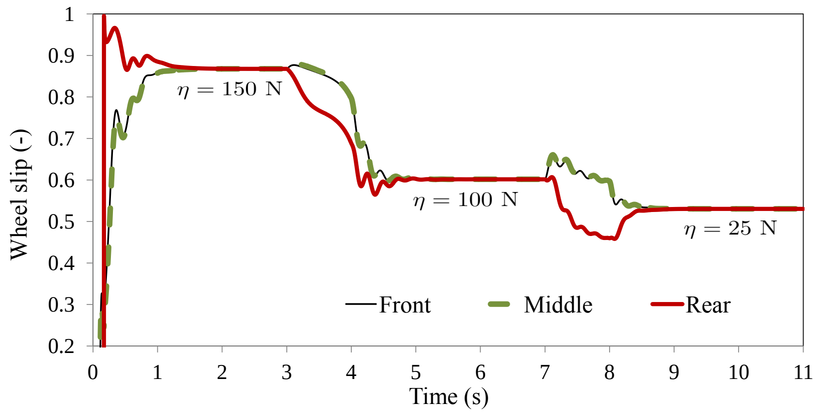

Fig. 6 Slip of the front, middle and rear wheels of the RCP during the climbing of a 12° slope

the default configuration the load dispersion is $\eta = 158.1$ N and the rover is able to negotiate a maximum slope of 11°. With the actuation strategies above described, the load dispersion goes down to $\eta = 24.2$ N and the rover becomes able to climb a 14.5° slope with the same level of slip.

The climbing manoeuvre of the RCP with online modification of η was simulated. In this simulation the RCP climbed a 12° slope. The soil properties used in the modelling were the ones listed in Table 1 with the exception of two parameters: the parameters related to the frictional aspect of the soil were chosen as $k_\phi = 1410$ kN/m^{n+2} and $\phi = 34.1°$. The reason for this modification was to simulate a scenario in which the slip developed to climb the slope in absence of redundant actuation exceeds 80Fig. 6 displays the results of the simulation. At the beginning of the simulation the rover was placed stationary on the slope. An angular velocity command of $\omega = 0.4$ rad/s was sent to the wheels of the rover. Initially, no internal torque was applied and the normal force dispersion was around $\eta = 150$ N. The rover reached a steady-state motion after $t = 2$ s, requiring 87% wheel slip to move forward. At time $t = 3$ s the torque applied on the bogies was increased gradually until $T_{bogie} = 20$ N.m. A new steady-state ensued after $t = 5$ s. The more favourable normal force distribution ($\eta = 100$ N) brought the slip percentage down to 60%. In the last part of the motion an additional increase in T_{bogie} until 50 N.m improved furthermore the evenness of the load distribution. With the new load distribution $\eta = 25$ N the rover was able to climb the same slope with 53% slip.

4 Experimental Results

In the previous sections the effect of CoM repositioning and redundant actuation on the mobility of rovers was studied based on simulation results. In this section an experimental study of the effect of these factors on the normal force distribution and consequently the rover performance is presented.

In the simulation studies the performance of the rover was measured by its ability to climb slopes. Drawbar pull tests can be considered analogous to slope negotiation tests since the application point of the dragging force was chosen to be close to the CoM of the rover, at least in the vertical direction. Drawbar pull experiments are also easier to carry out, because applying a variable external force to the rover requires less resources than building a soft soil slope with variable inclination.

A set of experiments, including drawbar-pull tests with variable load distribution and wheel slip was carried out on soft, sandy soil. These experiments took place in the Mars Dome which is a testing facility located in the UTIAS (University of Toronto Institute for Aerospace studies) campus. All the tests used for this study were carried out with 60% slip and the load distribution was modified via CoM repositioning and redundant actuation. The objective of these experiments was to study the effect of load dispersion on the ability of the rover in developing drawbar pull. The slip ratio was controlled by connecting the RCP to the winch shown in Fig. 7. By specifying the winch rotary speed the translational velocity of the rover and consequently its slip ratio were controlled.

Redundant actuation was realized by mounting two pneumatic linear actuators on each side of the chassis. One end of each actuator was connected to the front tip of the bogie and the other end to the main body. The force generated by the linear actuator resulted in a moment about the revolute joint between the body and the bogie. The actuator force was regulated by the input air pressure. Therefore, the load distribution between the front and the middle wheels was directly controlled via the pneumatic actuators. This also made the online modification of the load distribution during each test possible. The pneumatic actuator added to the original design of the RCP is shown in Fig. 7.

The RCP is equipped with six triaxial force-torque sensors mounted on each of its legs. These sensors measured the normal, tangent, and lateral terrain reactions on the wheels. However, for the purpose of online measurement of load distribution only normal force sensing is required. A digital force scale was used to measure the net drawbar pull developed by the rover. One end on the force scale was connected to the rope of the winch and the other end to the rear bogie of the rover.

In drawbar pull experiments the RCP travelled on a straight line on soft soil. The motion input was the angular velocity of the wheels, which was set to $\omega = 0.4$ rad/s. The rover was connected to the winch and its translational velocity was set to 0.027 m/s which resulted in about 60% wheel slip. The normal force readings from the sensors of the front, middle, and rear wheels of the port side of the rover are plotted in Fig. 8. The rover started its motion with the additional mass elements attached to the front of the rover and no actuation was applied on the bogies. The plot shows a very uneven distribution of the load among the wheels, with the middle wheel carrying most of the load. At $t = 120$ s the actuator pressure was raised to 15 psi, which resulted in 16 N.m moment on the the bogie about its joint. The effect of the actuation on the normal forces can be clearly seen in the plot. The load on the middle wheel was significantly reduced and transferred to the front and rear wheels.

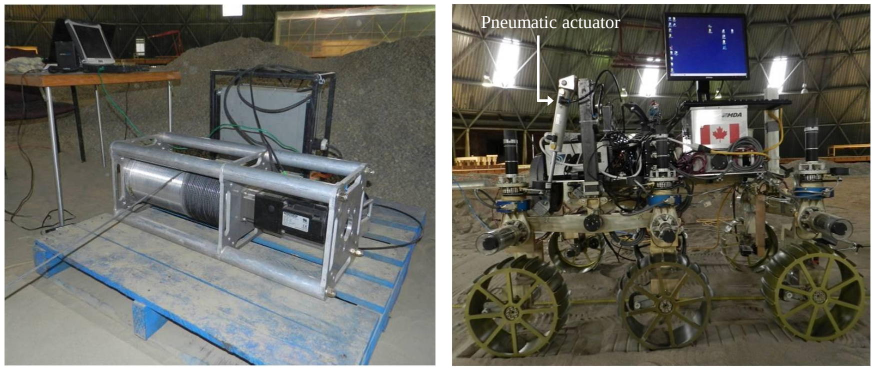

Fig. 7 Electric winch used for controlling the wheel slip in drawbar pull experiments (left) and design modification of RCP to add the redundant actuation option (right)

To magnify this effect the actuation was increased to 25 psi at $t = 160$ s. This translated into a 32 N.m torque applied to the bogie. As expected, this modification further balanced the load distribution among the wheels.

The normal force dispersion was computed for the duration of this test and is plotted in Fig. 8. The results show that only with the aid of the bogie actuation and without CoM repositioning η was reduced significantly in this experiment. This feature is specially useful for rover manoeuvres on terrains with various slopes. Data from force sensors can be used internally during the rover operation to calculate the required actuation for online tuning of the load distribution.

The presented results shows that redundant actuation has a significant effect on the normal force distribution. The final objective in this study, however, is the mobility improvement of rovers, in which the ability of the rover to develop a higher drawbar pull plays the key role. To this end, a similar set of experiments were conducted to study the way drawbar pull changes with variation of η. In these experiments η was modified by a combination of CoM repositioning and redundant actuation. The time history of drawbar pull during these tests is illustrated in Fig. 9.

The comparison of the experimental results shows that for the same slip ratio, the rover configuration with lower η provides more drawbar pull compared to the configurations with higher η. It was shown in [8] that the relation between the normal and tangential force generated at the wheel-terrain interface follows a non-linear curve. The shape of the curve is a function of the wheel slip and soil and wheel properties. Consequently, the relation between η and drawbar pull is also non-linear. The average value the drawbar pull for each test along with the value of η corresponding to the rover configuration in that test are tabulated in Table 2.

Among the reported experiments four cases were selected to be simulated with the Generic Multibody Dynamics Library. The same angular and linear velocity specification for the rover in the experiments were used for the simulations. Table 3 includes details of the configuration and redundant actuation for the selected tests.

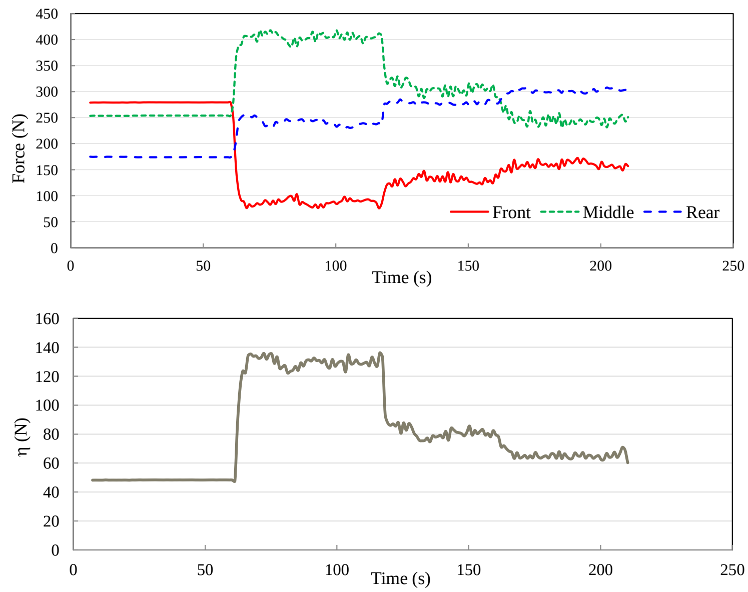

Fig. 8 Effect of redundant actuation on normal forces (upper plot) and on normal force distribution (lower plot)

Table 2 Experimental results of drawbar pull for different values of normal force dispersion (averaged for each test)

Case	1	2	3	4	5	6	7
η (N)	69.0	82.3	85.9	97.3	111.3	113.2	139.4
DBP (N)	322.9	313.9	307.9	306.8	281.8	272.6	268.2

Figure 10 shows the experimental and simulation results of drawbar pull in these tests.

Table 3 Operation conditions of experimental tests

Experiment	Mass element position	Bogie actuation (N.m)	η (N)
1	Rear	0	141
2	Front	0	125
3	Front	16	70
4	Front	32	63

Experiments 1 and 2 only differed in the position of the mass elements, which resulted in a more uniform load distribution in the latter. Both experiment and simu-

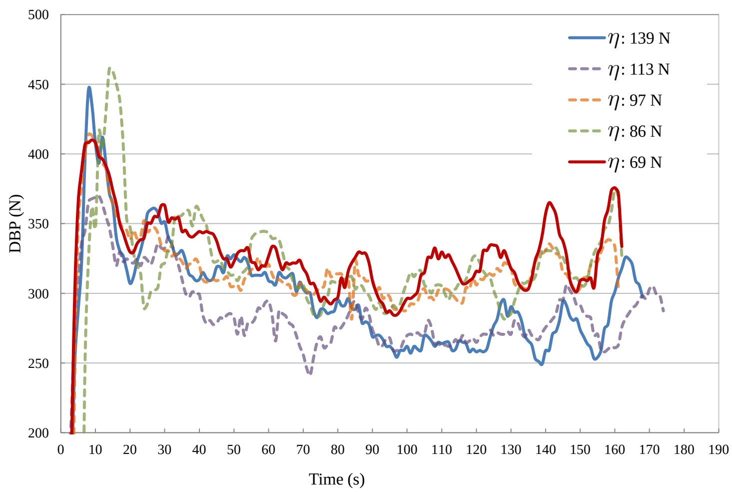

Fig. 9 Effect of normal force dispersion on development of drawbar pull

lation results showed that due to the lower value of η in experiment 2 more drawbar pull is generated. In experiment 3 the position of the CoM was the same as in experiment 2. However, after the initial period of the manoeuvre the pneumatic actuators exerted a 9 N.m torque on each bogie, reducing η for the rest of the motion. During this phase of the motion the drawbar pull increased in both simulation and experiment. In experiment 4 the actuation was changed in two steps during the motion: first, to 16 N.m and then to 32 N.m. After each increase in the value of the redundant actuation the rover reached a more uniform load distribution among the wheels, leading to its improved ability in developing drawbar pull. Therefore, both experimental and simulation results showed that for a given slip ratio it was possible to improve the ability of the rover to generate a higher drawbar pull via decreasing η.

In the real rover prototype the wheels have grousers and the chassis is considerably flexible. Since these factors were not present in simulation of the system the drawbar pull plot was a smooth curve. Additionally, modelling the wheels without grousers and uncertainties in the soil parameters led to the offset between the simulation results and the actual values of the drawbar pull. However, comparison of the plots in Fig. 10 shows that the simulations results correctly predicted the trend of change of the drawbar pull with η.

5 Conclusions

The ability of a wheeled robot to generate traction on soft terrain can be quantified by means of the normal force dispersion η. This performance indicator allows one to compare different vehicle configurations and actuation strategies in terms of

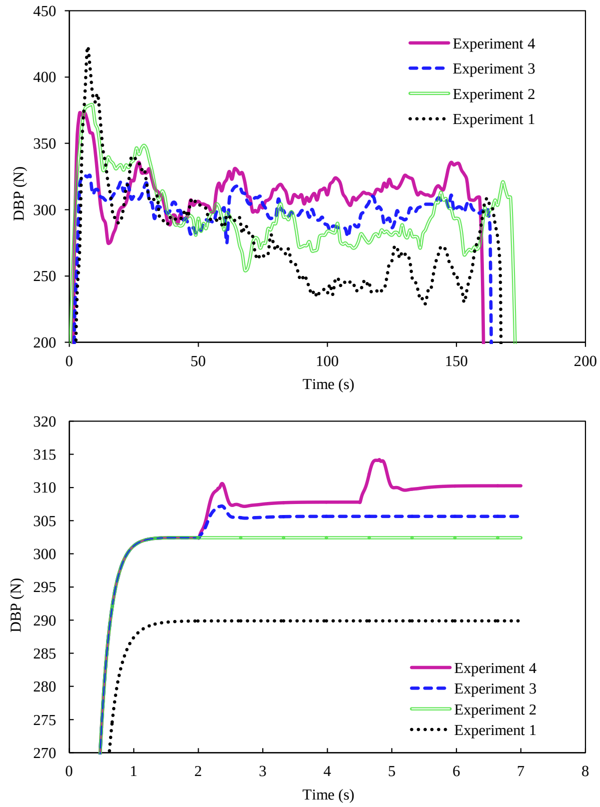

Fig. 10 Experimental (upper plot) and simulation (lower plot) results from the drawbar pull experiments

their suitability to improve the mobility for a given manoeuvre. In the reported research, the performance of a planetary exploration rover prototype was studied with simulations and experiments. Results consistently showed that reducing the normal force dispersion resulted in a better vehicle mobility. A low value of η allows the vehicle to develop less slip when climbing a given slope. Two strategies to reduce η were designed and tested on the rover prototype: changing the vehicle configuration by displacing its centre of mass, and introducing redundant actuation between suspension components. Both strategies proved effective in the reduction of the load dispersion and therefore, enhancing the vehicle mobility on soft terrains.

Acknowledgements The research work here reported was supported by the Natural Sciences and Engineering Research Council of Canada, and MDA Space Missions. The second author would like to acknowledge the support of the Spanish Ministry of Economy through its post-doctoral research program Juan de la Cierva, contract No. JCI-2012-12376. The support is gratefully acknowledged.

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