Effect of multi-pass on the mobility of wheeled robots on soft terrain

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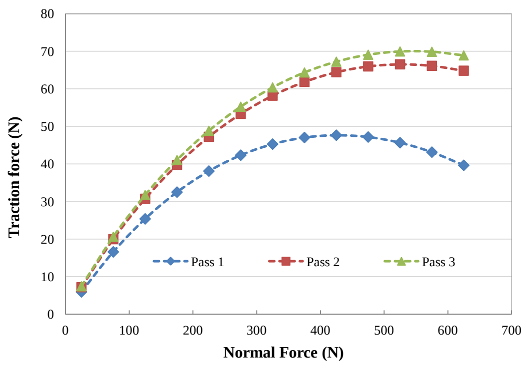
Abstract

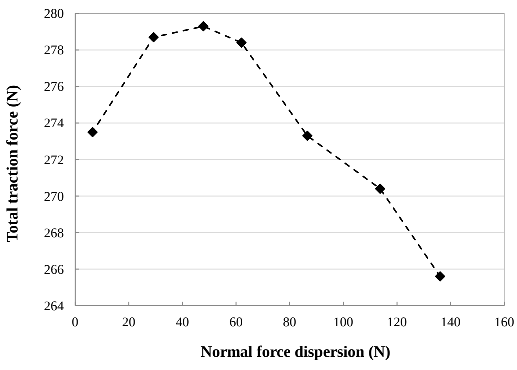
Mobile robots have shown significant potential for exploration missions in recent decades. Wheeled robotic platforms are advantageous for applications in unstructured environments due to their good stability and maneuverability properties. However, the mobility of wheeled robots can be reduced on soft, irregular surfaces. Terrain irregularity may give rise to a very uneven distribution of the robot load among the wheels. Furthermore, when the robot is in contact with soft soil excessive sinkage under one or several wheels can immobilize the whole system. Such situations must be avoided since a rescue mission can be very challenging and in some cases impossible. One approach to prevent mobile robots from falling into immobilized situations is monitoring the load distribution among the wheels during operation. This can also be advantageous from the stability point of view. In addition, continuous adjustment of load distribution during motion can improve the overall mobility of the robot throughout the mission.

The mobility of wheeled robots on soft terrain can be defined as their ability to move from a certain configuration or to move with maximum speed. This feature is greatly influenced by the rover ability to generate enough traction at the wheel-terrain interface. The tangential force generated at the wheel-terrain interface is a function of the wheel slip, the normal force, and the wheel and soil properties. The effect of each of these factors is studied in [1]. If the robot is operated under velocity control and all the wheels are commanded to move with the same angular velocity, it is reasonable to assume that all the wheels of the robot have the same slip ratio. In the above study, it was also assumed that all the wheels move on the same type of soil. This assumption is valid if multi-pass effect is negligible. For more general applications the multi-pass effect must be taken into consideration. In this work we solve a maximization problem to find the set of normal forces that results in the highest total tangential force that the rover can develop. This analysis is performed for a given slip ratio of the wheels and certain soil and wheel properties.

The interaction between a rigid wheel and soft soil under steady-state conditions is commonly modeled using terramechanics relations [2]. In multi-axle vehicles the terrain properties change after the passage of the front wheels. Therefore, the successive wheels experience a soil with different properties. A study of these changes was reported by Holm [3]. Factors such as the slip ratio of the front wheels influence the



(a)



(b)

Figure 1: (a) Relation between normal and tangential force for different number of wheel passage and (b) variation of total traction force with load dispersion.

magnitude of the changes. In [3] the variation of soil properties such as soil density is presented purely in the form of experimental data with no supporting theory or explanation. More recently, Senatore et. al. [4] presented the equations that fit Holm's reported experimental results. These equations give the variation of soil properties as a function of the slip and number of previous passes.

Table 1: Soil parameters used for terramechanics and multi-pass models.

n	c	ϕ	k_c	k_ϕ	K_d	k_1	k_2	k_3
-	[N/m^2]	[deg]	[N/m^{n+1}]	[kN/m^{n+2}]	[m]	-	-	-
1	220	33.1	1400	820	0.015	0.1178	0.1672	0.0348

The objective of this work is to find the best normal force distribution among the wheels of the robot for the purpose of generating an overall high tractive force. To this end, studying the relation between normal force F_n and tangential force F_t at the wheel-terrain interface is necessary. The terramechanics relations presented in [2] were combined with the model proposed in [4] to obtain the relation between F_n and F_t considering the multi-pass effect. Figure 1a illustrates the relation between normal and tangential forces for a soil with the properties shown in Table 1. Parameters n, c, ϕ, k_c, k_ϕ, and K_d are used in the terramechanics model, while k_1, k_2, and k_3 are multi-pass parameters. The passage of each wheel further compacts the soil and as a result the subsequent wheels will experience less sinkage in the compacted soil compared to the front wheels. Smaller sinkage leads to less resistant force. Also, for a given normal force and slip ratio, the traction force generated on compacted soil is larger. Therefore, as it can be seen in Figure 1a, for a certain value of the normal force the successive wheels develop more tangential force compared to the first wheels. This behaviour of the soil suggests that shifting the load toward the rear of the vehicle can increase the overall traction developed at the wheels and improve mobility.
To confirm this we formulated a maximization problem. First, for a vehicle with k axles, the F_t vs. F_n curve corresponding to wheel i is approximated by a polynomial $F_{ti} = f_i(F_n)$. The set of normal forces $\{F_{n1}, F_{n2}, \ldots, F_{nk}\}$ that maximizes $F_t = \sum_{i=1}^{k} F_{ti}$ is the solution of the problem. This problem was solved for different scenarios. One example is the operation of a six-wheeled planetary rover called RCP (Rover Chassis Prototype) on a soil with properties listed in Table 1, and 50% wheel slip. The solution of the maximization problem for the above operating conditions suggests that the contribution of the wheels on the second and third axles must be about 43% and 50% more than the wheels on the front axle, respectively. In Figure 1b, the resultant tangential force for different load distributions, including the solution of the maximization problem, are compared. Load distribution is quantified by the standard deviation of the six normal forces acting on the wheels [1]. The peak of the curve in Figure 1b occurs at the normal force distribution obtained by solving the maximization problem. The optimum load distribution among the wheels depends on the way in which the terrain reaction forces are affected by the multi-pass effect. On terrains for which the multi-pass effect is negligible, an even normal force distribution is advantageous. In contrast, if the passage of the leading wheels produces a strong change on terrain behaviour, then higher traction forces will be obtained if the load is partially transferred to the rear wheels. This study can also be applied to wheeled robots operation on non-homogeneous terrain.

References

[1] B. Ghotbi, F. González, J. Kövecses, J. Angeles. Effect of normal force dispersion on the mobility of wheeled robots operating on soft soil. In Proc. of 2014 IEEE International Conference on Robotics and Automation (ICRA), pp. 6612–6617. Hong Kong, China, 2014.

[2] J.Y. Wong. Theory of ground vehicles. John Wiley & Sons, Inc., New York, 2008.

[3] I.C. Holm. Multi-pass behaviour of pneumatic tires. Journal of Terramechanics, Vol. 6, No. 3, pp. 47–71, 1969.

[4] C. Senatore, C. Sandu. Off-road tire modeling and the multi-pass effect for vehicle dynamics simulation. Journal of Terramechanics, Vol. 48, No. 4, pp. 265–276, 2011.