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A hybrid force model to estimate the dynamics of curved legs in granular material

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Abstract

Robot locomotion on rigid terrain or in fluids has been studied to a large extent. The locomotion dynamics on or within soft substrates such as granular material (GM) has not been fully investigated. This paper proposes a hybrid force model to simulate and evaluate the locomotion performance of a legged terrestrial robot in GM. The model incorporates an improved Resistive Force Theory (RFT) model and a failure-based model. The improved RFT model integrates the force components of individual leg elements over the curved leg portion submerged in GM at any moment during a full period of leg rotation. The failure-based model is applied in a bar drag model to yield the normal and the lateral forces of the individual RFT elements as functions of the locomotion depth and speed. The hybrid model is verified by the coincidence between the theoretical predictions and the experimental results. The hybrid model is used to analyze the effects of angular velocity and leg shape with high precision and can guide the design of the legs with any profiles. Our study reveals that the interactions between locomotor and substrate are determined by the locomotor structural characteristics, the nature of the substrate, and the control strategy.

Keywords: Terrestrial robots; Locomotion; Hybrid force model; Dynamics; Granular material

1. Introduction

Developing robots able to overcome complex environments has aroused more and more interests. A number of research groups have done excellent work on exploring robot locomotion in solid, liquid, and the transitional environments (Saranli et al., 2001; Raibert et al., 2008; Crespi et al., 2013; Boxerbaum et al., 2005; Dudek et al., 2007). Understanding dynamics of locomotors in soft substrates is significant to improve the locomotory performance of the robots in terrains such as desert and beach. Generally, there are two methods to explore the interaction between robots and terrains. One is through semiempirical equations based on well-known pressure-sinkage model (Bekker, 1969) and shearing stress-displacement model (Janosi and Hanamoto, 1961), which has been widely used in design of locomotors and soil mechanics prediction (Asnani et al., 2009; Ding et al., 2013; Iagnemma et al., 2004; Ding et al., 2013; Patel et al., 2004). The other method is mainly through FEM or DEM simulation based on different contact models (Xia, 2011; Fervers, 2004; Smith and Peng, 2013), these works also promoted the in-depth understanding of material properties and their interaction with robots. However, the limitation of the existing models generally cannot be applied when the locomotors semi-submerge in loose terrain (Terzaghi, 1943), and the parameters in simulation model have to be carefully adjusted to reflect the practical situation. Considering this, robot locomotion in granular materials (GMs) is still in need of extensively study. Compared with solid and liquid materials, GMs show elastic deformation

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Nomenclature

σ	normal stress (Pa)
τ	tangential stress (Pa)
F_f	forward advancing force (N)
F_s	supportive force (N)
T	torque (N m)
γ	density of GM (g/cm^3)
h	height of the fixed motor axle (cm)
h_1	depth of bar (cm)
h_0	width of bar (cm)
L_s	subsurface part length of curved leg (cm)
β	angle of direction of $F_\perp$(°)
F_z	lift force on the bar (N)
ξ	angular position of element (rad)
d	submerging depth of element (cm)
ω	angular velocity of the leg (rad/s)
v	speed vector of element/bar (rad/s)
$F_\perp$	normal force component (N)
$F_\parallel$	tangential force component (N)
$C_\perp$	maximum $F_\perp$ (N)
$C_\parallel$	maximum $F_\parallel$ (N)
W_1, W_2	weight of GM in active/passive failure state (N)
a, b	axis of elliptical legs
ϕ, ϕ_w	friction angle within sand/between sand and bar (rad)
r	distance from element to rotating axle (mm)
M_x, M_y	torque caused by dF_f and dF_s (N m)
α_1, α_2	angle between active/passive failure plane and x -axis negative direction (rad)
X_1, X_2	forces among sands in various states (N)
P, P_w	force between bar and sands in passive failure region/force on sands in active failure region (N)
k, λ	coefficient for variation of GM bulk density (-)
ψ	angle from v to tangential direction of element (°)

below the yield limit and different rheological properties when destructed (Terzaghi, 1943; Kadanoff, 1999).

Some researchers have revealed GMs failure characteristics as well as the dynamics of intruders of regular shape moving in GMs. For example, Nedderman described the statics and the kinematics of GMs in a container (Nedderman, 2005); Albert et al. studied the forces applied to a cylinder as it was dragged in a GM at a low speed (Albert et al., 1999); Camorra et al. analyzed the projectile impact for improved calibration in particle dynamics simulation (Ciamarra et al., 2004). Recently, Maladen et al. proposed the “Resistive Force Theory” (RFT) to model the undulatory swimming of a sandfish lizard (Goldman et al., 2009). Despite these efforts, it is still difficult to estimate the interaction forces between the locomotion mechanisms and the substrate, which is crucial for the locomotion performance of desert robots, amphibious robots or planetary robots in GM environments (Goldman et al., 2009; Liang et al., 2012; Knuth et al., 2012; Zhang et al., 2013; Gao et al., 2012). One obstacle is that the locomotion of the robot legs with complex shapes in GM involves varying intruding depths and directions that can hardly calculated through a limited number of experiments.

In this paper, a hybrid force model that incorporates an improved RFT model and a failure-based model is proposed to explore the leg–GM interaction with a relatively high precision. The failure-based model calculates the forces on a dragged bar within GM at a low speed. With minor modifications, it can also be applied to move within GM at a high speed. By combining the failure-based model with an improved RFT model, one can conveniently estimate the forces applied to the locomotors as they penetrate in GM. The proposed hybrid model needs only a limited number of parameters that are readily measurable, as evidenced by our experiments. It is also observed that the angular velocity contributes negligibly to the leg–GM interaction within a certain working range. With such simplification, the forces and torques applied to different types of semi-elliptical legs are calculated in order to reveal the performance dependence of robot locomotion and guide the leg shape design. A major advantage of the proposed model is that it considers the macroscopic effect of force chains in the GM environment without the need to include the complicated microscopic parameters, such as the origination and the transmission of the forces among granular particles. In summary, this study forms the basis for leg–GM interaction analysis and may further guide the design of the robot legs for optimal locomotion performance in a GM environment.

2. Materials and methods

The locomotion performance of a terrestrial robot is determined by the propulsion modes associated with the structure of the locomotors. Two common types of locomotion structures are wheels and legs. As a popular man-made locomotion mechanism, the wheel is designed to accomplish many daily tasks on even terrain, and the wheel–soil interaction has been extensively studied (Asnani et al., 2009; Ding et al., 2013; Iagnemma et al., 2004; Senatore et al., 2013). Legged robots or human beings are able to adapt to rough terrain, and the leg-terrain dynamics is usually analyzed with an inverted pendulum model. Furthermore, the dynamics between straight legs and GMs are also explored with various experiments and simulations (Ding et al., 2013; Liu and Kushwaha, 2010; Yeomans et al., 2013; Scott and Saaj, 2012). As presented by the previous study, both of these two locomotion structures suffer the performance lost in GMs (Lejeune et al., 1998).