Extension of Resisitive Force Theory to Anchoring Modes During Locomotion

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***Abstract*—Resistive Force Theory (RFT) provides a simple empirical model to predict the drag and lift forces on a body moving through dry granular media such as sand, which is an environment that is typically difficult to model. Its simplicity enables quick, extensive exploration of the dynamic design space for robots that must locomote through sand, including planetary rovers. However, many rovers specialized to drive through sand do so efficiently by alternately driving and anchoring sets of wheels, and RFT does not inherently define the loads on a stationary body. This work proposes to approximate the loads that an anchored wheel or leg can support by using the vector of the net forces on that body in lieu of its velocity vector in the traditional RFT calculation. Experimental validation is still necessary, but this is a promising first step to expanding the applicability of RFT to all locomotive motions.**

I. Introduction

Improved models of interaction with natural substrates are essential to successful deployment of robots from the laboratory to unstructured environments. Contact surfaces are frequently approximated as rigid and non-slip but these are insufficient for robots which need to traverse natural terrain. In particular, sandy terrain caused mission-stopping entrapment for the Mars Exploration Rover Spirit over a decade ago and still poses an obstacle for both Martian and lunar rovers.

Interactions with dry granular media like sand are difficult to model in real time, which limits the extent to which designs can be optimized without extensive field testing. High fidelity solutions, such as discrete element methods and continuum modeling, require special computing equipment and long execution times. Even software specifically designed for wheeled locomotion typically cannot run in real-time or is dependent on many experimentally derived parameters. For example, the standard for off-road wheeled driving is the Bekker-Wong model, which requires 10 parameters fit from multiple experimental tests [3, 6].

Resistive Force Theory (RFT) is an alternative empirical model that depends on a single scaling coefficient to predict the drag and lift forces that act on a rigid intruder with any defined surface geometry and motion trajectory. Li et al. showed that multiple granular media with particle sizes typical of sand produce similar forces on a plate when decomposed as a function α of its orientation β and velocity direction γ [5]. The forces scale with penetration depth $|z|$, a medium-dependent scaling factor ζ, and plate area A, i.e. $F_{z,x} = \zeta\alpha_{z,x}(\beta,\gamma)|z|dA$. Notably, the forces are velocity independent, and a single vertical plate penetration test can be used to determine the scaling factor ζ for any medium. A surface can be decomposed into a small number of plate elements whose forces are superimposed to predict the total thrust and lift forces. The authors were able to use their model to accurately predict the optimal rotation speed and curvature of the legs for the fastest forward motion.

Agarwal et al. applied RFT to wheels, and its predictions of drawbar pull performed similarly to the Bekker-Wong model while significantly improving accuracy in wheel sinkage and drive torque prediction [1].

RFT is currently limited to flat, dry granular media and low speed (below 1 m/s) applications where inter-particle friction dominates resistance. However, RFT excels as a tool for exploring the design space of robot locomotion due to its simplicity. Leg and wheel geometries can be compared by their lift and thrust-generating abilities, and these geometries can be coupled with intentionally designed motions.

II. Expanded Dynamic Model

In application to planetary rovers, RFT can expedite virtual prototyping of chassis kinematics, which have traditionally required experimental exploration. Driving maneuvers like inch-worming (Scarab [4]) and wheel-walking (ExoMars [2]) have demonstrated improved forward locomotion in sand while reducing power requirements. Both rovers have active suspensions that allow them to drive one set of wheels while anchoring the remaining wheels. The anchored wheels provide a surface to react against the thrust generated by the driving wheels. However RFT cannot be applied as-is for these motions because forces are not defined in the absence of motion. Without modified handling of very low but numerically non-zero velocities, the velocity vector changes direction very quickly and causes the wheel to oscillate unstably as it faces high resistance forces in arbitrary directions.

In order to understand the effect of RFT upon acceleration and deceleration, force tests were performed which showed that when a plate decelerated slowly to a stop, it maintained the resistive forces acting on it, but at higher deceleration rates, a portion of force was dissipated. This effect can be visualized as a chain of forces that is generated between individual particles as they contact each other upon compaction. When decelerating quickly, the force chains partially dissipate as inertia allows some of particles to disperse.

These observations suggest that the sand can support a load up to that defined by RFT. Thus, for the zero-velocity condition applicable to anchored wheels, the wheel's constraint force vector may be more appropriate than the velocity vector for calculating allowable load. However, resistance forces cannot cause the reversal of motion, so the output force was limited to only enough to counteract the constraint force on the wheel. A hyperbolic tangent scaling was implemented to create a smooth transition between normal RFT operation and the zero-velocity condition to preserve force stability and computational ability. In Figures 2-4, an example of inchworming is simulated.

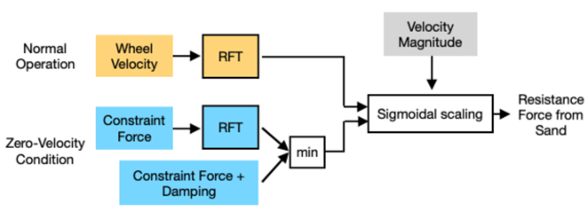

Fig. 1. A block diagram representing the modification to traditional RFT. When the wheel's velocity goes below a threshold, the force vector is used in lieu of the velocity vector to calculate the permissible anchoring force.

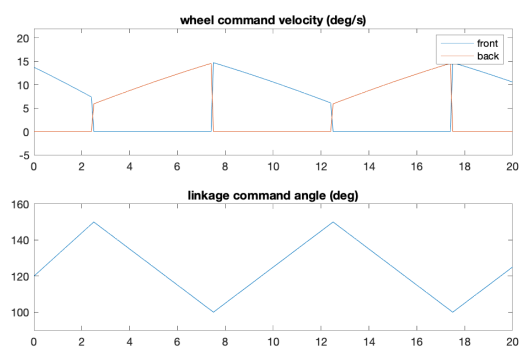

Fig. 2. An example simulation of inchworming. The front wheels are driven while the back wheels are anchored and the chassis linkage opens. Then the back wheels are driven while the front wheels are anchored and the chassis linkage closes.

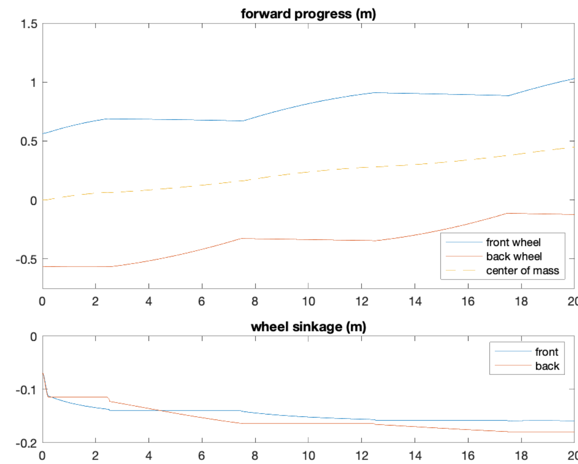

Fig. 3. The evolution of the rover's motion, both horizontally and vertically.

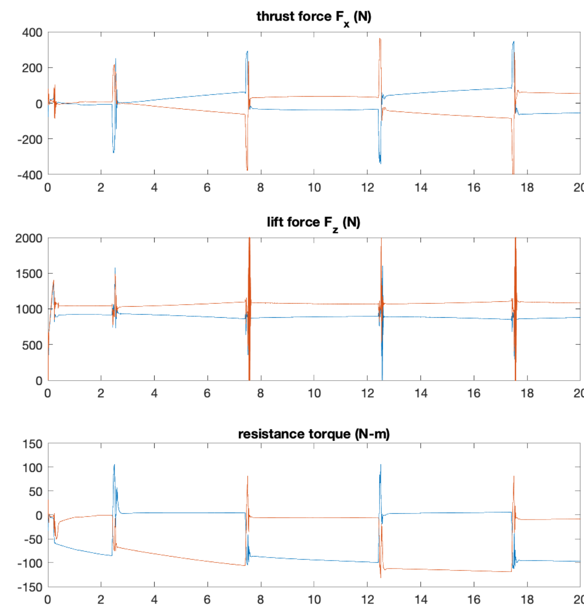

Fig. 4. The resistive forces calculated at each wheel.

III. Conclusion

The presented RFT modification is implemented in Simulink Simscape Multibody as a tool for the analysis of active rover suspensions and their drive kinematics. It can be expanded to different geometries, such as the original bio-inspired legged locomotion application of RFT.

While the force and trajectory outputs of the model at zero-velocity appear reasonable, experimental validation still needs to be performed. There is also ongoing work to improve the computational efficiency of the zero-velocity condition by approximating and replacing the existing circular reference to the constraint force. Finally, the aforementioned acceleration force tests were performed under velocity control. Pending implementation of force control, it will be informative to see if the static load that can be held upon anchoring varies from the kinetic resistance forces.

RFT is a promising model for the development of mechanisms and motions. Its simplicity can also facilitate the future creation of real-time controllers in sand. With only a single fit parameter, it would be possible to sample the terrain scaling coefficient in situ via a plate or wheel penetration test. As discrepancies between the robot's model and its motion develop, the coefficient could be updated over time, enhancing a robot's ability to adapt to changing terrains. Defining RFT for standstill conditions will expand its application in robotics by enabling predictions in the scenarios of anchoring and intermittent motion.

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