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RPPR Final Report
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Major Goals: The project has several primary objectives: (1) Determine a theoretical underpinning for the Resistive Force Theory (RFT) of granular intrusion. (2) Identify and test possible scaling laws in granular locomotion. (3) Attempt to optimize a locomotor using RFT. (4) Explore possible benefits of flexibility in locomotor design. Regarding (1) it is important to realize that should the simplifications present in RFT derive from a mechanical nature, our confidence and understanding of this approach would permit significant gains in modeling traction and locomotion problems in loose terrains. The RFT of granular media is a purely local model for resistive traction on moving submerged surfaces. Through use of RFT, driving simulations can be done without solving any partial differential equations or performing any costly discrete element method tests. Such a leap would comprise a milestone in the ability to optimize terramechanical designs. For (2), it is important to keep in mind that because RFT is so simple, it opens up doors in scaling that previously would not have been imaginable. When the number of input parameters to a problem is low, Buckingham Pi can produce broad families of scaling laws. In our case, it can be used how to infer the driving performance of a "big" wheel from the performance of a suitably downscaled "small" wheel. It could also apply much more generally to an array of interactions between solid objects and granular beds. For (3), the key idea is to first use RFT to optimize wheels with only one degree of design freedom. Then we can test this in the lab to see if indeed RFT found the best solution. This aspect of the project merges a "light" computational component, mostly using MATLAB, with a heavy degree of lab work to build and test a wheel that can actuate its shape in order to continually drive in the most optimal configuration even as conditions change. Designing an easily morphable locomotor is also a nontrivial task. Item (4) springboards off of item (3) in that the actuate-able wheel we create could be a guideline for how to make a naturally deforming wheel stay near the optimal shape. It will likely be easier to represent the deformability effect by doing computer experiments with discrete elements where the elastic modulus of the wheel components can be varied easily

Accomplishments: The primary accomplishments of this project can be summarized as follows:

1) The Resistive Force Theory (RFT) of granular media had been presented as a hypothesis/conjecture since it was first observed to work in granular intrusion experiments in the late 2000's. The idea was an extension of RFT for viscous fluids, an established simplification that can be derived as an approximation to the stokes equations. However, it was not known why granular RFT works. Not only does it work, ironically, it appears the RFT assumptions work better in sand than in viscous fluid. This comes in spite of the fact that the constitutive behavior of granular media is much more complex than a viscous fluid. Our work delved into this question and showed rather conclusively that the entire RFT of granular media can be deduced as an approximation to a frictional plastic continuum model of granular flow. This basic model treats the grains as a solid with pressure-sensitive yield stress and a separation rule that prevents states of tension. Using a model of this type, we were able to calibrate the

parameters to various granular materials and show that it generates all the RFT inputs previously documented for these materials. Moreover we showed that the most mysterious aspect of granular RFT, the so-called "superposition principle", is a direct consequence of plasticity. In doing so, a strange, never-before-seen invariance within plasticity theory has been revealed through this effort. RFT continues to be connected to plasticity through additional tests, including "scalene V" intrusion tests, which verify the superposition principle in asymmetric cases. For more details on this effort, please see the interim progress reports.

2) Unlike locomotion in fluids, locomotion in granular media has lacked a set of scaling relations. These, if found, could be used to inform the behavior of large or difficult-to-construct locomotors based on the behavior of smaller, lab-scale locomotors. A major benefit of the plasticity model described above, and its match to RFT, is that both approaches are simple enough to identify a family of locomotive scaling relations. In fact, both models produce the same scalings, as extracted using Buckingham's Pi-theorem. We were able to validate that the scalings actually work using several families of locomotive experiments and through DEM simulations. These tests utilized a variety of wheel shapes, loadings, and rotational speeds, showing that pairs of wheels differing in all dimensional quantities but sharing the same dimensionless numbers have matching dimensionless outputs. These scalings have been shown to hold not just on flat terrains but also for locomotors traveling up and down sloped granular beds as well as cohesive granular beds. For more details on this effort, please see the interim progress reports.

3) Because RFT is very computationally fast to run, one benefit is that it can be used in-situ to compute optimal wheel configurations to maximize traction. When coupled with a morph-able wheel, a rapid RFT solver can use detected inputs from the wheel dynamics to alter the wheel's shape to improve its tractive capability. Using an actuated, morph-able wheel we have designed and built, which we call "Franken-Wheel," we have tested this concept. We have written a fast, implicit, RFT solver that can try many future wheel states while the wheel is in operation to determine which wheel variations maximize/minimize some objective, be it the forward drawbar force or velocity of the wheel. We can show analytically that some wheel configurations are optimal "targets" for certain unconstrained locomotive goals, though a feedback loop using RFT is needed in general cases to find real-time optimal solutions. For more details on this effort, please see the interim progress reports.

4) Impact/penetration modeling: Using our frictional plastic model, we were able to show that granular impacts and penetration can be well-represented at the continuum level. Our model was able to match up against many years worth of impact data collected by the Behringer group, capturing behaviors such as penetration path vs time, flow fields around the intruding impactor, elastic wave propagation, splashing, and cratering. The model can capture these effects even as inputs such as intruder shape and impact velocity are varied. For more details on this effort, please see the interim progress reports.

5) Comparing models in wheel locomotion: With RFT and MPM-based continuum modeling firmly in our belts, we set off to perform an expansive, complete study of how these tools work compared to classic terramechanics models such as Bekker-Wong. We tested all models against a variety of experiments (c/o Goldman and Iagnemma) using different granular soils and different wheel shapes/sizes/loads under forced slip conditions, in which the wheels are given a forward speed and rotation rate but are unconstrained vertically. Torque, drawbar, and sinkage are primary variables of interest. We found that RFT and MPM tend to match experimental data the best. This is true especially for wheels that are not perfectly round, which is the focus of the classic terramechanics model(s).

Training Opportunities: Over the course of this project, one postdoc and several grad students and undergrad student were trained. All were given many opportunities to present their work orally at conference and through posters. In fact, posters on this work have won multiple poster competitions. All have also published peer-reviewed papers.

Results Dissemination: The project was disseminated through multiple peer-reviewed papers, as well as many invited talks, and posters. See previous interim reports for details.

Honors and Awards: Posters on this work won two poster competitions (NEW.Mech 2018 and EMI 2019). Kamrin received the Eshelby Award for young faculty in mechanics, the Journal of Applied Mechanics Award, and also received tenure during the award period.

Protocol Activity Status:

Technology Transfer: Kamrin visited ARL in Aberdeen this past Spring and gave a seminar. This has led to a MIPR. Kamrin also visited TARDEC in 2016, which led to short term additional funding. Kamrin also visited ERDC in Vicksburg to participated in the 2016 workshop on fluid-structure interaction, including granular structures.

PARTICIPANTS:

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Participant: Ken Kamrin 7154157
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Hesam Askari
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
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National Academy Member: N
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Authors: David, Motley
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Nothing to report in the uploaded pdf (see accomplishments)