

Roving Around the Moon and Mars: Active Weight Redistribution and Strategic Slip
Control for Augmenting Wheeled Mobility

By

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Abstract

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Planetary rovers have a history of entrapment in soft Martian sand, which is difficult to visually anticipate and results in high-stakes extrication efforts. As scientific objectives on Mars evolve and interest in lunar exploration increases, the need to traverse loose, sandy terrain incentivizes the design of more energy-efficient locomotion suspensions and gaits. Traditional rover designers consider wheel sinkage and slippage to be a consequence of vehicle and terrain parameters. However, articulation in suspension kinematics would allow wheel-terrain interaction to be manipulated in more dimensions to improve mobility.

Motivated by wheel-terrain interaction models in sand, specifically granular Resistive Force Theory, this thesis explores how load and slip can be controlled to augment the effectiveness of wheeled rovers. In simulation, dynamic front-back load redistribution using a gyroscopic moment is proposed for climbing tall step-like obstacles. Experiments with the load-responsive suspension controller of the Volatiles Investigating Polar Exploration Rover found that consistent wheel-ground contact was desirable for stability but mobility metrics were insensitive to quasi-static load distribution in nominal operating terrains. Meanwhile, in loose sandy terrain, slip is critical to generate forward traction when wheel sinkage is high. Driving wheels at different speeds to impose relative slip based on wheel load can lead to limited improvements in locomotion; this is an option to explore further for extrication efforts of existing rovers. More significantly, articulated suspensions can directly control wheel slip via the kinematics of the vehicle, and push-pull locomotion combined with controlled wheel slip can lead to faster and more efficient traversal of sink tanks and steep slopes. These works show that there is still significant room to improve traditional wheeled planetary locomotion and that suspensions with a couple additional degrees of control can be deployed robustly while safeguarding against entrapment.

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Chapter 1

Introduction

1.1 Challenges in Rover Locomotion

Despite a growing history of planetary rover deployment, many terrains remain difficult to impossible to navigate and continue motivating development of new locomotion systems. Planetary rovers have a history of entrapment in soft sand on Mars, which is difficult to remotely or locally visually anticipate because terrain properties are influenced by hidden, sub-surface composition [16]. Spirit spent weeks embedded in sand when its wheels broke through a friable crust that covered very loose sand [5]. Curiosity also struggled to traverse a dune field due to the short slopes that were wheelbase length in spacing and the looseness of the wind-drift sand [35, 7, 4]. A selfie with an example of these dunes is shown in Figure 1.1. Other failures in sandy, loose terrain are summarized in [27] and include the Apollo astronauts pushing the Lunar Roving Vehicle when its downhill wheels became embedded on slopes. Figure 1.2 shows a panorama taken by the Apollo astronauts that gives lunar terrain some scale.

These challenges and risks result in limitations to the regions reachable by rovers. Areas of scientific interest are often in more challenging terrain. For instance, lunar missions are currently interested in the water ice located deep in the permanently shadowed craters of the lunar poles [37]. Martian terrain that had past water activity and hence potential for interesting biochemical signals is rugged and rocky, as Curiosity found [48]. As a result of these experiences, rover operators choose circuitous routes to avoid hazards, which also consumes additional mission power and time.

Rover designers use suspension and wheel design to satisfy the mobility requirements of each mission and its expected terrain. Many recent configurations are discussed in [58]. However, studies have shown that mass-scaled testing on Earth cannot fully capture the looseness of soil in reduced gravity [42]. In mission operation, real time slip detection and response is still an open area of research, including numerous efforts to develop machine learning models for slip detection [27]. Unfortunately, these models are computationally intensive and are still relatively early in development.

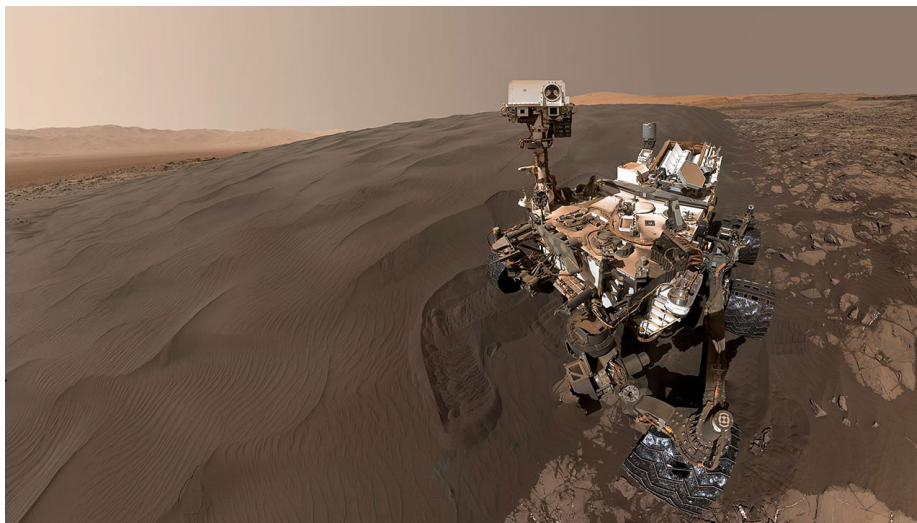


Figure 1.1: **Sandy wind-ripple dunes on Mars.** This selfie taken by Curiosity shows the shape of the dunes that challenged the rover along with the looseness of the sand in its wheel track [29].

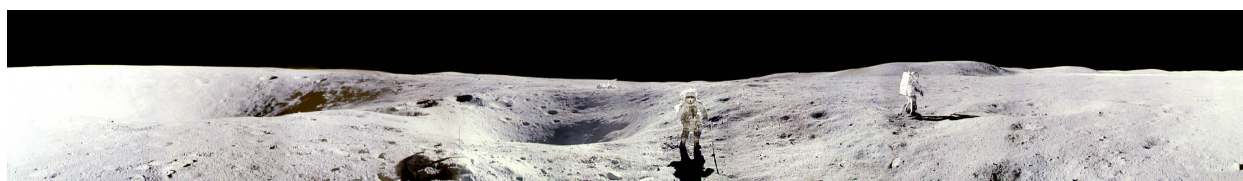


Figure 1.2: **Apollo 16 astronauts on the moon.** This panorama shows some craters in the equatorial regions with an astronaut for scale [41].

Wheeled locomotion remains one of the most power efficient methods of exploring a new environment. However, its limitations are well recognized. Wheeled rovers will likely continue to dominate as the most practical flight system, so there is high value in maximizing their access to the terrains we already know exist widely on Mars and the moon. This thesis approaches the task as a terrain interaction problem motivated by terrain models and finds that there are promising new suspension and control configurations that can be deployed in a straightforward manner with existing proven technologies for future missions.

VIPER

NASA's Volatiles Investigating Polar Exploration Rover (VIPER) is designed to prospect the lunar south pole for water, ice, and other resources that can be harvested in future missions to support further space exploration [52, 23]. Its goal is to drive 20 km over 100



Figure 1.3: **Mobility validation testing at NASA Glenn Research Center’s SLOPE Lab.** The rover is commanded to traverse a scene covered in rocks and craters that are estimated to be representative of the lunar surface.

Earth days, with a top speed of 0.2 m/s and traversing slopes of up to 15° and environments similar to the one built in Fig. 1.3. VIPER is NASA’s first robotic lunar rover and is part of the Artemis effort to return to the moon while leveraging support from commercial entities to reduce mission costs.

Previously, the Lunar Roving Vehicle (LRV) was sent to the moon during the Apollo era to support astronaut mobility, which imposed drastically different requirements on its design, including cost, schedule, and risk. The LRV was driven by astronauts in the equatorial regions, whereas VIPER will explore the poles via high-level remote operation and low-level autonomy, face more extreme thermal conditions, and generate power for itself throughout the mission.

VIPER will dip into and around potentially loose permanently-shadowed craters, and speed will be essential to ensure access to time-dependent solar power and communications [53]. These sites have not been previously visited and may include regolith that is looser than that found in the equatorial Apollo sites [39]. Accordingly, rather than following the design history of NASA’s Martian rovers with passive suspensions, VIPER’s suspension integrates additional actuation flexibility to prepare for a spectrum of mobility challenges. A mobility trade study for the VIPER mission determined that the ability to traverse more uncertain environments justified the increased mechanical complexity of an actively controlled suspension. As exploration of the moon increases, locomotion on loose, sandy or regolith-covered slopes will impact more missions and incentivizes the design of more energy-efficient locomotion suspensions and gaits.

1.2 Soft and Sandy Terrain

The strength of soft terrain, such as soils and sands, is characterized by its cohesion and friction angle, which together define the Mohr-Coulomb failure criterion via Equation 1. Cohesion c is the tendency of granular particles to stick together, and can be intuitively associated with the behavior of wet sand. Cohesion adds a fixed value to the shear strength of the soil. Friction angle ϕ relates the shear strength of the soil τ to the normal load σ on it, and is analogous to the friction coefficient between two rigid surfaces. A loose media has a low friction angle, similar to if it were made up of many slippery grains, so it easily shears. A high friction angle indicates that the soil can support significant shear even under small normal loads.

$$\tau \leq c + \sigma \tan \phi \quad (1.1)$$

Unlike rigid surfaces where the friction between the road and the wheel or the macro-sized mechanical interlocking between a rock's surface topology and the wheel generates forward thrust, generally some level of terrain moving and deformation is required to generate thrust on a soft terrain.

Mobility Metrics

Before diving into the methods of modeling mobility, it is important to understand terminology and common metrics that comprise a rover's performance.

During idealized driving, a wheel rolls with no slip over the ground, producing a translational velocity proportional to the driven angular velocity and the wheel radius: $v_{\text{no slip}} = \omega r$. In soft terrain, since the wheel often displaces soil to generate traction, the translational momentum at the ground contact may be distributed between the soil and the rover. The deviation of the achieved translational velocity v from the no-slip velocity defines the quantity **slip** s as follows

$$s = \frac{v_{\text{no slip}} - v}{v_{\text{no slip}}} = 1 - \frac{v}{\omega r} \quad (1.2)$$

Slip is a wheel-specific metric, but when all wheels drive at the same rate, it can also describe vehicle-level mobility. However, wheels do not need to be driven synchronously, and variation in driving speed can be beneficial in soft terrain as this thesis explores, so **travel reduction** TR is a more general metric for vehicle performance, where the reference drive velocity v_{ref} can be defined by kinematics or a baseline experiment.

$$TR = 1 - \frac{v}{v_{\text{ref}}} \quad (1.3)$$

Drawbar pull DP is the net forward force that a wheel generates when driving. While different models may calculate force components differently, the drawbar pull both includes tractive forces and subtracts resistive forces. It can be non-dimensionalized to facilitate

comparison between vehicles; the **drawbar coefficient** is the drawbar pull normalized by vehicle weight DP/mg . The drawbar coefficient can be used to roughly predict the slope θ that a vehicle can ascend, assuming the drawbar pull is equivalent to the downhill load of the vehicle's weight, i.e. $DP = mg \sin \theta$.

Power is a critical design and operating constraint of rovers. The non-dimensional form of power for vehicles is called the **power number** and represents the input power P required to move the rover's weight mg at the achieved velocity v . In the field of robot locomotion, this is commonly referred to as specific resistance.

$$PN = \frac{P}{vmg} \quad (1.4)$$

It is important to evaluate both the peak and average travel reduction and power consumption. The peak power or wheel torque indicate the rover's margin to its maximum operating condition, and the peak slip indicates the rover's ability to navigate a specific terrain environment. The mean values indicate the rover's efficiency of operation.

Motivated by terrain contact models, some rover controllers optimize the **force ratio** T/N at each wheel [32, 59]. When considering a typical Coulomb friction model of flat rigid surfaces, the tangential force that can be sustained before slip occurs is given by $T \leq \mu N$ where T is the applied tractive force, N is the normal load, and μ is the friction coefficient. Equation 1.1 is of a similar form even though it is representative of deformable terrains. Hence, applying a large tractive force can put a wheel closer to slipping, especially when terrain properties are unknown. To reduce wheel slip, some optimization methods attempt to minimize the force ratio.

Finally, stability is also critical to rover mobility. Geometric methods exist to ensure that a rover's center of mass remains within its contact polygon, but those methods will not specifically be employed here. For dynamic terrain contact, static geometric methods may not be enough, especially as engineers attempt to increase the travel velocity of rovers for the transportation of astronauts. Experimentally, stability can be quantified by the extremity of body pitch and roll magnitudes and rates.

Terrain Models

Terrain models that are available today are either low fidelity but simple empirical models or information dense, computationally heavy particle-based simulations. On the simple end of the spectrum, the Bekker-Wong model has been the standard in predicting off-road mobility both on and off Earth for decades, while granular Resistive Force Theory (RFT) is a newer and simpler generalized model of robotic interaction with cohesionless sands. On the computationally intensive end of the spectrum, the Discrete Element Method simulates the collisions and movement of individual grains, resulting in the most accurate distribution of loads and soil flow, but whose complexity scales exponentially with the number of grains in the model. Other recent work, in particular the Material Point Method (MPM) [21], attempts to bridge the gap between DEM and empirical models by employing continuum models to

reduce the computational workload of DEM, especially far from the robotic intruder or rover wheel. Since Bekker-Wong and RFT remain the most accessible models and thus are more often applied in practice, they will be covered in slightly more detail below.

The Bekker-Wong model is the traditional, most commonly used model of locomotion in deformable terrain [8, 62]. It was initially designed for heavy military or agricultural vehicles. The wheel's sinkage is first estimated via a pressure-sinkage relation measured using a loaded plate or wheel with representative geometry, producing 3 fit parameters. Then two additional parameters are characterized to define the submersion arc of the wheel's rim, i.e. the terrain contact angles at the front and back of the wheel. The wheel's sinkage geometry and the pressure-sinkage relationship define the normal stress on the wheel's rim with respect to its submersion depth. Finally, three more terrain parameters are used to estimate the shear stress along the wheel-terrain interface with respect to the wheel-terrain slip velocity. The shear and normal stresses can be integrated along the wheel's submerged surface to estimate the forward tractive force, bulldozing resistance and lift force generated by the wheel, along with the drive torque required to rotate.

While the Bekker-Wong model has a strong application history, its experimentally-dependent nature can make it difficult to work with and limits its accuracy. It requires upwards of 8 fit parameters, and changes in wheel geometry or terrain definition require additional experiments to recharacterize the model's parameters. It was initially developed for heavy, Earth-bound vehicles which are often tracked and have large wheel diameters, unlike rovers operating in low gravity. It is also a quasi-static model where the pressure-sinkage relationships are measured under static conditions, and therefore its sinkage estimate does not account for the transport of soil under a rotating wheel. Finally, the model does not account for 3D effects, such as steering or cross-slope travel, though several extensions and variations have been proposed to capture these. The model is sufficient for providing an estimate of the expected operating conditions, but it requires many inputs and can only describe simple motions.

RFT is a more recent model that estimates the total force experienced by an arbitrary body moving through a cohesionless granular media [36]. It operates under the hypothesis that loads along the body's surface are independent and can be integrated over its surface or summed over a mesh representation of the body. RFT is characterized by an experimentally measured closed-form mapping $\alpha(\cdot)$ from plate orientation β and velocity direction γ to drag and lift forces $F_{x,z}$, as expressed in Equation 1.5, which has been found to be relatively consistent among several natural and manufactured granular media and has a functional form that matches plasticity-based models. The loads are additionally proportional to plate depth $|z|$ and area dA . This base form of RFT assumes that frictional forces are velocity independent, which is generally an appropriate assumption at the low speeds that rovers currently drive. Its performance is comparable to the Bekker-Wong model at predicting the drawbar pull, sinkage, and drive torque of slip-controlled wheels of both cylindrical and non-traditional shapes in Martian sand simulants [2]. Additional empirical fits have characterized $\alpha_y(\cdot)$ such that RFT can be applied to arbitrary 3D wheel shapes and trajectories [61].

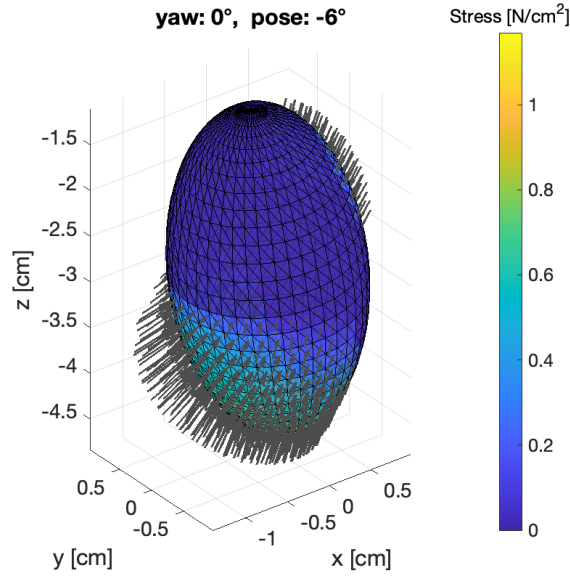


Figure 1.4: **RFT is dependent on plate and velocity geometry.** The total force and moment is a superposition of all the individual plate elements. Sample code is available at https://github.com/embody-dexterity-group/granular_rft_3D.

$$F_{x,z} = \int_S \alpha_{x,z}(\beta, \gamma) |z| dA \quad (1.5)$$

Relative to Bekker-Wong, RFT is restricted to cohesionless terrain, but its lack of soil- and wheel-specific parameters enable wider insights into generalized robotic locomotion in sand. Neither Bekker-Wong nor RFT account for vehicle dynamics, terrain topology, or multi-pass effects, whereas MPM and DEM inherently track the motion of particles. Vehicle simulation libraries use modified Bekker-Wong or DEM models to try to achieve higher fidelity than Bekker-Wong with lower computation requirements than DEM. For instance, Soil Contact Models (SCM) discretize the terrain to record terrain deformation and locally apply pressure-sinkage loads so that more complex interactions can be simulated, but the modified models may not accurately capture shear loads [57]. On the other hand, DEM can be accurate but requires micro-level characterization of granular properties and interactions and may take hours to weeks to compute depending on the size of the model, so it is best applied for smaller studies, i.e. to investigate specific behaviors or localized granular interactions.

At some level, it becomes challenging to characterize a terrain well enough for a high fidelity model to be helpful, especially since many real terrains are non-homogeneous and spatially distributed. Terrain models should be used to bound actuation requirements and performance, and quick iterations using an empirical model is more efficient for explor-

ing the mechanism and control design possibilities for robots that must locomote through sand. While RFT still needs further experimental validation to achieve similar robustness as Bekker-Wong, its accuracy thus far and its intuitive application for design evaluation and sensitivity analysis make it a good tool for expanding our understanding and control of wheel-terrain interaction.

Resistive Force Theory

Throughout the rest of this work, RFT is used as the primary modeling tool because it is easy to apply to robots with non-traditional geometry and control. For instance, the original work was applied to C-shaped legs of a legged robot [36]. In the limited experiments published thus far, RFT has predicted the mobility characteristics of single wheels better than Bekker-Wong, including for non-traditional pinwheel-shaped wheels [2]. Later works used it to model the swimming gait of the RP-15 rover, which was a precursor to VIPER [54]. The wheels of this rover cyclically drive, steer, and lift to improve drawbar pull in loose sand.

More recent works have extended the original model to 3D bodies and trajectories, which have been tested on ellipsoidal bodies, triangular prisms, and arbitrary mesh bodies [61, 1]. A sample of the output from the published GitHub code is shown in Fig. 1.4. Since the resistive force acting on intruders in sand is velocity independent at low velocities, and since RFT can be applied to arbitrary bodies with arbitrary trajectories, RFT can be sampled in a variety of directions in order to estimate the load capacity of an anchored body, as depicted in Fig. 1.5. This gives terramechanics researchers more tools for understanding more complex mobility gaits beyond normal driving, such as inch worming [19]. Dynamic effects where the momentum transferred to the sand is non-negligible can also be accounted for [3]. RFT’s assumed velocity independence is shown to approximately hold for $\omega < 0.5\sqrt{g/D}$, where D is the wheel diameter and g is the gravitational acceleration. At higher speeds, the effective depth of the rear surface of the wheel is modified by a factor proportional to the angular velocity squared, and this accounts for the additional soil excavation at higher speeds. These extensions to RFT require no additional experimental fit parameters to characterize the loads on the wheel, which makes it easy to modify the model for each appropriate driving scenario.

There is only one media-dependent parameter that can be measured by a single plate penetration test and a linear fit between the force and the plate depth. Since this coefficient proportionally affects the forces on all plate elements, modeling can be done without the scaling coefficient, and the scaling can be applied afterwards to understand the sensitivity of a robot to the “softness” or “stiffness” of the terrain, which can be affected by gravity.

Finally, algebraic analysis based on RFT shows that the non-dimensionalization of a wheel’s mass, velocity, and power can enable prediction of vehicle performance in a single media but across differing gravity levels, similarly to how the Reynold’s number is used to create sub-scale prototypes for fluid systems [56]. Dimensional scaling was experimentally validated for a limited subset of wheel geometry variation, and gravity scaling was validated in DEM. During single-wheel tests on Martian and lunar gravity-representative flights, [20]

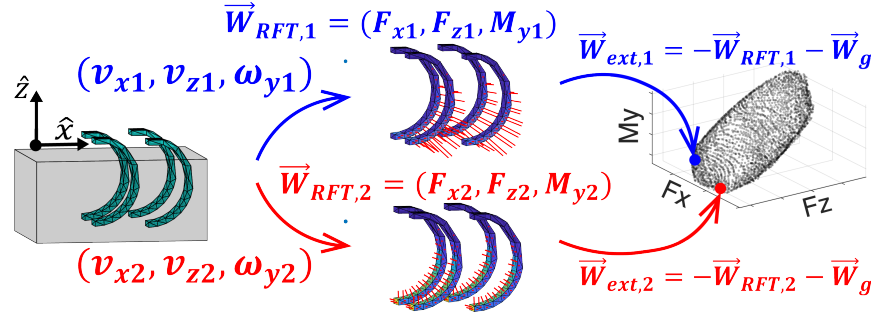


Figure 1.5: **Limit surface generation process** [31] © 2023 IEEE. A variety of motion twists (such as the ones indicated in red and blue) are applied to the 3D mesh. The forces on all mesh plates is added to generate a single point on the surface to the right. This limit surface represents the (up to) 6D load capacity of the anchors.

found that the scaling laws predicted mobility performance to within 30%, more closely and conservatively predicting the effect of low gravity operation than proportionally lowering the weight of a rover. More data is required to confirm these results, but they provide more of a framework for rover sub-scale prototyping than has been available previously. Note that this result is independent of the use of RFT for modeling but is a positive sign that the physical reasoning may be sound.

RFT is still inherently an imperfect empirical model that is primarily useful to gain better intuition for robot-terrain interactions. RFT assumes that the terrain surface is flat and that the granular media is relatively uniform and spherical. The generic coefficients of RFT were obtained by testing several media, both natural and manufactured. However, if higher resolution and accuracy is desired for a specific media, that media should be individually characterized by plate penetration tests. For instance, Huh et al. used a 2D lookup table rather than a first order Fourier fit because the Fourier fit was less accurate in the upward direction [31]. Furthermore, the RFT coefficients α are fit by linearizing force with depth at the depth of interest, whereas the Bekker pressure-sinkage relationship suggests that forces should scale with depth to a power n which may be closer to 1.1-1.3 for sands. While aspects of RFT can be modified to better fit specific applications, the principles of RFT create a versatile framework for the prediction of robotic interactions with cohesionless media with a low barrier to use.

Terrain Simulants

Many simulants have been designed to simulate different regions and different aspects of the terrain. For instance, some are focused on replicating geochemical composition, whereas the ones used for mobility testing attempt to match mechanical properties.

Oravec et al. published review of Martian simulants [44] and found that Mars 90 had a shear strength closest to the wind ripples that Curiosity encountered and struggled with [4].

Glenn’s Simulated Lunar OPERations (or SLOPE) Lab has a large tiltable sandbox filled with GRC-1, which is a lunar simulant designed to match the cone penetrometry measurements taken by the Apollo astronauts on the moon [43]. Creager et al. developed a terrain reset process to attempt to regularize the experimental reset process of an inherently noisy environment [18]. Finally, to stress test for extreme sinkage scenarios, there is also a tank of Fillite, a material composed of hollow ceramic microspheres with very low shear strength [22].

1.3 Load and Slip Control – Motivations and Outline

Wheeled locomotion is a mature field, with a lengthy history and standard solutions. Its limitations are also commonly recognized. However, wheels remain the most efficient form of mobility in many environments, and we have not exhausted their potential. This thesis explores how additional degrees of freedom in the suspension can expand the traversable limits of wheeled rovers.

The typical design scope of a rover consists of its passive kinematics and wheel geometry. Traditionally, the suspension equalizes the loads on each wheel, and the wheels’ diameter and width determine their sinkage and slip in an imposed terrain. In control and sensing, operators attempt to minimize slip.

However, with controlled articulation of the suspension, wheel-terrain interaction can be manipulated in more dimensions to improve mobility. In particular, deformable media requires slip to generate positive drawbar pull, and drawbar pull increases with slip, and at higher sinkage, the ceiling for drawbar pull generation also rises. Accordingly, an open question is: Can the load and slip of wheels be moderated to augment the mobility of rovers?

Load: Due to the physical limits of terrain, such as their friction coefficient and shear strength, many optimization models try to reduce traction to normal force ratio [32, 59]. Torque control has been tested and shown to reduce slip and drive torque compared to velocity control [34]. Previous works vary the torque applied by the drive motors, but an active suspension or another form of center of mass control would enable normal force to also be used as an optimization input. Chapter 2 explores the effects of load control, firstly in simulation with virtual center of mass redistribution, and secondly using experimentation with VIPER’s actuated suspension.

Slip: Both RFT and the Bekker-Wong equations model the forces on a wheel as fully dependent on slip and sinkage. Figure 1.6(a) shows this relationship as predicted by RFT for one of VIPER’s 50 cm diameter wheels. These models and experimental single-wheel tests both show that the drawbar pull, or net tractive force, at 0 slip is negative; positive slip is required to generate positive tractive force. Fig. 1.6(b) shows slices of the contour plot shown in Fig. 1.6(a) at different levels of wheel sinkage. For benign levels of sinkage, the drawbar pull plateaus once the wheel reaches a slip of about 20%. As sinkage increases, the slope of the drawbar pull curve is more positive, which allows the wheel to continue generating additional traction by increasing slip.

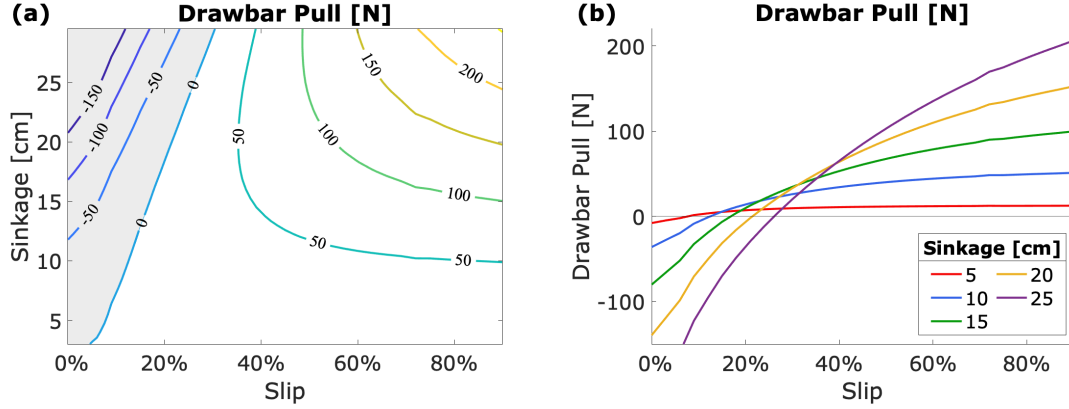


Figure 1.6: **Predicted drawbar pull of a VIPER wheel for varying wheel sinkage and slip.** (a) Operating in the gray region of slip and sinkage combinations, resistance on the wheel is greater than thrust generated, resulting in negative drawbar pull. (b) Each line is a slice of the contour plot in (a) for a fixed depth of wheel sinkage (disregarding wheel load). As wheel sinkage increases, greater slip is required to maintain net positive traction. At low sinkage, the drawbar pull plateaus after 20-30% slip, whereas at high sinkage, drawbar pull continues to increase with slip.

In extremely loose terrains, individual wheel slip and sinkage should not necessarily be avoided, contrary to common intuition. Articulated suspensions can take advantage of these relationships since wheel slip can be controlled by the coordination of the suspension translation and wheel rotation. Articulated suspensions can unload wheels to extricate them but also apply loads so that greater traction can be applied locally. Chapter 3 explores the effects of slip control while climbing sandy slopes, first by driving wheels at different speeds in accordance to their load and second by commanding slip internally for rovers with articulated suspensions.

While 6-wheel passive suspensions are the current state of the art, prior and current research indicates that 4-wheel rovers with more kinematic control may be an important configuration of the future. Especially as NASA expands its Commercial Lunar Payload Services contracts, more parties have an opportunity to launch and deploy a larger variety of rovers and iterate on existing designs. This thesis ideally gives a variety of modeling tools and experimental insights those with a blank slate to innovate with new suspension designs.

1.4 List of Publications

The results presented in this thesis are the consolidation of publications by the author, specifically:

- Section 2.1 is based on

C. Cao, D. K. Lieu, H. S. Stuart, “Dynamic Analysis of Gyroscopic Force Redistribution for a Wheeled Rover,” in *Earth and Space 2021*, pp. 318–327, Apr. 2021.

doi: 10.1061/9780784483374.032.

Available online: <https://ascelibrary.org/doi/10.1061/9780784483374.032>

- Section 2.2 is based on

C. Cao, A. Rogg, A. Tardy, “Actuated Suspension Tuning Characterization of the VIPER Lunar Rover,” in *2023 IEEE Aerospace Conference*, Mar. 2023.

doi: 10.1109/AERO55745.2023.10115796.

Available online: <https://ieeexplore.ieee.org/document/10115796>

- Section 3.1 is based on

C. Cao, C. Creager, D. K. Lieu, H. S. Stuart, “Mobility experiments assessing performance of front-back differential drive velocity on sandy terrain,” in *2021 International Society for Terrain-Vehicle Systems Conference (ISTVS)*, Sep. 2021.

Available online: <https://escholarship.org/uc/item/7cw263k9>

- Section 3.2-3.4 is based on

C. Cao, D. Moon, C. Creager, D. K. Lieu, H. S. Stuart, “Push-pull locomotion: Increasing travel velocity in loose regolith via induced wheel slip.” (Under review.)

Chapter 2

Ground Contact Load Control

This chapter explores the impact and utility of wheel-terrain contact load control. As introduced in Section [1.3](#), some proposed design and control optimization schemes minimize the force ratio by commanding wheel torque. However, they do not consider how contact loads can additionally be modified to reduce the force ratio.

First in Section [2.1](#), simulation is used to explore the use of control moment gyroscopes (CMG) to dynamically and drastically modify the front-back load distribution when climbing large step obstacles [\[12\]](#). Using a CMG with a large amount of stored angular momentum, very little actuation input would be required to drive the force ratio and maximum drive torques arbitrarily low, depending on the system design. However, CMG's have very complex dynamics and mechanical design and may not scale well to smaller systems, so this remains an intriguing thought experiment.

Active or actuated suspensions do not have the capability of rapid load redistribution in the same manner as a CMG, but they have been studied in prototypes and at least one will launch in the near future. Their extra degrees of freedom allow them to achieve more types of maneuvers and body orientation control, but the best method of controlling load distribution is still an open question. In Section [2.2](#), we experimentally characterize the effect of load distribution and suspension responsiveness on representative mobility scenarios for VIPER [\[13\]](#).

2.1 Dynamic Load Redistribution via Control Moment Gyroscopes [\[12\]](#)

The Mars 2020 rover is exploring a rocky region that may consist of long, unavoidable fractures in bedrock, which will require the ability to climb step-like obstacles. Current Mars rovers feature six wheels and large complex suspensions to overcome obstacles. However, unfavorable internal force distribution when the back wheels begin to ascend causes slip and high drive torque demands that limit mobility.

The rocker bogie passive suspension is the current standard for rover design, but researchers have proposed more configurations with varying degrees of active control to tackle existing mobility challenges. These solutions use a combination of passive kinematics and active manipulation of wheel pose to improve the distribution of mass over their wheels. Since the mass of the vehicle is concentrated at the center, significant force redistribution would require large suspension travel. A mode of contact force redistribution that has not yet been explored for wheeled locomotion is gyroscopic torque, which can be generated at large magnitudes for short periods and would be dynamically appropriate for step obstacle traversal.

A gyroscope is a flywheel that is gimbaled such that the angular momentum vector direction can be reoriented, or precessed. Upon precession, conservation of angular momentum causes a gyroscopic torque about a vector orthogonal to the spin and precession axes. The three standard gyroscope configurations are a single gimbal degree of freedom (DOF) gyroscope, a double gimbal gyroscope with two orthogonal control axes, and two single DOF gyroscopes that are spun and precessed in opposing directions. A single DOF gyroscope can create gyroscopic torques orders of magnitude greater than the input precession torque.

Control Moment Gyroscopes (CMG) are particularly useful in space applications where gravity is low and there are no surfaces available to react loads against, so disturbances must be counteracted internally. CMG's are a standard method for attitude control of satellites, including the International Space Station [28]. Anti-precessed CMG pairs, also called counter-rotating pairs or a twin gyro, were also studied for the control of robotic arms in space because they can control end effectors with torques that are decoupled from the rest of the robot body [11]. A cube-shaped robot called Hedgehog was designed to travel the surface of an asteroid using three orthogonal reaction wheels to roll the cube in the desired direction of motion [30]. Gyroscopic torques can also be used for reorientation when a wheeled robot falls [26]. This torque can be employed most effectively in low gravity (e.g. Mars or the moon) since the magnitude of its output is significant relative to gravitational forces. For a wheeled rover, an internal moment would modify the load distribution of the wheels, similar to the effect of rapidly shifting its center of mass.

Dynamic Model

A simplified static analysis of a four-wheel chassis driving over a step, as in Fig. 2.1, highlights the primary challenge of lifting the rear wheel. When the front wheels ascend, the load concentrates on the back wheels. Assuming an arbitrary tractive force can be applied, the back wheels need to apply high forces to counteract the concentrated load. However, a metal wheel on smooth rock can typically only apply a tractive force that is up to about 40% of its normal load before slipping. Tractive force can be applied at the front wheel to generate normal load on the back wheel, but as the obstacle gets much taller than a wheel radius, it becomes impossible to reduce the tractive force to normal force ratio to a level with no slip. If there are asperities in the surface that can mechanically support the load

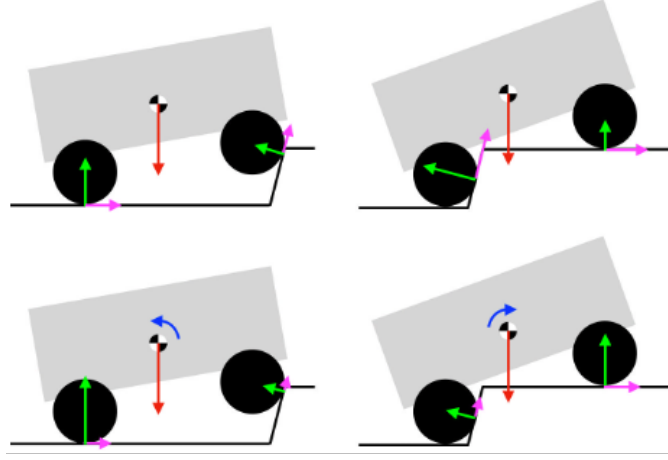


Figure 2.1: **Illustration of the forces acting on the rover when climbing a step.** During typical driving (top), the normal force at each wheel depends on the location of the center of mass relative to each wheel. An additional body torque (bottom, shown in blue) causes normal forces to redistribute.

by interlocking with the wheel treads, then a wheel can apply increased tractive force, but large drive torques are required.

Traction control strategies often use torque control to minimize tractive force to normal force ratio for each wheel, physically maximizing the margin to wheel slip on arbitrary surfaces [32, 34]. These previous works focus on passive chassis and use each wheel’s drive torque as the primary inputs. We propose using internal gyroscopic torque as an additional control input for further optimization.

To explore the dynamics of gyroscopic force redistribution, a rover is assumed to have four rigidly attached wheels and to be moving slowly enough to be considered a quasi-static problem. In a simplified 2D step-climbing context, this model could represent a driving mode of any of the four-wheel suspensions currently employed by NASA, including test rover Scarab and future lunar rover VIPER.

The tractive to normal force ratio of each wheel is minimized over the entire step traversal trajectory to estimate optimal drive torque and gyroscopic torque inputs. The rover’s kinematics were calculated at discrete points along its entire trajectory to create force and moment balance constraints at every location. Mathematically, the control optimization takes the following form, where the arguments are the drive torques of each wheel and the gyroscopically applied redistribution torque at every point in time.

$$\min \sum_t^T \left(\frac{1}{c_g} \tau_{gyro}^2 + \sum_i^n c_{FR} \left(\frac{T_i}{N_i} \right)^2 \right) \quad (2.1)$$

$$\text{s.t. at every } t, \Sigma F_x = 0 \quad (2.2)$$

$$\Sigma F_z = 0 \quad (2.3)$$

$$\Sigma M = 0 \quad (2.4)$$

In Equation 2.1, T_i and N_i are the tractive force and normal force applied by the i^{th} wheel at the surface contact point, n is the number of wheels, and c_{FR} and c_g are cost scaling variables to tune the weight of a high force ratio and a high gyroscopic torque application, respectively.

For dynamic simplicity, a twin gyro configuration was chosen. This gyro has two flywheels spinning in opposite directions such that their angular momentums sum to zero when their axes are aligned. They are gimbaled by equal and opposite angles to produce a change of angular momentum which is confined to a single vector direction, i.e. the pitch direction in this case, whereas a lone single-DOF gyro would produce a gyroscopic torque vector whose direction follows the changing gimbal position. Furthermore, the counter-balanced nature of the angular momentum in this system results in output torque insensitivity to external vehicle rates.

Since the goal is to produce torque about the pitch axis, we constrain the flywheel with spin axis in the vertical (vehicle yaw) direction and gimbal axis in the forward (vehicle roll) direction. Without considering vehicle rotation, the gyroscopic torque output by one flywheel is

$$\boldsymbol{\tau} = I_a \boldsymbol{\omega} \times \dot{\boldsymbol{\phi}} = I_a \omega \dot{\phi} (\cos \phi \hat{\mathbf{j}} + \sin \phi \hat{\mathbf{k}}) \quad (2.5)$$

$$\tau_{\text{gimbal}} = I_t \ddot{\phi} \quad (2.6)$$

where ω represents the vector spin rate in the direction of the spin axis, $\dot{\phi}$ represents the vector gimbal rate in the direction of the gimbal axis, and τ is the resulting gyroscopic torque. I_a is the axial moment of inertia of the flywheel, and I_t is the moment of inertia of the gimbaled system, approximated now as the transverse moment of inertia of the flywheel. Finally, τ_{gimbal} is the torque required to actuate the gimbal. Note that a similar result can be obtained from a flywheel with its spin axis forward and gimbal axis vertical. A twin gyro composed of two counter-rotating, counter-precessed single-DOF gyros as described above would instead be characterized as

$$\tau = 2I_a \omega \dot{\phi} \cos \phi \hat{\mathbf{j}} \quad (2.7)$$

$$\tau_{\text{gimbal}} = 2I_t \ddot{\phi} + (2I_a \omega \cos \phi) q \quad (2.8)$$

where vehicle rates are now considered, and q is the pitch rate. The external pitch motion causes a torque on each flywheel which is orthogonal to the spin axis, a portion of which must be sustained by the actuation axis.

Table 2.1: **Rover and gyroscope sample parameters for step-climbing optimization.**

Rover	Gyroscope	Optimization Parameters
• Mass: 400 kg • Wheel diameter: 0.5 m • Wheelbase: 1.2 m • COM height: 0.6 m • Velocity: 10 cm/s • Gravity: 3.71 m/s²	• Outer diameter: 0.35 m • Inner diameter: 0.2 m • Height: 0.05 m • Density: steel (~ 8000 kg/m³) • Spin rate: 15,000 rpm • Angular momentum: 827 kg-m²/s	• c_{FR}: 5 • c_g: 240

An example of an optimized step-climbing event, using the mechanical and optimization parameters listed in Table 2.1 and seen in Figure 2.2, shows how normal force concentrates on the wheel that is on the flat surface, where it can more effectively produce forward force. Normal force is shifted away from the inclined surface, which resists forward motion. Compared to a rover with no gyroscopic torque control (dashed lines), the gyro reduces the maximum force ratio from 1.6 to 0.5, which is a more achievable value. The drive torque is also reduced from a maximum of 113 N-m and 166 N-m for the front and back wheels, respectively, to about 100 N-m for both. The optimization is independent of gyroscope design and rover velocity.

Figure 2.3 shows the gimbal trajectory required to produce the desired gyroscopic torque, which is defined by the flywheel's angular momentum. The actuation torque depends on not only the angular momentum but also the pitch rate of the rover. As pitch rate is reduced by driving more slowly, the gyroscope must generate torque for a longer time, which is ultimately limited by saturation when the gimbal approaches 90°. Similarly reducing flywheel size and speed to reduce actuation torque would require faster gimbaling and larger angular sweeps. Larger obstacles also require increased gimbaling, so the parameters of a gyroscope must be designed with a specific use case.

Figure 2.4 shows the cumulative power requirement of each motor at every time step. The total power required by a standard rover is shown by the dashed purple line and is dominated by the rear wheel as it ascends the step. The total power required by the rover with a gyroscope is shown by the solid grey line. The gimbal motor draws the most power but significantly reduces the maximum power requirement of both drive motors. Over the full simulation period, the average power draw is about the same. No power optimization was done presently but could be a part of future work. Furthermore, the results assume a successful climb; however, we would expect that the rover without the gyro would spend more time struggling with slip or lack of sufficient torque, which would align with high power consumption events.

Trends for this rover as it ascends steps of varying heights are shown in Figure 2.5. The maximum force ratio and torque inputs occur either when the front wheels or back wheels first contact the step. Once the step is greater than wheel radius in height, the initial contact kinematics are roughly the same regardless of step height, thus the trends flatten for steps

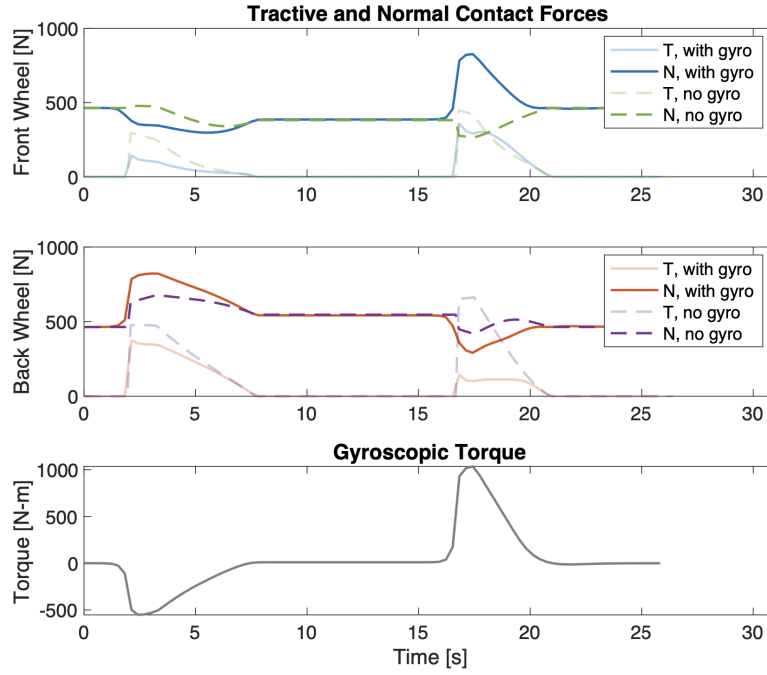


Figure 2.2: **A sample optimal drive traction and gyroscopic torque input trajectory for a rover climbing a 0.35 m step.** A negative gyroscopic torque is applied to lift the front wheel over the step and a positive torque to lift the back wheel. The step is 40% taller than the wheel radius and would be extremely challenging for a traditional rover, represented by the dashed lines.

greater than 0.25 m. The first 2 plots apply regardless of gyro size and rover velocity, while the gyro actuation torque and power vary. The balance between maximum force ratio and applied gyroscopic torque is controlled by their relative cost scales c_{FR} and c_g . The effect of c_g is shown in Figure 2.6. If surface conditions improve, such as by technology development in tire traction, then c_g can be decreased to increase the force ratio and decrease the applied gyroscopic torque.

Discussion

Gyroscopic redistribution of forces may be able to provide dynamic benefits to rover locomotion over obstacles. While a single rover configuration was considered, further design space analysis can be performed with varying rover size and mass, rover speed, wheel diameter, and obstacle height in order to understand their effects on locomotion and the application of gyroscopic torque. The concept would be most applicable to large rovers, since flywheel moment of inertia increases quartically with radius, or for lightweight rovers or rovers operating in particularly low gravity, such as on the moon.

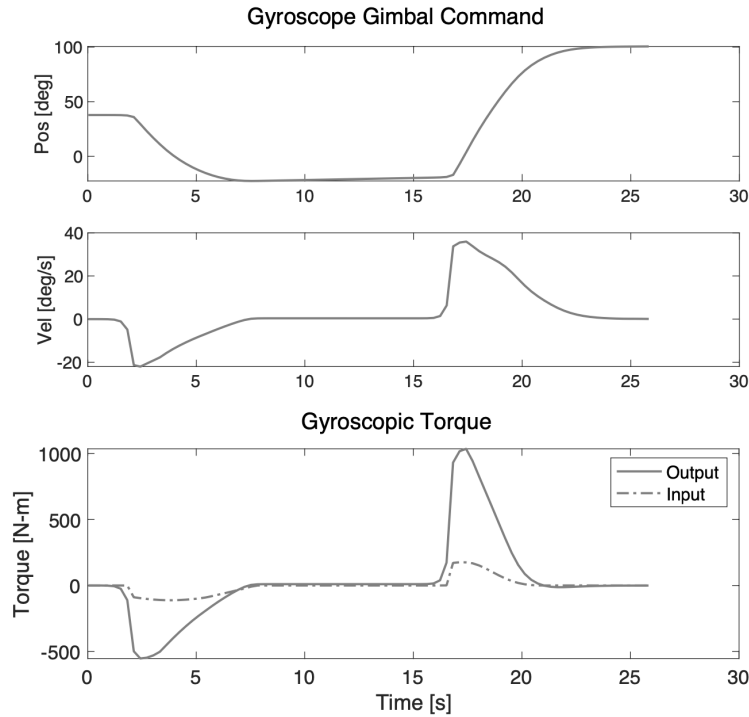


Figure 2.3: **Gimbal motion and torque output for sample optimized trajectory.** Note that a majority of the gimbal actuation torque is required in reaction to the pitch rate of the rover.

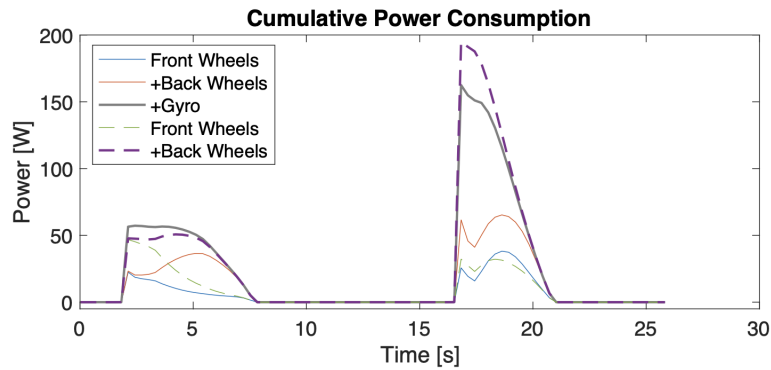


Figure 2.4: **Cumulative power contributions of the drive and gimbal motors.** Without optimizing power consumption of the gyroscope, the two systems have a similar mean power requirement (17.4 W vs. 18.2 W with and without a gyro, respectively).

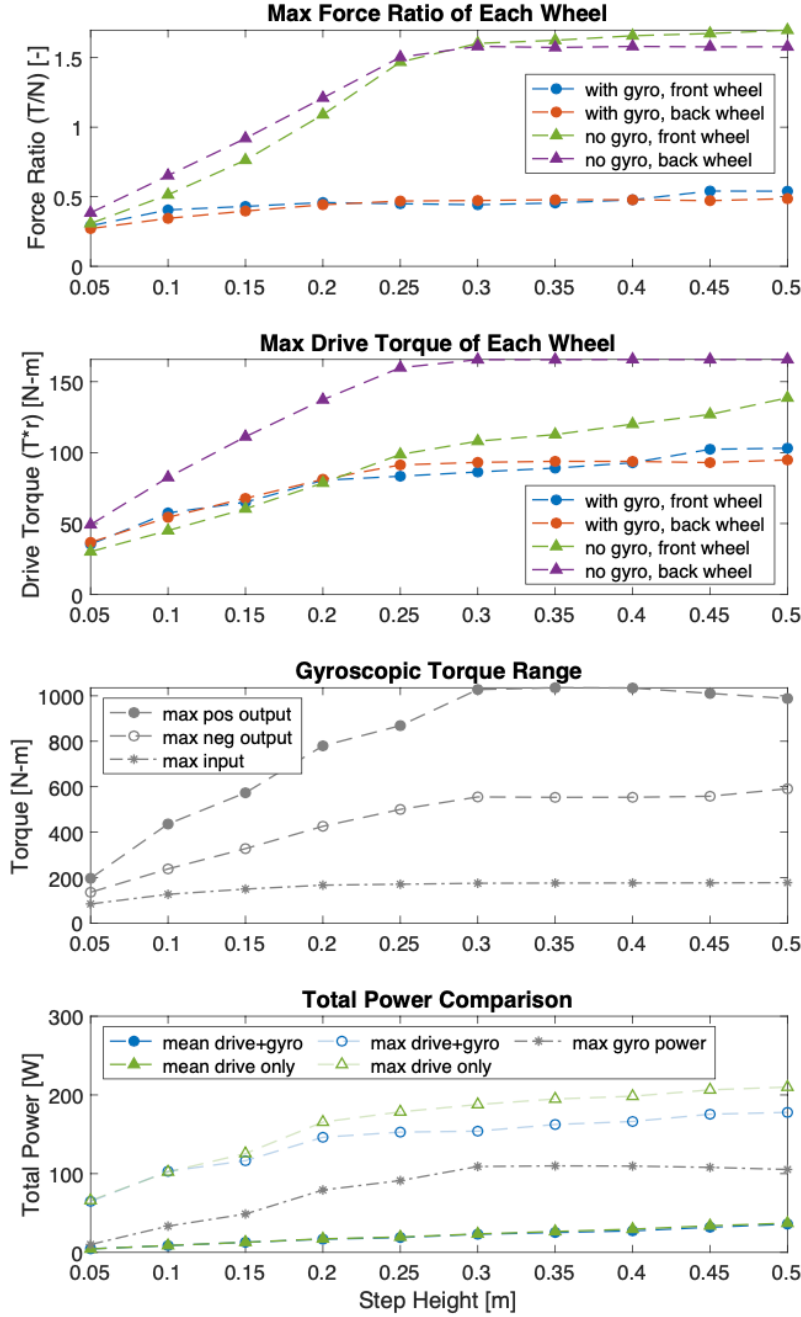


Figure 2.5: **Maximum force ratio and drive torque as step height increases.** The challenge increases with step height until it reaches wheel diameter due to less favorable initial wheel contact angles. Afterwards, every step height has roughly the same worst case impact on locomotion.

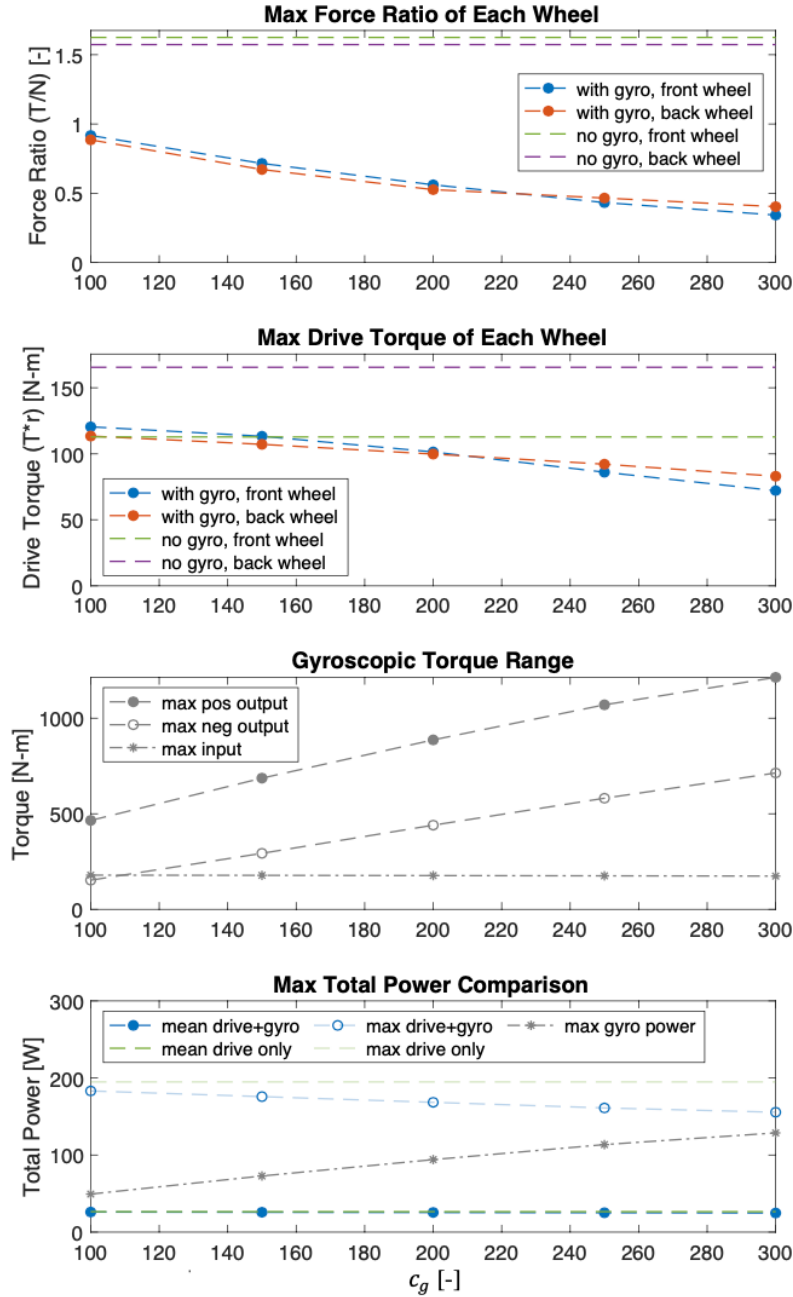


Figure 2.6: **Maximum force ratio and drive torque with varying relative optimization costs.** As the cost of applying torque decreases (c_g increases), the maximum force ratio and drive torque decrease. The gimbal input torque is insensitive to applied gyroscopic torque, since it primarily must counteract the vehicle pitch rate. However, gimbal power increases due to faster gimbal rates.

Gyroscope design depends on the desired torque output, for which magnitude and duration are limited by saturation. In order to produce greater or extended torques, a gyroscope must gimbal faster or over a longer range of angles, respectively. If close to saturation, the flywheel’s angular momentum must be increased, which increases the required gimbal holding torque during pitching.

This work presents a method for analyzing potential for mobility improvement via gyroscopic torque control, specific to ascending large, step-like obstacles. However, it addresses traction conservatively by minimizing contact force ratio, thus providing the best possible safety factor to prevent slip. Real surfaces are often not smooth and slippery, but rather have rough rocky features that improve traction and thus reduce the magnitude of load redistribution that is useful. The limiting factor may more often be the drive motor’s maximum torque. The optimization cost function can be changed according to actual requirements.

Conclusion

Gyroscopic force redistribution can reduce wheel slip, reduce drive motor torque requirements, and increase the region of traversable terrain of a future Mars mission. While some works previously introduce the concept of shifting mass using active suspensions, the achievable forces and speeds are small compared with the proposed gyroscopic solution. Control moment gyroscopes can uniquely influence highly dynamic maneuvering over larger obstacles. However, suspension kinematics, which often include passive joints to ensure wheels conform to ground topology, would impact the transfer of torque from the body to the wheels, and this would have to be considered.

A gyroscope is a precision mechanical system; flywheel balance and gimbal alignment are critical, so its value must be weighed against complexity and cost for each specific use case. This work is theoretical, and experimental execution would be necessary to determine practical challenges and feasibility. At the fundamental wheel-terrain interaction level, it is important to first characterize experimentally how dynamic contact force shifting could improve wheeled rover mobility.

While active suspensions may have less dramatic dynamics, they still have additional mobility features beyond passive suspensions and are more likely to be deployed. For instance, VIPER will launch in late 2024, and it also has the ability to adjust the loads on its wheels. The next section investigates how load distribution affects VIPER’s mobility.

2.2 Characterization of VIPER’s Load-Responsive Suspension Controller [13]

VIPER is a four-wheel rover with three degrees of freedom at each of its wheel modules – suspension, steering, and propulsion – which allows it to independently lift each wheel, turn in place, and drive in different directions without changing body orientation (also known as crabbing). VIPER’s actuated suspension enables the rover to control both its body



Figure 2.7: **MGRU’s actuated suspension.** Each wheel module has suspension, steering, and propulsion motors. Actuation of the suspension allows MGRU to keep its wheels on the ground when one wheel climbs a rock.

attitude and ground clearance to perform tasks such as lowering its science instruments to the surface. During lander egress, the suspension’s adjustable track width and individual wheel extension control make VIPER more tolerant to ramp deployment variations. It can also employ various push-pull locomotion gaits for extrication from and traversal of extremely loose media [15, 54]. Load cells on the suspension allow the rover to control the contact force at each wheel.

VIPER’s suspension contains no passive elements, which introduces control challenges for keeping all four wheels on the ground. Several research rovers with active suspensions, including Sherpa and RoboSimian, have successfully been field tested in challenging terrestrial environments using force tracking controllers [17, 49]. However, they have many degrees of freedom in their suspension legs, which cover a much larger workspace, and they rely on much higher frequency control loops than those on VIPER, which run at 10 Hz. Unlike these prototype rovers, VIPER is constrained by its flight-ready computing platform limitations and prioritizes simple controllers to mathematically complex ones.

As a result, it is important to understand (1) how sensitive is mobility performance to controller parameters, (2) what are the trade-offs between power and mobility performance, and (3) how will tuning change in the lunar environment, where the regolith compaction may have high variability and vehicle dynamics will differ due to higher vehicle inertia and center of gravity. Certain tuning parameters can cause oscillation in the system due to time delays in the control loop, noise in the load cell, and load redistribution on slopes. Equipped with a range of data characterizing the performance of the suspension controllers, the team can have increased confidence when choosing control parameters for flight and interpreting telemetry during the mission.



Figure 2.8: **MGRU-CG performing a point turn on a 10° slope in the Roverscape.** ArUco markers were used for motion capture.

Mobility-Representative Configurations

NASA has several mobility-representative configurations of VIPER, which are built upon the Moon Gravity Representative Unit (MGRU). The base configuration of MGRU, pictured in Fig. 2.7, is a ground-pressure (vehicle weight) equivalent model of VIPER. The center of gravity (CG) of MGRU is about half as high off the ground as VIPER's. MGRU-CG, pictured in Fig. 2.8, has the CG at the correct height but imposes about 30% additional wheel load. With the raised CG, the load distribution of MGRU-CG is more sensitive to changes in terrain topology and body orientation than MRGU.

Neither physical model has the same inertia, CG, and ground-pressure as VIPER, which will all affect how the suspension controller performs once deployed in lunar operations. MGRU has about 7% to 20% of the inertia of VIPER and experiences 6 times higher gravity. This results in faster rotational velocities when falling off obstacles and thus, greater stability challenges on Earth. The wheels and mobility joints are flight-representative, so their weight relative to the chassis is significantly higher than the actual flight vehicle. Each mobility configuration, including the flight configuration, requires different suspension controller tuning.

It is therefore desirable to understand the system's sensitivity to the tuning parameters and how the parameters should be adjusted between configurations. While simulations are in development, achieving high enough fidelity to account for complex dynamics, such as internal friction, forces from the soft goods required for thermal management and dust mitigation,

and wheel-soil and wheel-rock interaction, is difficult to execute and verify. Experimental data remain invaluable for capturing the real-world interaction of the rover's controllers with the environment.

Experimental Setup

The Roverscape at NASA Ames Research Center has a large, 0.4 m deep outdoor sandbox. It is filled with a crushed granite that has a 42° angle of repose when dry and un-compacted. It compacts easily but is soft and easy to sink into when fully loosened. Compared to GRC-1, the lunar mobility simulant, the Roverscape sand is stiffer and does not provide as much environmental dampening to the suspension. While it is more easily traversable than GRC-1, the load cells experience higher amplitude and higher frequency variation, which compound the existing noise in the load cell and may exacerbate the oscillatory responses of the suspension. This creates a challenging case for the controller to maintain stability and ensures rigorous testing.

Three unit tests were chosen to cover the spectrum of expected loading situations: (1) a medium 10 cm rock on a 15° slope, (2) a larger 20 cm rock on flat ground, and (3) a point turn on a 10° slope. The load-responsive controller is designed to react quickly upon contact with rocks in order to keep all wheels on the ground and distribute the tractive load more evenly. However, when the rover operates on slopes, there is an inherent asymmetry in the load distribution, and if a loading event triggers the controller to start extending the uphill wheels, this action can exacerbate the load distribution, creating a load exchange loop between the uphill wheels and causing full extension of the uphill suspension joints. These three test terrains encompass load scenarios where the controller must be reactive but not unstable.

Suspension Controllers

VIPER's suspension joints receive position commands by two cascaded controllers. First, a body attitude tracker (ATT) uses the rover's onboard pose estimation and known kinematics to level the chassis. Then a ground-seeking controller called the down-force thresholder (DFT) is used to maintain ground contact for each wheel based on the load measured by each load cell. Due to ground clearance constraints, the DFT can only extend the wheels beyond the positions calculated by the ATT controller.

The DFT is a bang-bang controller that operates on each wheel individually. As depicted in Fig. 2.9, the suspension extends when its load cell reads below a certain threshold (off-ground threshold), and continues to extend until the load increases past the on-ground threshold, after which the suspension offset is reduced gradually back to 0. Extension and retraction occur at the same constant speed. For example, upon climbing a rock, the wheel on the rock and its diagonal partner experience the majority of the load, whereas the two wheels on the opposite diagonal become unloaded and may lift off the ground. The DFT

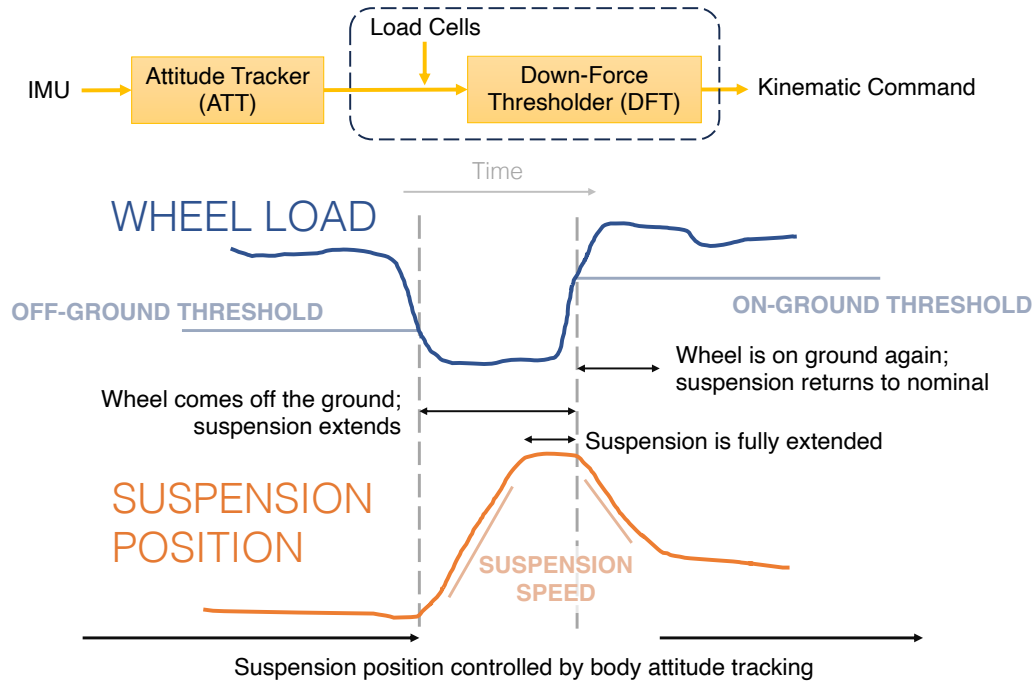


Figure 2.9: **VIPER suspension control diagram.** An attitude tracker (ATT) keeps the chassis level, subject to ground clearance constraints. Then the down-force thresholder (DFT) adjusts the suspension position to maintain wheel-to-ground contact.

extends the unloaded wheels until they carry at least the load prescribed by the on-ground threshold.

Loads are normalized to the rover weight so that controller logic is consistent among MGRU and flight configurations. A load of 0 means that the wheel is neither supporting nor supported by the chassis, a load of 1 means that the wheel is supporting 1/4 of the chassis weight, and a load below 0 implies that the chassis is lifting the wheel as opposed to being supported by the wheel.

The tested load thresholds are listed in Table 2.2. The lowest off-ground load threshold was chosen to be just above the unsupported load of the wheel, plus a noise margin for the load cell. The highest on-ground load threshold was chosen such that statically sitting on a 15° slope should not trigger the DFT. The thresholds were adjusted for MGRU-CG to account for the change in relative weight between the chassis and the wheels.

The suspension speeds were chosen to cover the range of achievable speeds. The suspension speed is converted into a position offset, which is added to the attitude tracking position command and sent to the motor controller. An example of the loads experienced and suspension response upon traversing a large rock is shown in Fig. 2.10.

Table 2.2: **Tested load threshold combinations.** Only combinations where the on-ground threshold is higher than the off-ground threshold are valid. The values in the grey boxes indicate the width of the load controller hysteresis.

Off-Ground Threshold		On-Ground Threshold						
		MGRU			MGRU-CG			
		-0.2	0.2	0.6		0.0	0.3	0.6
-0.6		0.4	0.8	1.2	-0.2	0.2	0.5	0.8
-0.2			0.4	0.8	0.1		0.2	0.5
0.2				0.4	0.4			0.2

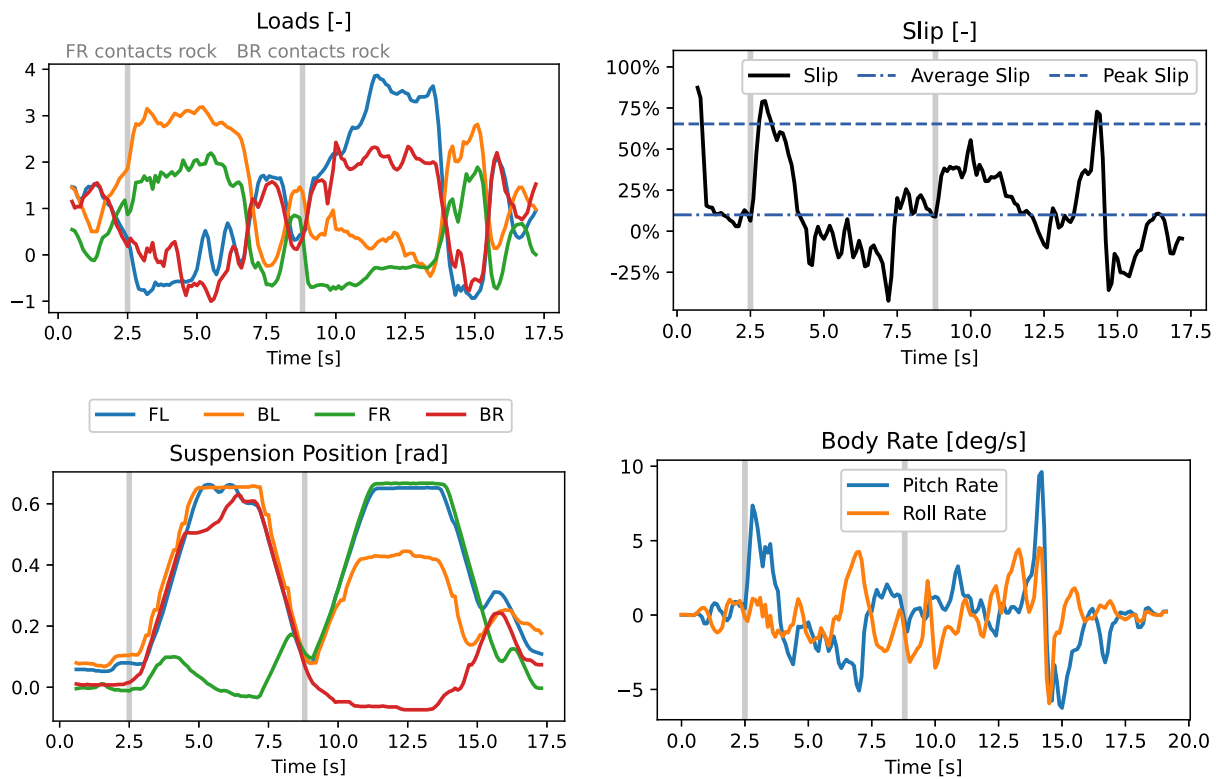


Figure 2.10: **Sample telemetry for load, suspension position, and slip from the 20 cm rock unit test.** The off- and on-ground thresholds are -0.2 and 0.2, respectively, and the suspension speed is 0.2 rad/s. Momentary suspension oscillation is visible between 5-6s and 16-17s. The unloaded wheels spend a significant time fully extended.

Mobility Performance Metrics

At a high level, VIPER’s mobility goals are to maximize traction and obstacle climbing ability while reducing power and minimizing instabilities.

Traction and obstacle climbing ability are often correlated with reducing slip, or the deviation of the executed trajectory from the intended trajectory. ArUco tags are used for ground truth motion tracking [24], while onboard wheel odometry predicts the ideal distance driven by the rover. Both average and peak slip over each trajectory were evaluated as they capture different facets of tractive capability; an example is shown in the bottom of Fig. 2.10. Average slip is easier to reliably measure via the total distance travelled and indicates overall travel efficiency. The average slip often remains low, not because the obstacle is easy to traverse, but because the rover skids off the back of the rock, as denoted by negative slip values. Peak slip highlights the most difficult moment of the traverse and can be used to predict obstacle climbing ability, since high peak slips indicate that the system is operating closer to its limit. The peak slip is reported as the 95th percentile over the entire trajectory to avoid noisy transients.

Similarly, the mean and peak power consumed by the mobility systems were also evaluated, characterizing mean efficiency and maximum actuation stress, respectively.

Finally, body instability is affected by both the terrain environment (e.g. an obstacle) and the suspension controllers. While stability can be quantified by maximum body pitch and roll, the rover experiences similar body angle trajectories across trials, but at different rates. Hence the peak pitch and roll rate captures both external and internal sources of instability, while suspension oscillation isolates the controller’s contribution. Suspension oscillation was quantified by low-pass filtering the suspension position and calculating the standard deviation of the difference between the actual and filtered positions.

DFT Behavior

Load distribution and loss of wheel contact are two metrics of interest for improving off-road mobility. Evenly distributing load can reduce the sinkage of any individual wheel and share the tractive load among the wheels. Load distribution is quantified by the average of the total absolute difference between each wheel’s load and the average wheel load. A high value indicates that the wheel loads are more imbalanced. Loss of wheel-to-ground contact inherently results in uneven distribution of load amongst wheels and can lead to chassis instability. Loss of wheel-to-ground contact is quantified by the length of time during which any wheel’s load cell reads below the unsupported wheel load.

Higher suspension speeds led to increased time in contact with the ground and more evenly distributed load, as visible in Fig. 2.11. However, higher suspension speeds also resulted in more time spent with at least one suspension joint at its limit, which is undesirable because it limits the rover’s ability to further adapt to the environment. Trials conducted without the DFT provide a baseline of mobility using only attitude tracking, and they are accordingly labelled “ATT Only” and have a suspension response speed of 0.0 rad/s. Early

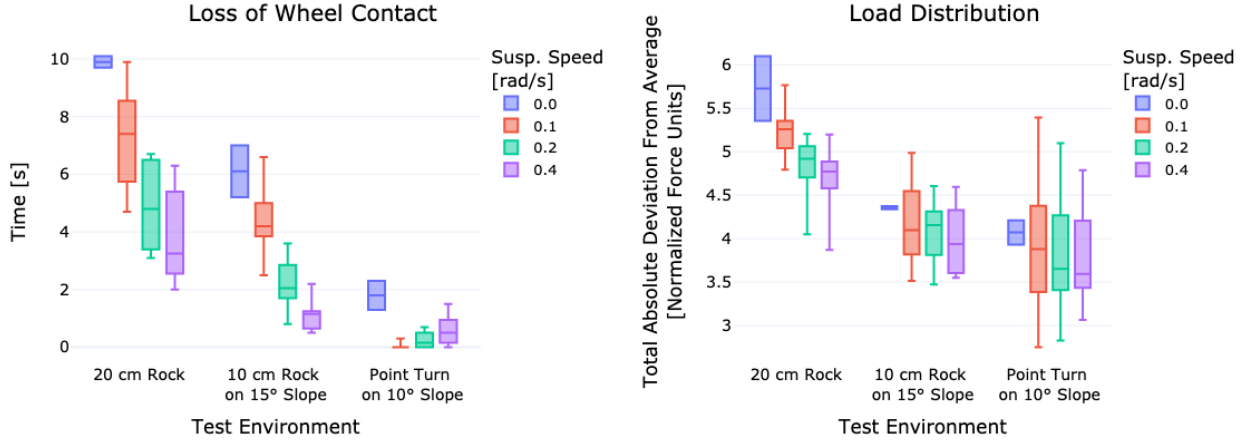


Figure 2.11: **DFT load balancing behavior with respect to suspension speed.** Faster suspension response keeps the wheels on the ground for longer when ascending obstacles, but it increases controller oscillation when roving on slopes (i.e. during point turns).

trials with a fixed suspension, i.e. neither ATT nor DFT on, resulted in frequent obstacle traversal failure and high slip, and were not pursued further in order to protect the rover.

Fig. 2.12 shows the load balancing and wheel contact relationships with varying load thresholds. DFT’s reactivity is most sensitive to the choice of off-ground threshold. As the off-ground threshold decreases, the DFT is triggered later and for less time, and it has a smaller improvement on load distribution. Paired with a high on-ground threshold, the DFT remains on for longer and therefore spends more time balancing the load distribution.

The three unit tests demonstrate how different aspects of the terrain affect the DFT’s performance. For instance, in the 20 cm rock scenario, the 0.1 rad/s suspension response results in the most loss of wheel contact (excluding 0.0 rad/s), while the 0.2 rad/s and 0.4 rad/s responses produce similar wheel-to-ground contact times. The climbing wheel ascends the rock faster than the other suspension legs can follow, so the response speed of the suspension is only helpful to the extent that the suspension is fully extended by the time the rock-climbing wheel begins to skid off the back of the rock. For ascending the 10 cm rock on the 15° slope, the difference in wheel-ground contact time between each suspension speed is clearer because the suspension can react fast enough to compensate for the variation in topography.

In a sloped point turn scenario, where the ground is almost flat, the suspension may misbehave by oscillating or over-extending when it responds too quickly to changes in load. The Roverscape sand is harder than the lunar simulant used in verification testing at the SLOPE Lab, resulting in occasional loss-of-contact when moving over imperfections. Unlike the two obstacle-traversal tests, the slowest suspension reaction results in the most wheel-ground contact because reacting too fast causes the rover to alternately load and unload the uphill wheels, leading to erratic load distributions.

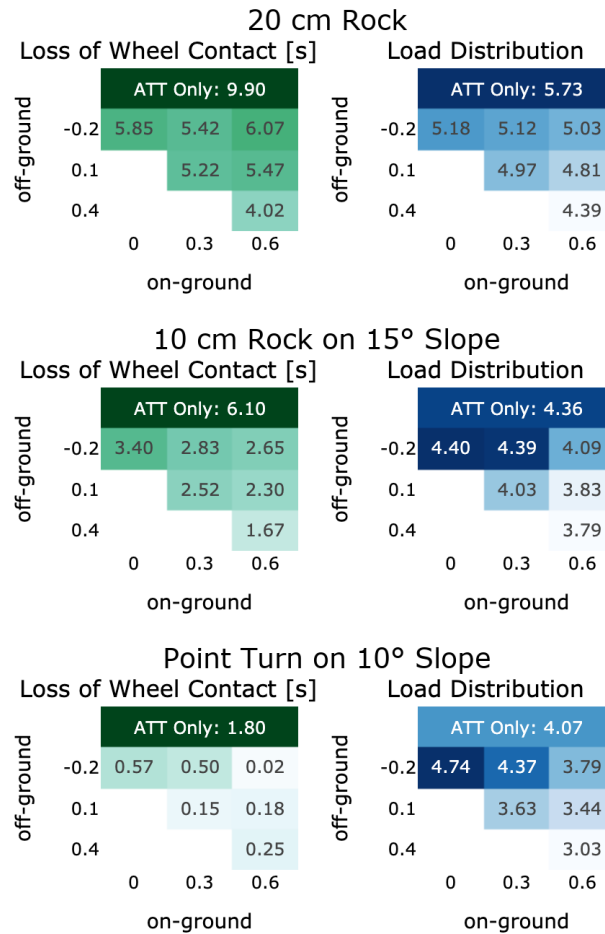


Figure 2.12: **DFT load balancing behavior with respect to load thresholds.** The DFT responds fastest with high load thresholds; responsiveness is most sensitive to off-ground threshold, then to on-ground threshold.

The DFT sometimes exacerbates load imbalance due to the positive feedback cycle that can occur on slopes. When the rover operates on a slope, weight is distributed away from the uphill wheels, and if triggered, the DFT reacts by extending the uphill joints, further unloading the uphill wheels until the joints reach their limits. Depending on the tuning, the suspension may oscillate instead of over-extending, which draws power unnecessarily. Both oscillation and over-extension are misbehaviors that should be minimized.

While the two metrics follow similar trends, load balancing and wheel-ground contact maintenance are different goals. The former requires more reactive load control, whereas the latter requires less actuation. The translation of DFT performance to mobility is explored next.

Mobility Evaluation

Each MGRU configuration performed all three unit test terrains, generating six total datasets. The average and peak slip are used to evaluate traction and obstacle climbing ability. Average and peak power indicate travel efficiency and maximum actuation stress. Finally, the peak body rate and suspension oscillation quantify chassis stability, both in response to the environment and from the controller.

A few parameter sets were repeated to understand the consistency of the results. In each trial, the desired traverse distance was fixed and the rover's approach to the obstacle was manually realigned. Each traverse was completed both forwards and backwards, denoted by circle and triangle markers respectively. Trials with only body attitude tracking and no down-force thresholding are included to characterize the benefit of the DFT controller specifically.

10 cm Rock on 15° Slope

The data for traversing a rock on a slope is shown in Fig. 2.13, where the forward direction corresponds with uphill driving, which induces more slip and pulls more power than the reverse or downhill direction.

Average slip remained low despite the slope, so no significant differences are observed. In the peak slip data, it is also difficult to discern trends from noise, but there is a visible peak slip reduction from the ATT-only runs to the DFT-enabled runs, which implies that the DFT provides the ability to climb obstacles more efficiently and operates with increased margin from the rover's performance limits. Peak slip decreases slightly with more reactive DFT parameters (from left to right in the plots), but the trend is not conclusive. Similarly, average power is fairly consistent, and peak power decreases when the DFT is enabled.

Fast suspension response (0.4 rad/s) resulted in distinctly higher oscillation, especially with the most reactive DFT load thresholds [0.2, 0.6], and did not lead to clear slip reduction or improved stability. Peak body rates were insensitive to tuning since the rover was not near its mobility limit and the suspension could keep up with the climbing wheel. This result provides no motivation for fast suspension response.

For MGRU-CG trials, slip, power, and stability metrics remained similar between different load threshold choices. However, suspension oscillation was about twice as large due to the increased sensitivity of the load distribution to body pitch.

In the balance of system performance metrics, the moderate suspension response speed (0.2 rad/s) provided sufficient maintenance of wheel-to-ground contact and peak slip reduction without the oscillations of a fast response (0.4 rad/s).

20 cm Rock on Flat Ground

The large rock case, shown in Fig. 2.14, was tested for rigor but is unlikely to be traversed during the mission. The current environmental specification indicates that the low density of such rocks should allow the drivers to navigate around them as they command the rover in real-time using visual information. However, uncertainty in surface conditions may lead to cases where large rocks must be traversed to avoid violating other flight constraints, such as rover orientation, antenna pointing, sun angle, craters, and other obstacles.

The rock was on level ground and approached from both sides. The differences in slip and power in each drive direction demonstrate the sensitivity of mobility to the shape and surface quality of the rock. In the forward direction, slip and power do not change significantly between tuning parameters. In the reverse direction, slip is reduced by enabling the DFT, and increased DFT reactivity (moving left to right between load thresholds) loosely correlates to reduced average slip. Increasing suspension speed has no effect. The clearest benefit of the DFT is the reduction of peak body rates by 20-40% and the reduction in loss of wheel-to-ground contact time by about half.

This test case suggests that the primary benefit of the down-force thresholding controller is to improve chassis stability. Enabling the DFT generally maintains or improves mobility performance in comparison to the ATT-only cases. While changes in traction and power metrics between tuning parameters are unclear, this implies that the system is robust to changes and increases confidence in future mission performance.

Point Turn on Slope

This maneuver is not challenging from a terrain perspective, but the redistribution of load can instigate controller instability. Across all tuning parameter sets, downhill slip during the 180° point turn was comparable and does not motivate a specific tuning. However, Fig. 2.15 shows clear differences in suspension oscillation, and hence power, for the CG-representative case.

These trends demonstrate how higher off-ground thresholds lead to more responsive controllers that are more susceptible to instability. Increasing the gap between on-ground and off-ground thresholds may improve stability by preventing the DFT controller from rapidly switching between on and off, but a high on-ground threshold can also lead to over-extension of the suspension. A low or moderate suspension speed and a middle-to-low off-ground threshold leads to the least misbehavior in this maneuver.

Conclusions

This test campaign experimentally characterized the behavior of the DFT and its impact on mobility goals of increasing traction, minimizing power, and maintaining stability. The test runs prove that the DFT more evenly distributes load across wheels and increases wheel contact with the ground. In comparison to using only attitude tracking for generating suspension commands, the addition of the DFT results in reduced body instability and in some cases, reduced slip. The DFT's primary utility is the reduction of chassis instability via increased wheel-to-ground contact. Any theoretical benefits from equalizing load distribution were not observed clearly enough in practice to justify increased controller complexity, power consumption, and motor performance.

Based on the results of all three test scenarios, the DFT should be responsive enough to maintain wheel-to-ground contact and stability upon traversing a large rock that represents a bounding case, but DFT responsiveness should be limited to this condition in order to avoid instabilities and misbehavior in the nominal sloped maneuvers that will comprise the majority of driving. In obstacle climbing tests, there was no significant difference in mobility performance between the moderate (0.2 rad/s) and fast (0.4 rad/s) suspension speeds. A low off-ground threshold, approximately equivalent to half the weight of the wheel, is also sufficient to respond to rock traversal, since a large load change occurs upon impact. Both MGRU configurations were able to traverse all of the attempted obstacles with little sensitivity to DFT responsiveness, which allows for a choosing parameters that are moderate and power efficient rather than fast and reactive.

Mission Impact

The concern that precipitated these tests was an observation that the down-force thresholding stage of the suspension control scheme sometimes resulted in internal chassis instability. However, comprehensive data or models were not available to make informed decisions about tuning the DFT and its impact on mobility. Furthermore, system dynamics will differ between MGRU operation in Earth gravity and VIPER operation in lunar gravity and regolith. While misbehavior is observable on Earth, it cannot be viewed so easily on the moon. This dataset suggests that DFT tuning can be reduced to a single maneuver and metric – chassis stability while traversing a large obstacle – which can expedite future tuning with other controllers and rover configurations. The observed insensitivity of the system to varying tuning choices increases mission confidence for robust deployment into unknown terrain.

Switching from the fast suspension response to a moderate one also allows the mobility team to reduce motor requirements and keep them from operating near their margins. Slowing the motor response allows it to maintain performance at low voltages, which may occur if the battery state of charge drops. This decreases control system complexity by removing the need to couple the motor controller tuning with the battery state of charge.

In comparison to MGRU, VIPER has an order of magnitude higher inertia and will be operating in lower gravity with softer regolith, which should produce more dampening, so

the vehicle will likely react more slowly to disturbances or impacts. Relative to lunar vehicle dynamics, the suspension and its controllers would act faster than they do relative to MGRU dynamics on Earth. Ideally this would reduce some of the control stability challenges that are currently faced, and if not, the test process and mobility trends measured on MGRU can be used to make informed decisions about tuning on the moon, should that be necessary.

Future Work

Chassis stability and suspension oscillation stood out in these test environments, but traction and power may play a larger role in soft soil. Changes in tractive performance are difficult to observe when rovers are not operating near their limits. A subset of these unit tests would be useful to execute at NASA Glenn Research Center’s SLOPE Lab, where driving on slopes incurred 2-3 times as much slip as in the Roverscape. The shear strength of soft, cohesionless soil is low and dependent on ground pressure, and simulations suggest that equalizing internal loads would improve slope climbing ability [25]. Alternatively, field testing of the SHERPA rover found very little change in slope climbing ability with different stances that balanced load distribution [17], so the impact should be measured experimentally.

Numerical model development would be ideal for reducing the time and resources required to gather experimental data. Modeling wheel-terrain interaction is an active field of research; a range of high fidelity to lower fidelity simulation solutions are being developed and explored for VIPER. Additional modeling challenges that remain include sensor noise models, internal friction, and interactions with soft goods. Simulation tools exist for individual features, but the integration of all tools into one simulation environment is still unfinished and would need significant time to validate.

Finally, the existing controller is limited to a simple bang-bang controller on individual wheels, but as previously mentioned, there is a positive feedback loop that can trigger run-away over-extension of the suspension on slopes. Variations of the controller that balance the load across the heavily and lightly loaded wheel diagonal pair, like the one used in [17], may result in more stable behavior.

2.3 Takeaways

In the area of wheel-terrain contact load control, this thesis has explored the dynamic application of gyroscopic torques to redistribute load when ascending step-like obstacles and has quantified the effects of VIPER’s load distribution on mobility metrics during nominal terrain traversal.

The use of control moment gyroscopes to produce highly dynamic internal moments can theoretically greatly reduce the maximum experienced force ratio in order to reduce likelihood of wheel slip or terrain failure. Its application can also reduce the maximum drive torque required, which would allow the rover to climb larger obstacles with a lower wheel torque specification. This could have greater effect on large rovers in low gravity, since a

large proportion of weight can be shifted around. However, gyroscopes are both mechanically and dynamically complex and they do not lend well to being scaled down, as their angular momentum decreases with their radius to the fourth power. If other functions, such as energy storage or high frequency vibration for compaction, become desirable, then they may be an interesting configuration to explore further.

For actuated suspensions, we found that load equalization is not a high priority mobility metric. Intuitively, better mobility performance is expected with a more responsive controller, but lower power consumption is expected with a slower controller. Experimental data showed the extent to which DFT responsiveness affects mobility performance and increases power demand in order to make trade-off decisions. Even if some wheels slipped more or were lifted into the air, the rover still completed its traverse as long as it had margin to generate traction with its other wheels. This suggests that the fully active suspension is relatively robust despite concerns about control bandwidth affecting its ability to conform to terrain. Furthermore, the system was able to reduce operating power and response speed without much impact to mobility.

Ultimately it appears that, as long as the vehicle can generate enough traction over all of its wheels, load equalization does not clearly improve mobility. Alternatively, load redistribution may hold potential for future research.

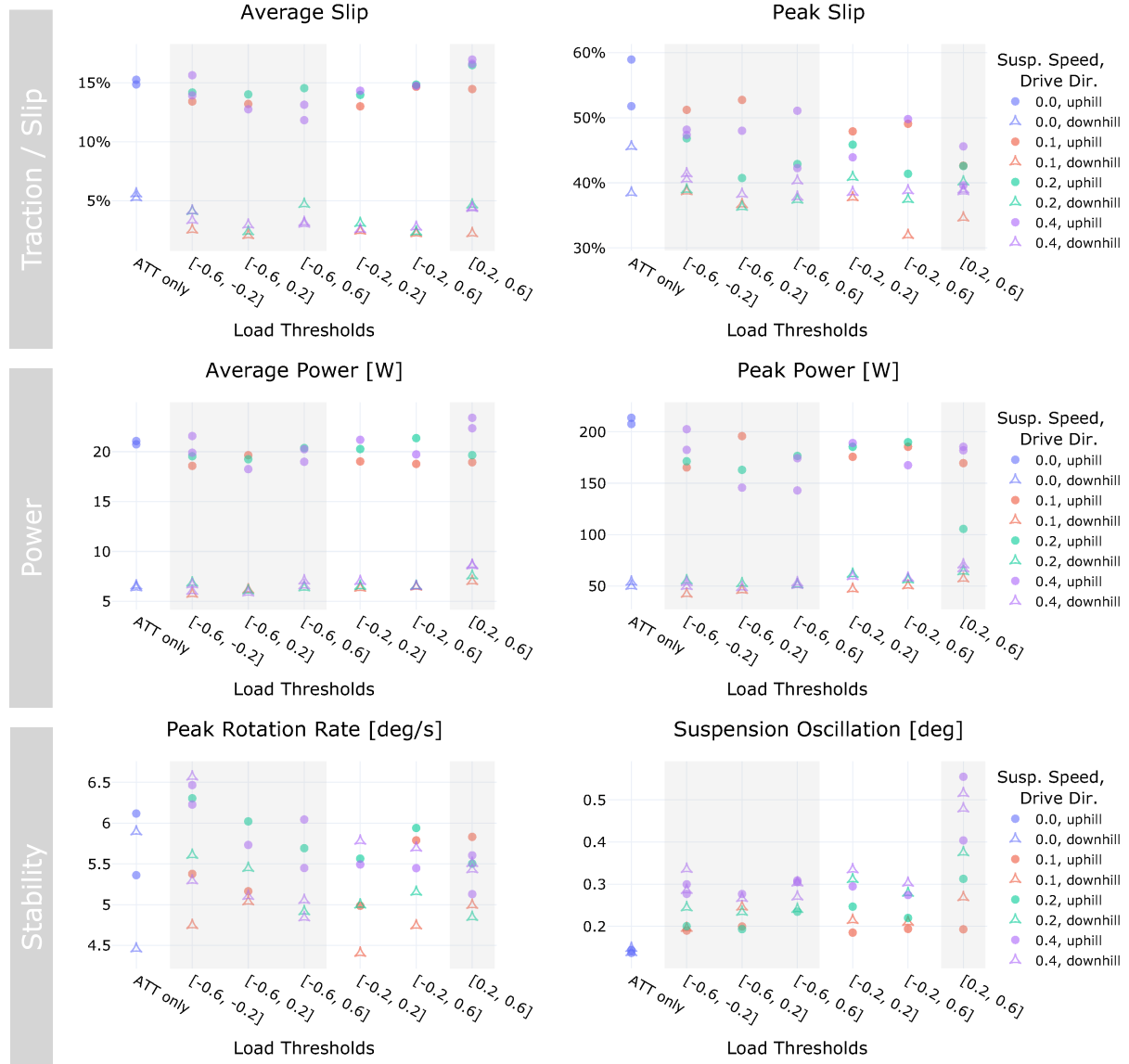


Figure 2.13: **Mobility metrics for the 10 cm rock on 15° slope traversal by the ground-pressure representative (MGRU) configuration.** Peak slip and power consumption are reduced by enabling the DFT, but the specific tuning does not make a clear impact on performance. A moderate (0.2 rad/s) suspension speed is sufficient to reduce peak slip without extraneous suspension oscillation.

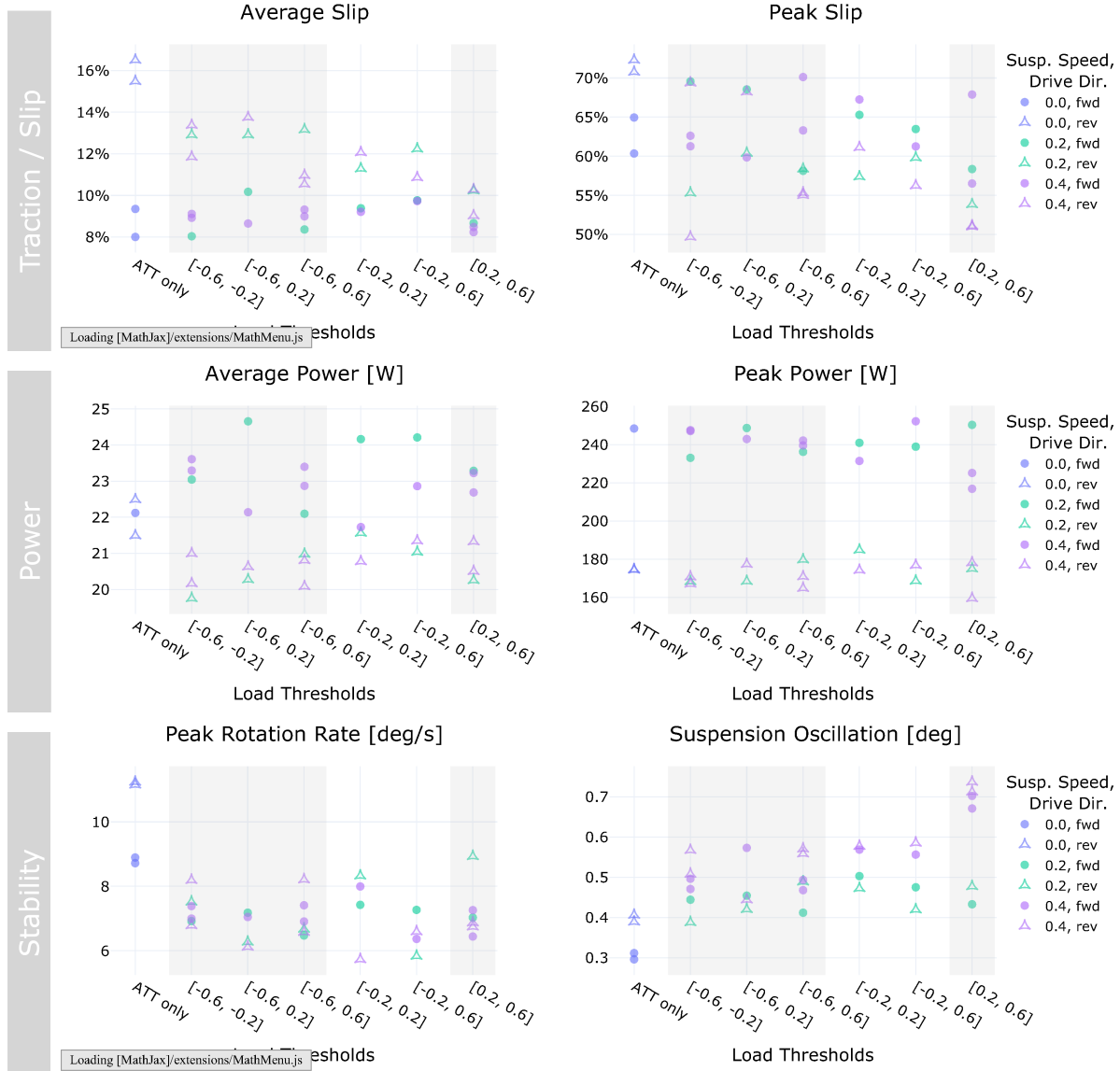


Figure 2.14: **Mobility metrics for the 20 cm rock on flat ground traversal by the ground-pressure representative (MGRU) configuration.** Differences in the rock's surface shape and texture due to the approach direction distinctly affected mobility. The clearest benefit of the DFT is the reduction of peak body rates by 20-40%.

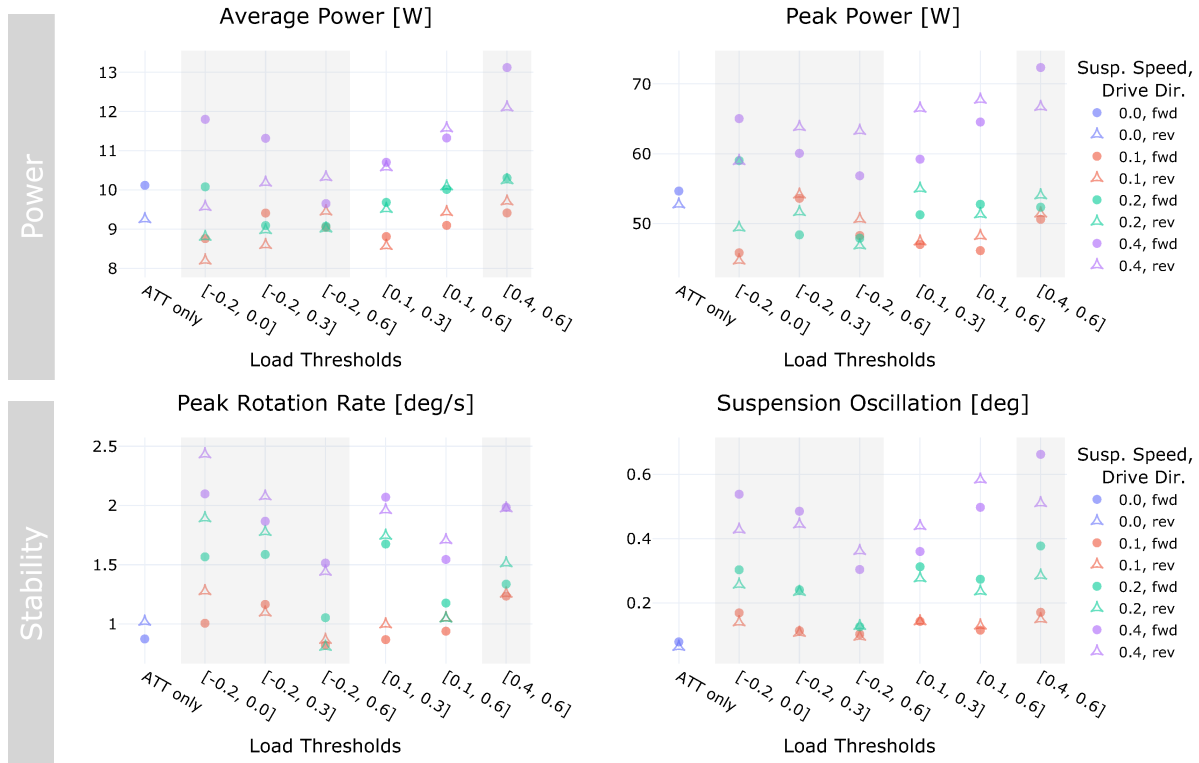


Figure 2.15: **Mobility metrics for a point turn on a 10° slope in the CG-representative (MGRU-CG) configuration.** The alternating grey and white backgrounds delineate changes in off-ground load thresholds. A low or moderate suspension speed and a low off-ground threshold leads to the least suspension oscillation.

Chapter 3

Strategic Wheel Slip Control

Traditional slip controllers try to minimize wheel slip [63] or coordinate slip between wheels [60, 27]. However, driving on soft, deformable soil requires the movement of soil, and hence wheel slip, in order to generate a forwards thrust. As visible in experiments [2] and predicted by models, including the one shown in Fig. 1.6, driving with zero slip in loose sand produces negative drawbar pull. While slip is traditionally regarded as a source of power loss which should be reduced indiscriminately, an alternative framework to consider is the effective application of slip among driving wheels.

Figure 3.1 depicts how varying levels of slip can drastically change the tractive and lift forces generated by a wheel in high sinkage media. The wheel in the figure is a simplified mesh representation of VIPER's wheel, and the small gray arrows along the rim show the force on each plate element as predicted by RFT. When a deeply embedded wheel drives

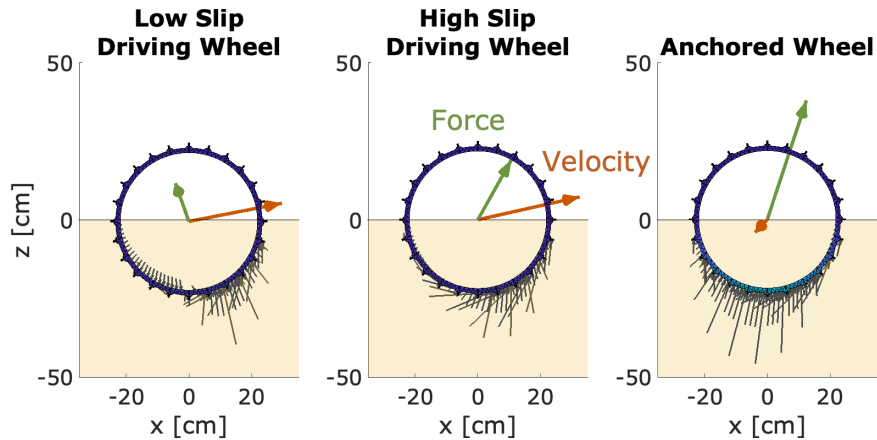


Figure 3.1: **Illustrations of the effect of slip and anchoring on tractive force.** The small grey arrows along the surface show the approximate distribution of force on the wheel, resulting in the net force indicated by the green arrow. In high sinkage, low slip (35%) results in net negative force, whereas high slip (77%) or anchoring results in useful tractive force.

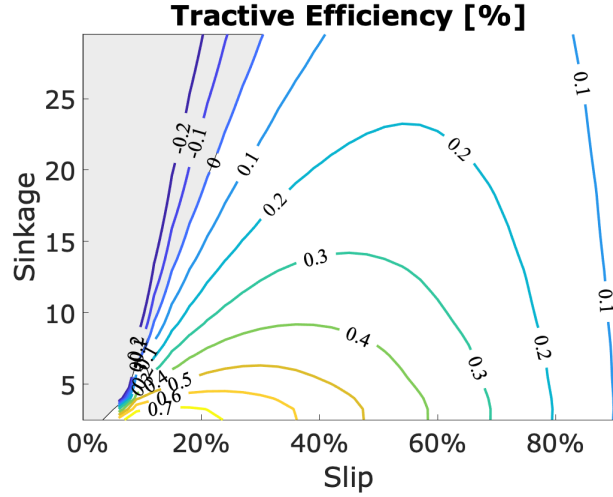


Figure 3.2: **Estimate of tractive efficiency with respect to slip and sinkage for VIPER’s wheel.** Tractive efficiency, or the drawbar pull generation normalized by input torque and slip, decreases with increasing sinkage, but may be improved by increasing slip when wheel sinkage is high in loose media.

with low slip, the resulting force shown by the green arrow is negative. A high slip is required to generate a forward force, and at high sinkage in extremely loose media, it may actually result in more efficient motion, as depicted in Fig. 3.2. Alternatively, pushing against a non-driven, anchored set of wheels also results in an efficient generation of forward tractive force, as employed during push-pull locomotion. In this chapter, the intentional adjustment of relative wheel slip is modeled and measured to understand how slip can be used as a control input.

Wheel slip is generally a consequence of driving in sand and cannot be specifically controlled as an input, but relative slip can be moderated between sets of wheels and/or the suspension. For a constrained, fixed suspension, slip can be induced by driving the front and back wheels at different speeds, forcing the faster pair to slip more. The experiments discussed in Section 3.1 found that driving the back wheels faster when resisting high longitudinal forces, simulating high slopes, could increase traverse velocity and efficiency [14]. However, the effectiveness was limited by the rover’s fixed suspension. The remainder of this chapter demonstrates that articulated suspensions can substantially improve vehicle performance by strategically inducing slip, e.g. by driving the wheels twice as fast as the suspension expands [15]. At best, an 8x improvement in travel efficiency on 20° slopes was observed, as described in Section 3.2 and strongly motivates future deployment of articulated suspensions and further research into inducing rather than avoiding slip.

3.1 Front-Back Differential Velocity Control [14]

On a flat homogeneous surface, a typical drive controller commands all wheels to identical speeds, producing equal slip on all wheels. However, the forward tractive force capacity of a wheel depends on both sinkage depth and slip. Force analysis shows that external resistance forces, i.e. a towed load or gravity on a slope, and the drive torque applied by the wheels increase the contact loads on and consequently the sinkage of the back wheels. The sinkage difference between front and back wheels is exaggerated by low-strength and sloped terrains. Driving the wheels at identical speeds may produce suboptimal tractive force in sloped, sandy environments.

In high sinkage, high slip scenarios, rover velocity can be improved by driving the back wheels faster than the front wheels. In this section, the application of mismatched slip is explored via both theoretical analysis using granular Resistive Force Theory and driving experiments.

Analytical Model

Given a wheel's geometry and motion, i.e. sinkage depth, driven angular velocity, and resultant translational velocity, granular RFT predicts the forces along the wheel-sand contact surface, which can be integrated to calculate the total forces and torques on the wheel. A wheel's slip can be calculated by its translational and angular velocities, and hence these forces, which are presented in Fig. 3.3, are solely a function of wheel slip and sinkage. These force and torque contours are generated for a cylindrical wheel with radius 1 m and width 1 m and a media with RFT scaling coefficient of 1 (previously measured sands have a coefficient in the range of 2-4) to demonstrate the non-linear trends. The values can be scaled according to the wheel dimensions and media of interest. For instance, forces should be scaled with the surface area of the wheel, i.e. quadratically with wheel radius and linearly with wheel width, and forces and torques scale linearly with the RFT coefficient.

Figure 3.3(a) illustrates the drawbar pull and closely resembles Fig. 1.6 from Section 1.3 despite the lack of grousers. It similarly shows that as wheel depth increases, more slip is necessary to generate forward traction rather than backward resistance (grey shaded region). Low slip values at high sinkage, i.e. low angular velocities relative to translational velocities, result in wheel motions that primarily bulldoze the media rather than efficiently moving the media backwards. The negative contour lines in the shaded region are close together and demonstrate that increasing sinkage quickly impedes vehicle motion. Figure 3.3(b) implies that the required drive torque asymptotes above 20% slip to a value that is dependent primarily on wheel sinkage. Figure 3.3(c) combines (a) and (b) to produce an efficiency-like metric, the level of drawbar pull output generated by a given torque input. Like Fig. 3.3(a), this indicates that wheels at deeper depths need to slip more to maintain efficient mobility. Finally, Fig. 3.3(d) shows the vertical load that a wheel can support given a slip and sinkage; for a fixed load, increasing slip will gradually increase sinkage.

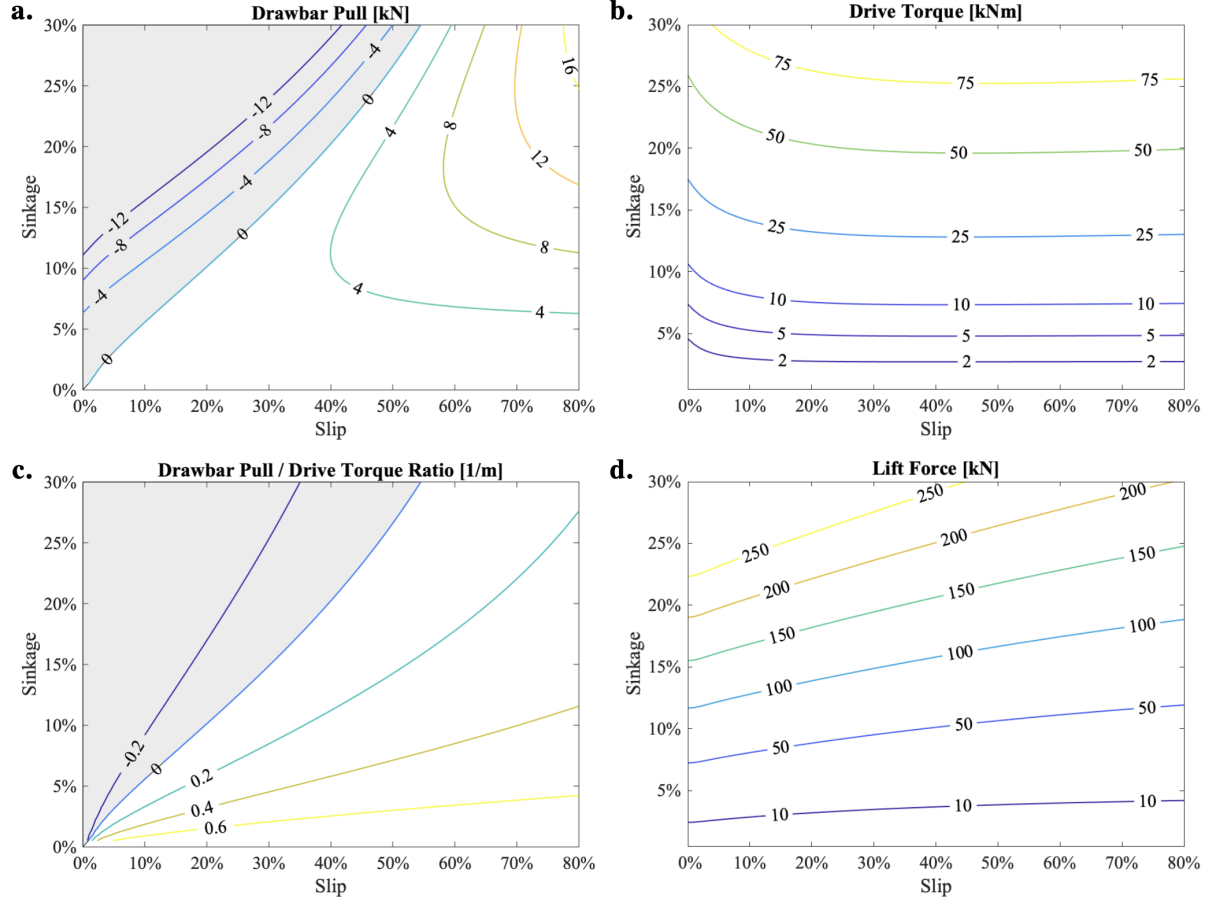


Figure 3.3: Contour plots that illustrate the forces and torques on a cylindrical wheel given a specified slip and sinkage depth, as predicted by granular RFT. These contour levels assume a wheel radius of 1 m, width of 1 m, and RFT coefficient of 1 such that the values can be scaled to relevant geometry and media. Sinkage is represented relative to the full wheel diameter.

Each rover wheel acts at a slip and sinkage coordinate on these contour plots, which informs how an individual wheel contributes to the vehicle’s overall motion. If all wheels are controlled solely to match slip, any wheels at greater sinkage depth, which are generally the rear wheels, will produce drawbar pull less efficiently. Furthermore, while general intuition predicts that increasing slip increases wheel sinkage, it also surprisingly should increase drawbar pull at a higher rate than sinkage increases and produce greater drawbar pull per unit input of drive torque, according to the model.

The free body diagram shown in Fig. 3.4 can be used to estimate the steady state driving configuration. Vehicle velocity and wheel sinkage depths are estimated by solving for the front and back wheel slip and sinkage that results in steady state behavior, i.e. constraining total forces and moments to be balanced. A horizontal resistance load is applied to the vehicle to mimic the effect of vehicle weight impeding progress up a sandy slope, as depicted by the dark blue arrow and in the inset on the left. The ratio of the resistance load to the vehicle weight, DP/W , is the drawbar coefficient, introduced in Section 1.2. Due to the moment balance constraint, both the resistance load and the drive torques required to counteract the resistance load cause the rear wheels to support a larger share of the weight of the vehicle. This suggests that in challenging scenarios with high differences in sinkage between wheels, vehicle mobility may be improved by driving the wheels at different speeds, i.e. slipping the wheels at different levels.

Figure 3.5 shows the velocity outcomes predicted by RFT given a drawbar coefficient, which is equated to an approximate analogous slope. The average commanded velocity is held constant while the front-back speed ratio $\omega_{front}/\omega_{back}$ varies. The maximum rover velocity occurs when the back wheels are driven faster than the front wheels (speed ratio < 1), and the peak velocities marked by x’s in Fig. 3.5(a) occur at lower wheel speed ratios as the resistance load increases. Fig. 3.5(b) shows that the force-moment balance predicts greater sinkage by the back wheel, which suggests that it will operate with a different locomotive efficacy as the front wheel. At low loads (red line), the wheel speed difference causes the sinkage difference of the wheels, but at high loads (yellow line), the sinkage differential exists largely independently from the wheel speed difference and is primarily influenced by the resistance load.

Experimental Setup

Differential drive velocity control is investigated at various analogous slope angles by applying a constant resistance load to the vehicle and commanding the front and back wheels to drive at a range of different velocities. Mobility is evaluated by measuring vehicle forward velocity, drive motor current, and wheel sinkage. The wheel speed ratio $\omega_{front}/\omega_{back}$ varies, while the total wheel speed $\omega_{front} + \omega_{back}$ remains constant. Each speed ratio is tested five times per resistance force level, and four force levels are used to observe the effect of varying wheel speed ratio across a range of terrain difficulty.

The test track is 1.5m long, 66cm wide, and 20cm deep and is filled with Sakrete All Natural Play Sand. Vertical plate penetration tests measure the RFT coefficient of

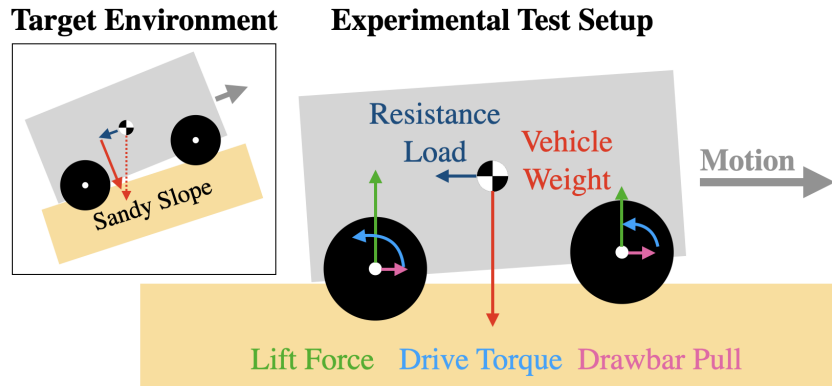


Figure 3.4: A free body diagram depicting the vehicle loads and the forces generated at the wheels by driving in sand. A resistance load aligned with the COM is applied to the vehicle driving on flat ground to imitate the effect of vehicle weight on a sandy slope.

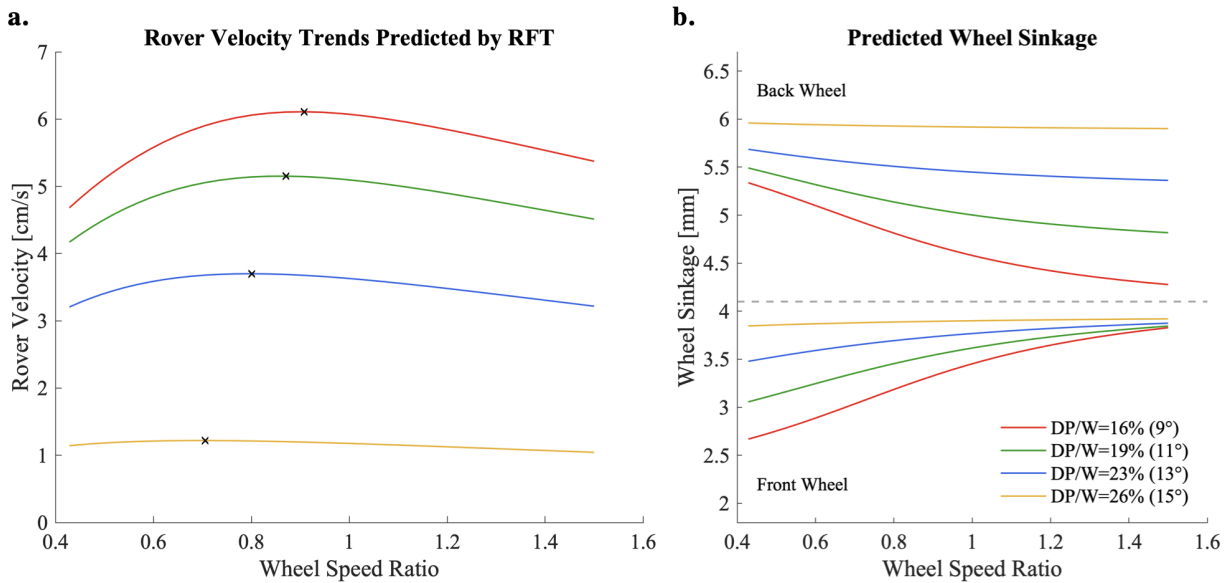


Figure 3.5: Rover velocity and wheel sinkage trends as predicted by RFT. Each line corresponds to a different drawbar coefficient DP/W , and an inverse tangent relation is used to estimate the analogous slope angle shown in parentheses. The peak rover velocity favors a back wheel speed that is slightly faster than the front wheel speed.

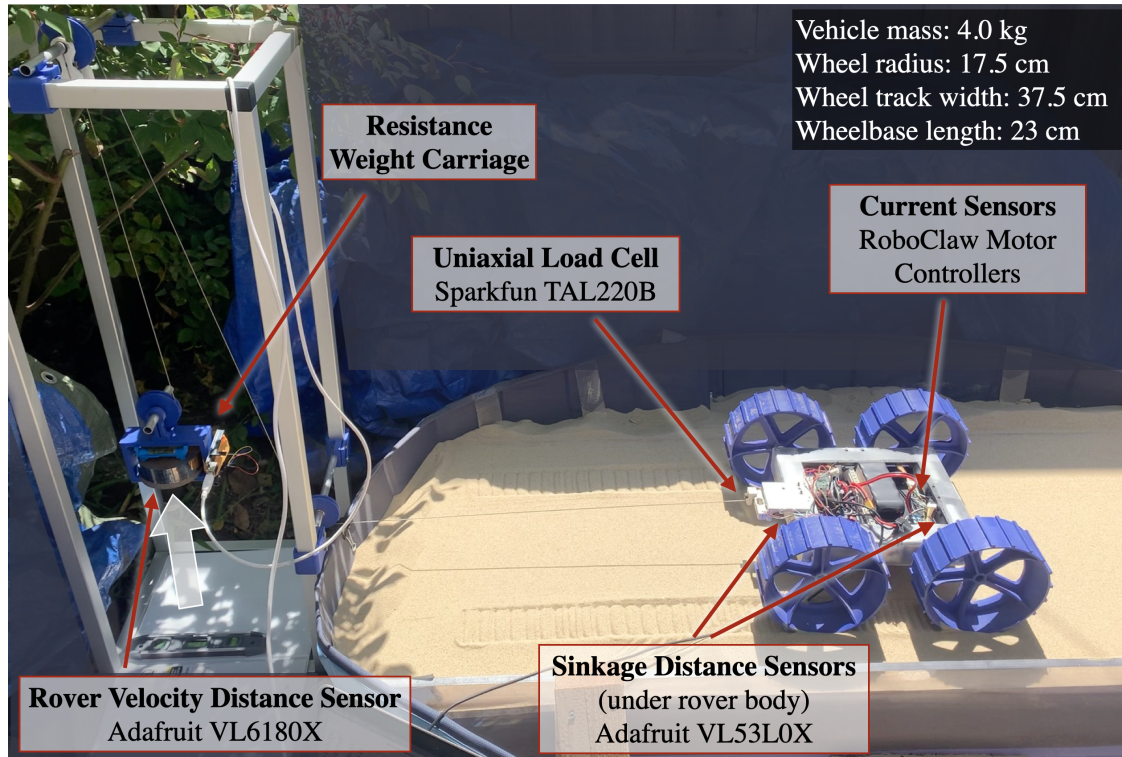


Figure 3.6: **Experimental setup.** A fixed resistance load is applied to the vehicle via a tensioned cable. The front-back wheel speed ratio varies between trials, while the vehicle velocity, wheel sinkage, and motor currents are measured.

this sand to be approximately 4. The test vehicle is a rigid platform weighing 4.0 kg with four individually driven wheels (ServoCity Prowler), which are each velocity-controlled by RoboClaw motor controllers. Each wheel is 3D printed with a diameter of 17.5 cm and width of 15.5 cm, and they are circumscribed with 20 grousers of 5 mm height and width. The rover has a wheelbase of 23 cm and a total track width of 37.5 cm.

A constant resistance force is applied to the rover via a tensioned cable, as shown in Fig. 3.6. The cable is attached to the rover at a height approximately aligned with the center of mass of the chassis. Since average wheel sinkage increases with load, the vertical position of the lowest pulley is adjusted with each resistance force value such that the cable is level when both wheels drive at the same speed.

Two distance sensors on the vehicle, aligned with the front and back wheels, estimate sinkage by measuring the distance between the chassis and the undisturbed sand surface. The RoboClaw motor controllers measure the current pulled by each drive motor such that the power consumed can be calculated. Finally, a distance sensor attached to the resistance weight carriage measures the speed of the rover, assuming an inextensible tension cable connecting the load to the vehicle.

Results & Discussion

Across all drawbar pull conditions, the maximum rover velocity occurs at front-back wheel speed ratios below or at 1, i.e. when the back wheels drive faster than the front wheels, shown in Fig. 3.7(a). The benefit of independent front and back velocity control becomes more pronounced as resistance load increases, as emphasized in Fig. 3.7(b) where the rover velocity is normalized by the velocity when all wheels are driven at the same speed (a wheel speed ratio of 1). For instance, in the highest resistance scenario of $DP/W = 43\%$, the rover velocity increases by 10% when the back wheels rotate 2.5 times faster than the front wheels (a wheel speed ratio of 0.4) compared to when they drive at equal speeds. Even at lower resistance levels, there is generally a region where driving the back wheel slightly faster than the front wheel (a ratio between 0.8 and 1) is comparable to conventional equal speed driving.

The shape of the velocity-speed ratio curves measured in the experiment match the trends generated in the RFT predictions using the same vehicle parameters and measured terrain coefficient, although there is variation in the absolute values. The modeled wheel did not include grousers, so the model predicts that the rover will fail to drive at lower loads (note the difference in DP/W levels in the legend). RFT predicts that the vehicle will experience 90% travel reduction when the resistance force reaches 26% of the vehicle's weight, but this happens experimentally at a load ratio of 43%. The load conditions in Fig. 3.5 were chosen such that the highest and lowest loads produce peak velocities that are comparable to the data, and the intermediate loads are equally spaced between them, similar to the experiment.

Figure 3.8 shows that wheel sinkage and drive motor current increase with resistance load. The motors' baseline current draw, which is measured by driving the wheels in the air, is subtracted from the raw measurements to produce Fig. 3.8(a). In the sand, the back wheels pull significantly more current than the front wheels, which indicates that they require more torque and are more heavily loaded. As the back wheels drive faster or slip more, the current draw from the back motors increases and from the front motors decreases. Consequently, when generating higher total drawbar pull, the maximum rover velocity is achieved by increasing load on the back drive motors, rather than by distributing load more evenly. This result is in line with previous torque control work, which claims that more torque should be applied by wheels which experience higher normal load since the terrain underneath can support more tractive force [32]. As the back wheel slip increases, the back wheels experience more sinkage and the front wheels rise; the RFT model correspondingly predicts that high slip reduces the lift force generated by a spinning wheel. Note that the wheel sinkage sensors measure the displacement of the front and back of the chassis relative to a flat rigid surface, but they do not indicate the sinkage of the back wheel relative to the sand pile that is created behind the front wheel.

Using the motor current and rover velocity data, a power efficiency comparison is shown in Fig. 3.9. The total power required by these motors is relatively insensitive to the wheel speed ratio, which results in improved energy efficiency when the vehicle achieves greater velocity. This preliminary analysis suggests that the goal of increasing rover velocity is

symbiotic with improving power efficiency, which is a critical mobility metric of planetary exploration rovers.

Some of the deviation between the measured and predicted velocity and sinkage is likely caused by assumptions of the model, which does not fully capture real-world granular interactions such as surface mounding, soil compaction, and particle size distribution. Single-wheel tests with controlled slip produce forces close to those predicted by RFT, but the initial surface is always pristine [2]. In full-vehicle experiments, lowering front wheel slip reduced the mound size left behind the wheels, thereby reducing the size of the obstacle that the back wheels must climb. This may amplify the benefit of low wheel speed ratios in loose media. However, in media that experiences more compaction, the front wheels may create a rut that is more efficient for the trailing wheels to traverse. If better absolute predictive performance is necessary, multi-pass effects should be included to capture the disturbances created by wheel ruts and mounds. Additionally, RFT assumes that the forces on a surface element of the body increase linearly with intrusion depth. With the sand used in the experiment, the force coefficient increases moderately with depth, which may explain why the rover's wheels sank further into the sand in order to generate the necessary drawbar pull. While the assumptions of granular RFT limit its absolute accuracy, RFT effectively predicts the observed trends, and its force model provides a feasible explanation for the observed benefits of front-back differential velocity control.

Modifications to RFT have also been developed to improve the accuracy of the model, and they can be included if a higher level of fidelity is desired. The wheel modeled in this

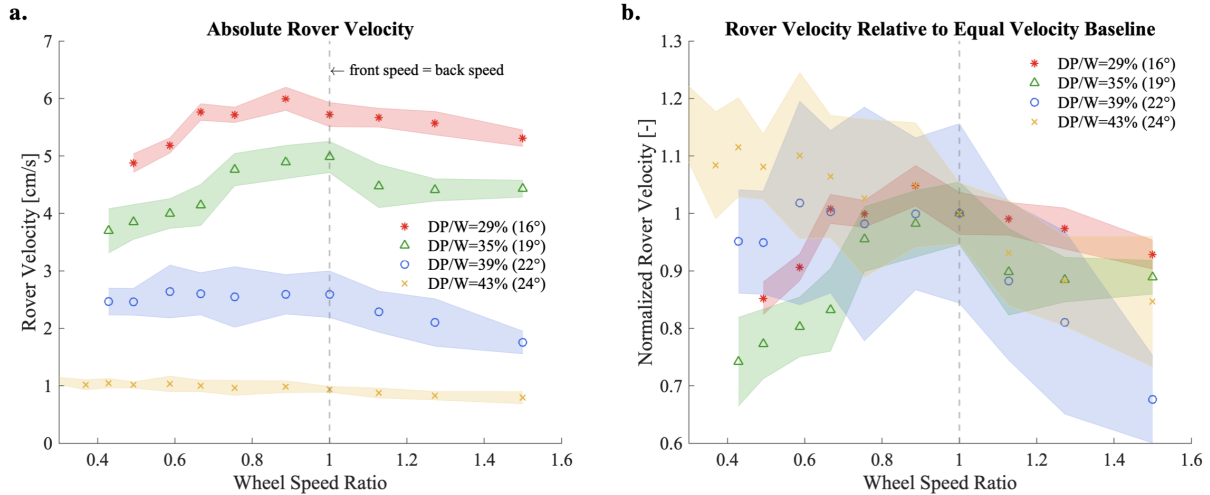


Figure 3.7: **Measured rover velocity as a function of front-back wheel speed ratio.** When the speed ratio is less than 1, the back wheels drive faster than the front wheels. In scenarios with high drawbar pull coefficient DP/W , the maximum rover velocity occurs at lower wheel speed ratios.

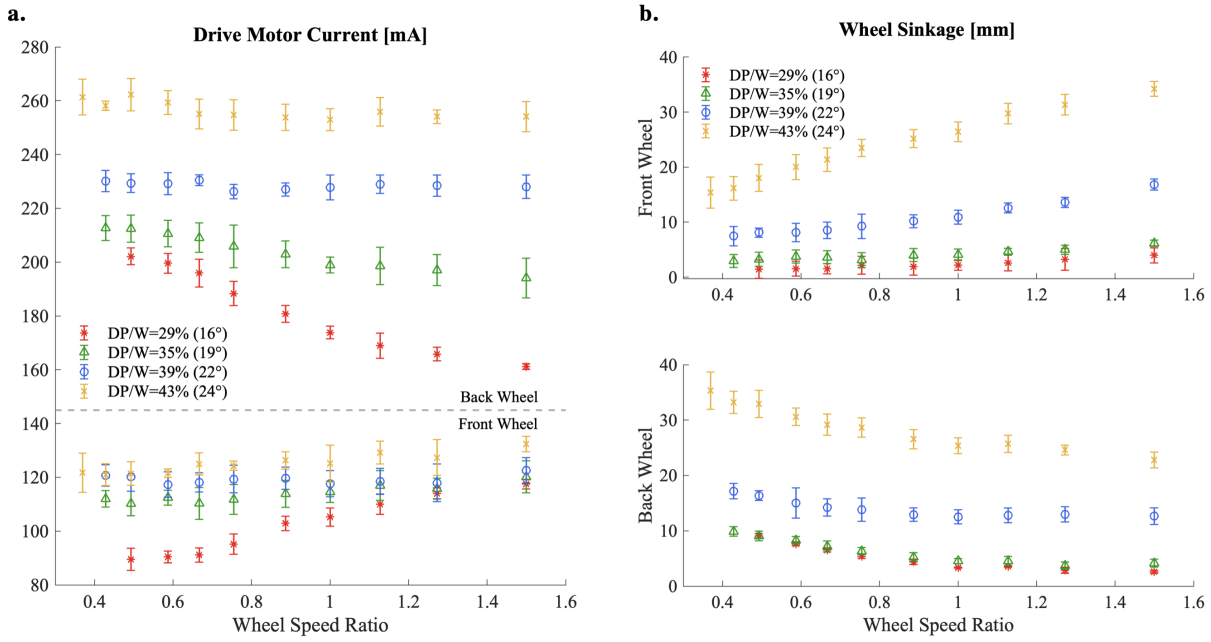


Figure 3.8: Measured motor currents and wheel sinkage.

section was cylindrical, but future work could use the proposed leading edge hypothesis to include the effect of grousers [2]. Dynamic RFT can account for the momentum transferred by the wheels to the sand, which generally results in additional wheel sinkage and slip when the wheels drive faster than about $0.5\sqrt{g/D}$, where g is gravitational acceleration and D is the diameter of the wheel [3]. Finally, the simplest version of RFT uses a first-order 2D Fourier function to approximate the force coefficients for each plate orientation and velocity angle [36]. However, a lookup table that linearly interpolates between data points provides better approximation of forces, especially when data is gathered for the media in use [31]. Each of these modifications results in estimated forces that better reflect measurements but require additional complexity and characterization.

Conclusions

There is potential to improve the mobility of 4-wheeled planetary rovers by driving the back wheels faster than the front wheels, particularly on soft sands or where high drawbar pull is required. Granular RFT suggests that increased sinkage in rear wheels causes them to exert different forces than the front wheels, and this implies that velocity matching among all wheels is not always optimal. On flat, low-slip surfaces with little sinkage, the existing standard of driving all wheels at the same speed remains preferred as it prevents kinematic inconsistency between wheels and distributes the tractive load between wheels. However, in loose terrain where the front and back wheels experience high sinkage, varying velocities of

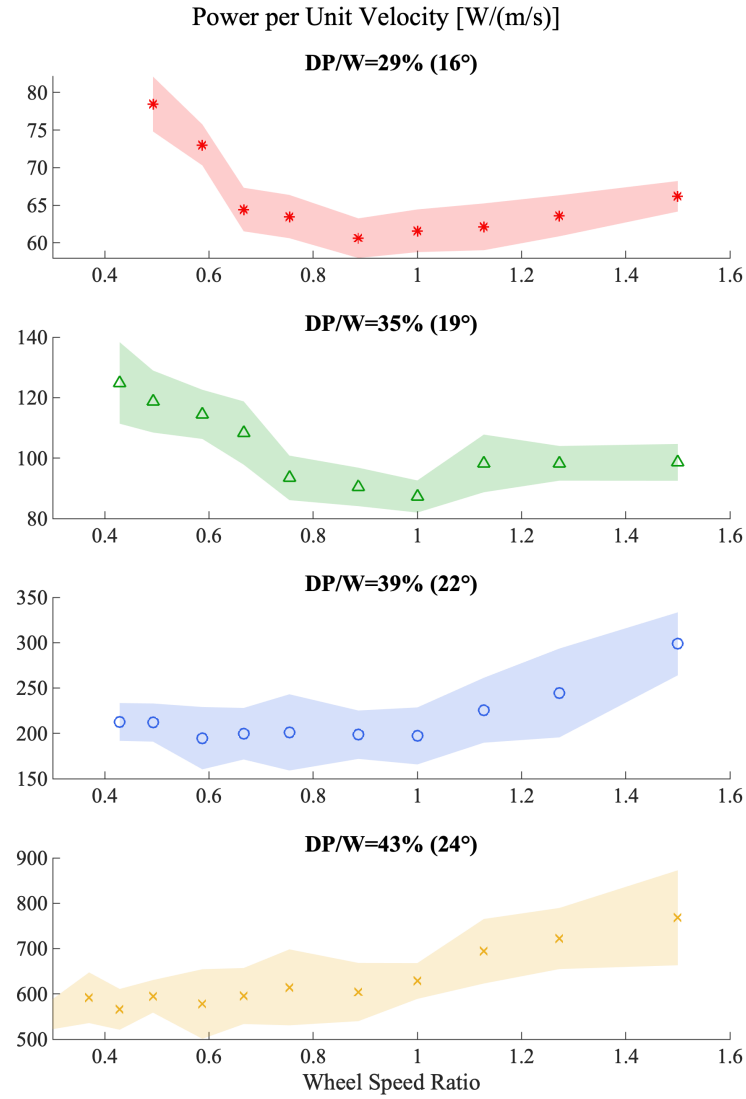


Figure 3.9: **Normalized power consumption in each resistance scenario.** Power consumption did not change significantly across wheel speed ratios, which results in improved efficiency when the rover is able to drive faster.

wheels with respect to their loads and sinkages can assist the rover achieve more efficient traversal, both with respect to travel time and power efficiency.

This type of control can be implemented on a variety of rover platforms without any hardware modification. It can be executed on existing rovers and without much change to conventional design and control practices, so it is valuable to explore further in more realistic scenarios. Future work should refine this finding by testing rovers of mission-representative size and ground pressure distribution and performing the experiment on a slope-controlled bed, where the sand may exhibit different mobilization behavior. Steepest traversable slope angle and power efficiency can then be analyzed more rigorously in order to inform future planetary rover control.

However, the kinematics of a fixed suspension limit the extent to which inducing slip can improve mobility. Articulated suspensions, which have translational control of suspension joints, enable engineers to more directly control wheel slip to increase drawbar pull. The following sections explore this in more depth as these more advanced suspension configurations achieve significant efficiency improvements for climbing loose slopes.

3.2 Push-Pull Locomotion: Inchworming [15]

Push-pull locomotion has been studied extensively, notably using the rovers Scarab [19] and ExoMars [6, 38]. These rovers can alternately drive half of their wheels while fixing the others in place to create a platform to push off of. For one wheel driving in high sinkage Fillite, Moreland measured a drawbar coefficient of 0.32 when the wheel was anchored, or locked and pushed on, in comparison to -0.10 when driven at 20% slip [40]. Shear Interface Imaging Analysis showed that the displacement of grains behind a non-driving wheel is consistently horizontal, whereas driving wheels excavate grains with their rotational motion [55].

Scarab has four wheels; its front wheels are paired against its back wheels, creating a specific push-pull gait called inchworming, which is shown in Fig. 3.10. In the suspension expansion phase, the front wheels drive while the back wheels provide a stationary platform to push against. In the contraction phase, the back wheels drive while the front wheels provide a platform to pull towards.

[47] evaluated the power efficiency of a push-pull gait compared to normal driving for the ExoMars rover and delineated ranges of terrain properties and slope angles for which it would be preferable to operate in each mode. As the media gets looser and the slope gets steeper, push-pull locomotion enables mobility, whereas on flat or benign terrains, push-pull locomotion draws excessive power.

Other notable extrication gaits include the swimming gait of RP-15 [54] and the squirming gait of MARCEL [9]. The squirming gait consists of oscillatory yaw control between the front and back halves of the rover, and one wheel is typically held stationary as the others drive synchronously with the side-to-side steering.

Bouton et al. built two rovers with a consistent weight and wheel design to explicitly compare many modes of push-pull locomotion, including squirming, inchworming, wheel-walking,

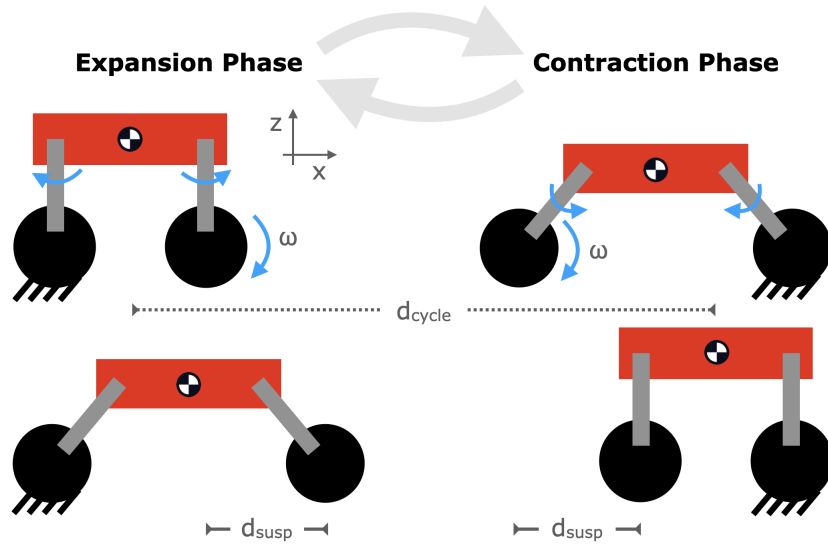


Figure 3.10: **Push-pull locomotion, or inch-worming, gait.** During each phase, one set of wheels remains stationary to act as a platform while the remaining wheels drive at speed ω and the suspension expands linearly by distance d_{susp} . The rover overall moves by d_{cycle} each cycle.

with passive and fixed suspensions [10]. They found that while inchworming and squirming reduce vehicle slip on 20°-30° slopes compared to a passive suspension, only squirming was able to do so at an energy consumption per distance comparable to a passive suspension. However, all wheel speeds in the experiment were driven at angular velocities that are synchronous with each suspension gait, producing theoretical no-slip translation.

Push-pull locomotion depends on using non-driving wheels as platforms or anchors to generate thrust from. Low magnitudes of wheel slip in conjunction with high wheel sinkage may result in negative drawbar pull generation and increase the backwards load on the anchored wheels. In practice, without purposefully driven wheel slip, we observe the anchored wheels skid when the forces on them exceed the load capacity of the soil. This results in oscillatory overall motion that is not as efficient as it can be. Increasing drawbar pull by inducing extra driving wheel slip can alleviate the load on the anchor and reduce travel inefficiency.

In this work, we evaluate the critical role of driving wheel slip in generating thrust while climbing sandy slopes and traversing high sinkage, loose granular media. In this section, we test a shoebox-sized rover climbing a sandy slope up to 20° using a wide range of wheel slips. In Section 3.3, we present data from four extrication trials by the VIPER lunar rover in an extreme high-sinkage simulant. In Section 3.4, we use RFT to estimate the forces on the wheels and predict whether or not the anchored wheels can sustain the load on them in order to resist skidding.

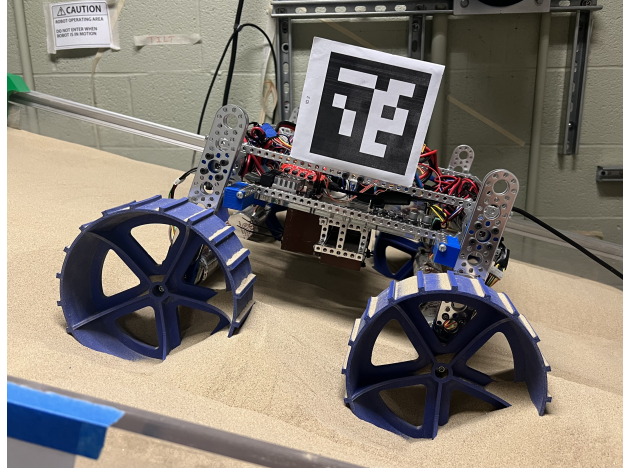


Figure 3.11: Shifty in its minimum wheelbase configuration driving up a 15° slope.

Sloped Driving Experiments

Shifty, pictured in Fig. 3.11, is a four wheel rover weighing 9.7 kg with the kinematics shown in Figure 3.10. It has a 27.2 cm minimum wheelbase, 13.1 cm suspension legs, and 17.5 cm wheels. Based on the scaling laws presented in [56], the rover’s performance is scalable to a 360 kg rover with 50 cm wheels on the moon, which would be similar to that of VIPER.

To quantify the relationship between rotational and translational inputs, we define a quantity called kinematic slip, which is equivalent to the wheel slip of the driving wheel (defined traditionally in Equation 1.2) assuming the anchored wheel stays fixed in place. Kinematic slip is thus defined as the deviation between the suspension translation and the no-slip driven distance of the wheels:

$$ks = 1 - \frac{d_{susp}}{\omega r t_{cycle}/2} \quad (3.1)$$

where d_{susp} is the linear travel of the suspension as defined in Fig. 3.10 and $t_{cycle}/2$ is the time length of one gait phase. This results in an average measure of slip over the gait, rather than an instantaneous slip, which changes depending on Shifty’s leg angle. The kinematic slip is equal to the ground-relative slip of the driving wheel only when the anchored wheel does not skid.

Experiments with Shifty comprise inchworming gaits with varying kinematic slip on a range of slopes up to 20°. These are compared to normal driving to characterize the efficiency of inchworming while climbing sandy slopes.

Experimental Setup

The tiltable sandbox is filled with Mars 90, which [44] found to best match the known mechanical properties of Martian wind-drift soil out of readily available lunar and Martian

simulants. The looseness of wind-drift soil has posed significant slippage and entrapment challenges for Mars rovers, and Mars 90 is the baseline simulant used for mobility assessments of the Curiosity and Perseverance rovers.

We test a range of kinematic slips from 0% to 85% and slopes of 0°, 10°, 15°, and 20°. Five kinematic slips plus one normal driving condition are tested for each slope with a wheel velocity equivalent to the 40% kinematic slip drive velocity. Three trials are performed for every test condition. The sand is stirred and then leveled between trials to reset any compaction that may have occurred, before being tilted to the test angle.

Fiducial markers attached to the tilt table and the rover are used to track the rover's motion. The motion of the wheels is calculated using a combination of the rover tracking data and onboard joint encoders. Current sensors on the input side of each motor controller measure the current consumed by each pair of legs and wheels separately.

Two datasets are taken, where the second dataset (dashed lines with triangle markers in Figures 3.12-3.13) confirms the results of the first (solid lines with circle markers). In the second dataset, electrical current was measured over a larger range of amperage and true voltage measurements were used instead of a nominal estimate to support the initial results with higher fidelity. The wheel velocity controllers were also adjusted for the second trials to track the target velocity better, and the plotted kinematic slips are all calculated using the measured joint velocities.

Results & Discussion

Tests of normal driving typically use wheel slip to evaluate mobility performance, where the velocities of all wheels are the same, resulting in the same value for wheel slip and overall vehicle travel reduction. Travel reduction TR for inchworming similarly quantifies the deviation of the vehicle's trajectory from its ideal trajectory where the anchored wheels are fully stationary and the chassis moves by the suspension expansion distance d_{susp} each cycle. Numerically,

$$TR = 1 - \frac{d_{cycle}}{d_{susp}} \quad (3.2)$$

where d_{cycle} is the actual travel distance of the rover's center of mass over one complete expansion-contraction cycle. These quantities are illustrated in Fig. 3.10. If the anchored wheel exceeds its load capacity and is pushed backwards, d_{cycle} will be less than d_{susp} and result in a positive travel reduction.

Figure 3.12 shows both travel velocity and travel reduction as a function of the achieved kinematic slip. The tested slopes are distinguished by color and the two datasets are distinguished by markers and line dashes. The separate datasets show good agreement and the shaded region represents one standard deviation of error, both indicating that the results are replicable. The horizontal lines show the average travel reduction during normal driving trials, when all four wheels are driven at the same velocity without inchworming. The travel reduction of a normal driving trial is equivalent to slip as defined in Eq. 1.2.

Travel velocity increases as wheel slip increases but generally plateaus around 60% kinematic slip. Moreover, travel reduction on slopes is not improved beyond the baseline all-wheel-drive until 20-30% kinematic slip is introduced. Past this point, substantial gains can still be achieved, with 60-80% kinematic slip resulting in about half of the travel reduction of normal driving on 10° and 15° slopes. On the 20° slope, travel reduction is reduced from 98% to 85% using 70% kinematic slip.

Travel reduction captures the state of the rover, quantifying its efficiency and chance of entrapment, but the values plotted are defined differently for normal driving and inchworming and so are not an exact comparison. The most direct comparison is the power number, which is unitless and can be compared between vehicles. In this rover, power is measured by the electrical power consumed at the bus.

As shown in Fig. 3.13, the power number is improved by high kinematic slip when driving on slopes, reaching better levels than normal driving once between 30 - 40% kinematic slip is applied. On 10° slopes, the power number is reduced by a factor of up to 3. On 20° slopes, the power number is reduced by a factor of up to 8. As kinematic slip increases, more power is drawn by the driving wheels while less is drawn by the leg motors, which do not have to apply as much force to move the sand.

These results also reconfirm previous findings that inchworming in benign terrains results in excessive and unnecessary energy consumption. Travel reduction while inchworming on flat sand (0°) is generally higher than the baseline driving slip of 0%. It only falls below 0% due to the mathematical definition of travel reduction, when the driving wheels generate so much tractive force that they drag the undriven wheels forwards, achieving higher velocity than solely from suspension actuation. Neither of these situations is efficient for locomotion

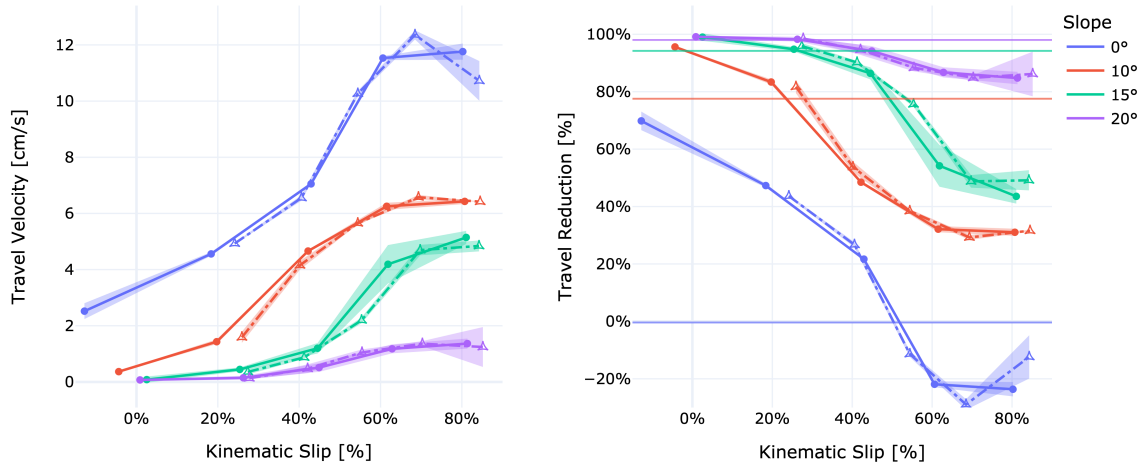


Figure 3.12: **Travel velocity and travel reduction.** Travel velocity increases with increasing kinematic slip. Inchworming becomes more effective than normal driving (horizontal lines) on slopes after about 20-30% kinematic slip.

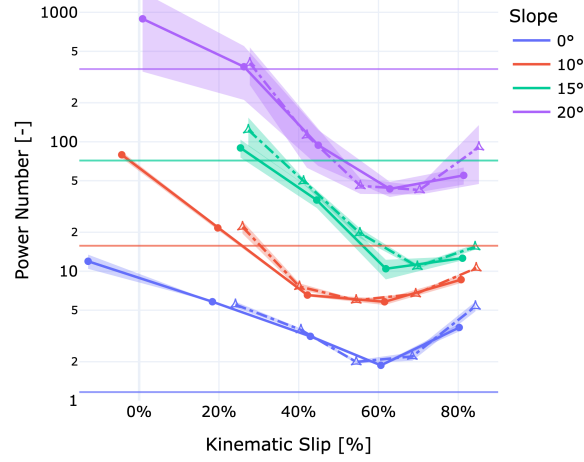


Figure 3.13: **Power number, or normalized energy consumption.** Inchworming becomes more power efficient than normal driving on slopes after about 30-40% kinematic slip.

and normal driving should be employed. The nature of the cyclical inchworming gait also means that the maximum achievable travel velocity is half the velocity achievable by driving all four wheels simultaneously on flat ground. Finally, inchworming on the flat ground draws at best 50% more energy than normal driving.

These relationships between kinematic slip and mobility are further explored via the VIPER rover’s mass-scaled mobility test unit in the following section.

3.3 Push-Pull Locomotion: VIPER Crab-Worming

VIPER’s suspension joints are actuated about its roll axis, which changes VIPER’s track width when the wheels are steered in the rover’s forward direction. This motion is perpendicular to the driving direction. Push-pull locomotion requires translation in the driving direction, so the wheels are steered as far as possible (45°) towards the suspension expansion direction to create a gait referred to as crab-worming. During each cycle, the suspension travels about 6 cm, but only 4.3 cm aligns with the wheel $+x$ direction. The resulting motion is depicted in Fig. 3.14. Kinematic slip as defined in Eq. 3.1 is modified to only consider wheel-aligned suspension motion.

Experimental Setup

The experimental rover is a mass-scaled mobility testbed of VIPER. In comparison to Shifty, which reaches 77% travel reduction on 10° slopes and 98% on 20° slopes in Mars 90, VIPER

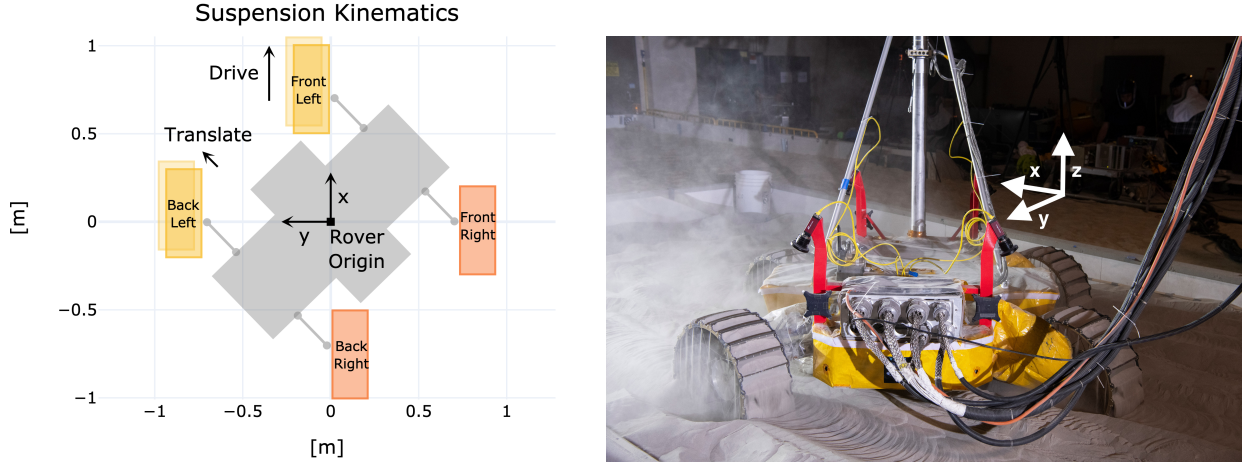


Figure 3.14: **VIPER crab-worming kinematics.** VIPER steers its wheels to 45° to maximize suspension travel alignment with the drive direction during its crab-worming gait. The left wheels (yellow) drive during the expansion gait while the right wheels (orange) drive during the contraction gait. The image on the right shows the Fillite sink tank at GRC.

achieves approximately 15% travel reduction on 10° slopes and 75% on 20° slopes in GRC-1 when performing normal driving.

To recreate extreme sinkage events at NASA Glenn Research Center (GRC), the Simulated Lunar Operations (SLOPE) Laboratory has a tank filled with Fillite [33], a material composed of hollow ceramic microspheres. The media is lightweight with low shear strength [22] and quickly fills itself back in, so trials are run without preparing the media's surface. All four wheels are first driven at the same velocity until the chassis is embedded in the Fillite and no longer makes forward progress. Then the crab-worming gait is initiated in the opposite direction as the vehicle extricates itself, as shown in Fig. 3.15.

This process is repeated four times, with two trials of the baseline drive velocity of 0.3 rad/s and one trial each of drive velocities 0.5 rad/s and 0.7 rad/s. The suspension actuation speed is held constant across all cases. In the baseline case, the wheel drives slightly farther (7.5 cm) than the suspension expands each cycle (6 cm), but only about 70% of the suspension's travel is aligned with the wheel's x direction, resulting in about 35% kinematic slip.

SLOPE lab has 16 OptiTrack Prime^x 41 cameras mounted around the ceiling, and four Optitrack pucks on the chassis capture the motion of the rover [51]. Onboard encoders for each joint track their positions and velocities so that each individual wheel's motion can be estimated.

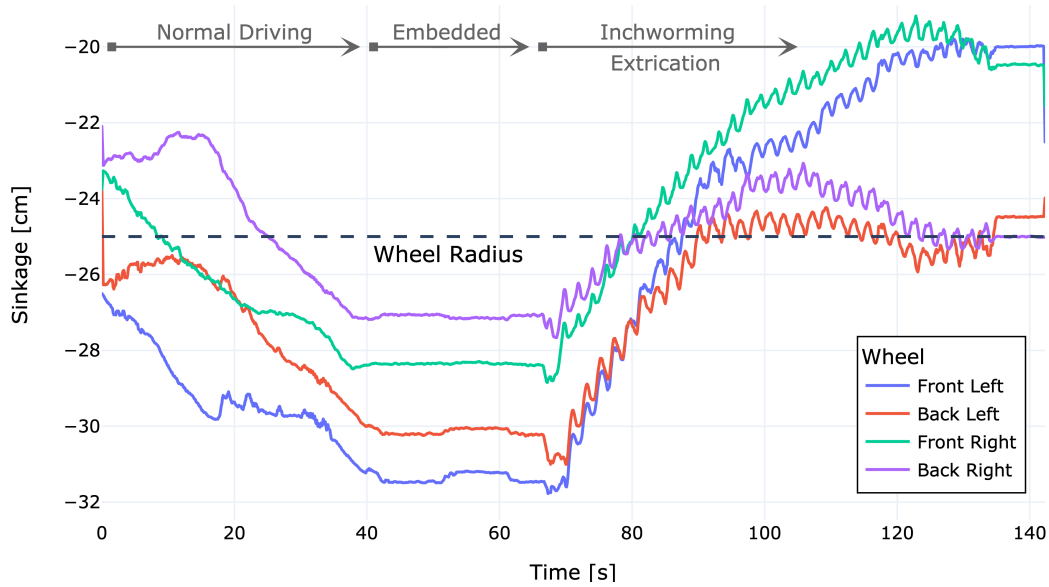


Figure 3.15: **Embedding and extrication during a single trial.** All four of VIPER's wheels are driven until they sink past their axles and the chassis is fully embedded in the Fillite. Engaging the crab-worming gait enables the rover to extricate itself from entrapment and significantly reduce wheel sinkage during travel.

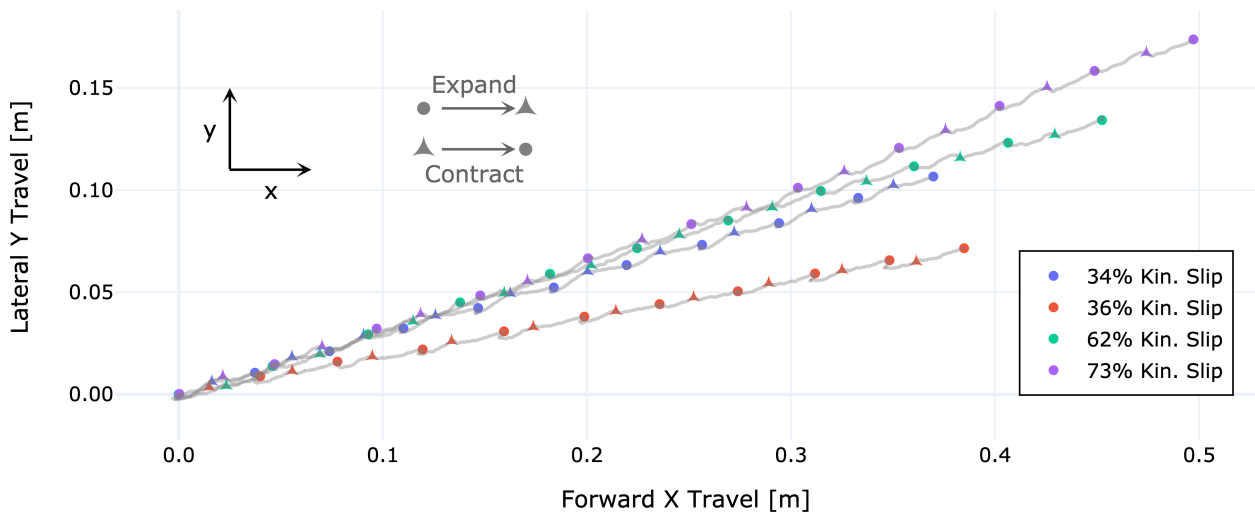


Figure 3.16: **Translation of the rover's origin over 10 crab-worming cycles.** The beginning of each expansion cycle is marked with a circle, while the start of each contraction cycle is marked with a triangle. VIPER's wheels are oriented in the $+x$ direction.

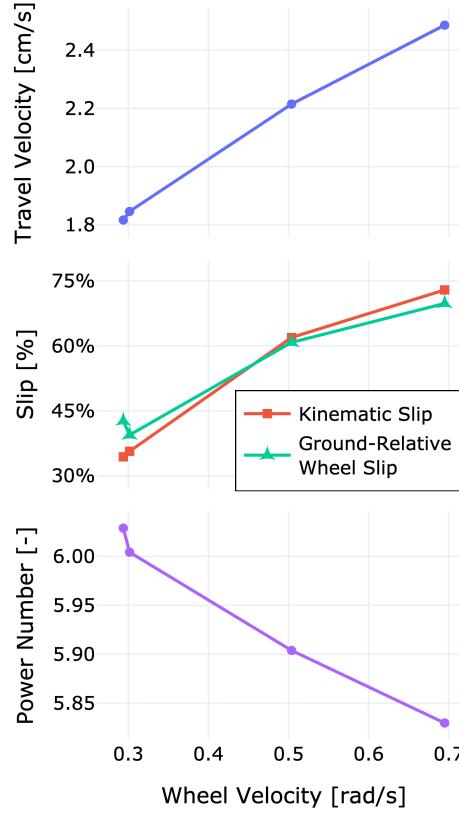


Figure 3.17: **Crab-worming mobility metrics.** By increasing kinematic slip, rover velocity is increased by 35% while slightly improving travel efficiency.

Mobility Performance

Fig. 3.16 shows a top view of the progress achieved in the last 10 cycles of each test. The start of each expansion cycle is marked with a circle, while the start of each contraction cycle is marked with a triangle. The data are aligned with the forwards direction of the wheels ($+x$ in Fig. 3.14). The low slip cases result in the least travel, and the highest kinematic slip results in the fastest travel. Particularly visible in the red markers (36% kinematic slip), the rover's center of mass moves backwards during portions of the gait.

The outcome is summarized in Fig. 3.17. The high slip case (77% kinematic slip, 2.49 cm/s) results in 36% higher travel velocity than the baseline (35% kinematic slip, 1.83 cm/s). The drive velocity and kinematic slip are calculated from the actual joint values measured onboard, which is why the two 0.3 rad/s drive commands result in slightly different slips.

The mechanical energy required to move each meter decreases with higher kinematic slip but relative change is small (within 4% across all trials). While the high slip gait does not substantially improve energy efficiency as it did for Shifty, the results imply that efficiency

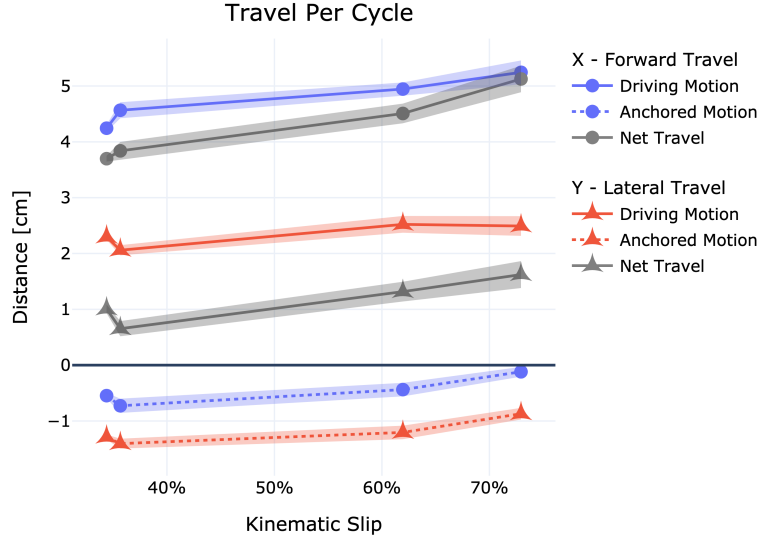


Figure 3.18: **Average longitudinal and lateral travel by each pair of wheels during each phase of the gait.** The shaded error bars indicate one standard deviation of the travel over the last 10 cycles. Net travel is highest when the negative travel or anchor skid is minimized.

is not sacrificed. Crab-worming (or any form of non-rolling locomotion) is a contingency gait for VIPER, which would only be triggered if the rover becomes entrapped. In such scenarios, there may be cases where travel velocity is critical to reach a location with access to solar power or communications. While instantaneous power draw would be higher for a high kinematic slip gait, the rover would not sacrifice overall energy consumption to reach its goal. The ability of crab-worming to extricate the vehicle reduces the risk of mission-ending entrapment, and the travel efficiency data give the mission operations team more mission planning flexibility and robustness should this situation be encountered.

Analysis of individual wheel travel per cycle in Fig. 3.18 show that the increase in net velocity results from both increased forwards travel of the driving wheels and decreased backwards skid of the anchored wheels. It is therefore interesting to understand when the anchored wheels are likely to skid because this hinders efficient travel. In the next section, we use RFT to explain and predict this effect.

3.4 Load Capacity Modeling of Anchored Wheels

In the past, hand-tuning was done to find control inputs that work, but recent models enable more methodical predictions and control. RFT-generated limit surfaces can predict the load bearing capacity of an object in sand [31]. RFT therefore holds potential for predicting the efficacy of non-driving or anchored wheels. It can be thus used to understand the level of

drive slip necessary to reduce anchor displacement.

Granular Resistive Force Theory can model the forces on a 3D wheel moving along a 3D trajectory¹. We use RFT to estimate the forces on the wheels given their experimentally measured motions. Given a wheel's sinkage, we can also generate a load bearing capacity curve, or limit surface, and estimate where the rover is operating relative to this limit. In an efficient gait, the driving wheels should generate just enough traction not to skid the anchored wheels while also not dragging the anchored wheels behind them. We use the limit surface to characterize this range.

Estimated VIPER Forces

Throughout this analysis, we estimate the RFT scaling coefficient of Fillite by picking a value to create agreement between the model's lift force and wheel torque outputs with the known weight of the vehicle and its drive torques as estimated from the motor current data.

Fig. 3.19 shows a sample of the calculated forces for one of VIPER's wheels in a (a) low slip (36%) case and (b) high slip (73%) case. Subfigure (i) shows the forces on the wheel during its driving phase, while (ii) shows the forces on the wheel during its anchored phase. The periodic black arrows with larger magnitudes show the forces on the grousers, which can provide substantially more thrust than the cylindrical wheel surface. The orange arrows show the velocity of the wheel, while the green arrows show the resultant force. In the low slip case (a)-(i), the sand in front of the wheel creates more resistance than traction, and the sand inside the wheel reduces lift. In the high slip case (b)-(i), the sand is more effectively displaced around the rim of the wheel and generates more net forward thrust. Subfigures (ii) in (a) and (b) show the forces on the wheel during its anchored phase. In both cases, the anchored wheel is similarly effective at generating thrust and lift.

Subfigure (iii) shows the velocity of the wheel, which is determined by a combination of the Optitrack-measured chassis velocity and the encoder-measured kinematics of each wheel module. RFT uses these measured velocities to produce the estimated forces shown in (iv). The forces during the anchor phase are filtered by a moving average, since the low magnitude of the input velocity and its small variations cause large swings in output force due to the lack of velocity-dependence in the model. Each of the shaded errors bars in (iii) and (iv) are produced by the standard deviation over 10 cycles. The velocities and forces are consistent once the rover reaches steady state. Notably, the forward F_x force generated by the low slip wheel (a) during the driving phase (average of 21 N) is lower than the F_x in its anchor phase (average of 198 N) and much lower than the high slip driving F_x (average of 155 N) in (b).

Figure 3.20 shows the resultant force profiles over all of the wheels, both over time each cycle (lines and shaded region) and on average over all time (markers with error bars). The left side subfigures, (a) and (c), show force generated by the driving wheels only, whereas the right side subfigures, (b) and (d), show the force generated by all wheels. The anchor forces

¹Code for 3D RFT can be found here: https://github.com/embody-dexterity-group/granular_rft_3D

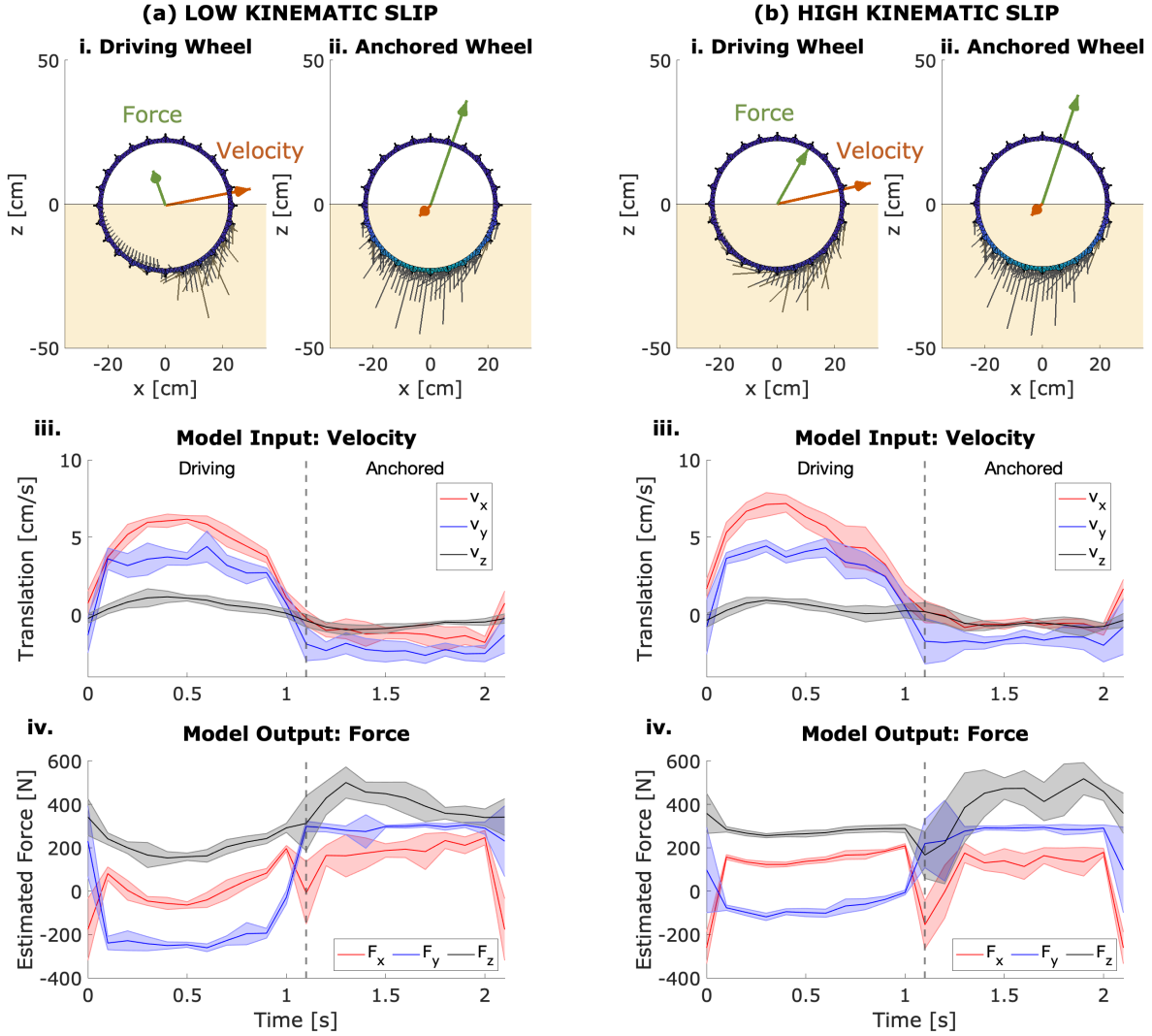


Figure 3.19: The forces generated by one of VIPER's wheels when driven with the (a) lowest kinematic slip and (b) highest kinematic slip inputs, as predicted by RFT. The forward F_x force generated by the low slip wheel (a) during the driving phase is lower than both the F_x in its anchor phase and the F_x generated by driving with high slip (b).

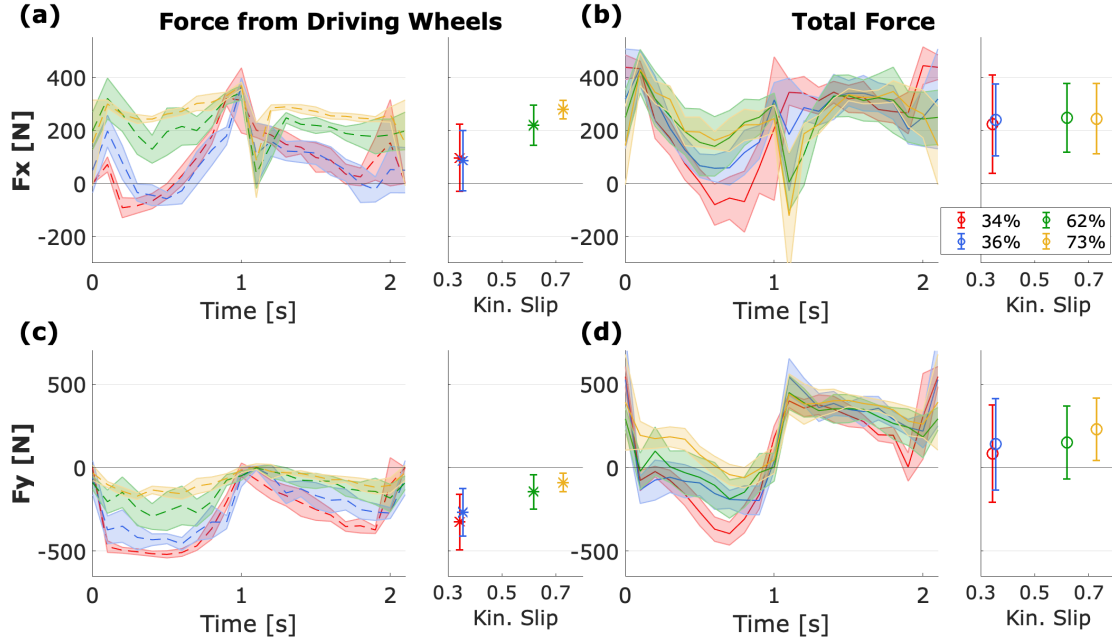


Figure 3.20: **Average modelled forces in the forward (a)-(b) and lateral (c)-(d) directions.** Subfigures (a) and (c) show the forces generated by only the driving wheels, while (b) and (d) show the total forces generated by all wheels. The shaded region depicts one standard deviation of the force time series over 10 cycles. The error bars show the range of forces (also one standard deviation) that is generated by the wheels over each entire cycle. As kinematic slip increases, the tractive force F_x of the driving wheels increases and the lateral resistive force F_y decreases.

by the stationary wheels will be over-estimated by RFT because of the ruts left behind the wheels. However, this effect should be similar for all trials. The takeaways are that: (1) the tractive force generated by the faster-driving, higher-slip wheels is higher than that of lower-slip wheels; (2) the predicted average total forces are consistent across all slip conditions, which is expected given that the rover experiences the same external forces; and (3) the lateral resistance force F_y , which is a consequence of misalignment between the suspension and drive axes, decreases in magnitude with higher slip, resulting in less oscillation in y and more net translation.

The effect of (1) is that the anchor wheels skid backward less far in the x direction, and the effect of (3) is that there is less lateral force and travel oscillation in the y direction. Altogether, this results in faster travel when operating with high kinematic slip. The following load capacity analysis will substantiate these claims.

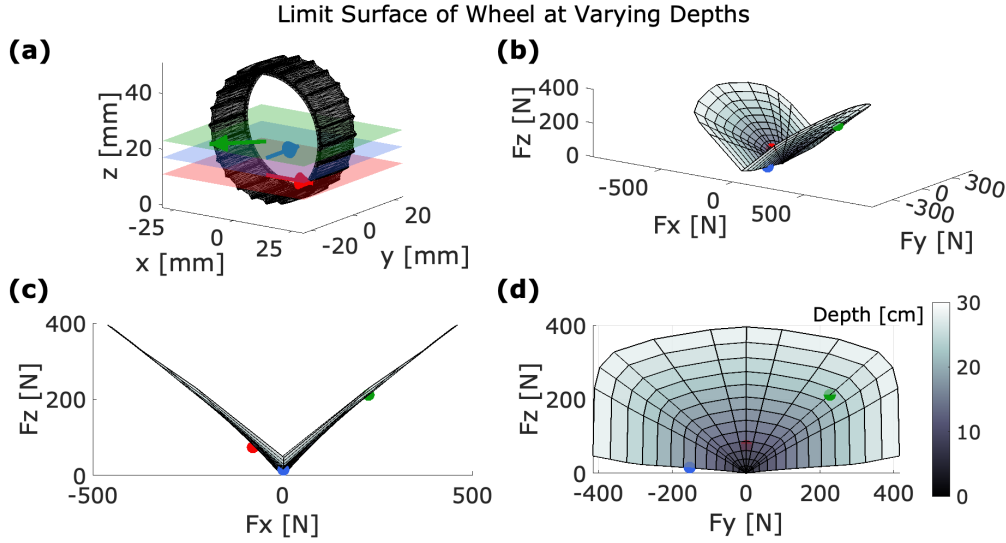


Figure 3.21: **Limit surface generation for the VIPER wheel shown in (a).** The horizontal translations at varying depths denoted by the arrows and planes result in the forces on the limit surface (b)-(d) denoted by the points of the same color. Each circumferential contour line represents a depth increase of 2 cm, and each radial contour line represents a change in displacement direction by 15° .

Anchor Load Capacity for VIPER

RFT generates a velocity-independent estimate of the forces that resist a moving object. In reality, when the object begins to displace sand, the resistive load gradually increases until the sand compacts by some critical distance and subsequently produces a constant resistive force. Applying RFT to a sample of possible motion states of the object will generate a surface of potential resultant forces which represents the load capacity of the anchored object in granular media [31]. Using this limit surface, we can predict the maximum force that the anchored wheels can support before the sand shears, and we can slip the driving wheels at a level that allows the anchored wheels to remain in place.

In the following analysis, we make several assumptions to reduce the complexity of the limit surface. First, there is no roll, pitch, or yaw motion of the rover – while there are a few degrees of yaw oscillation each cycle, the effect is small. Second, all four wheels are at a fixed and equal depth; the velocity of each wheel in the z direction is much lower than in the x and y directions. While there is some sinkage variation, the wheels are paired in the left and right direction, so the average sinkage of driving and anchored wheels is balanced, and the maximum observed difference is less than 5 cm in experiments (shown in Fig. 3.15). Finally, the terrain surface is assumed to be flat, whereas in reality there are variations as a cavity forms around the wheel during driving; this decreases the load capacity of a wheel being pushed backward.

In order to generate the limit surface shown in Fig. 3.21, horizontal translations (e.g. the red, green, and blue arrows) at different depths (red, green, and blue planes show the sand's surface) are applied to a mesh representation of the wheel. For each of these motions, RFT produces a point on the limit surface shown in (b)-(d). The red, green, and blue points show the forces generated by the red, green, and blue translations. A purely forward $+x$ translation (red) produces a purely backward $-x$ force, and a purely lateral $+y$ translation (blue) produces a purely lateral $-y$ force. The force increases as wheel submersion depth increases (green). Each circumferential contour line represents a depth increase of 2 cm, and each radial contour line represents a change in displacement direction by 15° .

To evaluate whether the rover is operating within the strength of the sand and the limit surface of the anchored wheels, we approximate the forces acting on the anchored wheel. Since the rover operates at low velocities, we approximate it as a quasi-static system such that the total net force is 0.

$$\sum F = F_{driving} + F_{anchor} - F_{resistance} = 0 \quad (3.3)$$

where $F_{resistance}$ represents all external resistance forces that the model does not account for. This may include the energy dissipated into the Fillite that causes it to become airborne. It may also result from over-estimation by RFT, since the wheels create surface variations and cavities in the Fillite that reduce the wheels' effective sinkage. Rearranged to isolate the anchored wheel, we see that the anchored wheels need to exactly counteract the resistance and driving wheel forces: $F_{anchor} = F_{resistance} - F_{driving}$. The average total force from Fig. 3.20 is the vehicle's $F_{resistance}$. Since the system is kinematically left-right symmetric, for the following analysis we only consider one pair of wheels, which includes one driving wheel and one anchored wheel.

Figure 3.22 depicts the force that the anchor experiences F_{anchor} when different levels of kinematic slip are employed, each represented by a colored bubble. The center of the operating range is located at $F_{resistance} - F_{driving}$, where $F_{driving}$ is calculated assuming the anchor is fully stationary and the kinematics fully determine the wheel's translational motion. The shape of the bubble is generated by accounting for potential anchor displacement and calculating the resultant variation of $F_{driving}$. We apply a fixed skid to the anchor in all directions with a velocity magnitude that is 10% of the suspension velocity. The shape of the bubble illustrates the sensitivity of the system to sliding of the anchor. For instance, for low kinematic slip, anchor skid results in substantial changes in forwards force F_x , whereas a high kinematic slip system is relatively insensitive and thus decreases operating uncertainty.

The dashed line shows the limit surface for the wheels at their average operating depth. A force on the anchor that is inside the dashed line should not cause anchor displacement, whereas a force outside the dashed line will have anchor skid. We only consider the x and y forces because the driving wheel generates similar lift forces as the anchored wheel and very little motion observed in the z direction. Kinematic slips of 10%, 30% and 50% impose forces on the anchor that fall outside the limit surface and will result in inefficient push-pull locomotion, since the anchor cannot support the load necessary to remain a stationary

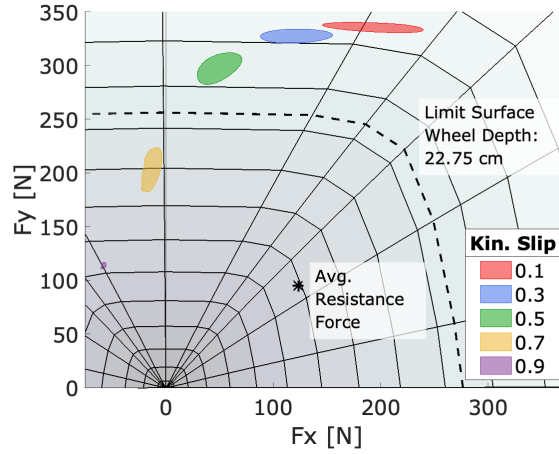


Figure 3.22: The load acting on the anchored wheels given a driving kinematic slip (colorful bubbles) in comparison to the load capacity of those wheels (dashed line). A kinematic slip of at least 60% is required to operate within the limit surface of the anchored wheel. Each colorful bubble represents the range of F_{anchor} that is applied to the anchored wheel given the average external resistance force (*) and the force generated by the driving wheel, which depends on both the controlled kinematic slip and uncontrolled anchor skid. The size of the bubbles indicates the sensitivity of the driving wheel force generated to anchor displacement.

platform. Kinematic slips of 70% and 90%, however, allow the anchor to operate inside the limit surface so the anchored wheels would displace minimally. Note that all of the bubbles are fixed relative to $F_{resistance}$, marked by the *, so a different average resistance force would alter the location of the operating bubbles relative to the limit surface.

Comparing VIPER Model with Experiments

The anchor behavior expected by Fig. 3.22 aligns with the experimental observations in Fig. 3.18, where approximately 70% kinematic slip is required to avoid anchor displacement. Kinematic slips at and below 62% result in less efficient push-pull locomotion due to the backward motion of the anchor, and a kinematic slip of 60% falls on the limit surface. While the model and experimental data generally agree on the boundary between anchor stability and anchor skid, the model over-estimates the stability of the anchor. This is likely due to several effects: (1) the average resistance force is a time-averaged estimate so it does not necessarily represent the worst-case moment in the cycle, and the instantaneous wheel slip also varies from the average slip that is modelled; (2) some sand must always be displaced in order to achieve its full strength under the anchor; (3) loads are unevenly distributed between the wheels, which are also at different sinkage, so one wheel may be within the limit surface

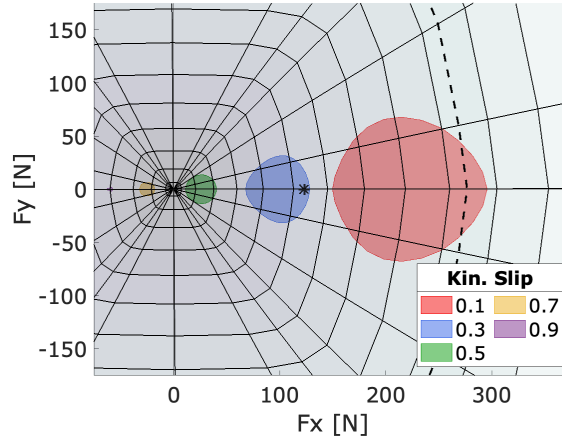


Figure 3.23: **The load acting on the anchored wheels given a driving kinematic slip in comparison to the load capacity of those wheels if the suspension travel was aligned with the driving direction.** Much lower levels of kinematic slip would be required to remain within the limit surface.

while the other is not; and (4) the limit surface optimistically assumes flat terrain, whereas the cavity around the wheel reduces its load capacity until the wheel skids far enough to build up a mound.

Operating at 73% kinematic slip is within the limit surface and results in very little backward displacement, but it may not be the most efficient use of the anchored wheels. As mentioned above, sand often needs to displace by a critical distance before it achieves its full strength. If no anchor displacement occurs, the driving wheels are generating all of the vehicle's thrust. Additionally, in the 73% slip trial, one wheel was often dragged forward when it was not driving, which meant it created drag rather than providing thrust. This is not considered in the limit surface analysis, which ignores vehicle yaw. The power and travel velocity data still confirm that 73% slip resulted in the best mobility, but it is unlikely that performance would continue to improve with even higher slip.

Despite the assumptions and limitations of this model, the limit surface analysis is consistent with the trends observed during experiments. The ideal kinematic slip for VIPER in Fillite appears to be between 65-70% in order to operate within the limit surface while still taking advantage of the potential of the anchor to provide thrust.

In other media with different terrain properties, the shape of Fig. 3.22 would not change because the RFT coefficient equivalently scales the forces generated by the driving and anchor wheels. However, $F_{resistance}$ may shift and cause the ideal kinematic slip to change. In more consolidated media, wheel sinkage would decrease, shrinking the limit surface. Similarly, $F_{resistance}$ would decrease and bubbles of lower kinematic slip may move into the limit surface. These new media would require more experimentation to characterize.

Note that the F_{anchor} operating ranges cross the limit surface primarily by exceeding F_y limits. This constrains the rover’s potential to generate force in the x direction. If VIPER finds loose and sloped terrain and future missions expect to traverse it, then redesigning the suspension such that the expansion and contraction direction can align with the wheel drive direction would significantly reduce the amount of kinematic slip necessary to maintain a stationary anchor during push-pull locomotion, as suggested in Fig. 3.23. We next apply this analysis to the Shifty sloped climbing data.

Shifty & Slope Climbing

Combining both experimental datasets collected with Shifty, we can observe how anchor skid varies with kinematic slip in Fig. 3.24. For slopes of 0° and 10° , wheel travel by the front and back wheels is similar, and anchor travel is minimized near 40% slip. Beyond 40% kinematic slip, the non-driving wheels are dragged by the driving wheels, which is an inefficient use of tractive force. Mars 90 was not loose enough to warrant an inchworming gait when the terrain is flat. On the 10° slope, 40% slip is the level at which the inchworming power efficiency improves beyond normal driving and energy consumption plateaus around its minimum at less than half that of normal driving. On steeper terrain (15° and 20°), higher kinematic slip is required to reduce anchor motion. The rover achieves minimal back anchor skid around 60% kinematic slip, but the system is limited by front anchor skid. In this case, the front wheel cannot generate a strong enough platform to support the back wheels.

To produce Fig. 3.25, we perform a similar analysis as the previous section, comparing the operating force range with the limit surface. In each subfigure, the limit surface contours are the same, generated with a mesh model of Shifty’s wheel, while the shifting dashed line indicates the limit surface for the average sinkage depth of the wheels on each slope. The forces are not scaled by a measured RFT coefficient because any changes in the shear strength of the sand due to its slope should be consistent and equally affect both wheels across every trial. The x axis is fixed to the rover’s longitudinal or driving direction, rotating with the slope of the tilt table. We do not analytically account for how the gravity vector direction changes relative to the rover x and y axes; instead we use the average RFT-estimated total force to generate the $F_{resistance} (*)$ values. As the slope increases, the average resistance force $F_{resistance}$ moves to the right in accordance with gravity, and this pushes the F_{anchor} bubbles closer to the limit surface. Therefore, the model captures why higher kinematic slip is necessary on higher slopes.

However, these model predictions do not correlate as clearly to Shifty’s observed behavior, since the model predicts that most kinematic slip values are within the limit surface whereas anchor skidding occurs at many levels of kinematic slip. Many of the assumptions of RFT are not maintained as well in this experiment as with the flat tank of Fillite. RFT was characterized for a flat sandy surface, so it does not capture how slopes and surface topology variation affects locomotion. VIPER performed its crab-worming gait in a flat tank of Fillite, which easily reflows around the wheels compared to Mars 90. Meanwhile, Shifty’s motion capture and kinematics data suggest that the front wheels sink more than the back wheels,

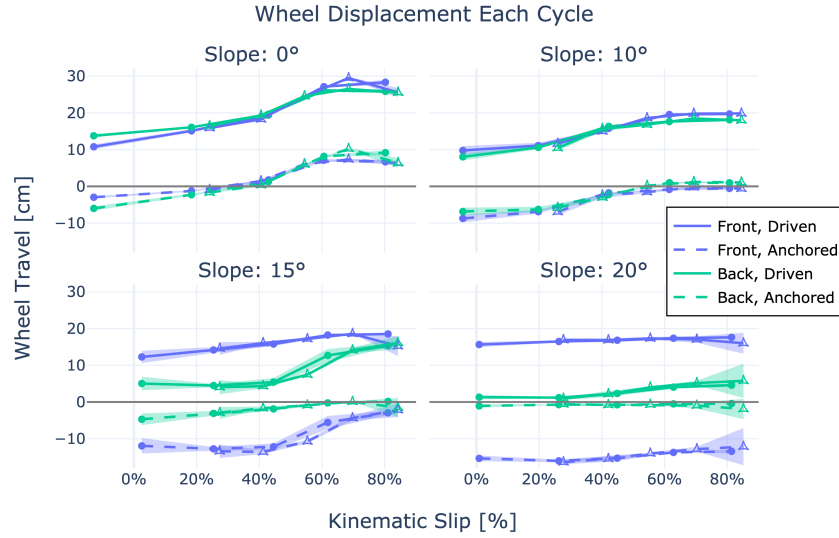


Figure 3.24: **Wheel displacement of Shifty during each phase of inchworming.** At high slopes, the system is limited by front anchor skid; the front wheel cannot generate a strong enough platform to pull on the back wheels from.

but visual examination of the sand surface clearly confirms that the front wheels excavate the sand as they drive, which results in less effective sinkage, and then build a mound that increases the effective sinkage of the back wheels. In order for the model to capture reality more closely, front and back wheel sinkage would have to be adjusted to account for topology change, and a load capacity reduction factor or lower effective sinkage may be needed to represent the cavity created by a driving wheel.

Rather than attempting to increase model complexity, we instead use the shape of the limit surface to discuss the observed trends and use wheel displacement data to estimate where the anchored wheels operate in reality. Conceptually, we know that the limit surface increases in magnitude for wheels with greater sinkage. For the flat 0° terrain, the anchored wheel can be either dragged forward (positive travel) or pushed backward (negative travel) because the wheel sinkage is low and the load capacity is easily overcome. During sloped driving, wheel sinkage increases and since the anchored wheel has a larger limit surface, if it moves it always gets pushed backward, crossing only one side of the limit surface. Total resistance force increases on higher slopes due to the additional load imposed by gravity. This moves the anchor operating range bubbles rightward toward and across the dashed limit surface boundary. Hence, as observed, inchworming with low slip often exceeds the load capacity of the anchored wheel, whereas increasing kinematic slip reduces anchor displacement.

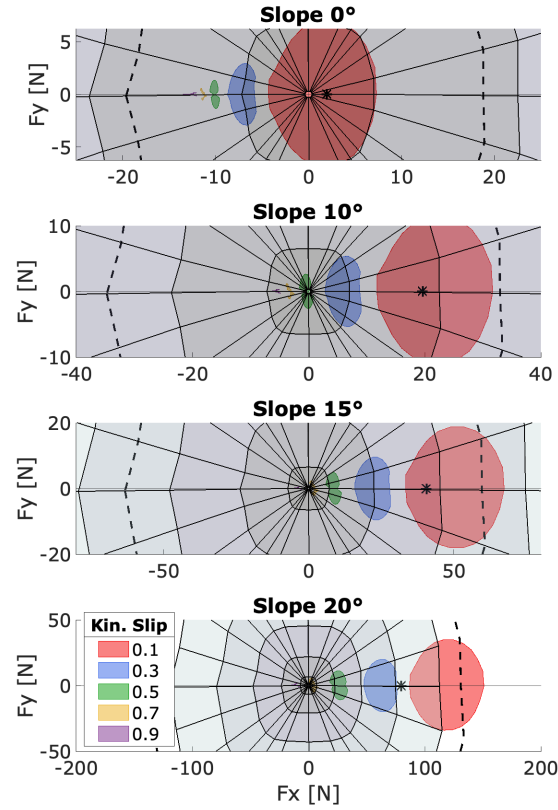


Figure 3.25: **Limit surfaces of Shifty’s anchor wheels for varying slopes.** Higher kinematic slip is necessary on higher slopes, but the actual relative locations of the operating loads and the load capacity cannot be captured by RFT because of the surface variations in the sand that are not accounted for.

Based on the wheel travel data, the high kinematic slip bubbles for the 0° case should actually cross the limit surface in both the $+x$ and $-x$ direction, since the anchored wheels are pushed both ways. On the 10° slope, the anchored wheels do not appear to operate within the limit surface until about 50% kinematic slip. On the 15° and 20° slopes, the limit surface of the front wheel is always exceeded, whereas the back wheel remains in place at high kinematic slip. The substantial difference in front and back wheel anchor capacity indicates that in order to enable more efficient slope climbing, future work should consider operating with different kinematic slip during the expansion and contraction phases, rather than keeping it constant throughout a given trial as in the present work.

Conclusion

In this work, experiments and theory demonstrated the great potential for improving the performance of push-pull locomotion gaits using purposeful wheel slip. Specifically, we investigated the crab-worming gait of VIPER and the inchworming gait of Shifty as case studies for this principle. Relative to normal driving, with inchworming we achieved an improvement in travel reduction from 98% to 85% on a 20° slope, from 94% to 44% travel reduction on a 15° slope, and from 77% to 30% travel reduction on a 10° slope. We found that the kinematic slip threshold to achieve less travel reduction than normal driving was between 20%-30% depending on the slope. The kinematic slip that resulted in more power efficient locomotion was between 30%-40%, reaching an efficiency improvement of between a factor of 3 for a 10° slope and a factor of 8 for a 20° slope. We achieved similar results on the VIPER rover in an extremely loose sand simulant. We first extricated the rover from an embedding incident and then, without increasing the normalized power consumption, increased travel velocity by 35% by increasing kinematic slip from 35% to 73%.

We also demonstrated the use RFT limit surfaces to visualize the theory behind the experimental results. We found that the higher slip driving wheels are more effective at generating positive tractive force and thus reduce the load on the anchored, non-driving wheels. This reduced the skid of the anchors, which resulted in more consistently forward locomotion. We also noticed that the suspension's kinematics and lateral motion generate a high F_y that limits the F_x that is achievable without overcoming the shear strength of the media. Unsurprisingly, an inchworming rover with its drive and suspension translation axes aligned would be a more effective kinematic design for continued access to loose, sandy slopes, compared with crab-worming. While we were limited by the assumptions of RFT from correlating theory to experiments for Shifty, we can still apply limit surface concepts to understand how kinematic slip should be adjusted to improve locomotion, given observations about the anchor skid states of the rover over a range of kinematic slips. This tool is therefore recommended as one method for considering the implications of new suspension kinematics and controllers in future rover applications.

3.5 Additional Articulated Gaits: Asterix & Obelix

Experiments thus far have used inchworming-like gaits for sandy slope climbing, but the application of kinematic slip can extend to a wider variety of gaits, such as those in [10].

Asterix, on the left of Fig. 3.26, has two actuated degrees of freedom in its suspension: a steering joint at its center (hidden in this image) and a bogie joint on its back wheels. The steering joint points the two halves of Asterix at different headings, while the bogie can either be actuated or fully decoupled. When actuated, the bogie increases the load on one wheel diagonal while unloading the other diagonal and can either be torque or position controlled such that wheels are fully lifted off the ground (circular wheel-walking). When passive, the bogie applies equal load on the rear wheels.



Figure 3.26: **Asterix and Obelix.** These rovers can collectively perform five articulated locomotion gaits, some of which can actively modify load distribution. They have the same vehicle parameters, and their kinematics and center of mass can be adjusted to test other metrics of interest.

Obelix, on the right, has three actuators and two kinematic configurations for COM motion. Each bogie can change the wheelbase on either side of the chassis, producing an inchworming gait. However, the black control box can be mounted kinematically such that the center of mass does not move in the vertical direction, producing a gait referred to as push-rolling. The two bogies can also expand and contract out of phase such that one diagonal is anchored while the other diagonal is driven in a gait called cross push-rolling. The last actuator is located under the black control box and drives the differential joint such that Obelix can also diagonally load its wheels.

The results published in [10] measured power at the electrical bus, which is implementation specific. Reanalyzing the data with only mechanical power in mind, we find that the normalized power required to execute an articulated gait is up to 35% lower when climbing 20° slopes. On 30° slopes, power number drops by 50% or more for squirming gaits. At 20° , push-pull gaits (inchworming, push-rolling, and cross push-rolling) and squirming gaits have similar power consumption. At 30° , without wheel contact load adjustment, cross push-rolling and squirming require the least power.

Center of mass adjustment to statically balance wheel loads has only minor effects on performance on 20° slopes, whereas power consumption drops by 40-50% for inchworming and push-rolling gaits with adjusted COM on slopes of 30° . Based on the previous inchworming data taken by Shifty, this may happen because without a COM adjustment the front wheels cannot engage effectively with the sand while the back wheels are overloaded.

Diagonal wheel load oscillation (i.e. load-adjusted gaits), which is unique from static load balancing, has minimal effect on mobility for 20° slopes while drawing additional power. However, load-adjusted gaits result in the most power efficient gaits on 30° slopes. Travel reduction falls from 79% to 75% adding load adjustment to squirming, and from 84% to 70% with the addition of load adjustment to push-rolling. Load-adjustment appears to allow the rover to more effectively generate drawbar pull while avoiding extraneous resistance. The benefit of load-adjustment is minor on nominal slopes but may be necessary to achieve more extreme climbing.

This data motivates the further development of articulated suspensions with mission-specific design trades. For instance, quasi-static load equalization does not appear to have high value unless an inchworming or push-rolling gait is used and squirming or cross push-rolling cannot be used. Similarly, active load-adjustment may not be worth the additional actuation complexity until facing extreme terrains. Another factor to consider is the allowable workspace of the suspension. Squirming carves out a large workspace compared to push-pull gaits, which translate the wheel purely longitudinally. However, the actuation direction of squirming does not require the steering actuator to carry the load of the entire weight of the rover, whereas the bogies must apply greater torques.

Static holding torques are largely overlooked by mechanical power analysis, so it may be necessary to integrate a clutch and brake with the motor to make a bogie-driven gait truly as power efficient as squirming. An implementation-specific power analysis should include considerations of motor efficiency. For this system, the suspension motors had five times higher winding resistance than the drive motors, and winding losses increase quadratically with motor current. Hence the actual operating efficiency will be design dependent.

Based on the experiments from the previous sections, kinematic slip may increase the performance benefit of articulated gaits. Given a fixed suspension command and varying wheel velocity commands, the travel velocity of the rovers increases until the wheels drive twice as fast as the suspension travels, or at 50% kinematic slip. After this point, performance plateaus or degrades because the progress is limited by the suspension speed and the wheel sinkage increases.

Kinematic slip is highly effective with push-rolling and cross-push rolling, which employ wheel-terrain interaction most similar to inchworming. When climbing the 25° slope with synchronous inputs (0% kinematic slip), the stationary wheels skid downhill, as was observed previously with Shifty. Cross push-rolling resulted in much less skid than push-rolling because one downhill wheel with high load capacity was always anchored, whereas during push-rolling the front wheels cannot resist the loads from the back wheels.

During squirming, kinematic slip does not appear to significantly impact travel velocity. At best, passive squirming is 17% faster. Rather than using slip to increase drawbar pull, the steering joint moves the driving wheels over fresh sand. Squirming visually appears to move the wheel to a lower sinkage regime, which would not require as much slip to be effective.

On a 25° slope, similar with the previous experiments, we observe a 37% normalized power consumption decrease from a passive four-wheel chassis to passive (pivot-induced) squirming at 0% kinematic slip. The plot below shows a comparison of the power number

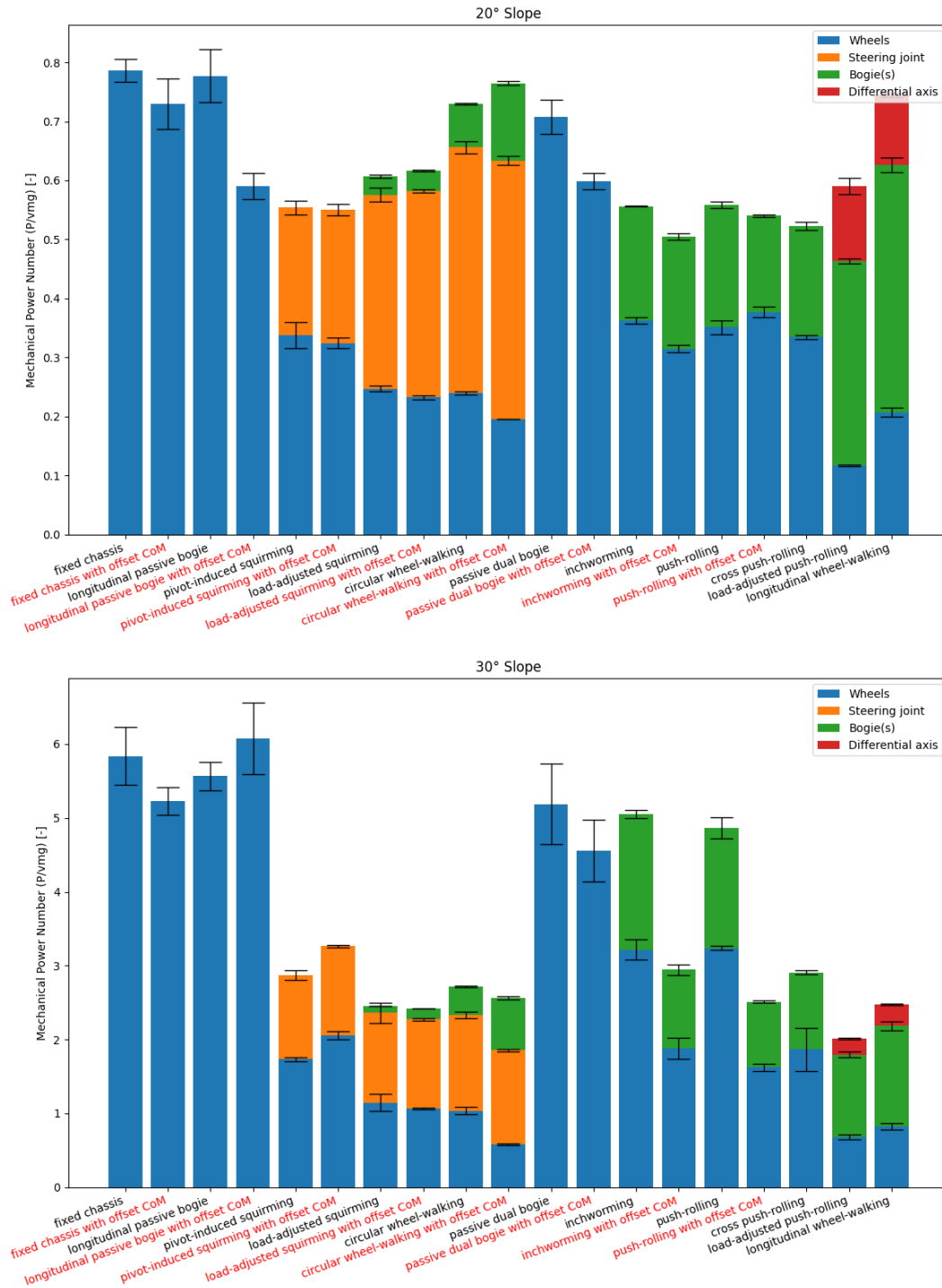


Figure 3.27: Mechanical power number for various articulated gaits. On 20° slopes, articulated gaits like squirming and push-rolling draw up to 35% less power. On 30° slopes, power consumption drops by 50% or more.

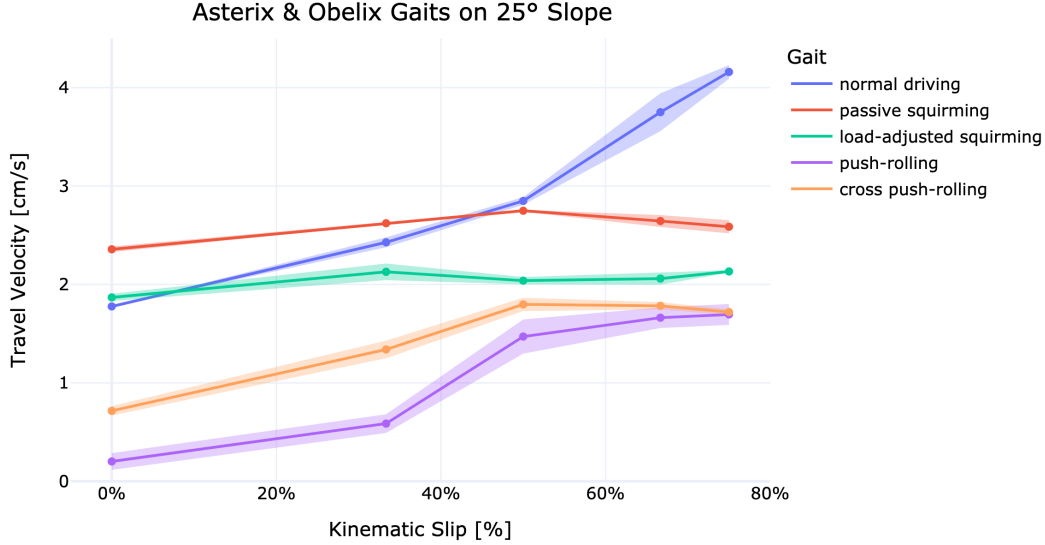


Figure 3.28: **Travel velocity of gaits with the application of kinematic slip.** With a fixed suspension command and varying wheel velocity commands, travel velocities typically increase until the wheels drive twice as fast as the suspension travels, or at 50% kinematic slip, after which performance plateaus or degrades.

between rovers and gaits. However, the ballast load was excluded from Asterix during these tests, so the comparison between Asterix (solid line gaits) and Obelix (dashed line gaits) power consumption is not as direct as in the previous experiment.

Load-adjusted squirming requires a similar level of normalized power consumption as passive squirming, but its travel velocity is 20% slower. This is not due to travel reduction but rather because the rover stops driving while actuating the bogie to gradually adjust load distribution without large accelerations. There may be further optimization of the load adjustment input trajectory to improve power number by running the bogie concurrently with driving. Sandy slope mobility does not clearly improve by enough to justify adding an actuated bogie, but if other functions necessitate one, simultaneous bogie and steer controllers should be explored.

One ambiguous aspect of applying kinematic slip to squirming was which wheels should be driven faster. Unlike standard push-pull locomotion, there is only one stationary wheel, along with two fast wheels and one slow wheel. In the previous data, the two slow wheels were kept at their nominal speed, while the two fast wheels were driven with extra slip. In the following data, the speeds of all wheels were amplified equally, and this resulted in clearer travel velocity improvement, while maintaining a relatively consistent power number. For instance, on a 30° slope, travel velocity increased by 60% when driving the wheels twice as fast as the suspension (50% kinematic slip) while consuming 7% more energy per unit distance. This increase can easily be compensated for by reducing the drive time and hence overhead operating energy consumption. Since travel velocity increases while suspension

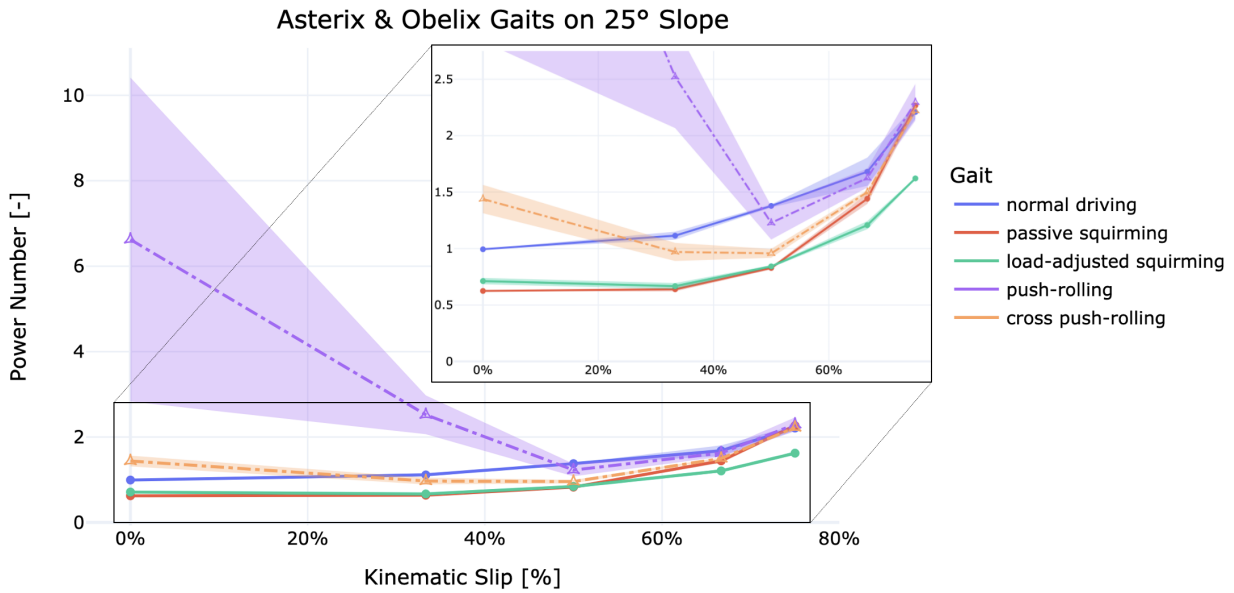


Figure 3.29: **Power number of gaits with the application of kinematic slip.** Kinematic slip is critical to the success of push-pull gaits such as push-rolling and cross push-rolling. Squirming visually appears to reduce wheel sinkage, so increased kinematic slip has less effect. Note that the relative performance of Asterix has improved relative to previous data without kinematic slip because it was not fully loaded with its ballast and therefore had lower ground pressure.

speed is constant, the rover is more effectively making forward progress each cycle, rather than sliding downhill. The anchored wheel continues to be more effective when *all* of the other wheels slip more.

It is also clear from the normal driving data that the results are not velocity-independent, despite operating below the dynamic RFT velocity threshold for flat ground. Slip increases from 64% to 80% as wheels drive four time faster, and excavation activity is qualitatively clear in conjunction with increasing wheel sinkage. Integrating dynamic, sloped models of terrain will be important for continued development of these rovers, especially to proactively optimize kinematic slip.

Finally, these rovers experienced much less slip and sinkage than Shifty and VIPER. Their light weight combined with their large grousered wheels made it such that the wheels usually operated in a relatively efficient regime. Kinematic slip was able to improve the push-pull gaits, but the squirming gaits typically drove the wheels onto fresh sand with low sinkage and did not need as much slip to perform well. Even during squirming, when up to 50% kinematic slip was applied to all wheels consistently, travel velocity increased without much efficiency penalty, and higher travel velocities mean that targets can be reached faster, consuming less overhead power. Articulated gaits continue to result in more mechanically efficient

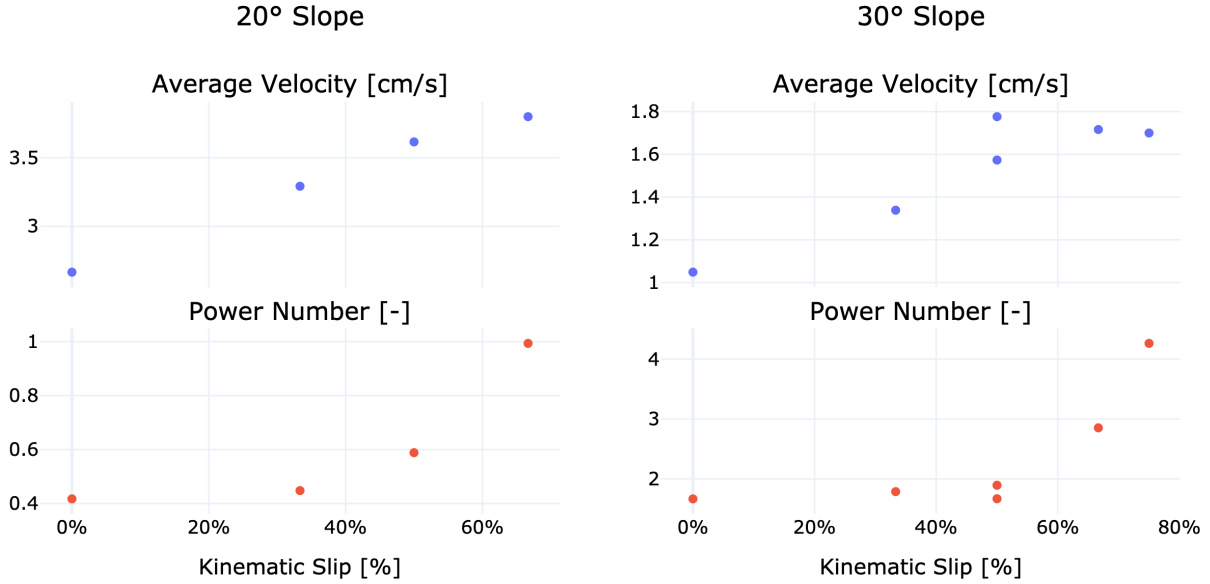


Figure 3.30: **Performance of squirming with kinematic slip applied to all wheels.** On a 30° slope, travel velocity increased by 60% when driving the wheels twice as fast as the suspension (50% kinematic slip) while consuming 7% more energy per unit distance. The anchored wheel continues to be more effective when *all* of the other wheels slip more.

locomotion than normal driving, although in this rover configuration, push-pull gaits were less effective and squirming was the most effective. While the Shifty data showed efficiency improvements when accounting for electrical power, the Asterix and Obelix experiments emphasize that careful work must be done to ensure that mechanically efficient rover gaits are also electrically efficient.

3.6 Future Work

Additional work is needed to further optimize push-pull locomotion gaits. Areas for development include improving simulation, implementing onboard sensing to inform responsive gait choices, and expanding experiments with induced slip in order to guide design and operation across diverse terrains.

The present RFT-based modeling method does not estimate the true mobility of Shifty, particularly due to the sloped terrain and surface variations in Mars 90. First, RFT is a rapid, first order model of forces on a moving body, whereas other more complex and time intensive simulation tools can more holistically predict performance, often with more granularity in the terrain specification. Some also consider multi-pass effects and sloped terrain, and they may be able to account for the surface topology effects that were encountered. Second, RFT depends on receiving motion tracking data as input to estimate the force. To answer

the inverse problem and be able to predict the motion of a rover, either quasi-static [31] or dynamic simulations can be employed. These methods may be additionally able to account for vehicle weight distribution, which is affected by vehicle pitch on slopes and subsequently affects wheel loading and sinkage. RFT provided rapid visualizations useful for conceptual understanding of the role of slip, but more detailed simulation may be useful to reduce the experimentation required to characterize mobility over a large range of media.

In order to responsively initiate and optimize push-pull locomotion gaits with an effective level of slip as terrain changes, additional sensing should be explored. For example, a high level of travel reduction during normal driving could trigger a rover to transition from normal driving to push-pull locomotion, but slip estimation is still open area of research [27]. Once inchworming is enabled, additional sensing would be useful to determine the proper level of kinematic slip. For an external observer, it is clear when the anchor skids and from the data, it is straightforward to pick a slip that minimizes skid. However, it is nontrivial to monitor the displacement of each anchor to allow for onboard adjustment of kinematic slip. Wheel sinkage may be easier to measure than skid and also provide insight into terrain properties to inform the desired wheel slip. However, more experiments to characterize the relationship between sinkage and load capacity are necessary to determine the feasibility of using sinkage measurements to make gait decisions. Alternatively, tractive force sensing at the wheel pairs may allow the operator to adjust kinematic slip until the measured load falls within an acceptable load capacity. It is expected that while the anchor is skidding, a relatively constant thrust force would be measured. Therefore, if kinematic slip is increased until a decrease in the thrust force is measured, this may be one sign that the wheel has come within the media's load capacity. Increasing kinematic slip past this point would likely then result in less efficient thrust generation, especially if the measured force flips sign and becomes a form of resistance (i.e. dragging the anchor instead of pushing off the anchor). Furthermore, sensing of individual wheels would enable individual adjustment of kinematic slip, for instance between the expansion and retraction cycles or if there is local variation in terrain properties.

Even without additional simulation methods or sensors to measure robot state, future work should expand the experimental data set achieved in this work to include, for example, different kinematic slip between the expansion and contraction phases or more types of terrains. Ultimately, the use of articulated suspensions provide operational flexibility for overcoming difficult terrains. At the same time, the deceptively simple choice of how fast to drive the wheels relative to that suspension can dramatically influence the effectiveness of such strategies.

3.7 Takeaways

Wheel slip can be a locomotion tool, rather than an undesirable outcome, but limited work has been thus far to explore its control application. This thesis investigates both the generation of wheel slip by driving wheels in a fixed suspension at different speeds and by driving

wheels faster than an articulated suspension translates.

In high sinkage, high resistive load scenarios, the back wheels are often loaded more heavily than the front wheels, which results in a sinkage difference between the front and back wheels. Wheels at higher sinkage need to slip more in order to generate positive drawbar pull values, so there was some benefit to both travel reduction and travel efficiency to drive the back wheels slightly faster than the front wheels. However, the outcome is mild. In the highest resistance scenario, driving the back wheels twice as fast as the front wheels resulted in about 10% improvement in travel reduction and efficiency. This is a small change but confirms that wheels can effectively be driven at different velocities, and this presents a potential method for extrication of existing or new rovers with no changes to hardware.

Introducing several extra degrees of freedom to articulate a rover suspension can much more drastically improve slope climbing ability. With an inchworming rover, driving the wheels in sync with the wheelbase expansion and contraction results in motion that is less efficient than normal driving. This is largely because the anchored wheels are heavily loaded and skid backwards. Increasing drive slip allows the driving pair to generate more traction and reduce the load on the anchored wheels, while still pushing off of them. Even on slopes as low as 10° , which are already achievable by normal driving, inchworming was able to improve the slope climbing efficiency, suggesting that their value is not limited to extreme terrains.

This chapter finds that strategically inducing wheel slip, especially kinematic slip in articulated suspensions, introduces important design and control considerations for efficient locomotion in steep and loose granular media.

Chapter 4

Conclusions

This thesis explores how rovers with articulated suspensions have the potential to use additional dimensions of control to interact with their environments for improved mobility. The control of relative wheel loading and wheel slip is not possible in traditional passive suspensions, and this research aims to fundamentally motivate a new generation of suspension development supported by models of wheel-terrain interaction. Granular Resistive Force Theory has grown in its applicable scope in the last few years, and it gives us more insight into robotic interaction with granular media than previously existed. By applying RFT to wheeled rovers, we can visualize and predict unintuitive behaviors and design new locomotion gaits. The main takeaways of this work are as follows:

Load equalization does not translate into better mobility performance. Instead, load variation may have more utility.

A commonly held belief embodied by the prevalence of the passive rocker-bogie design is that mobility is optimized by equalizing loads between all wheels. This should theoretically avoid excessive sinkage of individual wheels, while distributing tractive loads across all wheels such that the most drawbar pull can be generated. While there is merit to this approach, load distribution should not be a primary metric for the design of mobility systems. In the work with VIPER’s actuated suspension, we found little correlation between suspension load-balancing response and mobility performance, as measured by slip, power, and stability. While it was helpful to keep the wheels on the ground to improve stability, load distribution did not clearly change the rover’s ability to traverse its target terrains. In fact, this seems to be a relatively common result: SherpaTT modified its footprint to evaluate if they could reduce slip during slope climbing [17], several internal JPL and GRC experiments also tuned the stance of rover suspensions or center of mass placement, and the expansive Asterix & Obelix rover experimental campaign also tested different static load distributions and body inclination poses [10]. Rover slip and power consumption only ever change within a few percent.

Quasi-static load equalization does not influence performance strongly enough to make it a key feature of rovers and justify the additional actuation. Similarly, load equalization

does not need to be a key driver of low level mobility controllers for actuated suspensions. It can be argued that in the aforementioned experiments, the tests were not at the limits of terrain failure, and the motors are over-designed for the terrains that were tested, i.e. if one wheel lifted off the ground, the remaining wheels could likely still generate the traction necessary to move the vehicle. However, these are common design margins to provide fault tolerance and are unlikely to change. Furthermore, if the rover were operating at the limits of terrain failure, then the rover can and should transition into an extrication gait, which would be more efficient and effective than attempting to equalize loads.

Alternatively, dynamic load redistribution remains an open question. Contact load modulation is well-motivated by slip and terrain failure models and has more optimization potential than solely drive torque. The optimization process can be used to ballpark the effect of different magnitudes of load shifting. Control moment gyroscopes are an intriguing method of virtual center of mass relocation, but there are many challenges associated with mechanical design and controlling the dynamics. Load shifting generated by actuated suspensions may not be as dramatic, but they can still tackle obstacles one wheel at a time. Finally, while some may look towards legged robots for tackling extreme environments such as large rigid obstacles and steep slopes, we may be able to reap some of the benefits of walking dynamics using actuated suspensions, and it is worth exploring if this can be achieved with minimal additional complexity on top of our well-proven wheeled rovers.

Slip can be induced strategically for increased drawbar pull, especially if it can be controlled fully by an actuated suspension.

Contrary to popular belief, slip should not be universally minimized in sand. Engineers who work with deformable terrains understand that soil-moving and slip is necessary for tractive force generation. In soft-terrain entrapment scenarios, low slip with high sinkage will produce negative traction and potentially exacerbate sinkage.

Without any hardware changes, wheels can be driven at different speeds to preferentially induce slip on specific wheels. These experiments, discussed in Section 3.1, found that speed should be biased towards driving the back wheels faster than the front wheels since the back wheels experience higher loads and sinkage when the rover faces high resistance. This result falls in line with force ratio optimization, which proposes that more heavily loaded wheels should be driven with more torque. The added drawbar pull capacity of this method, and the ability to modify relative slip, is limited in fixed suspensions. However, it is a potential tool for rovers whose mechanical design is already fixed. In entrapment scenarios like Spirit, it is worth testing the addition of slip on more heavily loaded or deeply sunk wheels.

Alternatively, articulated locomotion has the ability to improve travel efficiency even when the rover already has the ability to climb the slope. Kinematic control of the wheelbase allows wheel slip to be controlled by the rover rather than the environment. The use of a push-pull gait, where a subset of the wheels is anchored while the rest drive, allows the rover to more efficiently generate forward thrust. Meanwhile, kinematically controlled slip reduces the load on the anchored wheels to minimize backward skid. Rather than increasing sinkage and motion resistance as intuition suggests, at best, the addition of slip reduced power

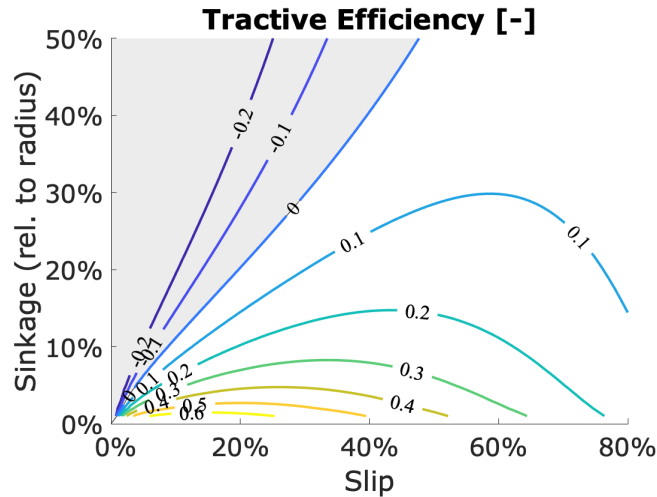


Figure 4.1: **Estimated tractive efficiency of a round wheel.** At high sinkage, additional slip can improve drawbar pull generation efficiency. Alternatively, the ability to unload the wheel and reduce its sinkage can also improve efficiency.

number by a factor of more than 8 when Shifty was climbing a 20° slope. It also enables greater overall travel velocity, which may be important when chasing time-dependent targets like the sun or for reducing operating power overhead when travelling long distances.

4.1 Future Work

Additional Model Validation

In order for granular RFT and articulated suspension with kinematic slip control to reach greater audiences within NASA, more studies must be performed over a larger design space. Mobility and experimental data are heavily affected by wheel design, actuation implementation, and terrain simulant, among other effects. Thus far, some favorable results have been published but more information is necessary to create more generalized robustness and confidence.

Regarding RFT, more validation of single wheels with varying shapes, sizes and simulants, along with comparison against the Bekker-Wong model, would enable increased adoption of the method. Its ease of use and wide applicability is already superior, but it needs to develop its validation history. In addition to traditional drawbar pull versus slip curves, it would be useful to experimentally generate something akin to the contour plots that have been shared in this thesis.

For instance, Fig. 3.2 depicts the predicted tractive efficiency curves for a grousered wheel, whereas Fig. 4.1 shows curves for a cylindrical wheel. If viewing these with sinkage

relative to the wheel radius, these curves are purely dependent on wheel shape, not media or wheel size. If they can be more rigorously validated, they can inform rover designers much more quickly and proactively about the impact of their wheel design, which previous models cannot do efficiently. Wheel design is the first avenue that rover designers should pursue for their terrain traversal needs. Note that wheel size and terrain strength still affect absolute drawbar pull and lift generation, so the sinkage operation point on these contours will depend on the wheel dimensions and media scaling coefficient.

The many extensions of RFT should also be independently validated, including dynamic RFT and 3D RFT. The predictions of trends by RFT appear to align with experimental results and with previous models and findings, but the localized forces have not been experimentally measured and confirmed.

Finally, the prospect of granular scaling laws as a more effective method of scaling rovers to obtain more representative mobility data is enticing but incomplete thus far. More data in low gravity and with more significant scaling differences in mass and size would help fill out the picture.

Integration of RFT into Dynamic Simulations

RFT has not yet been integrated into multi-body simulations, and since it is a velocity-independent model, it requires adjustments to its form to run efficiently. It should be as computationally efficient as simulations driven by Bekker-Wong, but with extended prediction capabilities and more intuitive user tuning. Soil Contact Models today use modifications of Bekker's pressure-sinkage relation to predict loads at each time step, and RFT should be able to substitute relatively directly. Since these simple models are inherently noisy, simulations should be run with a range of terramechanics properties and models to bound the expected behavior when deployed and to understand the sensitivity of the system.

As rovers are designed to move faster in coordination with their human counterparts, they may need springs and dampers to avoid the volatile dynamics of low-gravity driving, where the speed threshold for ballistic motion is lower. Multi-body simulation will be necessary to characterize the performance of more dynamically complex suspensions. Even below the ballistic threshold, high speed terramechanics models and data may quickly be relevant for missions [50].

With respect to the work presented in this thesis, rover operators will need to be able to predict the motion of a rover with induced slip in order to generate reference control trajectories to travel between specified waypoints. Simulation is also necessary to ascertain that the rover moves as expected. Rover operators will want a reference path to compare to the observed path in order to raise a flag if it is struggling to make progress and close to entrapment.

Finally, it should be possible to map the evolution of an articulated wheel's sinkage and slip during the course of a cyclic gait onto the contour plots such as in Fig. 3.3. A plot akin to a phase space diagram may be helpful for designing improved gaits. Again, model validation would increase the utility of an effort like this.

Expanding Experimental Results to Other Platforms

Several archetypes of articulated suspensions have already been tested in this work, but it is still not well predicted what level of slip is best and what factors affect this slip. The slope and terrain type at which it becomes more efficient to operate an articulated gait is also not characterized. More work can be done to elucidate this by both modeling and experimentation. Further experiments with slip control and suspension configurations will give rover designers additional understanding of the wheel-terrain interactions that are important.

If soft sand entrapment is still a concern on current missions, we can test driving the wheels at different speeds to differentially induce slip on rocker-bogie suspensions to determine if it is actually a viable strategy. The results with a fixed chassis are limited thus far but they show value for exploring. With rocker-bogie kinematics, it may be possible to passively control the freely rotating suspension joints by driving some wheels faster, moderating individual wheel sinkage to a limited extent.

Sensing and Control

Slip has traditionally been computationally challenging to measure in real time. Visual odometry is becoming faster and more robust, but load and sinkage sensing may be more tractable in real time and at higher rates. These signals may also provide information that is easier to wrap control loops around, especially in the context of terrain interaction. For instance, terrain contact load can be used to inform optimized torque control by distributing the applied drive torque proportionally to measured loads [34]. High average sinkage may trigger an extrication gait or a differential slip gait. Sinkage and tractive load measurements can also inform the level of slip that should be employed in push-pull locomotion. These signals have not yet been evaluated in depth for their utility for low level mobility control.

Another potential controller could integrate gradient descent methods for continuously optimizing travel efficiency. If visual odometry can determine traverse velocity and power consumption information is available onboard, gradient descent can be used to improve power number directly. With tractive load information, it may be possible to attempt to maximize the tractive output per power input.

Dynamic Load Adjustment

As discussed in the general conclusions, load oscillation may have utility that provides some control in the sinkage dimension in addition to slip. Diagonal wheel load control has been found to lower travel reduction for Asterix and Obelix [10]. While it draws slightly more power, it has the potential to extend the limit of traversable terrain, potentially by increasing the achievable slope angle or rigid obstacle height. It may be possible to gain some benefits of walking locomotion while still primarily driving for efficiency.

Flight Readiness

The six-wheel rover suspension has not only flight history but development history, specifically with regards to fault tolerance. New suspensions must similarly be studied to ensure that no faults disproportionally impact mobility. Some work has been done to assess VIPER with specific actuator failures [46], and additional work uses terramechanics models and varying levels of control to correct for a failed drive actuator [45].

Data evaluating the sensing and control needs of an articulated suspension will be necessary to inform the development of future flight-forward sensors and motor controllers with improved capabilities. Ideally, a trade study would find a suspension configuration that can maintain or improve mobility performance at a lower mobility mass to payload ratio than current rovers can achieve, which would justify additional actuation control complexity. This type of information is critical to building a complete picture of how an articulated suspension could be the next flight-ready mobility system.

4.2 Closing Remarks

The outcomes of this thesis support the hypothesis that 4-wheel rovers have the potential to perform mobility maneuvers as robustly as our heritage 6-wheel rovers. It reduces mechanical complexity and is more weight and volume efficient. We can integrate minimally more degrees of freedom to achieve noticeable improvements in steep and soft terrain mobility, resulting in mission security, improved scientific access, and shorter, more power efficient traverse routes. These suspensions can be deployed initially without load and slip control, but providing development runway for these strategic terrain interaction methods will bring further performance improvements. In fact, simple and imperfect suspension controllers on a fully actuated suspension remain robust to nominal operation, buying down risk and nullifying extraneous control requirements.

Future rovers may continue to nominally operate in a passive configuration, but the ability to perform an extrication gait, be it inch-worming or squirming, would protect against one of the most notable hazards currently experienced [27]. With this available fault response, more types of terrain can be traversed and faster, enabling more science to be performed. More work still needs to be done to converge to a “best” actuated suspension configuration, but Asterix’s squirming mode may be the simplest and most effective first pass [10]; it only requires one additional actuator and it is powered in a direction that does not need to support loads in normal operation, i.e. a bogie.

More funding has been driven towards commercial entities recently with the CLPS program, which means that there are new opportunities for blank slate rover design. They provide a platform to rewrite conventional design paradigms within lower cost lunar missions, and we can hope to see new perspectives on planetary mobility in the next decade.

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