Leg-Flipper Hybrid Design for Enhancing Robot Locomotion on Granular Slopes

Faiz Aladin[1], Jieming Deng[1], Feng Xue[1]

I. Introduction

Current leg robot locomotion strategies are able to safely traverse tightly compact and flat granular terrains, but are at risk of sinking in loose sloped granular terrain. Flipper based robots are able to "swim" in loose granular terrains but suffer from slippage when the slope increases, causing the robot to take much longer when climbing the slope. Our approach introduces a leg-flipper hybrid design to mitigate the issue of slippage and sinking when the slope of the granular terrain increases. By changing the axial the legs rotates, our robot will be able to avoid sinkage in leg mode under severe conditions and move efficiently despite a slope increase. This transformable hybrid design can allow robot to traverse fast on compact flat terrain, and provide a method to rescue itself from sinkage on fluidized terrain.

II. Related Work

Current research has extensively explored methods to improve locomotion on granular media, primarily focusing on tail-assisted stabilization, specialized interaction models, and hybrid locomotion mechanisms.

A. Tail Based Locomotion

Several studies have highlighted the utility of tails in stabilizing robots on soft substrates. A quadrupedal C-leg robot [1] and mudskipper-inspired robot [2] demonstrate that tails provide essential support and stable ground contact, which aids in recovering from stuck states. Another mudskipper-inspired robot [3] showed that tail oscillation can reduce shear force by fluidizing the sand, thereby increasing speed. However, these methods often face a trade-off: excessive tail motion can disturb the system negatively, fluidization can lead to increased sinkage and traversing velocity is limited. In contrast, our approach utilizes a rigid leg-flipper design that prevent sinkage and maintain efficiency without relying on complex tail-induced fluidization.

B. Flippers and Material Remodeling

Flipper based locomotion and material remodeling have proven to be useful in assisting with granular based locomotion. A sea turtle-inspired robot [4] introduced flipper-based designs, finding that all-soft flippers with a diagonal gait offered continuous propulsion. However, there was severe slippage on terrains with higher slopes. Alternative strategies, such as the "material remodeling" approach employed by the Mini Rover [5], allow the robot to paddle through sand by first building a supportive mound. While effective, this approach is limited to loose, dry media and requires a time-consuming preparation phase, making it inefficient for rapid traversal. In contrast to standard flippers that slip on steep slopes and remodeling techniques that require slow preparation, our custom angled flippers mitigates slippage without a preparation phase.

C. Hybrid Locomotion Strategies

To address the versatility needed for diverse terrains, hybrid designs have been a popular choice. The LinkWheg robot [6] introduces a linkage-based mechanism that reduces leg weight while increasing load capacity; however, it relies on rear rotator pedaling that requires high energy consumtption in changing the terrain. Similarly, the TurboQuad [7] is capable of transforming between wheeled and legged modes to handle flat and complex terrains respectively. However, it was not specifically evaluated on granular sand, leaving a gap in understanding how such transformable mechanisms interact with deformable slopes. Our work directly addresses this gap by implementing and evaluating a leg-flipper hybrid (by changing the angle of the flipper) specifically on granular slopes, experimentally determining the optimal correlation between flipper angle and terrain slope to maximize speed and prevent sinking.

III. Hypothesis

The optimal flipper angle θ directly correlates with the terrain slope β. As the slope increases, the gravity pulling the robot down, $mg\cos(\beta)$, increases as well. The robot must be able to generate enough force to continue moving upwards while not slipping as β increases. The control of the robot θ allow the flippers of the robot to move at a certain angle. For example if θ is 0, the robot's flippers are horizontal or paddling when submmerged in the sand. Similarly if θ is 90 then the robot's floppers are facing directly downward or walking in the sand. We hypothesize there exists a value $\beta_{critical}$ where if $\beta < \beta_{critical}$, then using a value of θ closer to 0 is optimal. If $\beta > \beta_{critical}$, then it is optimal to use a value of θ closer to 90. To support this claim, we look at the components of the flipper. The area of the flipper can be defined as A, which can be further broken down to the depth of the flipper in the sand d and the width of the flipper in the sand w. The depth and width are direct functions of θ. We also define the force generated by robot as $F \propto kd^2w$ where k is the resistive force factor of the granular terrain. Using this equation, we can determine that the least force generated occurs when $\theta = 0$ and the maximum

[1]Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, CA, USA.

force generated occurs when $\theta = 90$. When β is close to 0, the robot does not need to generate as much downward force i.e when $\theta = 0$. However as β increases, the robot will need to generate more force by increasing θ. We hypothesize that the robot will achieve the highest average speed over different values of β when $\theta = 45$.

IV. Experiment Plan

A. Robot Design

An adjustable θ leg design driven by motors is possible using a high torque motor. However, due to the torque limitation of the motor, we choose to use different toe attachments to change θ.

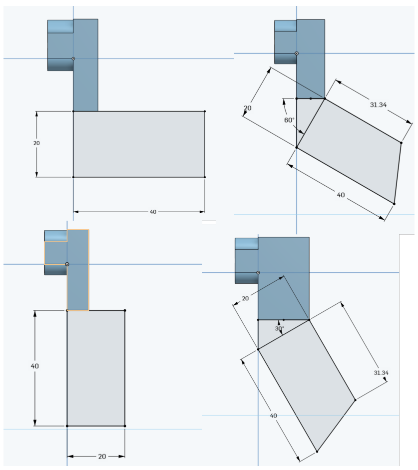

Fig. 1: Left top θ: 0; Right top θ: 30; Left down θ: 90; Right down θ: 60; The grey part of each leg has same area.

Our robot is 18cm in length and 8cm in width. (The widest part is 16cm) It has four legs and one tail. The four legs operate similar to RHex and can choose either trot or bound gait. The tail can rotate in X-Y plane

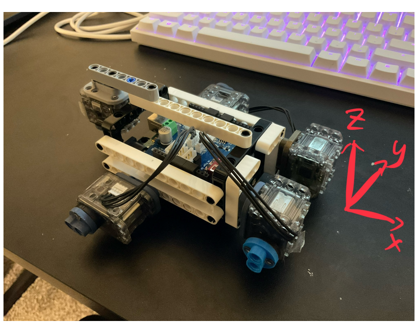

Fig. 2: Robot design. Leg and tail not attached.

B. Experiment setup

We choose to use the granular slope as our test environment. The robot will be placed at low end of the field. The expected trajectory will be a straight line toward the high end of the field. The granular slope has an adjustable β value relative to the ground. We plan to test different values of β equal to 0, 10, 15, 20 degrees. For each β, we select 5 different toe attachments. As mentioned in the previous section, each attachment has the same surface area, with different θ. For each slope and toe attachment, three trials will be conducted. Therefore, a total number of 60 trials of experiments are expected to be ran. For each trial, the only variable is the attachment of the toe. That means the rotation speeds of the leg motors and tail motors are constant through the trials. The tail shape is also consistent. We assume that the toe will be fully submerged at its lowest position. That means changing the toe attachments keeps the area of the flipper same in the sand. According to hypothesis, force generated by the toe is proportional to the depth square of the robot. Increasing θ will lead to increase in depth, which increase the force. We can measure how the resultant speed on x axis change with θ to verify our hypothesis. We will measure the movement speed of the robot on the granular surfaces. A camera will be mounted vertically above the test field, normal to the test surface. We need the camera to be tilted with the current value of β. The moving speed of the robot is measured by the distance (mm) it travels in a given time (30s). After measuring the speed of the robot under for each trial, we will evaluate if the resultant speed corresponds to our hypothesis. According to our hypothesis, the average speed of the robot will increase while θ increases to a certain point. If we keep β constant and increase θ, we find that the yield force exceeds the yield threshold of the granular terrain causing it to sink. We also consider if we keep θ constant and increase β the robot's speed will decrease. Therefore, we are expecting to see a highest average speed at $\theta = 45$ over the different values of β. We want to explain why or why not the hypothesis holds using experiment data and potentially a mathematical model analyzing the force exerting on the flipper.

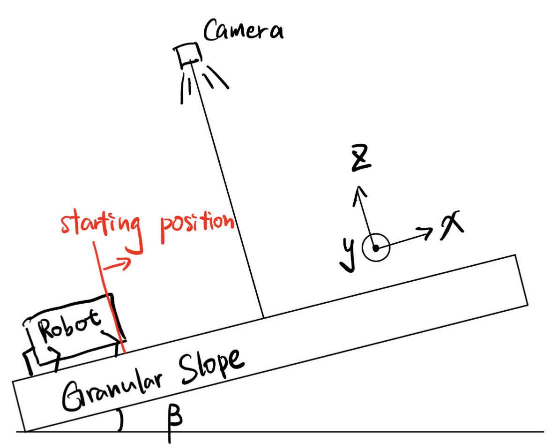

Fig. 3: Experiment Setup Sketch. Measure distance traveled in x direction from starting position in 30s.

V. Results and Discussion

According to Resistive Force Theory, the force applied on foot in granular terrain is related to the penetration depth. In this case $\alpha_z(\beta, \gamma)$ and $\alpha_x(\beta, \gamma)$ are constant. Given that our foot are fully submerged into the terrain, the bulk force applied to the foot is related to the integral of depth and corresponding

		Attachment 1			Attachment 2			Attachment 3			Attachme	
Slope /beta (°)		theta = 0°			theta = 30°			theta = 45°			theta = 6	
		trial 1	trial 2	trial 3	trial 1	trial 2	trial 3	trial 1	trial 2	trial 3	trial 1	trial 2
	X_Distance (mm)											
	Time (s)	30	30	30	30	30	30	30	30	30	30	
0	Speed (mm/s)											
	X_Distance (mm)											
	Time (s)	30	30	30	30	30	30	30	30	30	30	
10	Speed (mm/s)											
	X_Distance (mm)											
	Time (s)	30	30	30	30	30	30	30	30	30	30	
15	Speed (mm/s)											
	X_Distance (mm)											
	Time (s)	30	30	30	30	30	30	30	30	30	30	
20	Speed (mm/s)											

Fig. 4: Experiment Plan, Only three attachments are shown in figure, five attachments in total.

area. We calculate and obtain the force coefficient for each leg in Table I.

$$F_{z,x} = \int_S \sigma_{z,x}(|z|_s, \beta_s, \gamma_s) dA_s$$
$$= \int_S \alpha_{z,x}(\beta_s, \gamma_s)|z|_s dA_s$$

TABLE I: Force coefficient for different θ

θ	0	30	45	60	90
Coefficient	10	16.65	17.97	18.84	20

From our experiment, we found that the robot performs best at $\theta = 90$ on all slopes tested. This contradicts our hypothesis, where we stated that the robot would achieve the highest average speed when $\theta = 45$. Our results indicate that all values of θ saw a linear decrease in speed when we increase the value of β (see Figure.6). We see that the speed of the robot directly correlates with the depth d of the flipper. We can control d by changing θ where d increases as θ increases. We find that as d inc reases, the speed of the robot increases irrespective of β. This is surprising as we predicted the robot would sink into the sand when $\theta = 90$ and when $\beta \approx 0$. We also investigate how energy efficient each flipper angle is. We start with analyzing force exerting on each flipper. As shown in figure.6. We define efficiency as force over speed and observe how this ration changes by different slope and flipper angle. From figure.6, we observe that higher slope leads to lower efficiency and larger flipper angle leads to larger efficiency. The efficiency is the highest at $\theta = 90$ and $\beta = 0$. This means for $\theta = 90$ flipper, not only the force value is the largest, it also has smaller energy lost. A larger portion of the force converts into body speed.

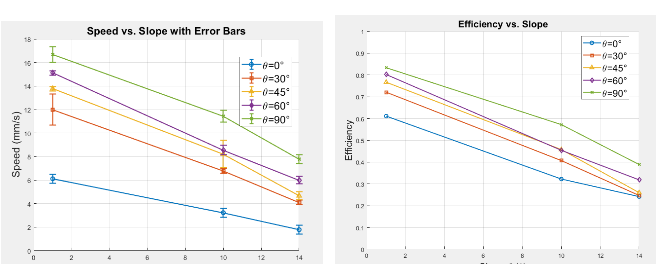

Fig. 5: Graph of speed and efficiency vs. slope of different shape of legs

Further on, we study the resistant force on each flipper motor while paving in sand through experiments. Although the servo motor provided does not a current sensor, we can still get estimated load readings based on PWM signal for each motor. In this experiment we keep β constant and study how different values of θ change the load on the robot. Our results are shown in Figure.6, where we see that the load is relatively the same between different values of θ. The Red dots (theta = 90) show slightly higher overall intensity (RMS) compared to Blue. But the difference is not drastically large across all legs. However, the peak distribution in the scatter plots often shows the red points hitting the saturation limits (±100) more frequently or densely in specific phases of the cycle. The load data collection is constrained by the sampling frequency and structure of the servo motor provided. The gearbox and lack of current reader makes force estimation extremely inaccurate. In the future, we can potentially replace servo motors with direct drive motors to get more accurate force readings.

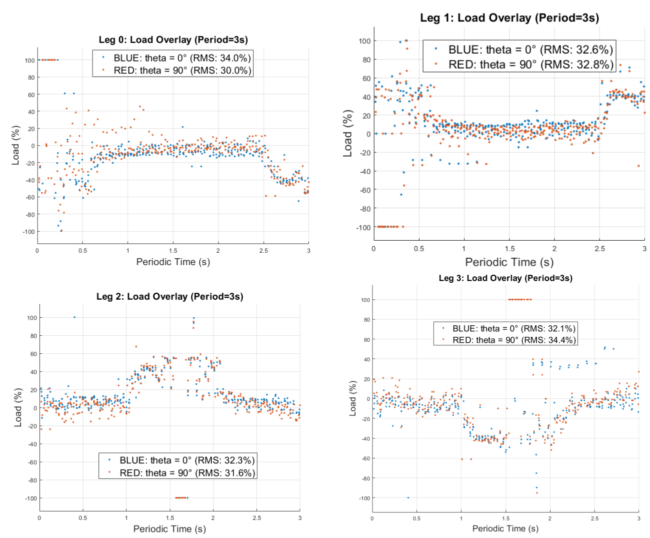

Fig. 6: The load of each leg during a whole period. Leg0 to 3 means right front, left front, left rear, right rear. Blue dots correspond to $\theta = 0$, red points correspond to $\theta = 90$.

This finding indicates that higher values of θ are not only more efficient in terms of speed but also in terms of energy. We can conclude it is overall optimal to use a flipper with $\theta = 90$ given the specific flipper size we use. A limitation of this study lies in the actual size of the flipper. We use small flippers due to the fact that the actuators cannot generate enough torque to move larger flippers in the granular media. However it is possible that using larger flippers would align more with our initial hypothesis where the robot would start to sink as θ increases. In future work, we aim to study if our findings can be generalized to robots with larger flippers and stronger actuators.

For the application of this research work, we want to suggest that the flipper robot toe design should be vertical instead of horizontal to provide the largest ground reaction force on granular media. However, a higher ground reaction force also means higher resistance force applied on motor, which might lead to higher energy cost. In the worst case, the robot is not able to drive the flippers penetrating into the granular media, which lead to failure in motion. This can be proved by our preliminary experiment on rigid flat ground, where vertical flipper eventually leads to break in robot structure. In general, we suggest that design a deeper flipper instead of a wider one to receive largest speed on granular terrain within the capability of the motors and robot structure.

References

[1] D. Soto, K. Diaz, and D. I. Goldman, "Enhancing legged robot navigation of rough terrain via tail tapping," in *Robotics for Sustainable Future - CLAWAR 2021, Virtual Event, Japan, 30 August - 1 September 2021*, ser. Lecture Notes in Networks and Systems, D. Chugo, M. O. Tokhi, M. F. Silva, T. Nakamura, and K. M. Goher, Eds., vol. 324. Springer, 2021, pp. 213–225. [Online]. Available: https://doi.org/10.1007/978-3-030-86294-7_19

[2] S. Liu, M. Sagare, S. Patil, and F. Qian, "Bio-inspired tail oscillation enables robot fast crawling on deformable granular terrains," 2025. [Online]. Available: https://arxiv.org/abs/2509.12468

[3] B. McInroe, H. C. Astley, C. Gong, S. M. Kawano, P. E. Schiebel, J. M. Rieser, H. Choset, R. W. Blob, and D. I. Goldman, "Tail use improves performance on soft substrates in models of early vertebrate land locomotors," *Science*, vol. 353, no. 6295, pp. 154–158, 2016. [Online]. Available: https://www.science.org/doi/abs/10.1126/science.aaf0984

[4] N. C. Chikere, J. S. McElroy, and Y. Ozkan-Aydin, "Embodied design for enhanced flipper-based locomotion in complex terrains," *Scientific Reports*, vol. 15, no. 1, Mar. 2025. [Online]. Available: http://dx.doi.org/10.1038/s41598-025-91948-3

[5] S. Shrivastava, A. Karsai, Y. O. Aydin, R. Pettinger, W. Bluethmann, R. O. Ambrose, and D. I. Goldman, "Material remodeling and unconventional gaits facilitate locomotion of a robophysical rover over granular terrain," *Science Robotics*, vol. 5, no. 42, p. eaba3499, 2020. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.aba3499

[6] J. Ma, M. Zhu, T. Zhang, E. Capello, and X. Yue, "Flexibility and granular terrain adaptability of a linkage-based wheel-legged robot: Linkwheg," *IEEE/ASME Transactions on Mechatronics*, pp. 1–11, 2025.

[7] W.-H. Chen, H.-S. Lin, Y.-M. Lin, and P.-C. Lin, "Turboquad: A novel leg–wheel transformable robot with smooth and fast behavioral transitions," *IEEE Transactions on Robotics*, vol. 33, no. 5, pp. 1025–1040, 2017.