Extending geometric mechanics beyond kinematic isotropic systems

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Abstract

Geometric Mechanics(GM) analysis of locomotion has provided valuable insights into how biological and robotic systems use changes in shape to move by exploiting mechanical interaction with the environment. However, the data-driven forms of these analyses currently work only in isotropic environments on kinematic systems. In this research, we aim to extend the classic geometric mechanics method to work in non-isotropic environments on systems with dynamic effects. We will conduct experiments with multiple robots in various environments. We will analyze the data using mathematical and statistical methods and data-driven techniques to create accurate models, expanding the applicability of geometric mechanics for robotic locomotion.

Background- Geometric Mechanics

Geometric mechanics form helps analyze biological and bio-robotic locomotion systems. By directly controlling a robot's shape $\boldsymbol{r}(t)$, geometric mechanics can be used for path planning and gait optimization. The approach effectively encapsulates the system's dynamics into a compact form, making it easier to apply algorithmic methods for analysis, planning, and control.

Kinematic model: $\mathbf{v_b} = A(\mathbf{r})\dot{\mathbf{r}}$

Dynamics model: $\begin{cases} \mathbf{v_b} = \mathbf{A}(\mathbf{r})\dot{\mathbf{r}} + \boldsymbol{\Gamma}(\mathbf{r})\mathbf{p} \\ \dot{\mathbf{p}} = \mathbf{f}(\mathbf{r}, \dot{\mathbf{r}}, \mathbf{p}) \end{cases}$

$\mathbf{v_b}$ - velocity of the body-fixed frame origin expresses in body frame.
$\mathbf{r}, \dot{\mathbf{r}}$ - shape position and velocity
$A(\mathbf{r})$ - matrix denoting mechanical connections.
$\mathbf{p}$ – generalized momentum vector
$\boldsymbol{\Gamma}(\mathbf{r})$ -matrix encoding the inertial influence of momentum on body motion
$\mathbf{f}$ - depends quadratically on $\dot{\mathbf{r}}, \mathbf{p}$ and nonlinearly on $\mathbf{r}$

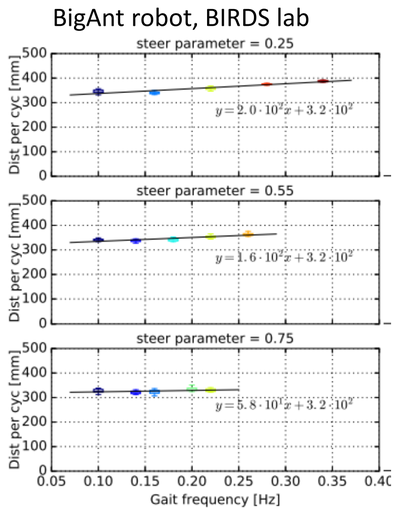
Previous Work

@ Michigan

Recently [1] showed a GM-based analysis of BigAnt, a six-legged robot. This included comparing a data-driven GM model of the robot to tracked motions with steering at multiple gait frequencies; the motion included skidding/slipping. When examining the results of distances traveled per cycle and turn angle per cycle, they obtained a small but systematic trend with respect to gait frequency for all three steering cases. This trend, which is not explained by the zero-momentum GM model might be an expression of the discarded momentum term.



BigAnt robot, BIRDS lab

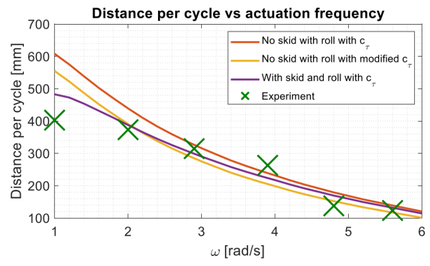


Geometric analysis of BigANT motion with steering gaits using three levels of steering input, and a range of gait frequencies.

@ Technion

Recently [2] presented an analysis of a wheeled three-link snake robot motion. This included comparing four developed models, accounting for skid and roll resistance in motion, to experimental results. The results showed that the actuation frequencies affected the non-kinematic models. The results showed that the wheels' skid, the dissipation, and the inertial forces created the major effect on the model that explained the robots' motion. The formulation in [2] was model-specific and needs to be generalized into the GM framework in order to enable further systematic analysis of gaits.

Wheeled three-link snake robot



Distance per cycle of the Wheeled three-link snake robot motion actuated in different gait frequencies. Comparisons of experimental results to three theoretical models.

Employing an extended GM method with momentum will provide deeper insights into the systems' motion.

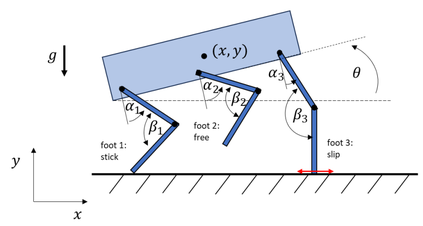
Research Goal

This research will extend the application of data-driven geometric mechanics models to non-isotropic and dynamically changing environments, including non-negligible inertial effects, while incorporating data-driven methods for constructing a compact model from real-time noisy measurements.

Robotic Systems

Our aim is to create a technique for overcoming a single limitation at each step, and then test it through analysis, simulations and experiments, while keeping our analytical models simple, and gradually increasing their complexity. For certain limitations, there are existing methods that could be used as a benchmark. The method will be implemented on the following robotic systems:

Planar Three-Legged Robot



Develop a piecewise continuous kinematic model with six different contact modes

Extend to incorporate

motion on known non-uniform sloped segments with different friction coefficients

Multi-legged robots: BigAnt and the Multipod -BIRDS Lab Michigan



6 legged Multipod robot

Develop Kinematic models based on the data-driven Geometric mechanic methods

Extend to

include dynamic effects

Steerable Wheeled Vehicle - Technion Lab



Steerable Wheeled Vehicle, unmodified and modified on granular terrain

Develop simple kinematic model

Extend to

consider non-ideal constraints- skid and slip

Extend to

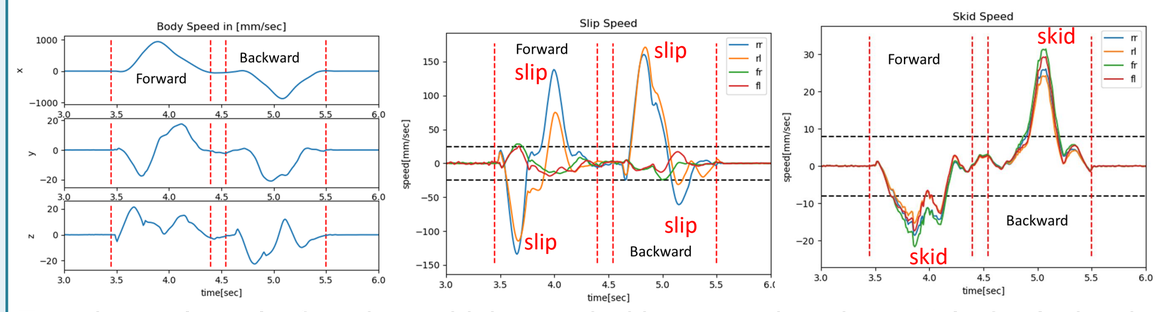
include dynamic effects

Extend to

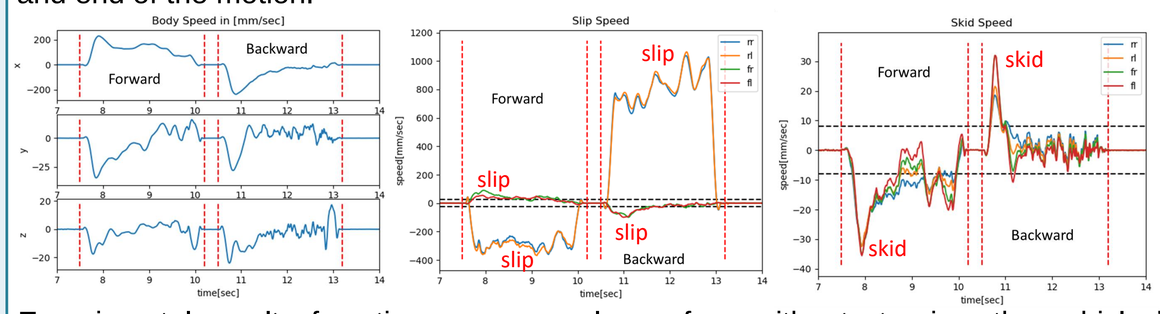
incorporate dynamic changes in granular terrain

Preliminary results

We have designed an experiment system for a Steerable Wheeled Vehicle that demonstrates the significant skidding and slipping of the wheels. We tested the robot on various terrains at different speeds and steering angles, clearly displaying the substantial skidding and slipping of the wheels and our ability to measure and estimate these phenomena accurately.



Experimental result of motion at high speed without steering, the vehicles' velocity, the slip and skid speed of each wheel. We can see a significant slippage at the beginning and end of the motion.



Experimental result of motion on a granular surface without steering, the vehicles' velocity, the slip and skid of each wheel. We can see a major slip of the actuated rear wheels.

[1] Zhao, D., Bittner, B., Clifton, G., Gravish, N. and Revzen, S., 2022. Walking is like slithering: A unifying, data-driven view of locomotion. Proceedings of the National Academy of Sciences, 119(37), p.e2113222119.
[2] Rizyaev ,2023 ,Locomotion dynamics of an underactuated three-link robotic vehicle, Msc thesis.