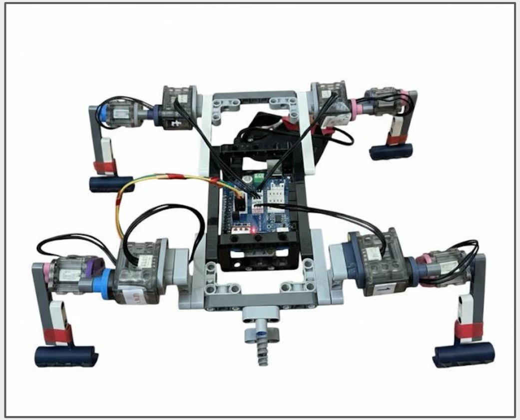
Inter-Diagonal Leg-Pair Phase Asymmetry in the Trotting Gait can Reduce Lateral Drift for a **Quadrupedal** Robot when **Climbing Sloped Inclines** with discrete footholds



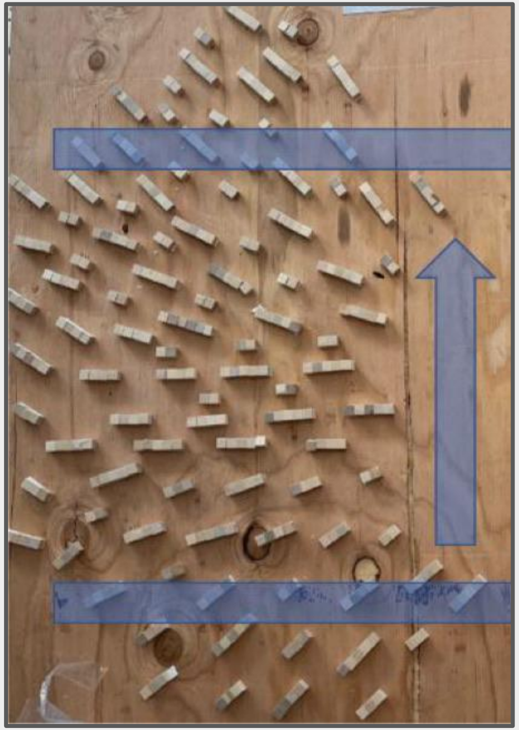
Presented by: **Pagnapech Chamroeun**, **Josh Hom**, **Eric Kwei**

Agenda

- Introduction
- Existing Work
- Research Question
- Novelty
- Robot Design
- Methodology
- Results
- Limitation and Future Work
- Conclusion
- Q&A

Introduction

- Symmetric Gaits (e.g., trot, walk).
- Most gait controller assume Left–Right Symmetry
- **Real terrain is asymmetric**—especially slanted, uneven footholds.
- Discrete footholds create **different contact angles and loads** on each side of the robot.
- **Knowledge gap:** It is unclear whether **bilateral asymmetric gaits** could improve stability and climbing performance on such terrain.



Research Question

Can applying an offset to the inter-diagonal leg-pair phase, deviating from the canonical π for symmetric gaits, reduce lateral drift for a quadrupedal robot navigating a sloped incline with slanted footholds?

Motivation:
Understanding gait asymmetry dynamics should allow robotic engineers to make better informed decisions when deploying legged robots during:

- Disaster response
- Planetary exploration
- Other applications involving asymmetric terrain

Existing Work

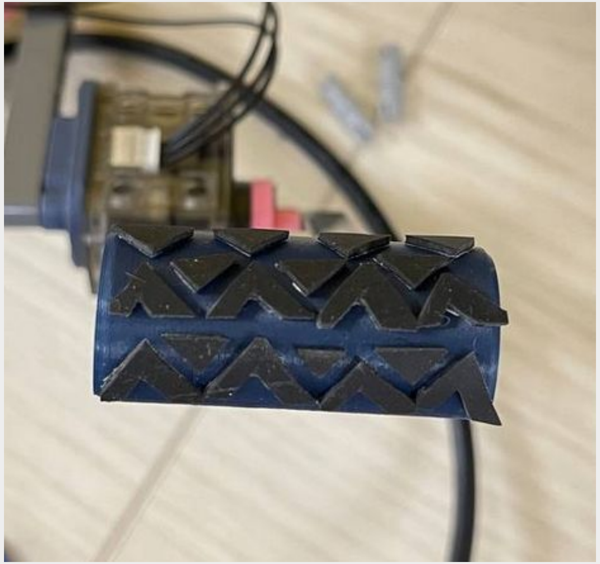
- Common gaits assume **symmetric, periodic coordination** → degrade on slopes/irregular terrain.
- **Free gaits** improve adaptability (Estremera 2002) → but asymmetry not quantified for slopes.
- **Energy-optimal asymmetry** shown on flat ground (Alqaham 2024) → no stability analysis on inclines.
- **Slope-climbing methods** (Guo 2019; Majithiya 2021; Li 2024): posture control only, assume uniform footholds, **no bilateral asymmetry**.
- **Simulation/CPG studies** (Sellers 2018; Song 2023): asymmetry improves robustness, but **not validated on slanted footholds**.
- **Biological evidence** (Frigon; Fukuoka): natural locomotion uses intrinsic asymmetry → but no robotic stability evaluation.

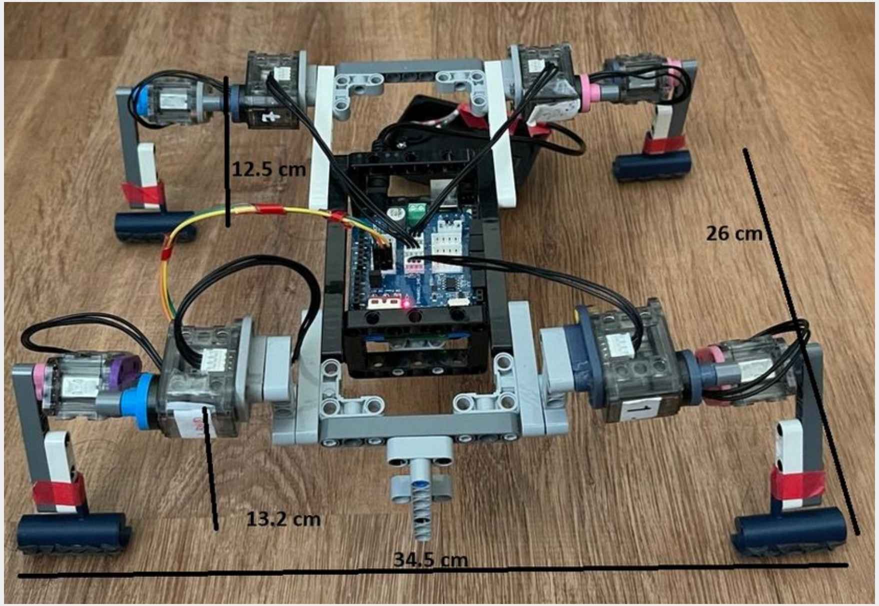
What are the novelty of this research?

- There are 2 reasons our work is novel:
    - Gait controller that intentionally introduces **asymmetry** as a deliberate strategy to **reduce lateral drift**
    - Foothold slant direction, terrain slope, and gait asymmetry **interactions** underexplored

Robot Design

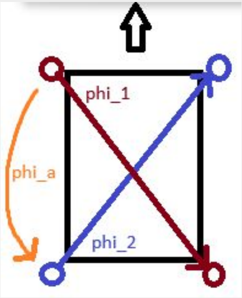
- 2 DOF per leg
- each leg moves in sagittal plane only
- 3D printed feet with rubber tread design for better friction



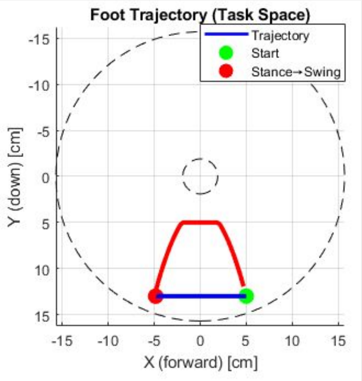


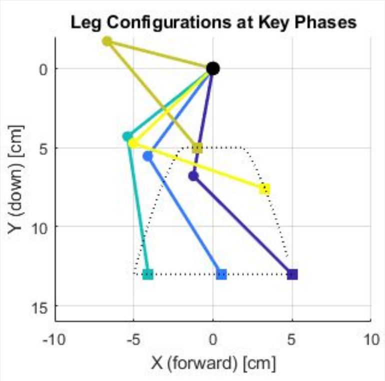
Methodology

- Inter-diagonal leg-pair phase asymmetry for trot:
  - $\Delta\phi_1 = \phi_{RR} - \phi_{LF} \neq 0$ (intra-diagonal leg-pair phase difference, first pair)
  - $\Delta\phi_2 = \phi_{RF} - \phi_{LR} \neq 0$ (intra-diagonal leg-pair phase difference, second pair)
  - $\Delta\phi_\alpha = \phi_{LR} - \phi_{LF} \neq \Pi$ (inter-diagonal leg-pair phase difference)
  - $\phi = 0$ when the LF-RR pair enters stance



- Independent Variables
  - β (slope incline) $\in \{5°, 10°\}$
  - $\Delta\phi_\alpha \in \{140°, 160°, 180°, 200°, 220°\}$ (when $\beta = 5°$)
  - $\Delta\phi_\alpha \in \{160°, 170°, 180°, 190°, 200°\}$ (when $\beta = 10°$)
- Dependent Variables
  - Δs (lateral drift in cm/trial)
  - t (time in sec)

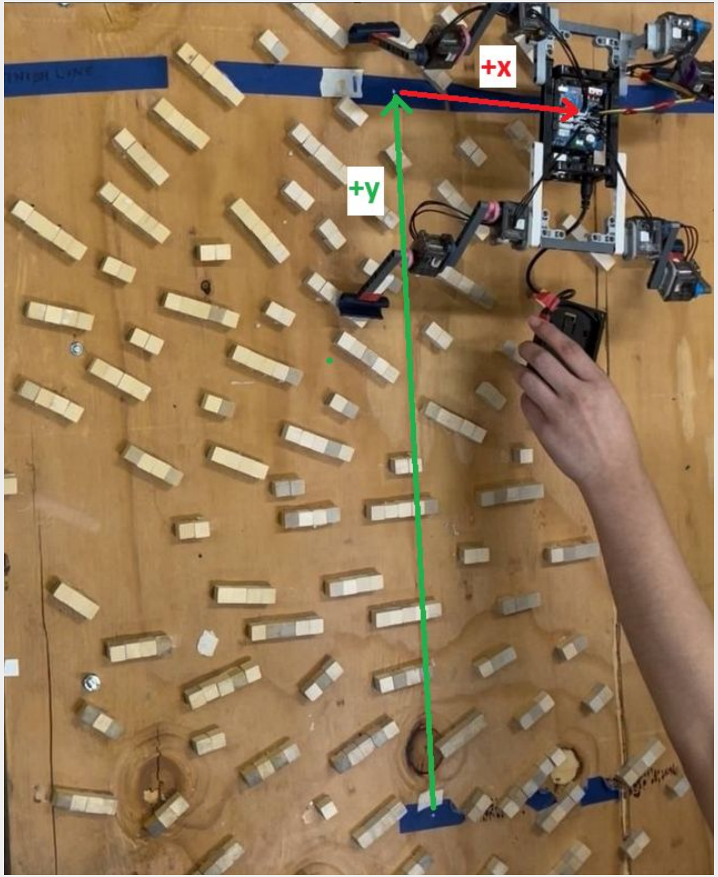




Methodology

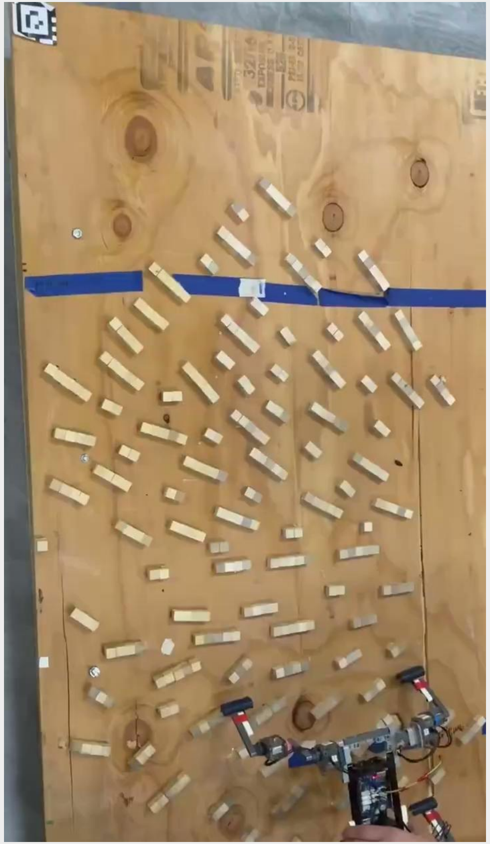
Experimental setup

- (2x5 data points with 3 trials each = 30 total)
    - Robot starts at fixed point on the board at $\phi \cong 0$ (start of LF-RR stance phase), facing uphill
    - Successful trial ends at 65 cm longitudinal displacement (finish line)
    - Robot's x,y position measured from center of Arduino Uno board.
- Robot was fine-tuned for each incline, then kept constant for every trial for that incline
- Failed trials: x,y recorded when x reaches +/-21cm (robot still on board, but would fall off next gait cycle)

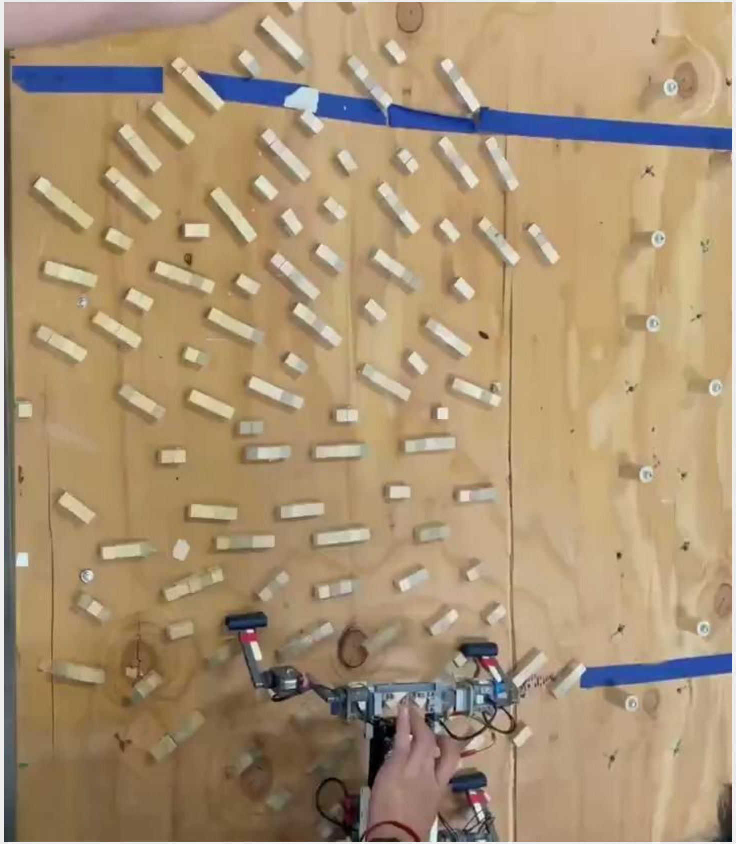


Results

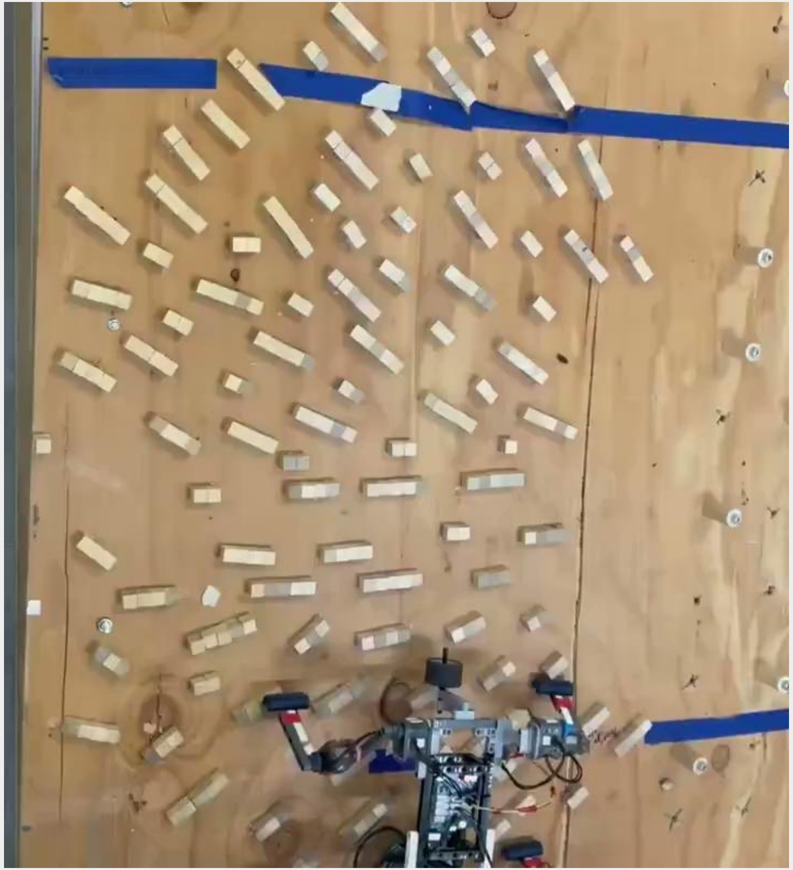
5° Slope, 160° Phase Difference



5° Slope, 180° Phase Difference



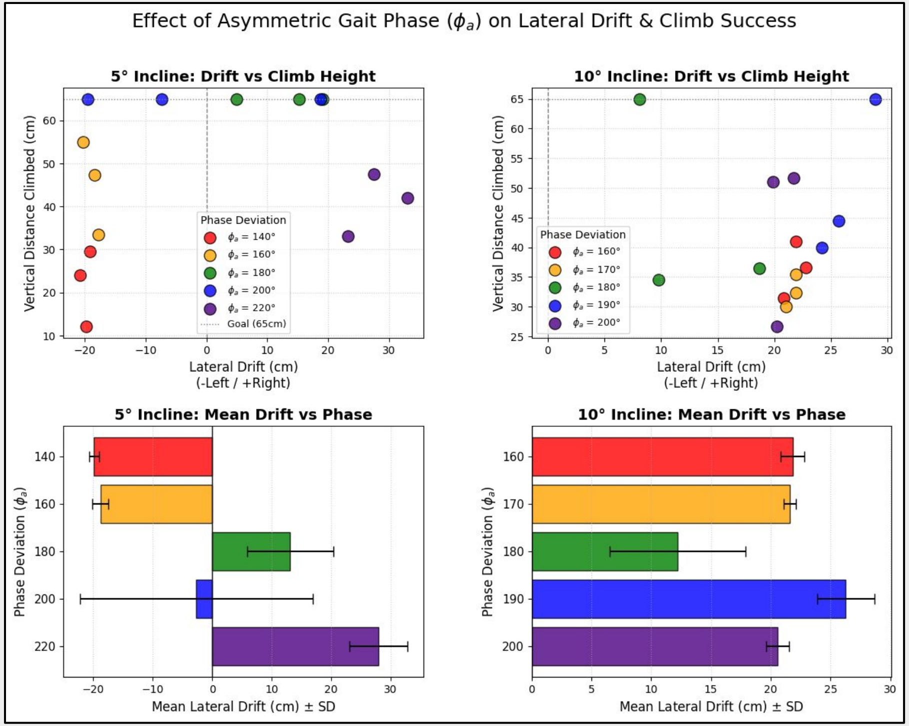
5° Slope, 200° Phase Difference



10° Slope, 160° Phase
Difference

Results

- At 5° incline
  - At 180° (symmetric), 13.3 cm mean drift
  - At 200° (expected right bias), -2.7 cm mean drift
- At 10° incline
  - At 180° (symmetric), 12.2 cm mean drift
  - At 200° (expected right bias), 20.6 cm mean drift
  - Any offset resulted in an increase in lateral drift



Conclusion

- At 5°, bilateral phase asymmetry is indeed a functional mechanism for steering and drift correction
- At 10°, reveal a critical boundary condition: the influence of steering via altering the $\Delta\phi\alpha$ of the gait is finite. From the data we do have, we cannot reach any conclusion for the 10° incline, other than that our tested $\Delta\phi\alpha$ offsets all resulted in an increase in lateral drift.
- Phase asymmetry between concurrently actuating diagonal leg pairs provide a controllable and monotonic “fine-tuning” method of steering correction at lo inclines but cannot compensate for larger influential conditions like steeper terrain or foothold geometry which can overpower gait-based corrections and more drastically impact the robot’s trajectory.

Limitation and Future Work

- More $\Delta\phi\alpha$ data points, more trials per data point, tighter array of $\Delta\phi\alpha$
  - (e.g. $\Delta\phi\alpha$ = {172, 174, 176, 178, 180, 182, 184, 186, 188})
  - More reliable data, better to find a possible optimal $\Delta\phi\alpha$ for reducing mean lateral drift.

- More / stronger motors to increase the anchoring strength
  - Allows asymmetric testing and higher inclines and different footholds

- Implementation of force sensors on the feet
  - Reveals more data on specifically which foot is being more depended on

- Improved Foot design
  - Give more support on a step without a foothold

Reference

[1] J. Estremera and P. Gonzalez-de Santos, “Free gaits for quadruped robots over irregular terrain,” I. J. Robotic Res., vol. 21, pp. 115–130, 02 2002.

[2] Y. G. Alqaham, J. Cheng, and Z. Gan, “Energy-optimal asymmetrical gait selection for quadrupedal robots,” IEEE Robotics and Automation Letters, vol. 9, no. 10, pp. 8386–8393, 2024.

[3] G. Guo, H. Chai, Y. Li, X. Rong, and B. Li, “Practical techniques research on climbing the steep slope of quadruped robots,” in 2019 IEEE 9th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER), 2019, pp. 1150–1155.

[4] W. I. Sellers and E. Hirasaki, “Quadrupedal locomotor simulation: producing more realistic gaits using dual-objective optimization,” Royal Society Open Science, vol. 5, no. 3, p. 171836, 2018. [Online]. Available: https://royalsocietypublishing.org/doi/abs/10.1098/rsos.171836

[5] A. Majithiya and J. Dave, “Static gait scheme for horizontal posture slope climbing with quadruped robot,” Journal of Physics: Conference Series, vol. 2115, no. 1, p. 012005, nov 2021. [Online]. Available: https://doi.org/10.1088/1742-6596/2115/1/012005

[6] Z. Song, J. Zhu, and J. Xu, “Gaits generation of quadruped locomotion for the CPG controller by the delay-coupled VDP oscillators,” Nonlinear Dyn., vol. 111, no. 19, pp. 18 461–18 479, Oct. 2023.

[7] P. Li, B. Yin, L. Zhang, and Y. Zhao, “Adaptive control algorithm for quadruped robots in unknown high-slope terrain,” Journal of Engineering Research, vol. 13, no. 3, pp. 1771–1784, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2307187724001305

[8] A. Frigon and J.-P. Gossard, “Asymmetric control of cycle period by the spinal locomotor rhythm generator in the adult cat,” J. Physiol., vol. 587, no. Pt 19, pp. 4617–4628, Oct. 2009.

[9] Y. Fukuoka, Y. Habu, and T. Fukui, “A simple rule for quadrupedal gait generation determined by leg loading feedback: a modeling study,” Sci. Rep., vol. 5, no. 1, p. 8169, Feb. 2015.

Q&A

Thank you for your Attention