Legged Locomotion Leveraging Spring-Loaded Obstacle Terrain

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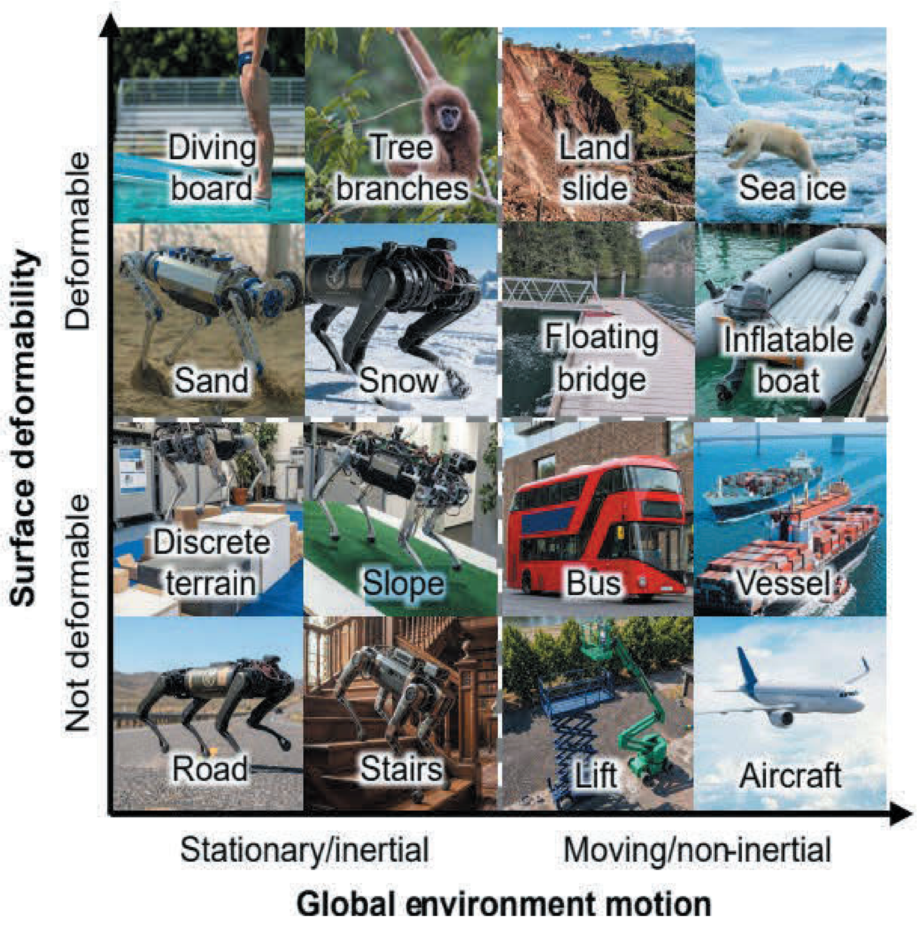
Motivation

Obstacle-robot, motion-coupled locomotion on deformable terrain

- Locomotion on deformable terrain, where robot–terrain motion coupling occurs, remains a gap in existing literature [1].

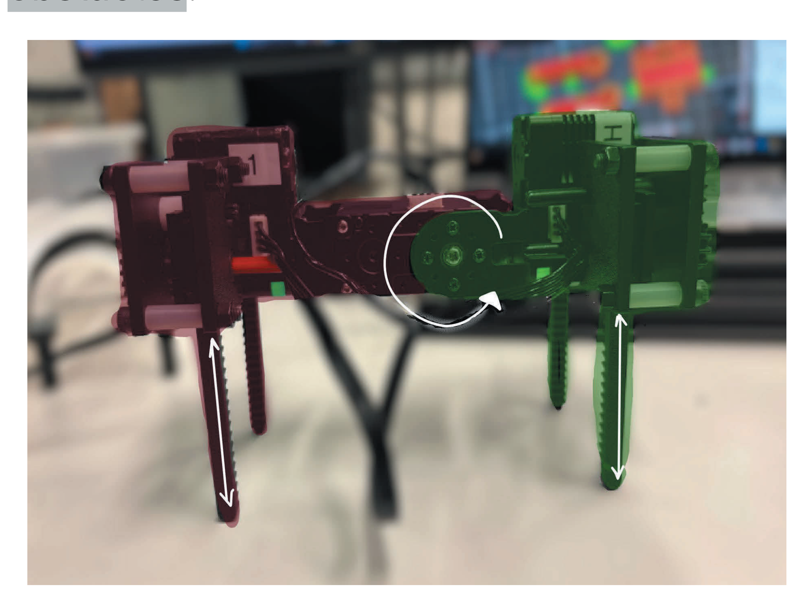


Potential robotic deployment environments, with non-inertial and deformable characterizations [1].

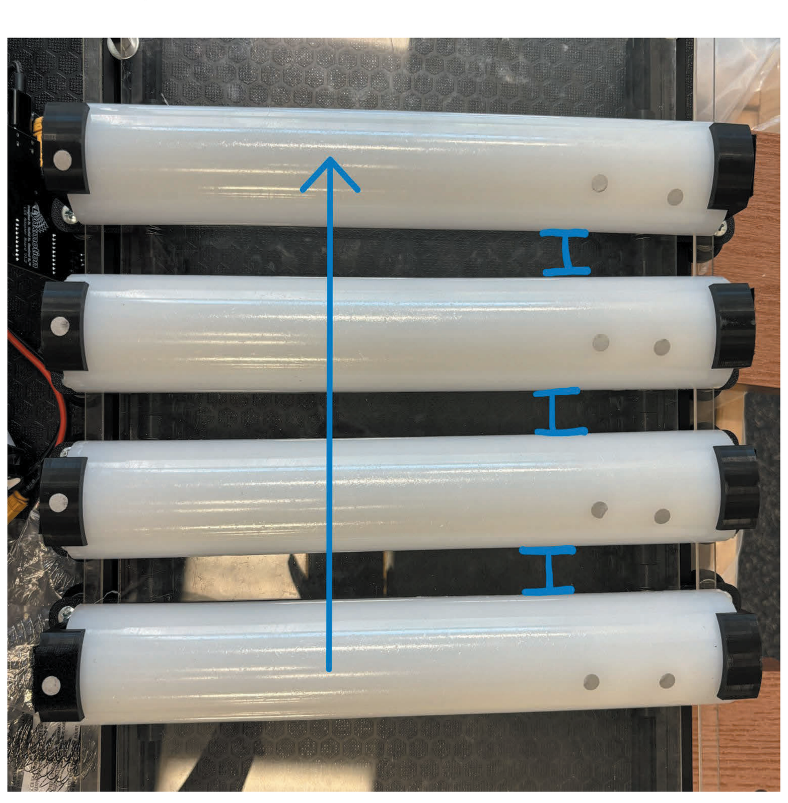
- Discrete probe-then-decide traversability strategies [2] and deployment of legged robots in obstacle-dense environments like substations and construction sites [3], [4], raise a further question: Can a robot successfully exploit a yielding obstacle field?
- Key question: assuming a greater range of successful ϕ_{fb} values signals robustness to gait variation and less dependence on tuned leg length or gait-selection design, how does obstacle stiffness/deformability alter the feasible range of ϕ_{fb}?

Prior Work

- Prior work linked leg-body position wave phase offset (ϕ_{fb}) to horizontal traversal velocity
- This work considered locomotion over static obstacles.



Legged robot with 3 DOFs. Forward motion is defined by motion in the direction of the green body module. Arrows denote DOFs.

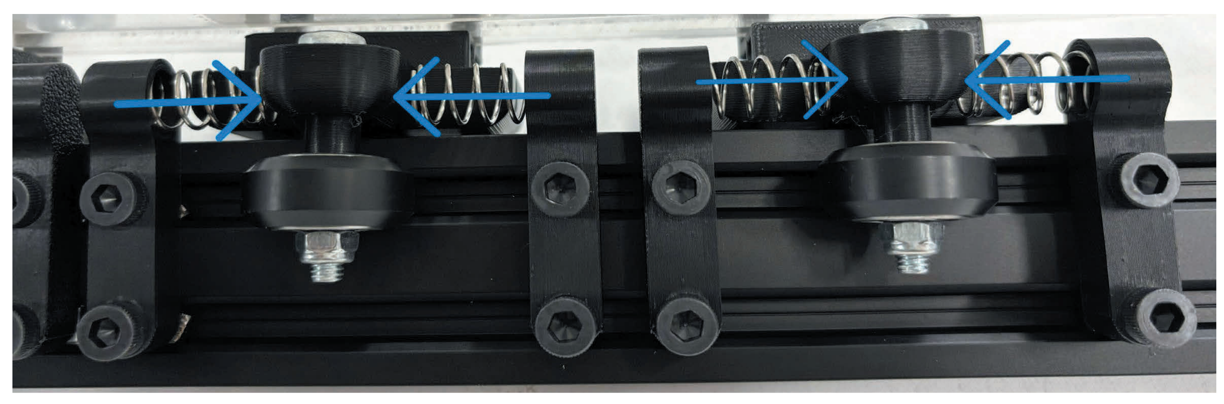


Static obstacle terrain composed of evenly-spaced hemispherical PVC obstacles. Blue arrow denotes robot traversal axis.

Methodology

Experiment Setup

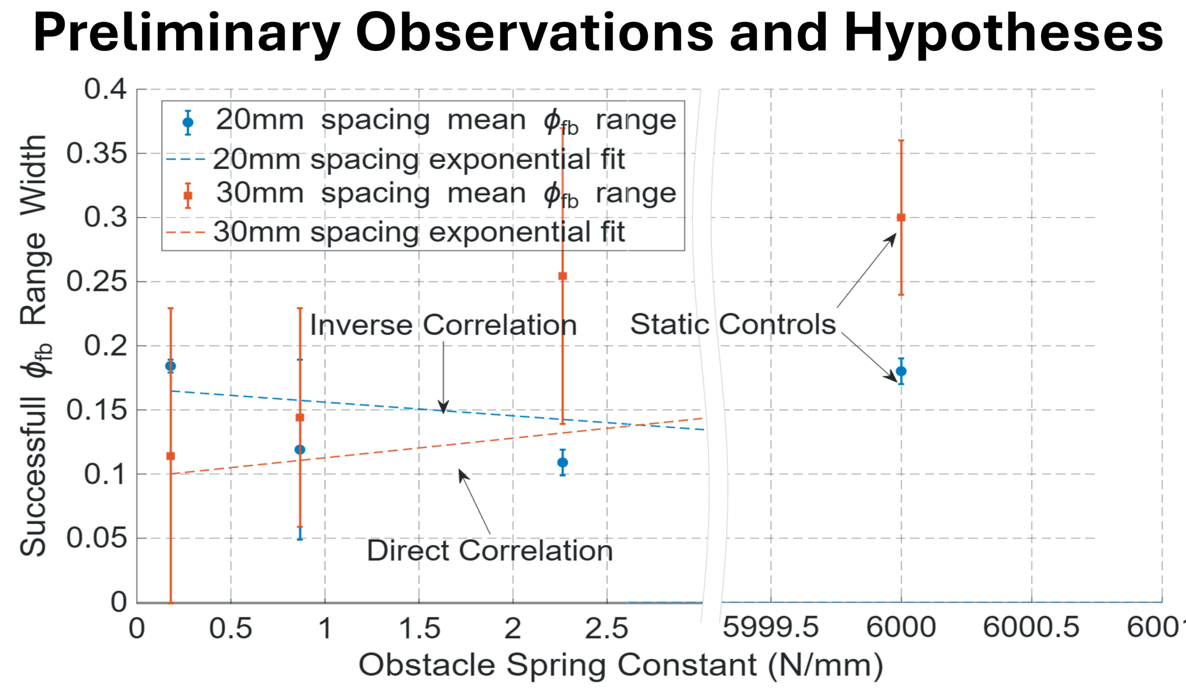
- At small-to-moderate deformation, yielding terrain behaves approximately like a spring [5]. This motivates a spring-loaded obstacle model.



Obstacles are mounted on spring-loaded linear sliders.

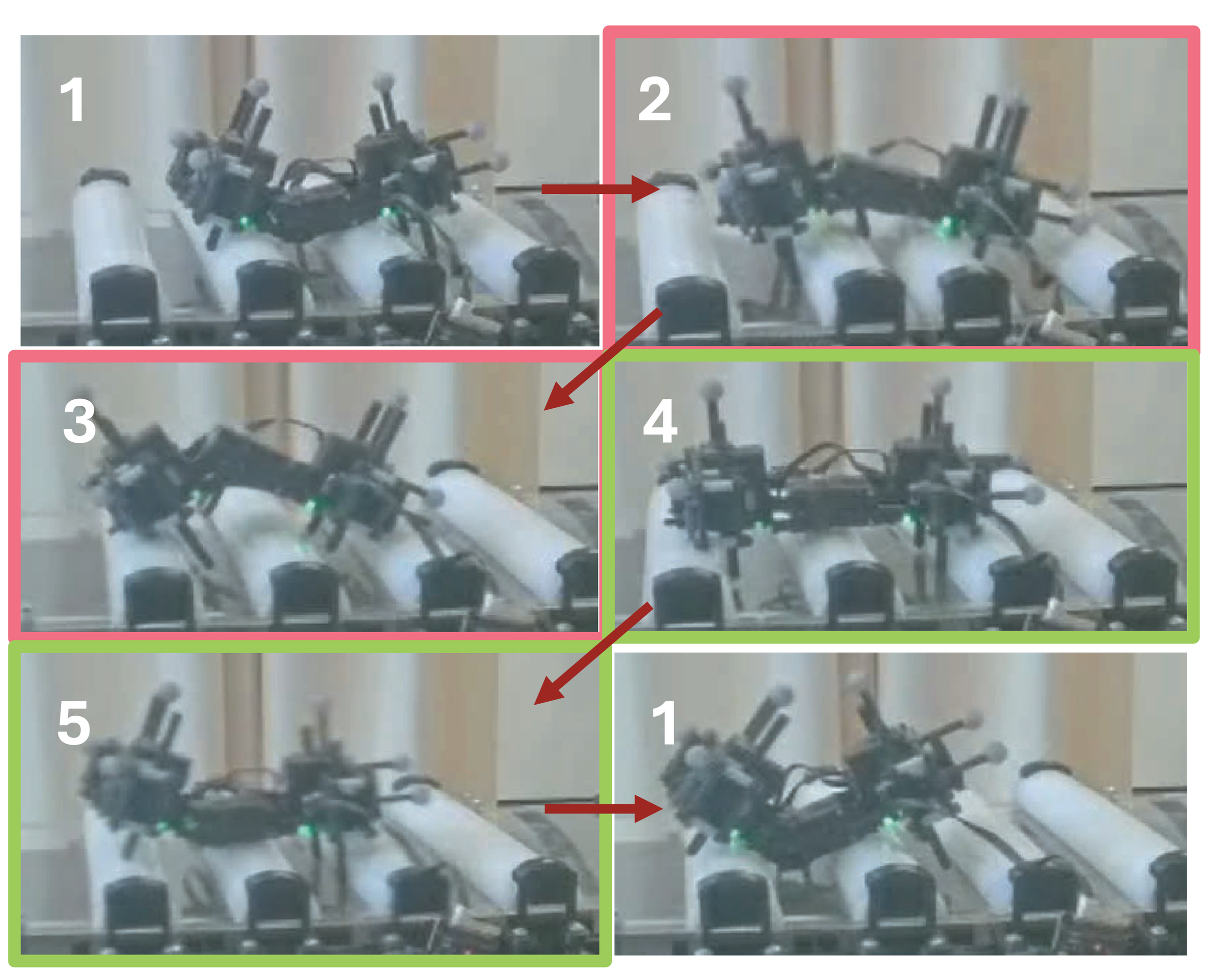
- Our initial, rigid obstacle setup can be modeled as a loaded obstacle with a very high spring constant, consistent with prior spring–damper obstacle-contact formulations [6]. This served as a theoretical limit for observed trendlines.

Preliminary Observations and Hypotheses



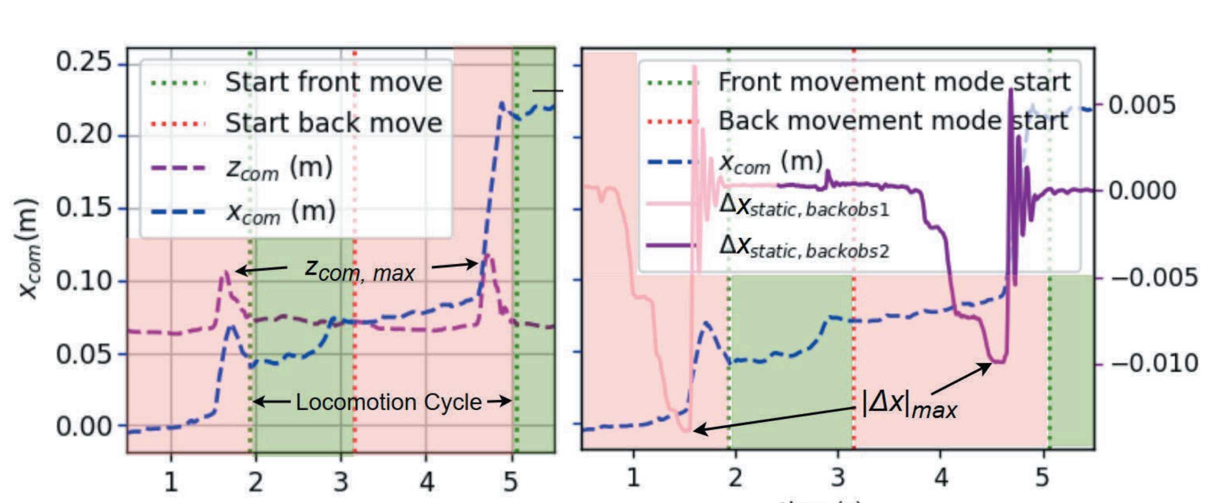
Successful ϕ_{fb} Range Width vs Obstacle Loading

- 20mm trials demonstrate inverse correlation
- 30mm trials demonstrate direct correlation
- Robot motion is cyclical and can be divided into two movement modes (each with a failure mode):



Front movement mode (failure mode: back leg slips)
Back movement mode (failure mode: legs squeeze PVC)

Tracked Metrics

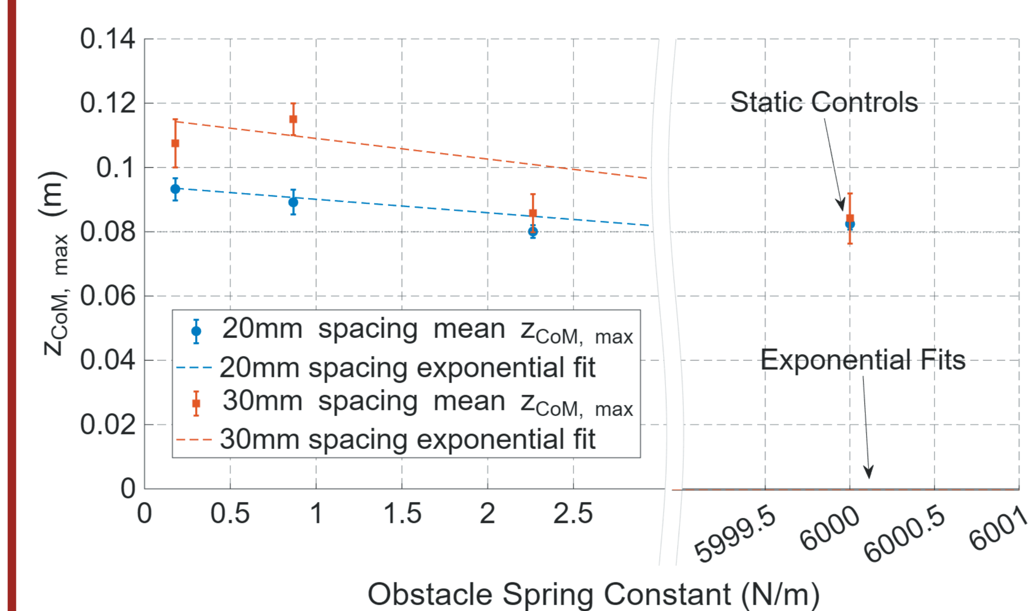


Left: Robot center of mass x and z-coordinates over time. Tracking maximum z-coordinates.

Right: Robot center of mass x-coordinate and obstacle x-displacements (from equilibrium) over time. Tracking maximum x-displacement of back obstacle.

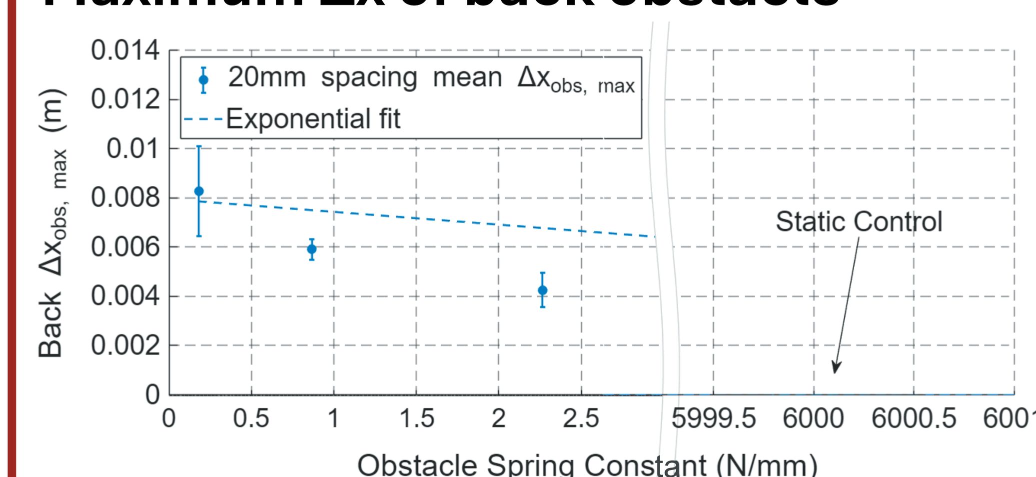
Results

Maximum z-coordinates



- Trials of 30 mm spacings feature consistently greater CoM vertical displacements than 20 mm trials.
- If obstacle spacing is greater, robot is better able to traverse "stiff" terrains.
  - Robot can overcome squeezing failure mode by dislodging back leg through CoM vertical displacement

Maximum Δx of back obstacle



- Maximum Δx of back obstacle demonstrates inverse correlation with obstacle loading
- If terrain is soft, robot is better able to traverse smaller obstacle spacings
  - Robot can overcome slipping failure mode by displacing rather than crossing back obstacle.

Discussion

Significance

- Within elastic deformation ranges, a legged, quadruped robot might leverage a deformable obstacle field for terrain traversal, despite significant yielding.
- In low spring constant or "soft," obstacle-dense terrains, and higher spring coefficient or "stiff," obstacle-sparse terrains, this legged robot achieves locomotion performance comparable to static terrains.
- In "stiff," obstacle-sparse terrains, legged robots may "squeeze" obstacles, within certain range of leg-body position phase offsets, to achieve greater vertical displacement and large obstacle-gap traversal.

Limitations/Future Work

- As this robot is a simple, research-oriented robot, further work includes similar investigations on state-of-the-art legged robots and quadrupeds.

Acknowledgements

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References

[1] I.-C. Chang, X. Huang, T.-Y. Lin, S. Teng, W. Li, M. Ghaffari, J. Yi, and Y. Gu, "A survey of legged robotics in non-inertial environments: Past, present, and future," arXiv:2604.20990, 2026.
[2] G. Haddeler, M. Y. M. Chuah, Y. You, J. Chan, A. H. Adiwahono, W. Y. Yau, and C.-M. Chew, "Traversability analysis with vision and terrain probing for safe legged robot navigation," Front. Robot. AI, vol. 9, art. 887910, 2022.
[3] Oxmaint, "Quadruped & legged robots for substation & switchyard inspection 2026," oxmaint.com, Feb. 2026.
[4] Y. Xu, C. Cheung, M. S. Ng, A. Yunusa-Kaltungo, T. Ishizawa, and K. Fujimoto, "Construction robotics: A systematic review of robot types, applications and human robot collaborations," Results Eng., 2026.
[5] H. Zhuang, J. Wang, N. Wang, W. Li, N. Li, B. Li, and L. Dong, "A review of foot–terrain interaction mechanics for heavy-duty legged robots," Appl. Sci., vol. 14, no. 15, art. 6541, 2024.
[6] A. A. Transeth, R. I. Leine, C. Glocker, K. Y. Pettersen, and P. Liljebäck, "Snake robot obstacle-aided locomotion: Modeling, simulations, and experiments," IEEE Trans. Robot., vol. 24, no. 1, pp. 88–104, Feb. 2008.