

# Forceful milli-robot teams on varied natural terrains

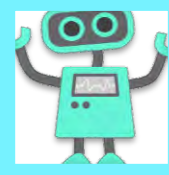


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Assistant Professor, Mechanical Engineering

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Jadesola Aderibigbe



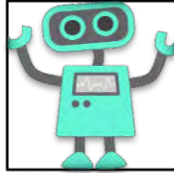
Cyndia Cao



Erin Chang



Yuri Gloumakov



Tae Myung Huh



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Sebastian Lee



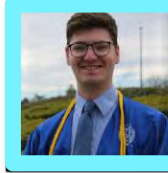
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Drew McPherson



Justin Page



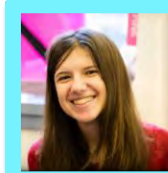
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**Early Career Faculty (ECF)**

Collab.: Steven Jorgensen

80NSSC21K0069 (Huh/Aderibigbe/Page)

**Space Technology Research Fellowship**

Collab.: Colin Creager, Christopher Yahnker

80NSSC19K1166 (Li)

80NSSC19K1167 (Cao)



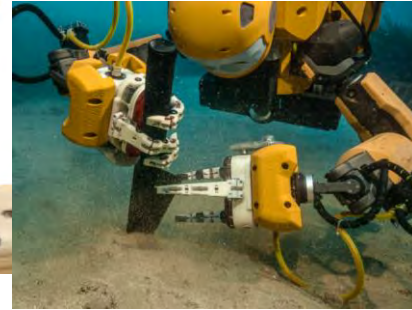
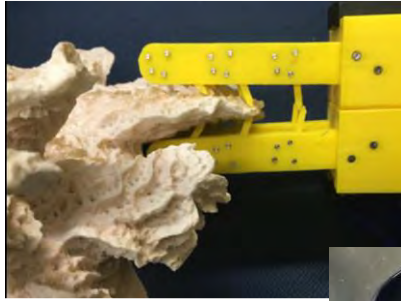
**NDSEG**  
(Treers)





# Modeling contact for robotics design

Contact ↔ Embodied Agent



An artist's concept of the Axel rover rappelling into a lunar pit. (Courtesy NASA / JPL-Caltech ). Smithsonian Magazine.



A permanently shadowed lunar crater. Credit: NASA's Goddard Space Flight Center



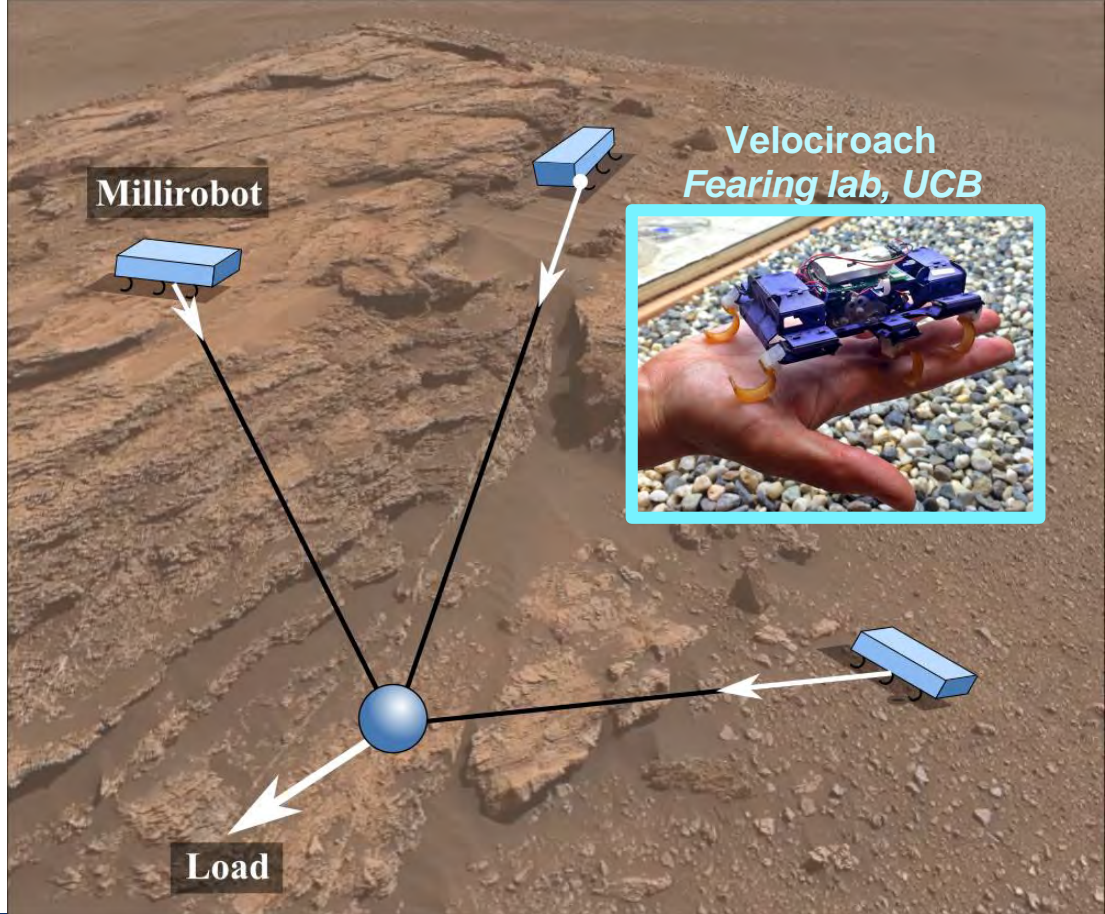
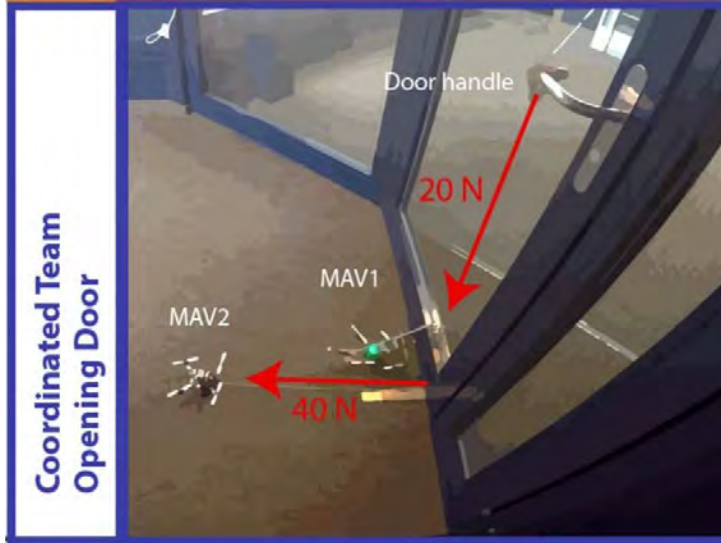
Sand dune sliding over fractured bedrock  
NASA/JPL-Caltech/Univ. of Arizona (2015)





# Millirobot ensemble

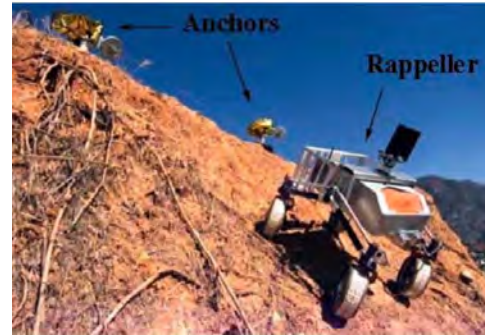
Estrada, Matthew A., et al. "Forceful manipulation with micro air vehicles." *Science Robotics* 3.23 (2018).



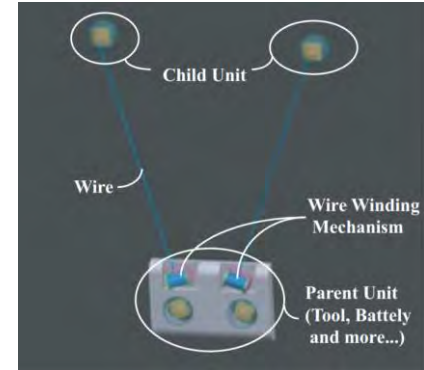
An artist's concept of the Axel rover rappelling into a lunar pit. (Courtesy NASA / JPL-Caltech). Smithsonian Magazine.



→ What's at the other side of the rope, and can we rely on it?



Mumm, Erik, et al. "Planetary cliff descent using cooperative robots." *Autonomous Robots* 16.3 (2004): 259-272.



Kitai, Shinya, et al. "The proposal of swarm type wall climbing robot system" Anchor Climber." *2005 IEEE/RSJ IROS*.

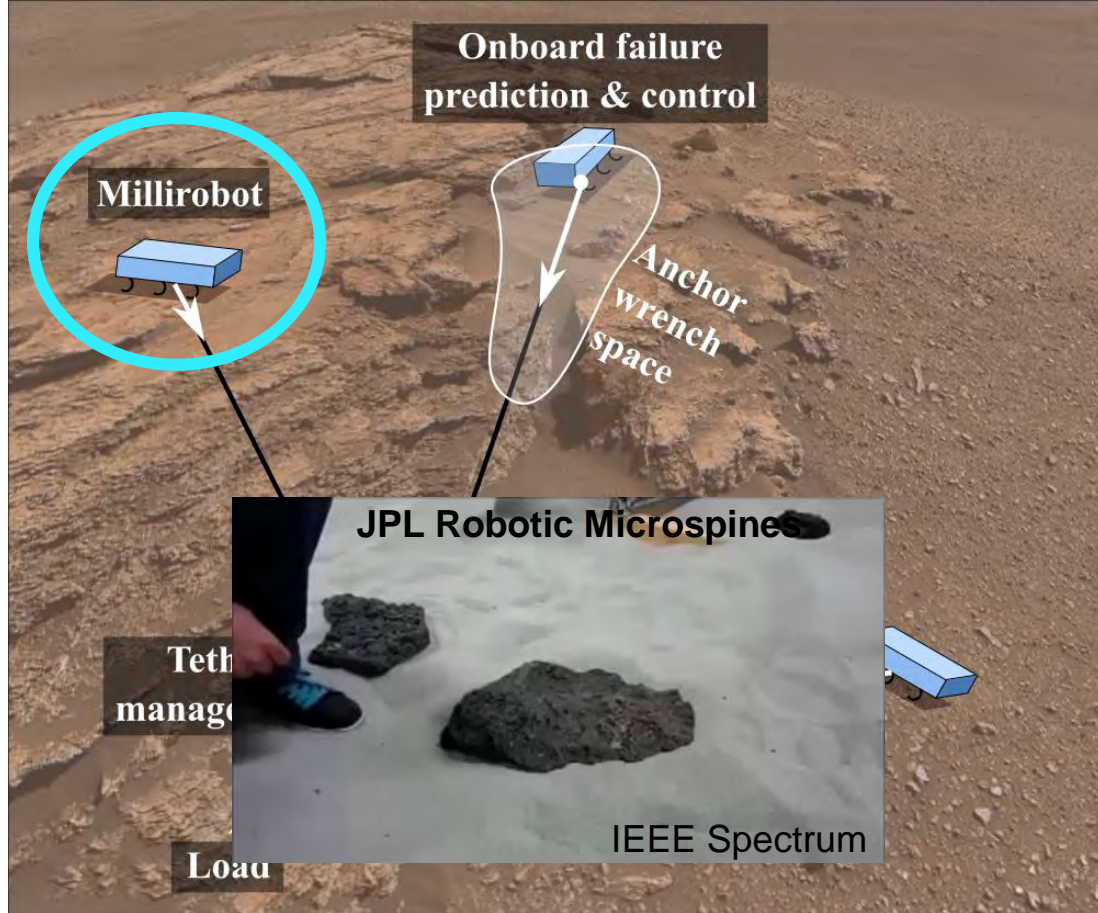
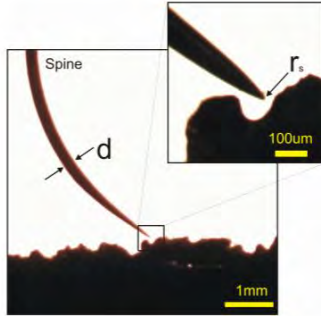


# Millirobot ensemble

Significant existing work on attached to rocky surfaces



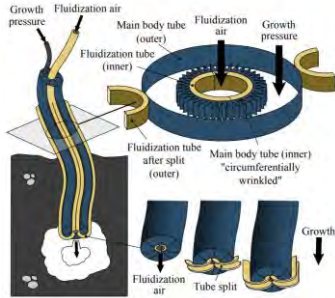
LEMUR



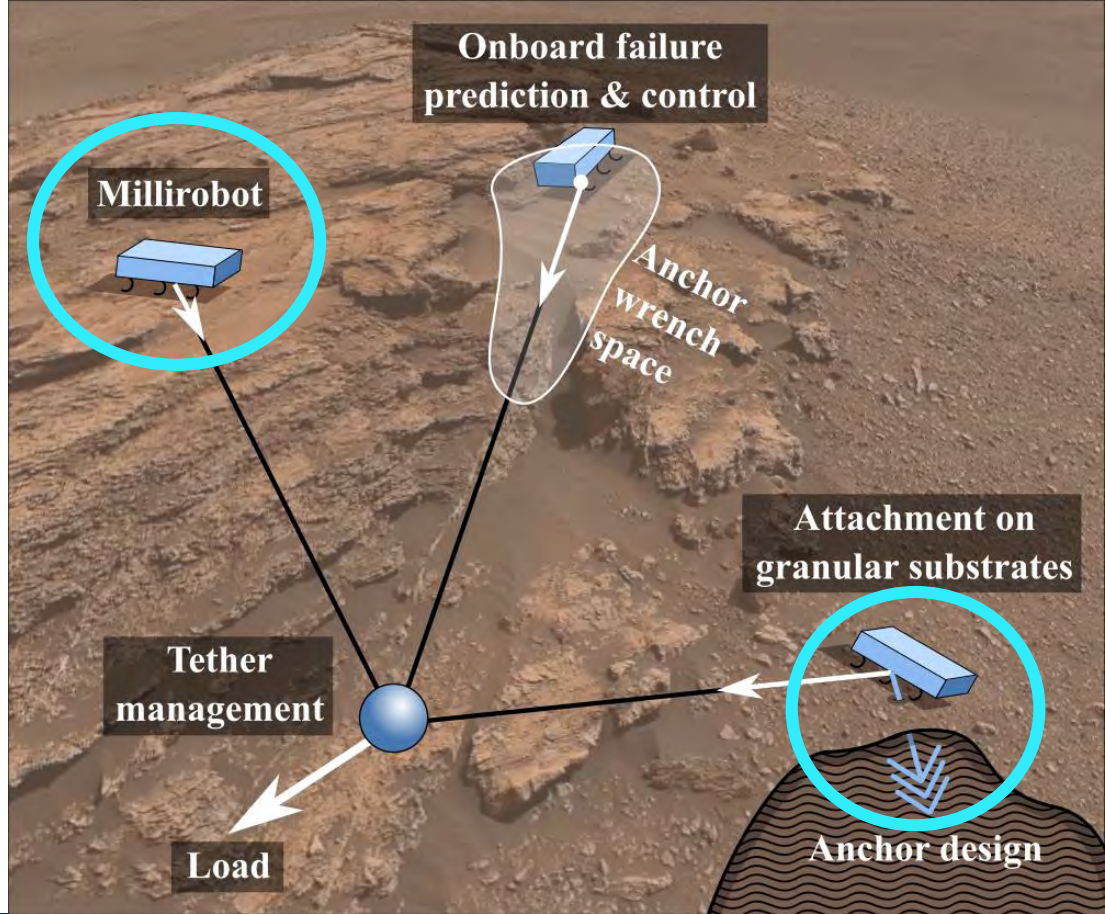
# Millirobot ensemble

Relatively less work on the design of sand anchors *for millirobotic systems*

Naclerio, et al. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). 2018.



Fernandez and Mazumdar. *IEEE Robotics and Automation Letters* 6.2 (2021): 1232-1239.

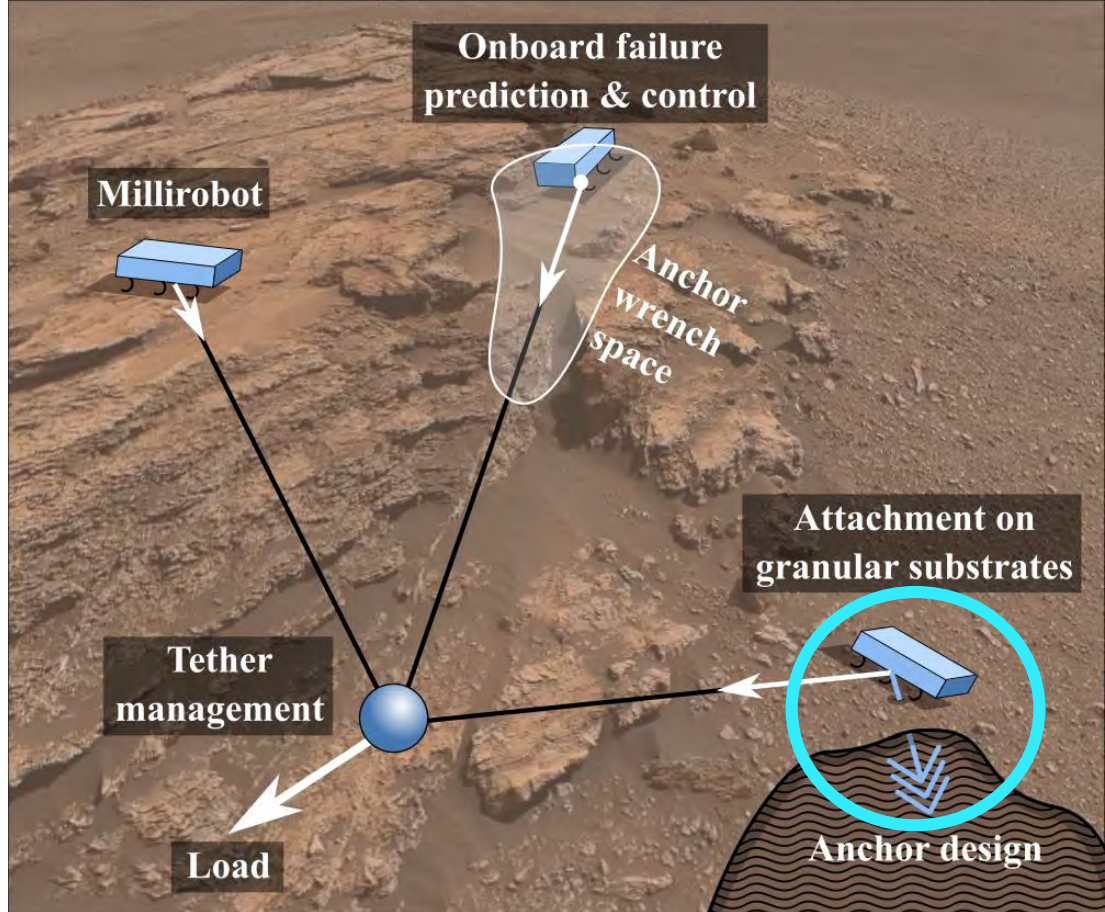




# Millirobot ensemble

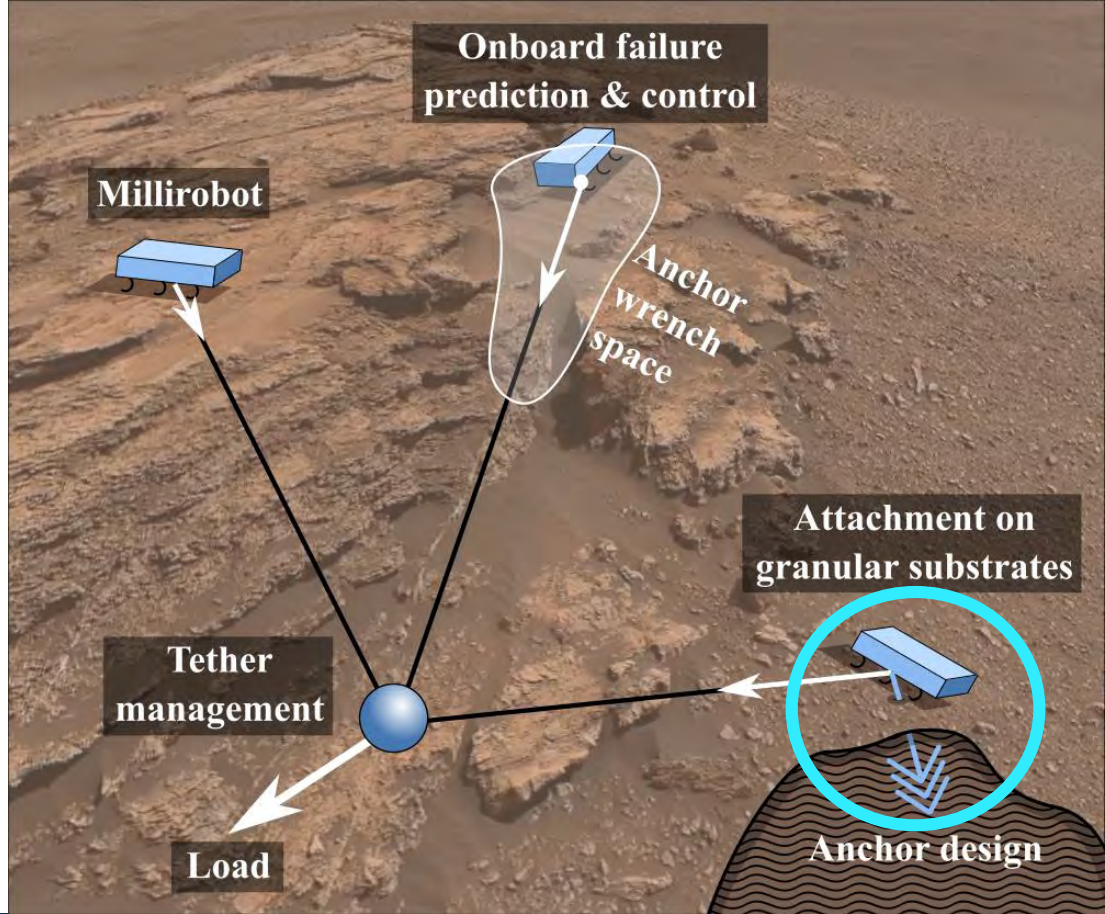
→ 2 pronged approach

- ◆ Interact better to sand, with design simulation tools
- ◆ Distribute agents to harness the environment



# Millirobot ensemble

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# A range of modeling methods

Discrete Element Method (DEM)

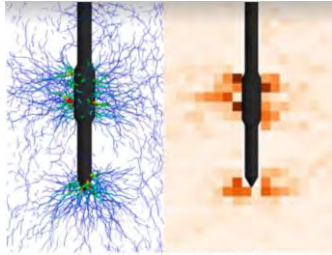
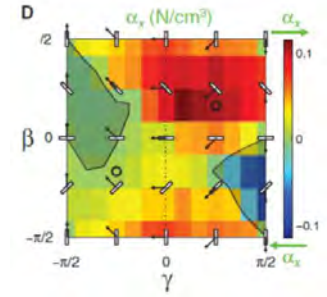


Photo from Granular Materials Lab, UC Davis, Prof. Alejandro Martinez

Material Point Method (MPM)

Resistive Force Theory (RFT)



Most robust

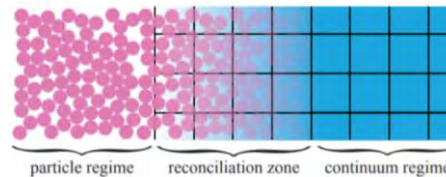
Least robust

~Days-weeks

~milliseconds

(simulation time)

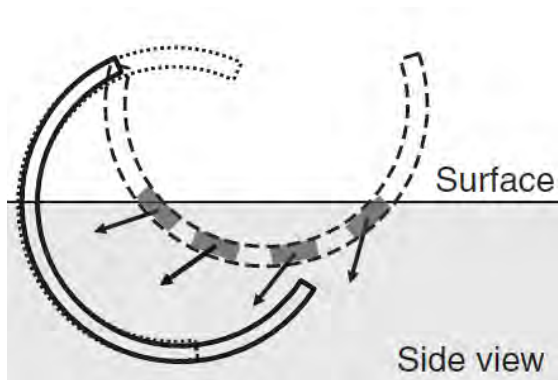
Hybrid DEM/MPM



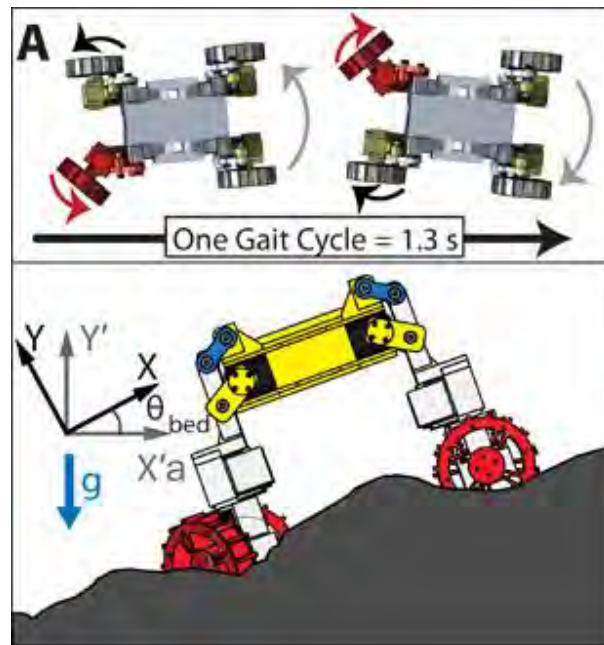
[10] Yue et al

# Granular Resistive Force Theory (RFT)

- First-order approximation for intrusion forces
- Relies on experimentally characterized scaling factors
- **Only characterized in 2D or 2.5D**



**2D**

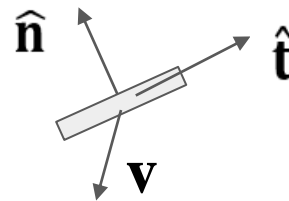


**2.5D**



# Granular Resistive Force Theory (RFT)

- First-order approximation for intrusion forces
- Relies on experimentally characterized scaling factors
- 3D RFT open source coming soon at lab GitHub!



$$\mathbf{F} = \int ds [f_{\perp}(\mathbf{v}, \hat{\mathbf{t}})\hat{\mathbf{n}} + f_{\parallel}(\mathbf{v}, \hat{\mathbf{t}})\hat{\mathbf{t}}]$$

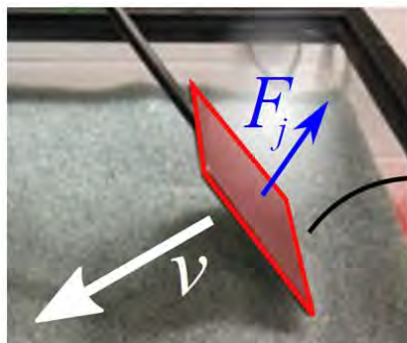
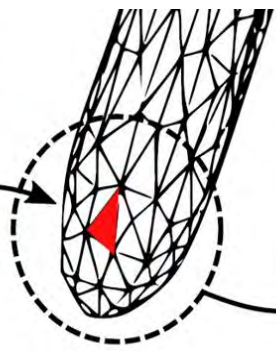
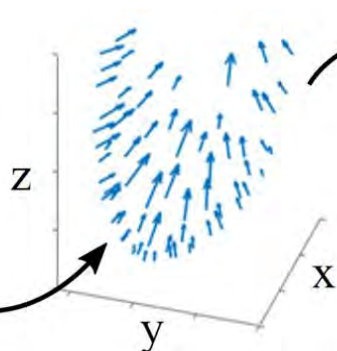


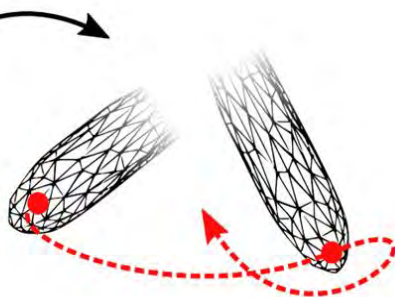
Plate penetrometry  
characterization



Forces summed  
over all elements

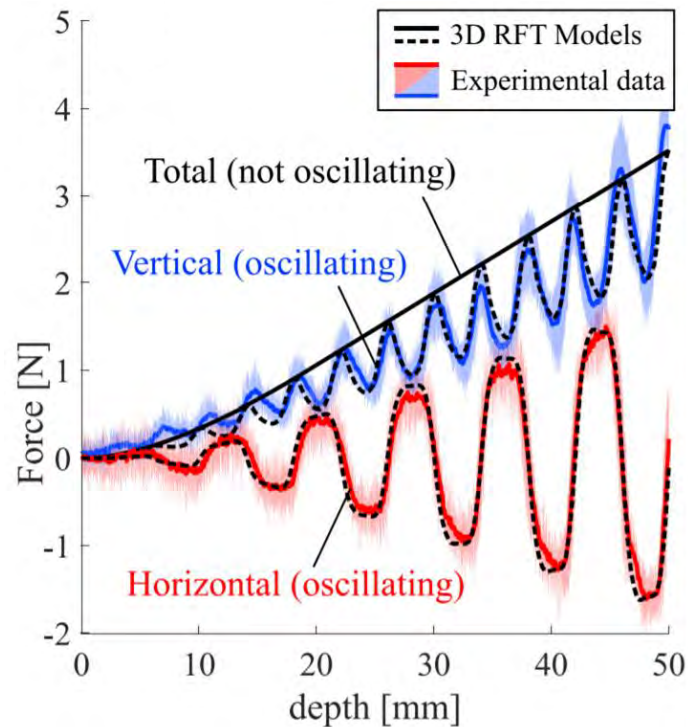


Element  $j$  on a  
discretized body



Estimate resultant  
throughout motions

# Example: bioinspired burrowing

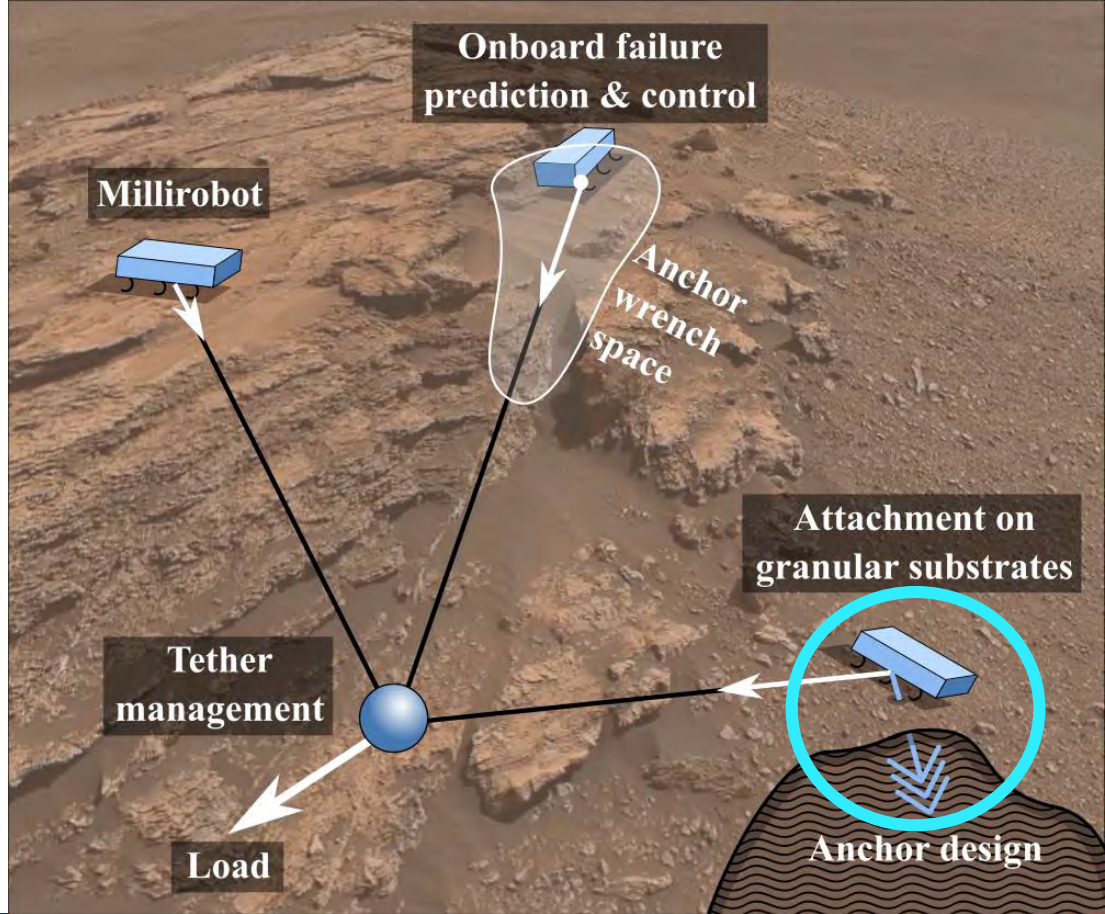




# Millirobot ensemble

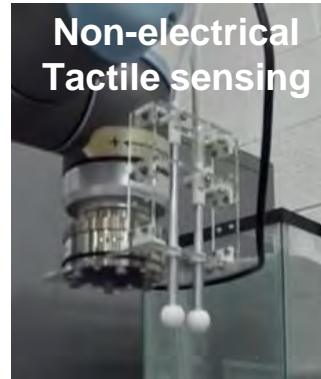
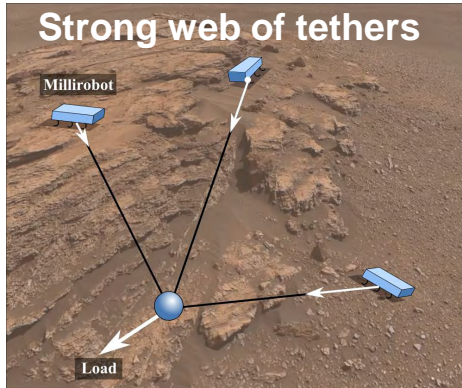
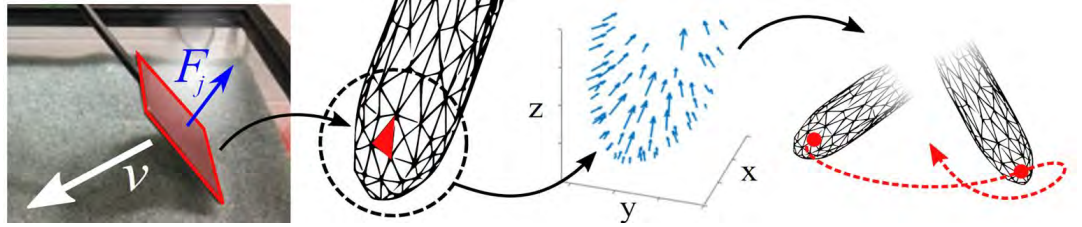
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# Questions

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*Granular media*