Drag and Swimming in Granular Media

Matthew Bzdega, Tristan Dennon, Stephan Koehler
Department of Physics, Emory University

motivation

- civil engineering - bridges, highways and foundations set into granular soils
- land-slides, avalanches
- self-propulsion in granular media

opportunity

outline

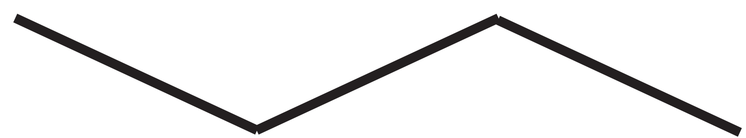
self-propulsion in granular media

drag experiments in granular media

swimming at low Reynolds number

flagellated swimmer

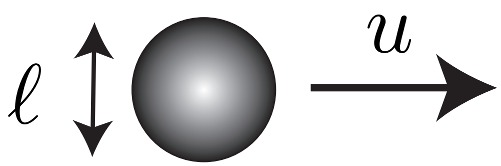
single-hinged



two-hinged

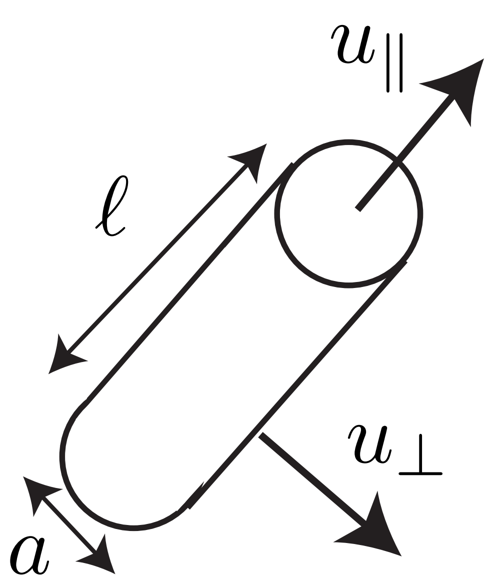
E. M. Purcell, 1977
Becker et al, 2003

Low-Reynolds number hydrodynamic drag



sphere :

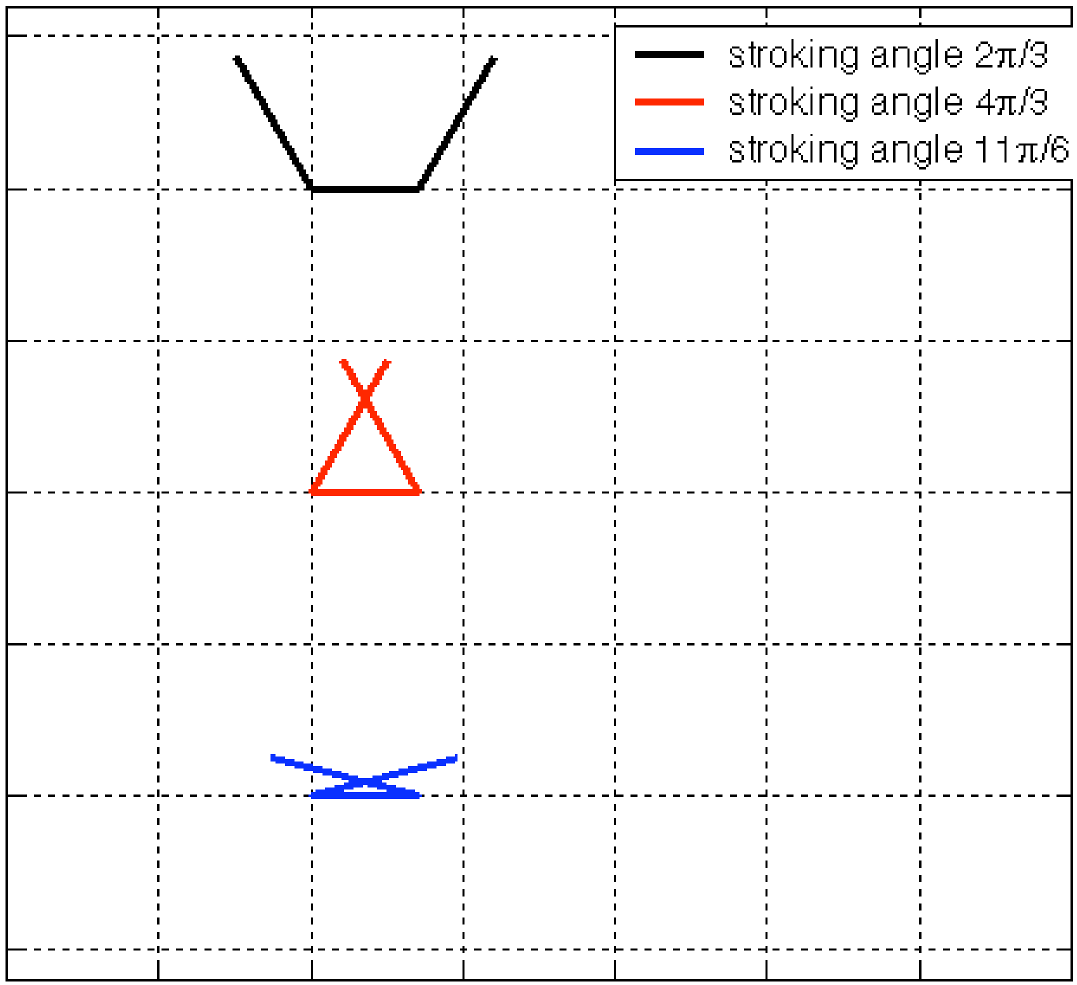
$$F = 6\pi\mu \, \ell u$$



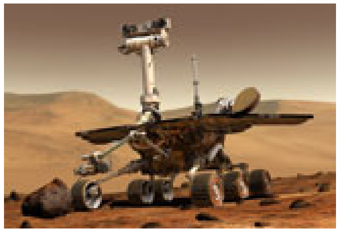
slender rod :

$$F_{\parallel} = (2\pi\mu/log(a/\ell)) \, \ell u_{\parallel}$$
$$F_{\perp} = (4\pi\mu/log(a/\ell)) \, \ell u_{\perp}$$

effect of stroking angles



top speed: 8 cm/sec



Opportunity Mars Rover Stuck in Sand

By Leonard David
Senior Space Writer
posted: 28 April 2005
08:40 pm ET

NASA's Opportunity Mars rover has run into a sandy snag. All of its six wheels have sunk in deep into a large ripple of soil.

Rover operators are optimistic they can extricate the robot from its jam, having gotten dug in before. But ground controllers will need time to wheel back on top of the soil again.

Time will also be spent figuring out what's different about the soil that has bogged down Opportunity, hoping to keep this problem from occurring down the road.

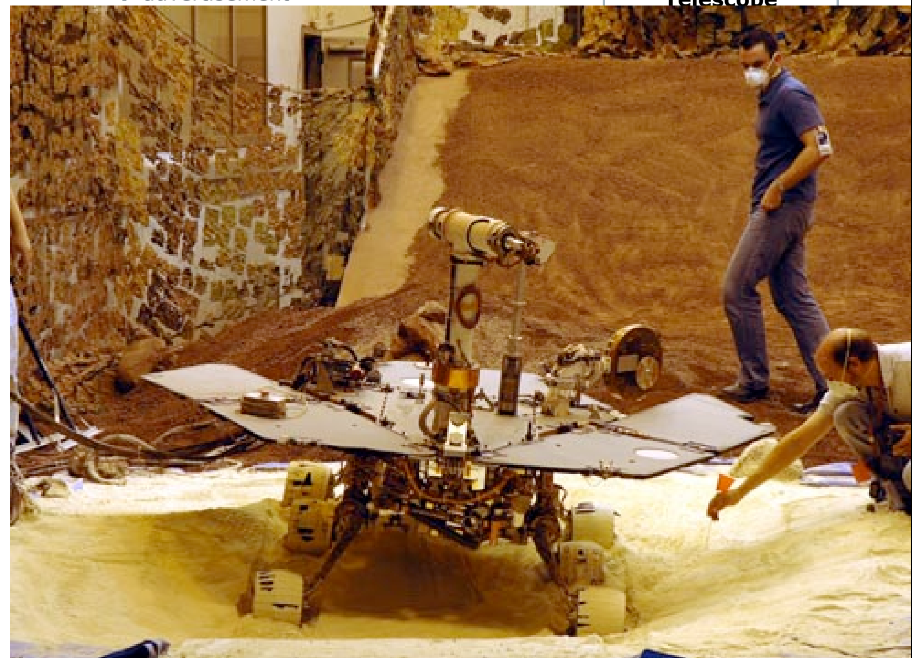
The Mars machinery had been cruising southward across the open parking lot-like landscape of Meridiani Planum, full of larger and larger ripples of soil. Opportunity has been en route to its next stopover, Erebus crater, nestled inside an even larger crater known as Terra Nova.

Be very, very patient

"A note to all you Opportunity fans: Get used to the current scenery, because we're going to be here awhile," said Steve Squyres, lead scientist on the Mars Exploration Rover effort at Cornell University in Ithaca, New York. "We are very optimistic that we'll be able to get out of here, but we're really going to take our time doing it."

Squyres said the first rule in this case is "do no harm" – and that means don't rush anything.

"We're going to take lots of pictures of all the terrain around the vehicle, to get a very complete picture of the situation. We're going to do lots of testing with the rovers

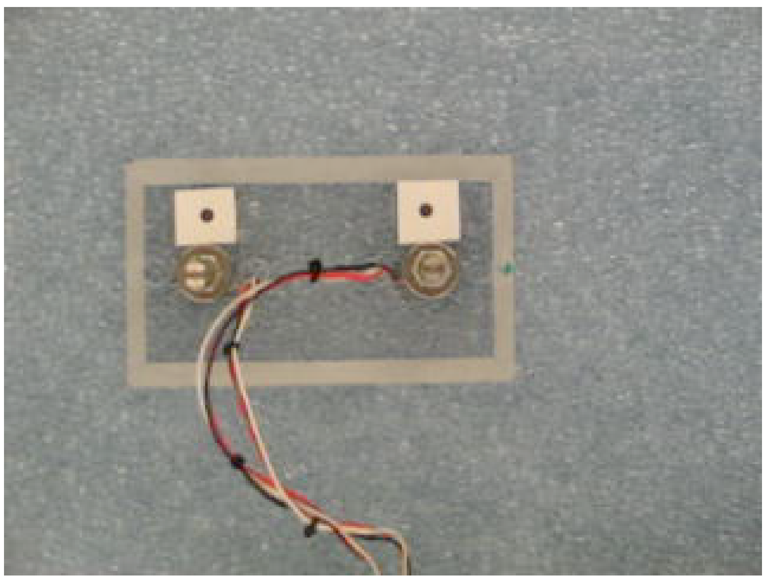


Images

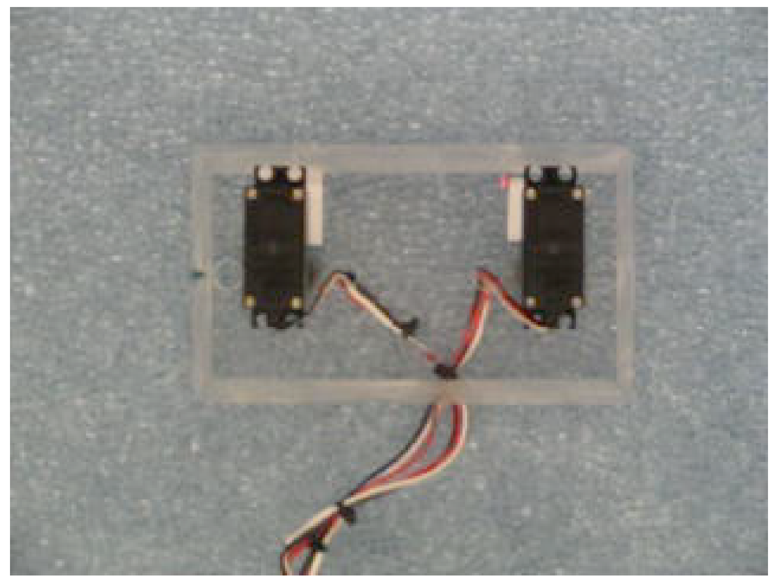
Opportunity Mars rover has encountered deep soil. Credit: NASA/JPL

Before becoming bogged down, Opportunity rover discovered tiny craters imbedded in the open landscape of Meridiani Planum.

Purcell's swimmer in granular media (glass beads)



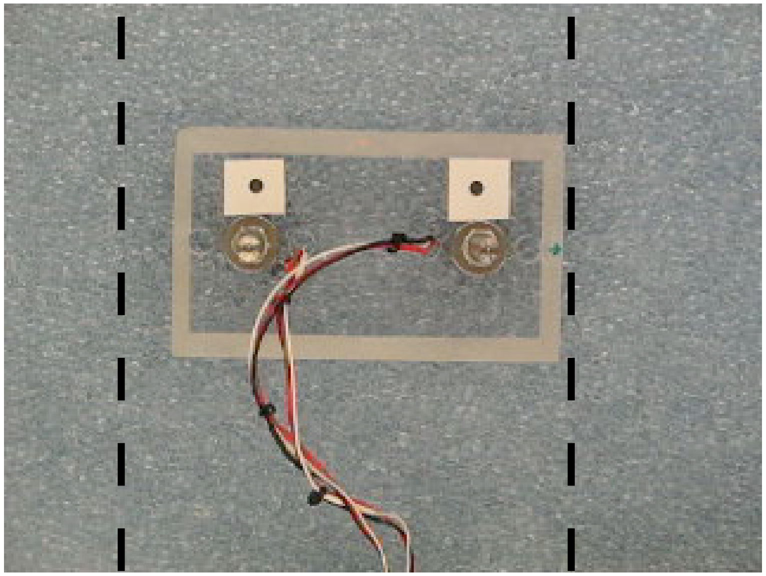
motion



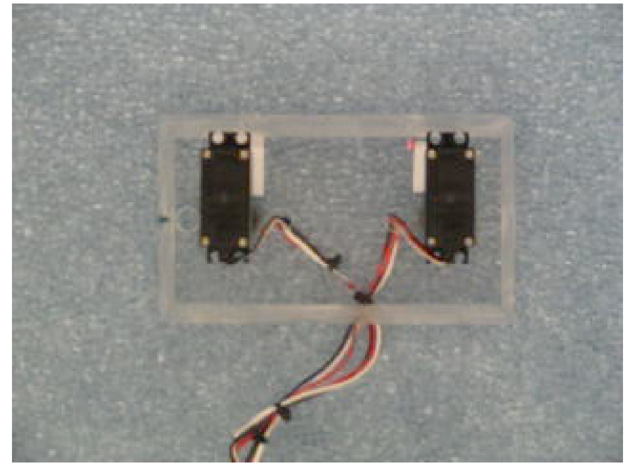
up-side down

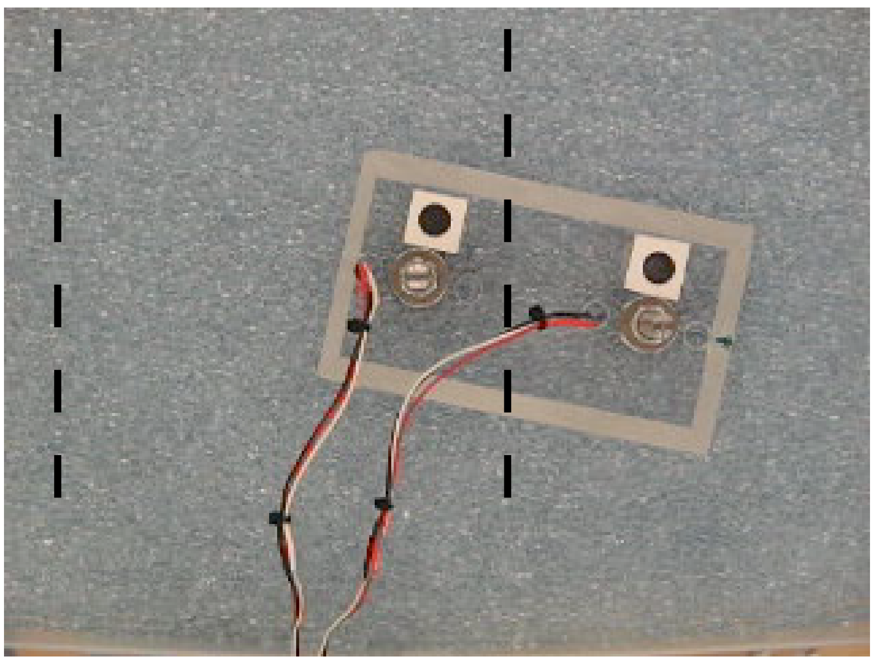
top speed: 1 mm/sec

Different Swimming Strategies

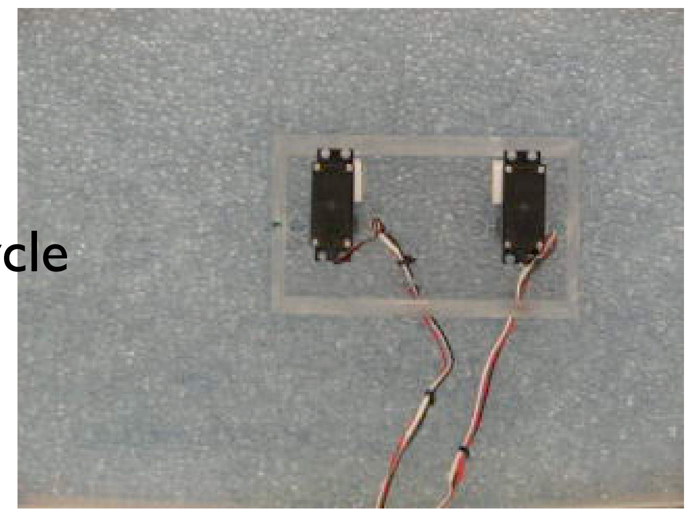


speed:
2 mm/cycle

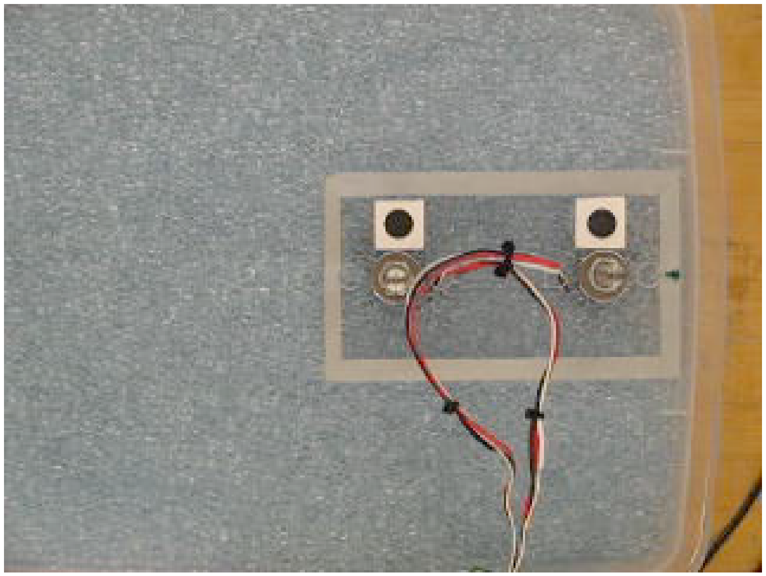


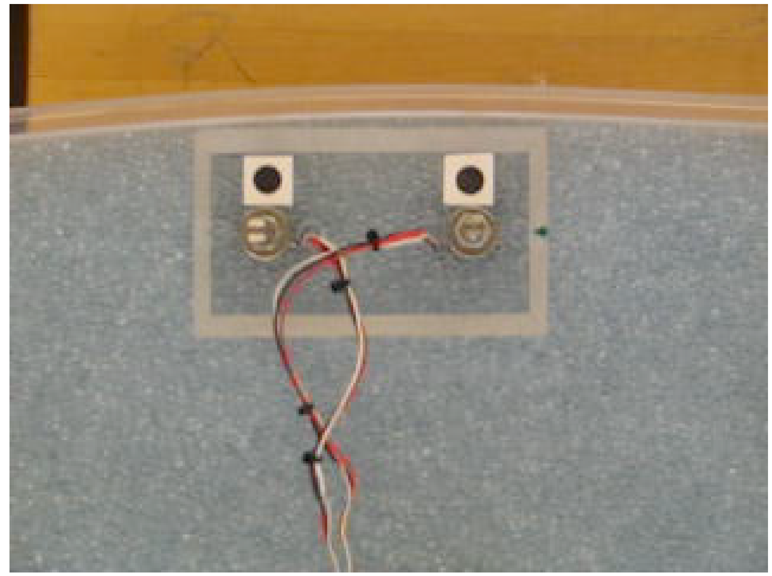


speed:
4.5 mm/cycle

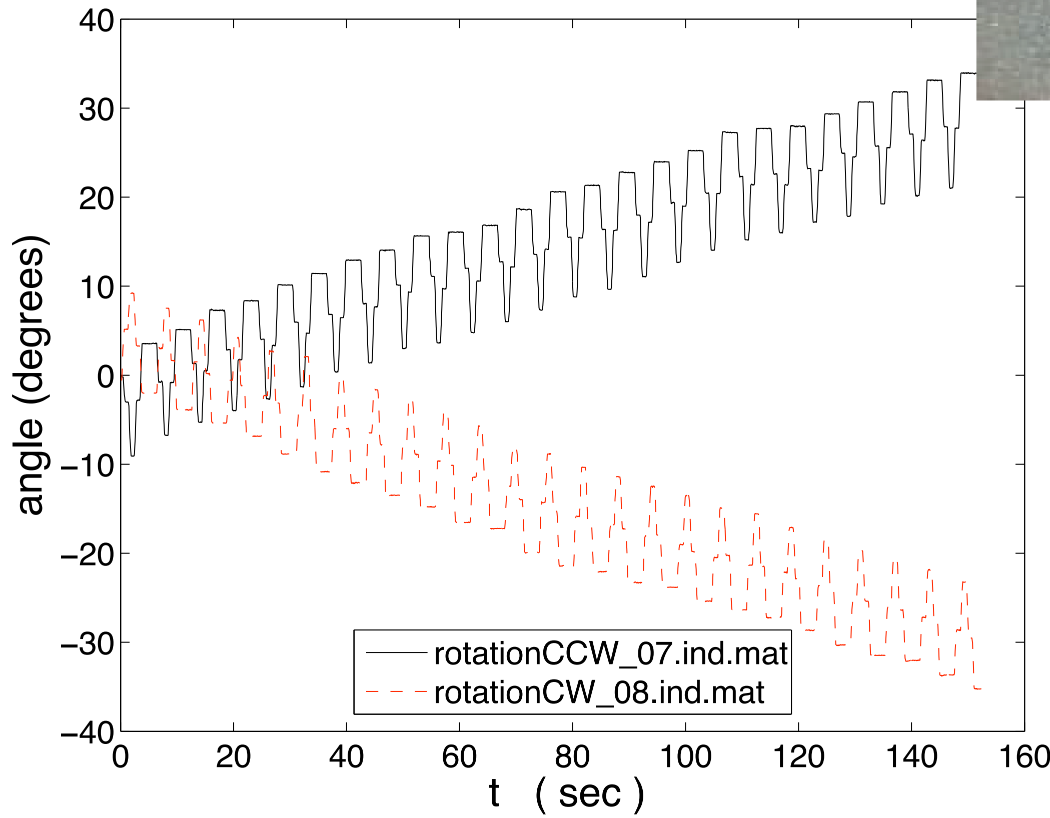


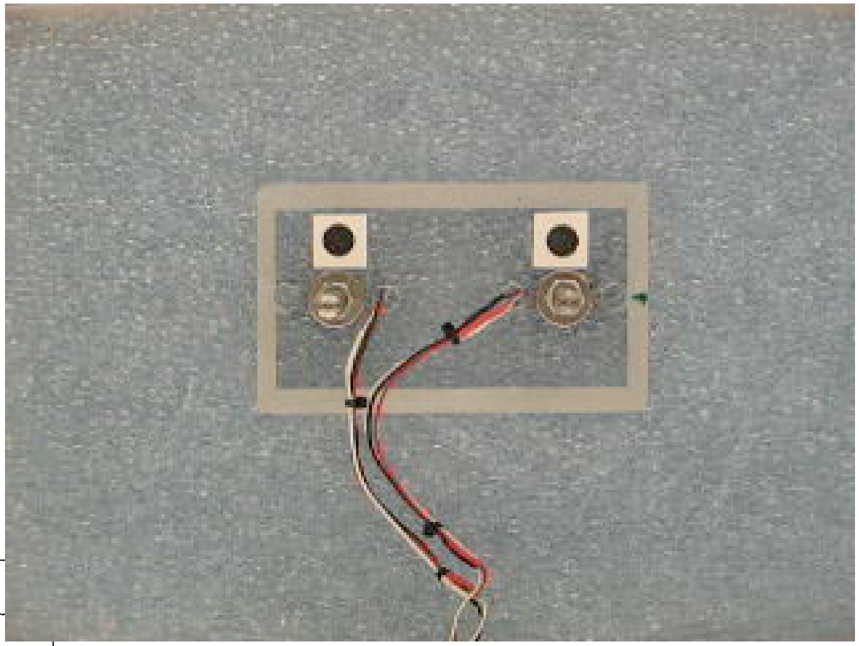
climbing out of box

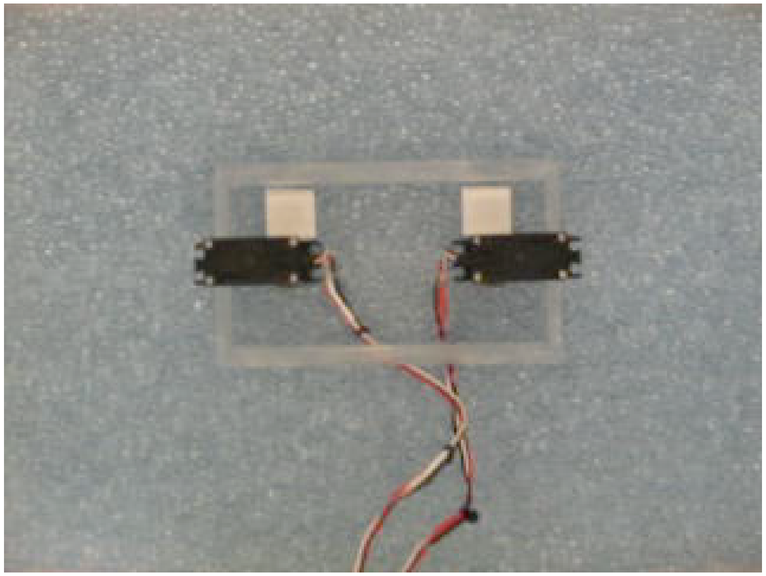




making a turn

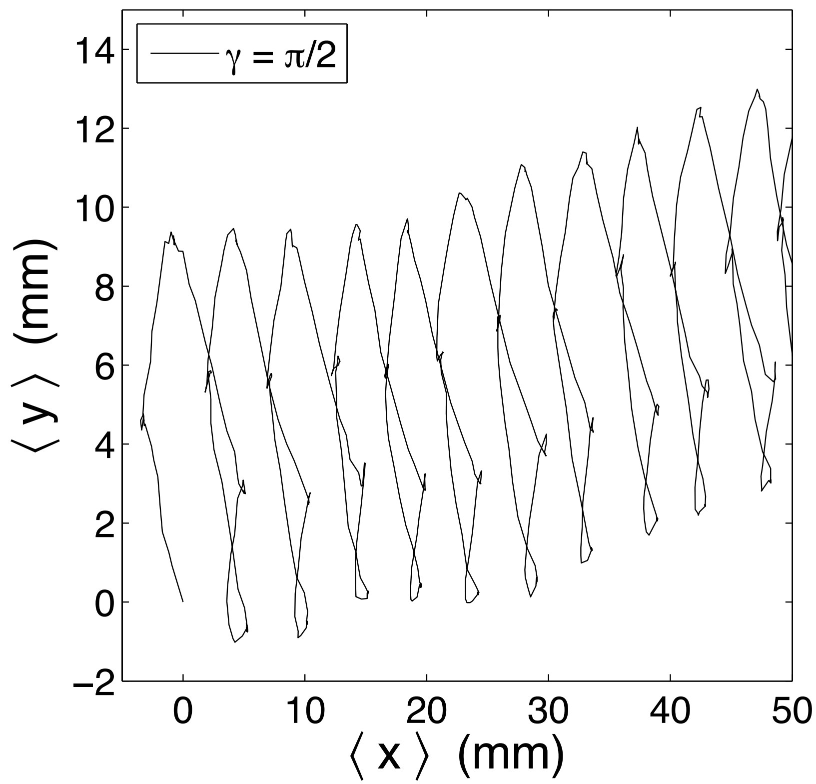




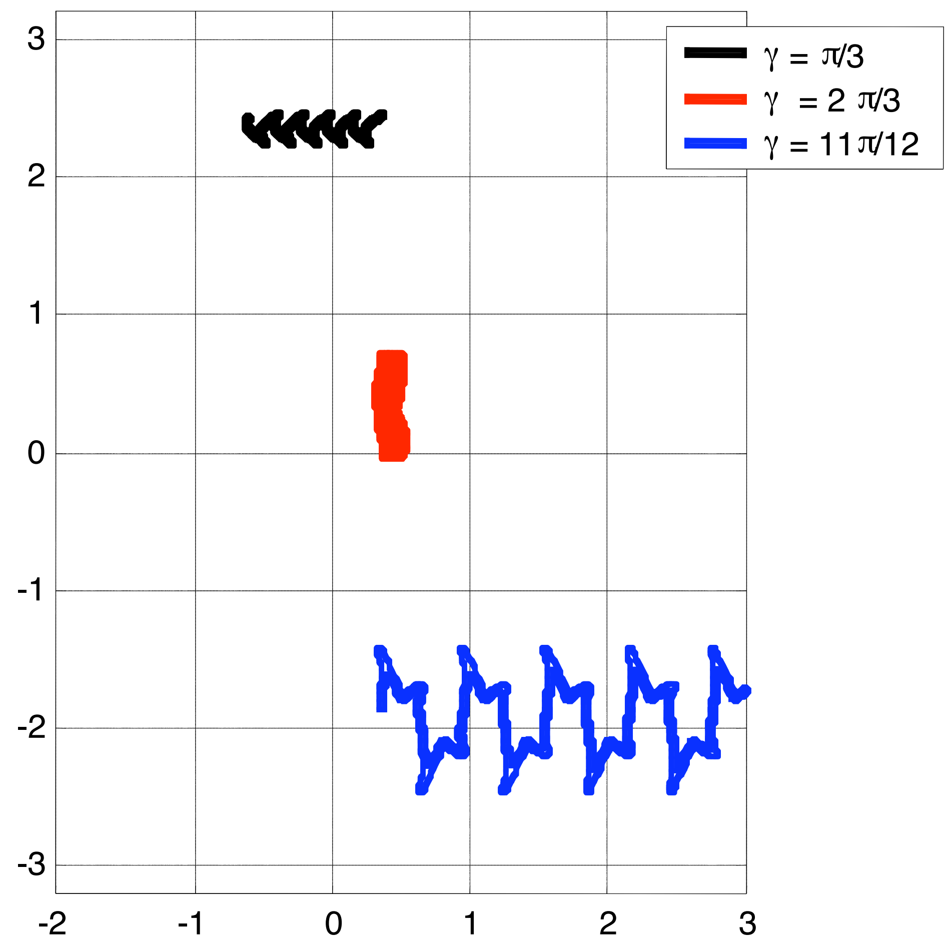


tracking middle position

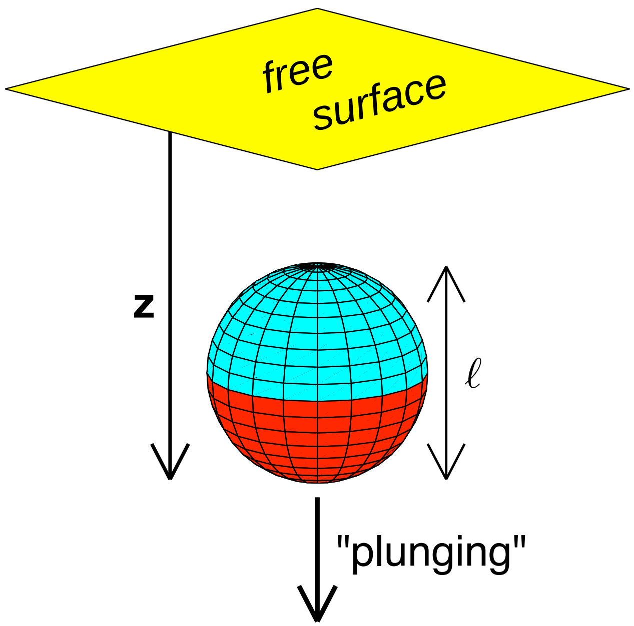
glass beads

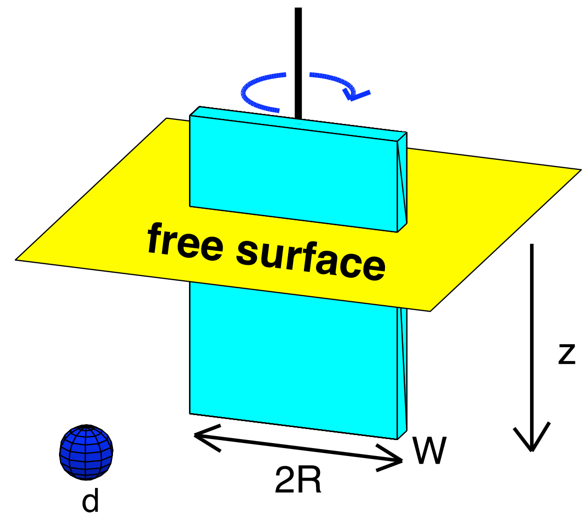


hydrodynamics



granular drag experiments

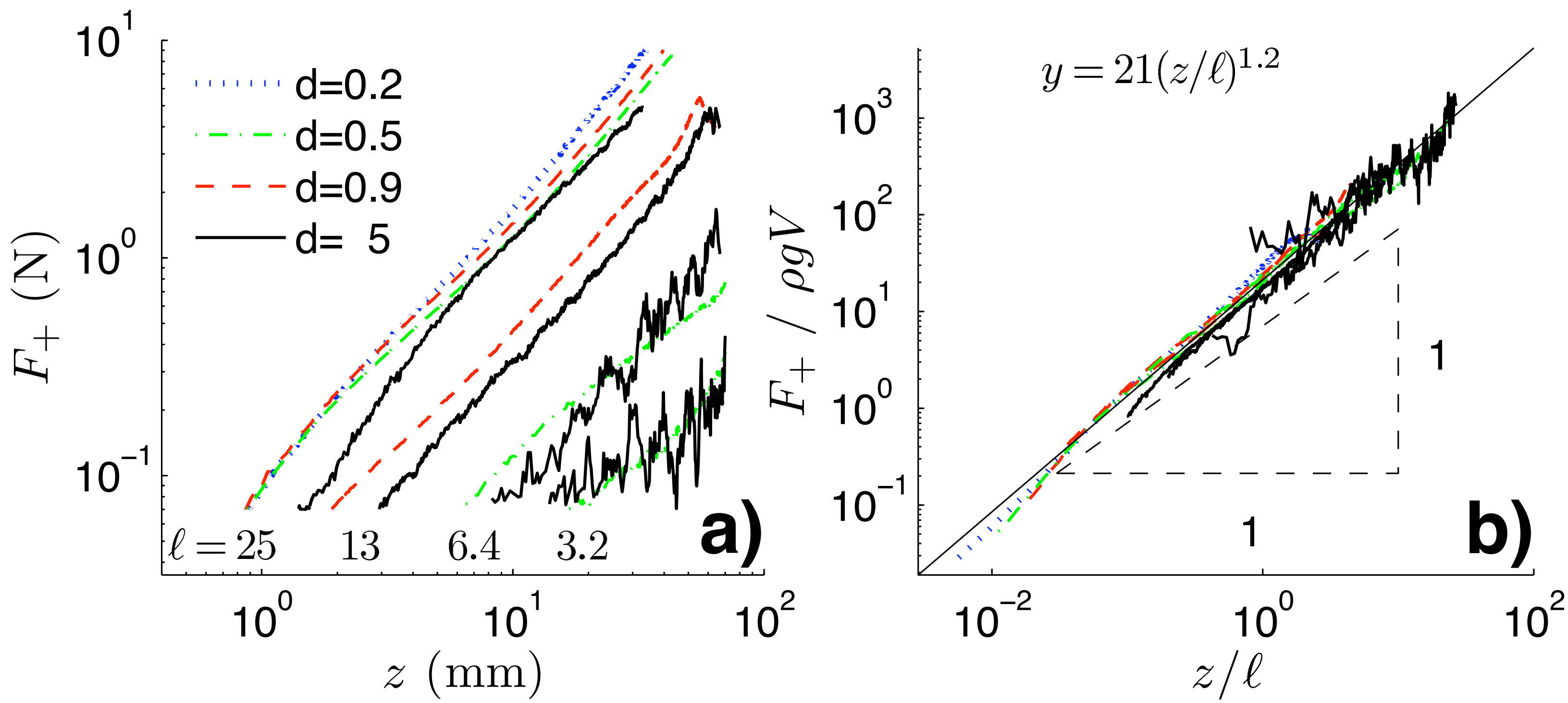




rotating vane

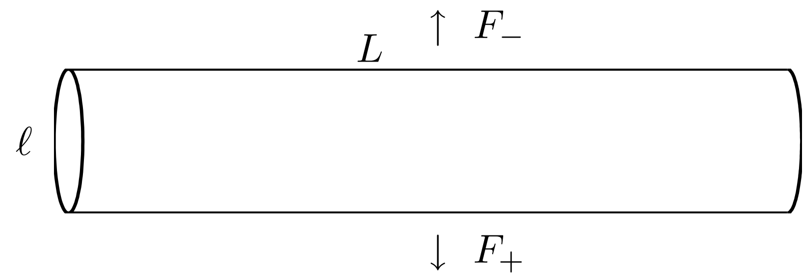
Albert et al, 1998

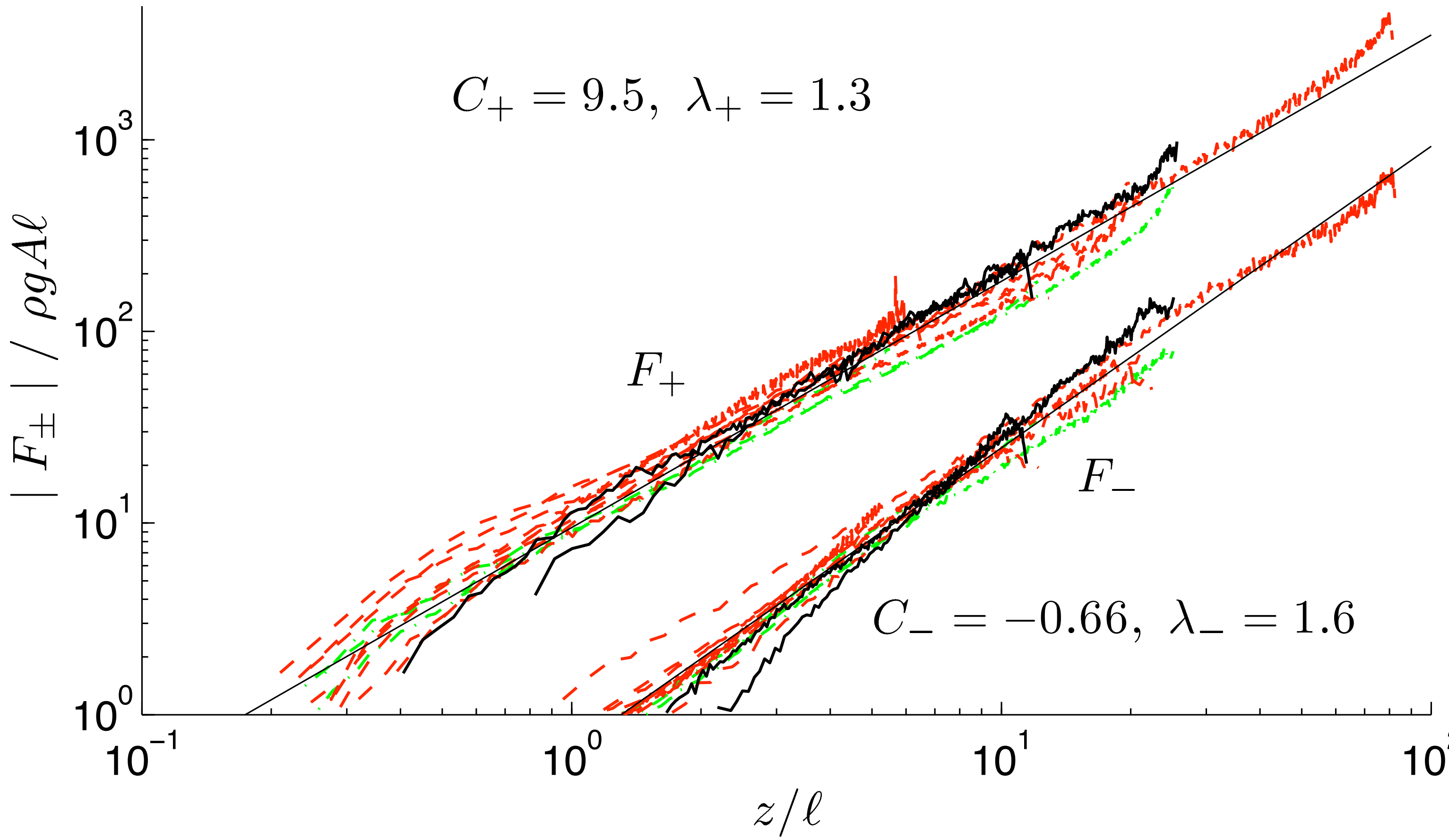
plunging sphere



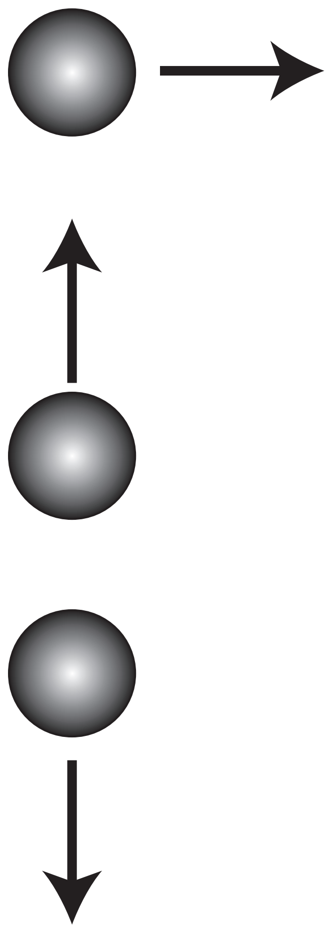
horizontal rod

$$F_\pm / (\rho g A \ell) = C_\pm (z/\ell)^{\lambda_\pm}$$





granular drag anisotropy

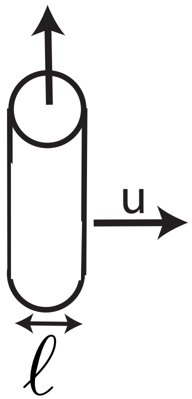


$$F \approx \mathcal{O}(1)\rho g \ell^2 z$$

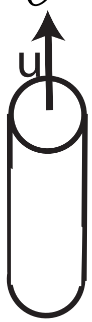
$$F \approx \mathcal{O}(0.1)\rho g \ell^{1.3} z^{1.7}$$

$$F \approx \mathcal{O}(10)\rho g \ell^{1.7} z^{1.3}$$

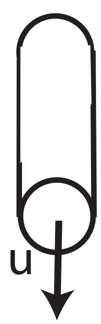
slender body drag I



$$
\begin{aligned}
F_{\text{drag}} &\approx \mathcal{O}(1)\rho g \ell z^2 \\
F_{\text{lift}} &\approx \mathcal{O}(0.1)\rho g \ell^2 z^{1.7} d^{-0.7}
\end{aligned}
$$

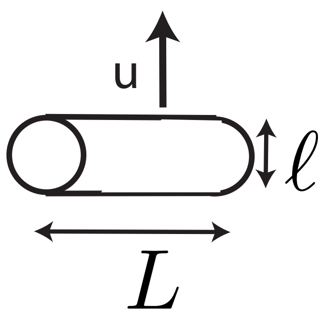


$$F \approx \mathcal{O}(0.1)\rho g \ell^{1.3} z^{1.7}$$

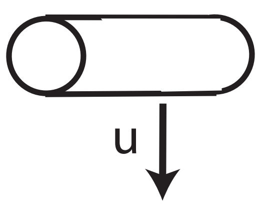


$$F \approx \mathcal{O}(10)\rho g \ell^{1.7} z^{1.3}$$

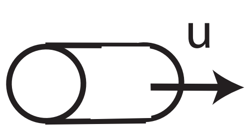
slender body drag II



$$F \approx \mathcal{O}(0.1) L \ell^{0.3} z^{1.7}$$

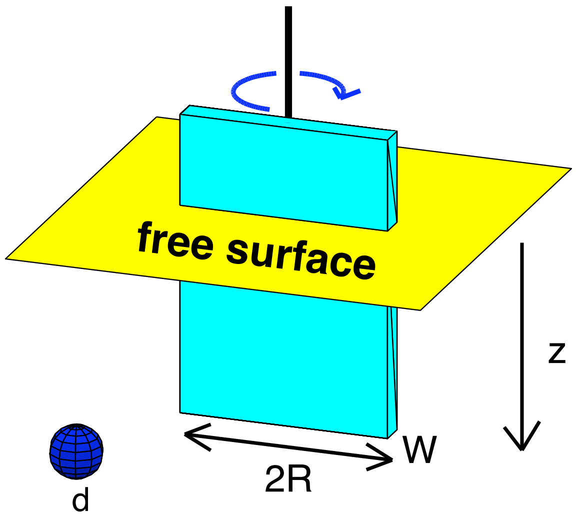


$$F \approx \mathcal{O}(10) L \ell^{0.7} z^{1.3}$$



$$\begin{aligned} F_{\text{drag}} &\approx \mathcal{O}(1) \rho g \ell^{0.8} L z^{1.2} \\ F_{\text{lift}} &\approx \mathcal{O}(1) \rho g \ell^{0.4} L^{0.8} \left(z^{0.8} - (z-\ell)^{0.8}\right) d^{1} \end{aligned}$$

slender-body drag III



rotating vane

$$\tau_{\text{drag}} \approx \mathcal{O}(1)\rho g R^2 z^2$$
$$F_{\text{lift}} \approx \mathcal{O}(1)\rho g R^1 W^{0.3} z^{1.4} d^{0.3}$$

summary for granular drag

- depends on
  - alignment of intruder relative to motion
  - dimensions of intruder
  - type of medium (i.e. glass beads, sand)
  - direction of motion relative to gravity
  - immersion depth
- independent of
  - bead size
  - velocity (slow limit)

Outlook

- Empirically constructing drag tensor for spheres, plates and rods
- Simulations/theory for dense granular media
- Improving robot