Overview of meeting

Locomotion and Manipulation are related to each other. Both are heavily based on controlling physical interaction with an environment; both are ruled by the same laws of motion and contact; and both are subject to the same constraints and limitations imposed by our models of those laws. Despite these similarities, there exists a current dichotomy in techniques for approaching planning, control, perception, and design for locomotion and manipulation.

Part of the specialization can be attributed to the assumptions they respectively make, either (a) about the nature of the interactions with the environment, for example ranging from the spaced and periodic in time to the continuous, and from the localized in space to the distributed; or (b) the nature of the uncertainty, either in the state of the robot or the environment. Many of the grand challenges that both fields face require, pushing the boundaries of those assumptions. In this workshop we would like to explore in depth the reasons for these differences and come up with ideas to bring them closer together.

The workshop will consist of invited talks, breakout sessions, and discussion panels to initiate a conversation between the two communities, identify tools and algorithms from locomotion with potential application in manipulation and vice versa, and create a summary document with relevant research topics at the intersection of locomotion and manipulation.

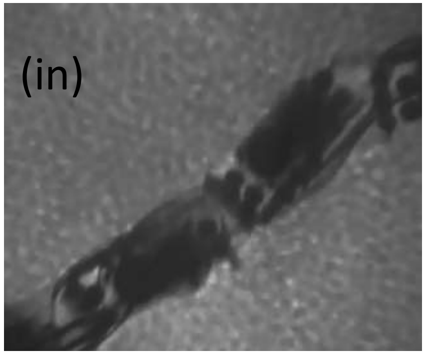
Locomotion & Manipulation: Why the Great Divide?

Session 2: High Dimensional Locomotion and Manipulation

Locomotion and manipulation **on**, **in**, and **of** deformable granular media

Prof. Daniel I. Goldman

School of Physics
Georgia Institute of Technology



FUNDING

NSF CAREER/PECASE, NSF PoLS, DARPA YFA, BWF, Blanchard Milliken, ARL, ARO

A plea for humility…

There are more things in heaven and earth, Horatio,
Than are dreamt of in your ROBOTICS
- *Hamlet* (1.5.167-8), Hamlet to Horatio

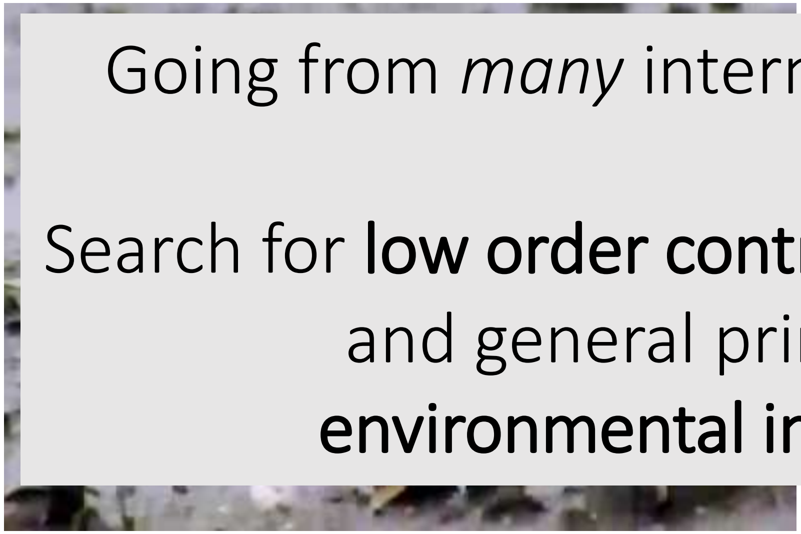
Questions from the organizers

State-of-the-art methods for locomotion and manipulation can be pushed to deal with systems up to 50 DOF, which is fairly impressive compared to what we could achieve just a few years ago.

- ● How can we push this dimensionality even further, perhaps all the way to infinity?
- How do we locomote with soft structures?
- ● How do we manipulate deformable objects?
- ● How do we plan and control continuum robots?
  - Templates (low DOF control targets) to manipulate the body and environment to effect locomotion

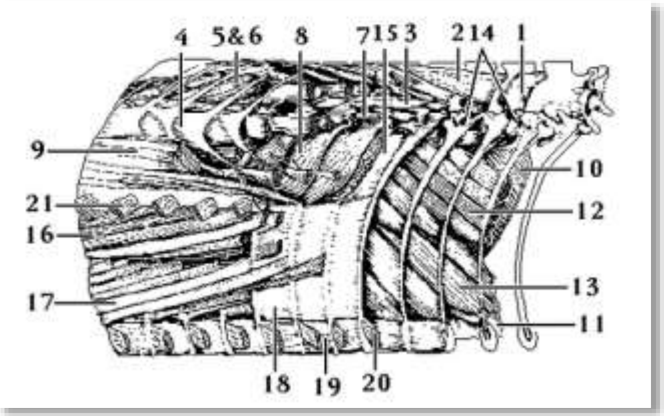
Physics of Locomoting Systems

Study of the *emergence* of movement resulting from **many** degree of freedom, hierarchically organized, nonlinear biological & robotic systems interacting effectively with their environments



Going from *many* internal DOF to behavior is hard!

Search for **low order control templates** (Full & Koditschek, 1999) and general principles for effective **environmental interaction** (manipulation?)



(J.P. Gasc, 1974, Cundall, 1987)

Howie Choset, CMU, 2001…

Locomotor-environment interaction

~~Terrestrial~~ ~~Aerial~~ ~~Aquatic~~

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Forbes online

Prof. Howie Choset, CMU

Robotic Snakes Slither Their Way Into Ancient Archaeology

+ Comment Now + Follow Comments

To paraphrase REM, the ancient Egyptians were all too familiar with the "horrible asp."

But not even the most clairvoyant pharaohs could have imagined their kingdoms invaded by robotic snakes.

In arguably an archaeological first, that's exactly what happened a

Search and rescue

IED detection

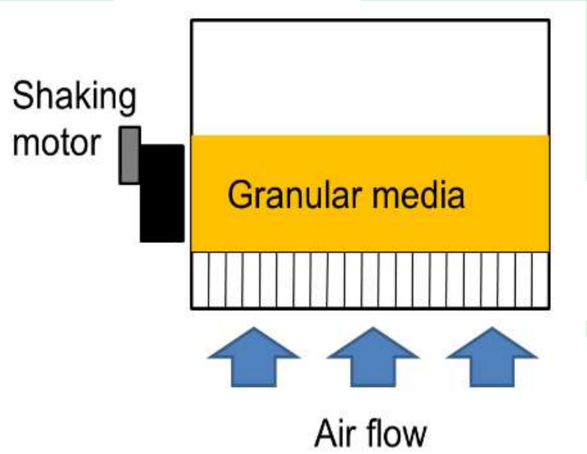
Exploration

Discover principles of terrestrial locomotion

goldmanlab.gatech.edu

Bio/neuromechanics

Substrate control



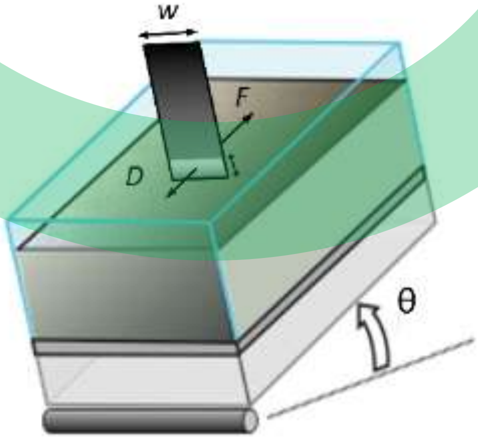
Physical models

“robophysics”

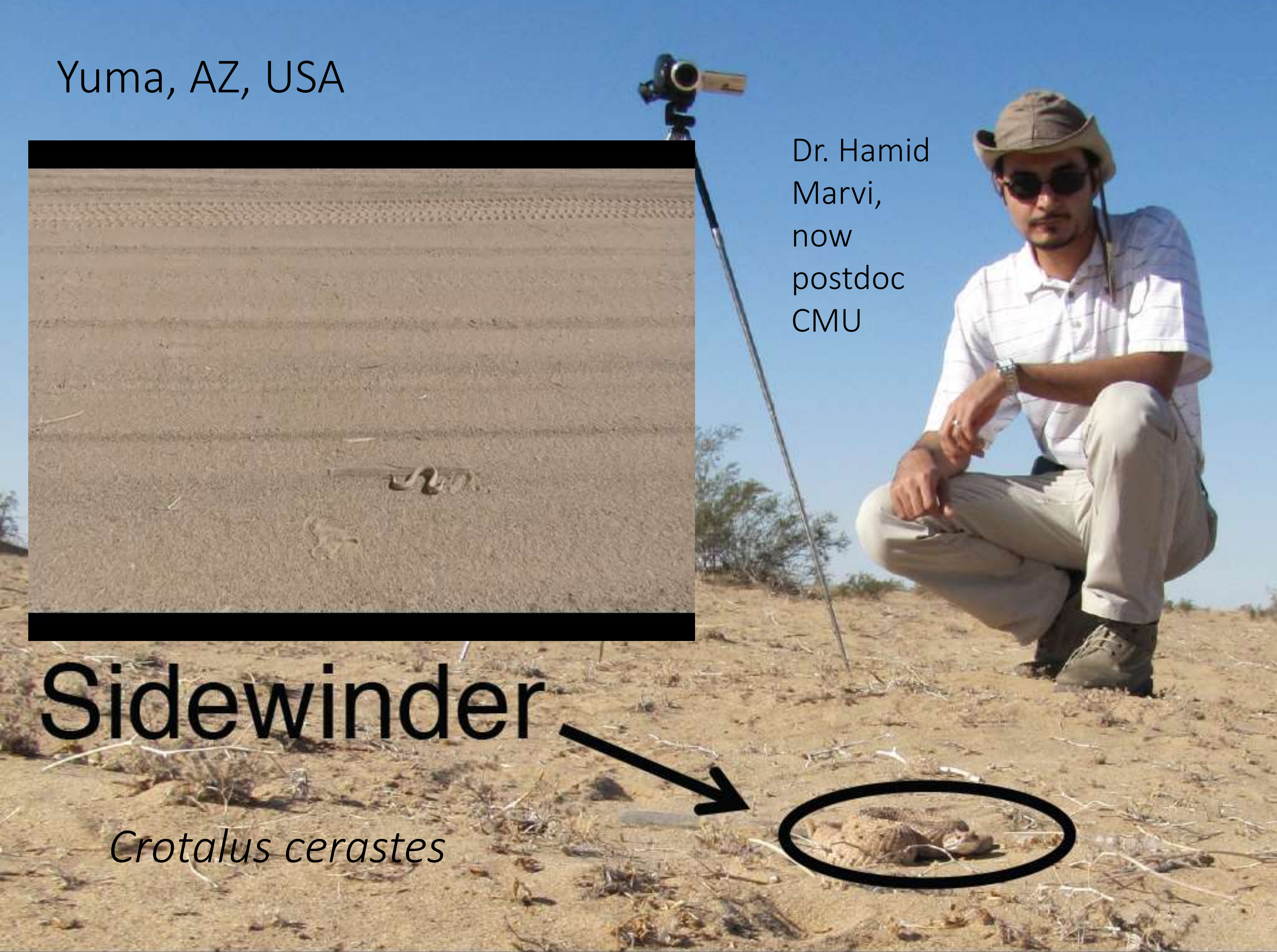
Aguilar et al, *Rep. Prog. Physics*, in prep.

Choset, CMU

Soft matter interaction physics



Yuma, AZ, USA



Dr. Hamid Marvi, now postdoc CMU

Sidewinder

Crotalus cerastes

Sidewinding snakes

Sidewinding only occurs in snakes that move on loose material

Slowed 5x

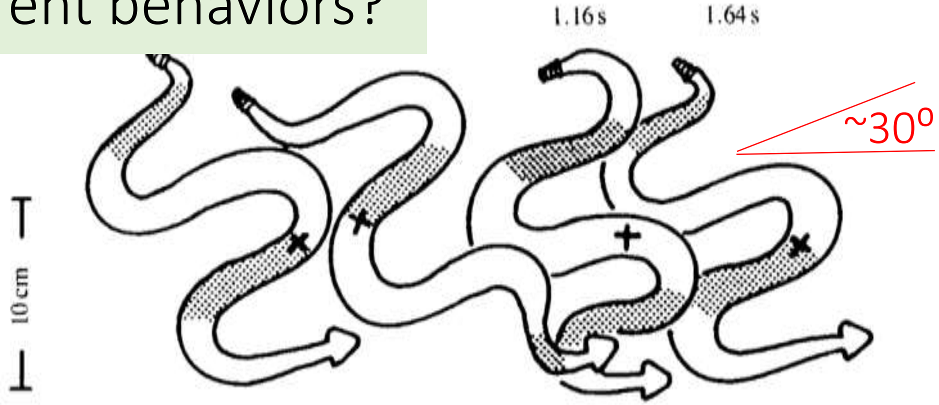
Why use this gait?

How is it controlled to generate different behaviors?

Studies of straight sidew
hard ground (1 on flat sand)

- Qualitative description
  Mosauer (1930) and Gray (1946)
- Kinematics, muscular mechanisms
  Jayne (1986, 1988)
- Energetics
  Secor, et al. (1992)
- Robotics
  Burdick et al. (1995), Hatton et al. (2010)

ntact region



Secor et al. 1992

Direction of motion

Crotalus cerastes, Sidewinder rattlesnake

($N = 6$, mass= 98 ± 18 g, body-length, tip-to-tail, $L = 48 \pm 6$ cm)

Surprisingly good study subject! They move on “command”

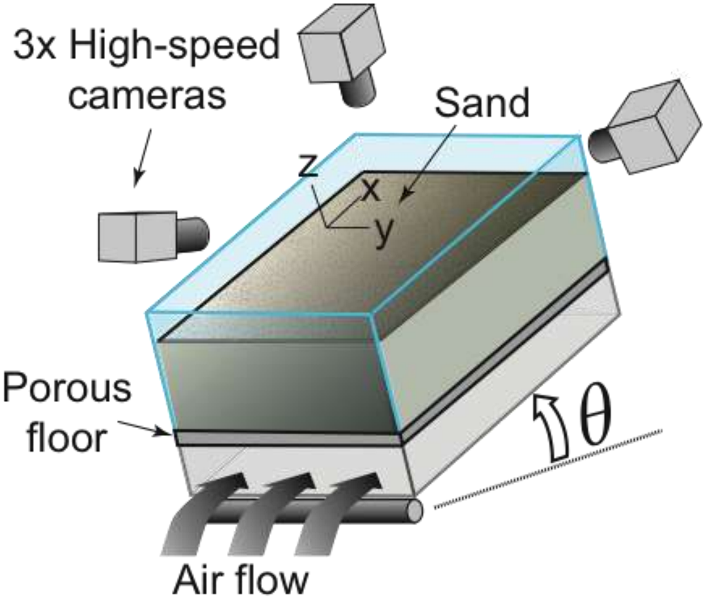
Facility at Zoo Atlanta

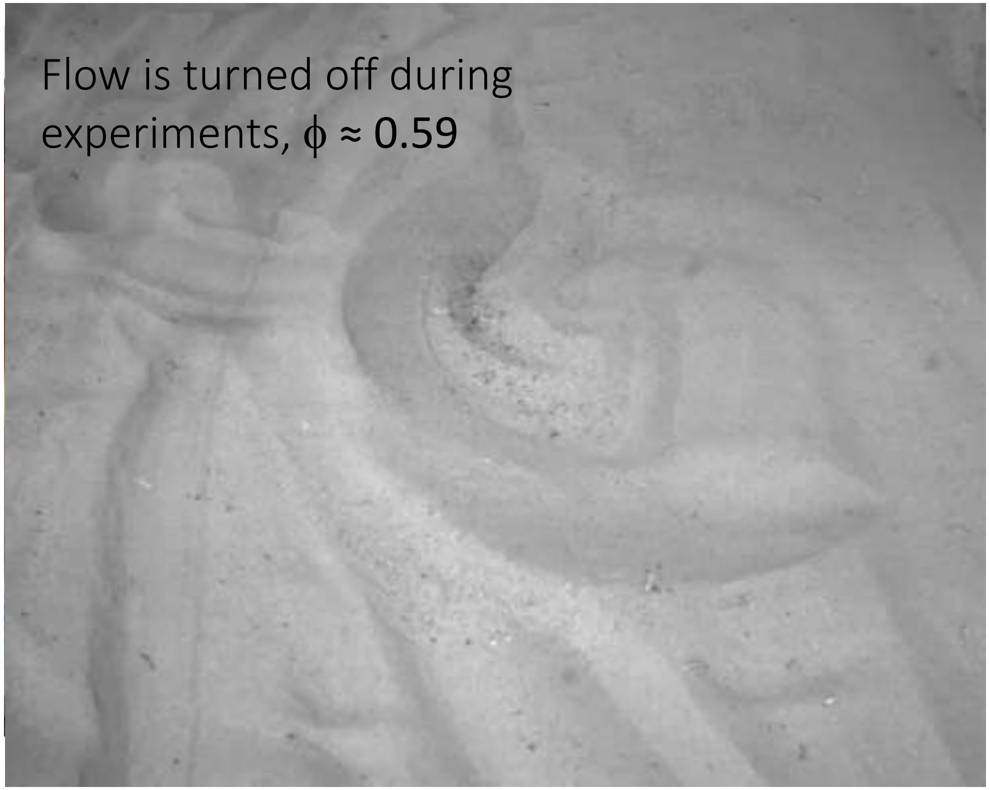

Dr. Hamid
Marvi,
postdoc CMU


Dr. Henry
Astley,
postdoc GT


Prof.
David Hu,
ME, GT


Dr. Joe
Mendelson,
Zoo ATL



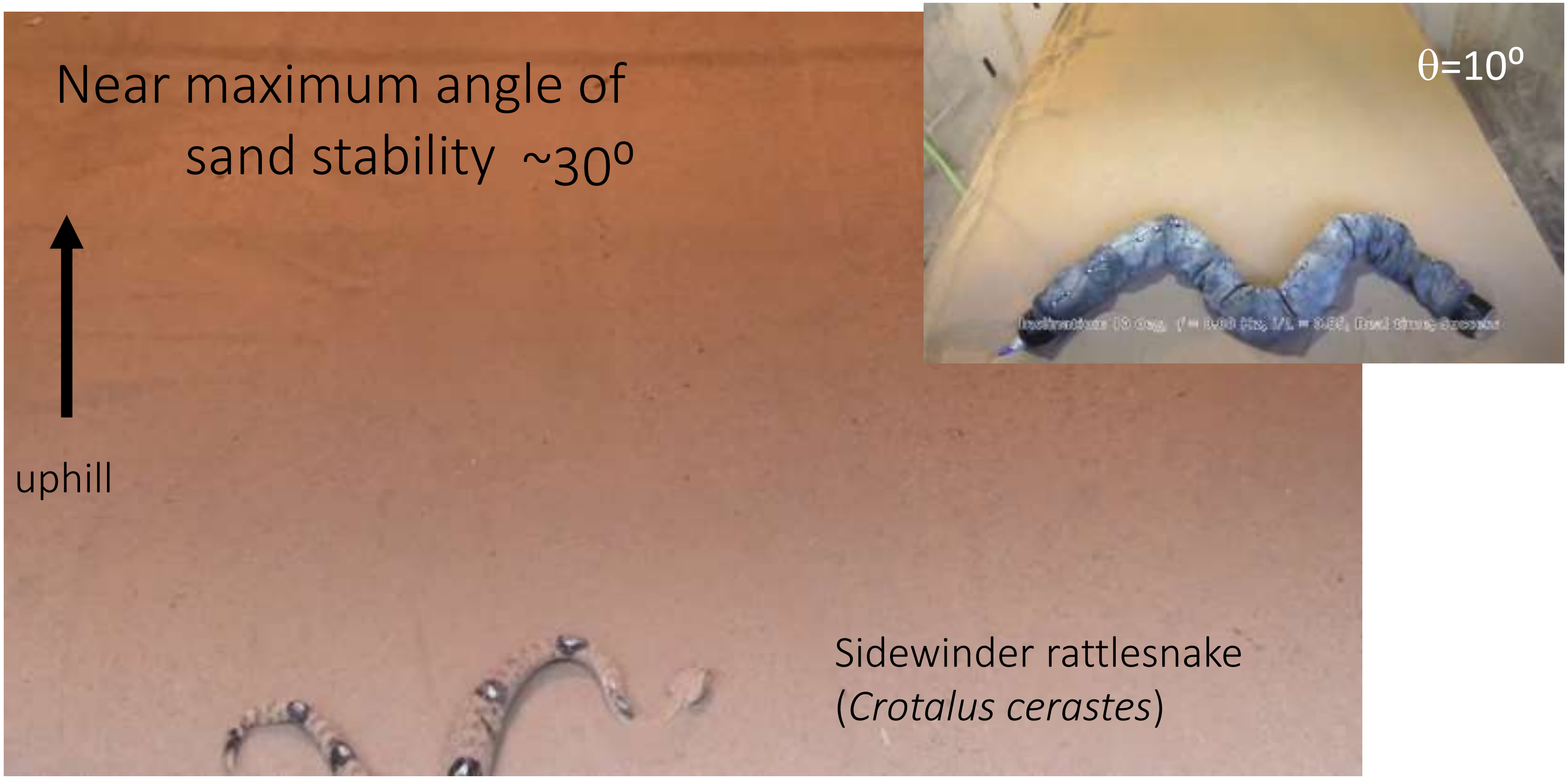

Flow is turned off during experiments, $\phi \approx 0.59$

Air-fluidized bed: A ground control system to create smooth surface, set volume fraction (ϕ) and inclination angle, θ

Substrate manipulation through contact length modulation to remain below yield stress enables effective locomotion

Marvi, Gong, Gravish, Astley, Travers, Hatton Mendelson,
Choset, Hu, Goldman, *Science*, 2014

Modsnake



θ=10°

Near maximum angle of
sand stability ~30°

uphill

Sidewinder rattlesnake
(*Crotalus cerastes*)

Manipulate the ground to generate a solid state during a step

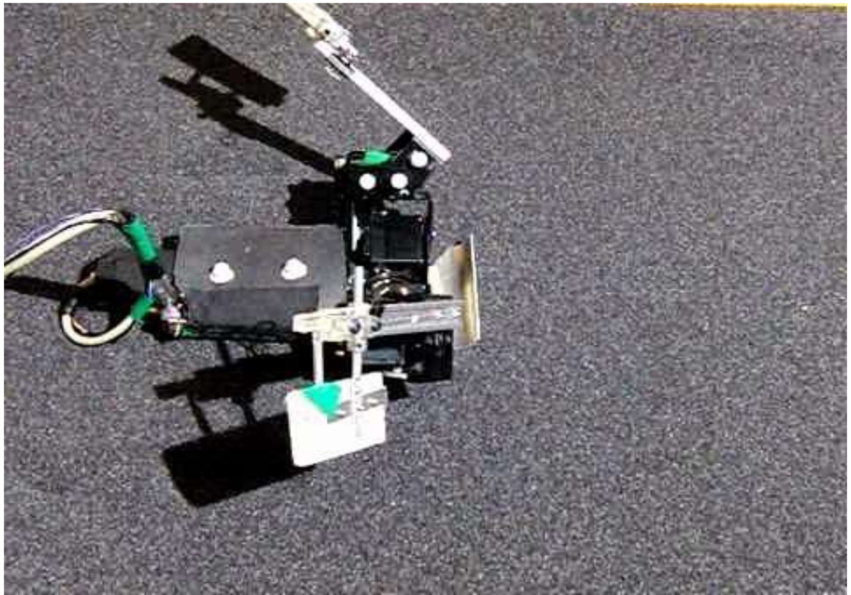
Sidewinder rattlesnake

Marvi, et al, *Science,* 2014

Mazouchova, Gravish, Savu, DIG, *Biology Letters*, 2010

FlipperBot

Mazouchova, Umbanhowar, DIG, *Bioinspiration & Biomimetics*, 2013



SandBot (mini RHex)

Li, Komsuoglu, Umbanhowar, Koditschek, DIG, *PNAS*, 2009

Related snakes (vipers) are challenged by GM, sidewinding not common

Dr. Henry Astley,
postdoc GT

10 degree sand inclines

Dr. Joe Mendelson,
Zoo ATL

Agkistrodon piscivorus

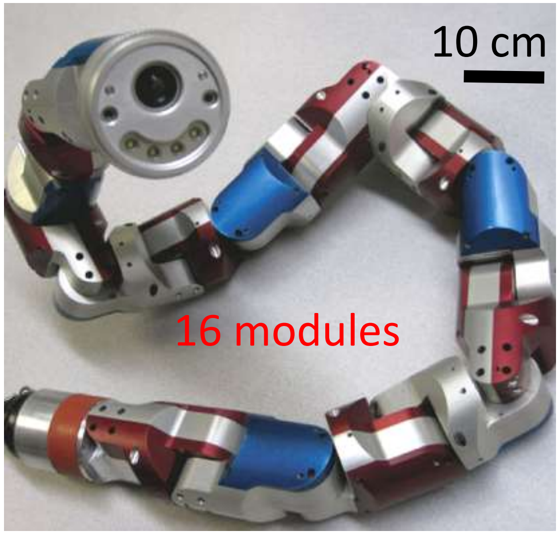
Crotalus willardi

Sistrurus catenatus

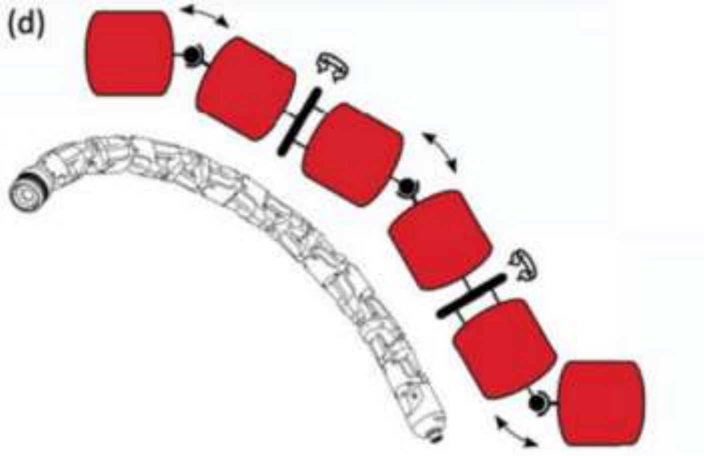
Sidewinding robot, a physical model of the snakes

Modsnake

Prof. Howie Choset, Carnegie Mellon U



Command joint angles vs time to execute sidewinding gait

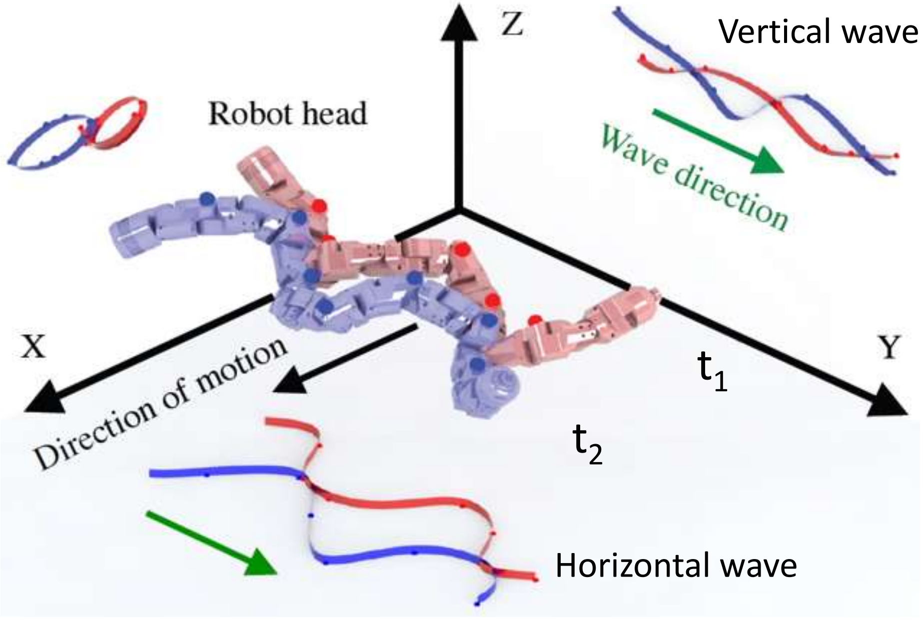


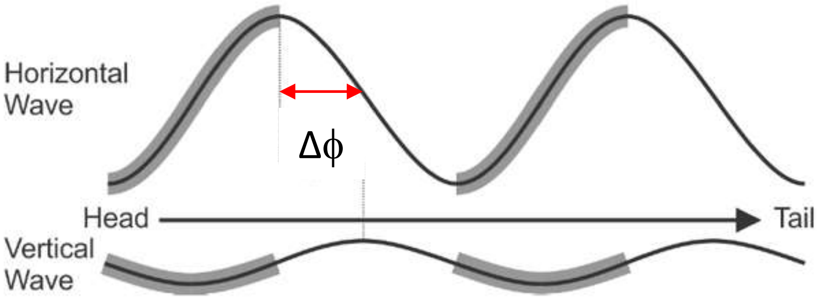
Sidewinding **template**: appropriate mixture of 2 orthogonal body waves

Sidewinding robot: Command $\Delta\phi = \pi/2$ phase difference between vertical and horizontal waves

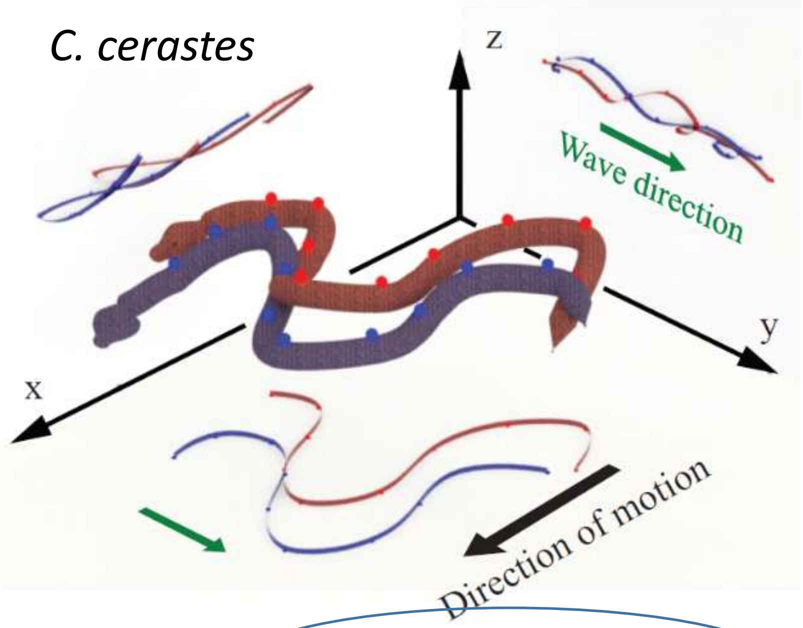
Mass=3 kg, length=1 m

16 modules





(schematic of shape of robot in two projections/planes at a time instant, gray=contact region)


C. *cerastes*

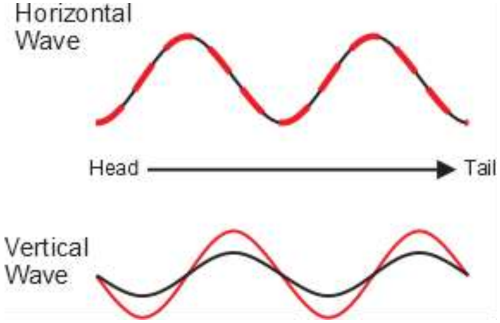
(in snakes $\Delta\phi = 1.51 \pm 0.17$ rad)

Modulating the template to manipulate shape to move in the real world

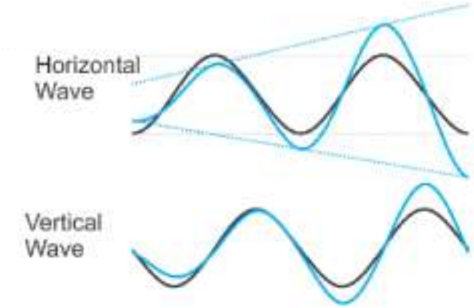
Astley, Gong, Dai, Travers, Serrano, Vela, Choset, Mendelson, Hu, Goldman, *PNAS*, 2015

Marvi, Gong, Gravish, Astley, Travers, Hatton, Mendelson, Choset, Hu, Goldman, *Science*, 2014

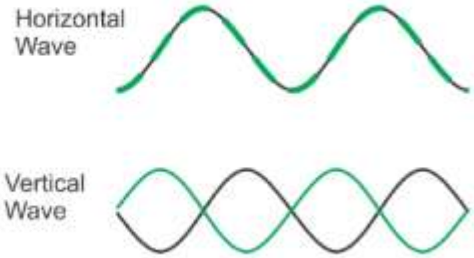
- Sandy slope ascent: modulate amplitude of vertical wave to generate contact length that minimizes slip by remaining below yield stress



- Slow turn (“differential”) : modulate amplitude of horizontal wave to create differential amplitude from head to tail

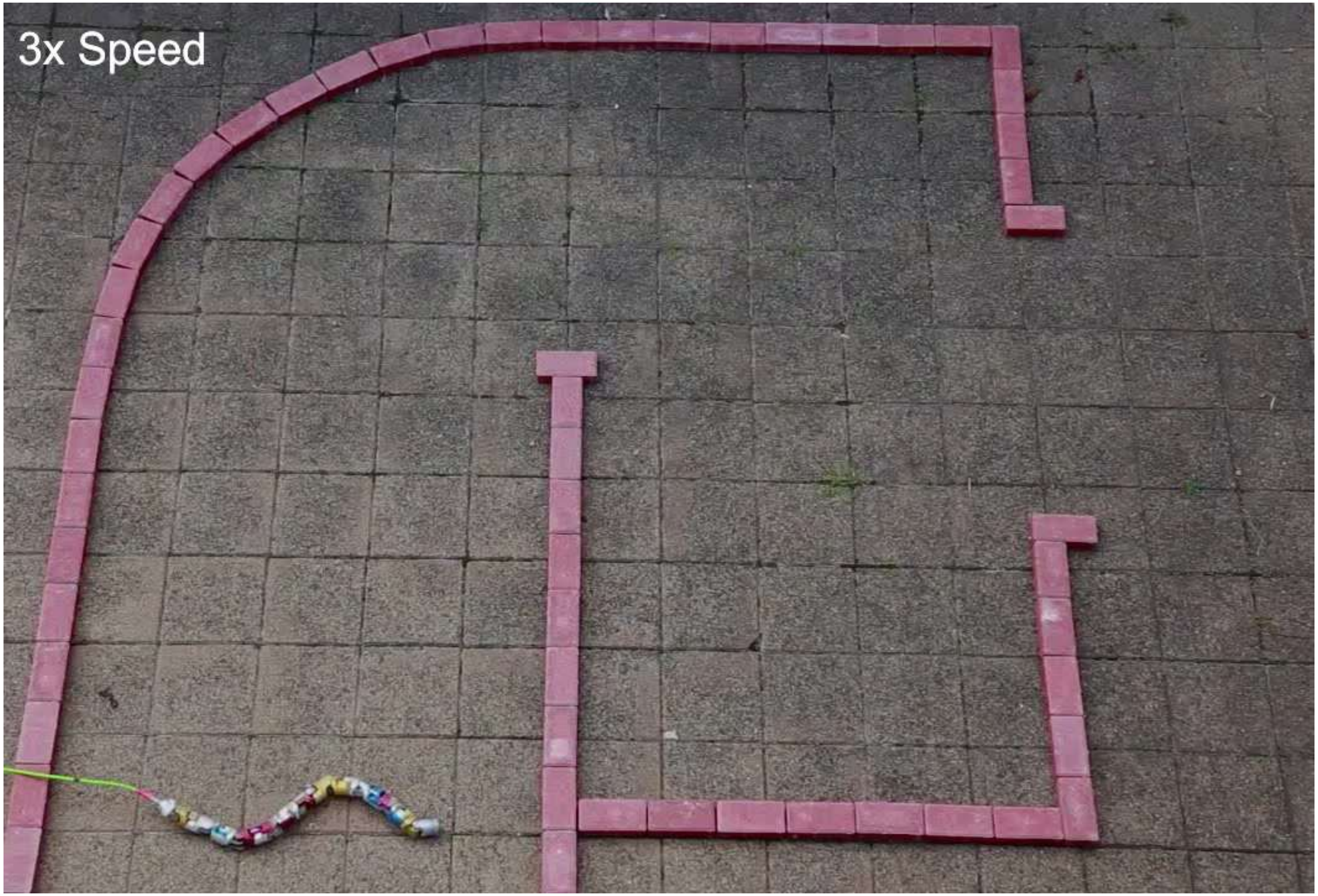


- Rapid turn (“reversal”) : modulate phase of vertical wave to generate sudden change of direction



Maneuverability: sequencing modulations of sidewinding template

Chaohui Gong,
Prof. Howie Choset,
Carnegie Mellon U.



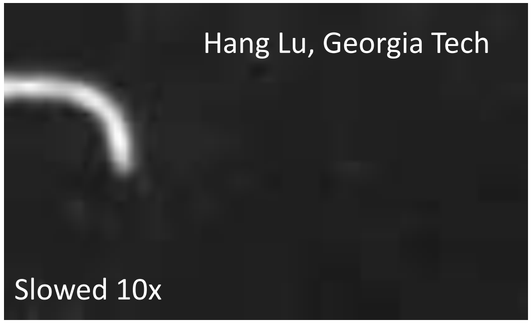
Questions from the organizers

State-of-the-art methods for locomotion and manipulation can be pushed to deal with systems up to 50 DOF, which is fairly impressive compared to what we could achieve just a few years ago.

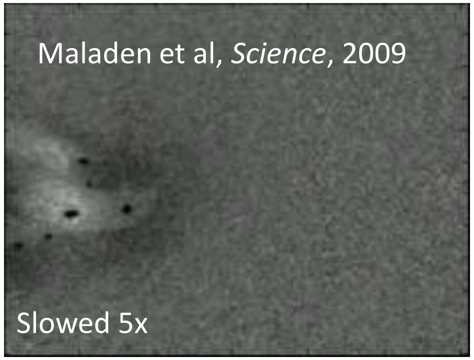
- How can we push this dimensionality even further, perhaps all the way to infinity?
    - Geometric mechanics can produce useful predictions for motion for few DOF and ∞ DOF swimmers
- How do we locomote with soft structures?
- How do we manipulate deformable objects?
- How do we plan and control continuum robots?

Swimming (with no inertia)

R. Gaugler, DEEZ, Rutgers U


Hang Lu, Georgia Tech

Nematode worm in fluid

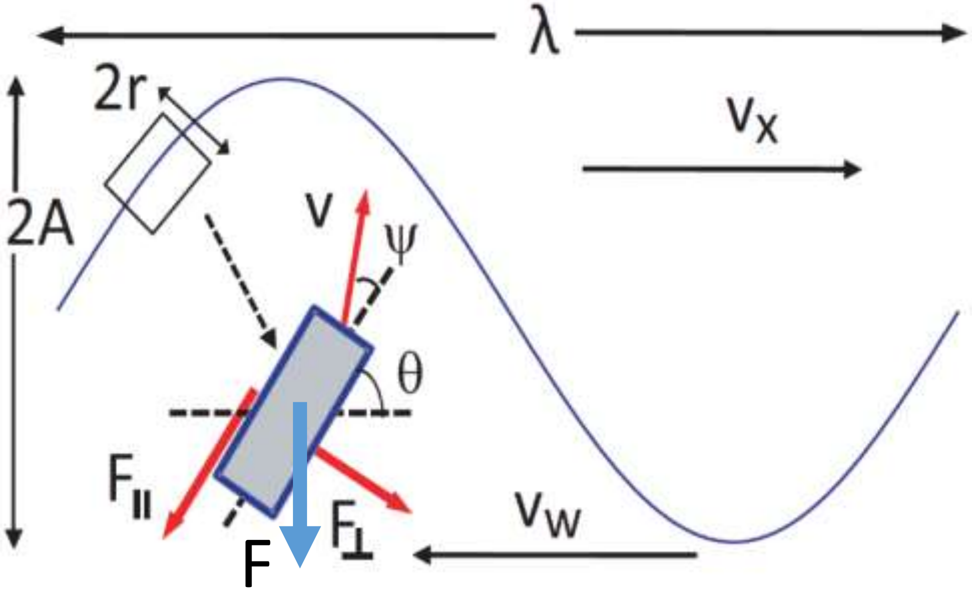

Maladen et al, *Science*, 2009

Sandfish lizard in dry sand

CAN WE UNDERSTAND SAND-SWIMMING LIKE WE DO FLUID SWIMMING?

Resistive Force Theory (RFT) for non-inertial swimming

Biological control assumption: animal controls for pattern of self-deformation



$$\delta F_x = \delta F_\perp \sin\theta - \delta F_\parallel \cos\theta$$

Thrust from Normal force

Drag from parallel force

steady speed swimming

LINEAR, INDEPENDENT, SUPERPOSITION $F_x = \int dF_x = 0$

Stokes' law:

$$\delta F_\perp \propto C_\perp V_\perp$$

$$\delta F_\parallel \propto C_\parallel V_\parallel$$

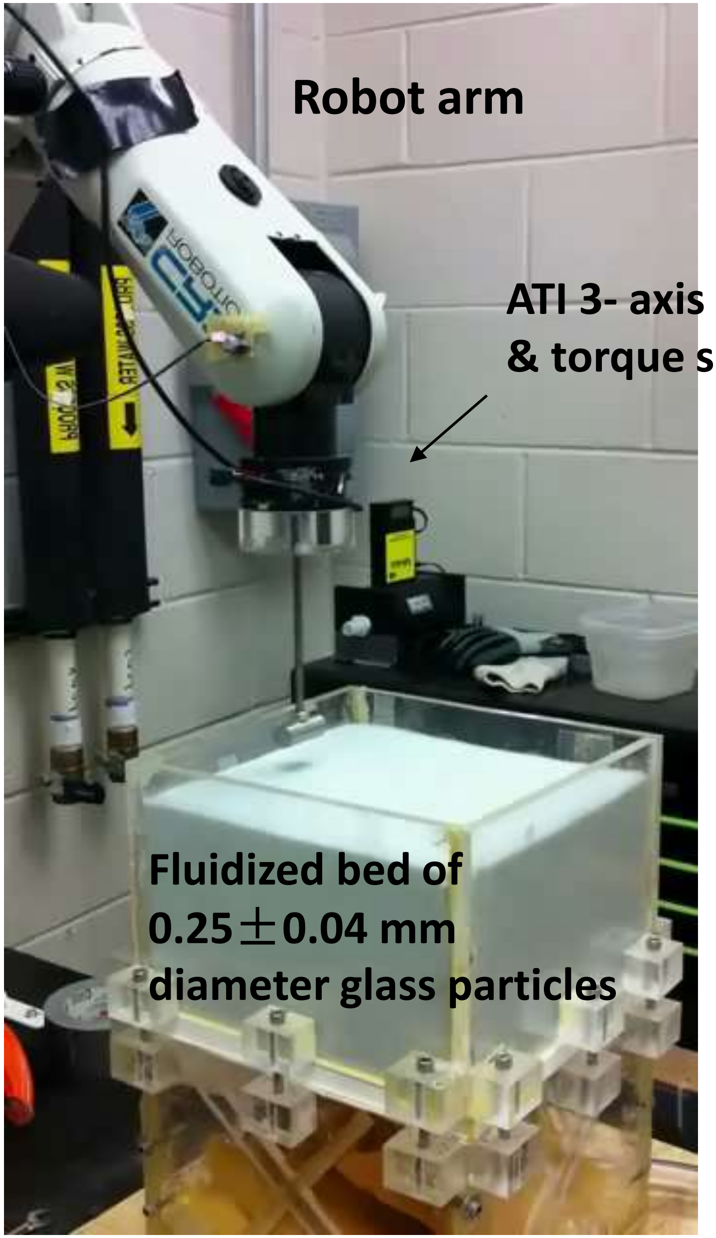
DRAG ANISOTROPY

$$C_\perp / C_\parallel > 1$$

(long thin cylinder, $\frac{C_\perp}{C_\parallel} \to 2$)

Taylor (1951)
Gray & Hancock (1955)
Lauga & Powers (2009)

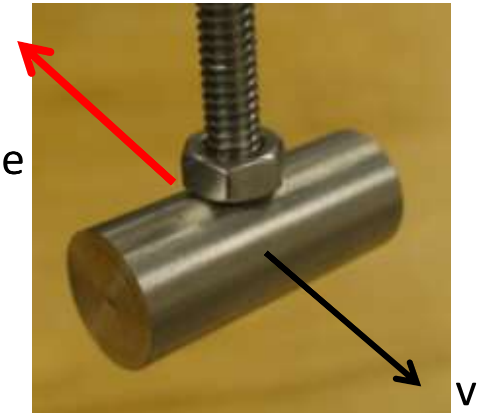
Resistive forces in GM



Robot arm

ATI 3- axis force & torque sensor

Fluidized bed of 0.25±0.04 mm diameter glass particles



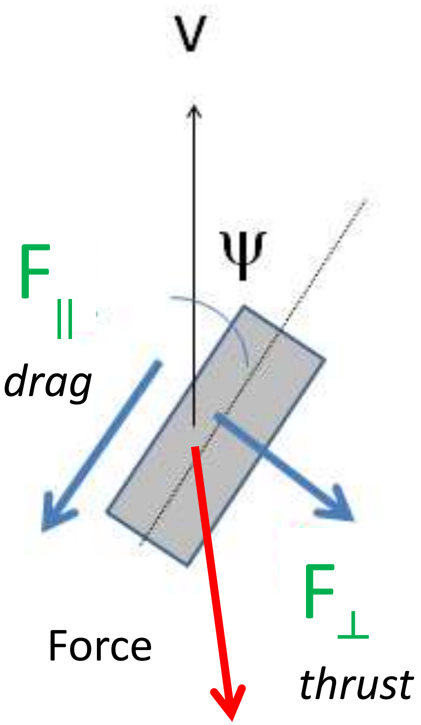
Force

v

1.5 cm diameter, stainless steel rod

(friction ~ sandfish skin~0.2)

(overhead view)



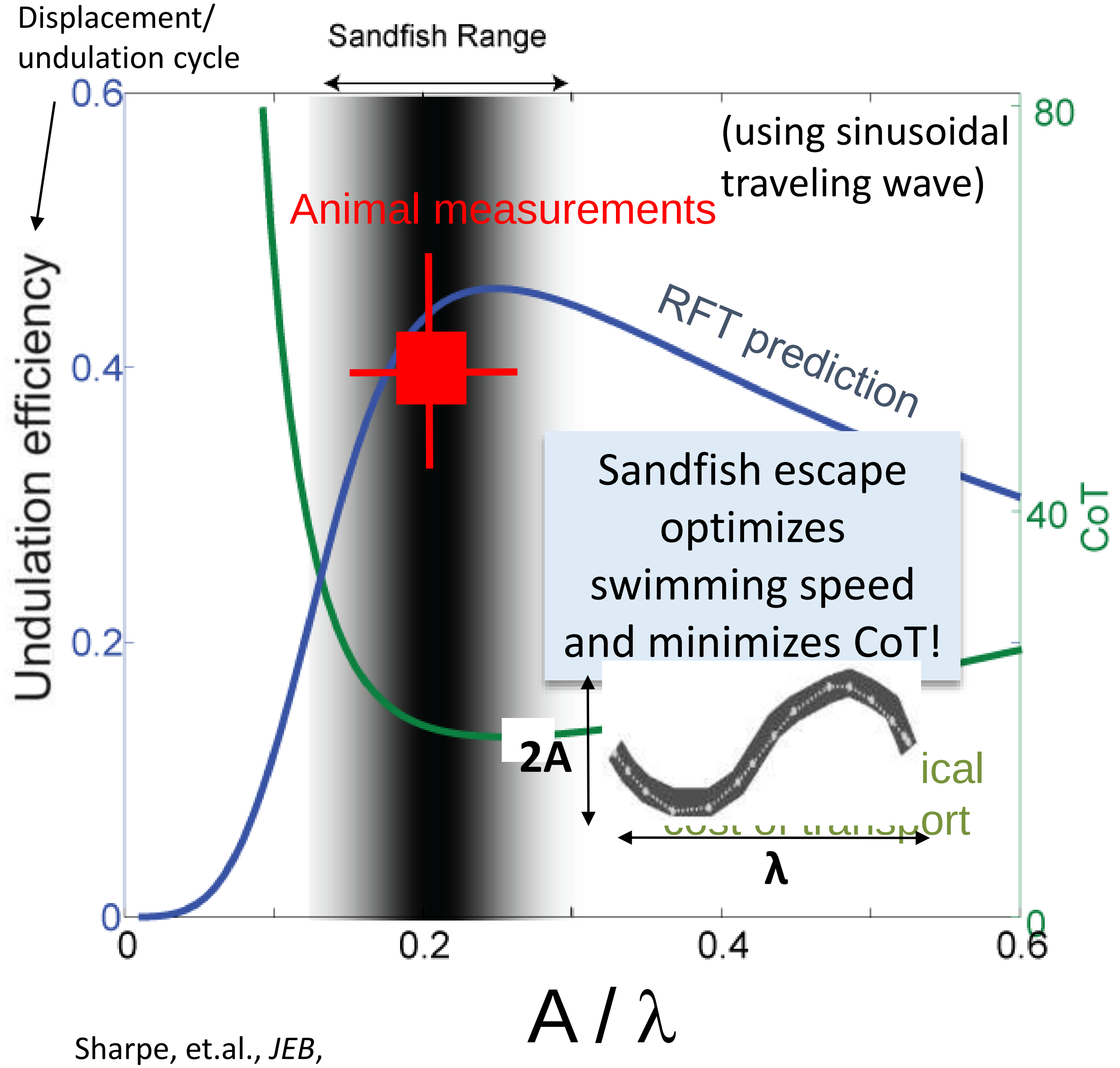
Granular "frictional fluid" analog to Stokes' drag

(Zhang & Goldman, *Physics Fluids*, 2014)

- $\frac{C_{\perp}}{C_{\parallel}} \sim > 3,$
- no speed dependence

Optimal sand-swimming in the sandfish

Maladen et al, *Science*, 2009, *Interface*, 2011



Displacement/ undulation cycle

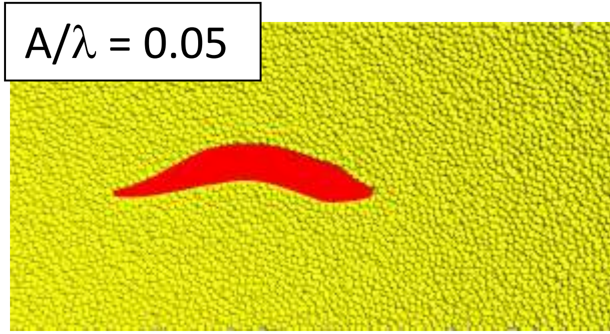
Animal measurements

(using sinusoidal traveling wave)

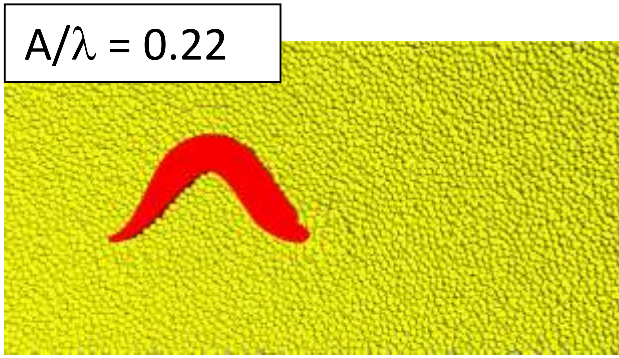
Sandfish escape optimizes swimming speed and minimizes CoT!

f=2 Hz

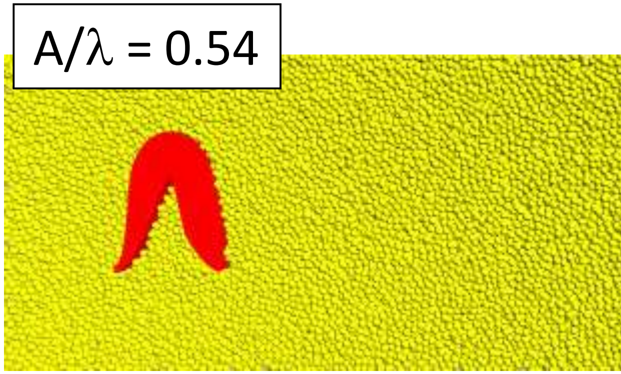
A/λ = 0.05



A/λ = 0.22

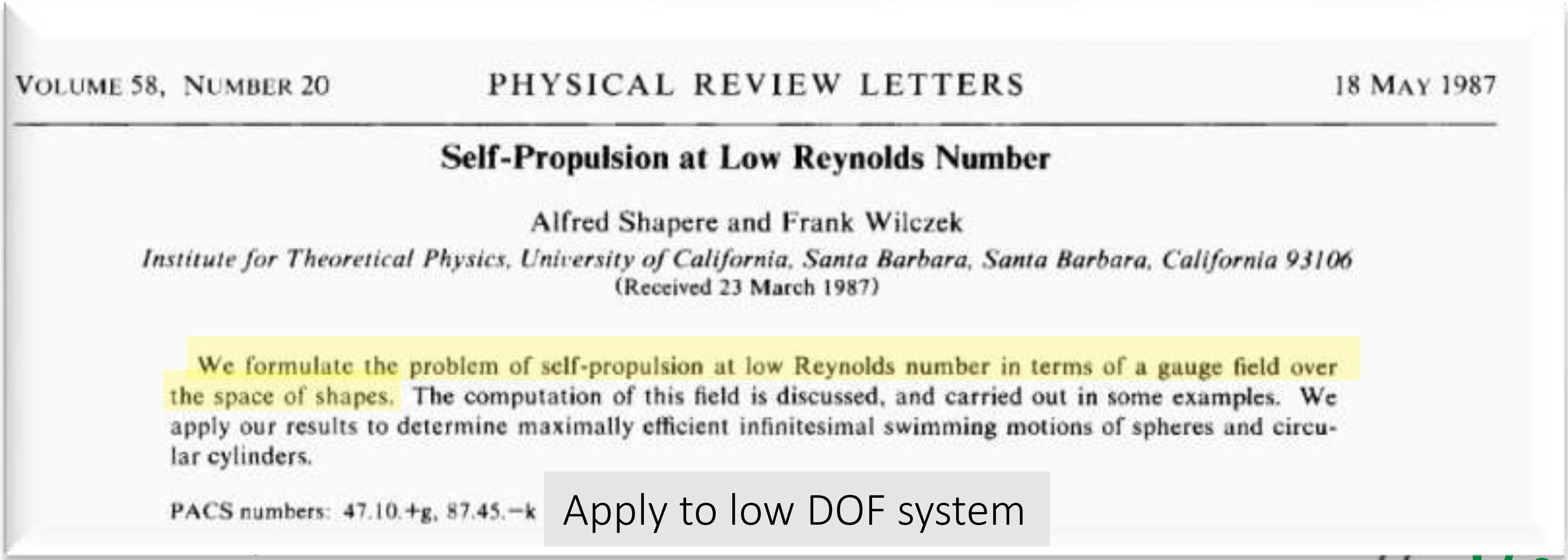


A/λ = 0.54



Sharpe, et.al., *JEB*, (2012) 216, 260-274

Geometric mechanics applied to (non-inertial) self-propulsion



VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

Self-Propulsion at Low Reynolds Number

Alfred Shapere and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106

(Received 23 March 1987)

We formulate the problem of self-propulsion at low Reynolds number in terms of a gauge field over the space of shapes. The computation of this field is discussed, and carried out in some examples. We apply our results to determine maximally efficient infinitesimal swimming motions of spheres and circular cylinders.

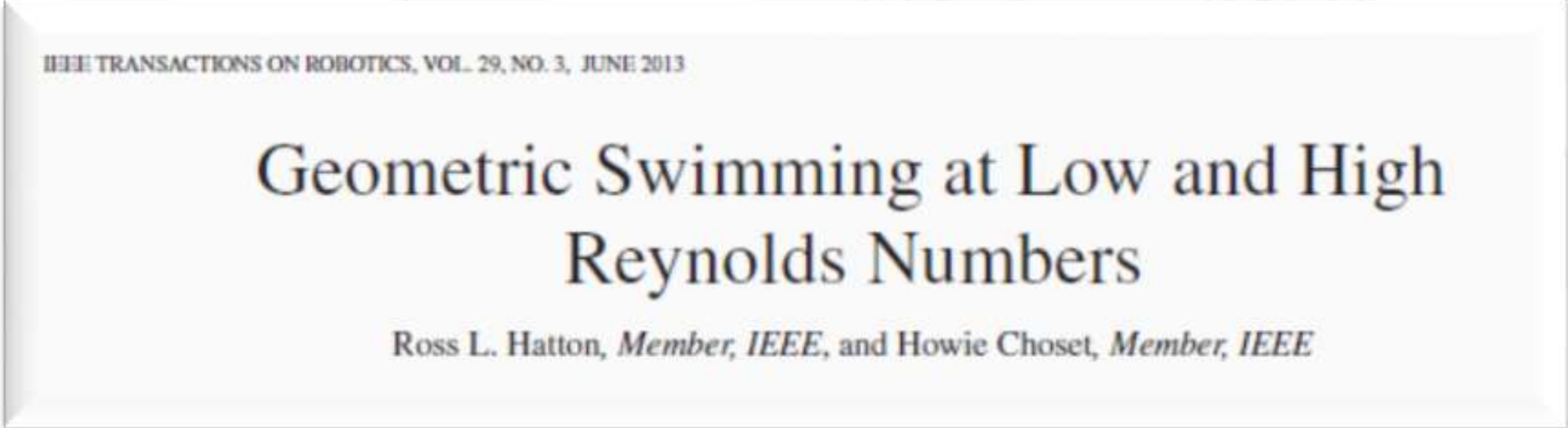
PACS numbers: 47.10.+g, 87.45.−k

Apply to low DOF system

Body velocity

$$\xi = A\vec{\alpha}$$

Symmetries at low Re + kinematic motion



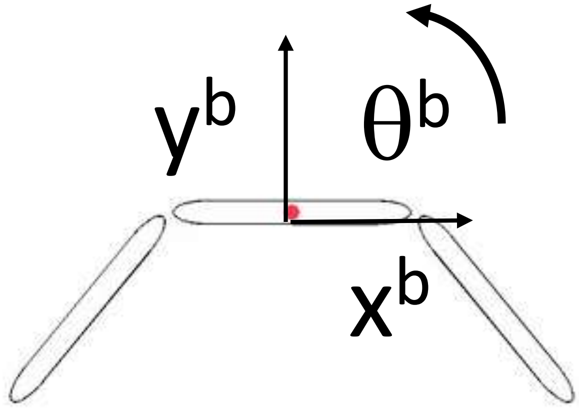
IEEE TRANSACTIONS ON ROBOTICS, VOL. 29, NO. 3, JUNE 2013

Geometric Swimming at Low and High Reynolds Numbers

Ross L. Hatton, *Member, IEEE*, and Howie Choset, *Member, IEEE*

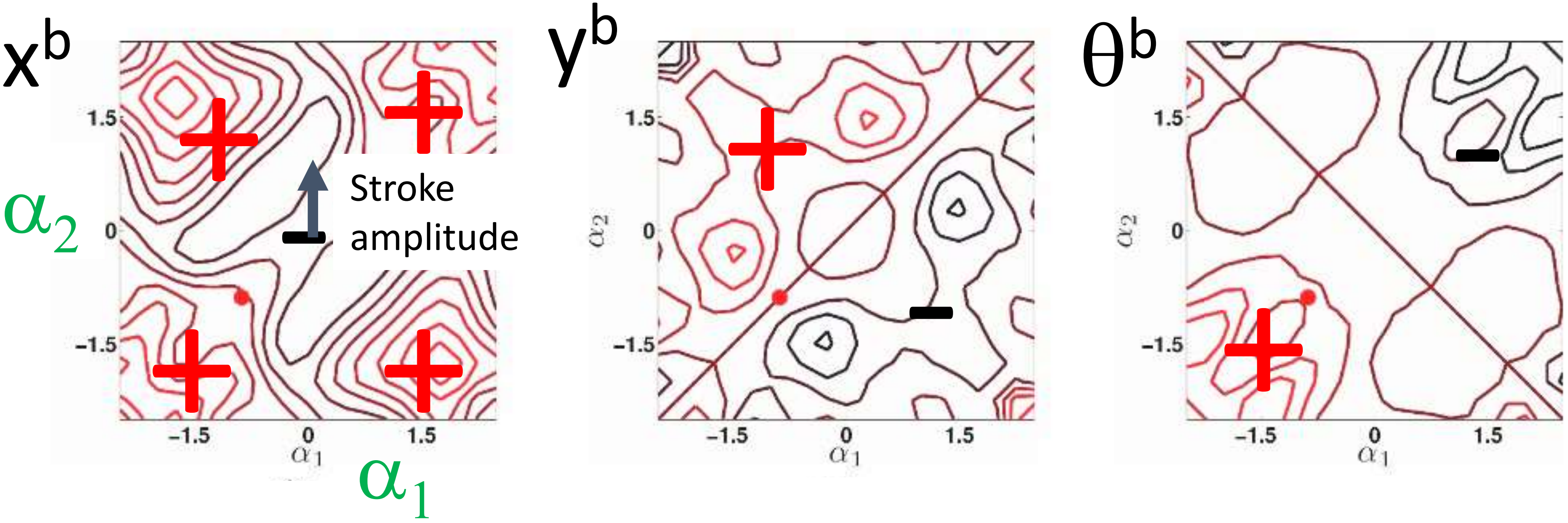
Calculate motion for large self-deformations using optimal coordinates

CCFs allow visualization of how shape changes lead to net translation/rotation



Area in CCF space ~ net displacement or rotation after cycle

CCFs

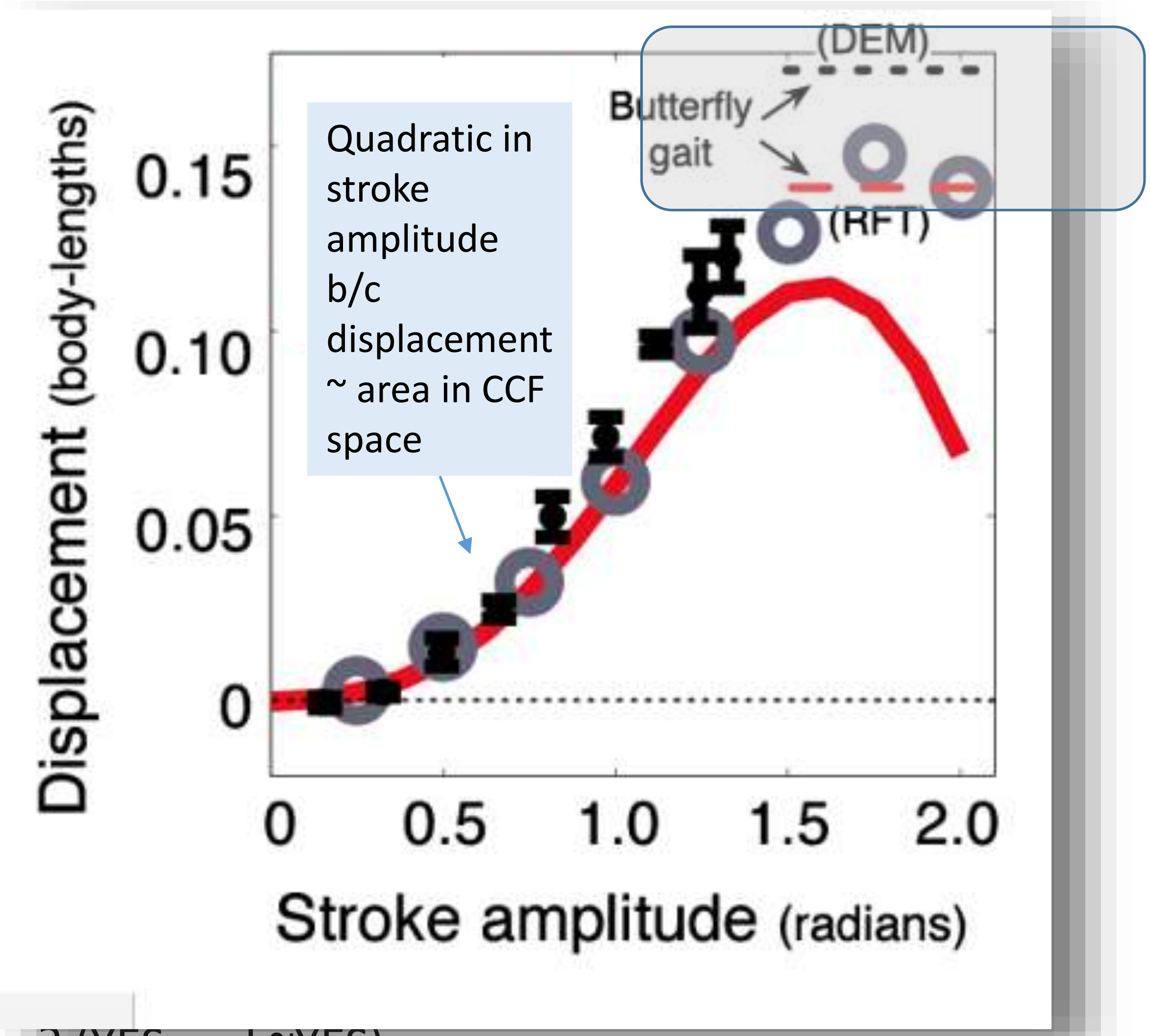


Geometric mechanics of a granular 3-link swimmer

Hatton, Ding, Choset & Goldman, *PRL*, 2013

Ca

D



Quadratic in stroke amplitude b/c displacement ~ area in CCF space

Assumptions in model:

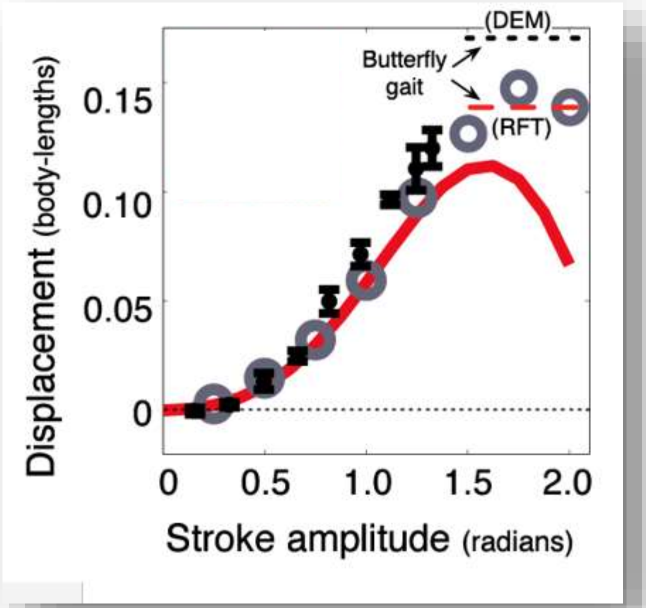
→kinematic (no inertia) (YES

→Linearity in local connectic

→symmetry in space and time? (YES and ~YES)

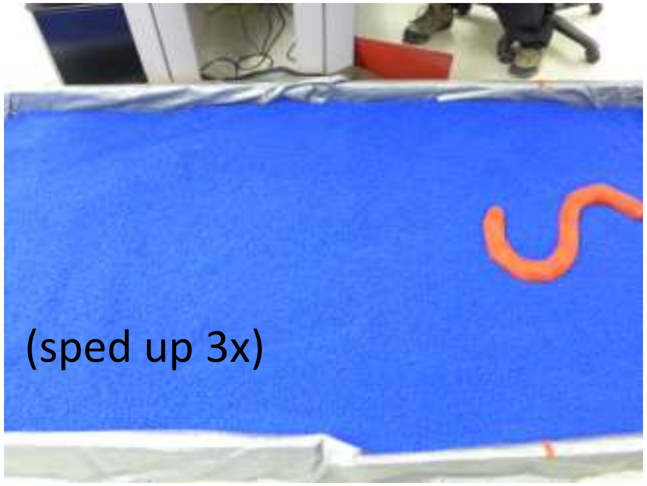
Gait optimization

(Butterfly gait)

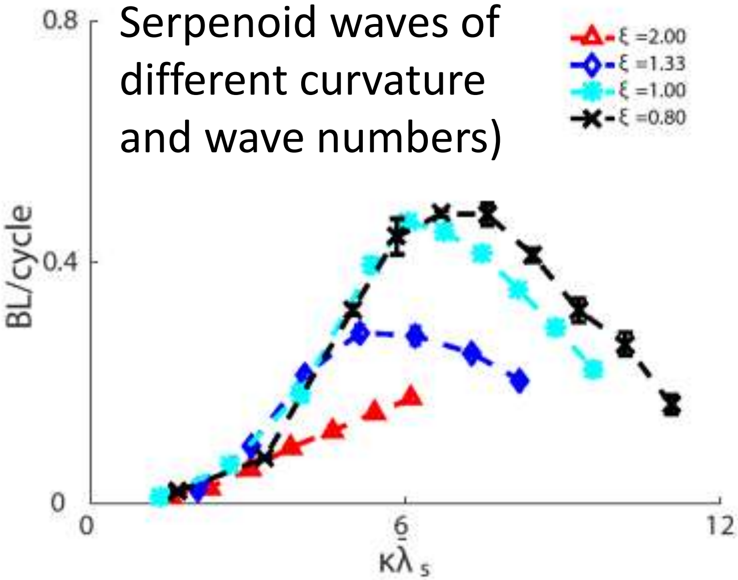


Can we apply these techniques (geometric mechanics + optimal coordinates) to higher DOF “real world” kinematic systems?

Dai, Gong, Hatton, CMU

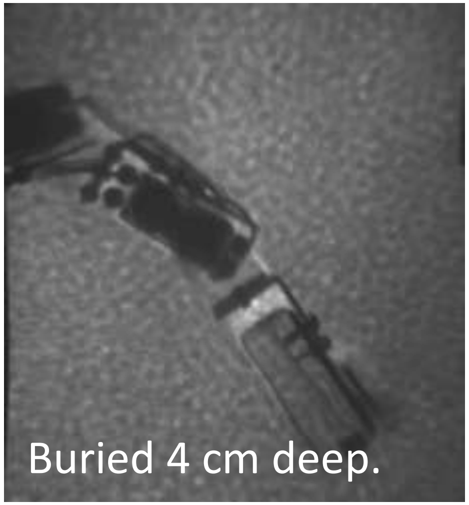


(sped up 3x)

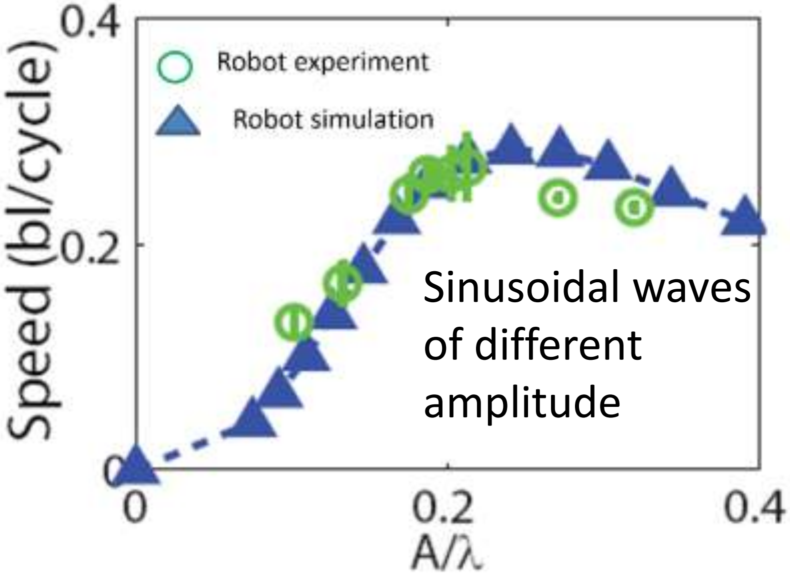


Serpenoid waves of different curvature and wave numbers)

Maladen et al, GT



Buried 4 cm deep.



Sinusoidal waves of different amplitude

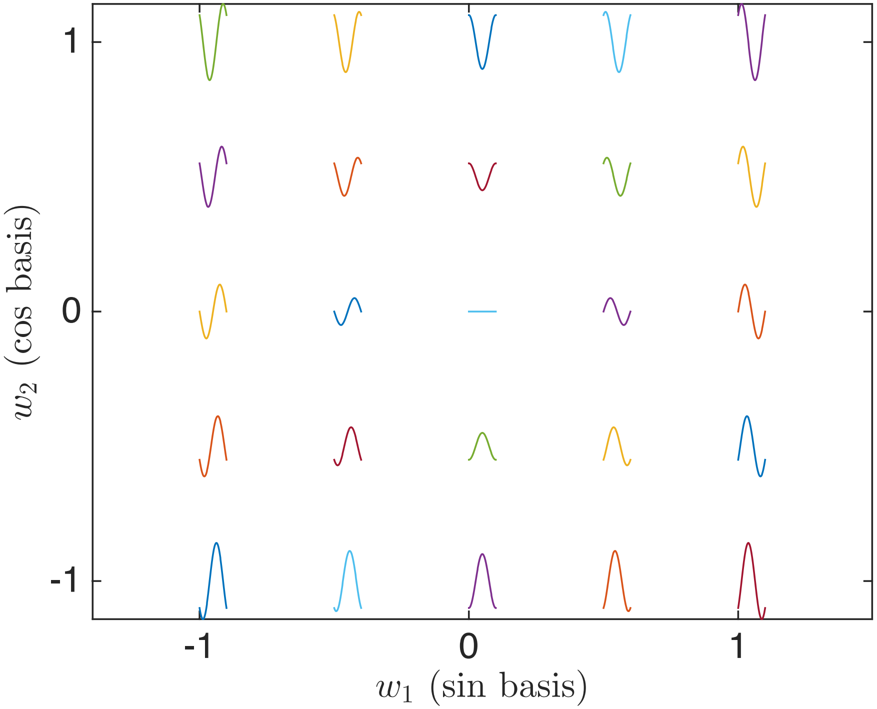
Reducing a continuum robot to 2D

Chaohui Gong,
Prof. Howie Choset,
Carnegie Mellon U.

$$\kappa(s) = w_1\beta_1(s) + w_2\beta_2(s)$$

$\kappa(s)$: curvature along the arc length

$\beta(s)$: curvature basis function

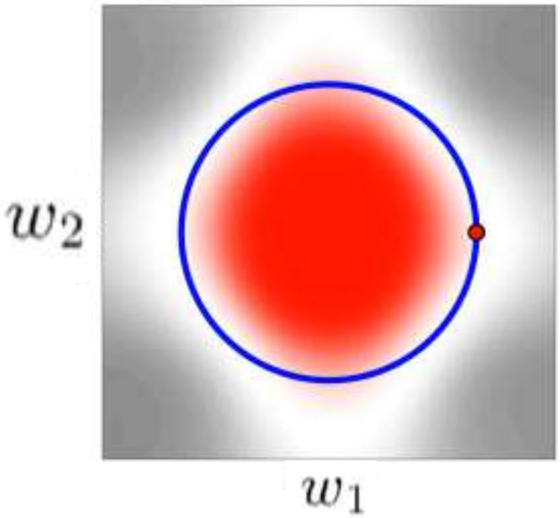


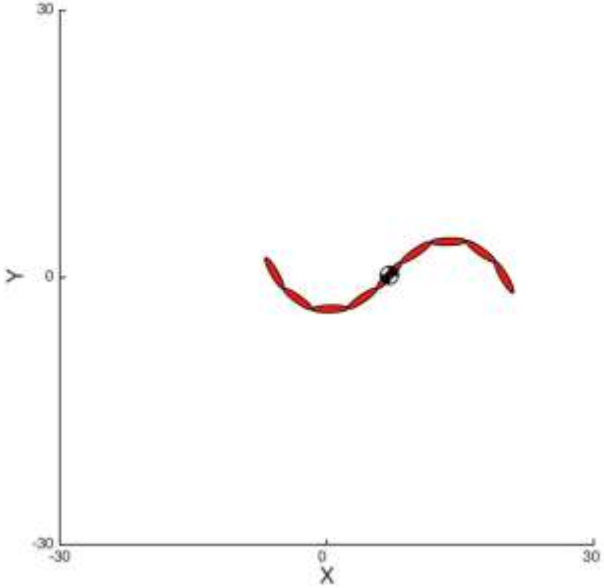
A gait is defined together by the shape bases and the trajectory in the reduced shape space which is defined by the shape bases:

- Approximate arbitrary curve as sum of bases, and compute CCFs
- Optimize shape bases, recompute CCFs

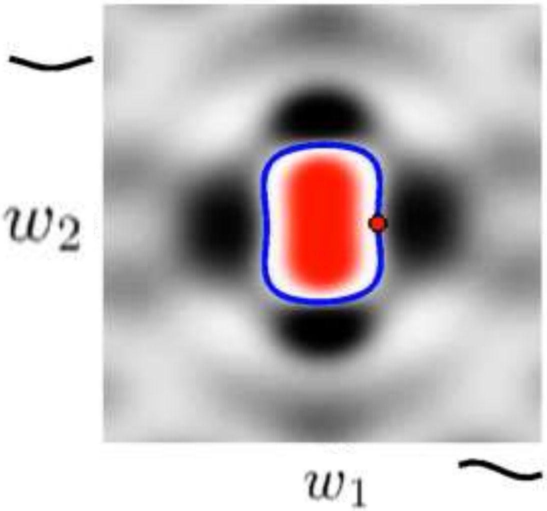
(9 links used so can implement on robot)

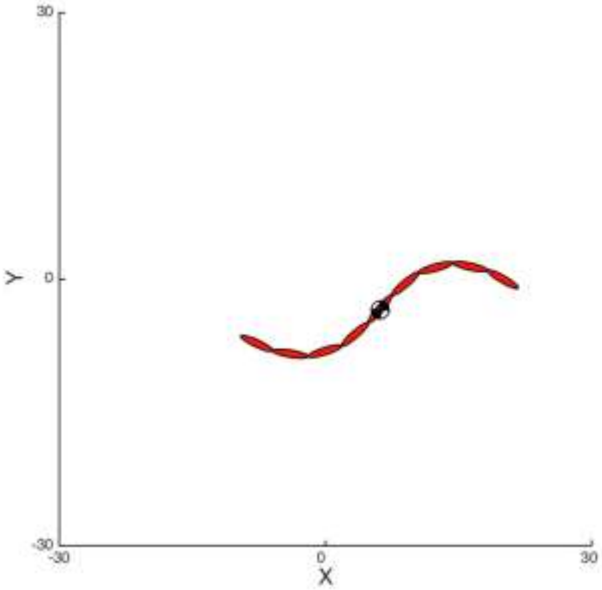
x^b CCF in sin & cos bases (serpenoid)





x^b CCF in optimal bases

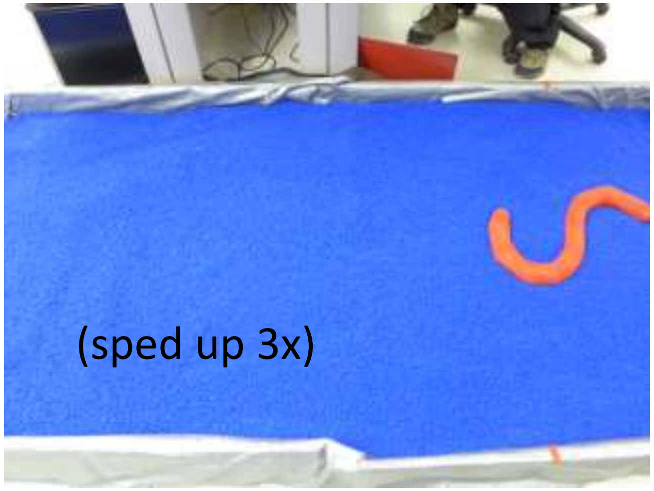




2 bases CCFs predict optimal movement!

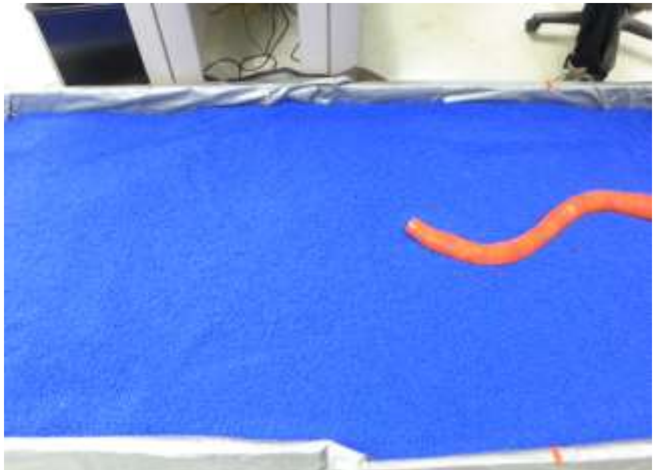
Chaohui Gong,
Prof. Howie Choset,
Carnegie Mellon U.

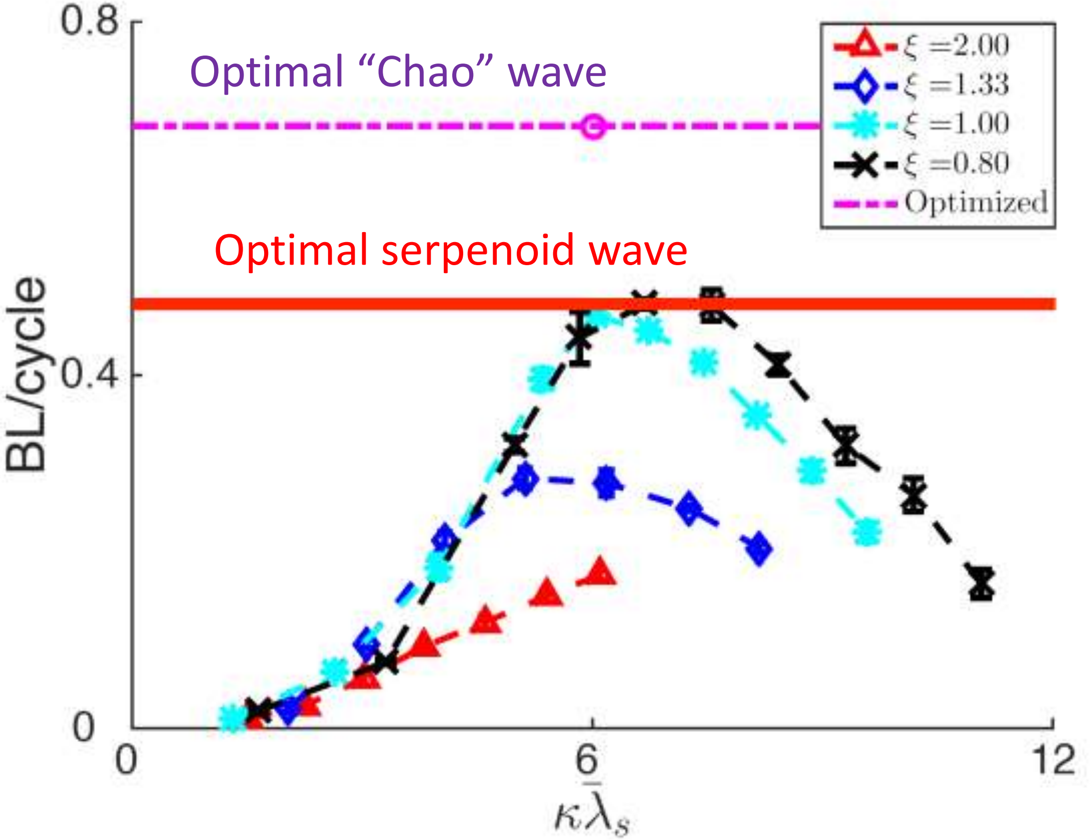
Serpenoid waves



(sped up 3x)

“Chao” waves





Optimal “Chao” wave

Optimal serpenoid wave

Questions from the organizers

State-of-the-art methods for locomotion and manipulation can be pushed to deal with systems up to 50 DOF, which is fairly impressive compared to what we could achieve just a few years ago.

- How can we push this dimensionality even further, perhaps all the way to infinity?
- How do we locomote with soft structures?
- How do we manipulate deformable objects?
  - Fire ant nest construction requires sophisticated manipulation and mobility of and in deformable granular materials
- How do we plan and control continuum robots?

Arthropod manipulation of dry and wet granular media

“Rakers”

“Pushers”

“Pullers”

“Carriers”

*Videos are courtesy of YouTube users. **Behavior lit.: Evans (1966), Muma (1967), Price (2009), Williams (1966), Formanowicz (1991), Springthorpe & Full (2013)

Red imported fire ant (*Solenopsis invicta* Buren)

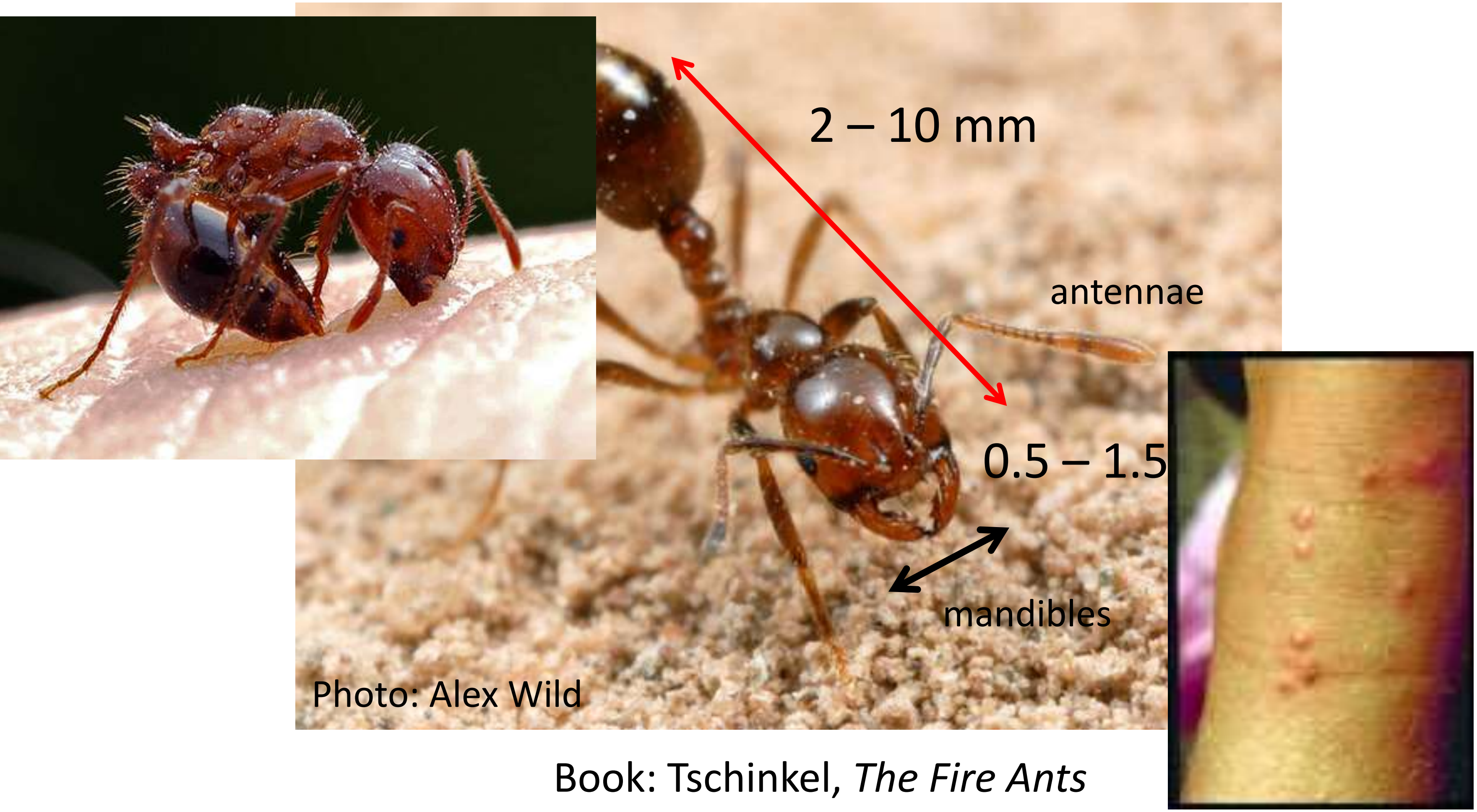
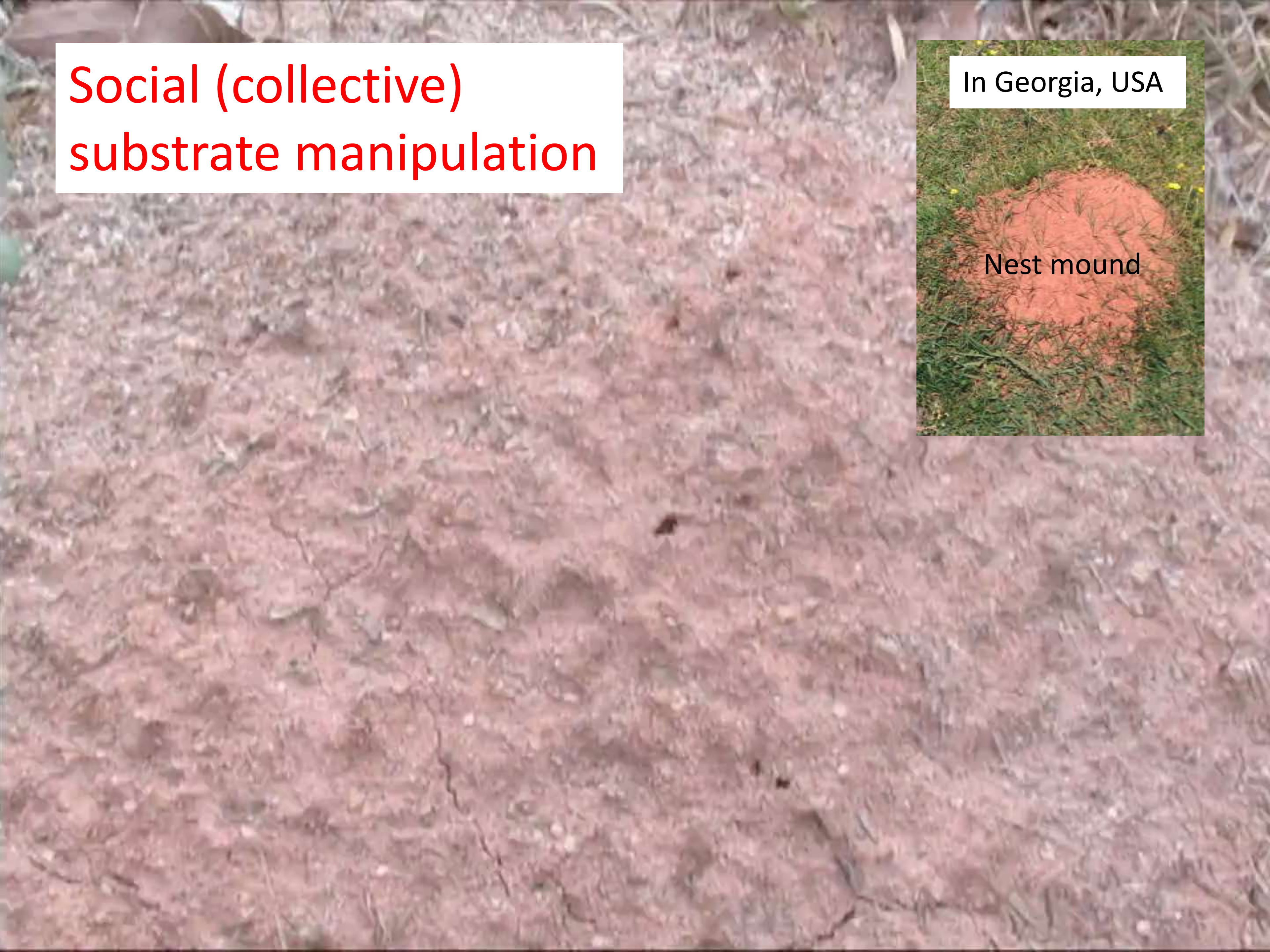


Photo: Alex Wild

Book: Tschinkel, *The Fire Ants*

- Monogyne colonies (single queen) contain 10^2 to 10^6 workers
- Worker lifespan ~months, colony lifespan can be greater than 10 years
- Dig to create subterranean nests which house the colony → "extended phenotype"

Social (collective) substrate manipulation



Nests of social insects (fire ants)

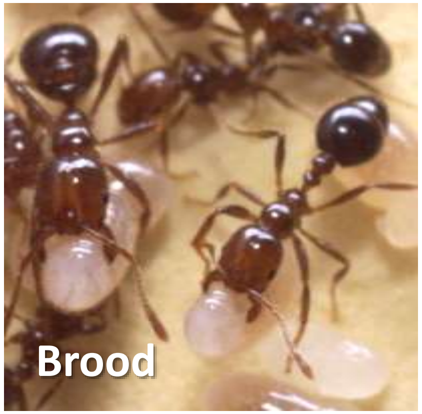
Nest cast*

$10^3 - 10^6$ ants

2-6 mm

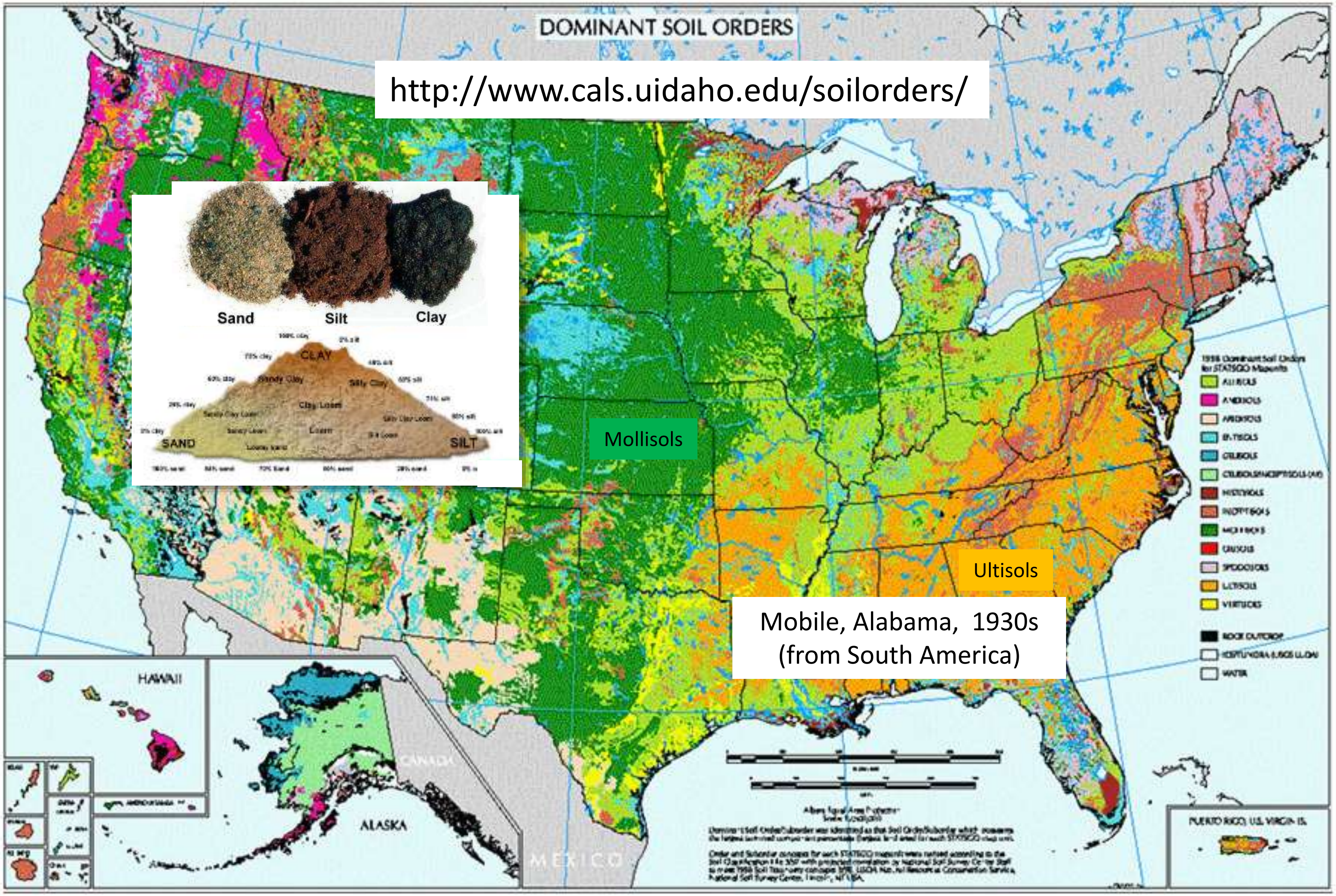
Social functions:
- Brood care;
- Communication;
- Mating;
- Food sharing and food provision.

Robut manipulators



images: sbs.utexas.edu, insectexpertphd.com, msucares.com

Manipulate any granular media



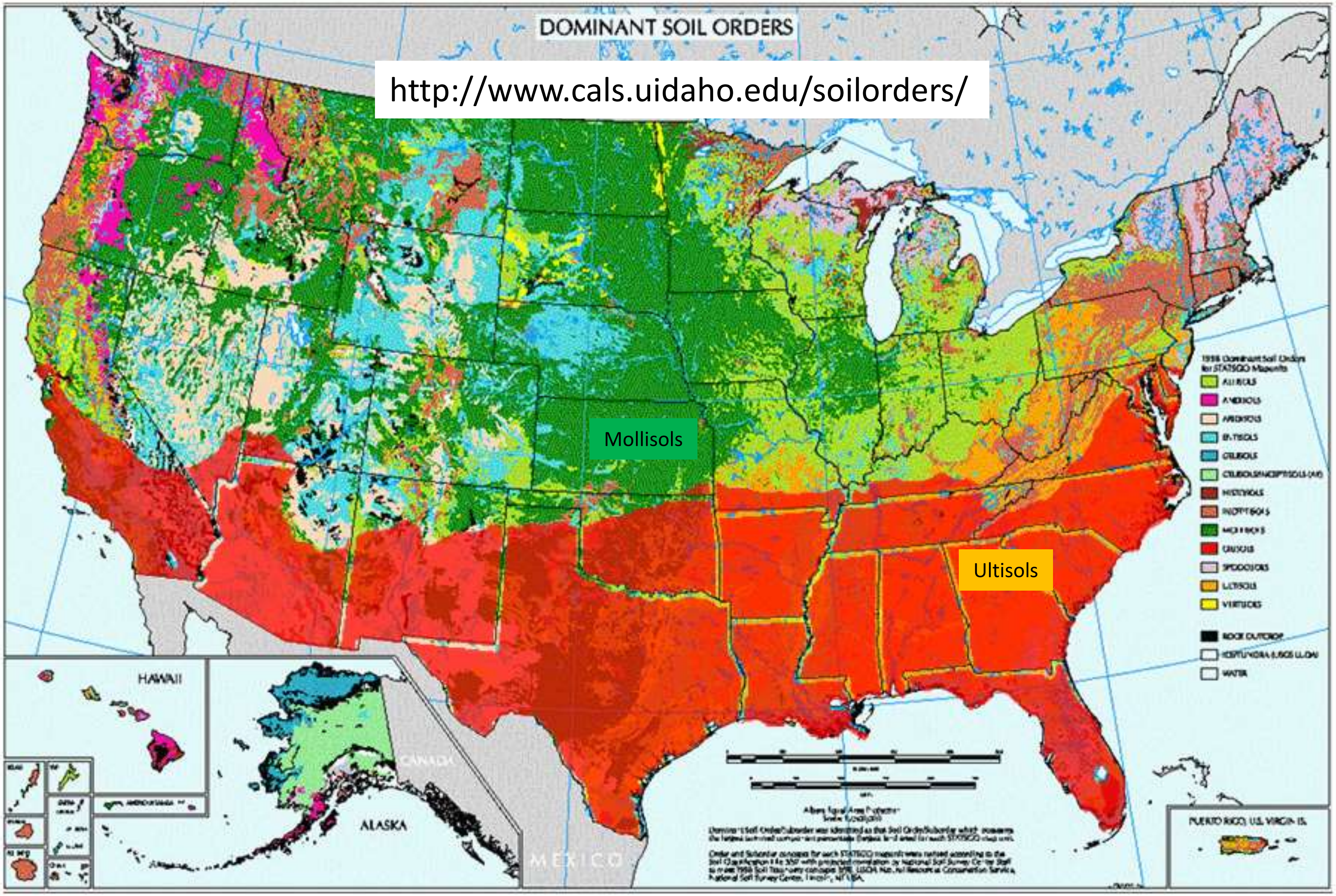
http://www.cals.uidaho.edu/soilorders/

Mollisols

Ultisols

Mobile, Alabama, 1930s
(from South America)

Manipulate any granular media



http://www.cals.uidaho.edu/soilorders/

Mollisols

Ultisols

We are interested in how soil properties affect **manipulation & locomotion** strategies and nest structures during collective excavation

- Substrate can deform and fall apart!
- Space constraints (confined & crowded)
- Irregular surfaces
- Perturbations (jostling)
- Lack of vision (dark)

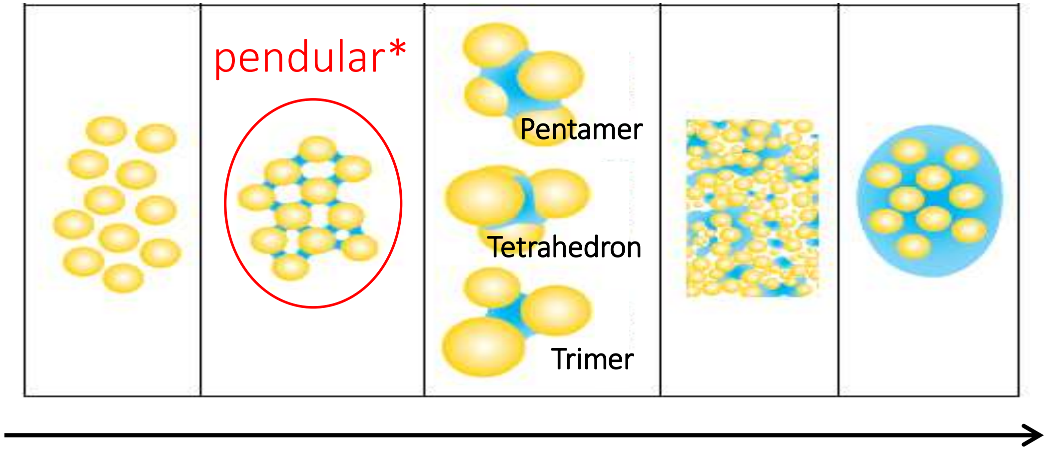
Simplified laboratory *cohesive* soils: mixtures of sand and water

Dry

Slightly wet

Microscopically well characterized regime: slightly wet granular media

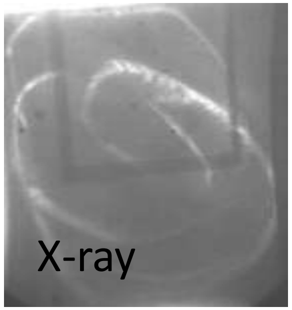
*Particles are held together by liquid bridges at their contact points



Increasing wetness

Kudrolli, et al. (2008)
(adapted from Mitari & Nori, 2006)

Challenge: create repeatable homogeneous states in sandy soils

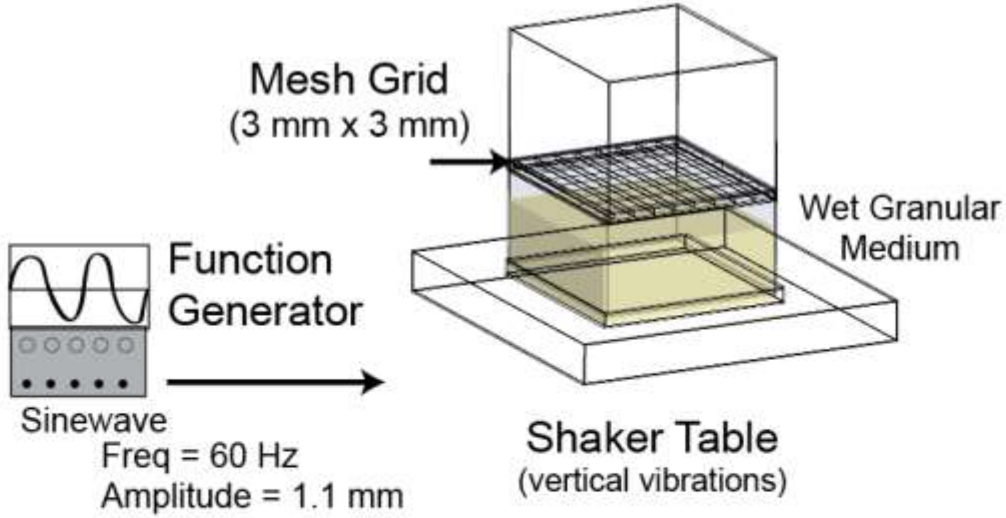


x5

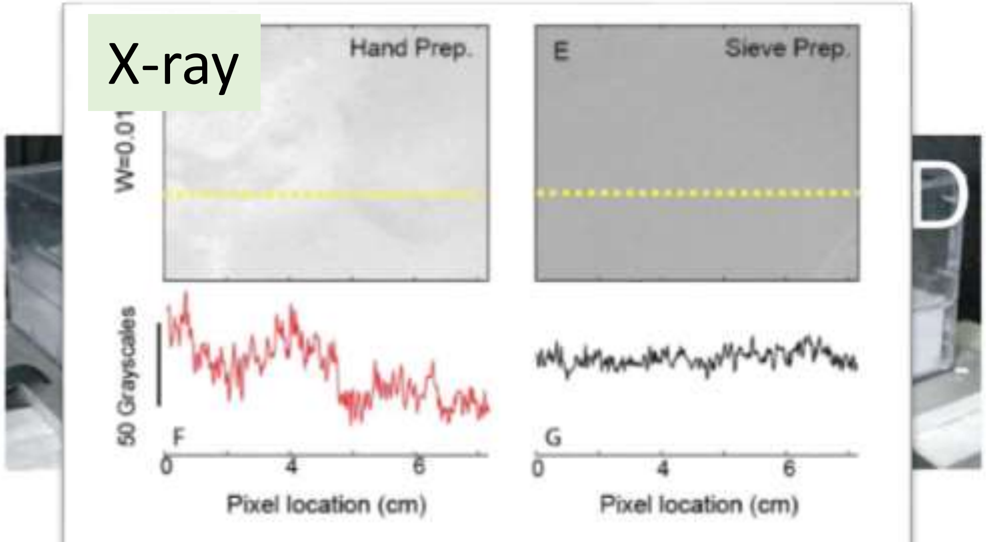
New method* to create repeatable & variable homogeneous wet sandy substrates

- Sharpe, Kuckuk, Goldman, *Phys. Bio.*, in review 2015
- Monaenkova et al, *J. Exp. Biol*. 2015

0.27± 0.04 mm diameter glass particles



X-ray



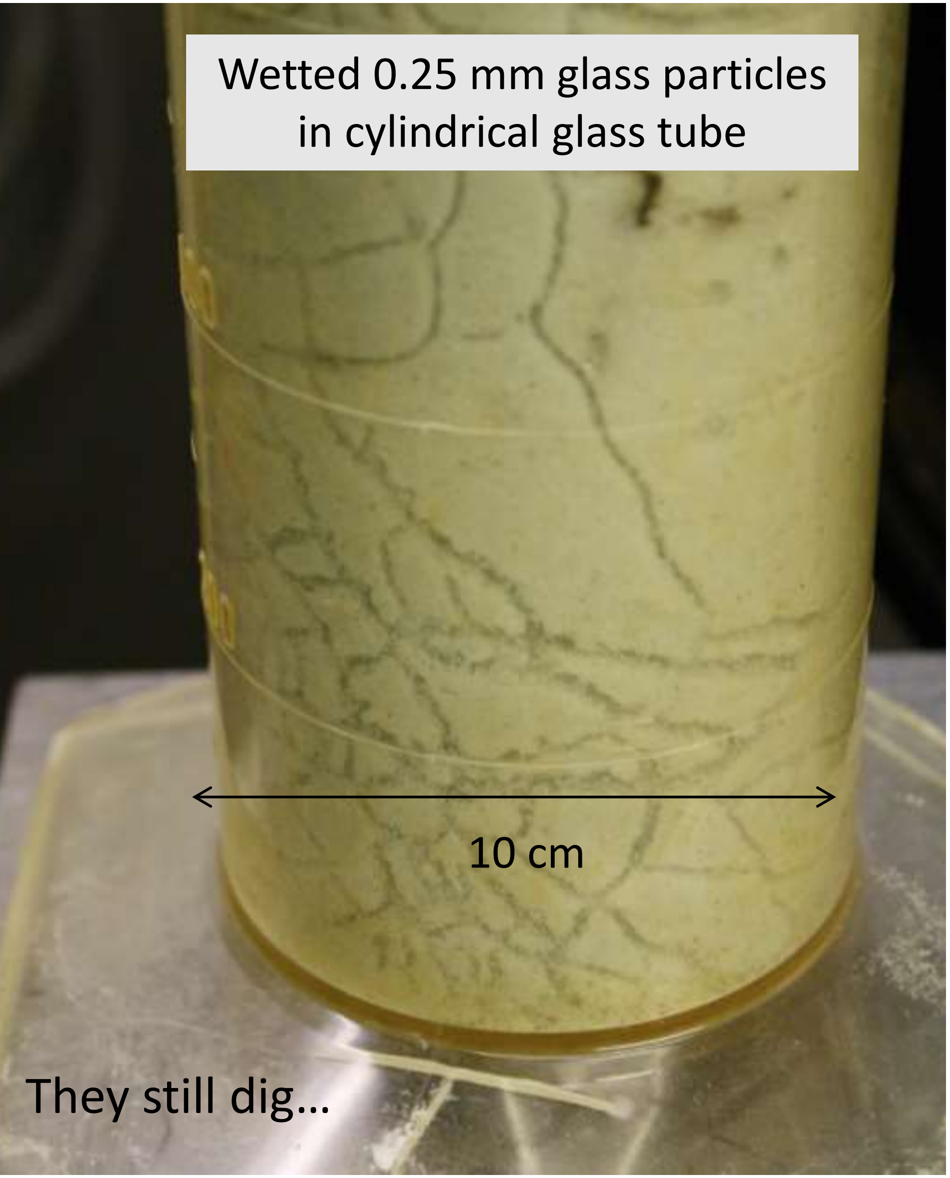
“Make it Rain”

Real Time

*thanks to Nick Gravish

First study of nest architecture in 3D

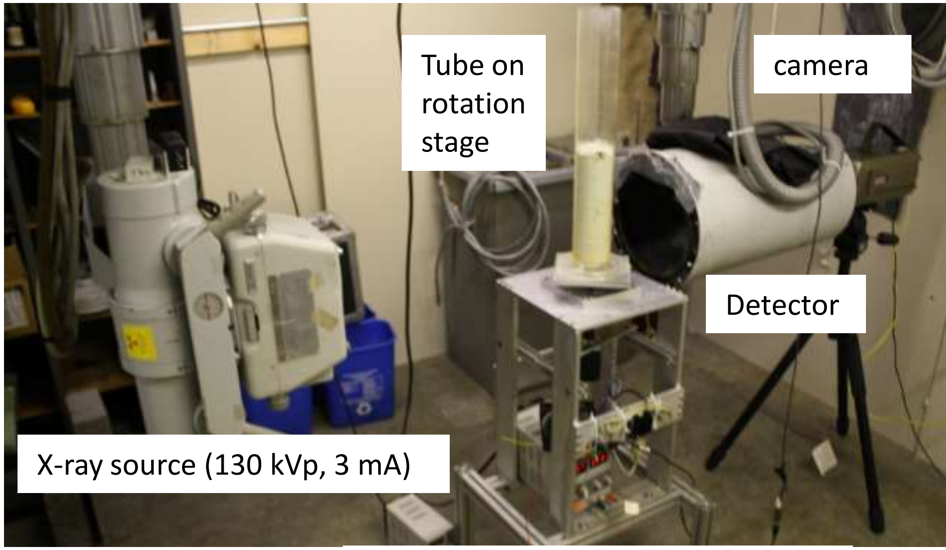
Monaenkova et al, *J. Exp. Biol*. 2015

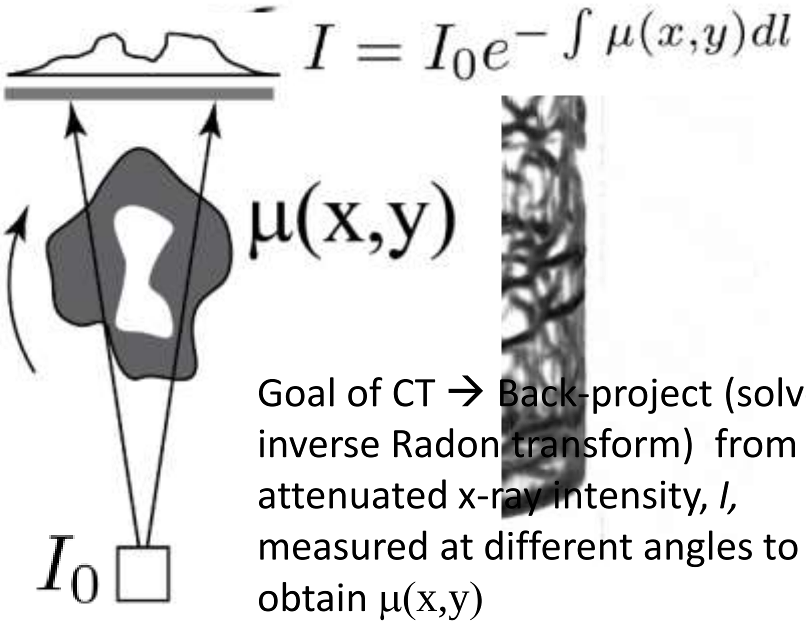


Wetted 0.25 mm glass particles in cylindrical glass tube

10 cm

They still dig…



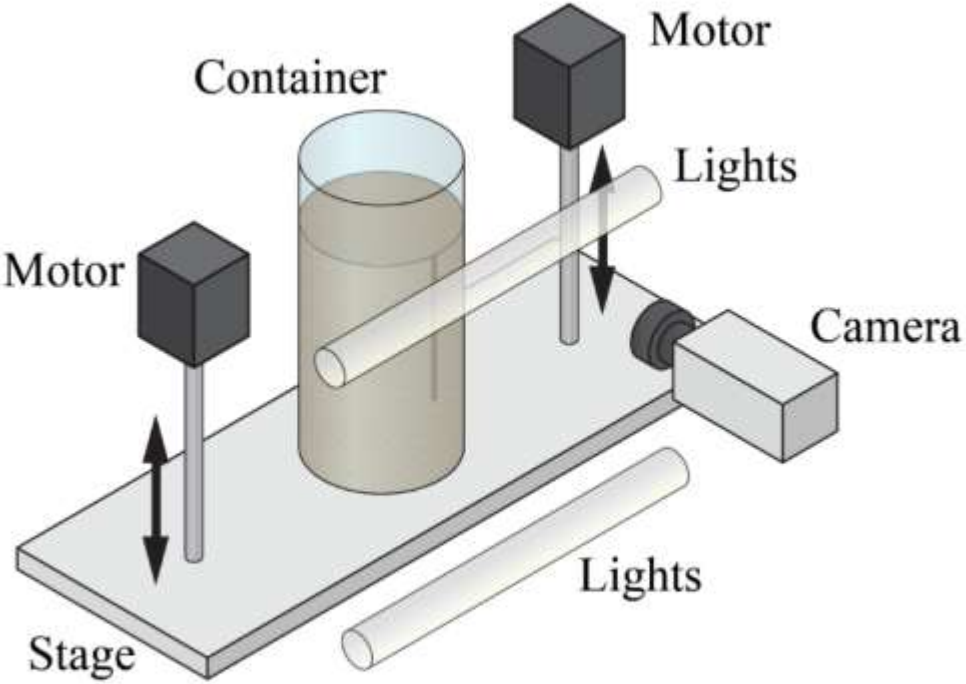


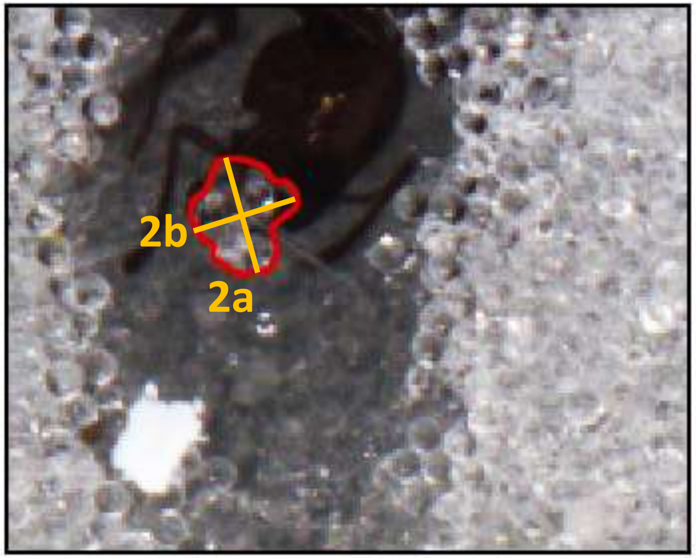
$$I = I_0 e^{-\int \mu(x,y)dl}$$

Goal of CT → Back-project (solve inverse Radon transform) from attenuated x-ray intensity, *I*, measured at different angles to obtain $\mu(x,y)$

Visualizing manipulation & excavation behaviors

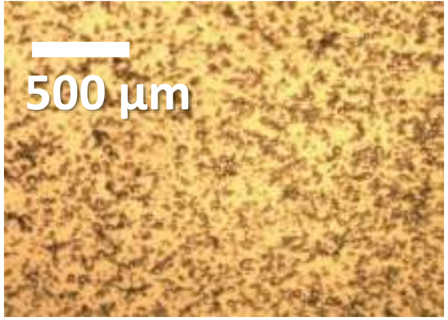
Dr. Daria Monaenkova



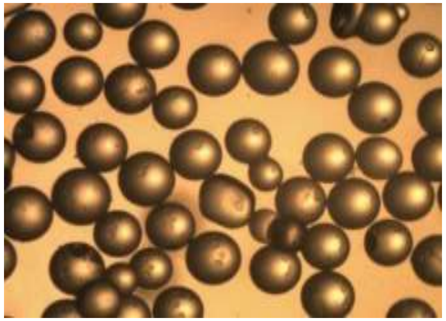


Effective area: πab

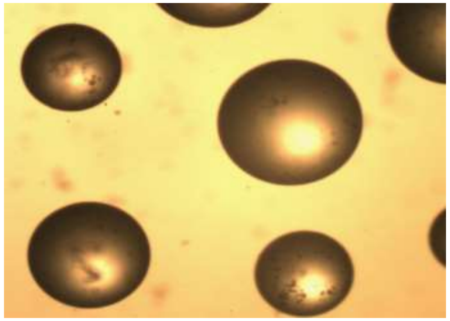
"Clay": 0-50 um



210-270 um



"Sand": 0.6-0.8 mm



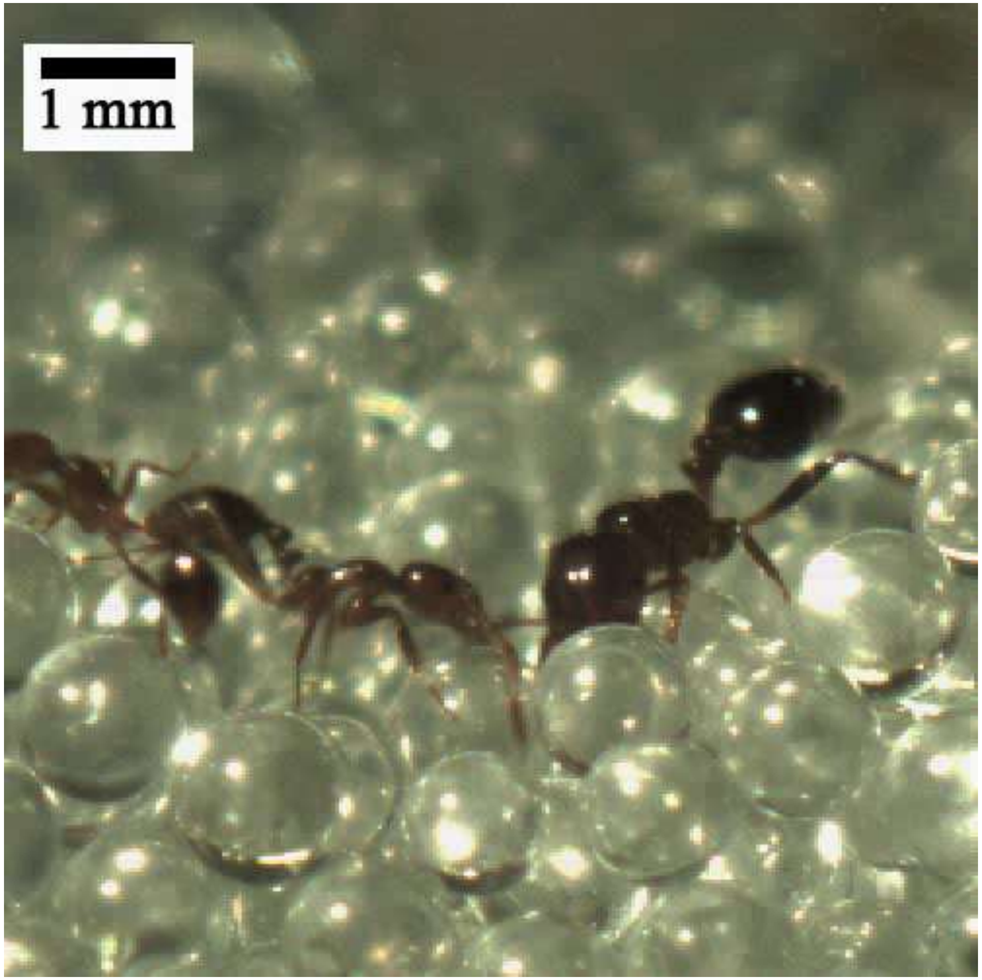
Manipulation techniques

“Pulling” mode

“Formation” mode

Coordinated use of jaws, limbs and antennae!

Unrealistic substrate, but the coordination is quite visible!



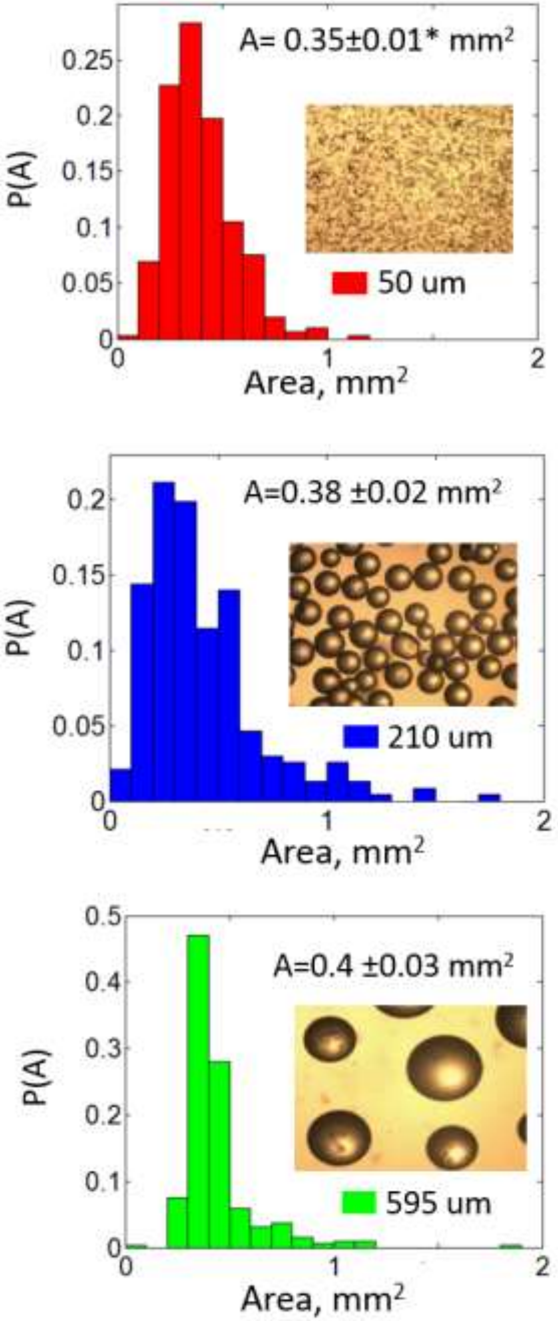
Slowed 3x

Effect of grain size on pellet area

Monaenkova et al, *J. Exp. Biol*. 2015

~NONE!

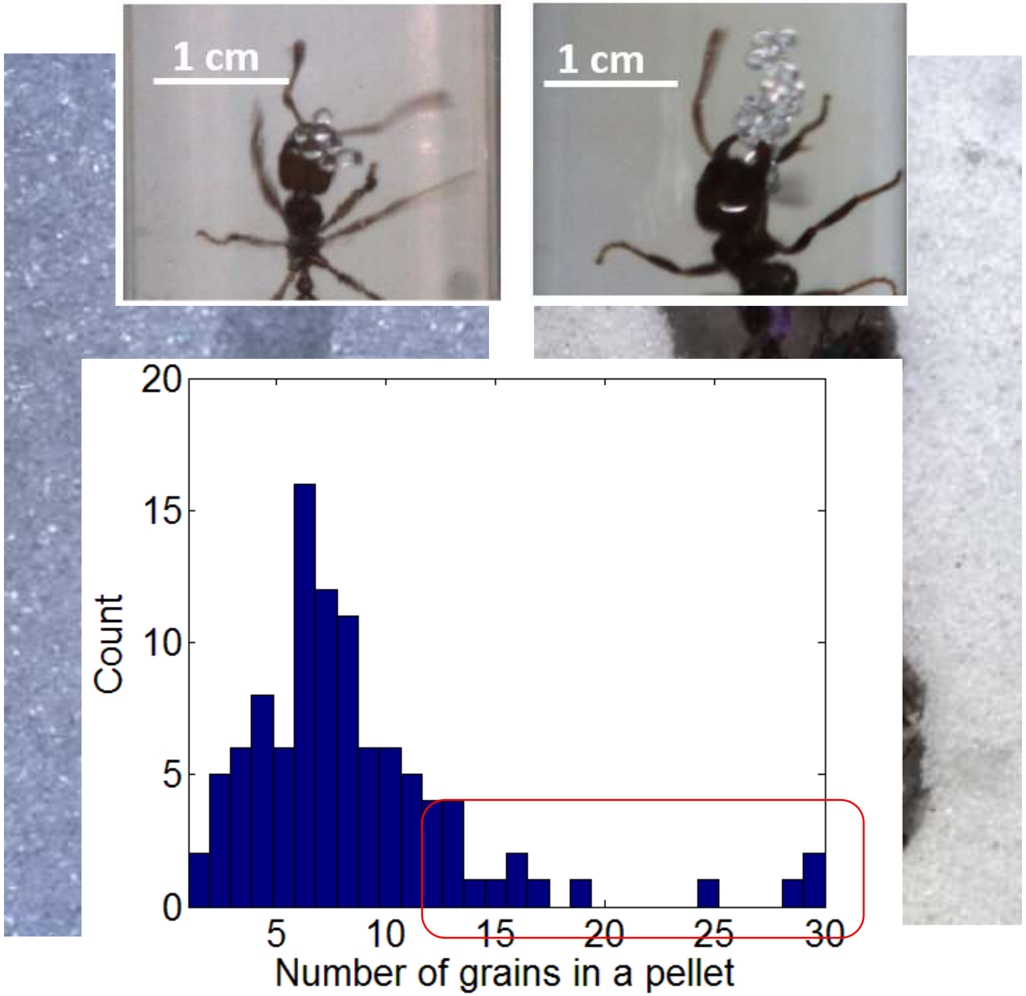
Mean projected area of the pellet independent of particle size, moisture content



Factors which are important for manipulation of soil to form intermediate pellet

Fire ants are capable of carrying large pellets

- Pellet stability during transport (“passive sieving”)
- Biomechanical constraints (carrying bulky loads long distances is challenging)
- Collective constraints (neighbors)

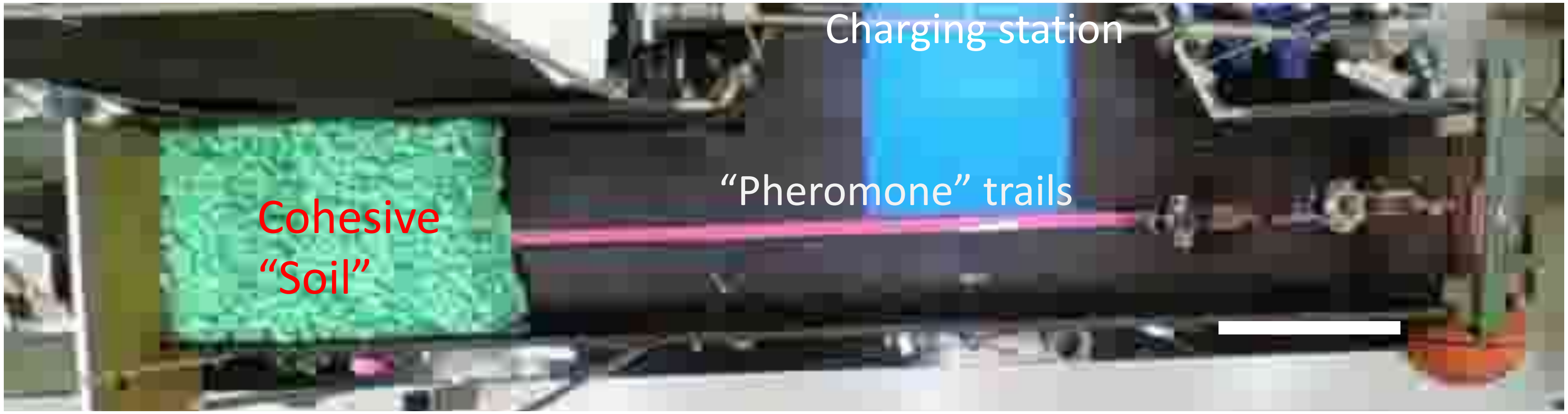


Vadim Linevich

Multiple autonomous granular diggers: task oriented social locomotion and manipulation

Dr. Daria Monaenkova

(2 robots, 17 hours of digging shown)



- Excavate cohesive GM
- Fully autonomous (locomote, dig, recharge, locate “soil”)
- CoTS components
- **Test hypotheses of social laziness**

Questions from the organizers

State-of-the-art methods for locomotion and manipulation can be pushed to deal with systems up to 50 DOF, which is fairly impressive compared to what we could achieve just a few years ago.

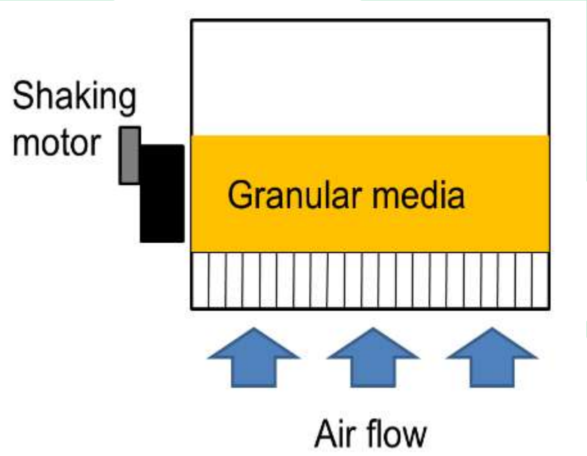
- How can we push this dimensionality even further, perhaps all the way to infinity?
  - Geometric mechanics can produce useful predictions for motion for few DOF and ∞ DOF swimmers
- How do we locomote with soft structures?
- How do we manipulate deformable objects?
  - Fire ant nest construction requires sophisticated manipulation and mobility of and in deformable granular materials
- How do we plan and control continuum robots?
  - Templates (low DOF control targets) to manipulate the body and environment to effect locomotion

Discover principles of terrestrial locomotion

goldmanlab.gatech.edu

Bio/neuromechanics

Substrate control

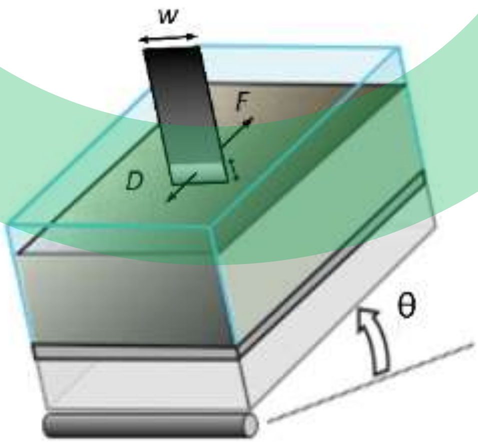


Physical models

“robophysics”

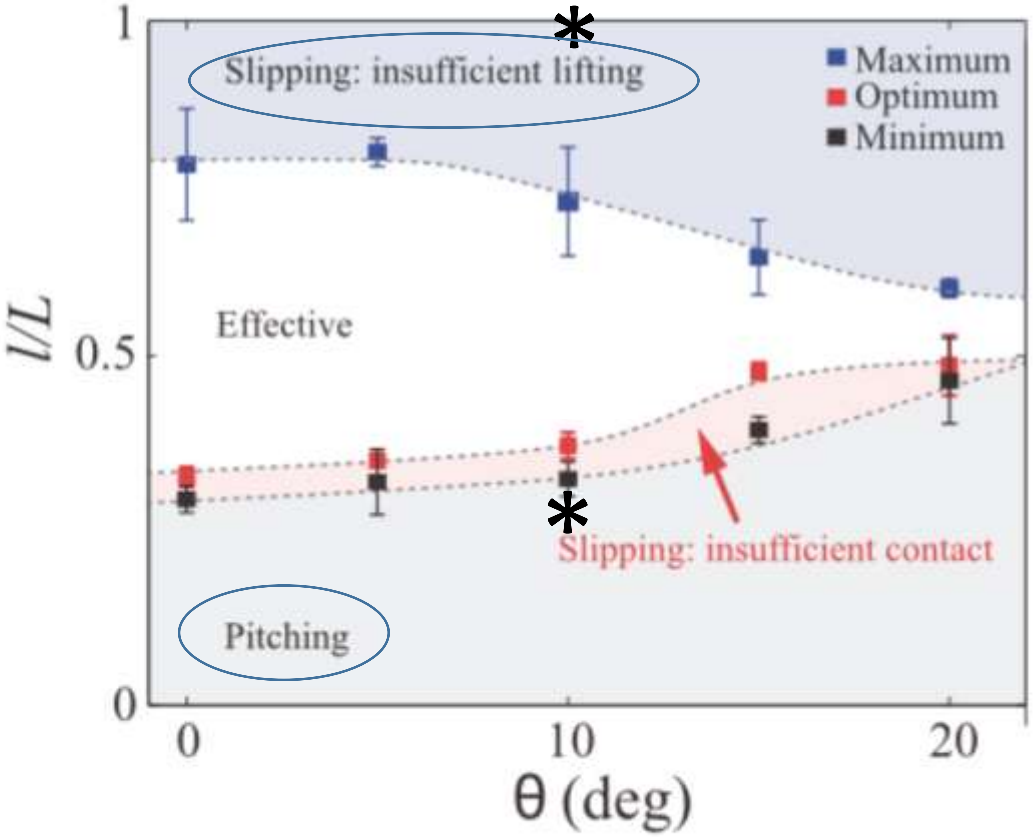
Aguilar et al, *Rep. Prog. Physics*, in prep.

Soft matter interaction physics

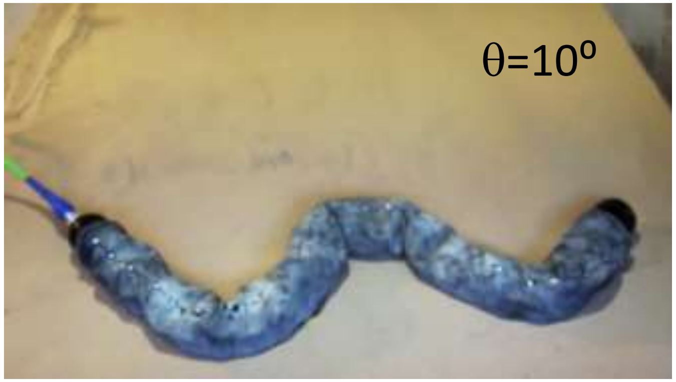


Robophysics “phase diagram” for robot sidewinding

Marvi, Gong, Gravish, Astley, Travers, Hatton, Mendelson, Choset, Hu, Goldman, *Science*, 2014



Slipping failure (l/L=1)



Pitching failure (l/L=0.27)

Robot failure is often more interesting (and useful) than robot success!

END