Nonprehensile Robotic Manipulation: Progress and Prospects

Kevin M. Lynch

Laboratory for Intelligent Mechanical Systems
Mechanical Engineering Department
and
Northwestern Institute on Complex Systems (NICO)
Northwestern University

SpongFest 2012

Major contributors to this talk:
Tom Vose and Paul Umbanhowar

Other contributing colleagues, students, and postdocs:
Adam Barber, Matt Elwin, Bobby Gregg, Yu-Wei Liao, Andy Long, Matt Mason, Nelson Rosa, Ji-Chul Ryu, Eric Schearer, James Solberg

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National Science Foundation
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International Workshop on Recent Developments in Robotics and Control?

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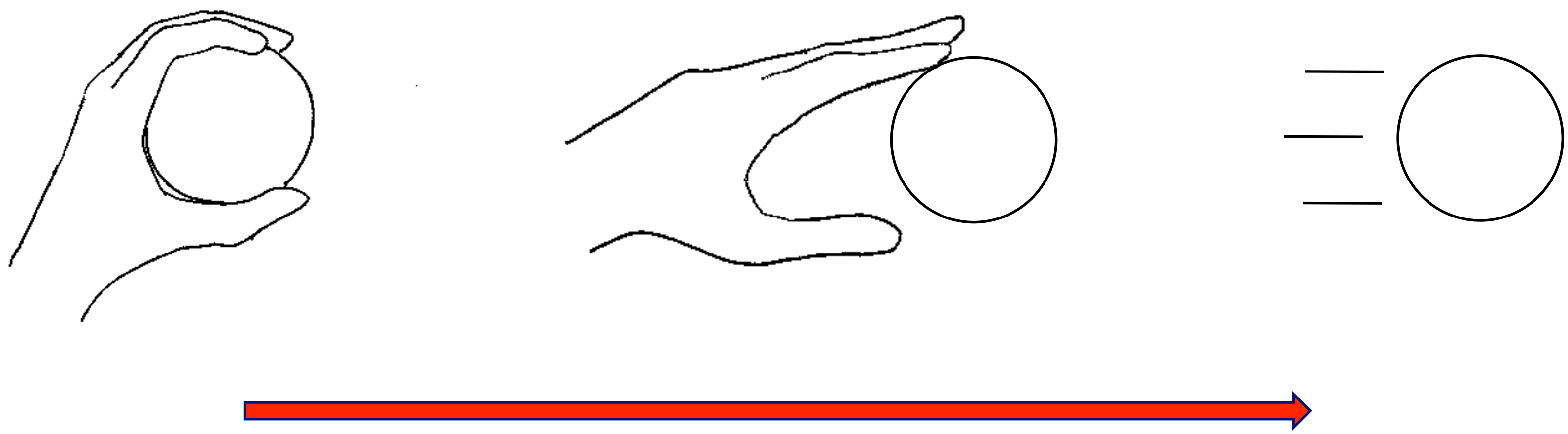
Nonprehensile Manipulation



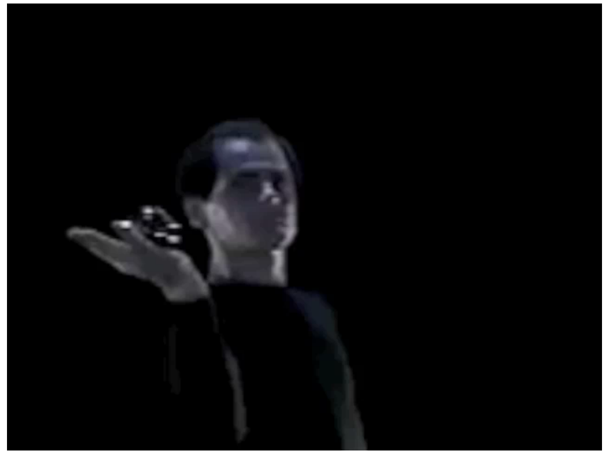
hand controls ball:
prehensile

shared control:
nonprehensile

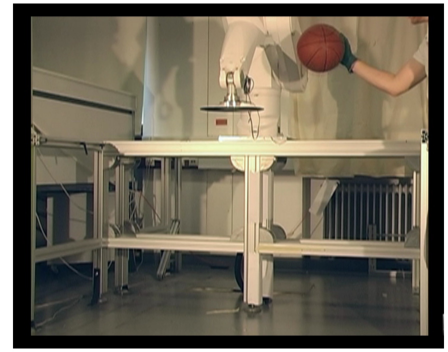
environment
controls ball

form or force
closure grasping

nonprehensile manipulation

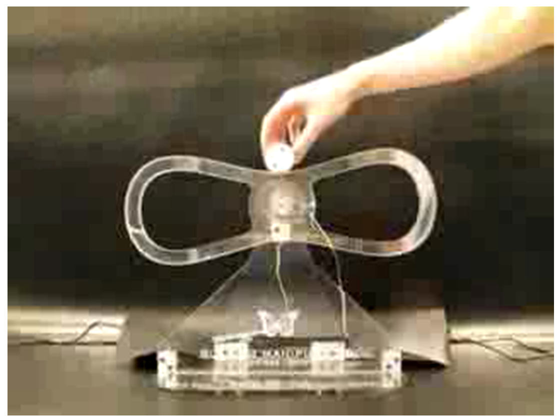


rolling (Michael Moschen)

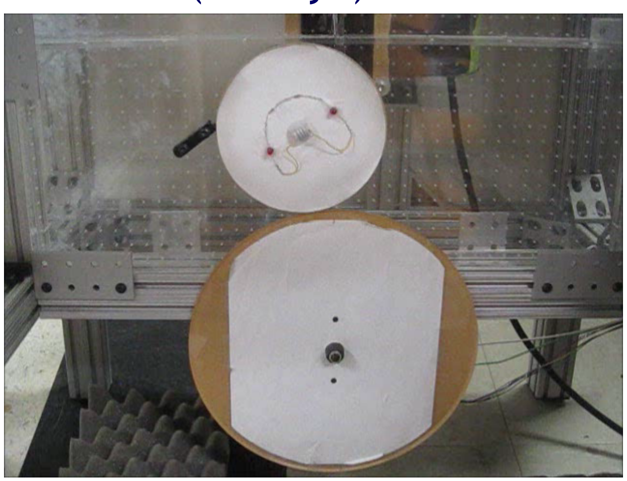


dribbling
(TU Munich)

throwing and batting
(U Tokyo)



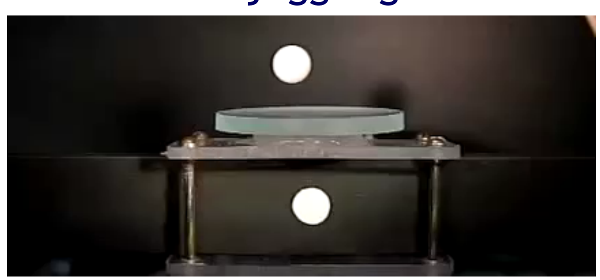
vibratory feeding (Sony)



rolling and
balancing

dung beetle
(Nat'l Geo)

bat juggling



Why Nonprehensile Manipulation?

After all, grasp and carry is “easy” (once a grasp is established); decouples grasp planning and kinematic motion planning.

Why Nonprehensile Manipulation?

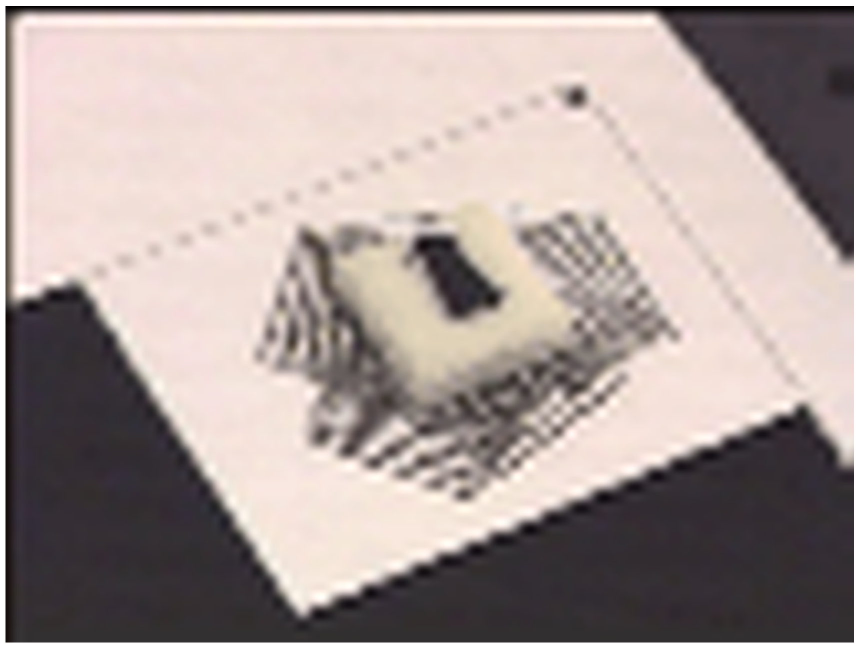
- Manipulate objects too large or heavy to be grasped
- Manipulate several objects simultaneously
- Given a task, use cheaper, lower-DOF robots (automation)
- Given a robot, increase the set of solvable tasks
- Most manipulation is nonprehensile!

Research Topics

- sensing/observability/uncertainty
- contact modeling and mechanics
- motion planning
- feedback control
- understanding what tasks are solvable (e.g., reachable sets, controllability)

Carnegie Mellon, ca. 1994

mechanics, controllability, and planning for pushing

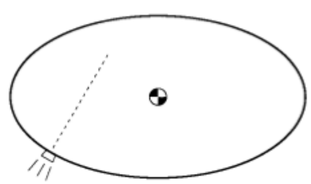


Controllability of a Rigid Body through Unilateral Contact

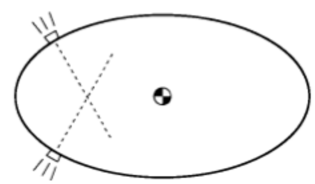
IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 44, NO. 6, JUNE 1999

Controllability of a Planar Body with Unilateral Thrusters

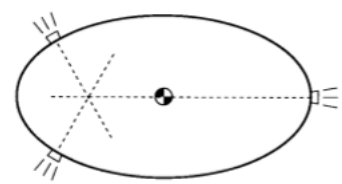
Kevin M. Lynch



accessible



globally controllable

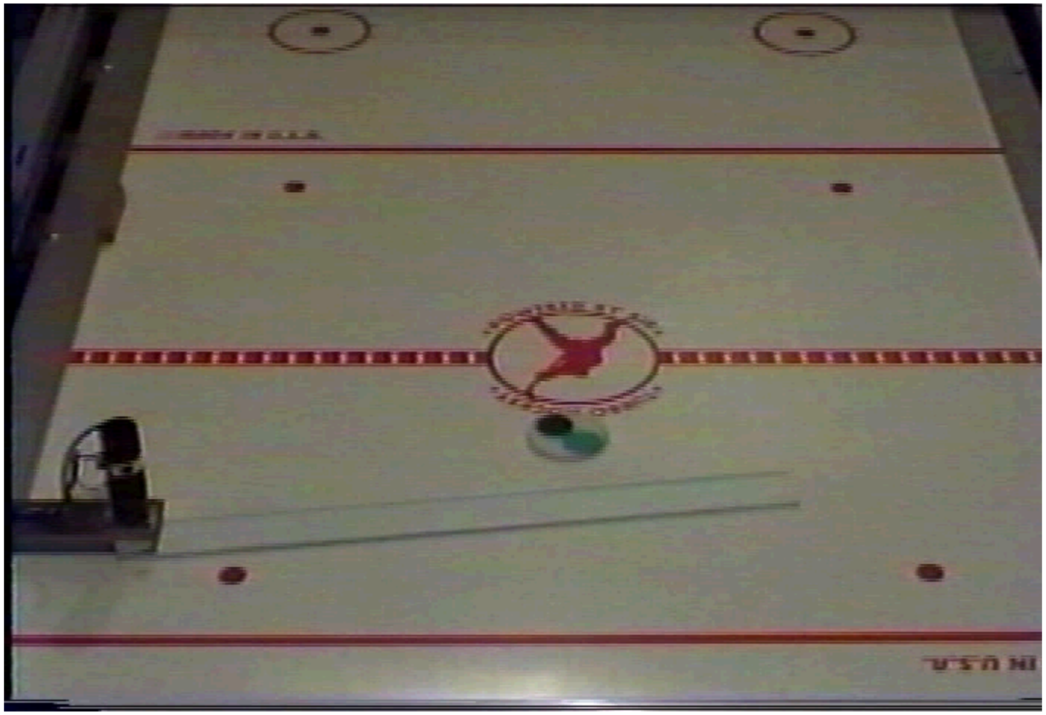


STLC

Northwestern, ca. 1998

feedback stabilization of control-recurrent systems

"juggling"



Controllability of a Rigid Body through Unilateral Contact

ELSEVIER

Systems & Control Letters 42 (2001) 333–345

SYSTEMS & CONTROL LETTERS

www.elsevier.com/locate/sysconle

Impact controllability of an air hockey puck ☆

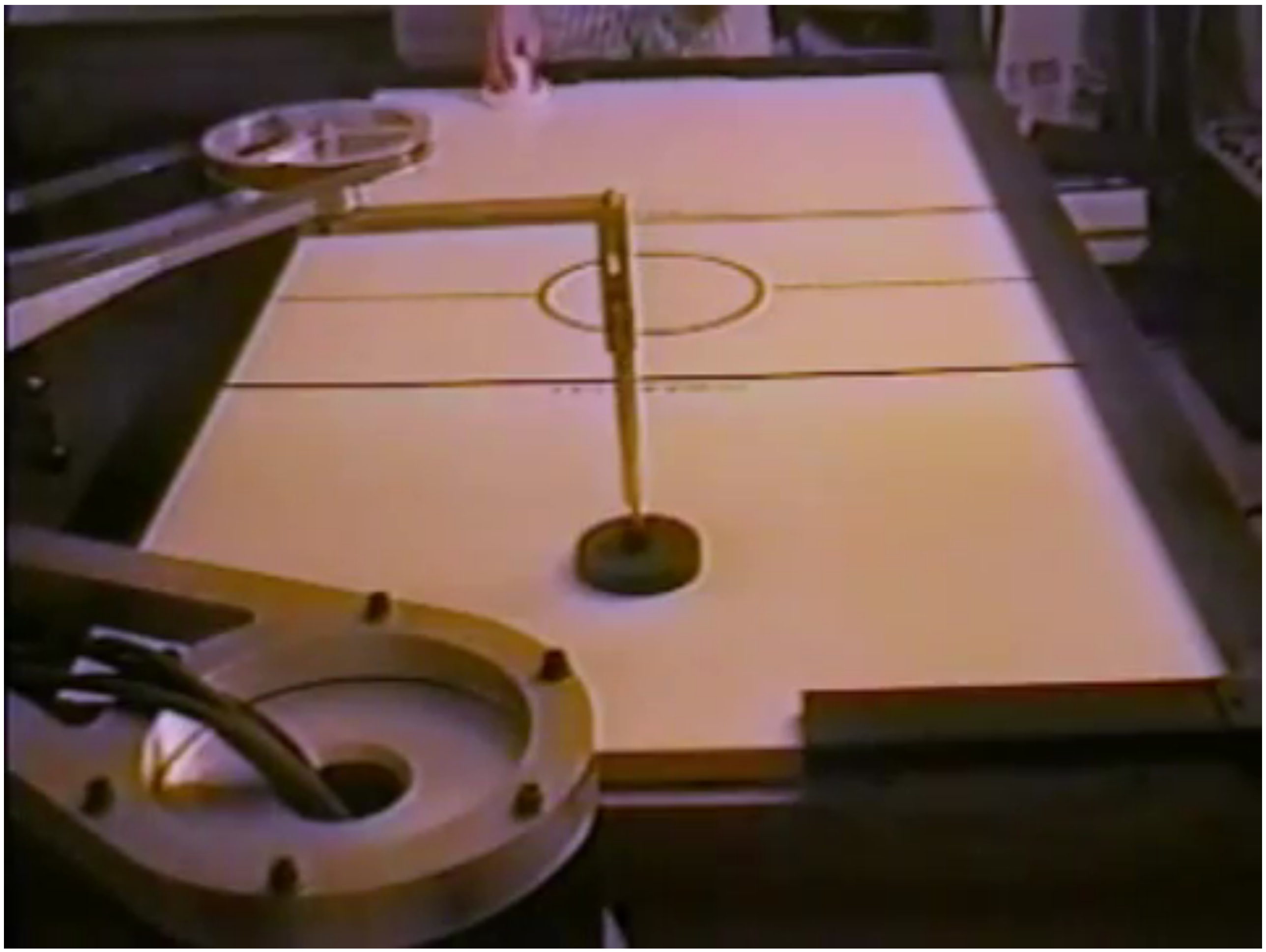
Mark W. Spong *

Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, 1308 W. Main Street, Urbana, IL 61801, USA

Received 15 April 2000; received in revised form 19 October 2000

UIUC, ca. 1999

Bishop and Spong



a few nice things Mark's done for me

- research inspiration
- invited me to my first Allerton conference
- hooked me up with Francesco
- my first trip to Mexico City, CCA 2001
- letters (tenure, IEEE Fellow, etc.)

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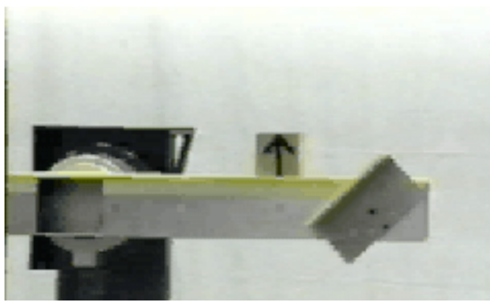
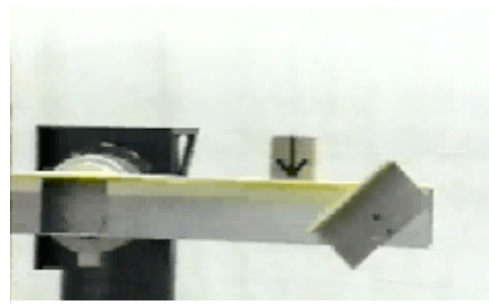
- sent Bobby Gregg my way!

Carnegie Mellon, ca. 1995

underactuated hybrid dynamic manipulation
one actuator, three part DOF

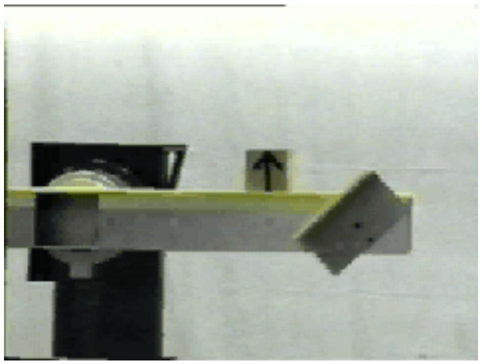


start

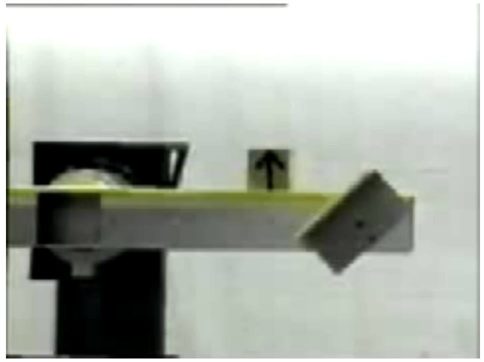


goal

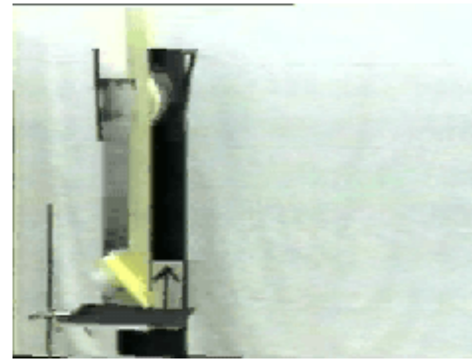
Underactuated Hybrid Manipulation



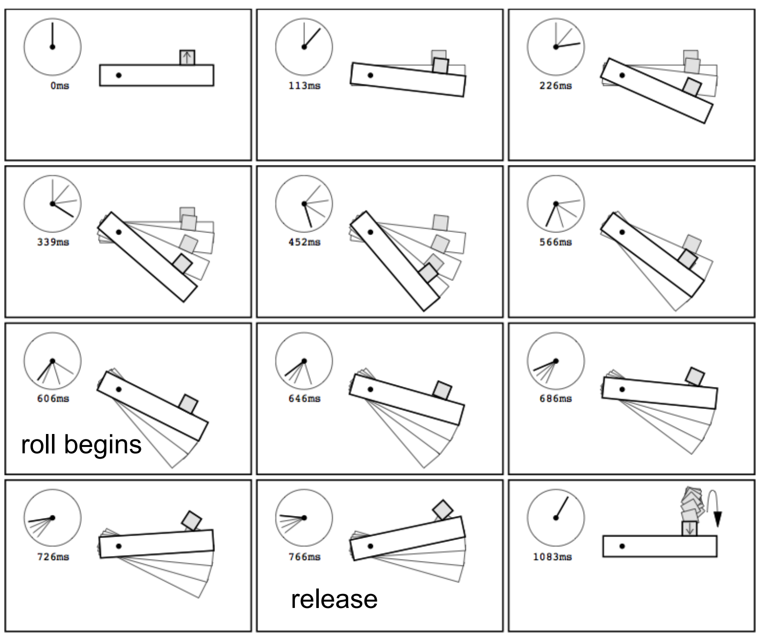
“grasp” + roll + free flight

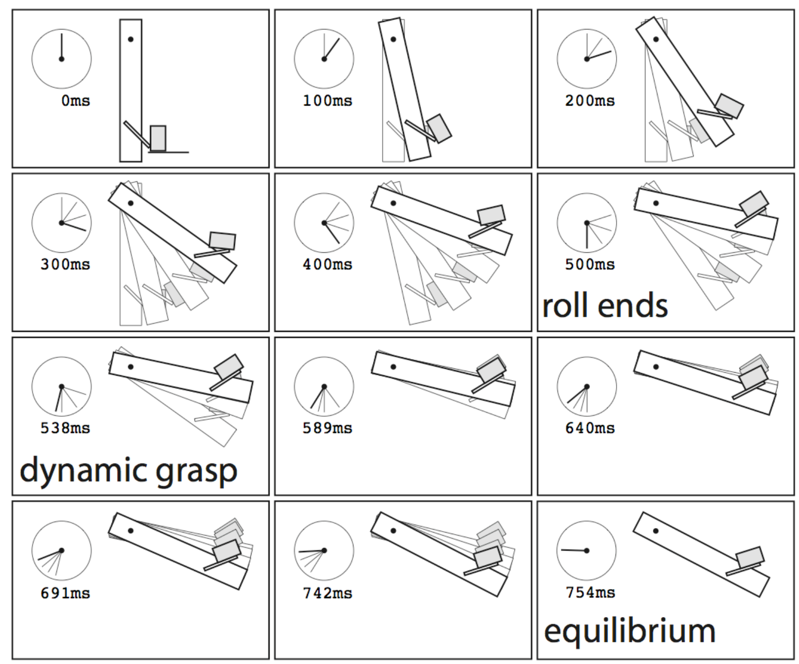


¼ speed



roll + “grasp” + free flight





Sequencing Primitives

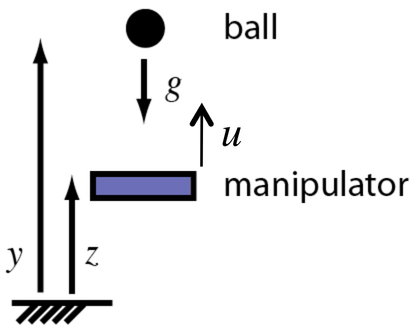
Manipulation consists of a sequence of primitives:

- grasping
- rolling
- manipulator transit motions (no contact)
- pushing
- pivoting
- toppling
- caging
- etc.

Each primitive is described by different contacts and equations of motion.

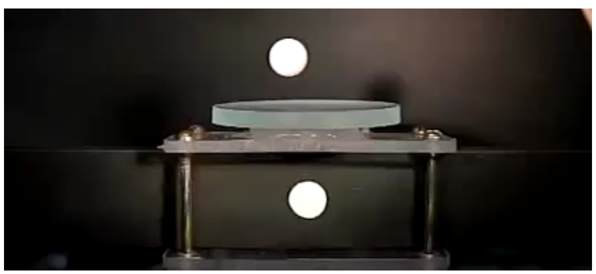
A sequence of primitives defines a ***hybrid system***.

Manipulation as a Hybrid System

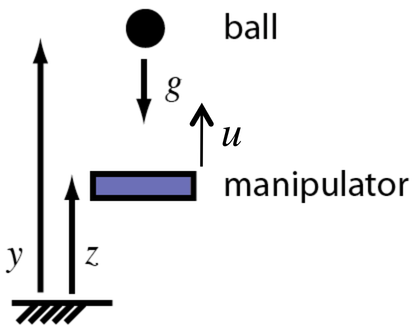


5-D state-control space

$(y, \dot{y}, z, \dot{z}, u)$



Manipulation as a Hybrid System



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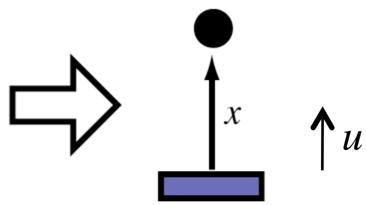
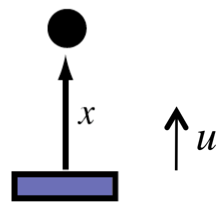


reduced 3-D
state-control space
$(x, \dot{x}, u)$

Manipulation as a Hybrid System



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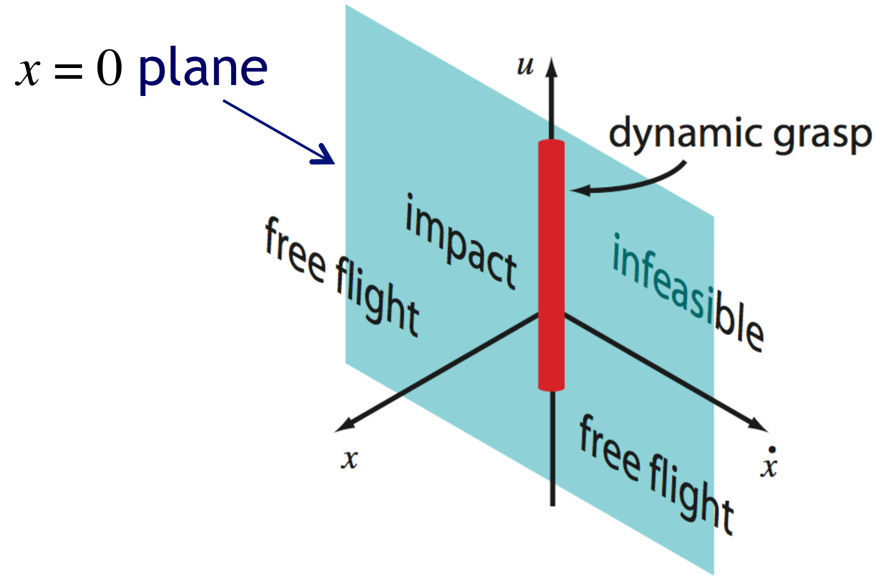


state-control vector: $w = (x, \dot{x}, u)$

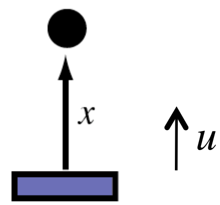
infeasible: $\{w : x < 0\}$

impact: $\{w : x = 0, \dot{x} < 0\}$

"dynamic grasp": $\{w : x = 0, \dot{x} = 0, u > -g\}$

free flight: remaining w

Manipulation as a Hybrid System



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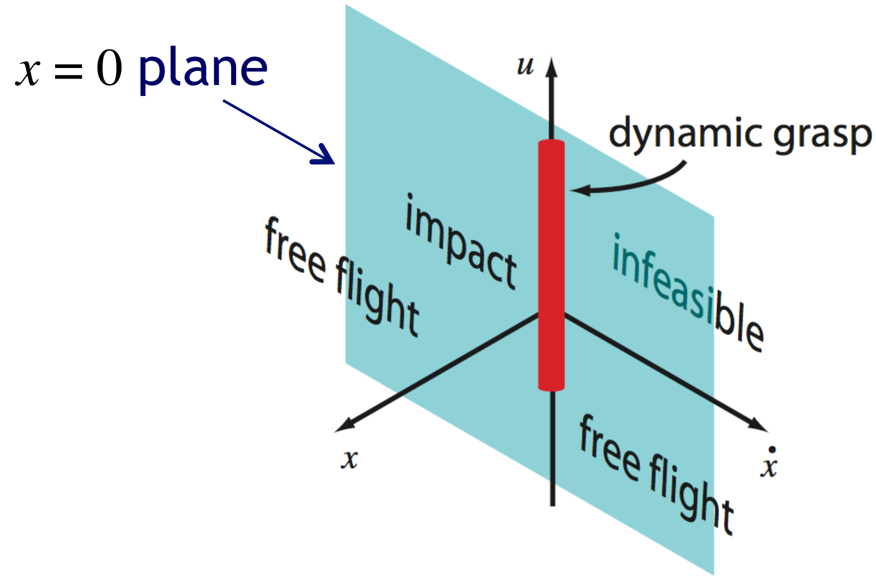

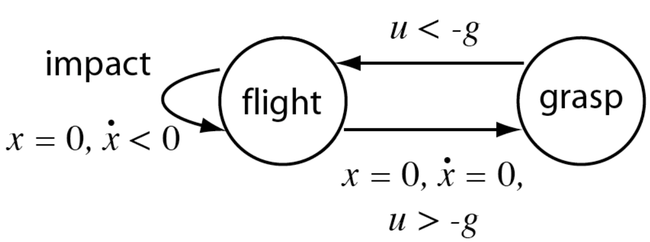

graph representing the
topology of the hybrid system

state-control vector: $w = (x, \dot{x}, u)$

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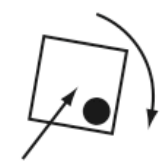
free flight: remaining w

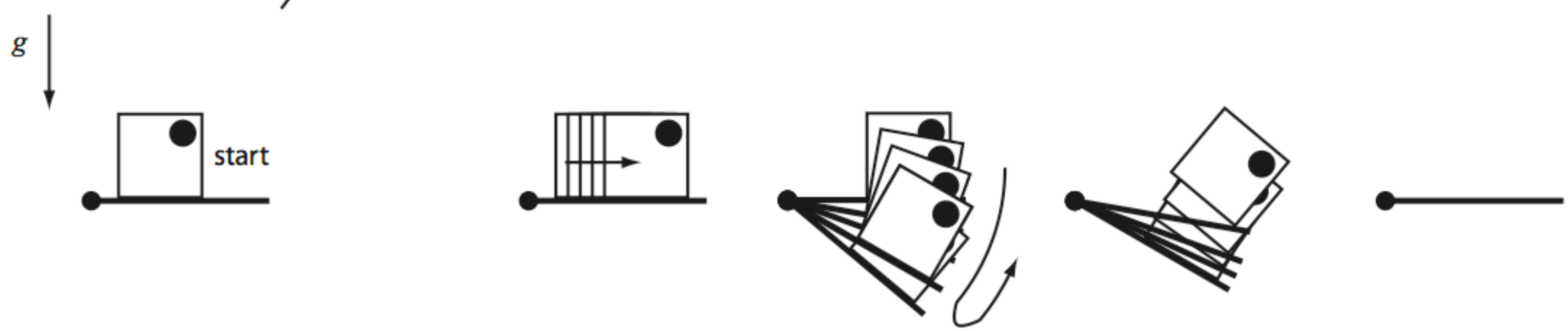
Hybrid Sequence Planning

  3 part positions
+ 3 part velocities
+ 1 arm position
+ 1 arm velocity
+ 1 arm control

9-dimensional state-control space

The 9-D space is carved into regions corresponding to primitives, creating a graph whose nodes are primitives and edges are jump conditions.



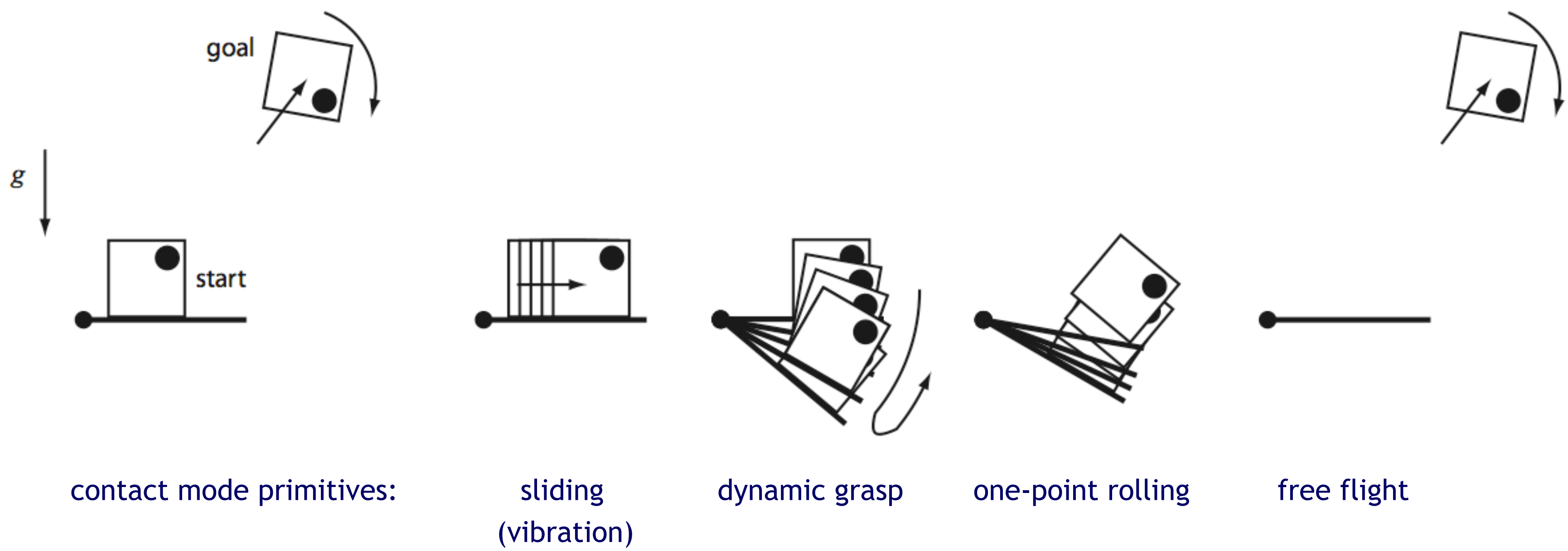


contact mode primitives: sliding (vibration) | dynamic grasp | one-point rolling | free flight

Hybrid Sequence Planning

1. Choose a sequence of primitives and find the state-control jump conditions between them. Jumps occur at contact transitions (established/broken, sticking/sliding).

2. Find controls within each primitive between jump conditions.



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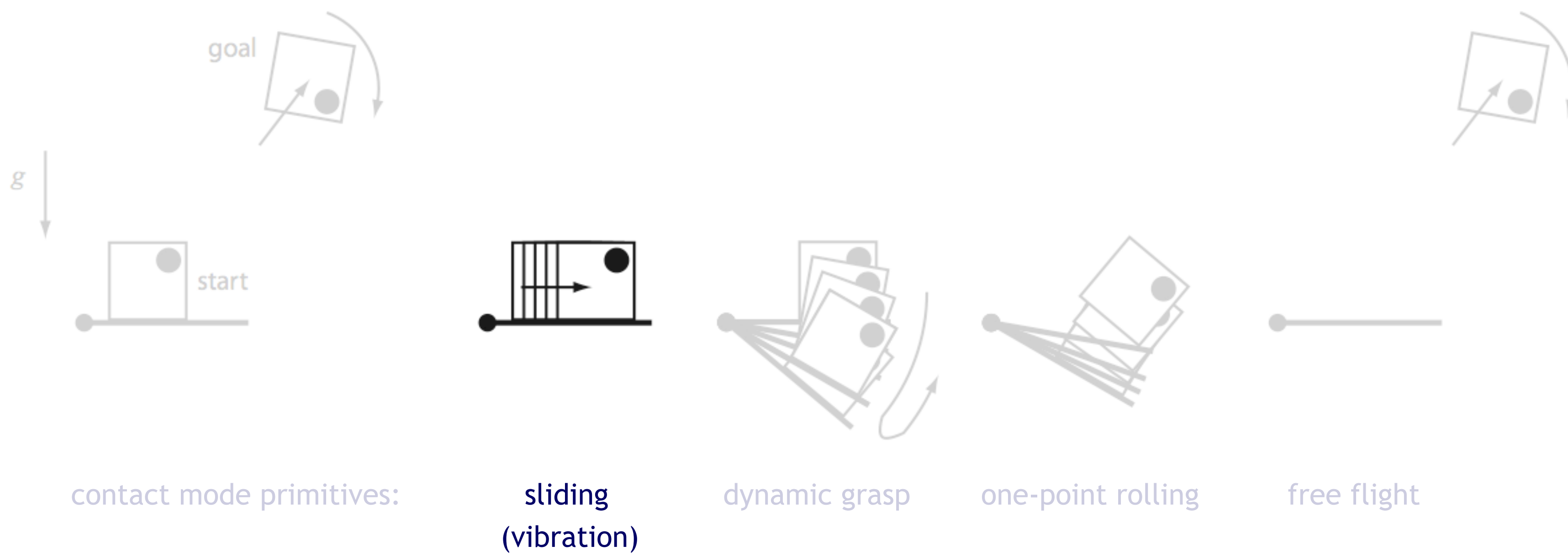
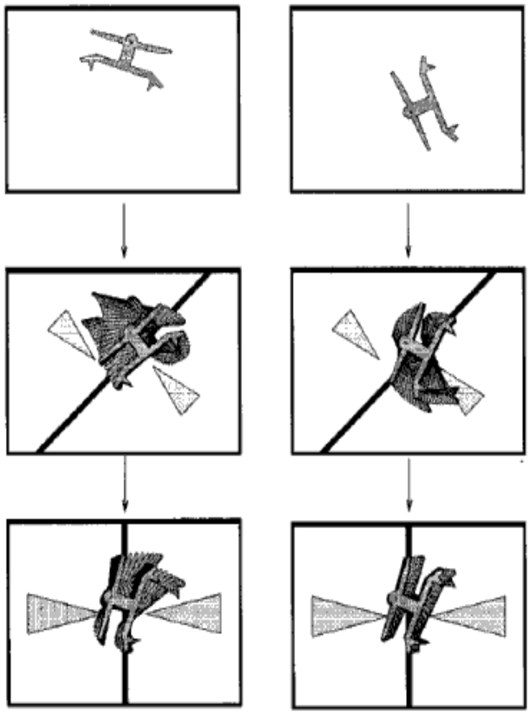


Some Simpsons-Inspired Research

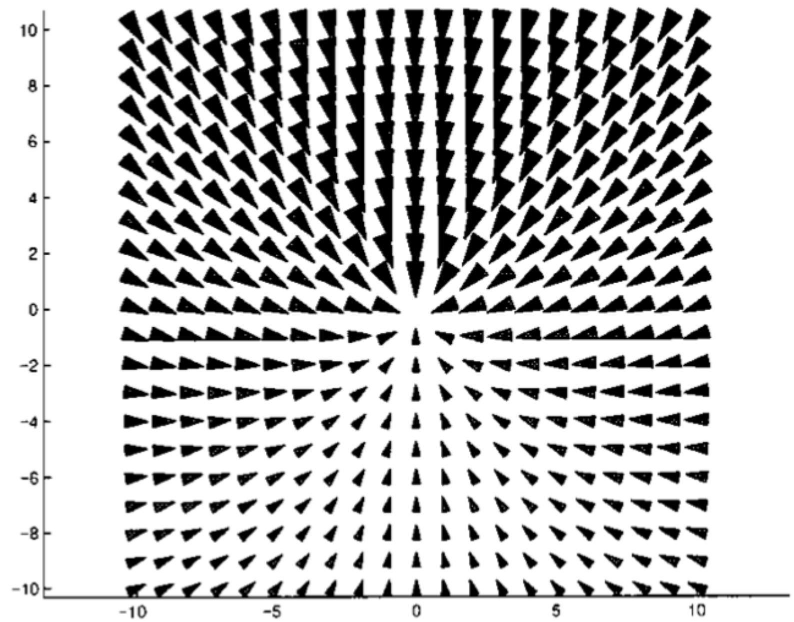
More Simpsons-Inspired Research

More Simpsons-Inspired Research

Programmable Motion Surfaces



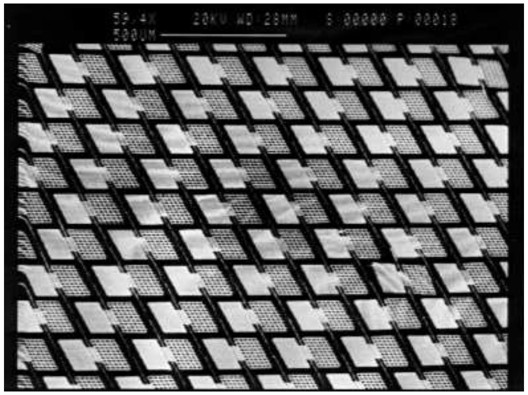
a sequence of force fields
for sensorless orienting



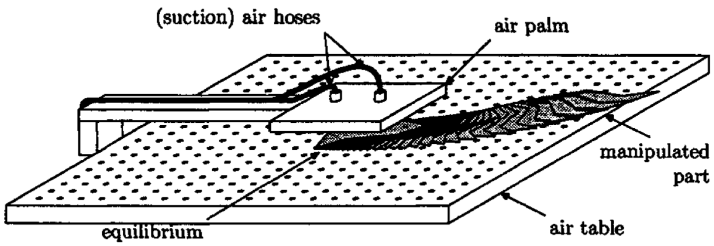
a force field for single-step
positioning and orienting

Bohringer, Donald, MacDonald, Kavraki, Lamiraux, Goldberg

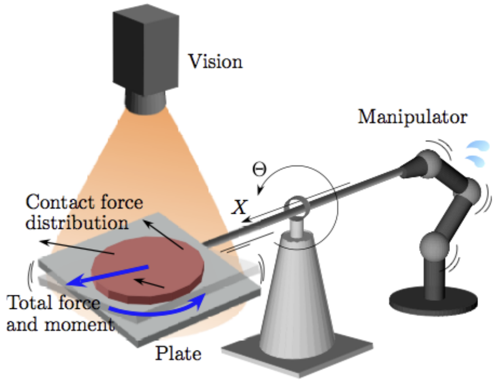
Motion Surface Implementation



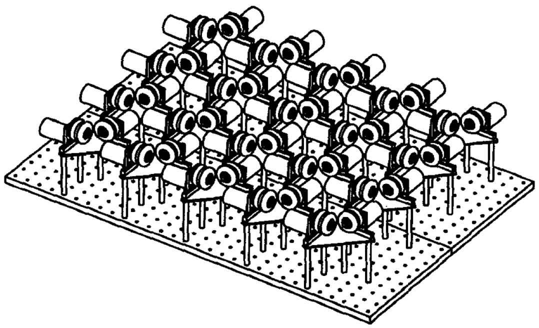
MEMS actuator arrays
Bohringer, Donald, MacDonald



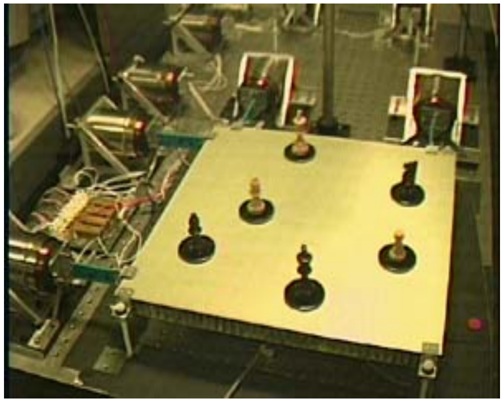
air flow
Luntz, Moon, Laurent



2-DOF pizza manipulation
Higashimori and Kaneko

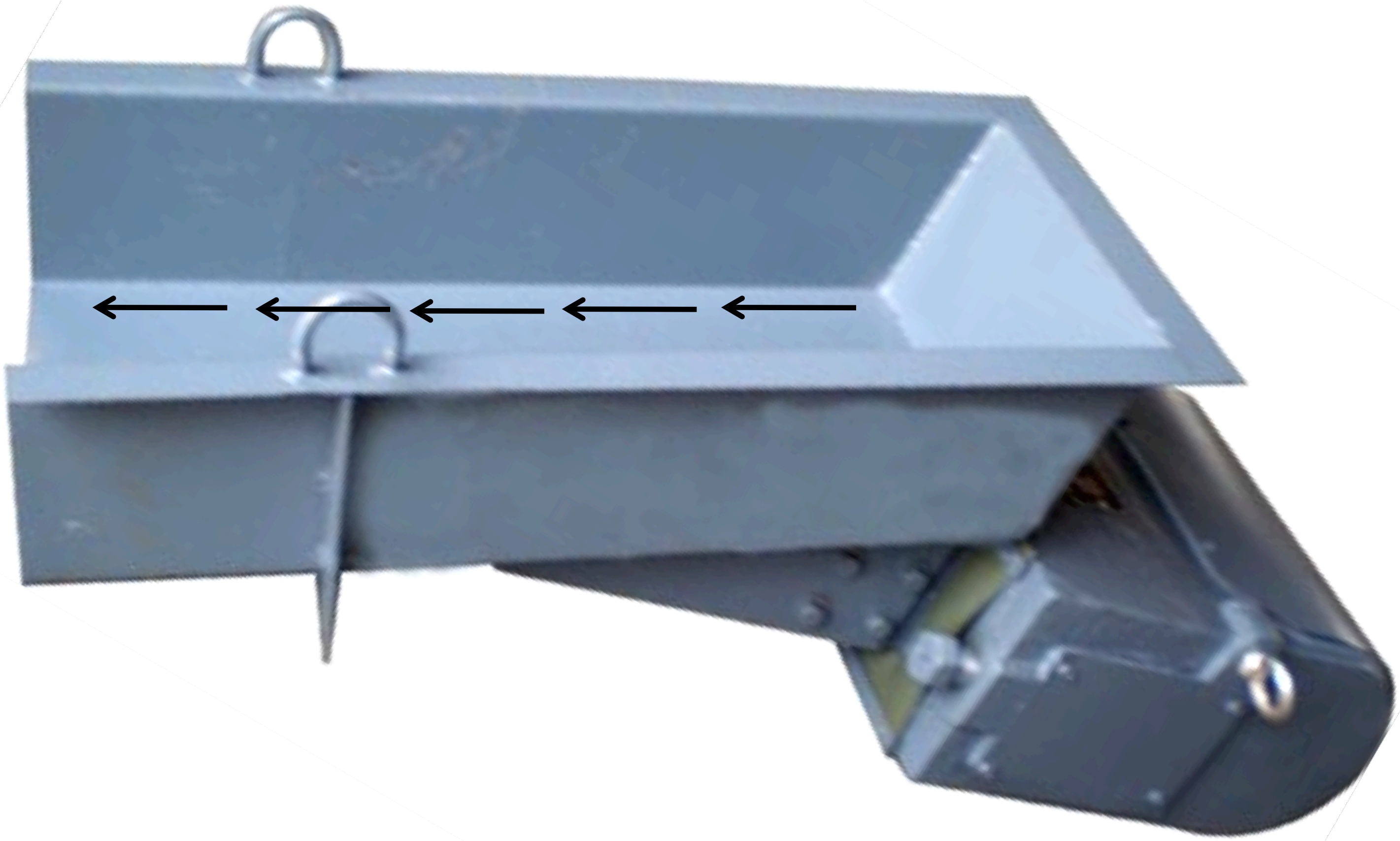


rolling wheels
Luntz, Messner, Choset, Murphey, Burdick

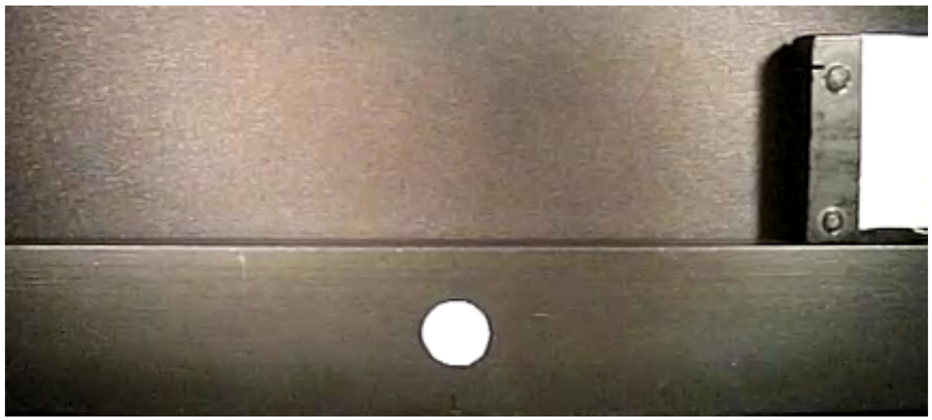


3-DOF horizontally vibrating table
Reznik and Canny

Industrial Vibratory Feeder



Sliding Manipulation



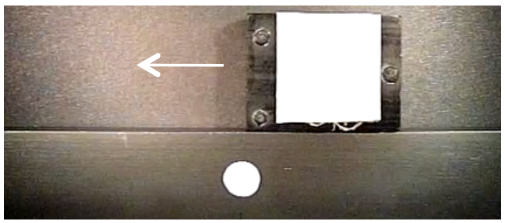
15 Hz vibration

1/20 speed

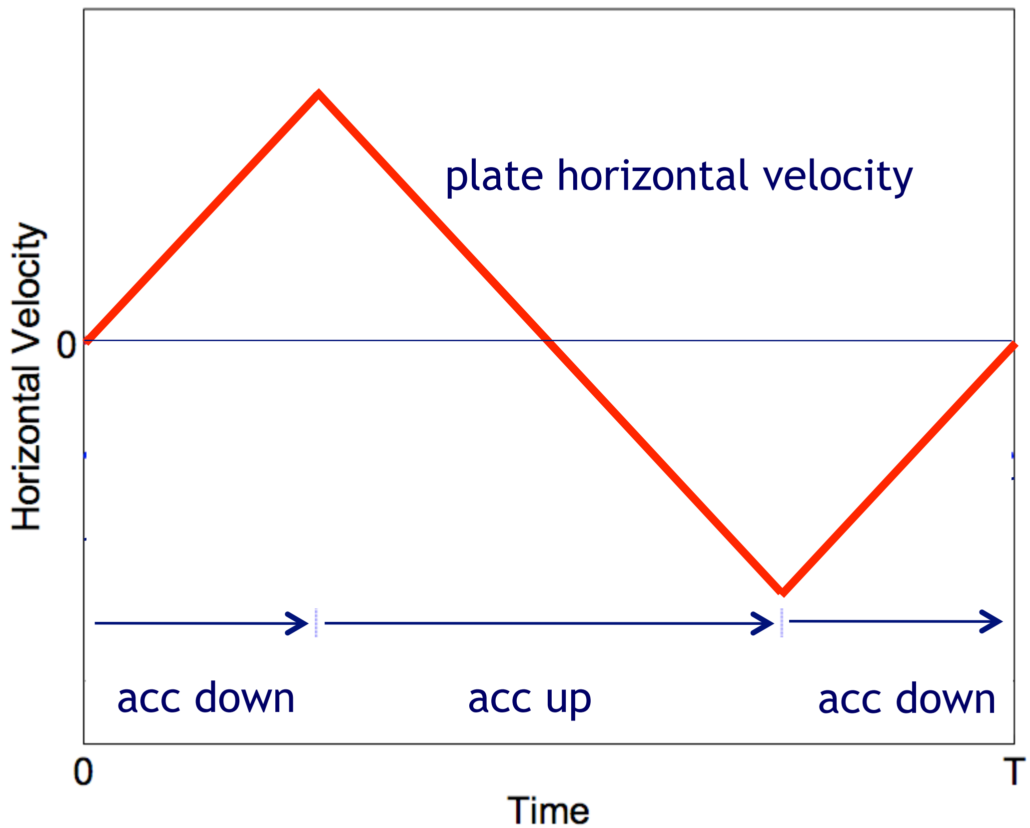
$$f_{\text{fric}} = \mu f_{\text{normal}} \frac{\mathbf{v}_{\text{rel}}}{\left\|\mathbf{v}_{\text{rel}}\right\|}$$

Sliding Manipulation

$$f_{\text{fric}} = \mu f_{\text{normal}} \frac{\mathbf{v}_{\text{rel}}}{\left\| \mathbf{v}_{\text{rel}} \right\|}$$



bang-bang vertical and horizontal acceleration



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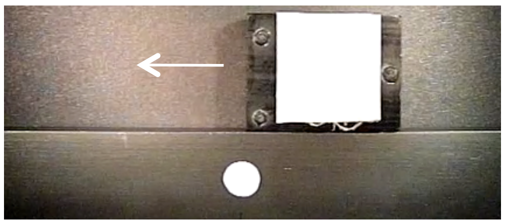

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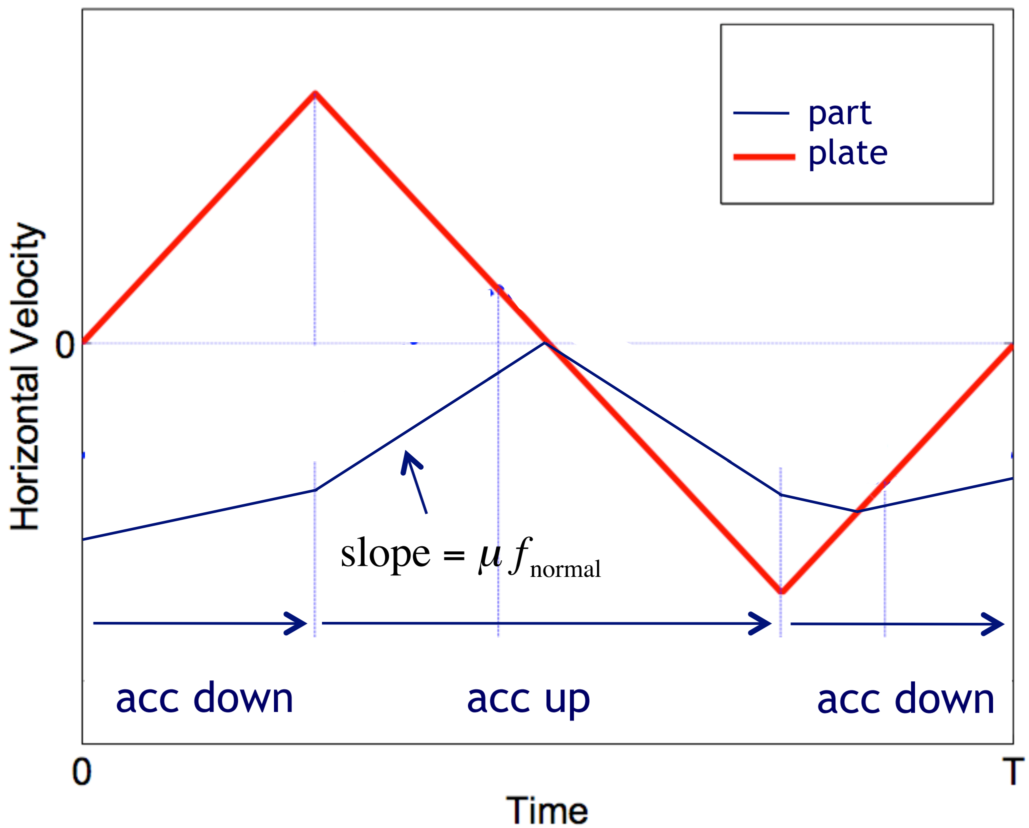

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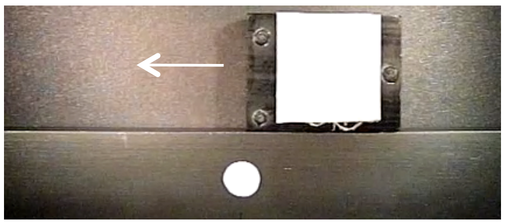

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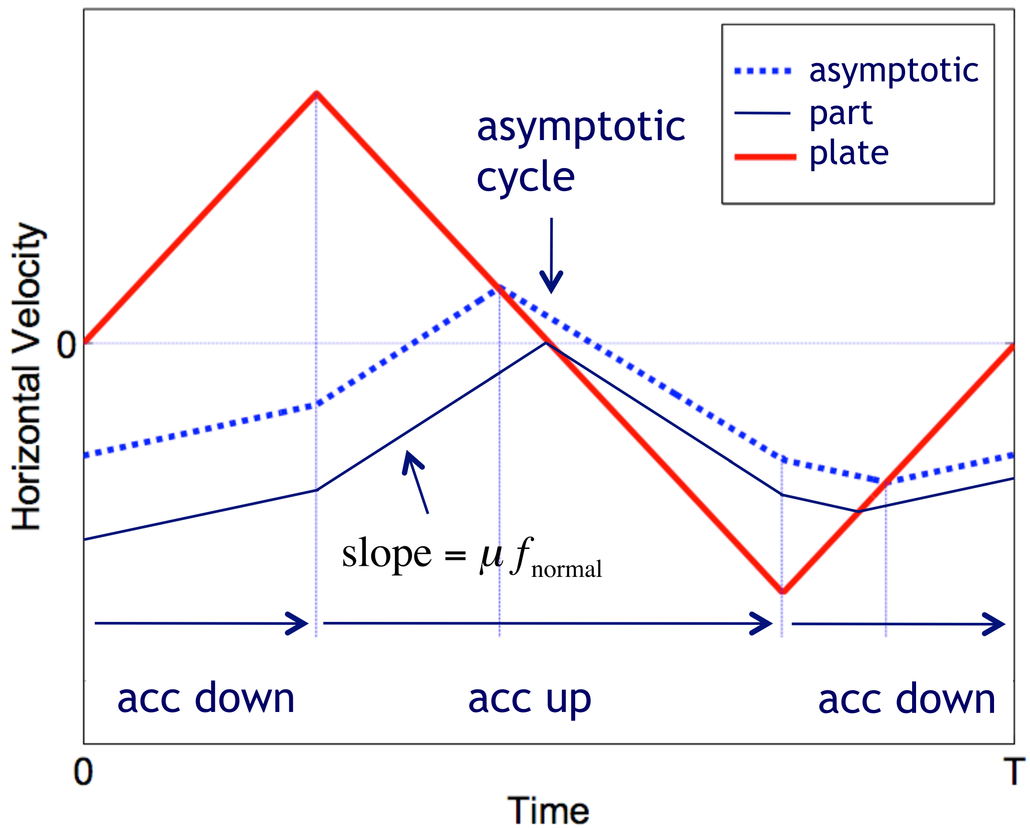

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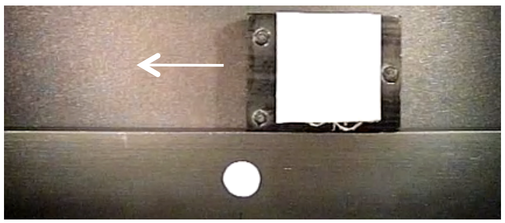

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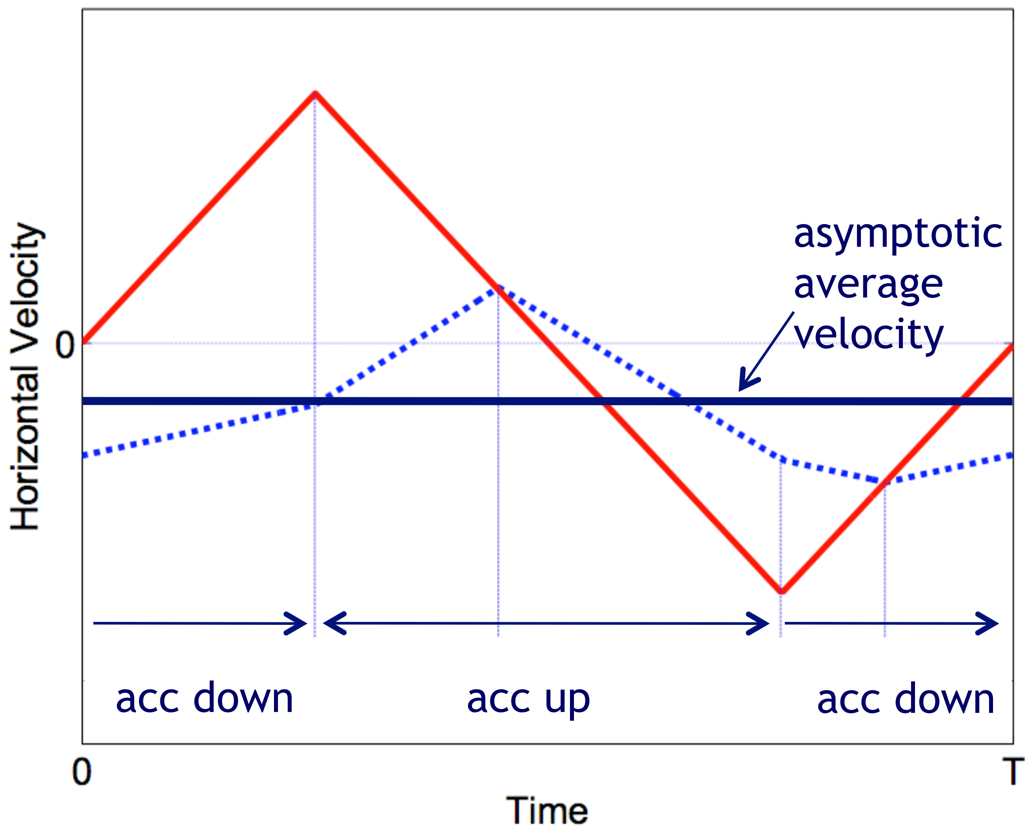
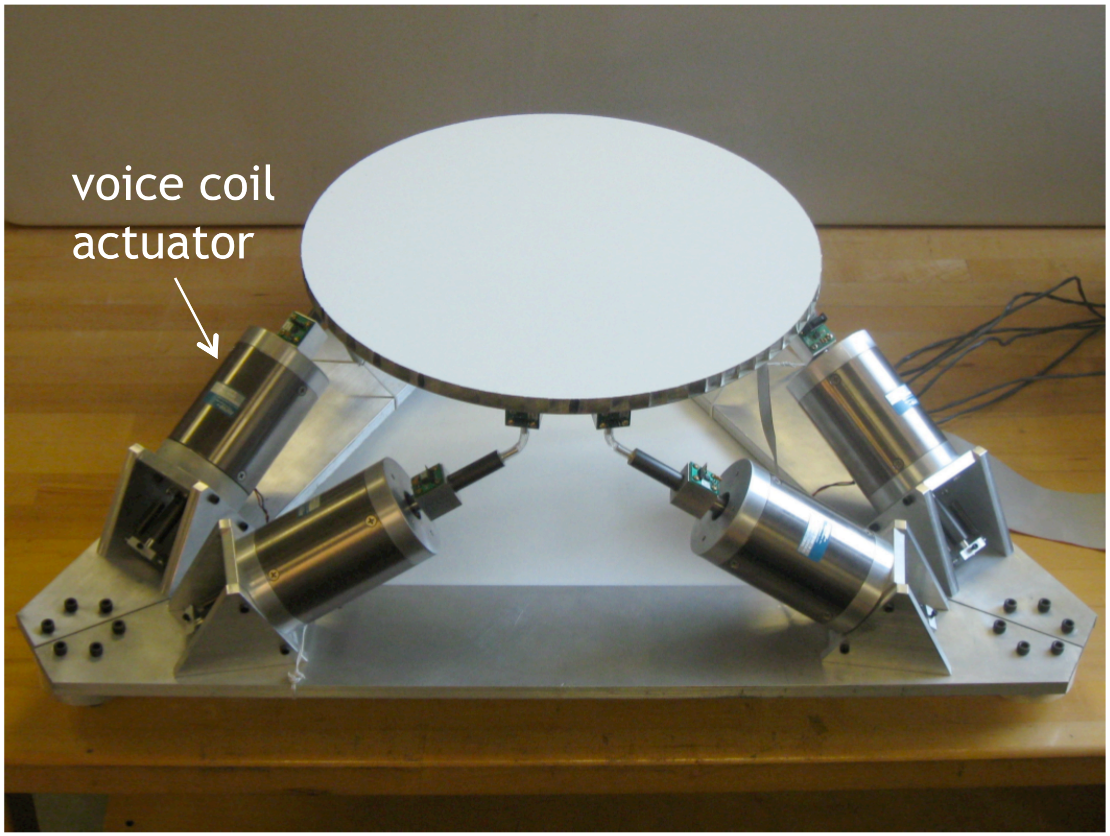
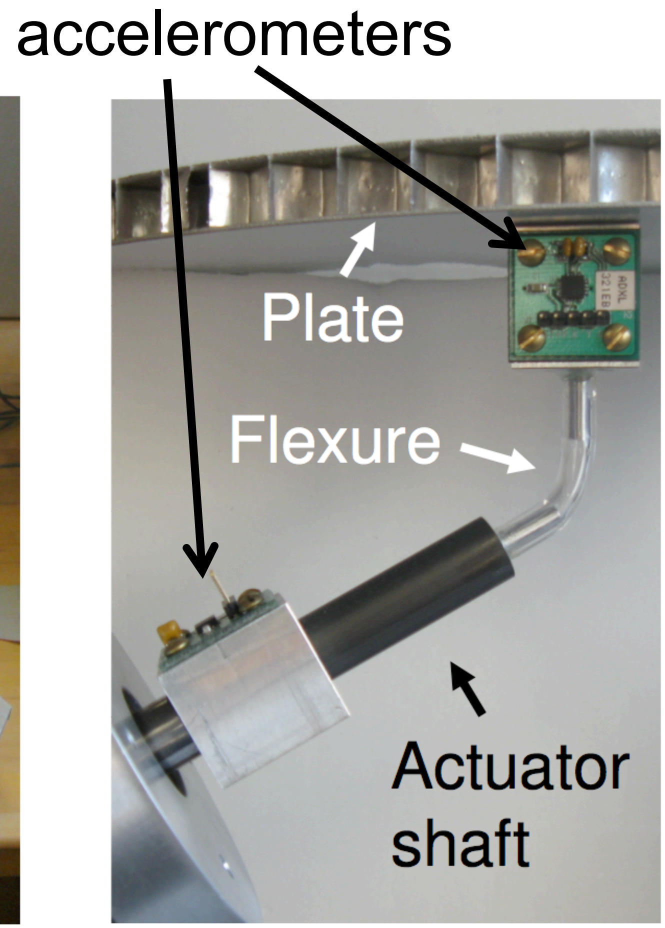


The 6-DOF PPOD

(Programmable Parts Orienting Device)





flexure-based Stewart platform

audio
amps

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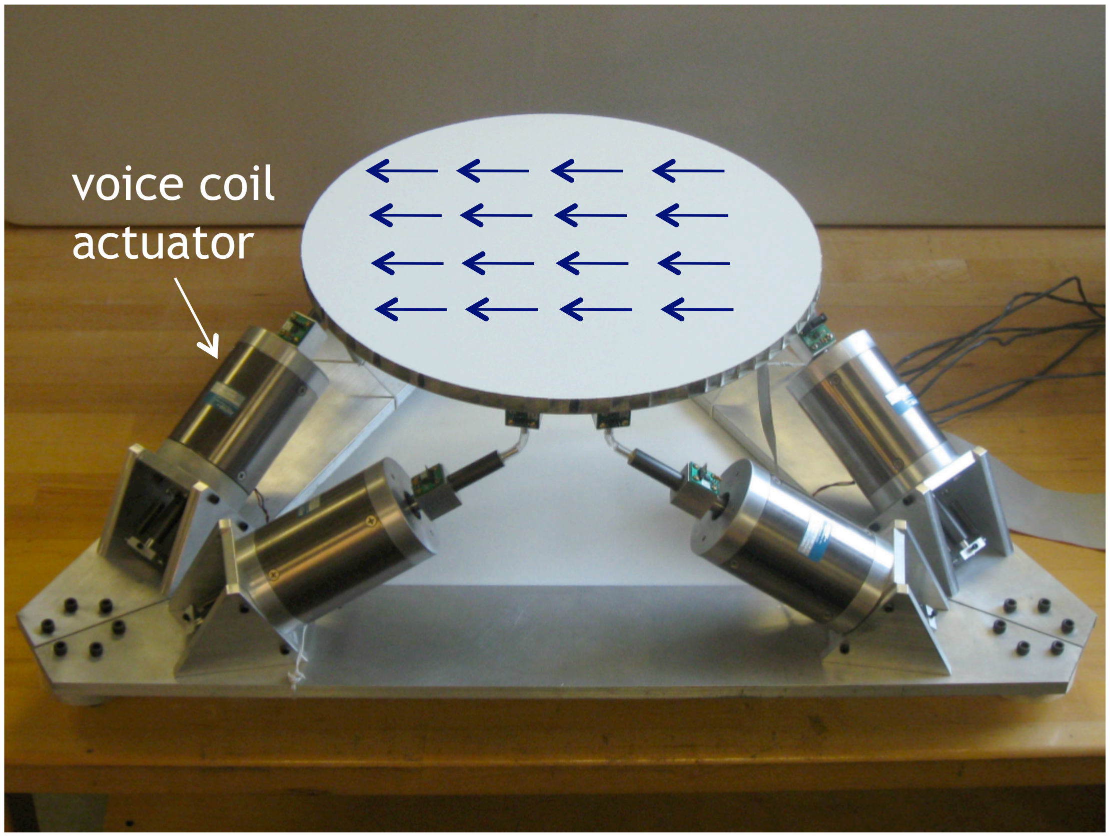
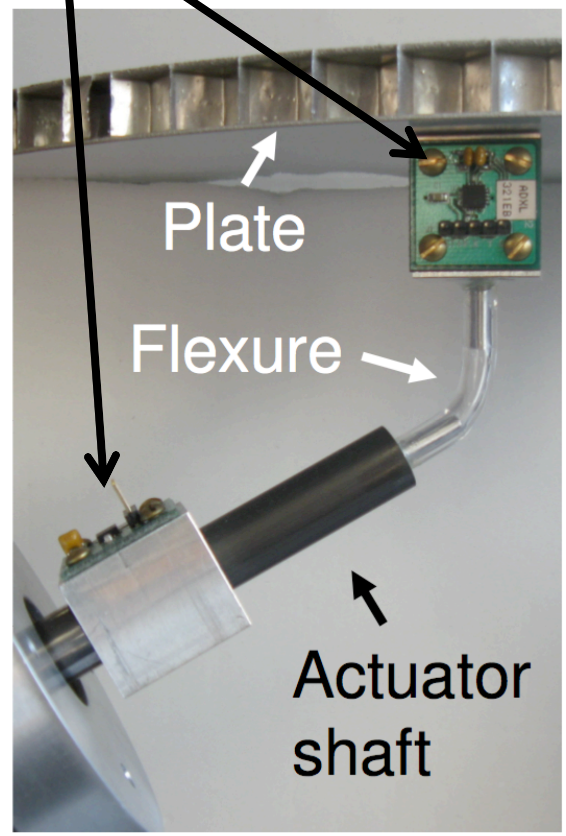


flexure-based Stewart platform

accelerometers



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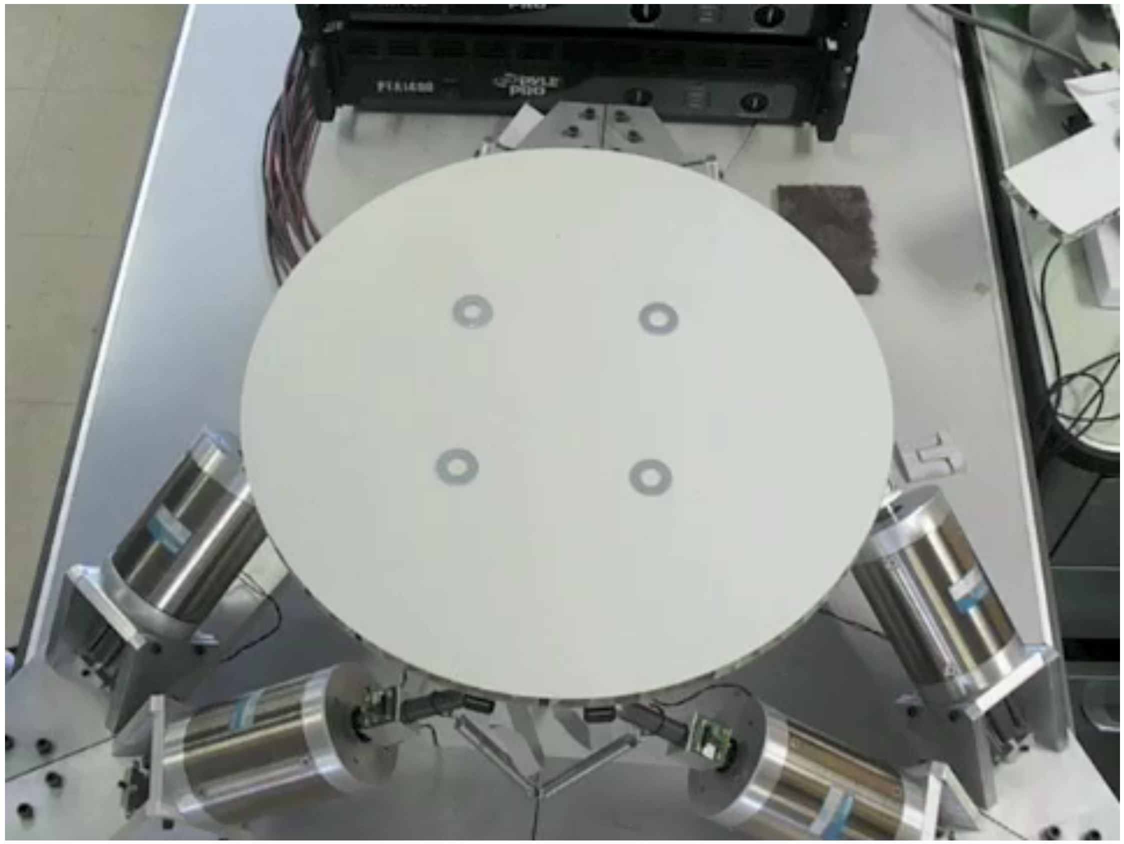

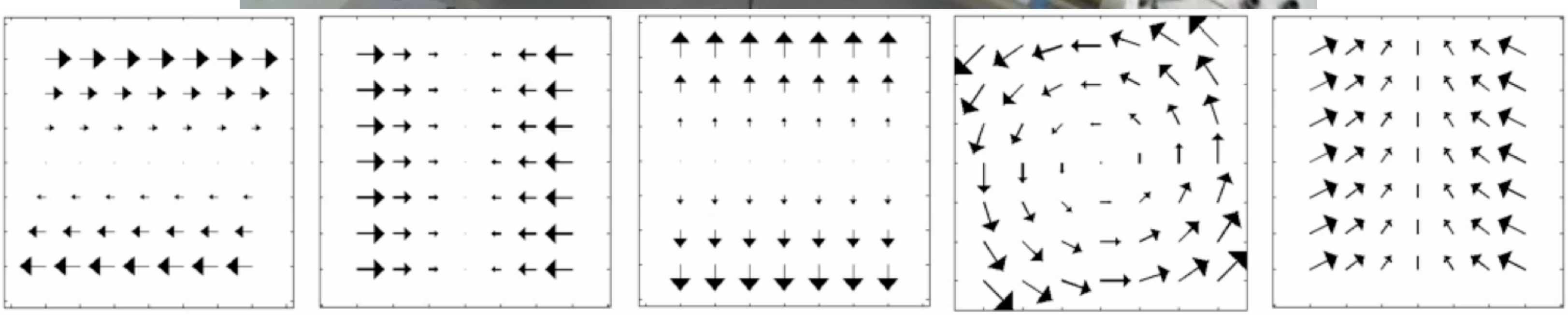

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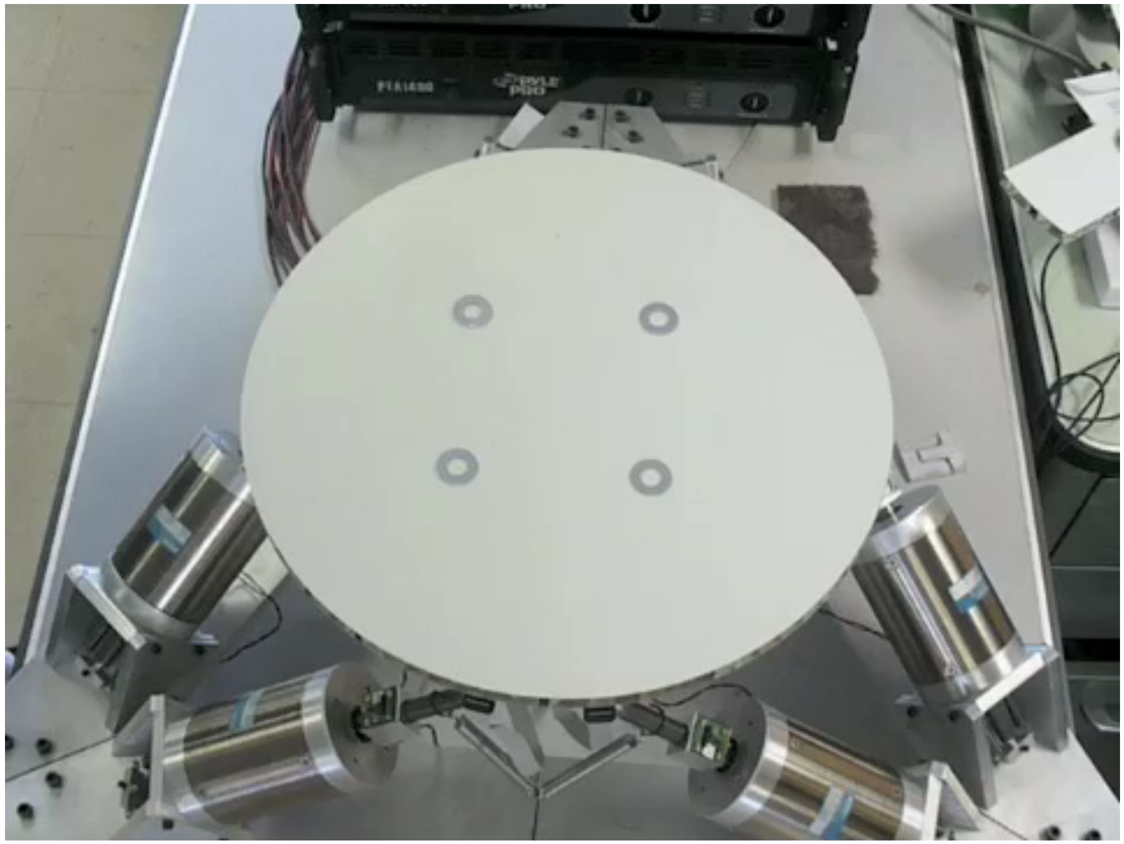
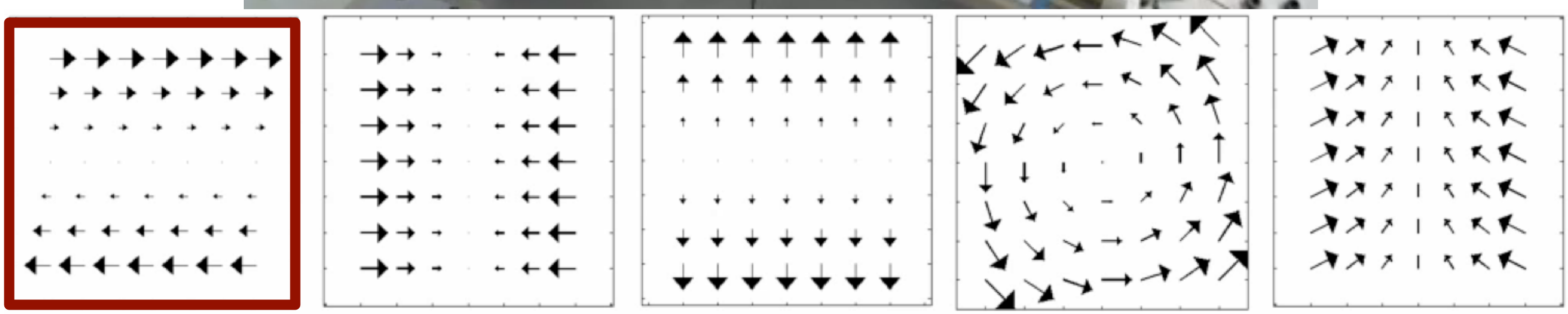
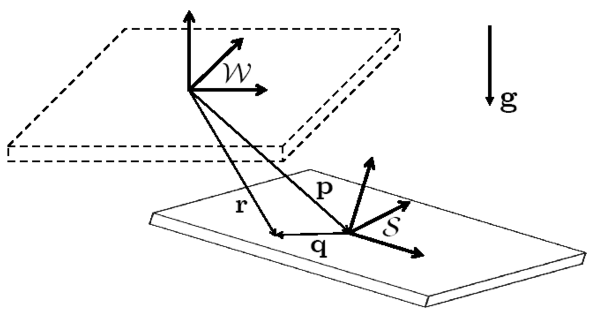
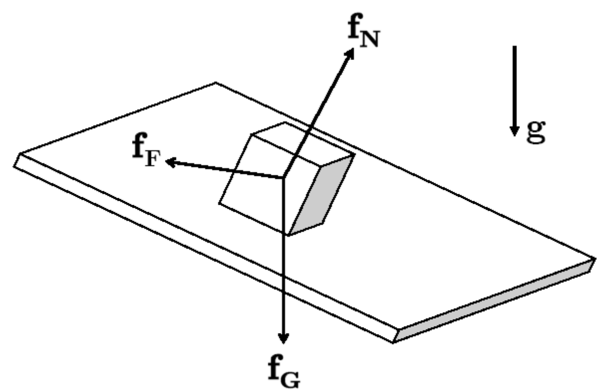
(Programmable Parts Orienting Device)





Part Dynamics

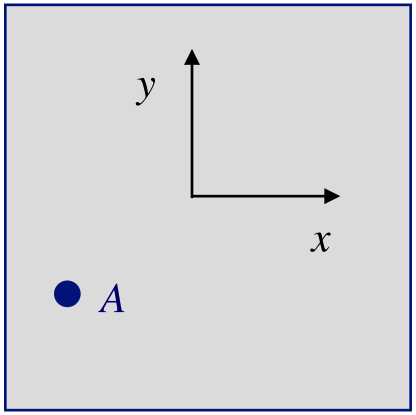




$$f_{\mathrm{fric}} = \mu f_{\mathrm{normal}} \frac{\mathbf{v}_{\mathrm{rel}}}{\left\| \mathbf{v}_{\mathrm{rel}} \right\|}$$

- $\dot{p}_x,\ \dot{p}_y,\ \omega_z$: horizontal velocity determines friction force **direction**
- $\ddot{p}_z, \alpha_x,\ \alpha_y$: vertical acceleration determines friction force **magnitude**
- 6-DOF motion allows **position-dependent** fields with **nonzero divergence**

Asymptotic Behavior



top view of plate (positions)

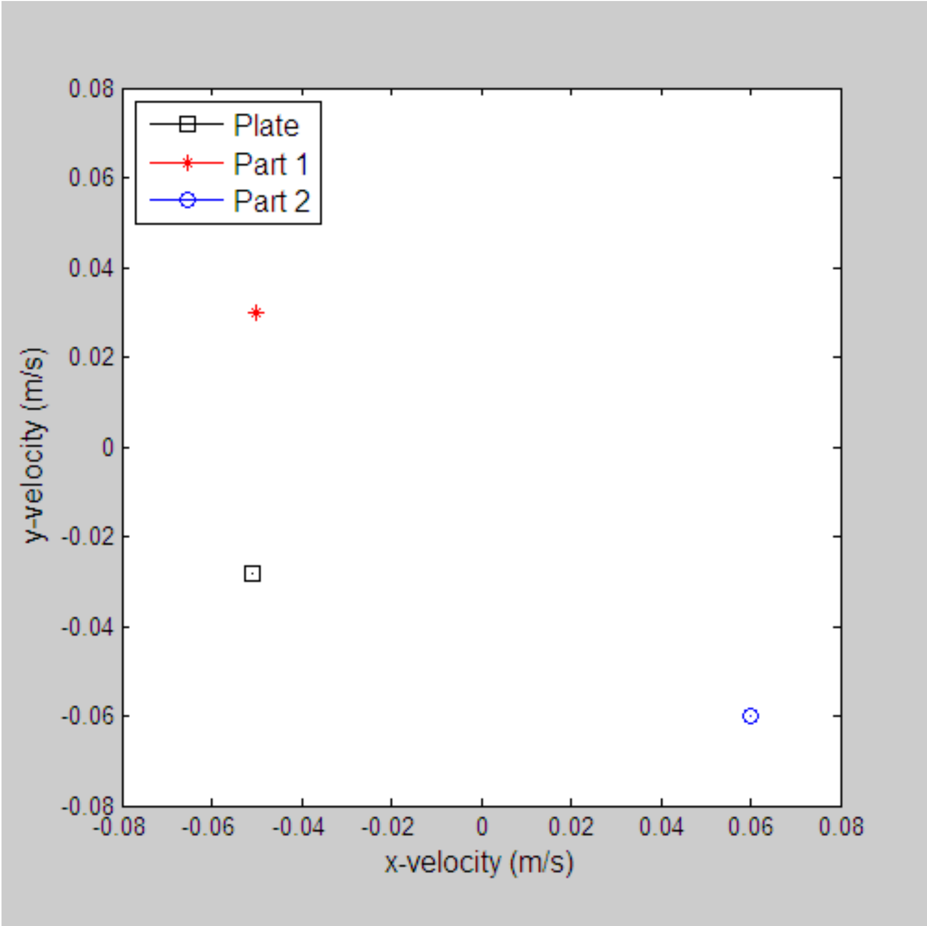
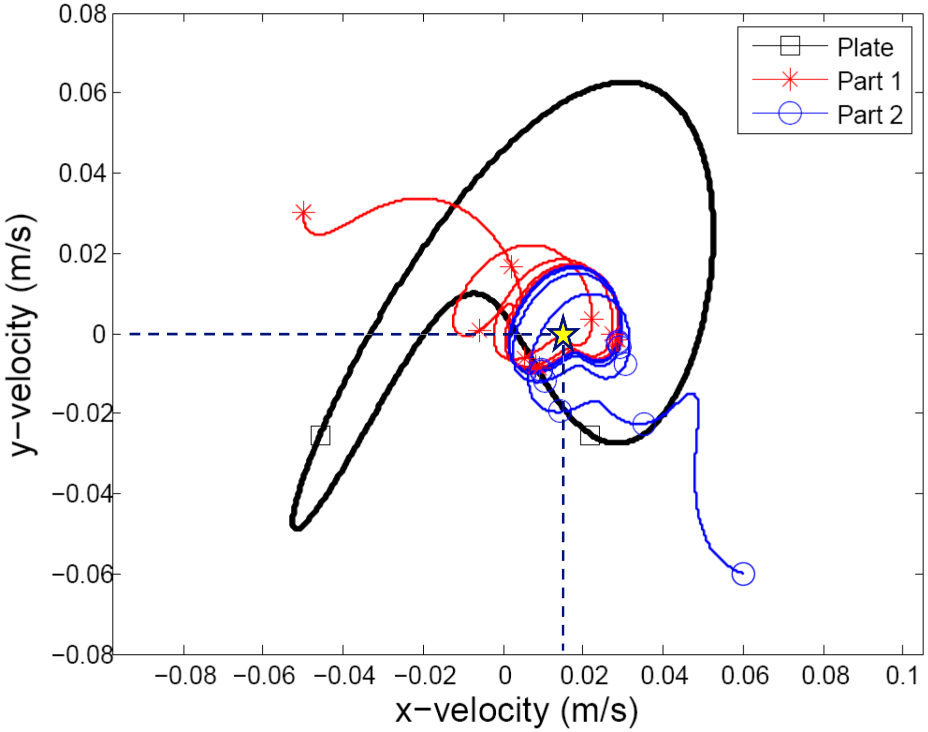


plate and part horizontal velocities at A

$$f_{\text{fric}} = \mu f_{\text{normal}} \frac{\mathbf{v}_{\text{rel}}}{\|\mathbf{v}_{\text{rel}}\|}$$

Asymptotic Velocity

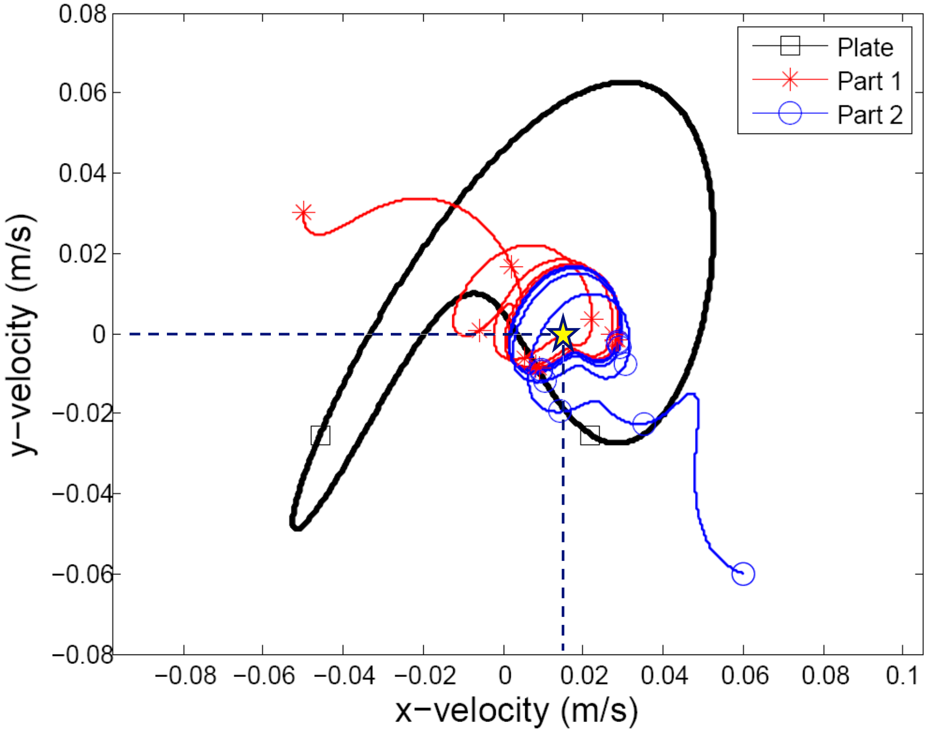


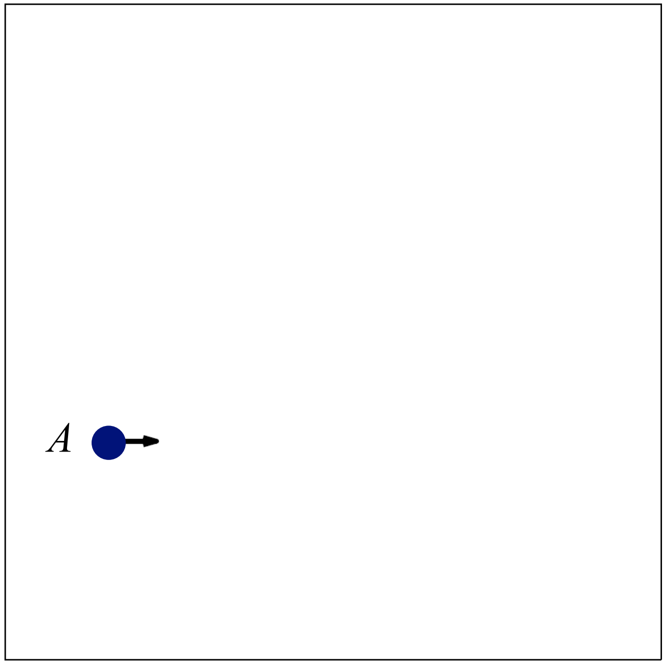
Asymptotic velocity at (x,y):

$$\mathbf{v}(x,y) = \frac{1}{T}\int_0^T \mathbf{v}'(t)\,dt$$

where $\mathbf{v}'(t)$ is the limit cycle.

Asymptotic Velocity





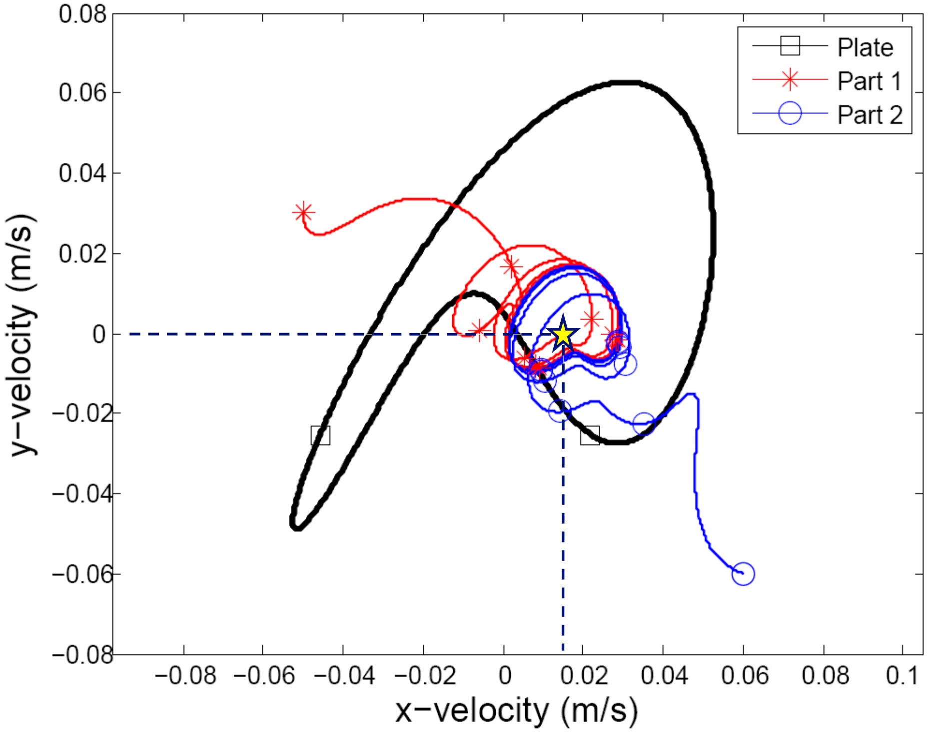
Asymptotic velocity at (x,y):

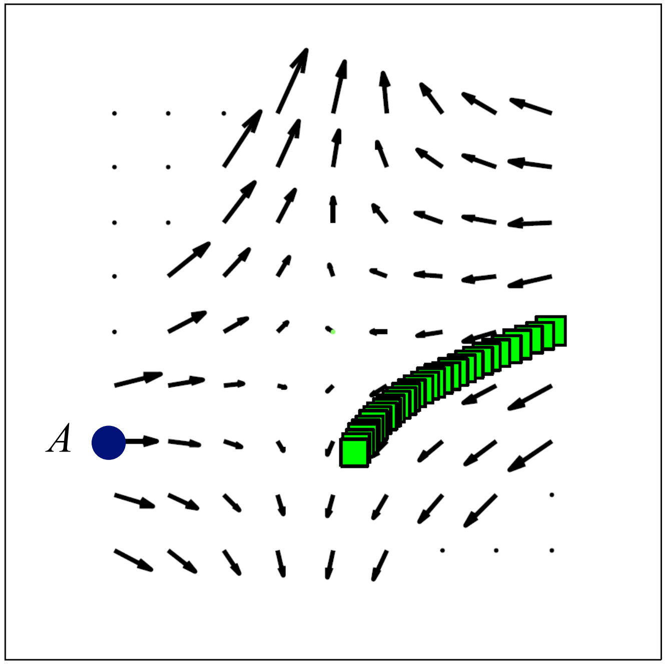
$$\mathbf{v}(x,y) = \frac{1}{T}\int_0^T \mathbf{v}'(t)\,dt$$

where $\mathbf{v}'(t)$ is the limit cycle.

asymptotic velocity vector at A

Asymptotic Velocity





Asymptotic velocity at (x,y):

$$\mathbf{v}(x,y) = \frac{1}{T}\int_0^T \mathbf{v}'(t)\,dt$$

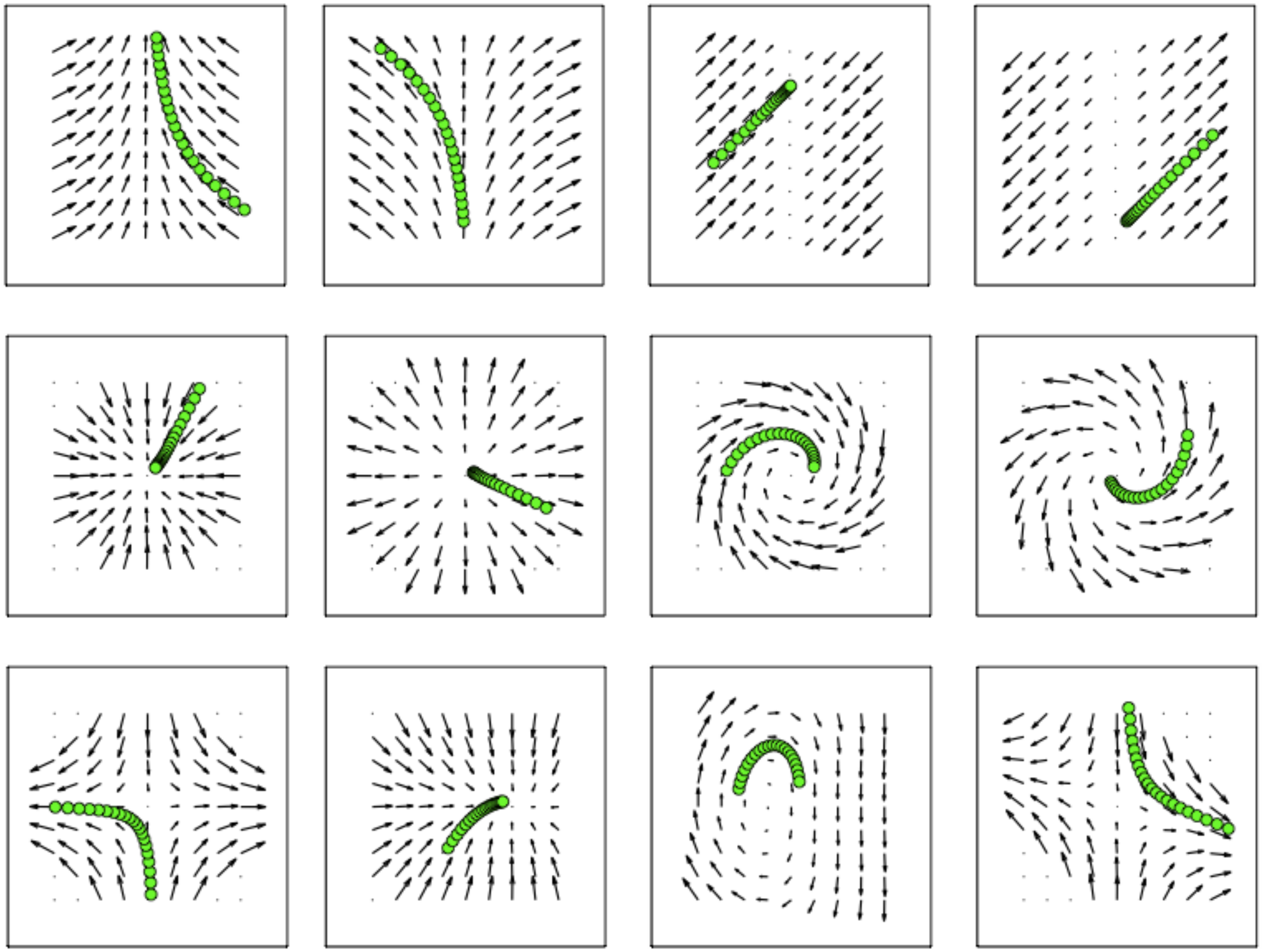
where $\mathbf{v}'(t)$ is the limit cycle.

asymptotic velocity vectors at all points:

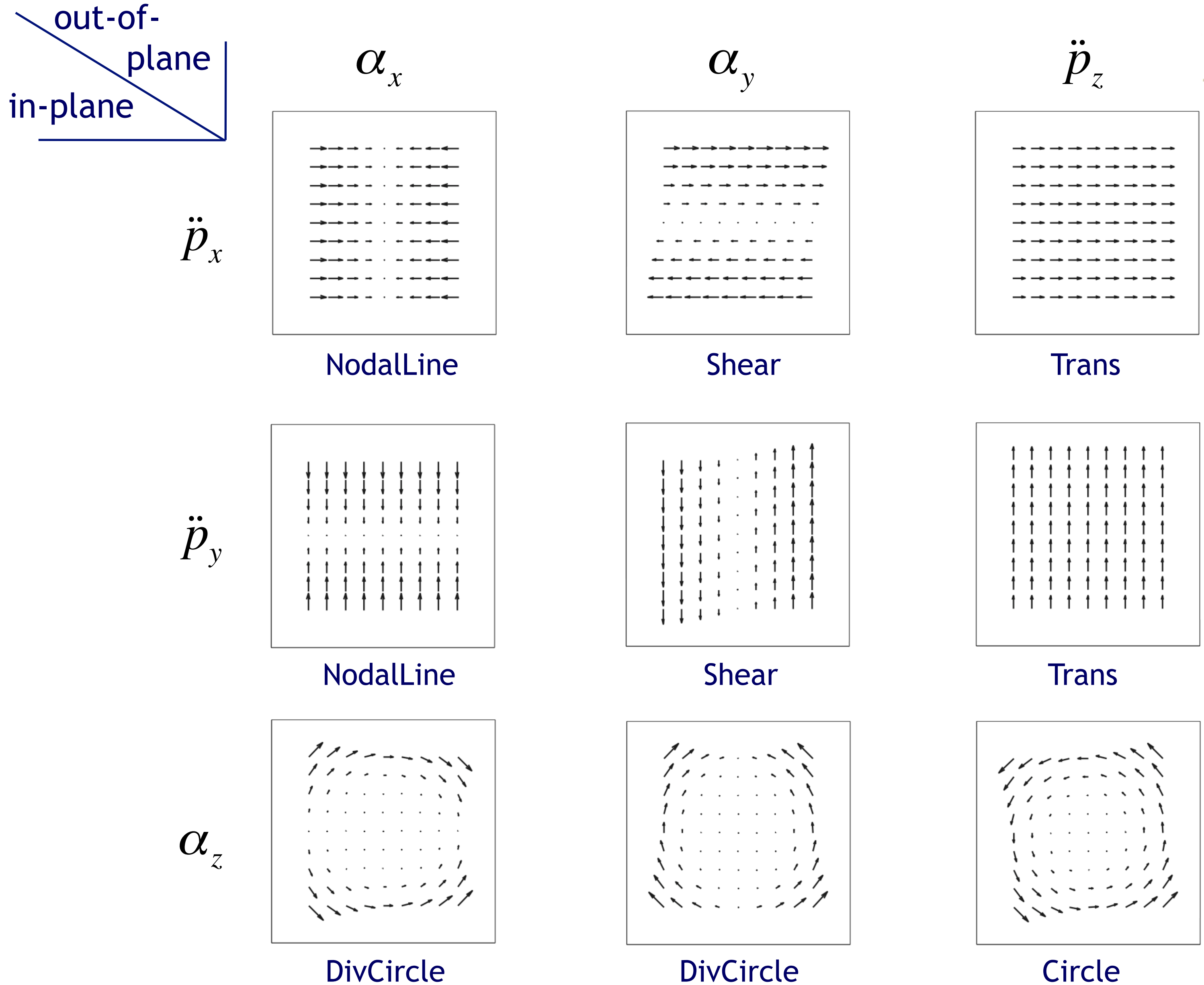
asymptotic velocity field

(not a force field)

Which Velocity Fields Are Possible?



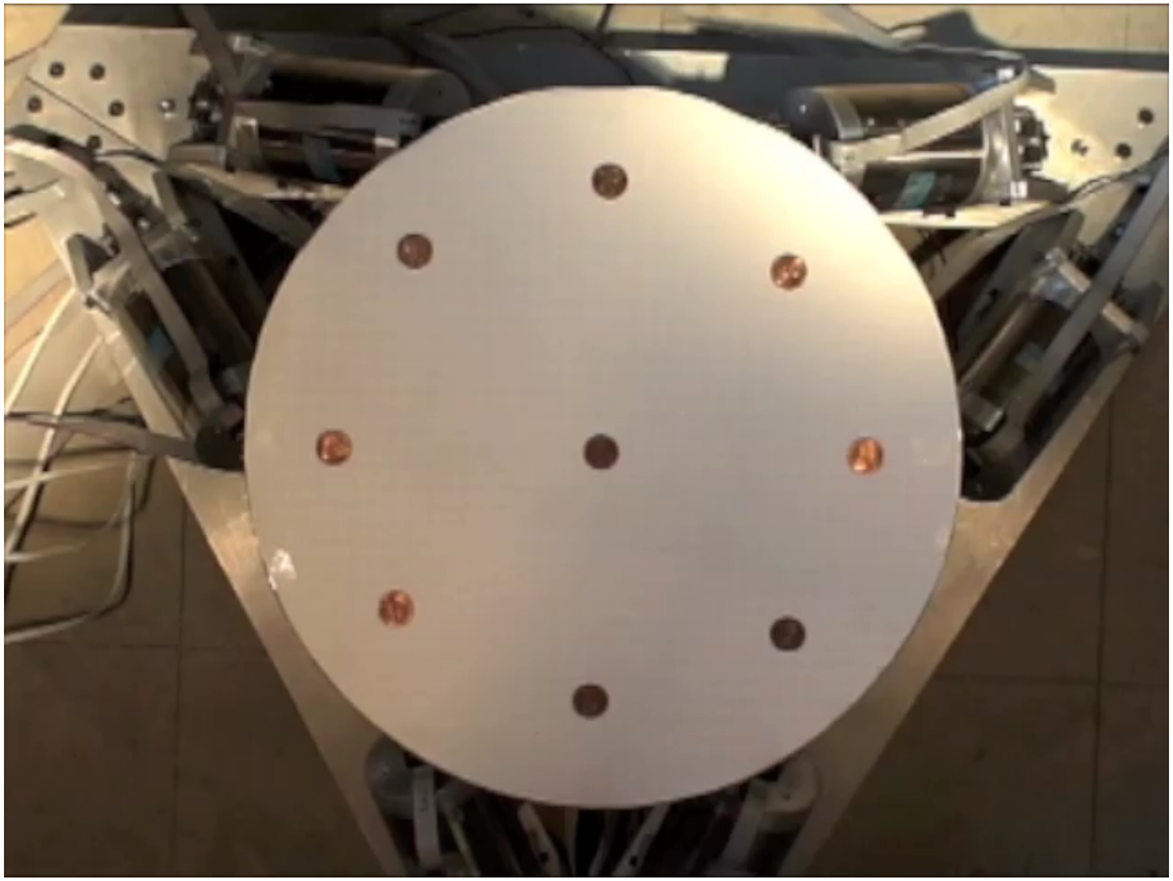
Single Frequency “Basis” Fields

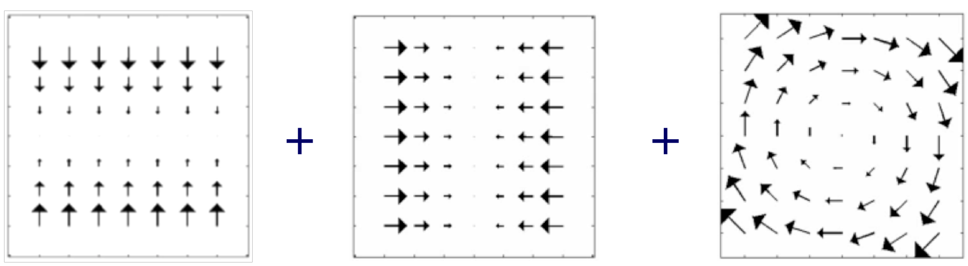


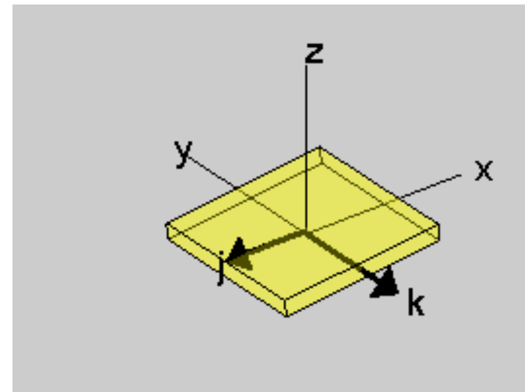
$\ddot{p}_z = A_z \sin(2\pi f t + \phi_z)$

… but dynamics are nonlinear, so no simple superposition rule

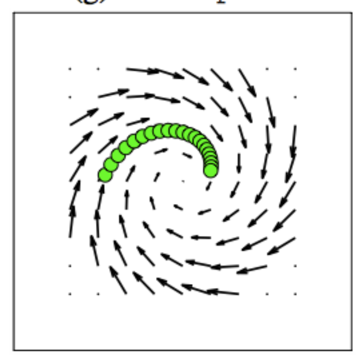
Whirlpool







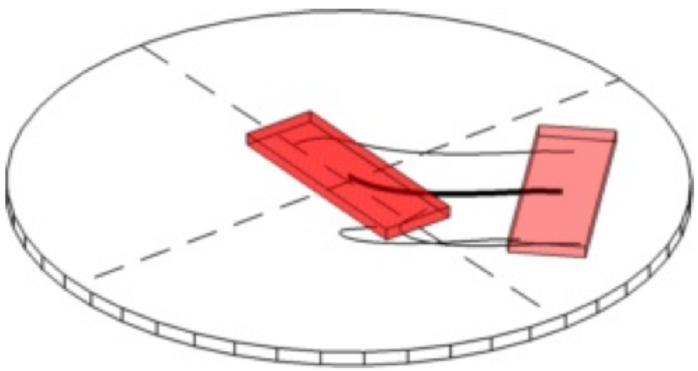
(g) Whirlpool

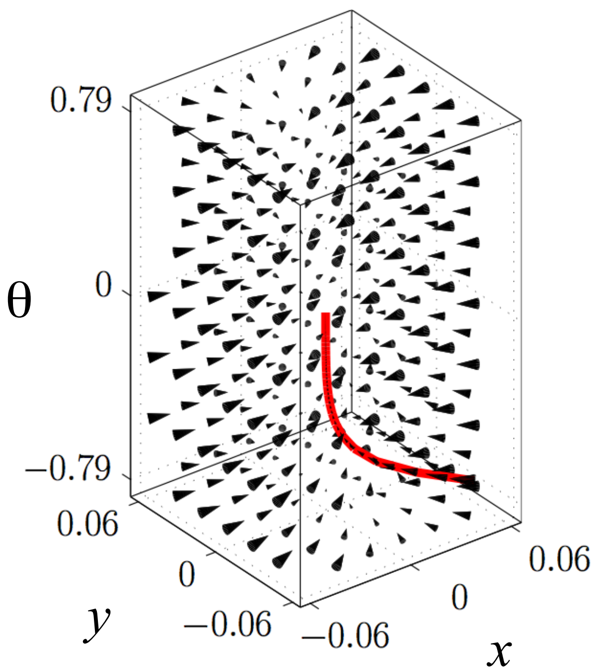


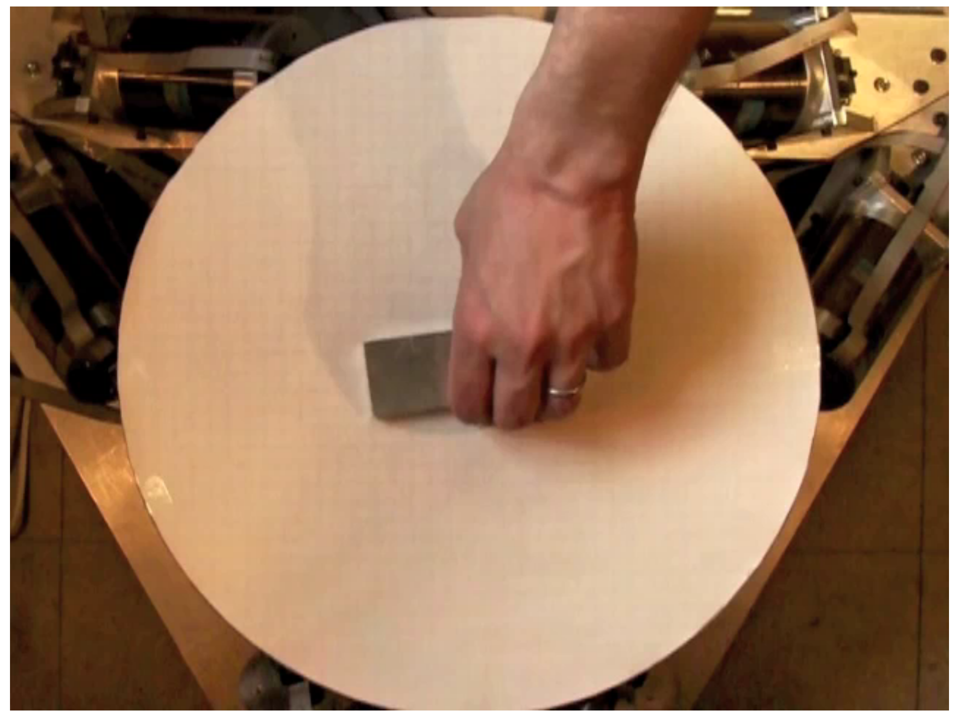
$$\ddot{p}_x = 10\sin(60\pi t)$$
$$\ddot{p}_y = 10\sin(60\pi t + \tfrac{1}{2}\pi)$$
$$\alpha_x = 100\sin(60\pi t + \tfrac{3}{2}\pi)$$
$$\alpha_y = 100\sin(60\pi t)$$

$$\mathbf{v}_\mathrm{a} \approx \begin{bmatrix} -0.22x + 0.36y \\ -0.36x - 0.22y \end{bmatrix}$$

Extension: 3D Velocity Field



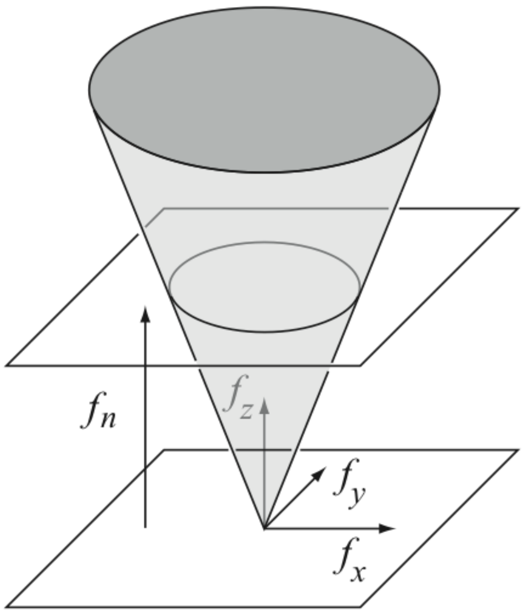




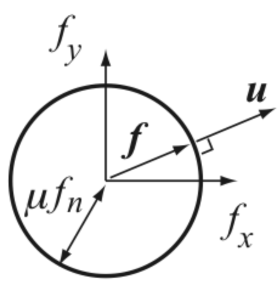
a sink field that uniquely positions and orients a part,
a la MEMS programmable vector fields
(Bohringer and Donald, Lamiraux and Kavraki)

Extension: Generalized Friction

Coulomb friction cone



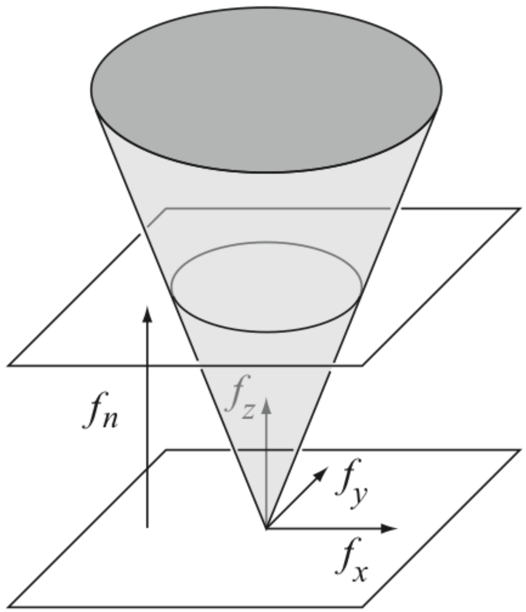
limit curve (LC) of possible friction forces at the specified normal force

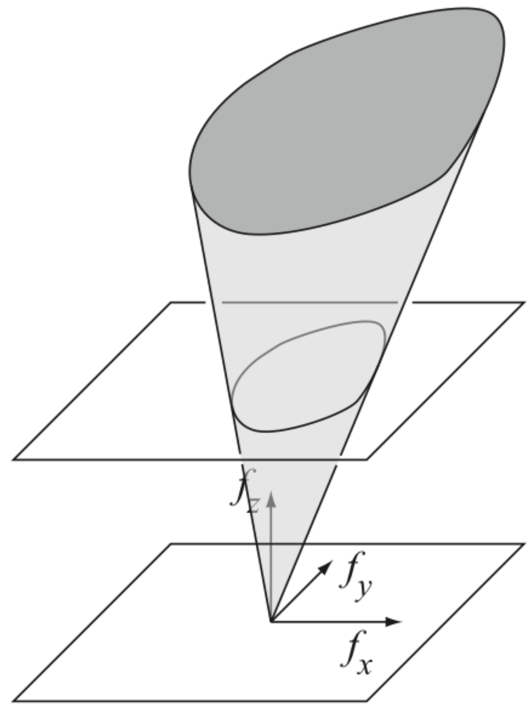


$\boldsymbol{u}$ sliding direction of support plane
$\boldsymbol{f}$ force applied by support plane

Extension: Generalized Friction

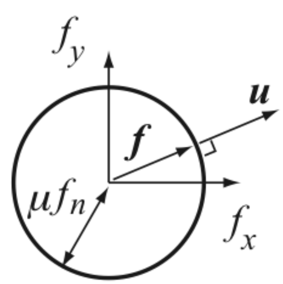
Coulomb friction cone



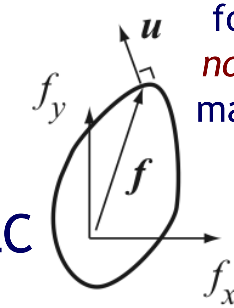


generalized *anisotropic* friction cone

limit curve (LC) of possible friction forces at the specified normal force



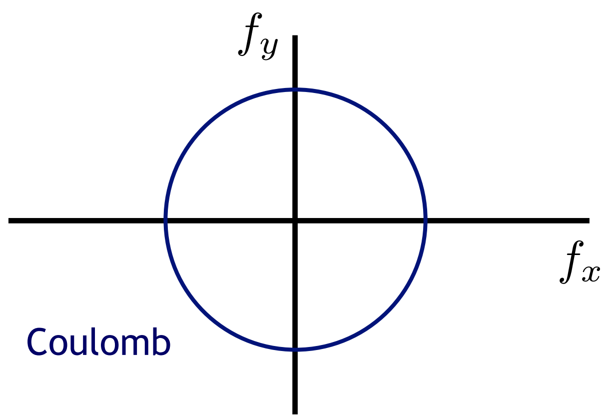
LC

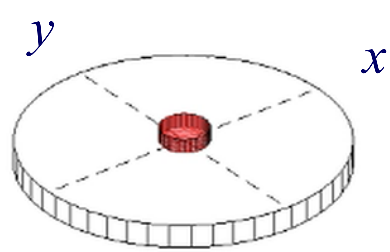


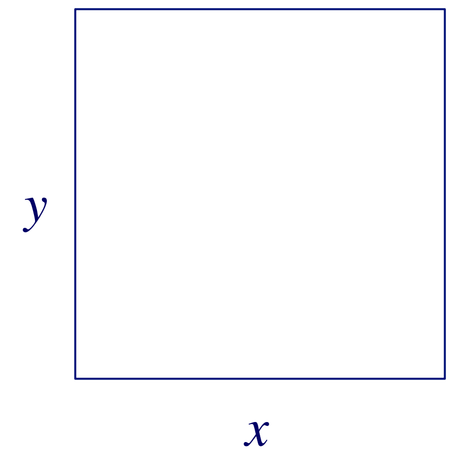
force and velocity satisfy *normality* at LC due to the maximum power inequality (Goyal, Ruina, Papadopoulos)

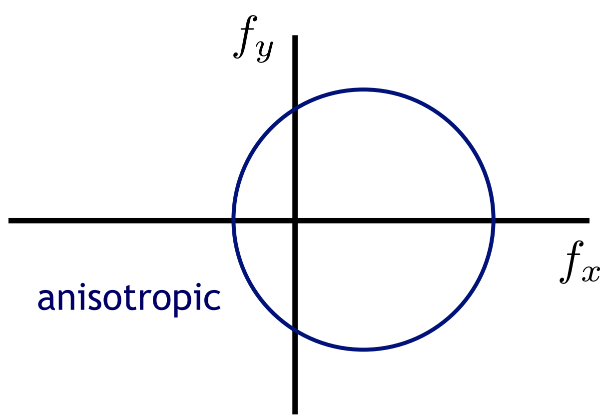
Linear Conveyance

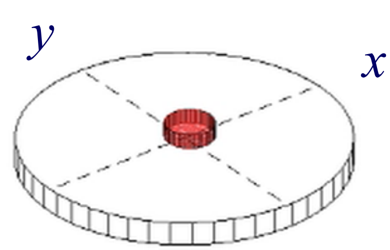
limit curve | sinusoidal plate motion | velocity field

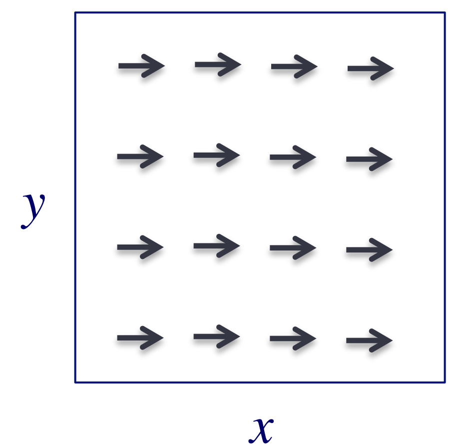








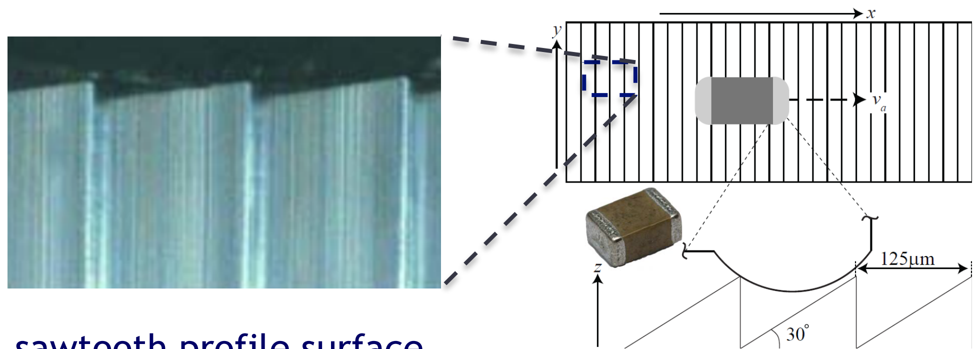




Extension: Generalized Friction

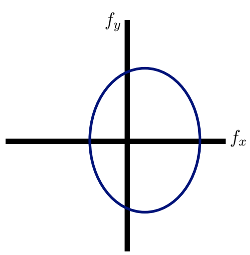
surface mount capacitor
on textured surface

top view

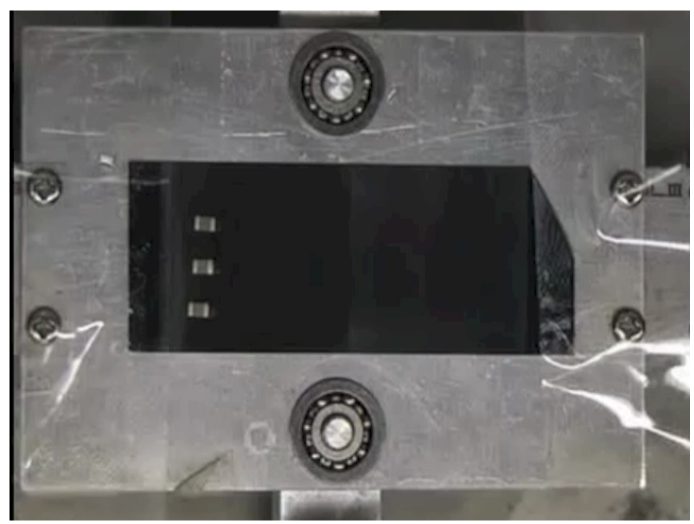


sawtooth profile surface

side view



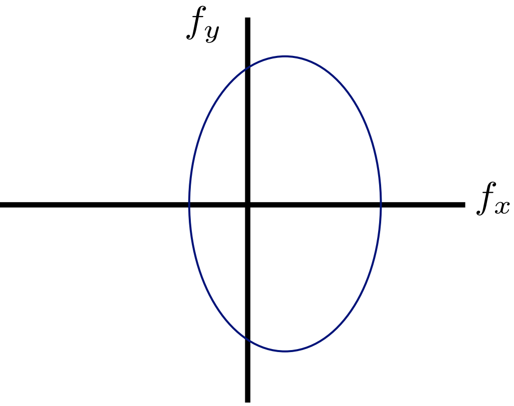
approximate anisotropic
friction limit curve

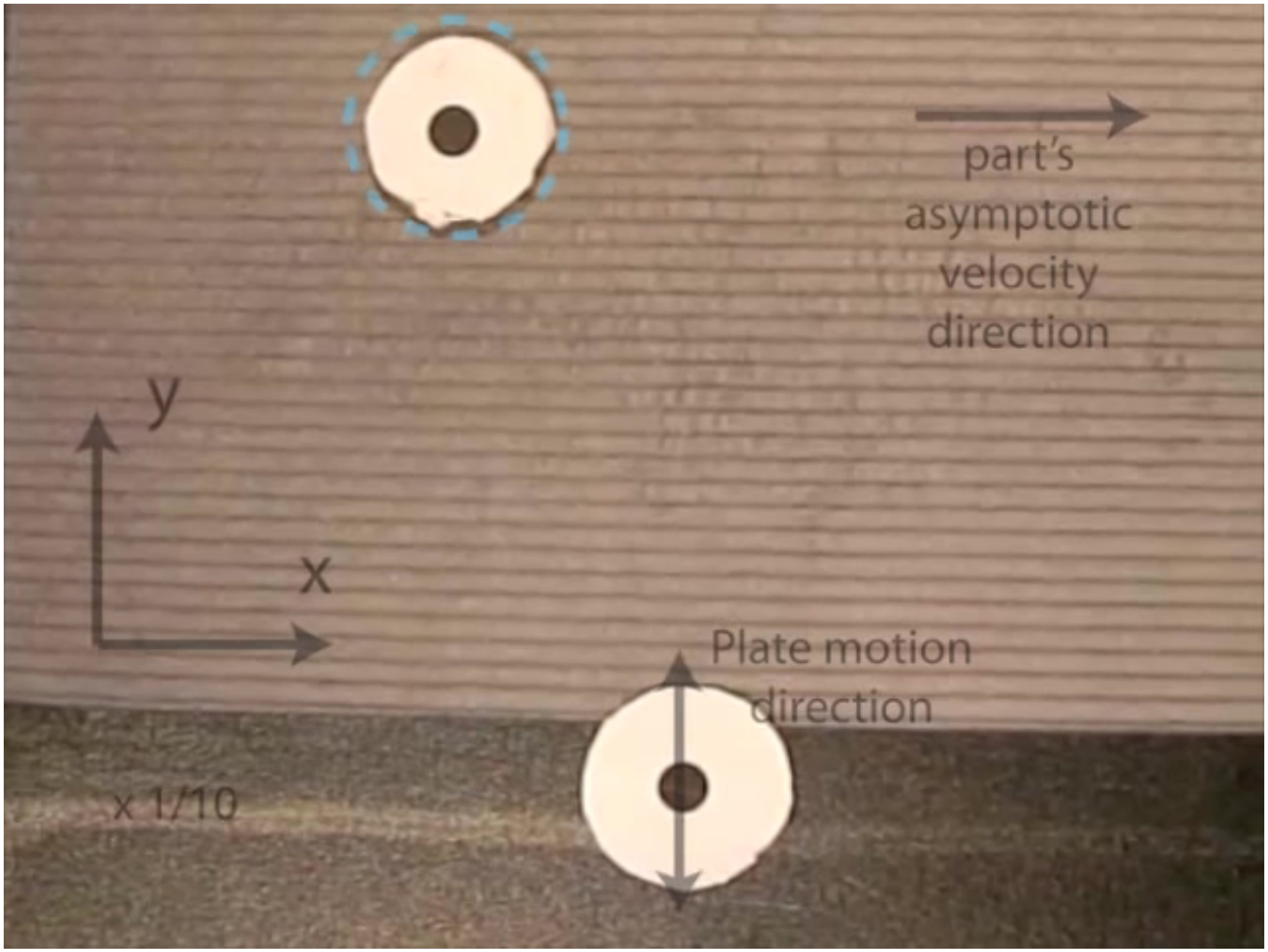


Mitani, Sugano, and Hirai 2006

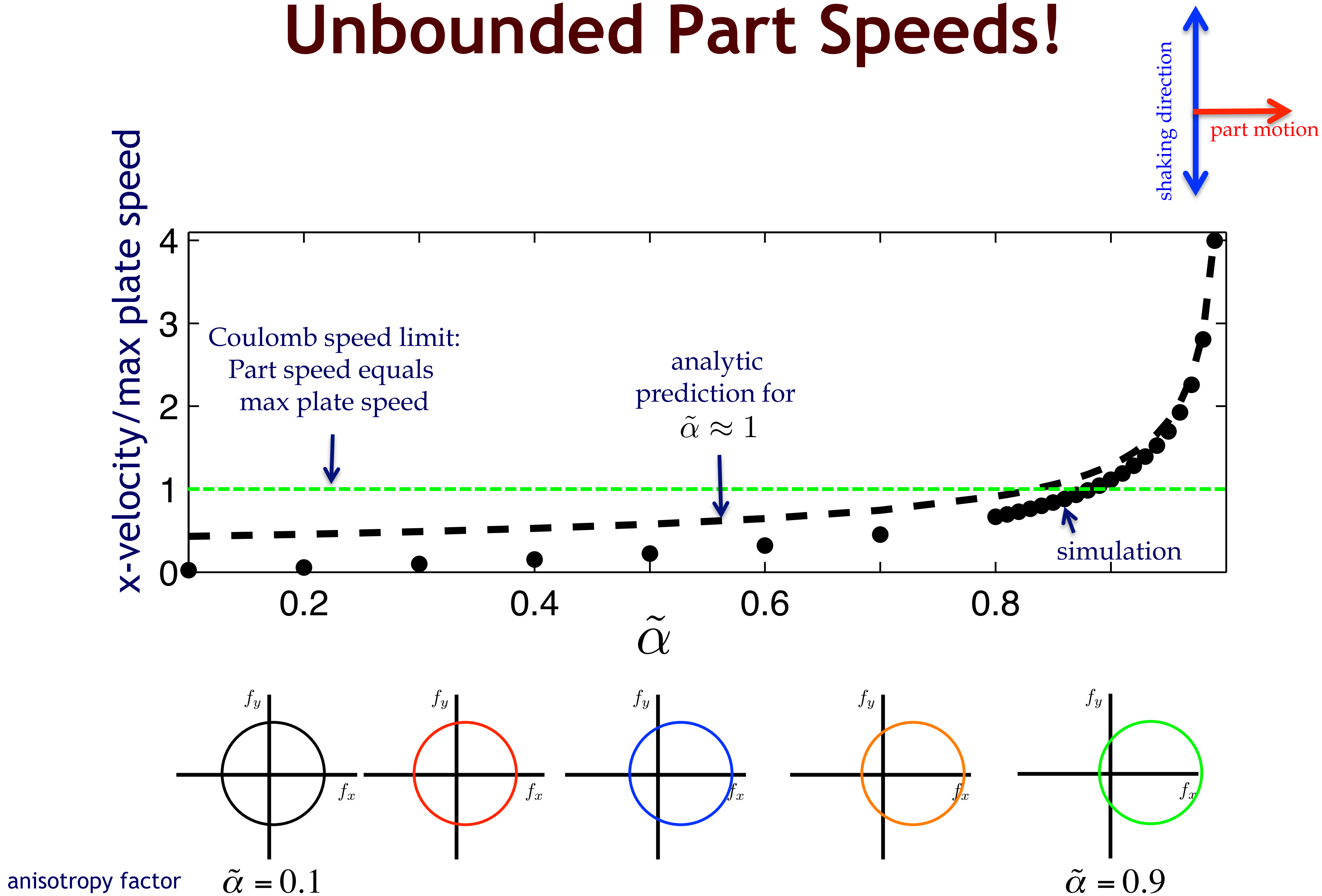
Example: Corduroy Fabric

Overhead view of plate

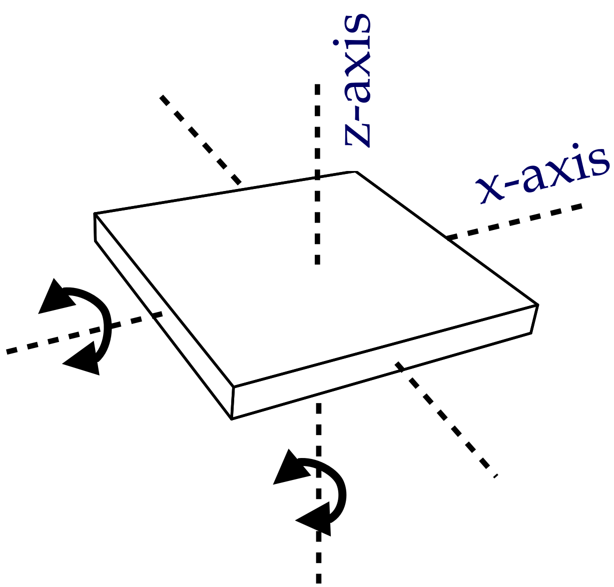


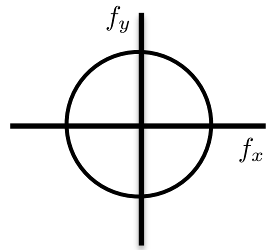


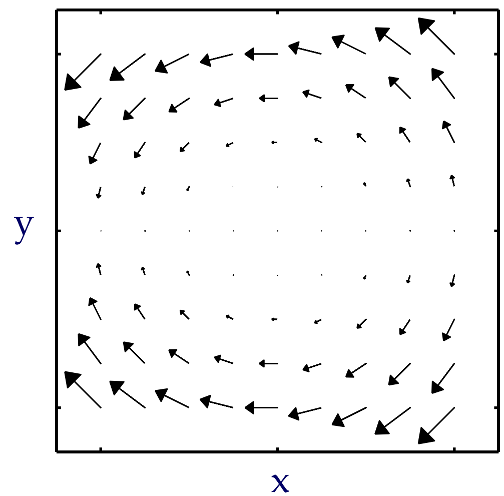
Unbounded Part Speeds!

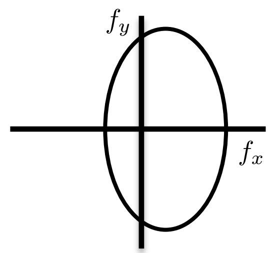


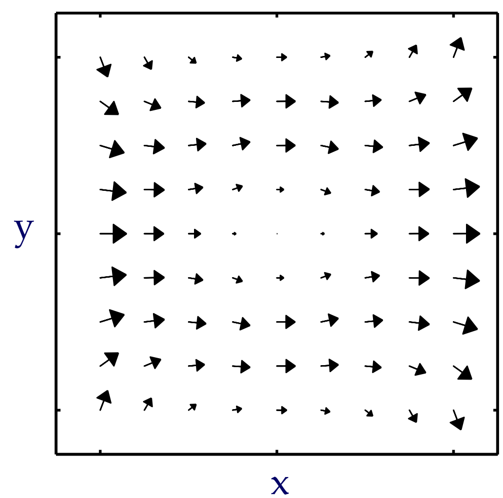
Morphing Velocity Fields











anisotropy adds nonlinear bias

Challenges

programmable motion surfaces

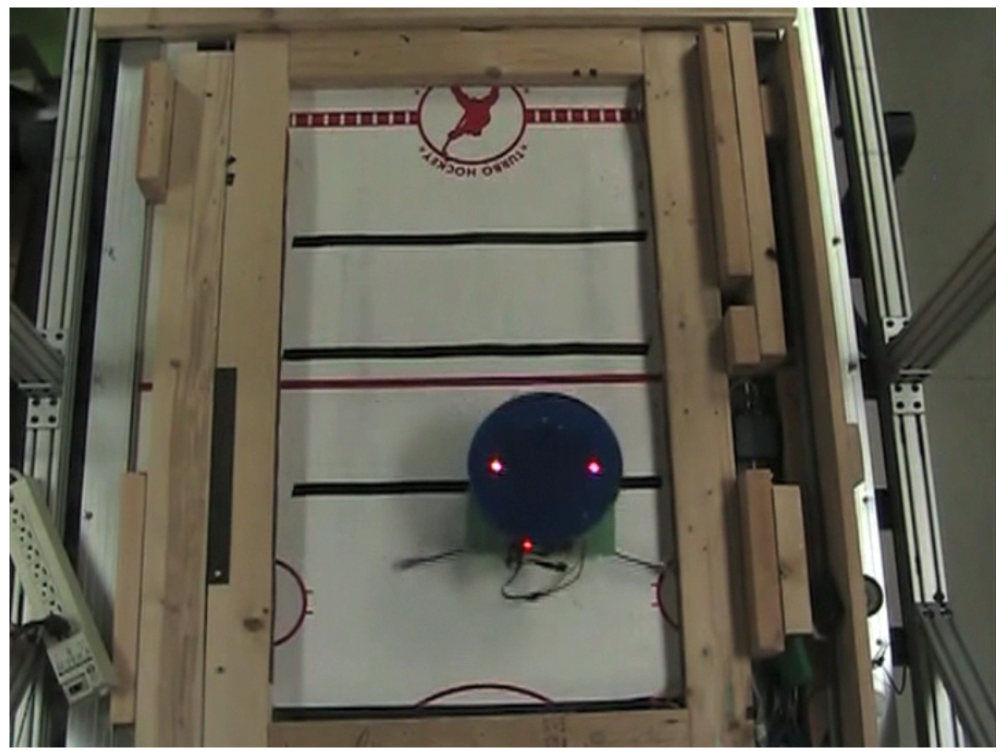
- texture design for desired anisotropic friction
- self-assembly
- impact for 6 DOF manipulation
- integration into flexible manufacturing cells

hybrid nonprehensile manipulation

- state estimation: integrating far-field (vision, depth), near-field (electrosense, capacitive), and contact (tactile) data in real time
- library of primitives: motion planning and control
- automatic sequence planning with uncertainty
- estimating reachable sets

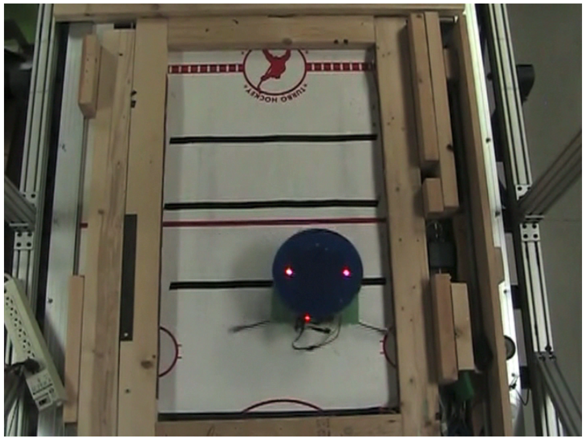
unified approach to dynamic manipulation and locomotion

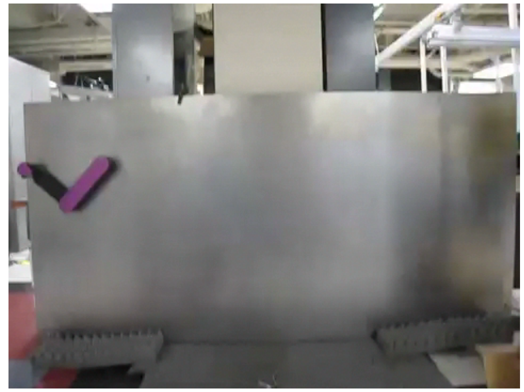
Parkour



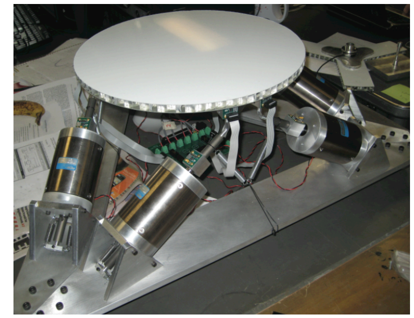
ParkourBot
with Degani, Feng, Long, Brown,
Choset and Mason

Congratulations Mark!   (and Matt!)



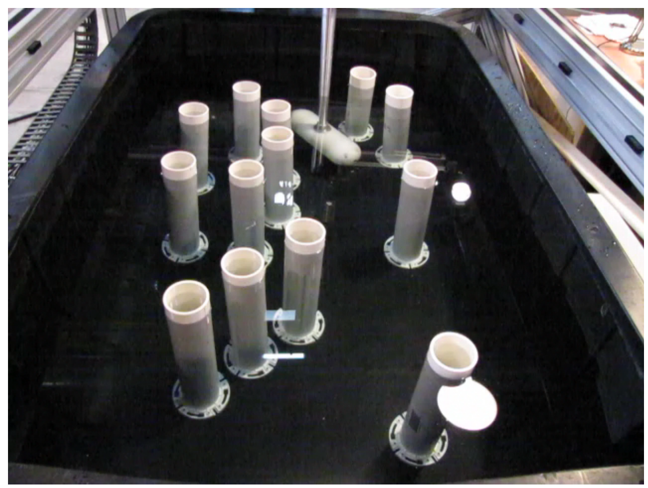


parkour, dynamic locomotion

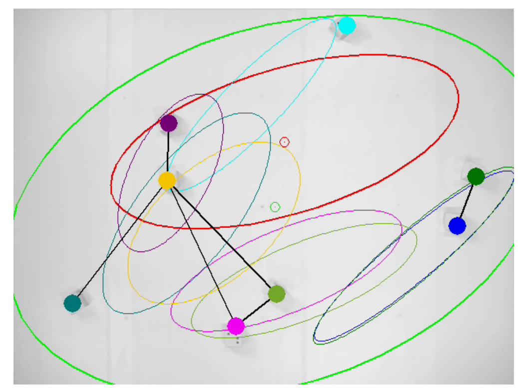


robot manipulation

restoration of function to paralyzed subjects by functional electrical stimulation



bio-inspired sensing: electrosense



self-organizing swarms of mobile sensors