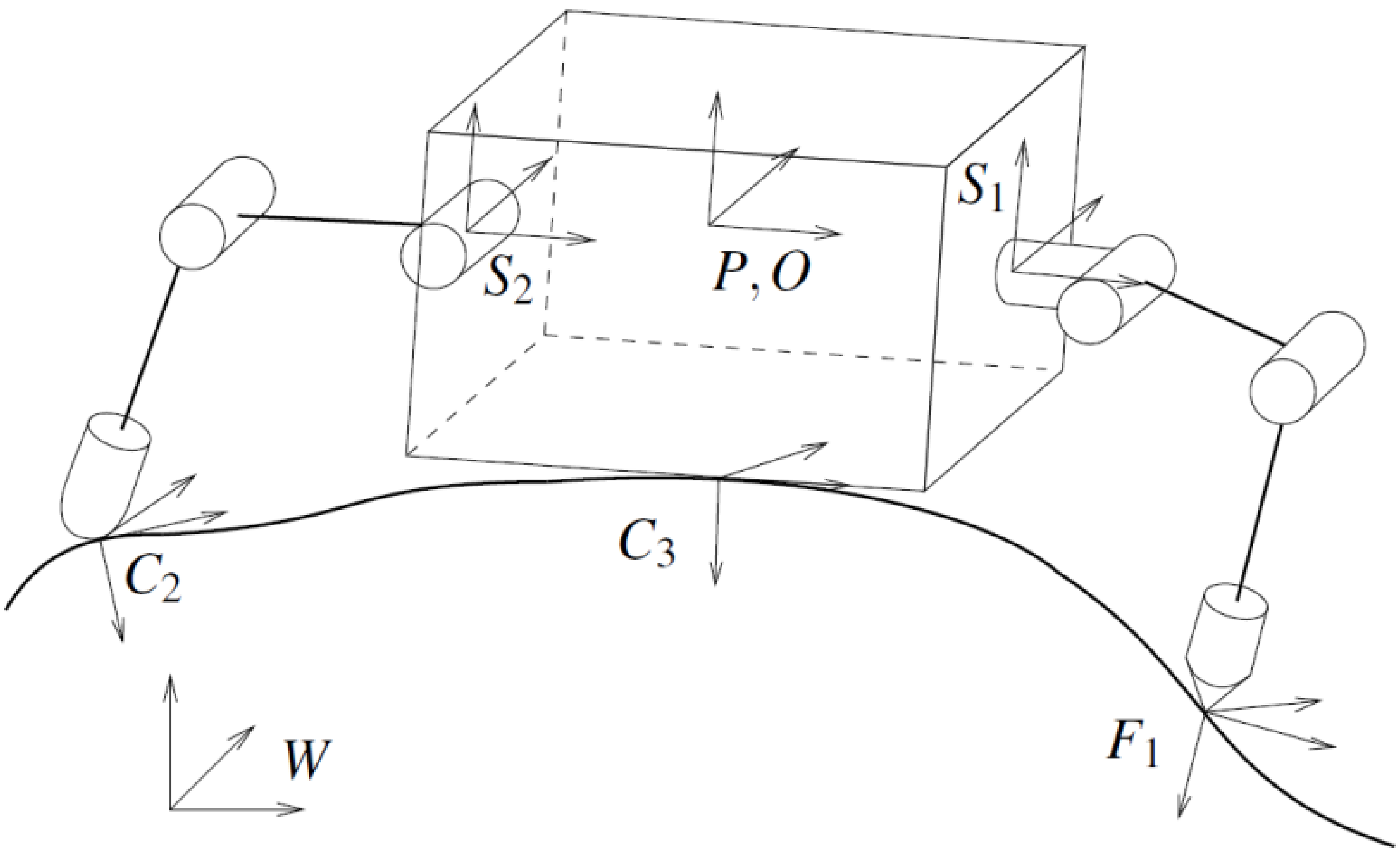
(Self-)Manipulation Challenges



Aaron M. Johnson

April 2nd, 2015

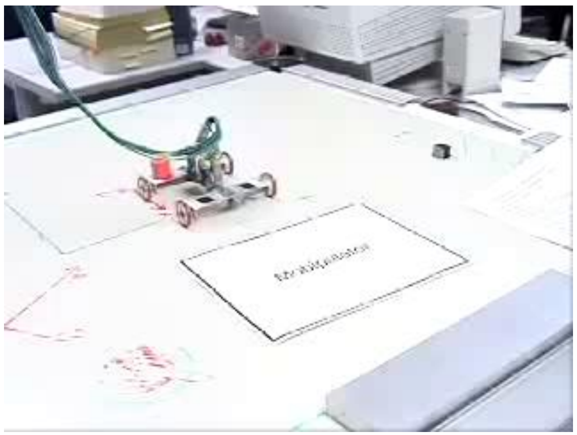
Locomotion/Manipulation Duality

Is the insect using its limbs as arms to manipulate or as legs to locomote?

 “Bug workout”, https://www.youtube.com/watch?v=ZbIHK28ZI0M

Locomotion/Manipulation Duality

- Locomotion can be viewed as “self manipulation” – Kevin Lynch



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A. Shapiro, E. Rimon, J. W. Burdick. *Passive Force Closure and its Computation in Compliant-Rigid Grasps,* IROS, 2001.

Locomotion/Manipulation Duality

- Locomotion can be viewed as “self manipulation” – Kevin Lynch
- “A different way to view a person walking on a globe is say the person is manipulating the globe with his feet” – Mark Yim
- “…the planet earth’s radius and mass are R0 and M0 respectively…” – B. Beigzadeh, et al.

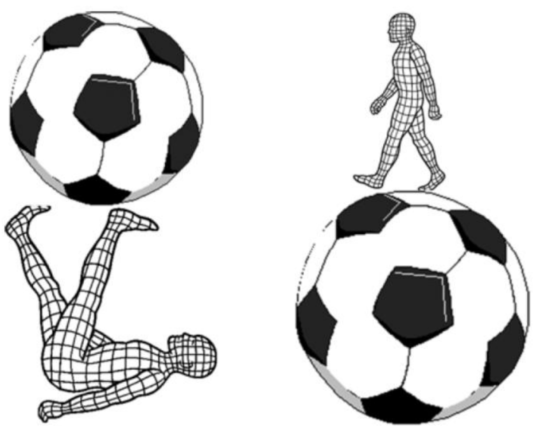
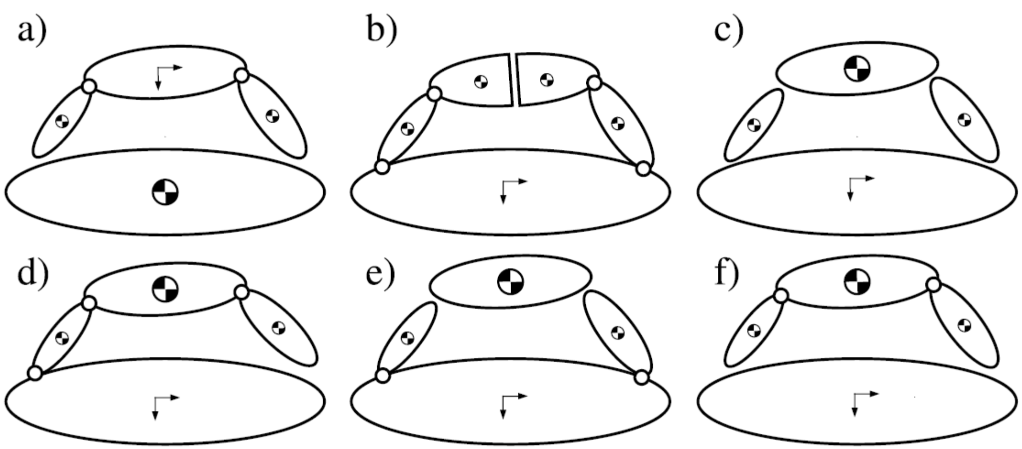


Fig. 1. Manipulation and locomotion from an absolute point of view.



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http://robotics.stanford.edu/users/mark/loco-loco.html

B. Beigzadeh, et al. *A dynamic object manipulation approach to dynamic biped locomotion,* Robotics and Autonomous Systems, vol. 56, no. 7, *pp. 570* –582, 2008.1

A. M. Johnson and D. E. Koditschek, *Legged Self-Manipulation,* IEEE Access, Vol 1, 2013

Self-Manipulation

The robot "Palm" is fixed,
and the Object moves

Object

Robot

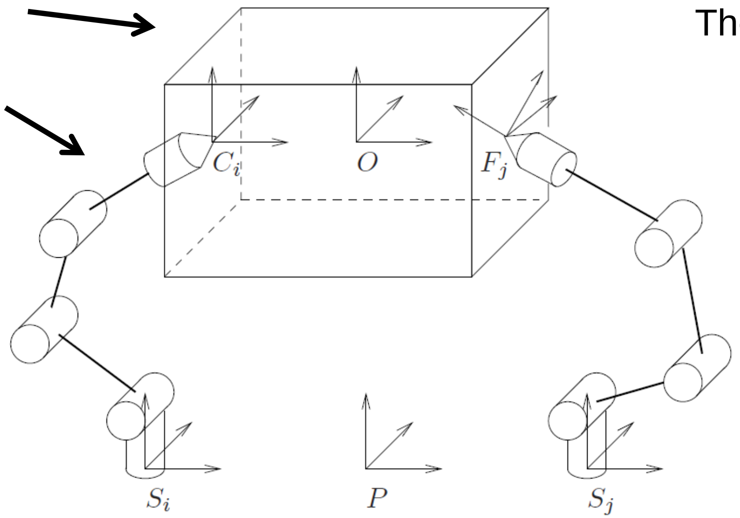
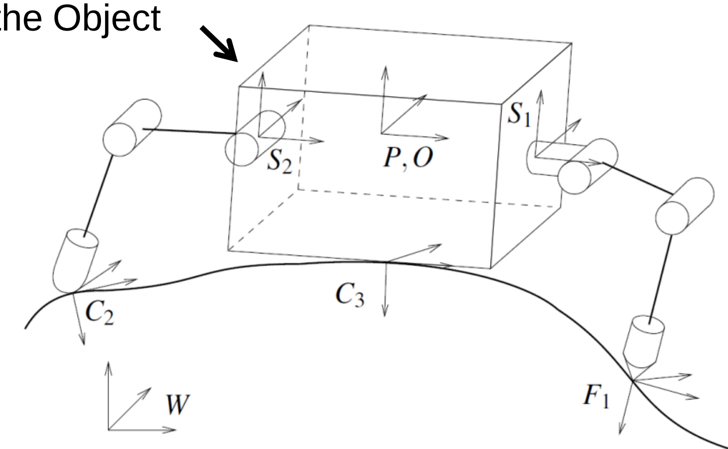


Figure 5.14: Grasp coordinate frames.

Manipulation

The World is fixed,
and the Robot moves

The Robot is the Object



(Possibly) Unknown World Location

Self-Manipulation

R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation. Boca Raton, FL: CRC Press, 1994.*

A. M. Johnson and D. E. Koditschek, *Legged Self-Manipulation,* IEEE Access, Vol 1, 2013

Grasp Map and Hand Jacobian

- Manipulation kinematics is often decoupled into the *Grasp Map*:

$$\mathbf{G} := \begin{bmatrix} \mathbf{A}^T_{co_1}\mathbf{B}_{c_1} & \mathbf{A}^T_{co_2}\mathbf{B}_{c_2} \end{bmatrix}$$

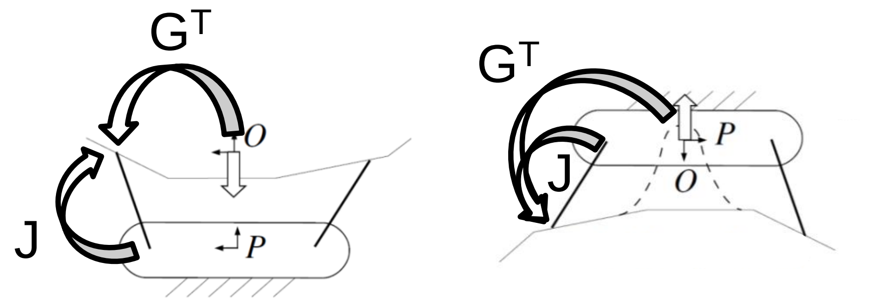
  and *Hand Jacobian:*

$$\mathbf{J}_h := \begin{bmatrix} \mathbf{B}^T_{c_1}\mathbf{A}^{-1}_{sc_1}\mathbf{J}^s_{sf_1} & 0 \\ 0 & \mathbf{B}^T_{c_2}\mathbf{A}^{-1}_{sc_2}\mathbf{J}^s_{sf_2} \end{bmatrix}$$

- Leading to the closed loop constraint:
  - $\mathbf{J}_h \dot{\theta} = \mathbf{G}^T \mathbf{V}_o,$

- The dynamics are more complicated but take a familiar form:

$$\underbrace{\overline{\mathbf{M}}(\theta,\phi)\ddot{\mathbf{q}} + \overline{\mathbf{C}}(\theta,\phi,\dot{\mathbf{q}})\dot{\mathbf{q}} + \overline{\mathbf{N}}(\theta,\phi)}_{\text{Same for all contact modes}} + \underbrace{\mathbf{A}^T(\mathbf{q})\lambda}_{\text{Changes per-mode}} = \underbrace{\Upsilon(\tau)}_{?}$$



Manipulation Self-Manipulation

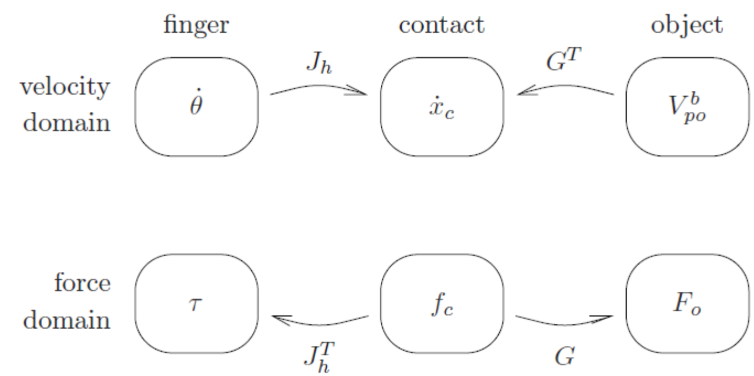


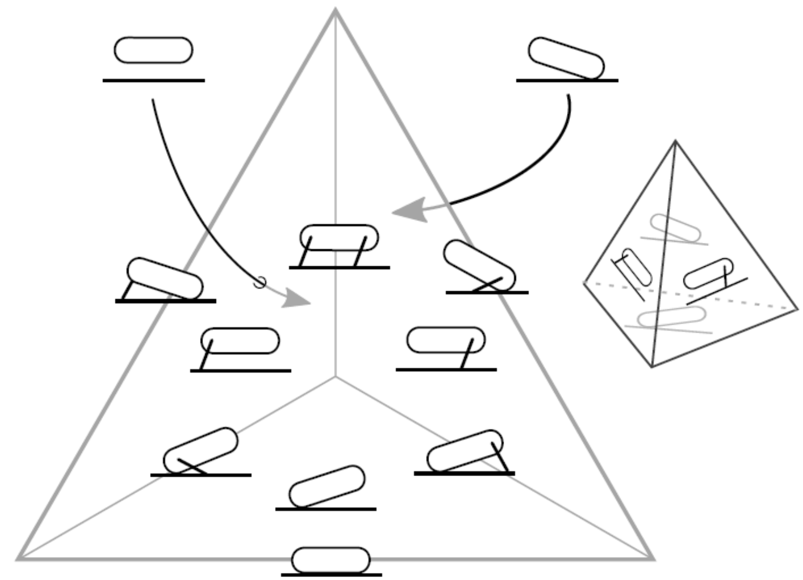
Figure 5.15: Diagram of relationships for a multifingered grasp. The contact force must satisfy $f_c \in FC$ for these relationships to hold.

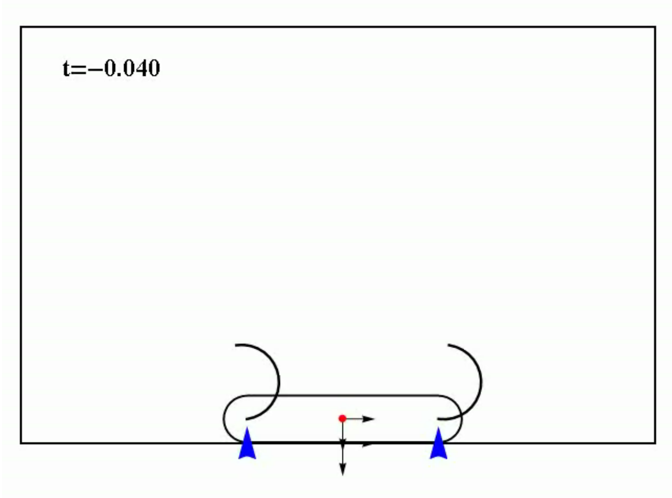
R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation. Boca Raton, FL: CRC Press, 1994.*

A. M. Johnson and D. E. Koditschek, *Legged Self-Manipulation,* IEEE Access, Vol 1, 2013

(Self-)Manipulation Hybrid System

- Simplifying physical assumptions:
  - Rigid bodies, plastic impact, Coulomb friction, massless limbs, etc
- Combined into a "consistent" formal hybrid dynamical system:
  - Deterministic
  - Non-blocking
  - Finite transitions (Zeno-free)
  - No dynamics in the "label"





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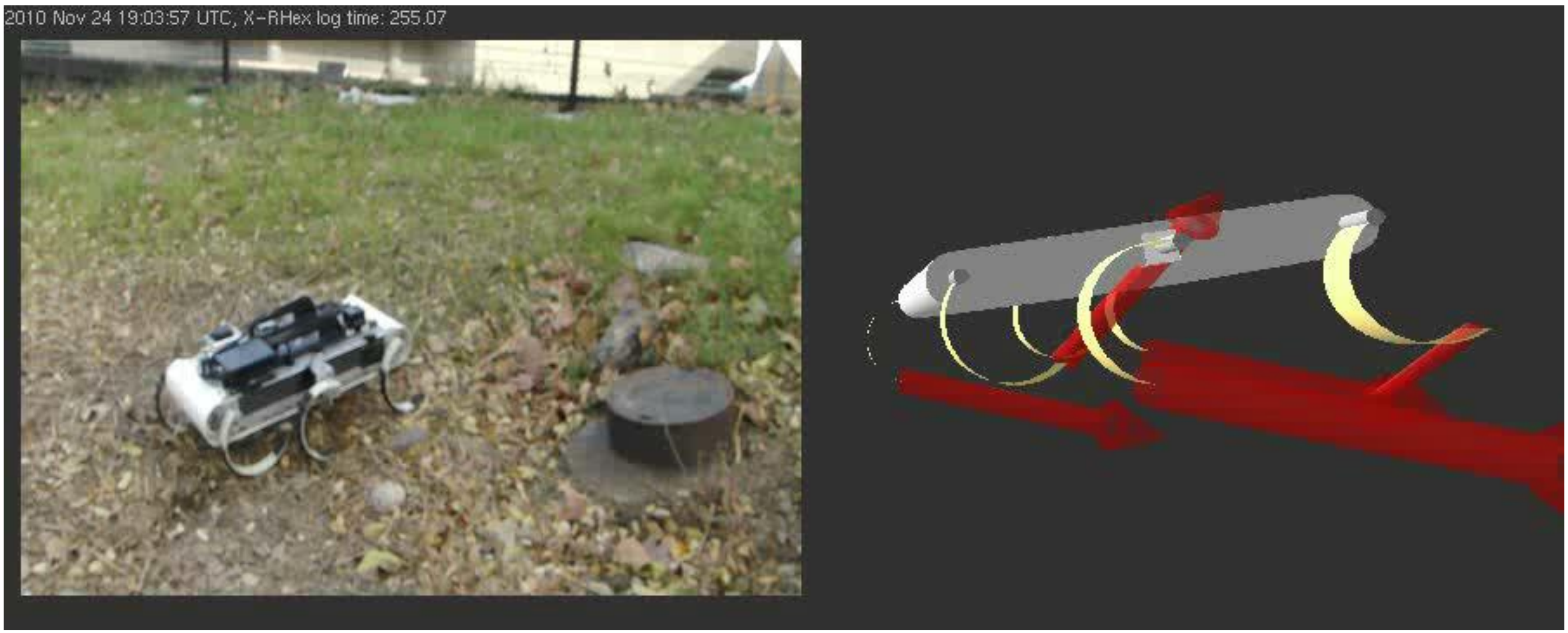
A. M. Johnson, S. Burden, and D. Koditschek, *A Hybrid Systems Model for Simple Manipulation and Self-Manipulation Systems*. arXiv:1502.01538 [cs.RO], 2015.

Low Power Standing

- How can we reduce the power needed to stand on rough terrain?
- Internal forces are those that lie in the null space of the *grasp map*

Table 5.4: Grasp properties.

Property	Definition	Description
Force-closure	Can resist any applied wrench	$G(FC) = \mathbb{R}^p$
Manipulable	Can accommodate any object motion	$\mathcal{R}(G^T) \subset \mathcal{R}(J_h)$
Internal forces	Contact forces f_N which cause no net object wrench	$f_N \in \mathcal{N}(G) \cap \operatorname{int}(FC)$
Internal motions	Finger motions $\dot{\theta}_N$ which cause no object motion	$\dot{\theta}_N \in \mathcal{N}(J_h)$
Structural forces	Object wrench F_I which causes no net joint torques	$G^+ F_I \in \mathcal{N}(J_h^T)$



Visualization of the motor torque needed to walk and stand

R. Murray, Z. Li, and S. Sastry, *A Mathematical Introduction to Robotic Manipulation.* 1994.
A. M. Johnson, G. C. Haynes, and D. E. Koditschek, *Standing self-manipulation for a legged robot,* IROS 2012

Leaping Divergence

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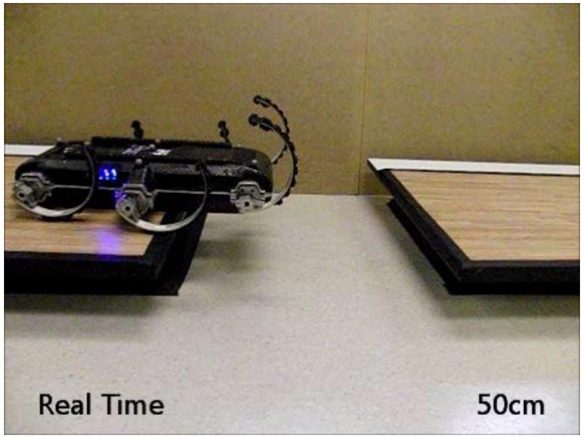

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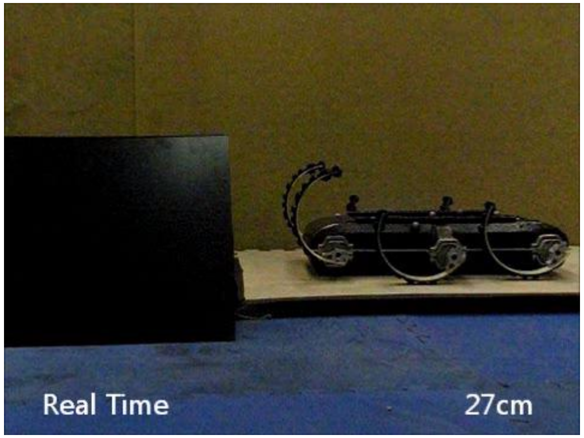

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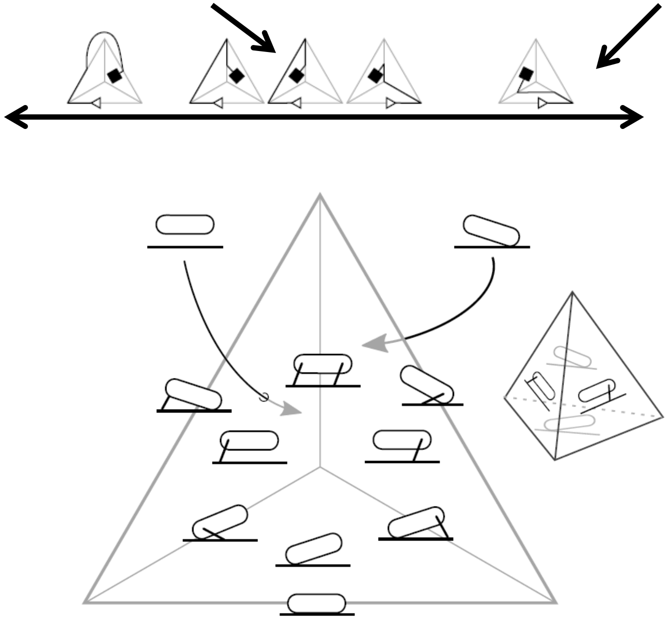

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Leaping Divergence

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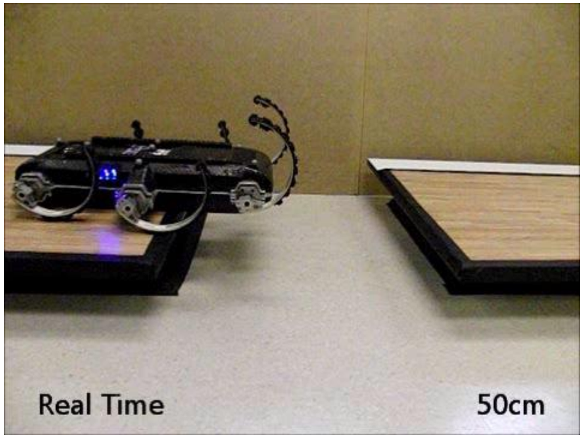

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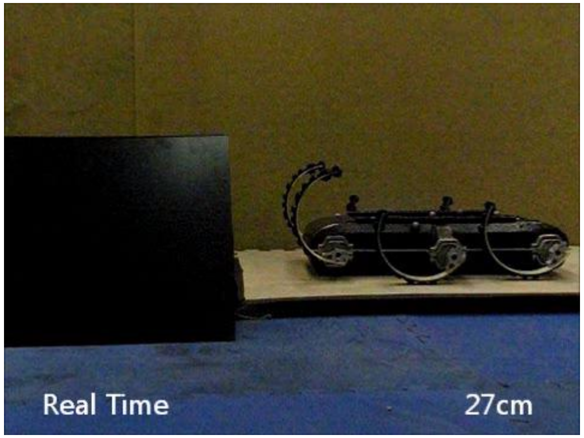

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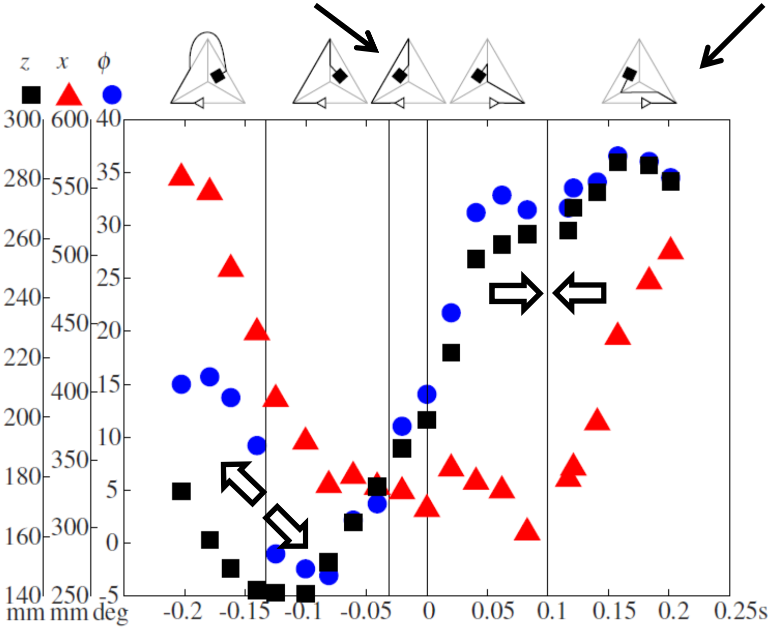
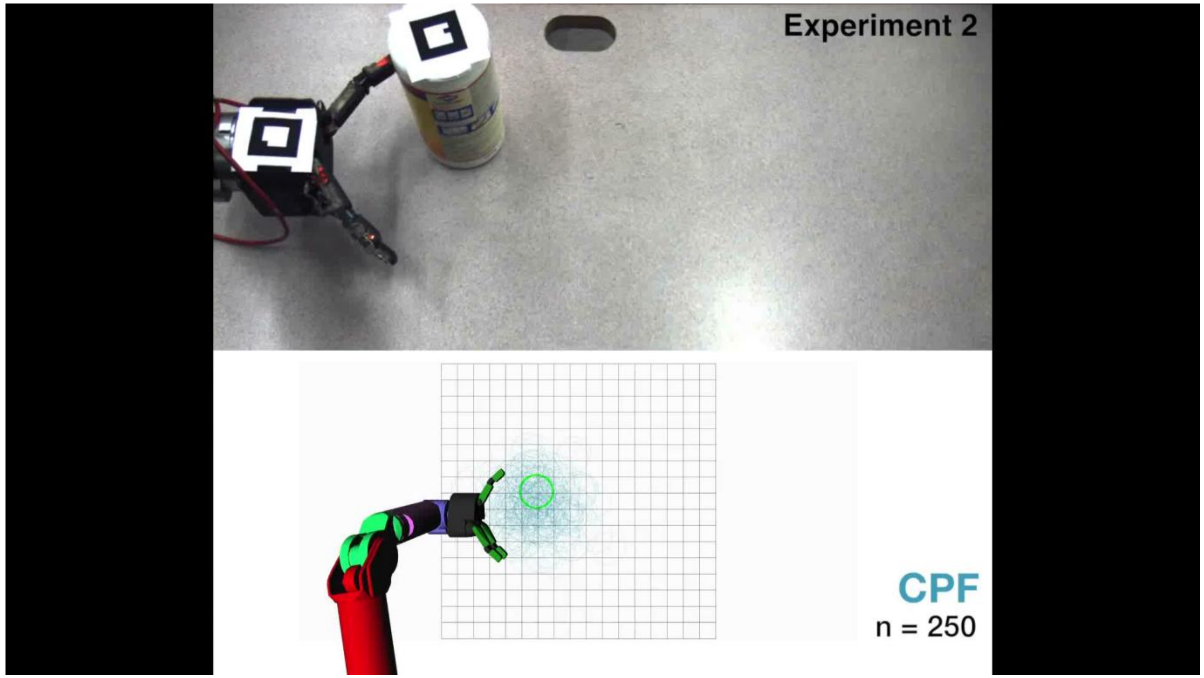
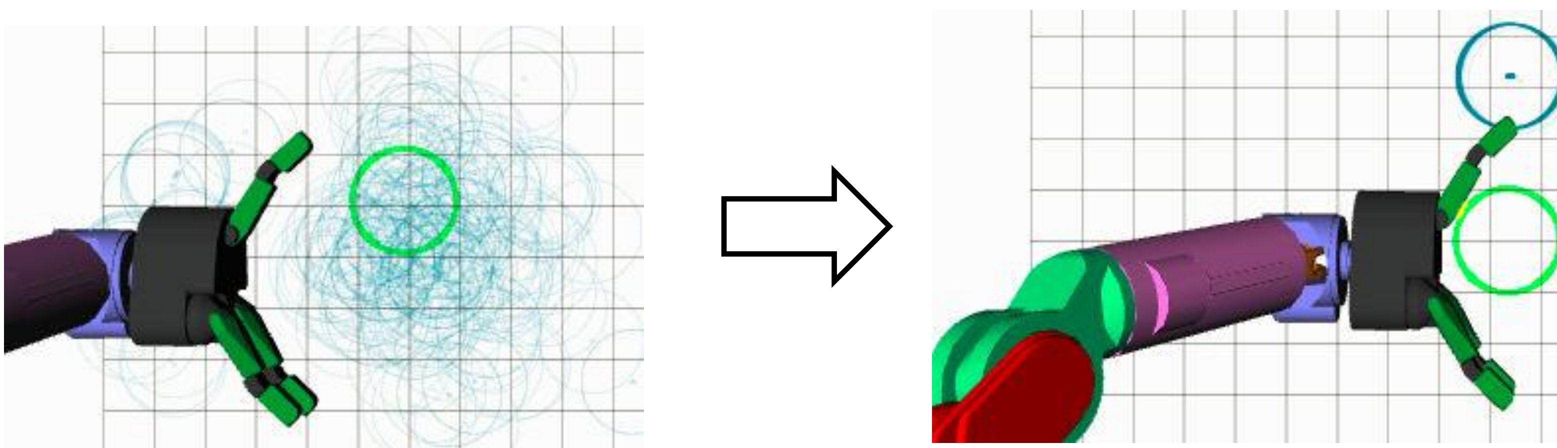


Divergent Convergent

 A. M. Johnson and D. E. Koditschek, *Toward a Vocabulary of Legged Leaping*, ICRA 2013.

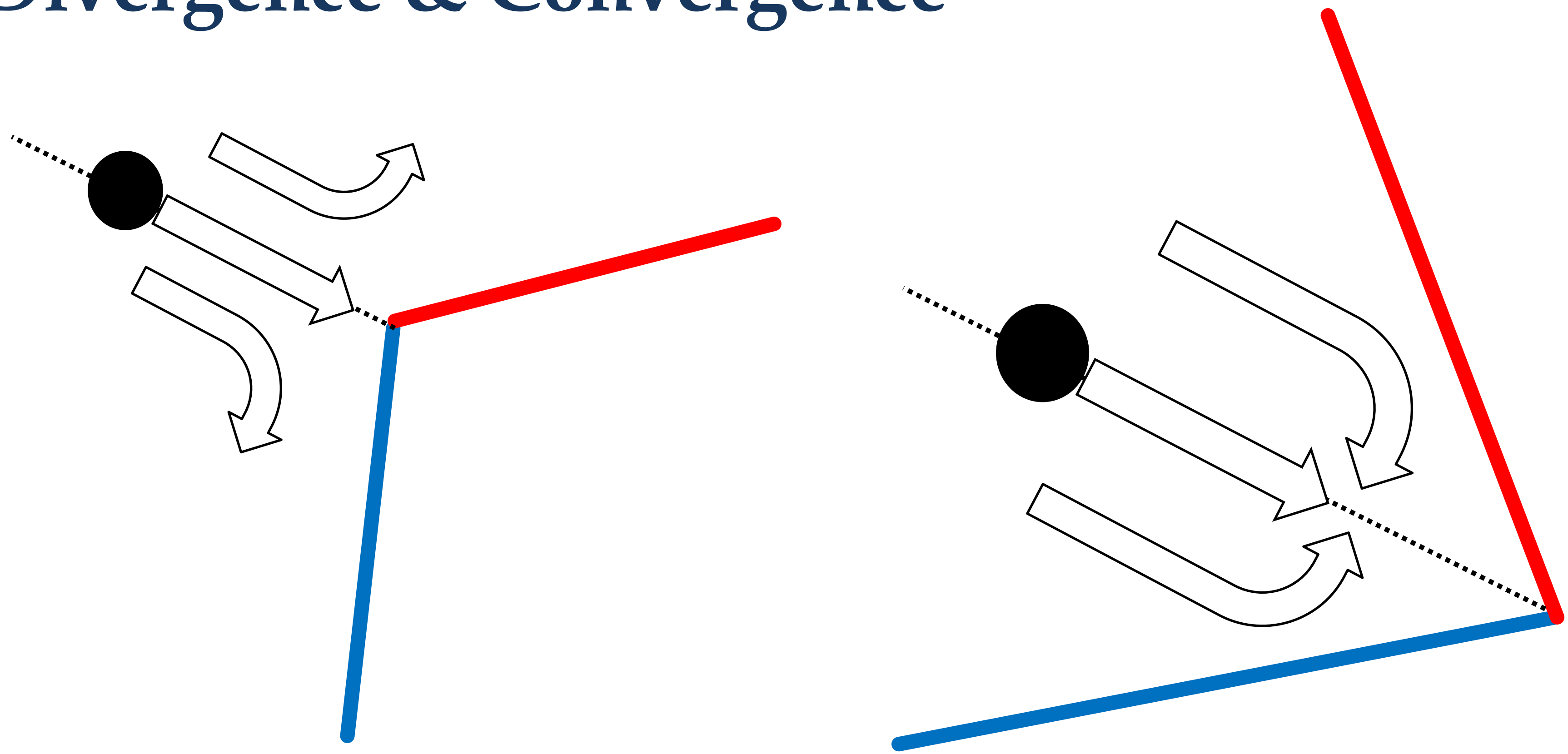
Manipulation Divergence





Michael Koval, Mehmet Dogar, Nancy Pollard, and Siddhartha Srinivasa. *Pose Estimation for Contact Manipulation with Manifold Particle Filters.* IROS 2013.

Divergence & Convergence



Divergent

Convergent

In general, what topological properties of contacts should we study?

Manipulation Challenges

Uncertainty, Cluttered Environment, Operational Speed, Power Limits

Jen King, Michael Koval, and Annie Holladay. *Robust Push Planning Under Uncertainty.*
https://www.youtube.com/watch?v=rQqoKncGdvg

Locomotion Challenges

Uncertainty, Cluttered Environment, Operational Speed, Power Limits

Carnegie Mellon University
THE ROBOTICS INSTITUTE
Penn
UNIVERSITY of PENNSYLVANIA

Summary of Differences
Between Manipulation and Self-Manipulation

- Motion of the joints results in the opposite object motion

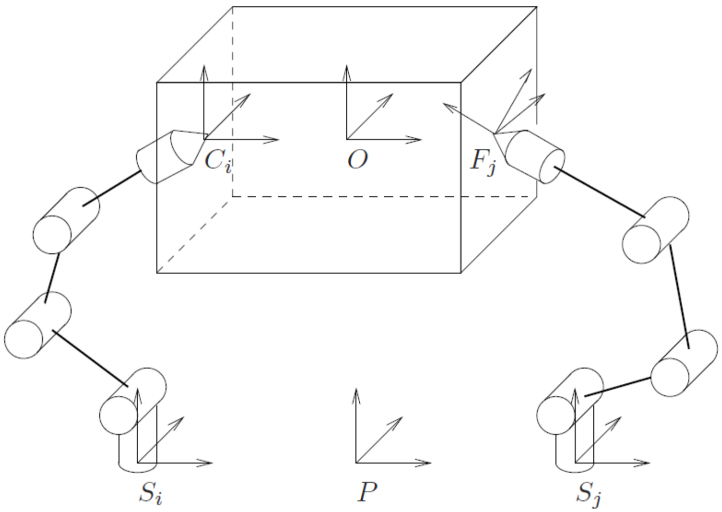
$$\mathbf{G}_s := -\mathbf{G}$$

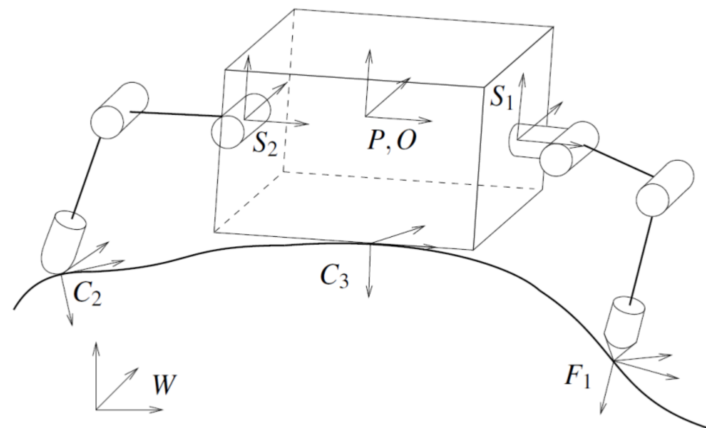
- The robot is the object, and so P is coincident with O
- Since the "palm" is accelerating, M and C are more complicated

$$\widehat{\mathbf{M}} := \begin{bmatrix} \sum_i \mathbf{J}^{bT}_{pl_i} \mathbf{M}_{l_i} \mathbf{J}^{b}_{pl_i} & 0 \\ 0 & \mathbf{M}_b \end{bmatrix}$$

$$\widehat{\mathbf{M}}_s := \begin{bmatrix} \sum_i \mathbf{J}^{bT}_{pl_i} \mathbf{M}_{l_i} \mathbf{J}^{b}_{pl_i} & \sum_i \mathbf{J}^{bT}_{pl_i} \mathbf{M}_{l_i} \mathbf{Ad}_{g^{-1}_{pl_i}} \\ \sum_i \mathbf{Ad}^{T}_{g^{-1}_{pl_i}} \mathbf{M}_{l_i} \mathbf{J}^{b}_{pl_i} & \mathbf{M}_b + \sum_i \mathbf{Ad}^{T}_{g^{-1}_{pl_i}} \mathbf{M}_{l_i} \mathbf{Ad}_{g^{-1}_{pl_i}} \end{bmatrix}$$

- Contact fames can only agree with either the finger or the object





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A. M. Johnson and D. E. Koditschek, *Legged Self-Manipulation,* IEEE Access, Vol 1, 2013

Conclusion

Challenges:

- Uncertainty
- Cluttered Environment
- Operational Speed
- Power Limits

Key question:

- Does contact topology help?

Thank you to my collaborators at Penn & CMU and my sponsors:

ARL/GDRS RCTA

DARPA M3 Seedling

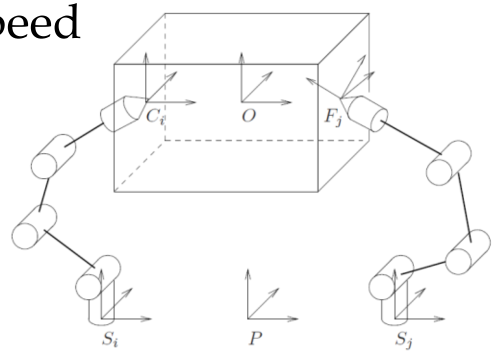
IC Postdoc Program

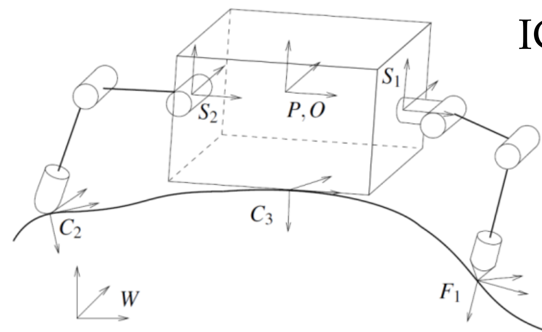
NSF CABIR

Boston Dynamics

SwRI

Toyota





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