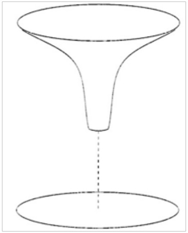
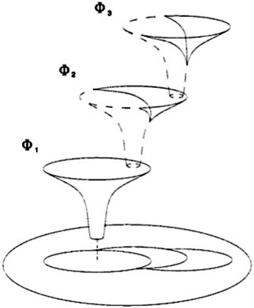
Sequential Composition: Back-Chaining Basins



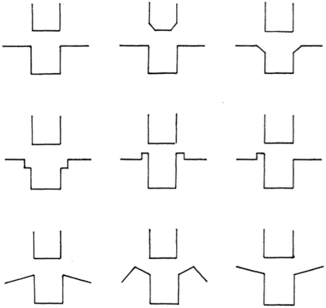


Burridge et.al. [1996]—Juggling obstacle avoidance

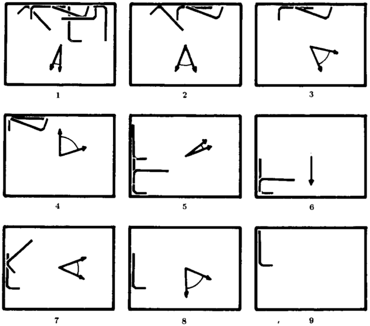
https://www.youtube.com/watch?v=NfdG8ZZdtgI

Sequential Composition: Examples from the Literature

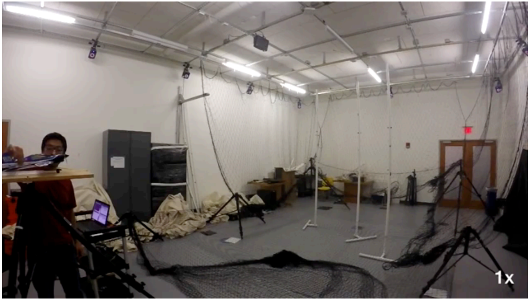
Lozano-Perez et. al. [1984]—peg in hole



Erdmann and Mason [1988]—sensorless tray tilting manipulation



Majumdar and Tedrake [2013]—Funnel libraries



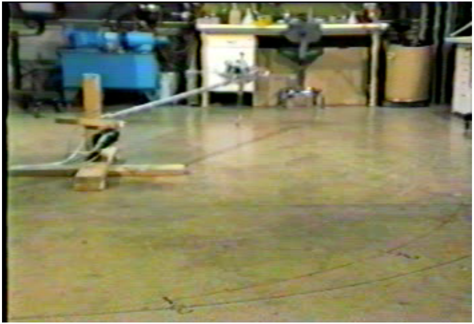
https://www.youtube.com/watch?v=cESFpLgSb50

Parallel Composition: Idea and Examples

Two juggle—Rizzi and Koditschek [1994]

Raibert [1986]

https://www.youtube.com/watch?v=u8I7EXXgTvk

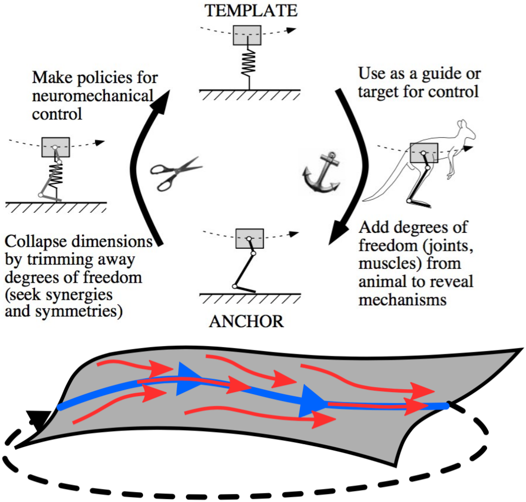


Summary

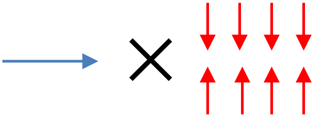
- Robot control can be thought of as flowing "downhill" on artificial energy functions
- Sequential composition formalizes a sequence of tasks using back-chaning of basins
  - Sequencing coarse manipulation: juggling to palming
  - Assembly tasks
  - ...
- Parallel composition describes satisfying multiple objectives at once
  - Controlling multiple DoFs for hopping etc.
  - Juggling two balls
  - ... (more coming in 4.2)

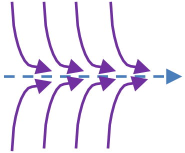
Templates and anchors (recap from 2.1)

From Full and Koditschek [1999]



Anchoring is a parallel composition!

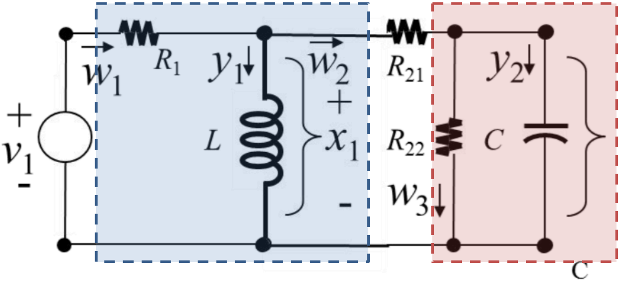


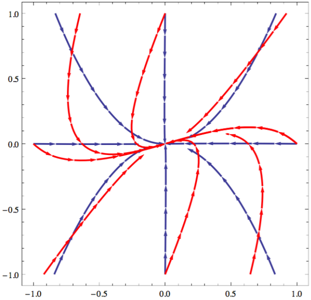


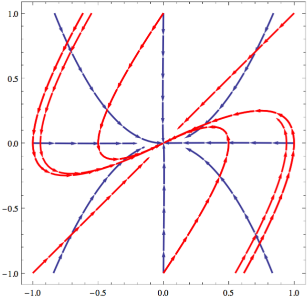
Template

Anchoring dynamics

Decoupled vs. coupled systems







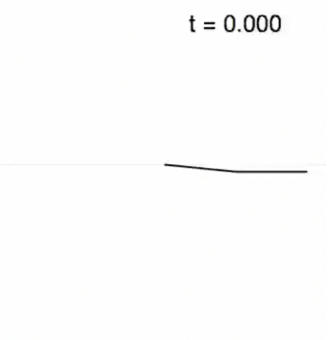
$R_{21} \to \infty$

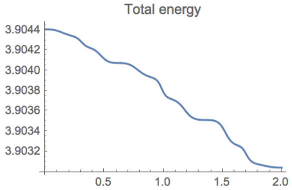
- Physical decoupling (circuit disconnected)
- Solutions decoupled (diagonal A)

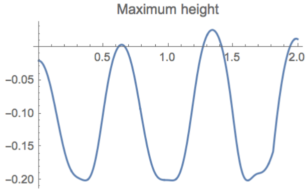
$$\dot{x} = Ax = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} x$$

Cross-talk in mechanical systems

- Double pendulum
- Controller is gravity + natural damping
- "Template:" decaying oscillator

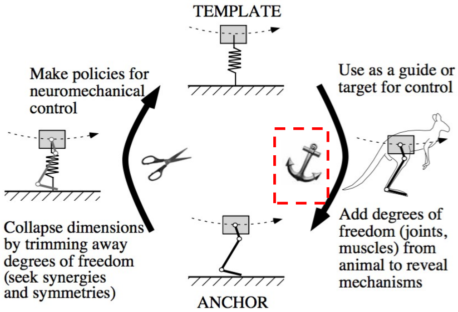


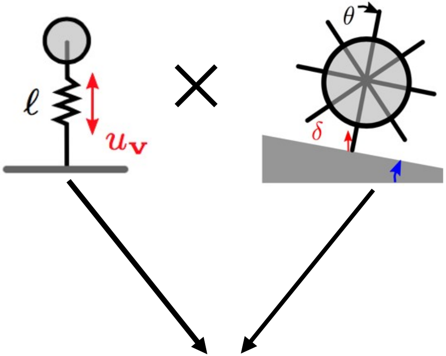


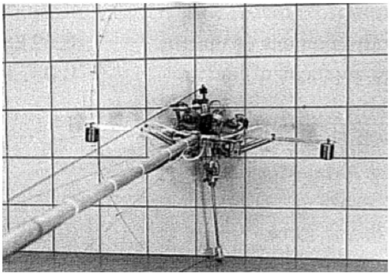


Synthetic view of anchoring

From Full and Koditschek [1999]



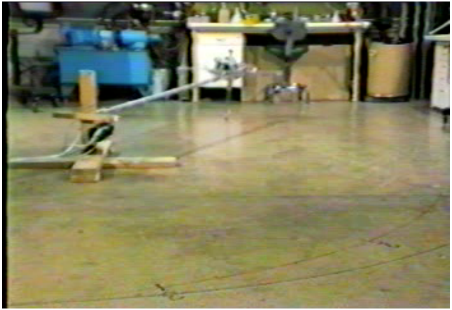




- Map *controllers* T → A
- Anchor multiple templates in parallel
- Decoupled controllers
- Conditions for correctness

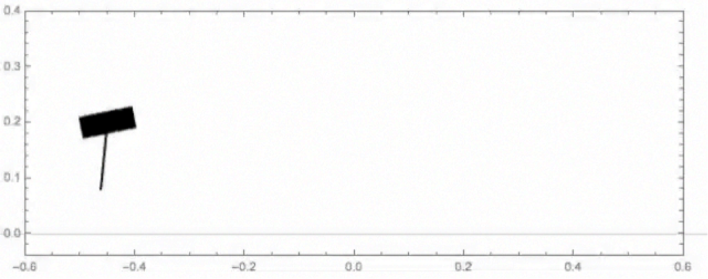
Empirical parallel compositions – Raibert hopper

From Raibert [1986]



Body:leg inertia

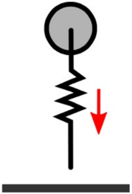
- 14:1 (Raibert)
- 7:1 (10 g)
- 1:1 (70 g)



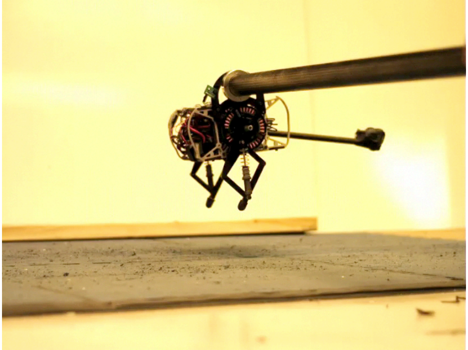
Summary

- On a high DOF robot, there is no alternative to thinking about either parallel composition, or preflexes
- Coupling forces try to screw us up
- Parallel composition = "anchoring multiple templates simultaneously with decoupled controls"
- Verification is important, but also difficult

Controlled 1DOF vertical hopper (VH)



- From De and Koditschek [2015b],



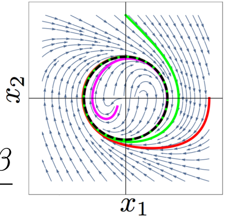
- Phase-energy EoM (De and Koditschek [2015a])

$$\dot{a} = \cos(\psi)u, \qquad \dot{\psi} = \omega - \frac{1}{\omega a}\sin(\psi)u$$

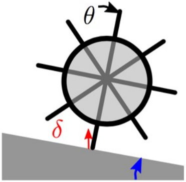
- Oscillatory energization, natural damping

$$u = (k - a\beta)\cos(\psi)$$

- On average (De and Koditschek [2015a]) $\dfrac{da}{d\psi} \overset{\text{avg}}{=} \dfrac{k - a\beta}{2}$



Controlled 1DOF Active Rimless Wheel

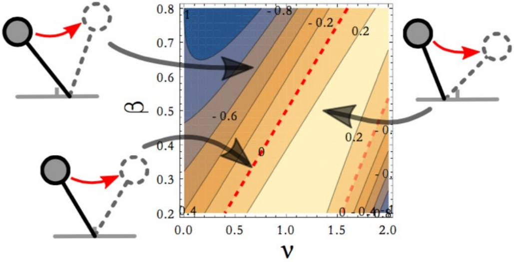


- Rimless wheel (McGeer [1990])
- Add liftoff impulse
- *Simplistic view:*

$$F(a_{\mathrm{LO}}) = a_{\mathrm{LO}} + \gamma$$
$$R(a_{\mathrm{TD}}) = \delta a_{\mathrm{TD}},\ 0 < \delta < 1$$
$$P(a) = \delta(a + \gamma)$$

- Equivalent to stepping (Raibert [1986])

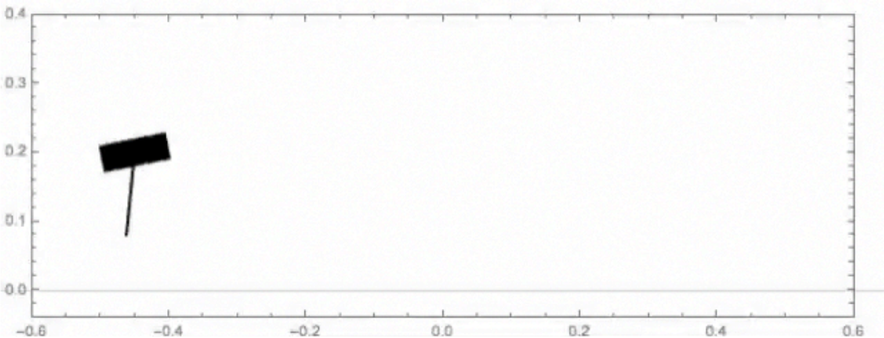
From De and Koditschek [2015a],



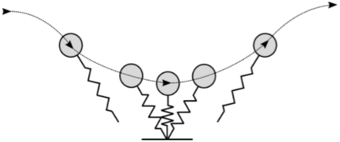
Bhounsule et al. [2012]

SLIP as a composition

Clearly works in practice



SLIP as a composition—verification



- Does SLIP anchor a VH?
- i.e. the dynamics are "the same" on an invariant (attracting) submanifold—Full and Koditschek [1999]
- Radial stance dynamics: $m\ddot{r} = -\nabla\varphi(r) - g\cos\theta - r\dot{\theta}^2$
- Say $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} := \begin{bmatrix} r \\ \dot{r} \end{bmatrix}$
- Then

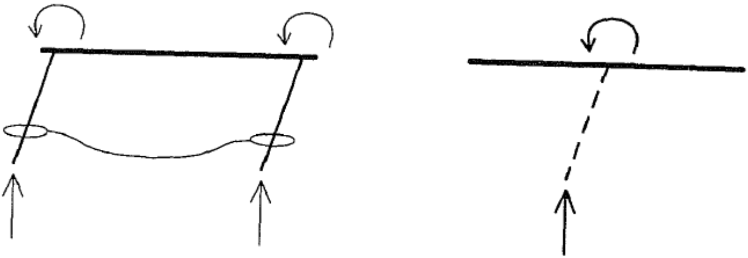
$$f(x) = \begin{bmatrix} x_2 \\ -\nabla\varphi(x_1) - g\cos\theta - x_1\dot{\theta}^2 \end{bmatrix} \qquad f_{\mathrm{VH}}(x) = \begin{bmatrix} x_2 \\ -\nabla\varphi(x_1) - g \end{bmatrix}$$

- Clearly $f\big|_{\theta=0,\dot{\theta}=0} = f_{\mathrm{VH}}$
  …but not otherwise
- New research: $\bar{f} \sim \bar{f}_{\mathrm{VH}}$ —De and Koditschek [2015a]

Summary

- SLIP can be decomposed
- A vertical hopper can be controlled by active damping
- A rimless wheel can be controlled with active liftoff impulse
- SLIP as a composition empirically works
- But exact anchoring cannot be shown in general

Virtual leg

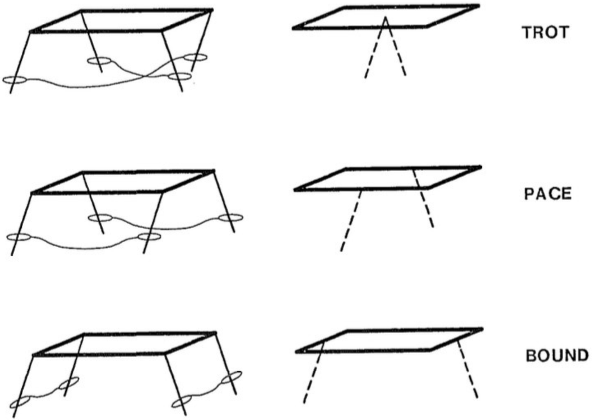


- From Raibert [1986]

- Intra-group control
  - Toe positioning (flight)
  - Touchdown synchronization
  - Virtual hip positioning (stance)

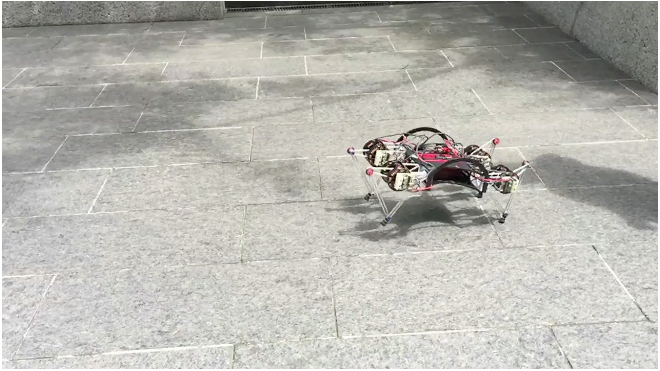
- Inter-group control

Virtual bipeds (trot, bound, pace)

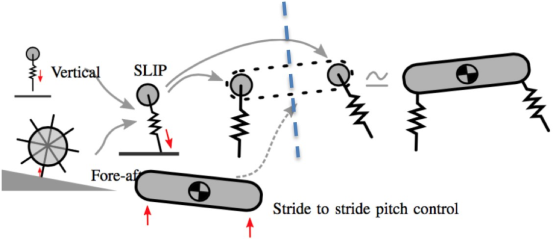


- From Raibert [1986]
- Control action "mirrored," repeated step-to-step
- Location of virtual hip
- Move using internal forces in stance

Minitaur bounding



Pitch coordination: antiphase

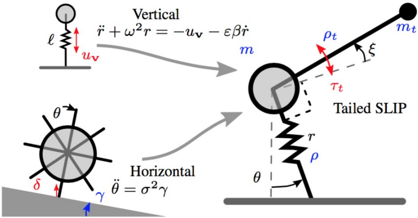


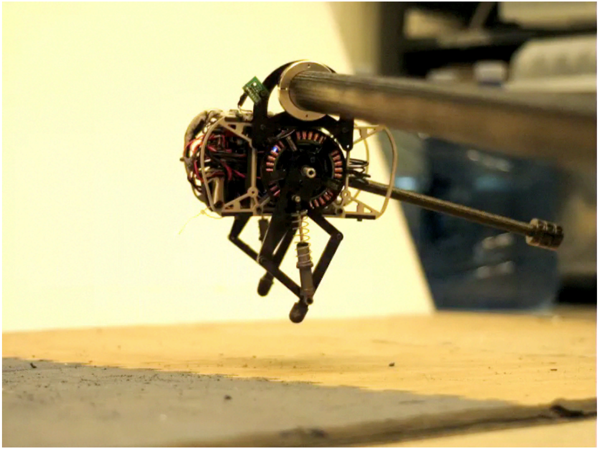
Summary

- Multilegged robots can be controlled as compositions of monopeds
- Virtual legs allow you to think of groups of legs as a single leg
- A virtual biped with a leg-to-leg symmetric control action is a composition of identical monopeds
- Phase coordination can be active or passive

Jerboa planar hopping

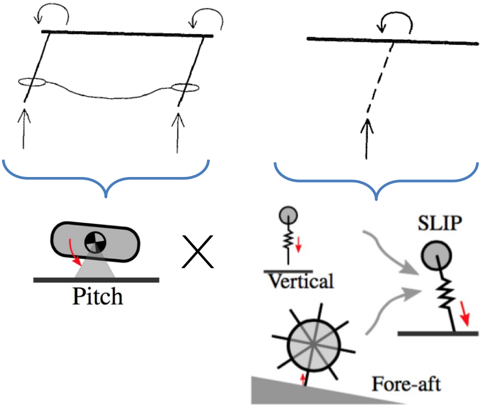
- Tail-instantiated vertical hopping—De and Koditschek [2015a,b]

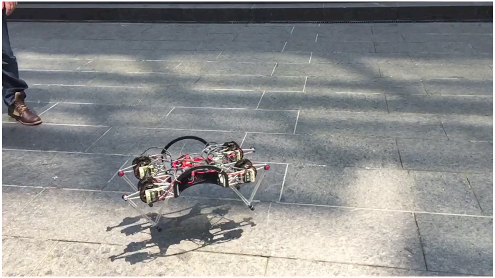




Minitaur pronking

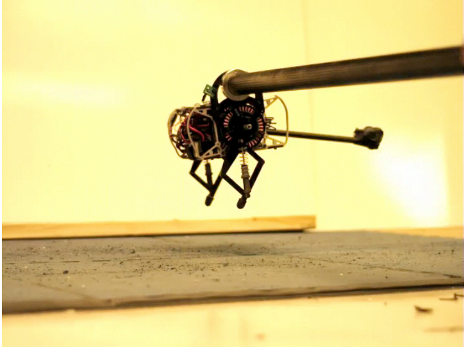
- Monoped control: SLIP as parallel composition (same controllers as Jerboa)
- Intra-group synchronization ≈ attitude control

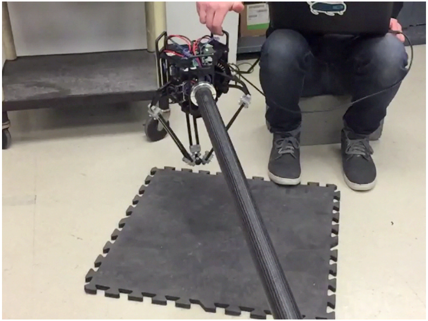


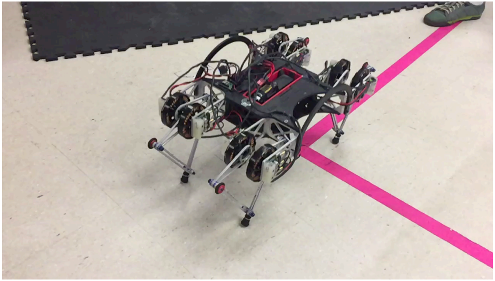


https://www.youtube.com/watch?v=iligVlcxwps

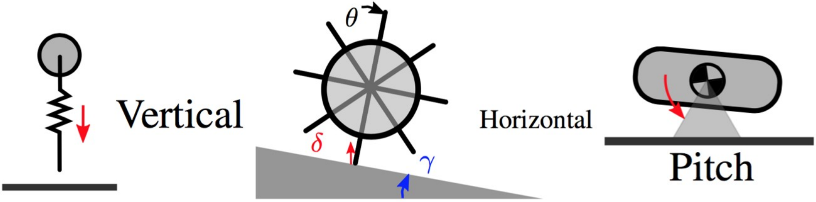
Reuse

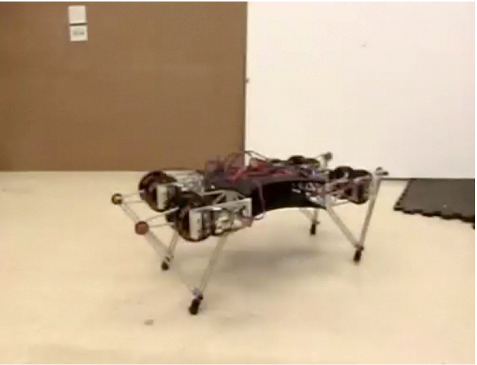


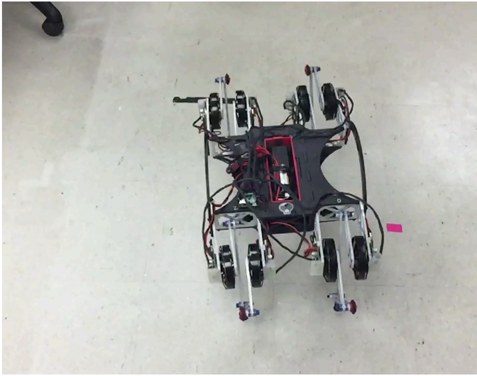




Generate







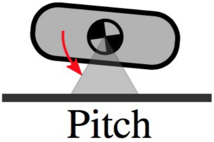
Where do compositional techniques lie?

	Holistic	Compositional
Stability guarantees	Methods exist	Not yet, but progress e.g. De and Koditschek [2015a]
Underactuation	Principled methods exist (but need very good models)	✗
Optimality guarantees	Possible	✗
Modeling/calibration	Must be precise	Can be crude
Controller synthesis (e.g. optimization dims)	(n inputs, n outputs) = x^n	(1 input, 1 output) x n = n
Reuse	✗	✓
Generate	✗	✓

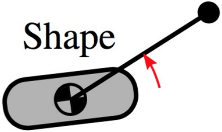
Summary

- A compositional approach to synthesis allows us to reuse templates on different robots
- …and also the generate new combinations

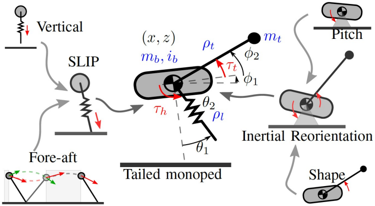
Attitude control templates



Inertial reorientation Johnson et al. [2012]

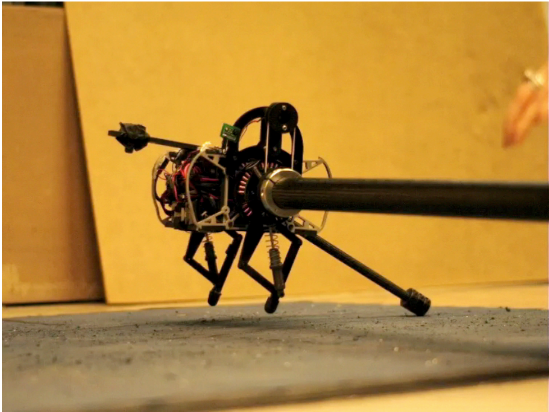


Four-way composition for tail-energized planar hopping

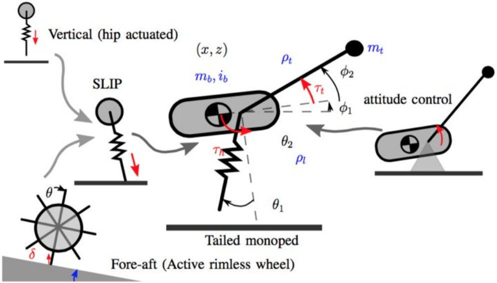


From De and Koditschek [2015b]

Experiments WIP

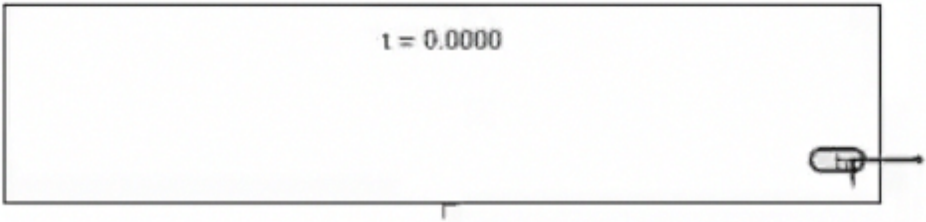


Hip-energized planar hopping



Alternate solutions

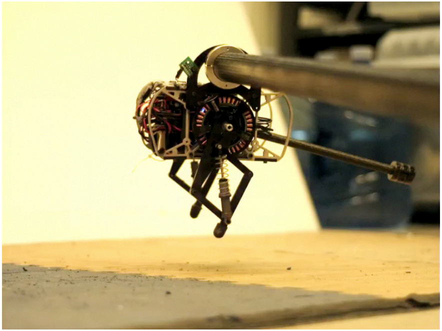
- Trade-off: speed vs. traction
- Morphological reduction (Libby et al. [2015])—constraint on CoM location

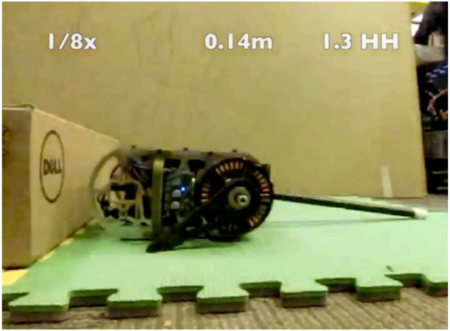


Summary

- We can have different *anchorings* for the same *templates*
- Can be thought of as "alternate solutions" for the same behaviors
- Allow freedom to select the most efficient/most robust/etc. for the specific operating conditions

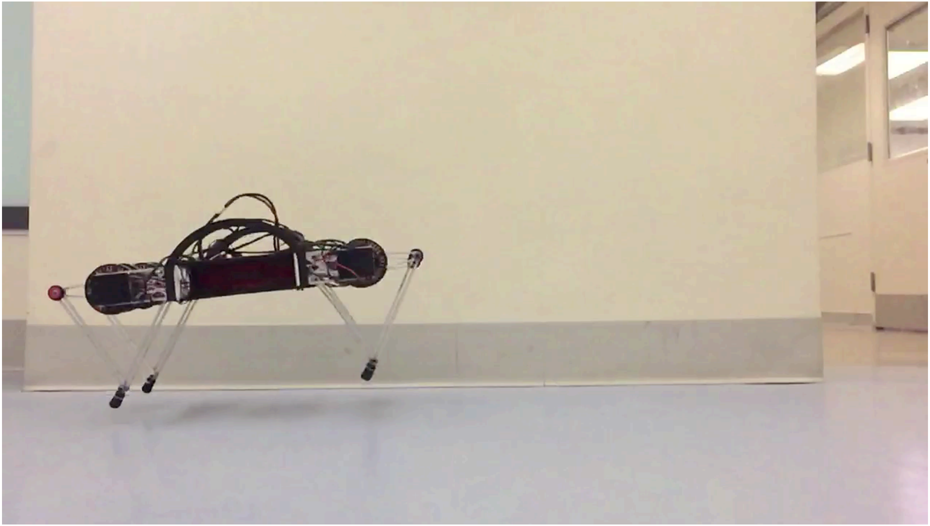
Hybrid self-manipulation systems



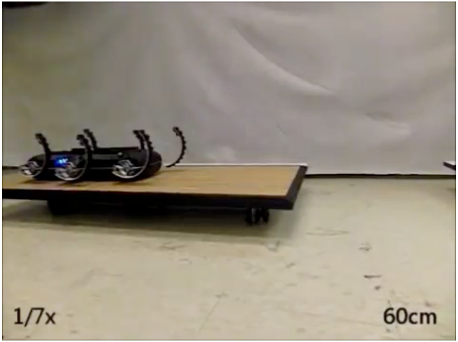


Johnson et al. [2015], Burden et al. [2015].

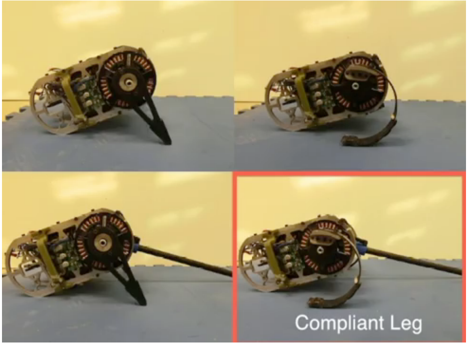
Minitaur leaping



RHex and Jerboa leaping



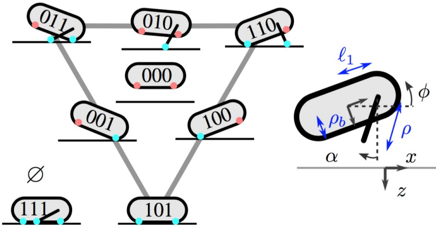
https://www.youtube.com/watch?v=kV9J-oayCBU



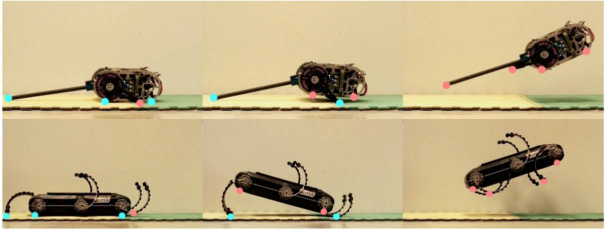
https://www.youtube.com/watch?v=0p-ye6bSqbc

From Johnson and Koditschek [2013], Brill et al. [2015],

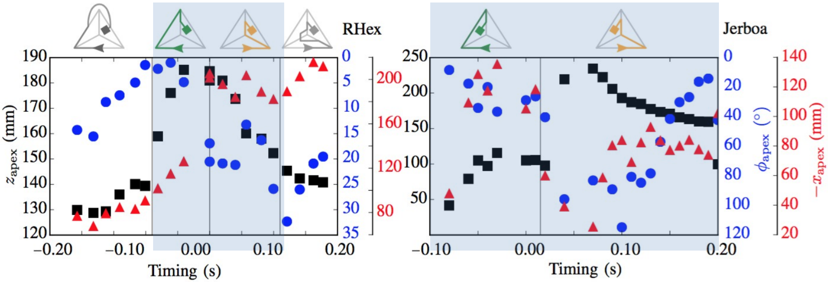
- Hybrid system with many modes, simultaneous transitions
- Organize into "ground reaction complex"



Leaping: stability and convergence



When do RHex, Jerboa leap "the same"?—Brill et al. [2015]



Summary

- Transitions go through various hybrid modes
- Some transitions are nicer than others
- Minitaur leaps using parallel composition
- RHex and Jerboa leap using the ground reaction complex