

edX Robo4 Mini MS – Locomotion Engineering

Week 1 – Unit 1

Big Picture and Motivation

Video 1.1

Segment 1.1.1

Overview of the Course

Daniel E. Koditschek

with

Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos

University of Pennsylvania

September, 2017

Week1 – Big Picture & Motivation

- Legged Mobility

- an emerging area of robotics
- increasing commercial activity
- still under active development

GHOSTROBOTICS

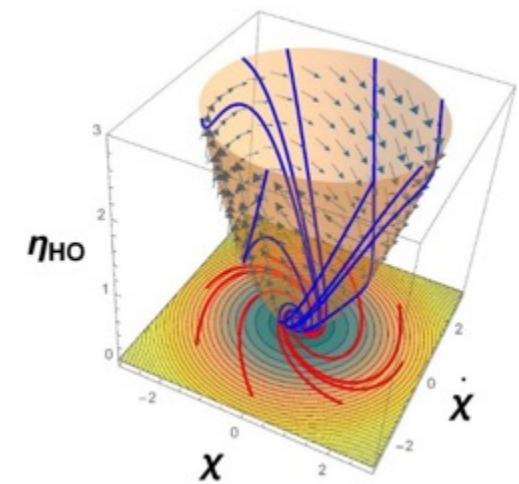
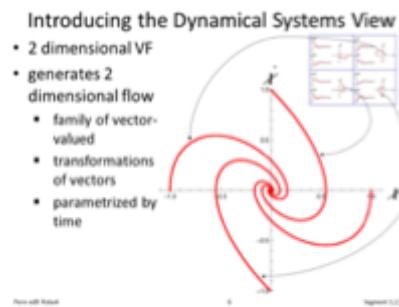
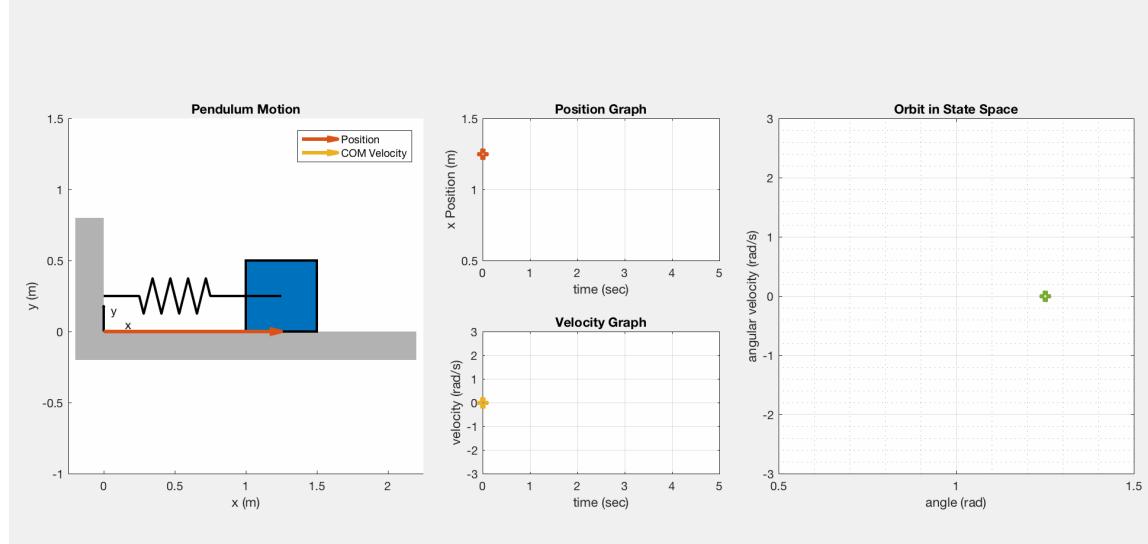
- Focus on Foundations

- principled bioinspiration
- underlying physics & math
- emerging engineering theory
- application to successively more realistic simulation models

A. De and D. E. Koditschek, “Averaged anchoring of decoupled templates in a tail-energized monoped,” in *Robotics Research*, Springer, 2018, pp. 269–285.

Week 2 – 1 DoF Prismatic Mechanics

- Linear spring-mass-damper physics
- Dynamical systems theory
 - vector fields
 - flows
 - change of coordinates
- Energy, power, basins

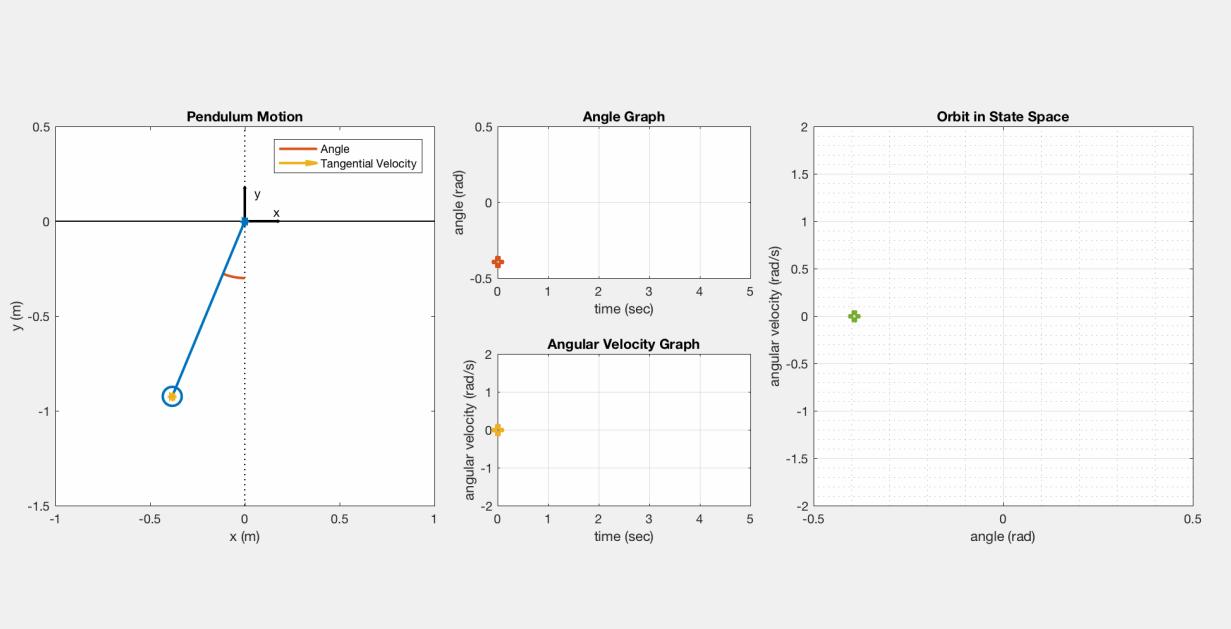


Week 3 – 1 DoF Revolute Mechanics

- Pendulum Dynamics

- Energy
 - conservation laws
 - qualitative theory

- Stability



Need a Qualitative Theory

- Damped Harmonic Oscillator
 - LTI: closed form solutions
 - total energy: norm-like
 - an explicit norm
 - in the "right" coordinates
 - yields scalar LTI energy ODE
- Damped Pendulum
 - NLTI: no closed form solutions
 - total energy: sometimes norm-like
 - what is the "norm-like" property?
 - how to get rigorous conclusions without a scalar ODE?

$$\tilde{\eta}_{HO}(\mathbf{y}) = \frac{1}{2} \|\mathbf{y}\|^2$$

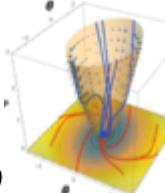
$$\dot{\tilde{\eta}}_{HO} = \sigma \tilde{\eta}_{HO}$$

$$\begin{aligned} \eta_{DP}(\mathbf{q}) &= \frac{m\ell^2}{2} \dot{\theta}^2 \\ &\quad + mgl \sin \theta \\ \dot{\eta}_{DP}(\mathbf{q}) &= -b \dot{\theta}^2 \\ &\quad ? \\ &\quad \neq \text{func}(\eta_{DP}) \end{aligned}$$

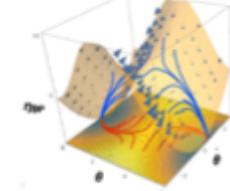
Segment 1.2.2.b

Simulations Suggest What's Happening

- total energy at "bottom"
 - level curves enclose neighborhoods (norm-like)
 - stable FP
 - with basin of attraction

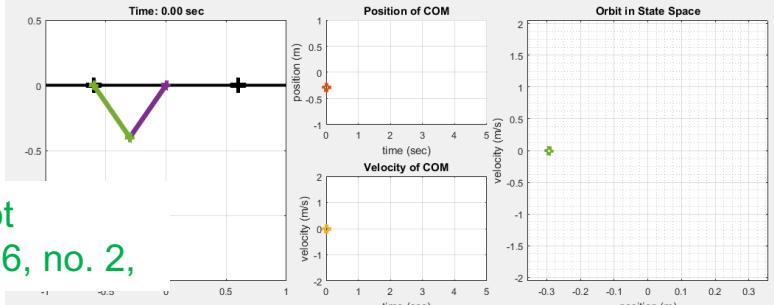
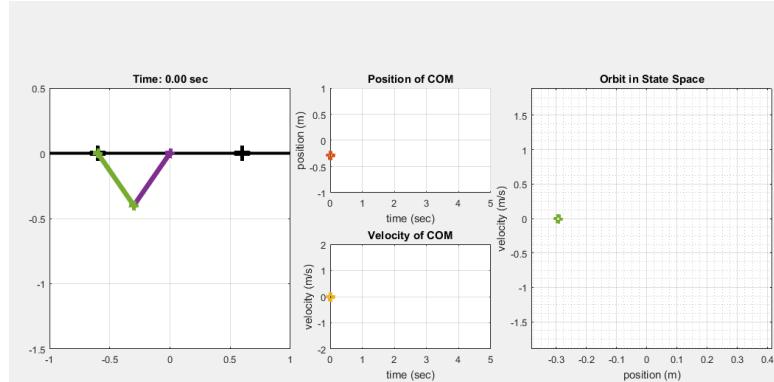


- total energy at "top"
 - level curves run off
 - unstable FP
 - no basin



Week 4 – Project #1: Brachiating Robot

- Numerical study of early “ape-inspired” robot
- Warm up intuition for higher DoF nonlinear systems
 - 2 DoF RR dynamics are highly nonlinear and chaotic
 - need only 1 actuator to “force” 1 DoF prismatic behavior



J. Nakanishi, T. Fukuda, and D. E. Koditschek, “A brachiating robot controller,” *Robotics and Automation, IEEE Transactions on*, vol. 16, no. 2, pp. 109–122, 2000.

Week 5 – Dynamical Systems Theory

• Normal form theory

- Taylor series approximation
 - constant (“flowbox” theorem)
 - linear (“hyperbolicity” theorem)
- Linearization: normal form near a fixed point

• Lyapunov theory

- generalized energy as a metric
- generalized power as a stability criterion

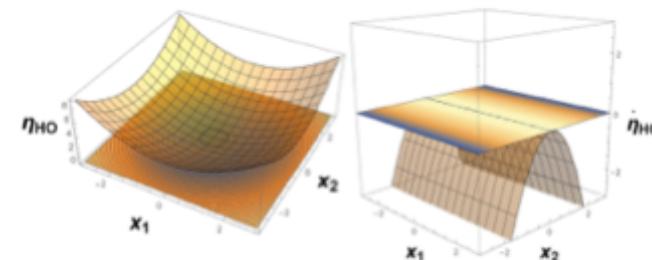
Conditions for FP Normal Form: Vectors

- But for VF to have LTI normal form at vector FP x_e
- need more than simply $F(x_e) := D_x f(x_e) \neq 0$
- e.g. $\dot{\mathbf{y}} = f_{\text{NLRC}}(\mathbf{y}) := \begin{bmatrix} \|\mathbf{y}\|^2 & -1 \\ 1 & \|\mathbf{y}\|^2 \end{bmatrix} \mathbf{y}; \quad \mathbf{y}_e := 0$
 $F_{\text{NLRC}}(\mathbf{y}_e) := D_y f_{\text{NLRC}}(\mathbf{y}_e) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} =: J \neq 0$
- hence linearized VF cannot be conjugate
 $\hat{f}_L(\mathbf{y}) := F_{\text{NLRC}}(\mathbf{y}_e)\mathbf{y} \not\sim f_{\text{NLRC}}(\mathbf{y})$
- because, e.g., $\eta(\mathbf{y}) := \|\mathbf{y}\|^2/2 \Rightarrow$
 $\dot{\eta}_L(\mathbf{y}) = D_y \eta \cdot f_L(\mathbf{y}) = \mathbf{y}^T J \mathbf{y} \equiv 0$
vs $\dot{\eta}(\mathbf{y}) = D_y \eta \cdot f_{\text{NLRC}}(\mathbf{y}) = 8\eta(\mathbf{y})^{3/2}$
 - so η grows without bound along flow of f_{NLRC}
 - whereas it is constant along flow of f_L

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Segment 1.2.3.1.b

PD and NSD Quadratic Forms



$$\begin{aligned}V(x) &= \eta_{\text{HO}}(x) \\&= \frac{1}{2}mx_2^2 + \frac{1}{2}kx_1^2 \\&= \frac{1}{2}\left\|\begin{bmatrix}\sqrt{k}x_1 \\ \sqrt{m}x_2\end{bmatrix}\right\|^2\end{aligned}$$

$$\begin{aligned}\dot{V}(x) &= \dot{\eta}_{\text{HO}}(x) \\&= -bx_2^2 \\&= -\left\|\begin{bmatrix}\sqrt{b}x_1 \\ \sqrt{m}x_2\end{bmatrix}\right\|^2\end{aligned}$$

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Segment 1.2.3.2.b

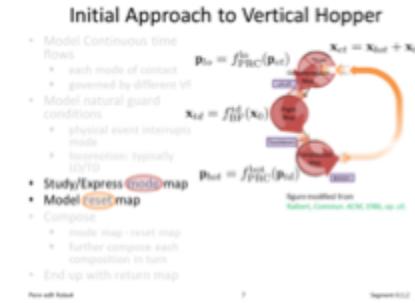
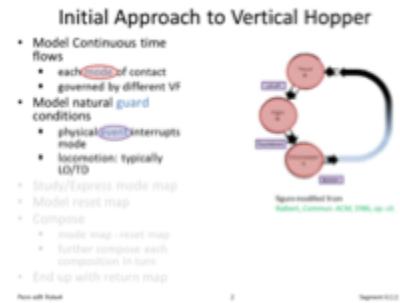
Segment 1.1.2

Week 6 – Raibert's Vertical Hopper

- Core
“heartbeat” of
Raibert’s
pioneering
legged runners
- Develop vector
fields for each
mode
- Derive flows for
each mode

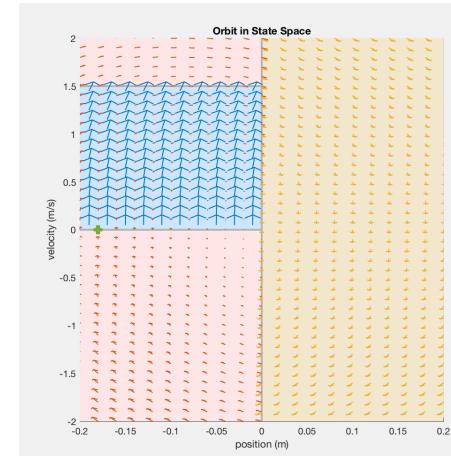
video from:

Plastic Pals. “Robots from MIT's Leg Lab”. YouTube video,
02:28. Posted [October 31, 2011].
<https://www.youtube.com/watch?v=XFXj81mvInc>



Week 7 – RVH as Hybrid Mechanical System

- Hybrid Dynamical System
 - different contact modes
 - and transitions between them
- Derivation of Poincare' Map
 - state of next hop
 - as function of previous
- Gait Stability Analysis
 - fixed point analysis
 - linearization yields insights
 - when will Raibert-controller work
 - what might go wrong



Steady state gait representation

- Periodic hopping orbit
 - a cycle in steady state limit
 - called **limit cycle**
 - "parallel" direction to flow
 - very little change
 - per flow box theorem
- Behavior summarized by
 - one dimensional **section**
 - "transverse:" flow cuts across
 - "return:" flow brings section back
 - no unique choice of **section**
 - stance bottom state
 - flight apex state
 - touchdown state
 - liftoff state
 - flow takes one section to next
 - represented by mode maps
 - each a CC between sections (uniqueness)

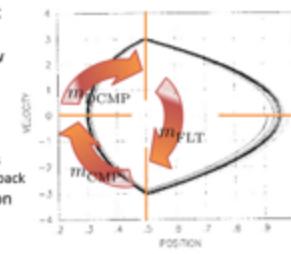


figure from
D. E. Koditschek and M.
Büller, International Journal
of Robotics Research, op. cit.

Segment 6.2.2

Poincare' Map: Bottom Coordinates

- Bottom coordinates $\rho := \omega^2(1 + \beta^2)\chi^2$
 - total energy at maximum compression
 - measures spring potential
- Poincare' map $\rho_{k+1} = PRVH(\rho_k)$
 - expresses next bottom energy
 - as function of previous bottom energy

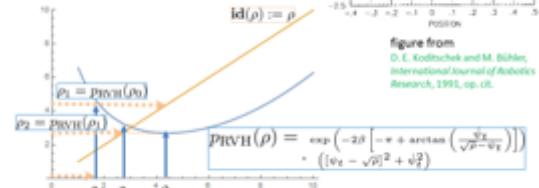
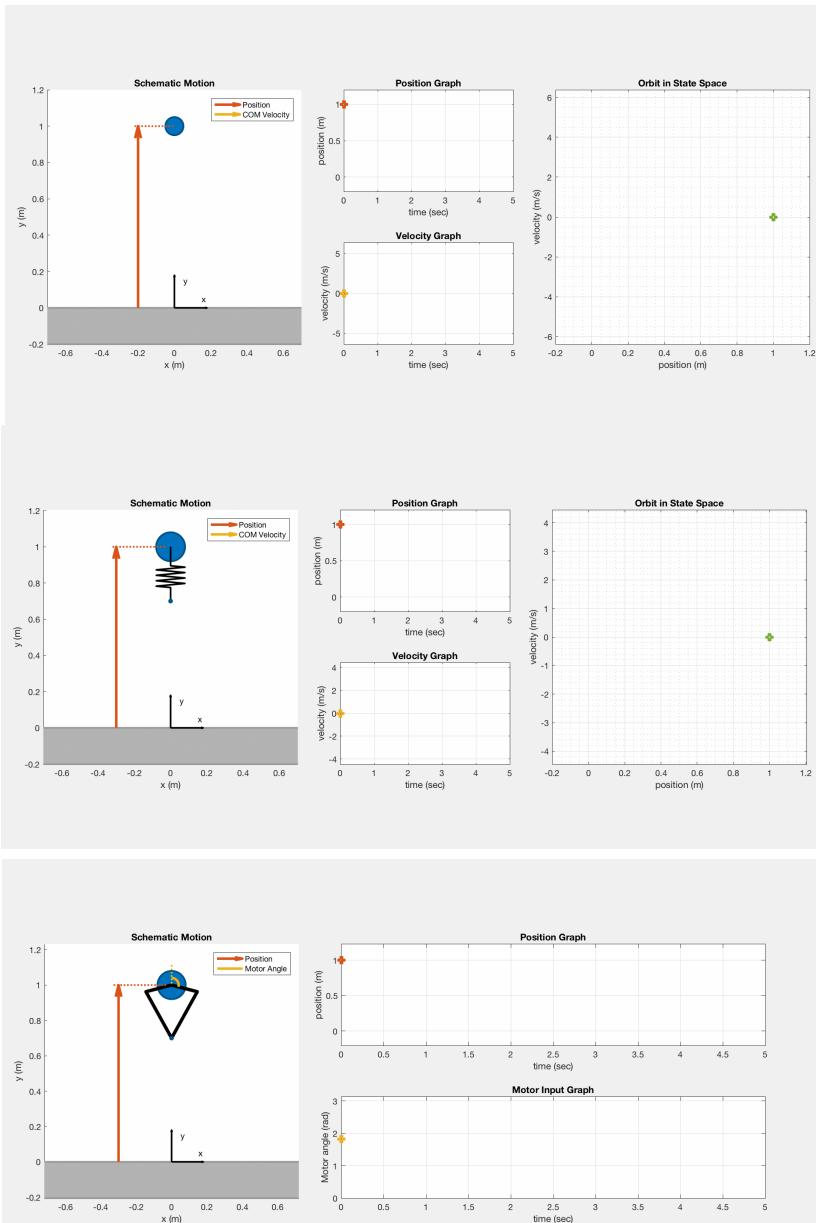


figure from
D. E. Koditschek and M.
Büller, International Journal
of Robotics Research, op. cit.

Segment 6.3.2

Week 8 – Project #2: Raibert Vertical Hopper

- Progression of computational models
 - 1 DoF hybrid dynamics
 - work with all the theoretical ideas developed so far
- Increasing mechanical complexity
 - bouncing Ball
 - Raibert Vertical Hopper
 - motor-actuated, linkage-anchored RVH



Week 9 – Spring Loaded Inverted Pendulum

- Bioinspiration: animals as pogo sticks
- Fundamental problem
 - Poincare' map
 - stride control systems model
 - entails closed form flow
 - Pogo sticks
 - coupled nonlinear 2 DoF systems
 - formally non-integrable

- The way forward
 - lossless central force approximation
 - 2 conserved quantities yield closed form flow expressions

Animals Run Like Pogo-sticks

- Biologists discovered
 - all running animals
 - exhibit pogo-stick dynamics

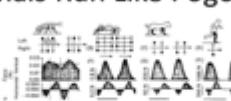


figure from:
R. J. Full, "Concepts of efficiency and economy in land locomotion," in *Efficiency and Economy in Animal Physiology*, R. W. Blake, Ed., Cambridge University Press, 1999, pp. 97–131.

- They used
 - the simplified dynamics
 - to classify
 - animal gait parameters

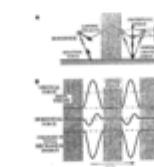


figure from:
R. J. Full and C. T. Farley, "Similarity in multilegged locomotion: Bouncing like a monopode," *Journal of Comparative Physiology A: Sensory, Neural, and Behavioral Physiology*, vol. 173, no. 5, pp. 509–517, 1993.

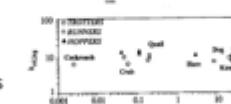
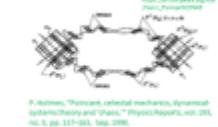


figure from:
R. J. Full and C. T. Farley, "Musculoskeletal dynamics in rhythmic systems: a comparative approach to legged locomotion," in *Biomechanics and neural control of posture and movement*, J. M. Winters and P. Crago, Eds. Springer, 2000, pp. 192–205.

Segment 8.0.1

Addressing A Fundamental Road Block

- Problem: fore-aft DoF is coupled in stance
 - pinned toe becomes revolute joint
 - bioinspired running models have compliant shank
 - both polar DoFs contribute to speed
- Nonlinear 2 DoF Systems
 - Generally Non-Integrable
 - flows become "chaotic"
 - no closed form integrals can exist
 - Historical Precedent
 - find closed form approximations
 - this week: ignore stance gravity



Segment 8.0.2

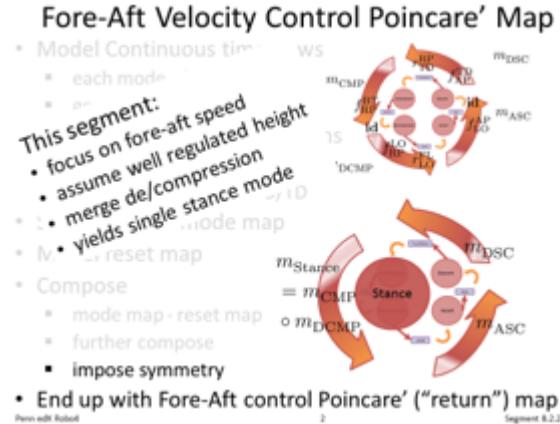
Closed Form 0-Grav Approximation

- What does it mean to be "integrable"
 - Math/physics: reduction to "elliptic" integral
 - Robotics/control: need closed form analytical expression
- In general, need further approximation of integrals
- For purposes of this course, pick special spring law
 - air spring from vertical hopper unit (max. extension χ)
 - $\varphi_{AS}(q_X) := \frac{1}{2} k \left(\frac{1}{q_X^2} - \frac{1}{\chi_l^2} \right) \Rightarrow \Phi_{AS}(q_X) := -D \varphi_{AS}(q_X) = \frac{1}{q_X^3}$
 - yields closed form expressions for elliptic integrals, hence flow: (branch selected by compression or decompression mode)

$$\begin{bmatrix} t(q_X) \\ q_\theta(q_X) \\ p_X(q_X) \\ p_\theta(q_X) \end{bmatrix} = \begin{bmatrix} t_0 + \frac{\mu q_{\theta 0}^2}{p_{\theta 0}^2 + \mu k + q_{X 0}^2 p_{X 0}^2} [q_X p_X(q_X) - q_{X 0} p_{X 0}] \\ q_{\theta 0} + \frac{p_{\theta 0}}{\sqrt{p_{\theta 0}^2 + \mu k}} \arccot \left[\frac{p_{\theta 0}^2 + \mu k + q_{X 0} p_{X 0} q_X p_X(q_X)}{\sqrt{p_{\theta 0}^2 + \mu k} [q_X p_X(q_X) - q_{X 0} p_{X 0}]} \right] \\ \pm \left[p_{X 0}^2 + \frac{(p_{\theta 0} + \mu k)(q_X^2 - q_{X 0}^2)}{q_X^2 q_{X 0}^2} \right]^{\frac{1}{2}} \\ p_{\theta 0} \end{bmatrix}$$

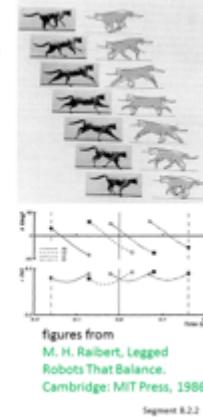
Week 10 – SLIP Stepping Controllers

- Closed form expression for stepping control model



Introducing Symmetry

- Raibert identified the importance of symmetry
 - apparent forward-reverse time similarity
 - in animals and machines
- Time reversal symmetry
 - deep, important idea in Physics
 - lossless systems are reversible
 - "time's arrow" due to dissipation
 - growing insights for locomotion
 - SLIP model: "piecewise Hamiltonian"
 - generally: non-conservative effects play a "merely perturbative" role



Conditions for FP Stability

- Compute linearized dynamics at FP

$$P_F(\mathbf{x}^*) := D_{\mathbf{x}F}(\mathbf{x}^*) = I_2 + ab^T$$

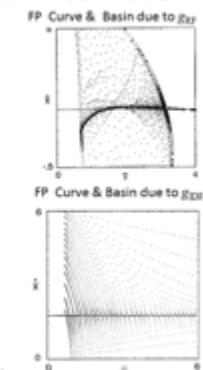
$$a := \begin{bmatrix} 2k\dot{b}_x^* \sqrt{\dot{b}_y^* - \chi_\ell \sin g_F(\mathbf{x}^*)} - \chi_\ell \cos g_F(\mathbf{x}^*) \\ -\frac{1}{k}\sqrt{\dot{b}_y^* - \chi_\ell \sin g_F(\mathbf{x}^*)} \end{bmatrix}$$

$$b^T := D_{\mathbf{x}}\bar{g}_F(\mathbf{x}^*)$$
- So eigenvalues of $P_F(\mathbf{x}^*)$ are $\lambda_1=1, \lambda_2=1+a^T b$
 - degeneracy: was inevitable
 - physically: total energy conserved; each energy IC has own FP
 - mathematically: unity eigenvector is tangent to $\bar{g}_F^{-1}(\pi)$
 - use Center Manifold Thm.
 - to show $0 > a^T b > -2 \Rightarrow |\lambda_2| < 1$
 - implies local attraction to FP curve of apex states in $\bar{g}_F^{-1}(\pi)$

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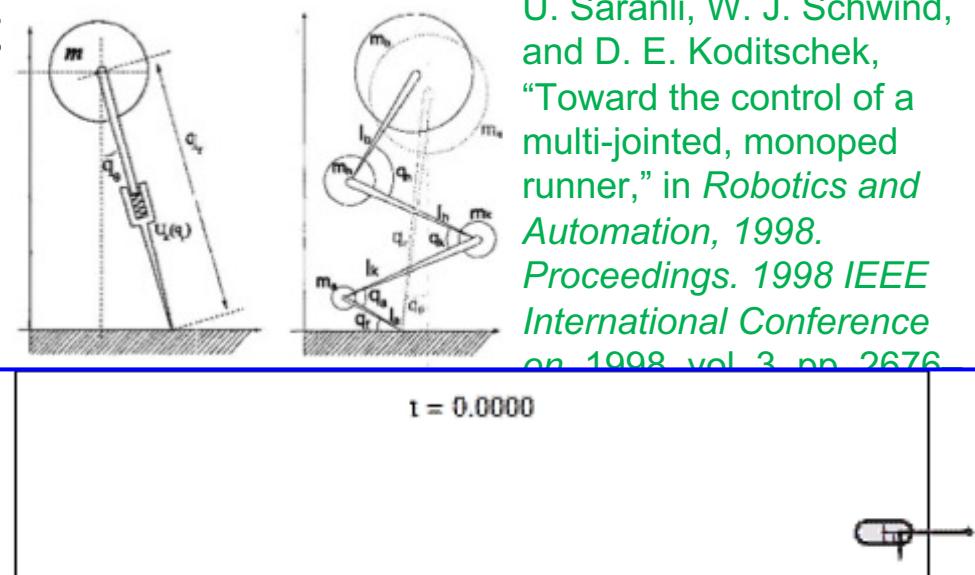
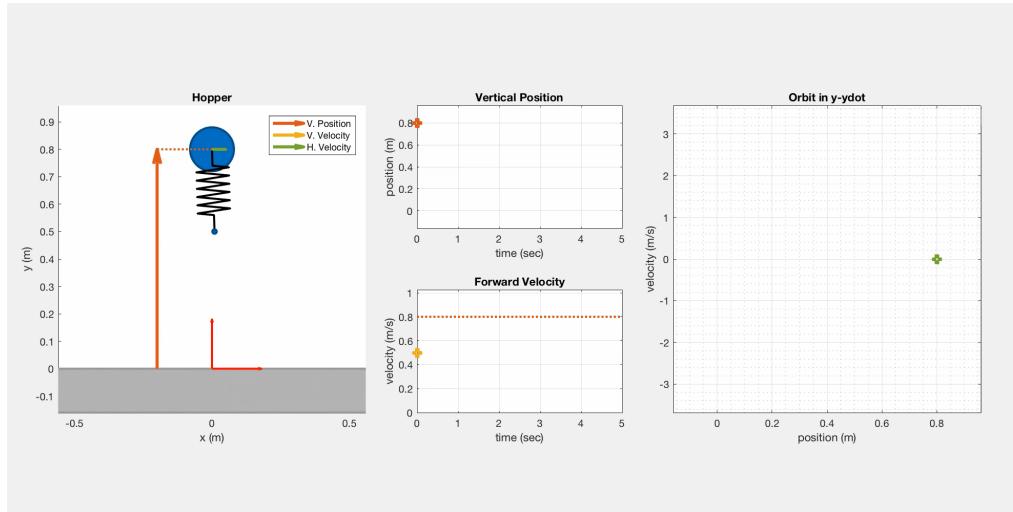
Simulation Study of Exact Linearization

- Numerical results compare
 - Raibert stepping (g_{RF})
 - Inverse dynamics (g_{ARD})
- Inverse dynamics
 - better basin volume
 - better regulation
- Raibert stepping
 - more robust against modeling errors



Week 11: Project #3: Higher DoF Systems

- Start with full SLIP model combining
 - vertical height loop
 - fore-aft stepping loop
- Introduce more realistic running bodies
 - anchor more complicated leg models
 - add appendages and actuators



A. De and D. E. Koditschek, “Parallel composition of templates for tail-energized planar hopping,” in 2015 IEEE International Conference on Robotics and Automation (ICRA), 2015, pp. 1562–1569.

U. Saranli, W. J. Schwind, and D. E. Koditschek, “Toward the control of a multi-jointed, monoped runner,” in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on* 1998, vol. 3, pp. 2676.

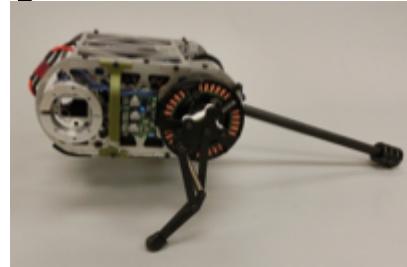
Week 12 – Project #4: Jerboa Robot

- Numerical study of a physical robot

- 12 DoF (only 4 motors)
- designed to explore parallel composition

- Under active research development

- new behaviors each year
- cutting edge of contemporary legged locomotion research



A. De and D. Koditschek, "The Penn Jerboa: A Platform for Exploring Parallel Composition of Templates," Technical Reports (ESE, U. Penn), vol. arXiv preprint arXiv:1502.05347, Jan. 2015.

A. L. Brill, A. De, A. M. Johnson, and D. E. Koditschek, "Tail-assisted rigid and compliant legged leaping," in 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015, pp. 6304–6311.

G. Wenger, A. De, and D. E. Koditschek, "Frontal plane stabilization and hopping with a 2DOF tail," in Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on, 2016, pp. 567–573.

A. De and D. E. Koditschek, "Averaged anchoring of decoupled templates in a tail-energized monopod," in Robotics Research, Springer, 2018, pp. 269–285.

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Week 1 – Unit 1

Big Picture and Motivation

Video 1.2

Segment 1.1.2

Overview of the Week

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University of Pennsylvania

September, 2017

Principled Bioinspiration

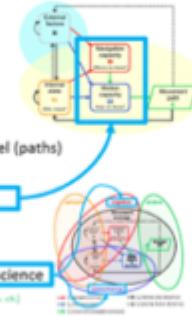
- Bioinspiration
 - animal mobility: long studied by humans
 - many different disciplines
 - our focus: mechanics
- Paths not taken
 - inspired – not copied!
 - embodied autonomy
 - active mobility
 - as the origin of intelligence

Why Do Animals Move?

- Movement Ecology [Nathan et al., PNAS'08]
 - must understand at many scales
 - limbs over seconds
 - bodies over minutes
 - places over days
 - migrations over years
 - basic components of study
 - external (environment) & record of travel (paths)
 - motivational & evolutionary drivers
 - capabilities (mechanical; navigational)
 - connections to biology
 - evolutionary ecology
 - biomechanics, neuroscience, cognitive science

[R. Nathan et al., "Proceedings of the National Academy of Sciences, 2008, pp. e14.]

our focus:
synthetic
versions

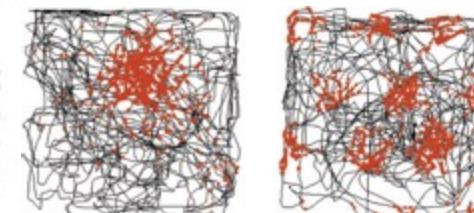


1x

[Alex Dunkel (Maky) - Own work]



Fig. 1. Hypothesized structural and functional transitions in vertebrate evolution. The postulated functional states (capital) precede the modified structures (lower case letters) involved with them.

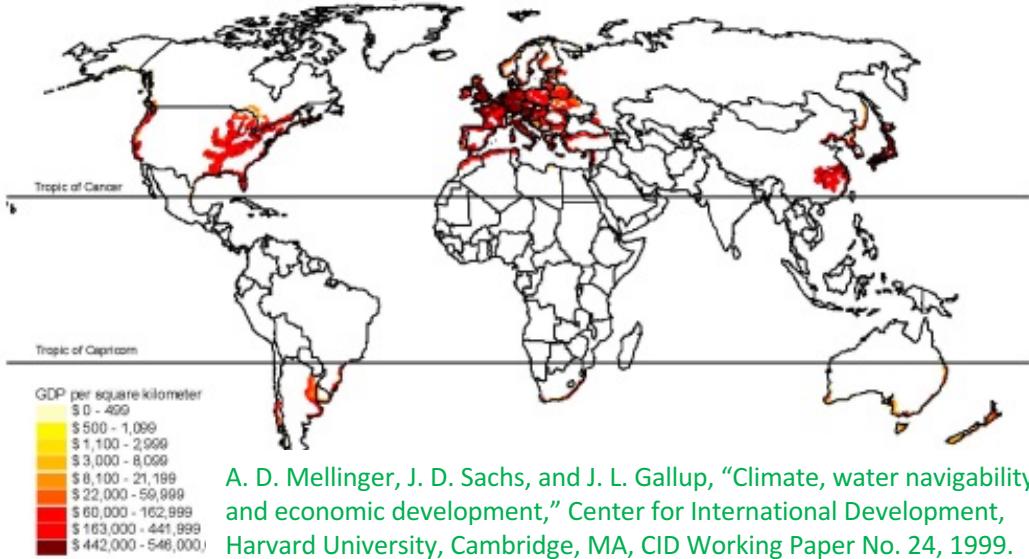


E. I. Moser, E. Kropff, and M.-B. Moser,
"Place cells, grid cells, and the brain's
spatial representation system,"
Neuroscience, vol. 31, no. 1, p. 69, 2008

Compelling Need

- Ground Mobility
 - for daily human affairs
 - for human disasters
 - and for human exploration

Figure 5. GDP-PPP 1995 in \$US in temperate climate zones 0-100km from the coast and sea-navigable rivers



A. D. Mellinger, J. D. Sachs, and J. L. Gallup, "Climate, water navigability, and economic development," Center for International Development, Harvard University, Cambridge, MA, CID Working Paper No. 24, 1999.



“‘Scorpion’ robot mission inside Fukushima reactor aborted,” Phys.Org, 16-Feb-2017. [Online]. Available: <https://phys.org/news/2017-02-scorpion-robot-mission-fukushima-reactor.html>.



F. Qian et al., "Ground robotic measurement of aeolian processes," Aeolian Research, vol. 27, pp. 1–11, Aug. 2017.

Property of Penn Engineering and Daniel E. Koditschek

Segment 1.1.2

Principled Engineering

- Foundations
 - physics
 - mathematics
- New Horizons
 - formally guaranteed behaviors
 - usefully composed in programs

Dynamics as Management of Energy

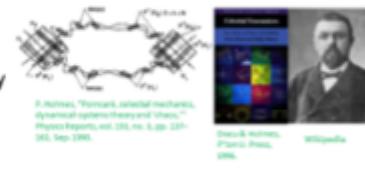
- Mobility starts with physics

- Newton: $F=ma$
- Lagrange: least action
- Hamilton: energy; conserved or lost



- But then needs mathematics

- Lyapunov: Stability
- Poincaré:
 - attractors & basins
 - chaos



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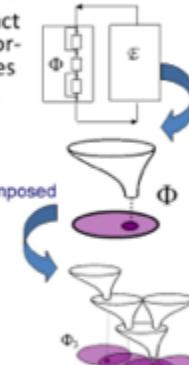
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Segment 1.2.3

Toward a Language of Work

- Basins are symbols

- translate abstract goals into sensor-torque strategies
- that alter the "energy landscape"
- encode tasks as "composed landscapes"



[Burridge, et al. IROS'95]

[Rizzi, A.A., et al., IEEE Comp'92]

- Symbols can be programmed

- formal proofs
- predictable results



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Segment 1.2.3

edX Robo4 Mini MS - Locomotion Engineering: Week 1 – Unit 2

Locomotion in Machines and Animals

Video 1.3

Segment 1.2.1 Need for Mobility

Daniel E. Koditschek

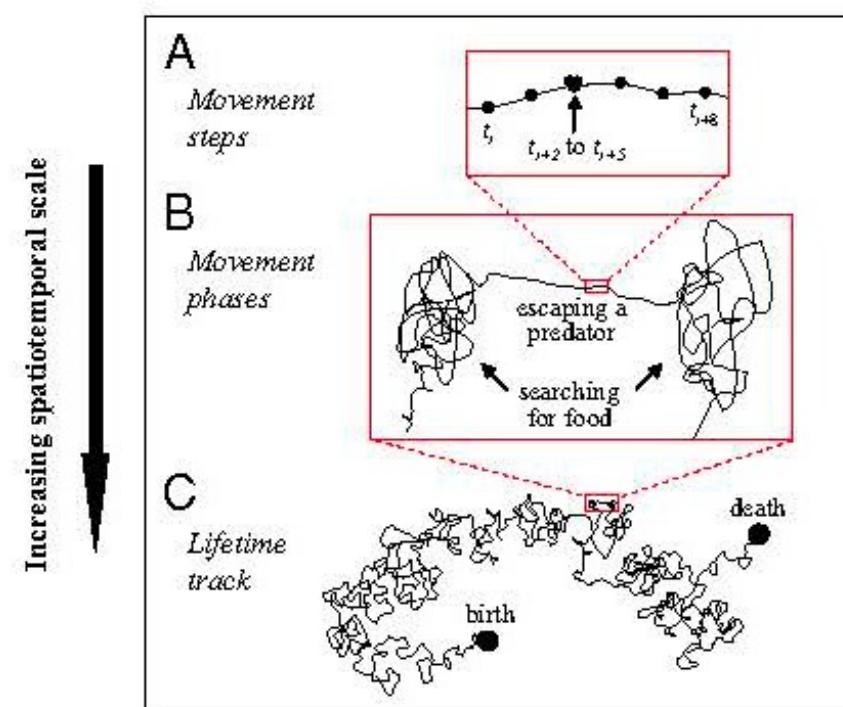
with

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University of Pennsylvania

June, 2017

Why Do Animals Move?

- Aristotle [*De Motu Animalium*, c.300 BC]:
 - cognition (imagination)
 - desire (appetites)
 - perception (change world state)
- Movement Ecology [Nathan et al., PNAS'08]
 - modern synthesis
 - comprehensive over many scales
 - limbs over seconds
 - bodies over minutes
 - places over days
 - migrations over years

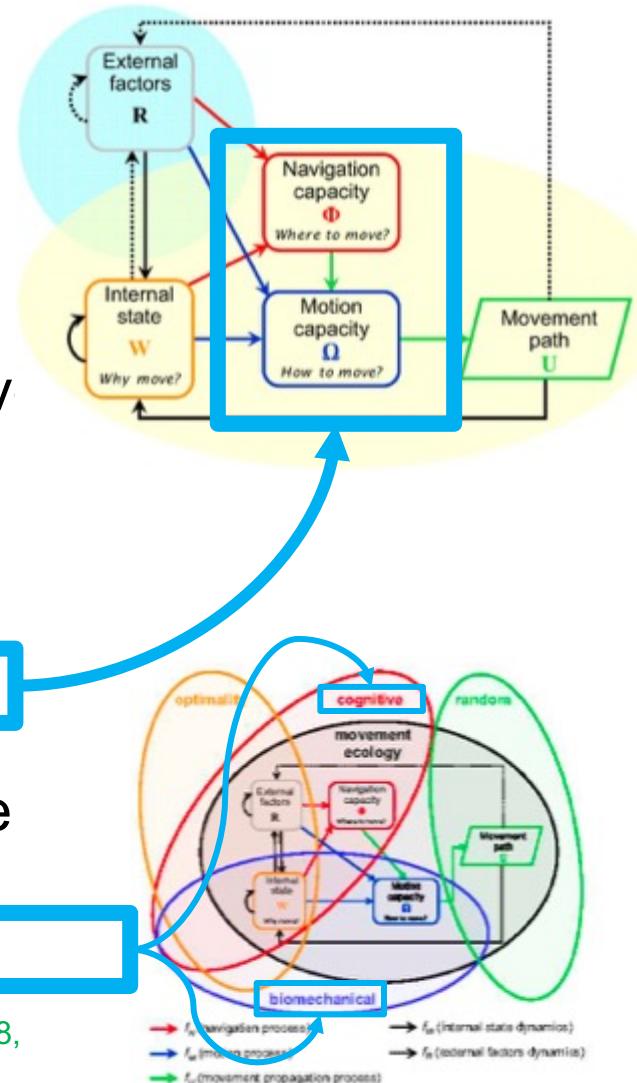


[R. Nathan, W. M. Getz, E. Revilla, M. Holyoak, R. Kadmon, D. Saltz, and P. E. Smouse, "A movement ecology paradigm for unifying organismal movement research," *Proceedings of the National Academy of Sciences*, vol. 105, no. 49, pp. 19052–19059, 2008.]

Why Do Animals Move?

*our focus:
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 - evolutionary ecology
 - biomechanics, neuroscience, cognitive science



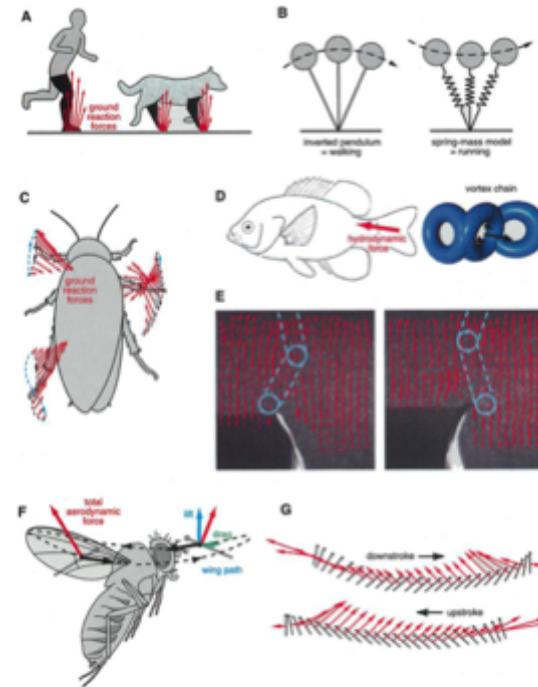
How Do Animals Move?

- Newton says

- body accelerates due to force
- of reaction against environment
- carried by appendages

- Now begins a long, unfinished story

- appendages must oscillate
- in tight coordination

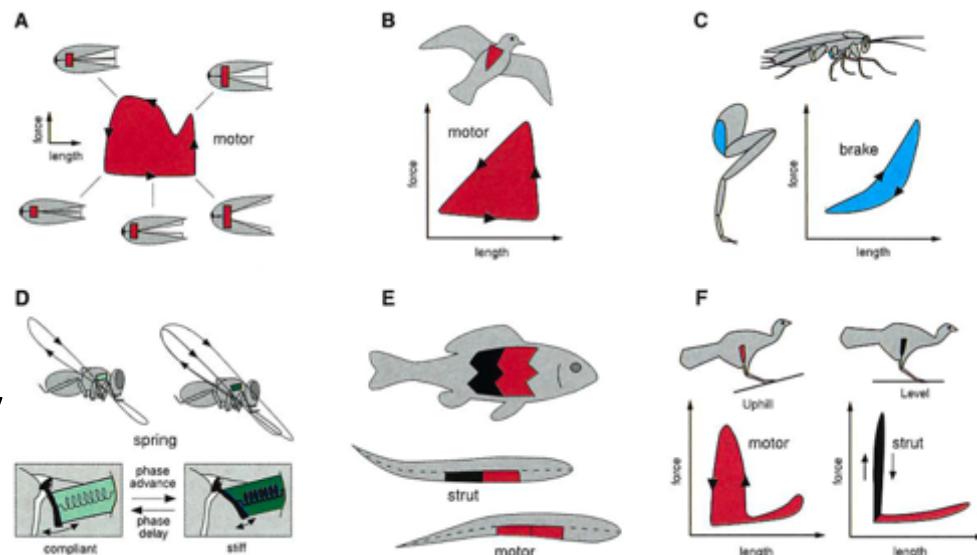
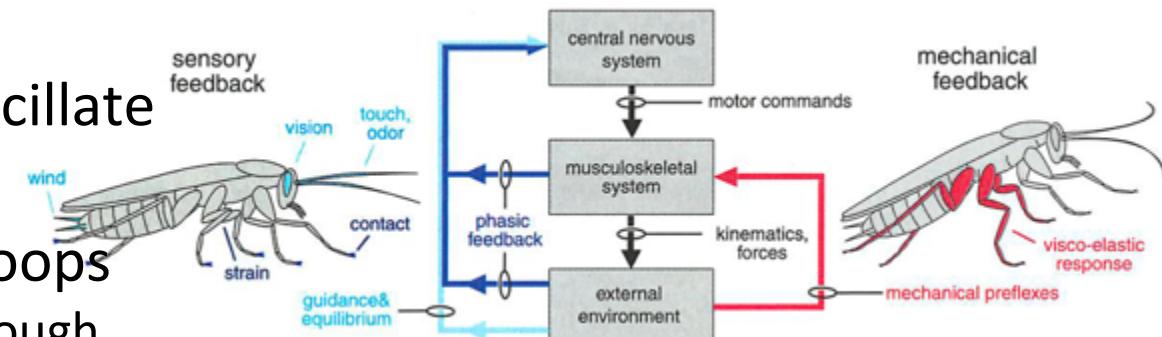


[M. H. Dickinson, C. T. Farley, R. J. Full, M. A. Koehl, R. Kram, and S. Lehman, "How Animals Move: An Integrative View," *Science*, vol. 288, no. 5463, pp. 100–106, 2000.]

How Do Animals Move?

- Now begins a long, unfinished story

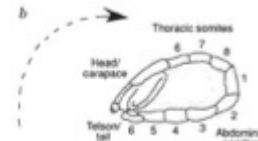
- appendages must oscillate
- in tight coordination
- requiring feedback loops
 - from environment through limbs
 - from environment through nerves
 - within body through limbs & nerves
- mixing form and function
 - muscles: motors, brakes, springs,
 - intelligence: “baked into” body design



How Don't Animals Move?

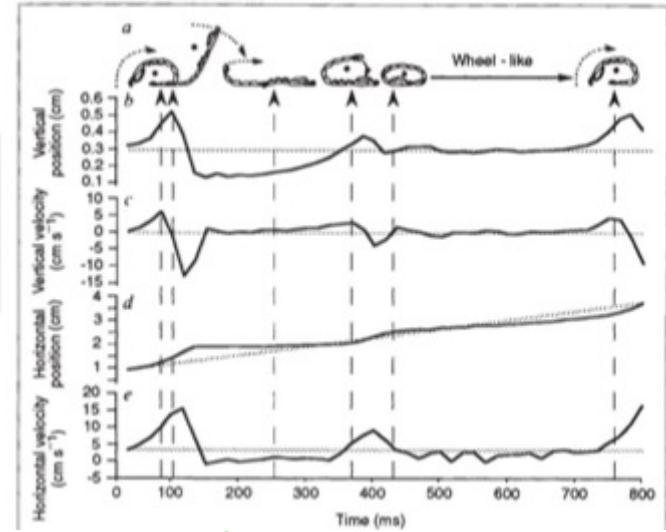
- Animals inspire this course

- limbed mobility
 - body-based sensing



- On land

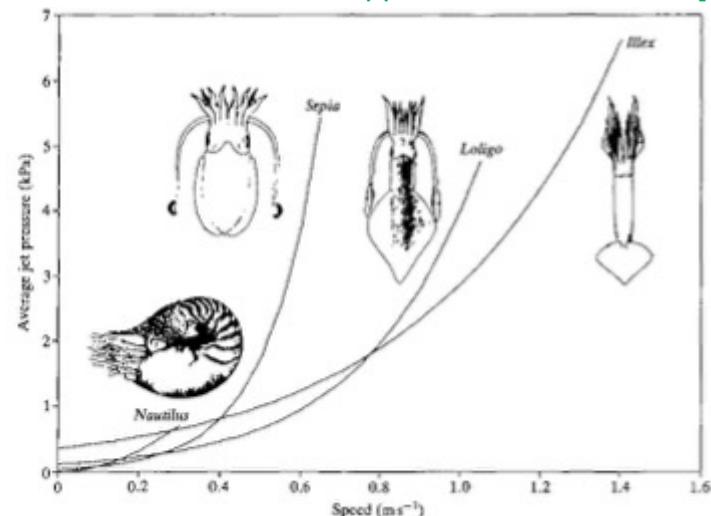
- they stride
 - no wheels?
 - molecular motors
 - mantis shrimp



[R. Full, K. Earls, M. Wong, and R. Caldwell, "Locomotion like a wheel?," *Nature*, vol. 365, no. 6446, pp. 495–495, Oct. 1993]

- In liquid

- they slither or swim
 - no jets?
 - squid ("just hearts set free")
 - inefficient to contain reaction mass



[R. O'DOR and D. M. Webber, "Invertebrate athletes: trade-offs between transport efficiency and power density in cephalopod evolution," *Journal of Experimental Biology*, vol. 160, no. 1, pp. 93–112, 1991.]

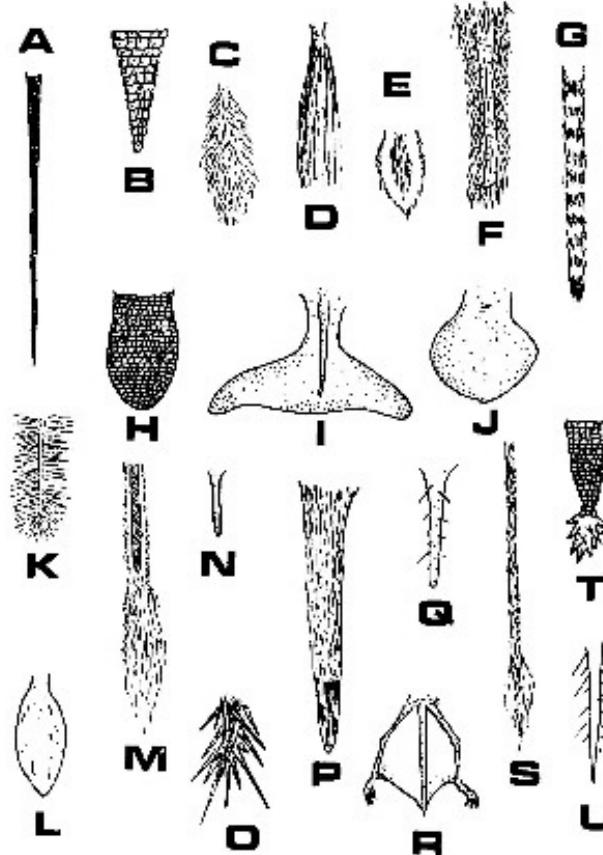
Bioinspiration – not copying

- Study limbed mobility

- Be inspired,
 - but don't copy!!

- Cautionary example

- e.g. tails
 - used for
 - play-time signalling
 - storing fat
 - vestigial
 - do we need them in robots?



G. C. Hickman, "The mammalian tail: a review of functions," Mammal Review, vol. 9, no. 4, pp. 143–157, Dec. 1979.]

Bioinspiration – extract principles

- Study limbed mobility
 - be inspired
 - but don't copy!!
- Work with principles not appearances
 - lizard self-righting inspires tailed robots
 - wheel-tailed cliff jump
 - leg-tailed cliff jump



[A. M. Johnson, T. Libby, E. Chang-Siu, M. Tomizuka, R. J. Full, and D. E. Koditschek, "TAIL ASSISTED DYNAMIC SELF RIGHTING," in *Proc. 15th Intl. Conf. Climbing and Walking Robots*, 2012, vol. 23, pp. 611–620.]

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Locomotion in Machines and Animals

Video 1.4

Segment 1.2.2

Bioinspiration

Daniel E. Koditschek

with

Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos
University of Pennsylvania

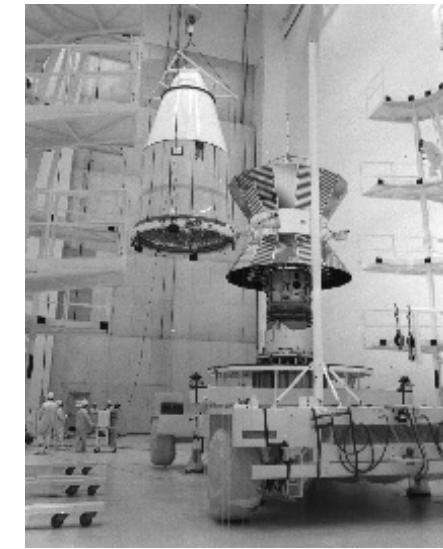
June, 2017

Machines Move Better?

- Machines – specialists

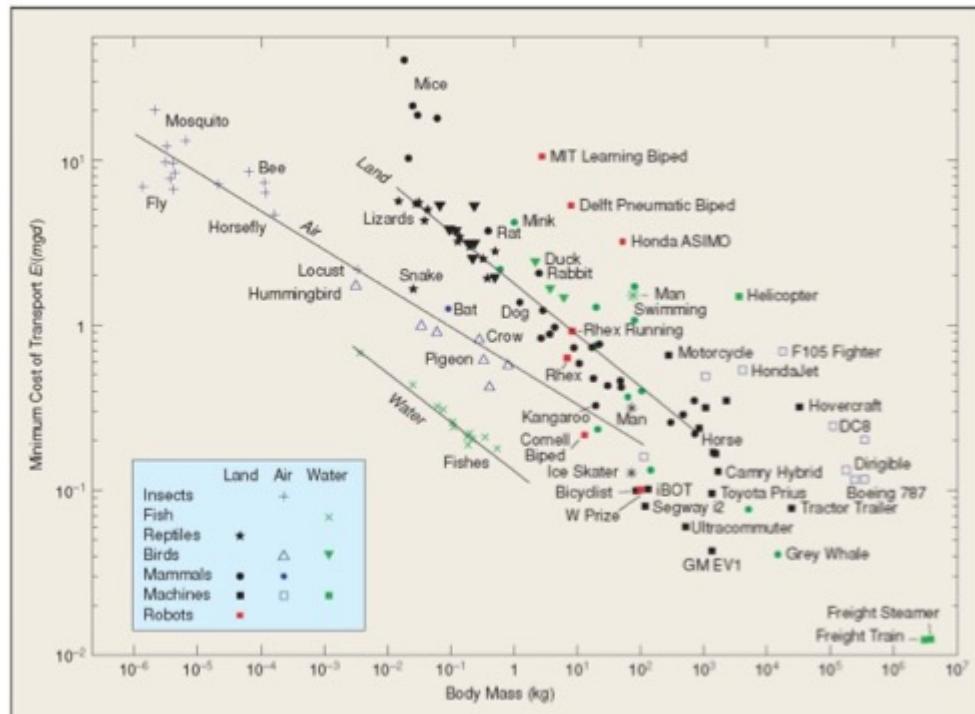
[*Wikipedia source*]

- faster: Helios 2 (0.22 km/s = 0.000234c)
- more load: MSC Oscar (~200,000 m³)



- Animals – generalists

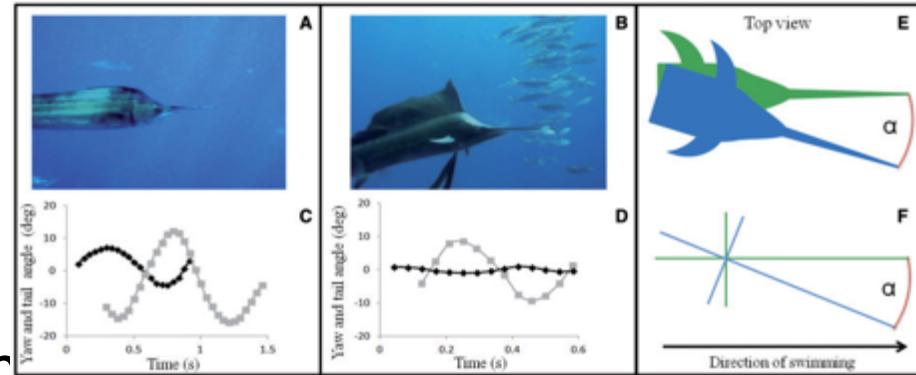
- e.g., efficiency
 - specific resistance:
Energy/load-distance
= S Power/mass-speed dt
- unmatched on general terrain



[A. D. Kuo, "Choosing Your Steps Carefully," *IEEE Robotics & Automation Magazine*, vol. 14, no. 2, pp. 18-27, June 2007]

Machines Move Better?

- Machines – specialists
- Animals – generalists
 - cheaper on general terrain
 - at least as agile
 - Porsche: 12 m/s^2 $\frac{1}{4}$ 0-100 km/hr in 2 s
 - Sailfish: 8 m/s^2 at 25 km/hr
 - Cheetah: 13 m/s^2 at 60 km/hr



[S. Marras, et al., "Not So Fast: Swimming Behavior of Sailfish during Predator–Prey Interactions using High-Speed Video and Accelerometry," *Integr. Comp. Biol.*, vol. 55, no. 4, pp. 719–727, Oct. 2015]



[A. M. Wilson, et al., "Locomotion dynamics of hunting in wild cheetahs," *Nature*, vol. 498, no. 7453, pp. 185–189, Jan. 2013.] Segment 1.1.2

Mobility: Origin of Intelligence

- “Shift to vertebrate...

- modification of filter feeding
 - promoted active dispersing
 - via segmented muscle
 - and “notochord”
- permitted selective predation”
 - promoted active seeking
 - distal external sensing
 - centralized “neural crest”

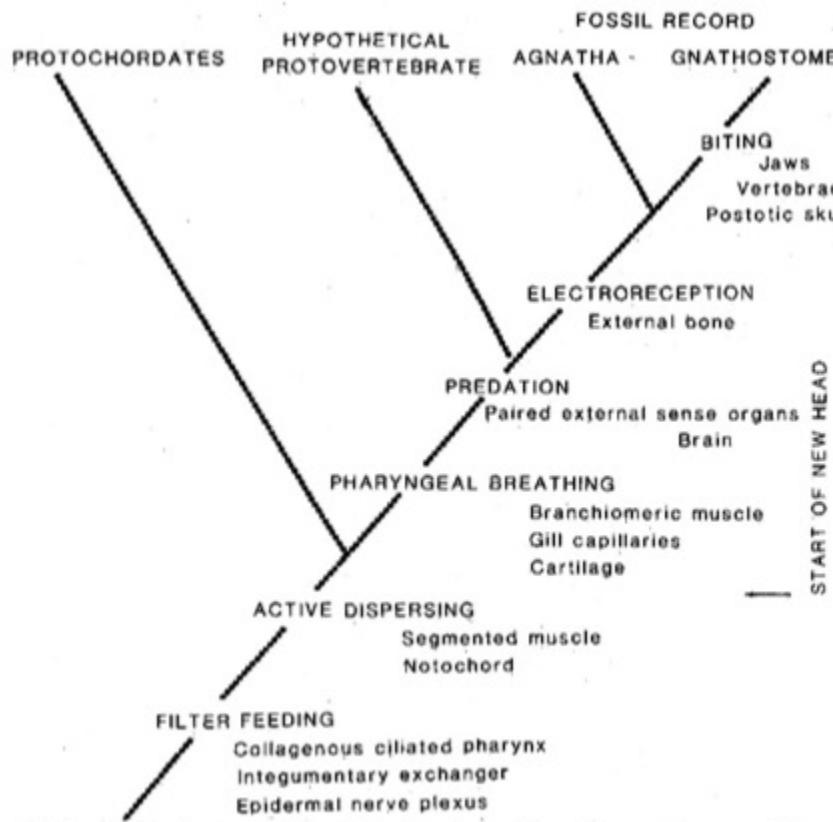


Fig. 1. Hypothesized structural and functional transitions in vertebrate evolution. The postulated functional states (capitals) precede the modified structures (lower case letters) involved with them.

C. Gans and R. G. Northcutt, “Neural Crest and the Origin of Vertebrates: A New Head,” *Science*, vol. 220, no. 4594, pp. 268–273, 1983

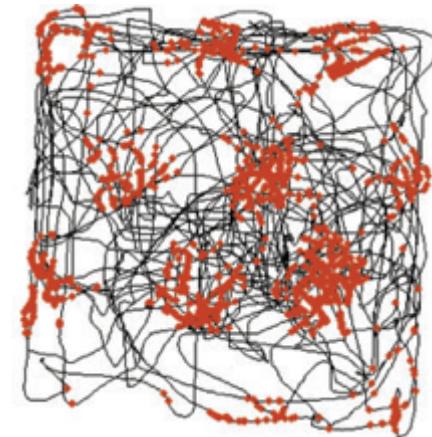
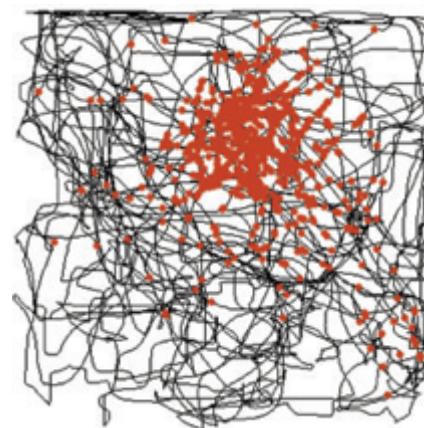


First Vertebrates may have resembled the Hagfish

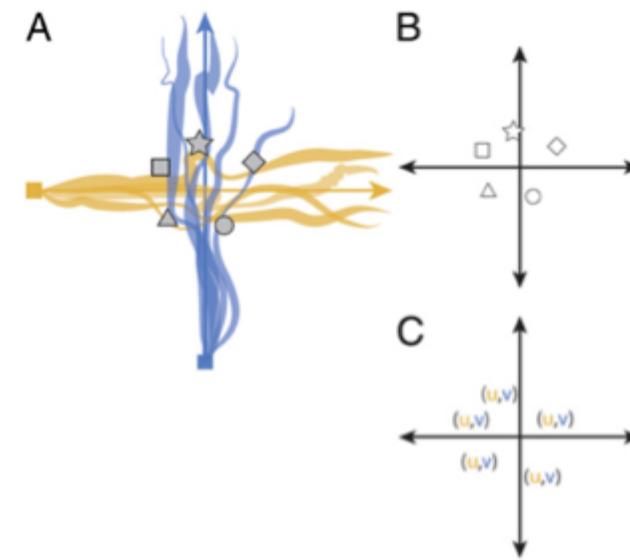
C. Zimmer, “In Search of Vertebrate Origins: Beyond Brain and Bone,” *Science*, vol. 287, no. 5458, pp. 1576–1580, 2000

Mobility: Origin of Intelligence

- Mobile “Seeking” Brains
 - mammalian hippocampus
 - Mosers’ 2014 Nobel Prize
 - seat of spatial navigation
 - episodic memory
 - general cognitive map loci
 - competitive navigation
 - arose in Cambrian period (~500 mya)
 - built from chemotaxis
 - supported both “gradient” and “topological” navigation
 - diverse olfactory trackers
 - honey bees
 - deep water sharks
 - homing pigeons
 - larger with “seeking” mobility



E. I. Moser, E. Kropff, and M.-B. Moser, “Place cells, grid cells, and the brain’s spatial representation system,” *Neuroscience*, vol. 31, no. 1, p. 69, 2008



L. F. Jacobs, “The Evolution of the Cognitive Map.,” *Brain, Behavior & Evolution*, vol. 62, no. 2, pp. 128–139, Jun. 2003

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Week 1 – Unit 2

Locomotion in Machines and Animals

Video 1.5

Segment 1.2.3 Legged Mobility

Daniel E. Koditschek

with

Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos

University of Pennsylvania

September, 2017

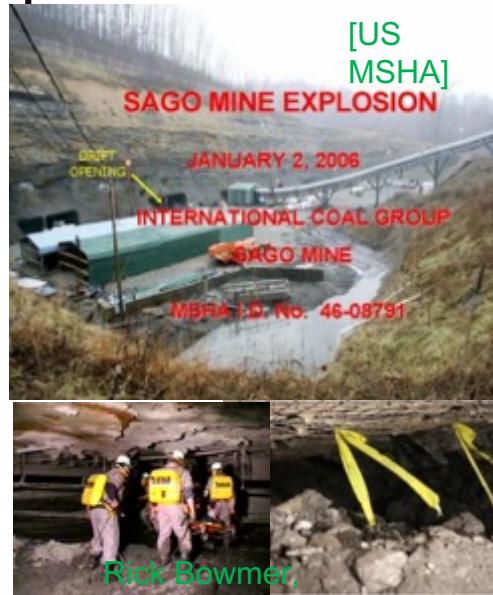
Ground Mobility – Where Humans Live

- Navigable, temperate earth ecozones

- 8% world's inhabited landmass
- 50% world's economic output

- Inhospitable environments

- construction, mining, ...
- disaster



Property of Penn
Engineering and
Daniel E. Koditschek

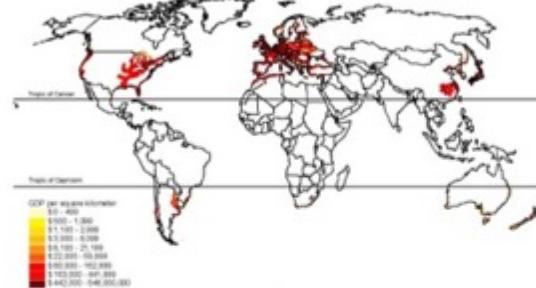
A. D. Mellinger, J. D. Sachs, and J. L. Gallup, "Climate, water navigability, and economic development," Center for International Development, Harvard University, Cambridge, MA, CID Working Paper No. 24, 1999.

Figure 3. Land within 100 km of an ice-free coast or sea-navigable river



28

Figure 5. GDP-PPP 1995 in \$US in temperate climate zones 0-100km from the coast and sea-navigable rivers



29

Ground Mobility – Where Humans Don't Live

- Human planetary science

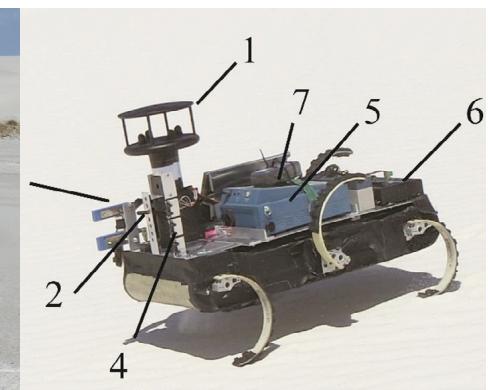
- extra-terrestrial
- world's un/der-inhabited terrain

- poorly understood
- strong impacts on habitable

- Robot assistants are coming



<http://wotfigo.tumblr.com/post/23095754403/global-warming-desertification>



S. Roberts et al., "Desert RHex Technical Report: Jornada and White Sands Trip," U. Penn. 2014.

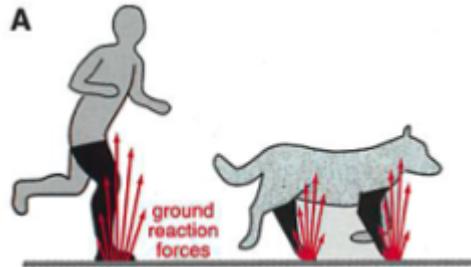
F. Qian et al., "Ground robotic measurement of aeolian processes," Aeolian Research, vol. 27, pp. 1–11, Aug. 2017.

Focus on Legs

- Legs are better than wheels
 - directing ground reaction forces
 - self-manipulation
 - proprioception
- Legged Mobility:
 - general steady state still poorly understood
 - transitions even less



M. McKee, "Mars Rover Spirit Stuck in Sand as Winter Approaches" New Scientist, 27-Nov-2007



Dickinson, et al., *Science*, 2000, Op. Cit.

G. C. Haynes, et al. "Laboratory on legs" in SPIE Unmanned Systems Technology XIV Proceedings Vol. 8387, 2012, vol. 8387, p. 83870W–83870W–14.

A. M. Johnson, G. C. Haynes, and D. E. Koditschek, "Standing self-manipulation for a legged robot," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, 2012, pp. 272–279.

A. M. Johnson and D. E. Koditschek, "Toward a vocabulary of legged leaping," in *IEEE Int. Conf. Rob. Aut.*, 2013, pp. 2553–2560

T. T. Topping, G. Kenneally, and D. E. Koditschek, "Quasi-static and dynamic mismatch for door opening and stair climbing with a legged robot," in *Robotics and Automation (ICRA), 2017 IEEE International Conference on*, 2017, pp. 1222–1227

Focus on Dynamical Systems Approach

- Quasi-static settings
 - (i.e., no kinetic energy)
 - need to coordinate gait
 - need to react to environment
- Dynamical settings
 - inescapable
 - steady state tasks
 - (e.g., steady running)
 - full arsenal of mathematical tools
 - not yet always clear how to use
 - transitional tasks: next horizon



M. J. Spenko et al., “Biologically inspired climbing with a hexapedal robot,” Journal of Field Robotics, vol. 25, no. 4–5, pp. 223–242,



A. De, K. S. Bayer, and D. E. Koditschek, “Active sensing for dynamic, non-holonomic, robust visual servoing,” in 2014 IEEE International Conference on Robotics and Automation (ICRA), 2014, pp. 6192–6198.

Dynamics as Management of Energy

- Mobility starts with physics

- Newton: $F=ma$
- Lagrange: least action
- Hamilton: energy; conserved or lost



Encyclopedia Britannica



Encyclopedia Britannica



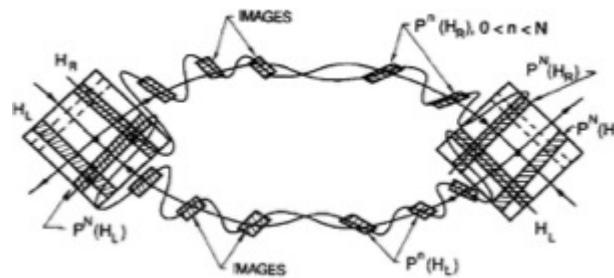
Wikipedia



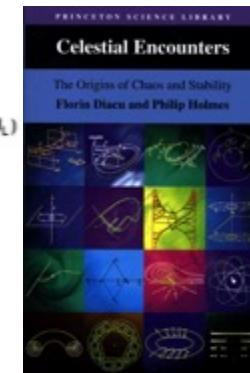
Wikipedia

- But then needs mathematics

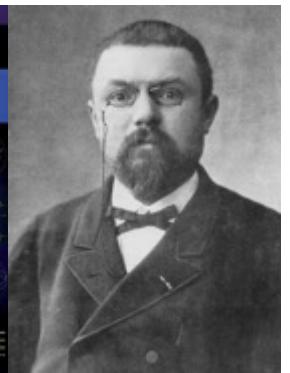
- Lyapunov: Stability
- Poincaré':
 - attractors & basins
 - chaos



P. Holmes, "Poincaré, celestial mechanics, dynamical-systems theory and 'chaos,'" Physics Reports, vol. 193, no. 3, pp. 137–163, Sep. 1990.



Diacu & Holmes, P'ton U. Press, 1996.



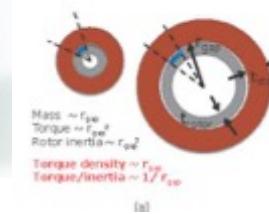
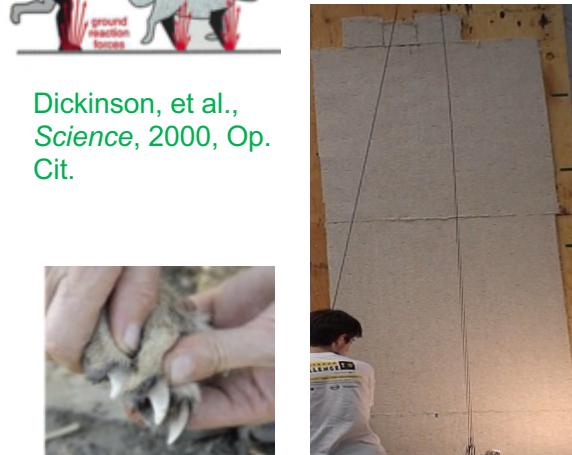
Wikipedia

Energy Exchange: Topics Not Covered

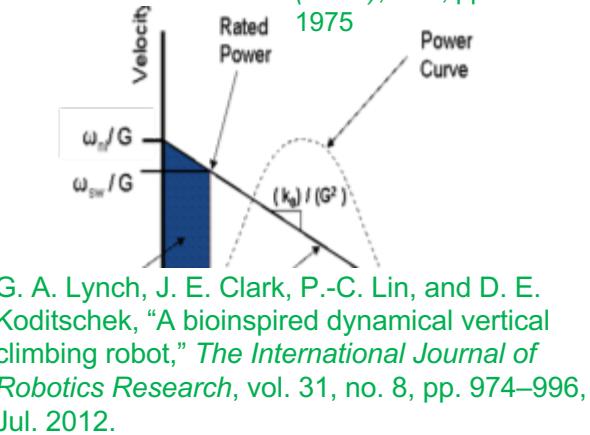
- Fundamentally scarce resources
 - specific force: apply GRF
 - traction: direct GRF
 - specific power: move energy
- Computational architectures



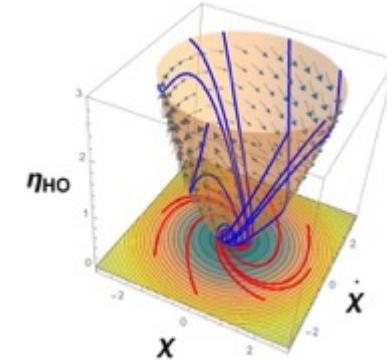
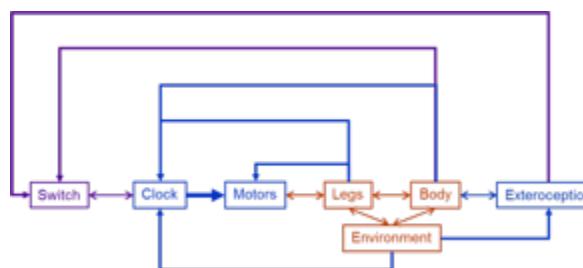
Dickinson, et al.,
Science, 2000, Op.
Cit.



S. Seok, A. Wang, D. Otten, and S. Kim,
“Actuator design for high force proprioceptive control in fast legged locomotion,” in 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Oct., pp. 1970–1975

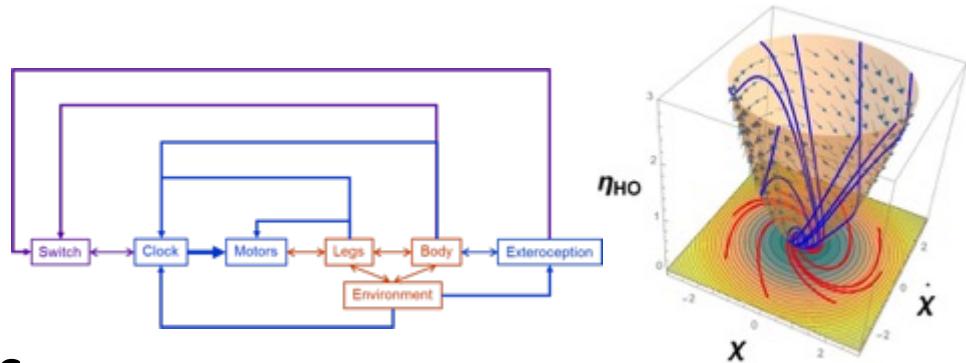


G. A. Lynch, J. E. Clark, P.-C. Lin, and D. E. Koditschek, “A bioinspired dynamical vertical climbing robot,” *The International Journal of Robotics Research*, vol. 31, no. 8, pp. 974–996, Jul. 2012.



Programming the Exchange of Energy

- Mobility starts with physics
- ...
- ... takes a tour through materials & technology
- ... uses mathematical models & analysis to encodes specific behaviors
- ... aiming to solve problem of programming work
 - architecture achieves basins
 - basins become symbols
 - symbols can be composed
 - seek language of work



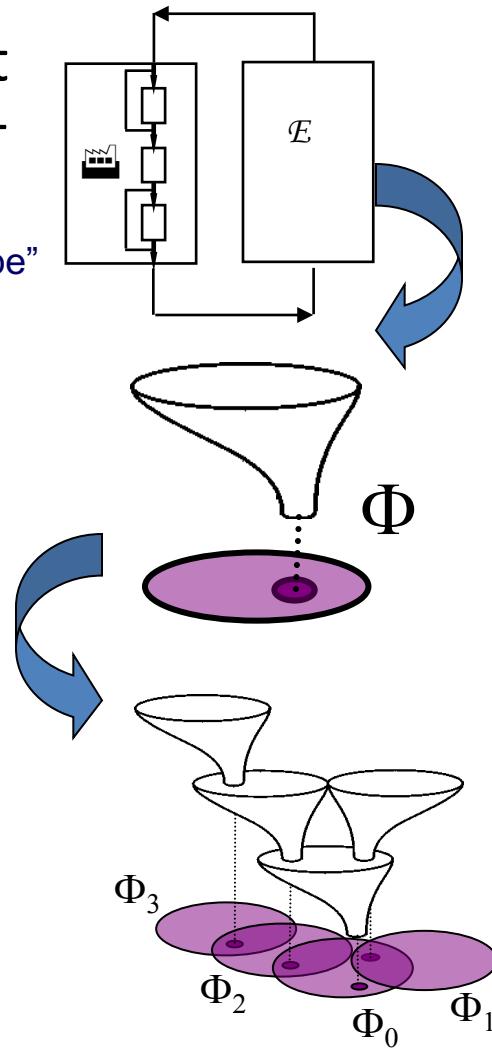
A. De and D. E. Koditschek, "Averaged anchoring of decoupled templates in a tail-energized monoped," in *Robotics Research*, Springer, 2018, pp. 269–285.

Toward a Language of Work

- Basins are **symbols**

- translate abstract goals into sensor-torque strategies
- that alter the “energy landscape”
- encode tasks as “composed landscapes”

[Rizzi, A.A., et al., IEEE Comp'92]



- Symbols can be programmed

- formal proofs
- predictable results

[Burridge, et al. IROS'95]