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

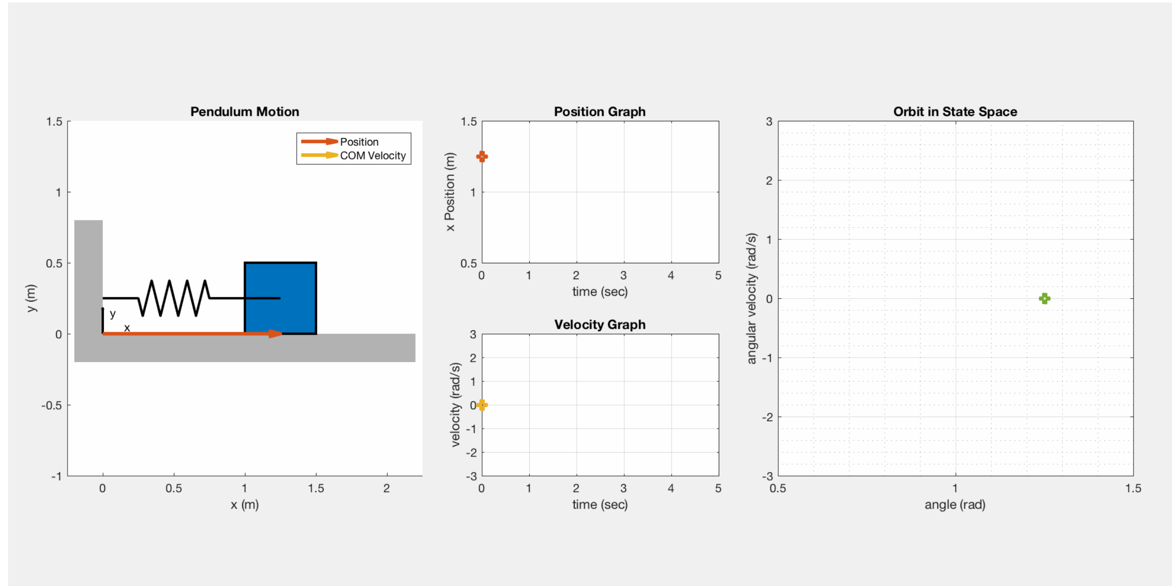
Week1 – Big Picture & Motivation

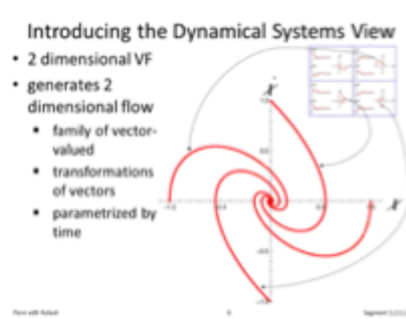
- Legged Mobility
  - an emerging area of robotics
  - increasing commercial activity
  - still under active development GHOSTROBOTICS
- Focus on Foundations
  - principled bioinspiration
  - underlying physics & math
  - emerging engineering theory
  - application to successively more realistic simulation models

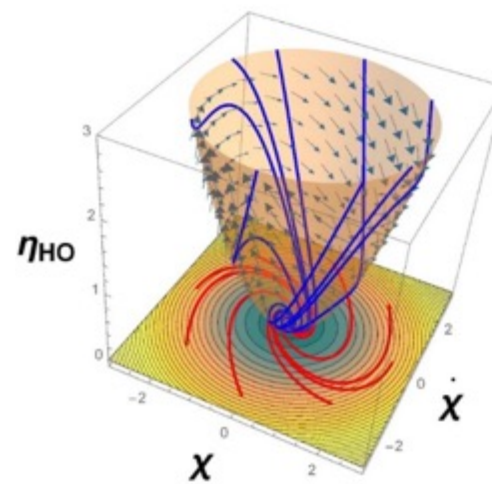
A. De and D. E. Koditschek, “Averaged anchoring of decoupled templates in a tail-energized monoped,” in Robotics Research, Springer, 2018, pp. 269–285.

Week 2 – 1 DoF Prismatic Mechanics

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

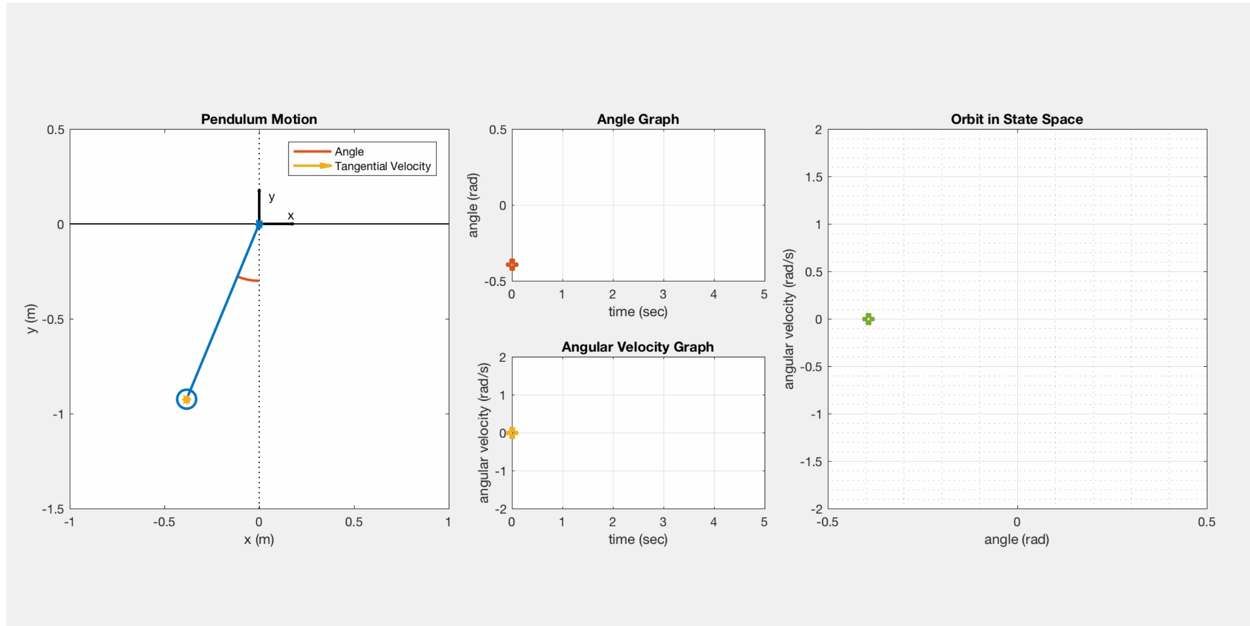






Week 3 – 1 DoF Revolute Mechanics

- 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?

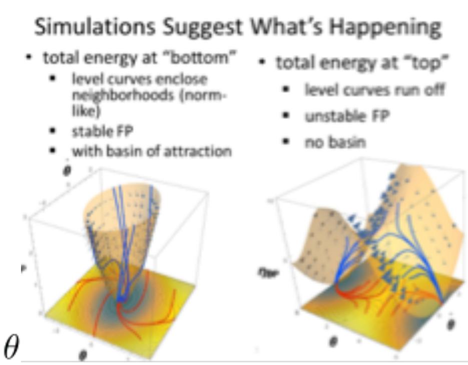
$$\tilde{\eta}_{\mathrm{HO}}(\mathbf{y}) = \frac{1}{2}\|\mathbf{y}\|^2$$

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

$$\eta_{\mathrm{DP}}(\boldsymbol{q}) = \frac{m\ell^2}{2}\dot{\theta}^2 + mg\ell\sin\theta$$

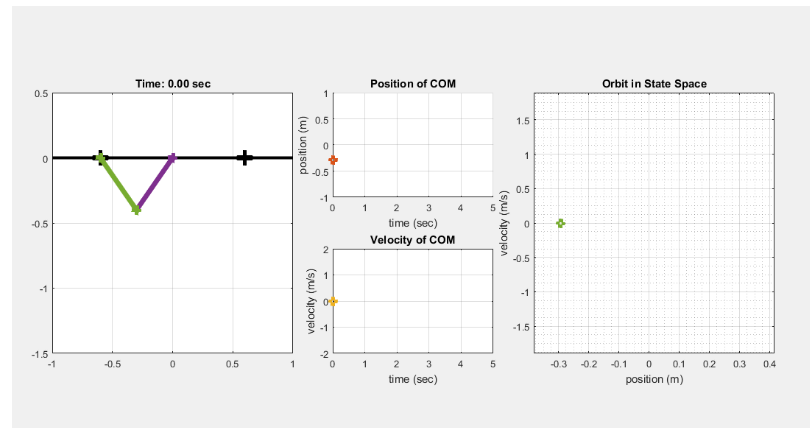
$$\dot{\eta}_{\mathrm{DP}}(\boldsymbol{q}) = -b\dot{\theta}^2 \overset{?}{\neq} \mathrm{func}(\eta_{\mathrm{DP}})$$

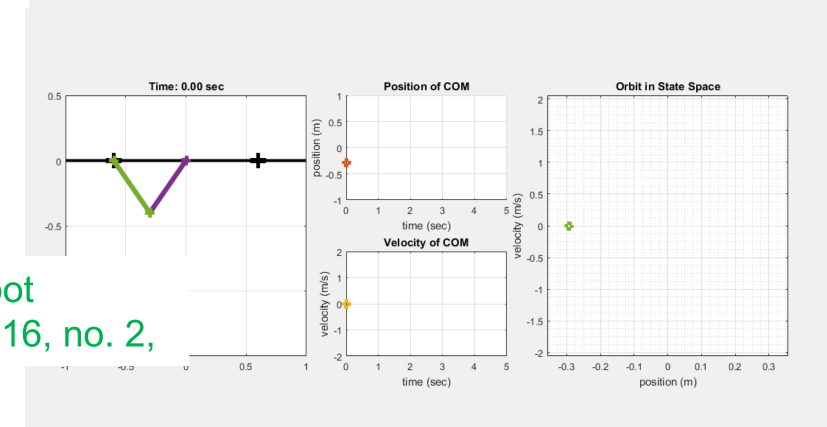
Penn edX Robo4 6 Segment 1.2.2.2.b



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. 109–123, 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. $\dot{\mathbf{y}} = f_{\mathrm{NLRC}}(\mathbf{y}) := \begin{bmatrix} \|\mathbf{y}\|^2 & -1 \\ 1 & \|\mathbf{y}\|^2 \end{bmatrix}\mathbf{y}; \quad \mathbf{y}_e := 0$

  $F_{\mathrm{NLRC}}(\mathbf{y}_e) := D_{\mathbf{y}} f_{\mathrm{NLRC}}(\mathbf{y}_e) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} =: J \neq 0$
  - hence linearized VF cannot be conjugate

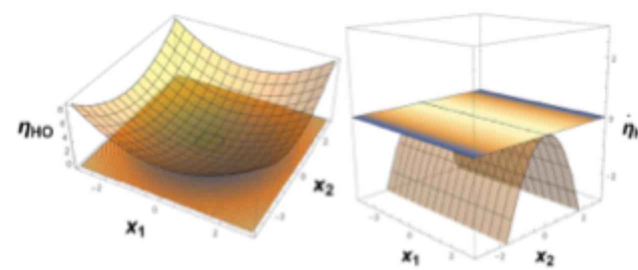
    $\hat{f}_{\mathrm{L}}(\mathbf{y}) := F_{\mathrm{NLRC}}(\mathbf{y}_e)\mathbf{y} \not\sim f_{\mathrm{NLRC}}(\mathbf{y})$
  - because, e.g., $\eta(\mathbf{y}) := \|\mathbf{y}\|^2/2 \Rightarrow$

    $\dot{\eta}_{\mathrm{L}}(\mathbf{y}) = D_{\mathbf{y}}\eta \cdot f_{\mathrm{L}}(\mathbf{y}) = \mathbf{y}^{\mathrm{T}} J \mathbf{y} \equiv 0$

    vs $\dot{\eta}(\mathbf{y}) = D_{\mathbf{y}}\eta \cdot f_{\mathrm{NLRC}}(\mathbf{y}) = 8\eta(\mathbf{y})^{3/2}$
    - so η grows without bound along flow of f_{NLRC}
    - whereas it is constant along flow of f_{L}

Penn edX Robo4 4 Segment 1.2.3.1.b

PD and NSD Quadratic Forms



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

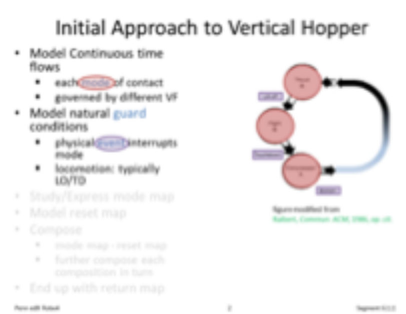
$$\dot{V}(x) = \dot{\eta}_{HO}(x) = -b x_2^2 = -\left\| \begin{bmatrix} \sqrt{0}x_1 \\ \sqrt{b}x_2 \end{bmatrix} \right\|^2$$

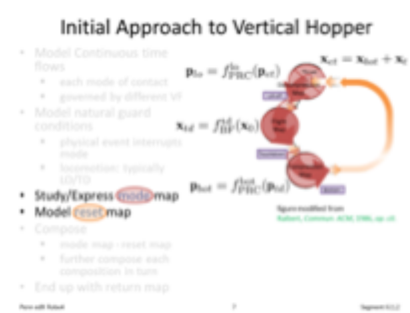
Penn edX Robo4 6 Segment 1.2.3.2.b

Week 6 – Raibert’s Vertical Hopper

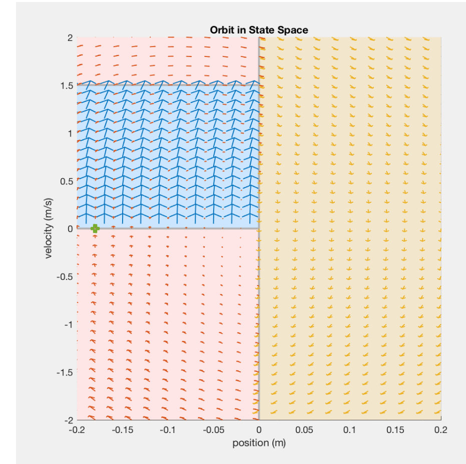
- Core “heartbeat” of Raibert’s pioneering legged runners
- Develop vector fields for each mode
- Derive flows for each mode

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

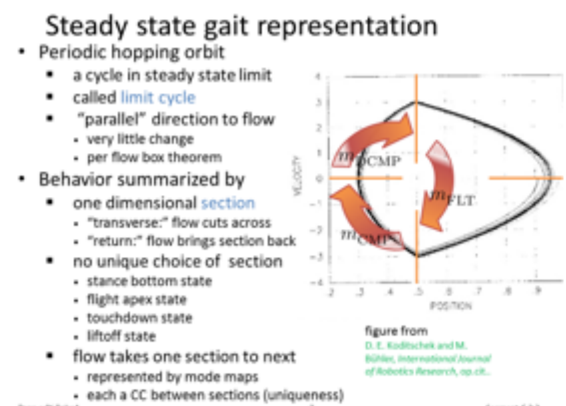


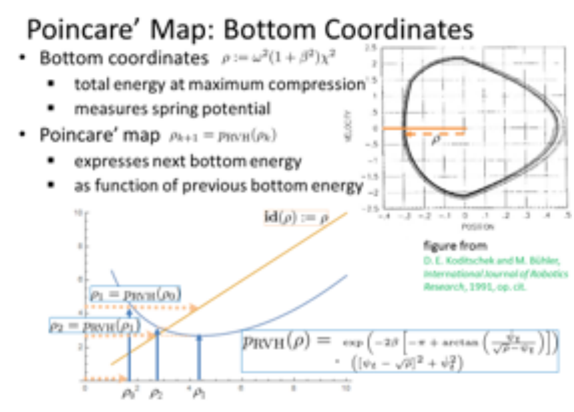


Week 7 – RVH as Hybrid Mechanical System



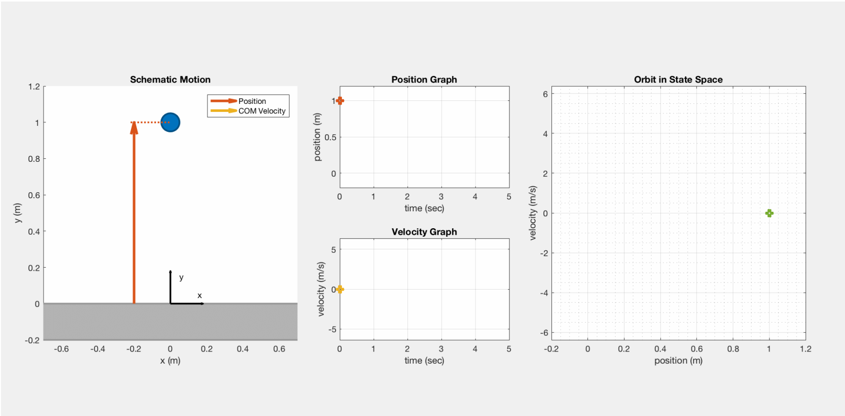
- Hybrid Dynamical System
  - different contact modes
  - and transitions between them
- Derivation of Poincare' Map
  - state of next hop
  - as function of previous
- Gait Stability Analysis
  - fixed point analysis
  - linearization yields insights
    - when will Raibert-controller work
    - what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

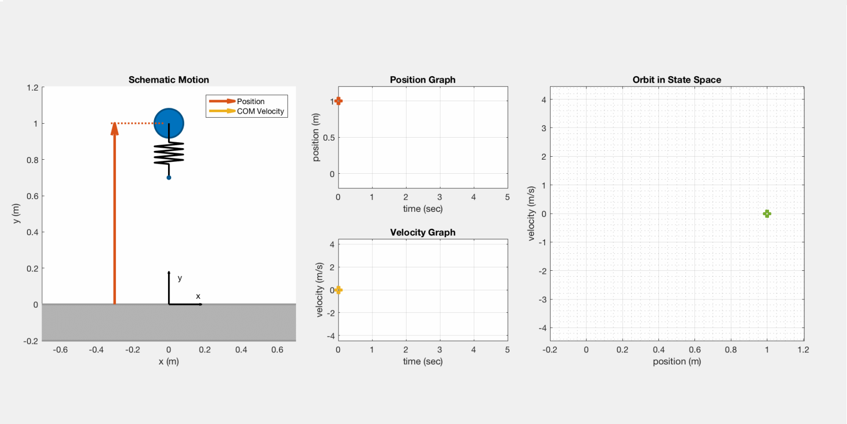


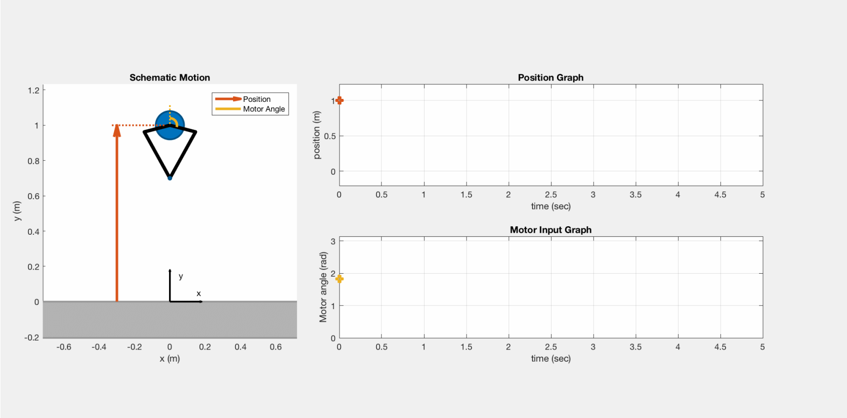


Week 8 – Project #2: Raibert Vertical Hopper

- 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

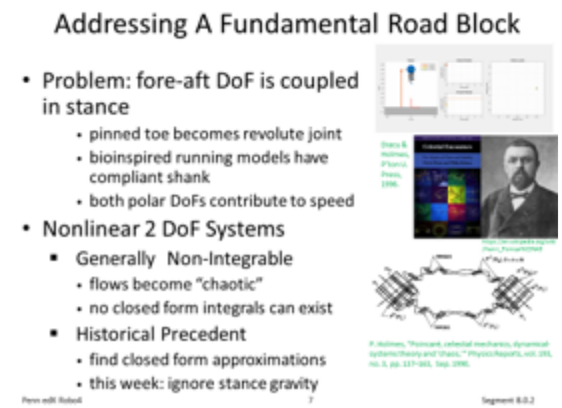


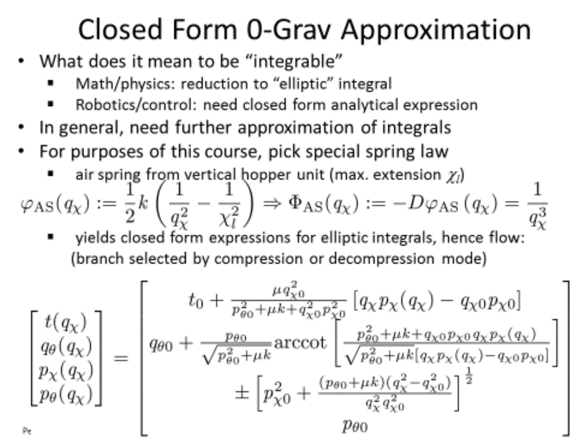




Week 9 – Spring Loaded Inverted Pendulum

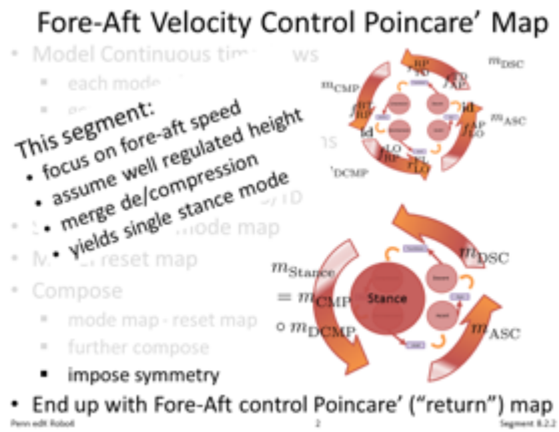
- Bioinspiration: animals as pogo sticks
- Fundamental problem
  - Poincare' map
    - stride control systems model
    - entails closed form flow
  - Pogo sticks
    - coupled nonlinear 2 DoF systems
    - formally non-integrable
- The way forward
  - lossless central force approximation
  - 2 conserved quantities yield closed form flow expressions

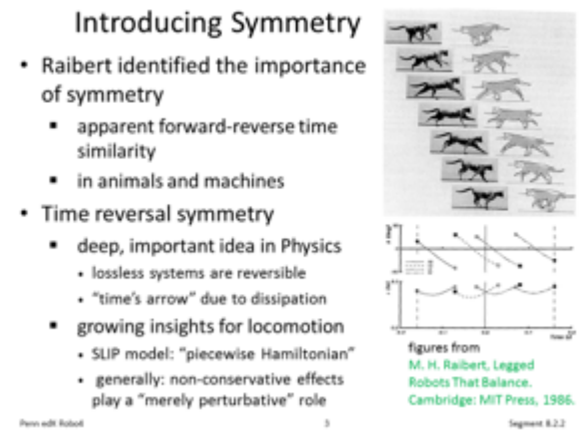


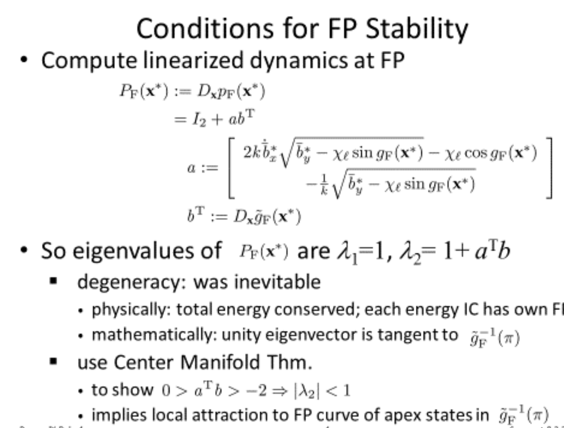


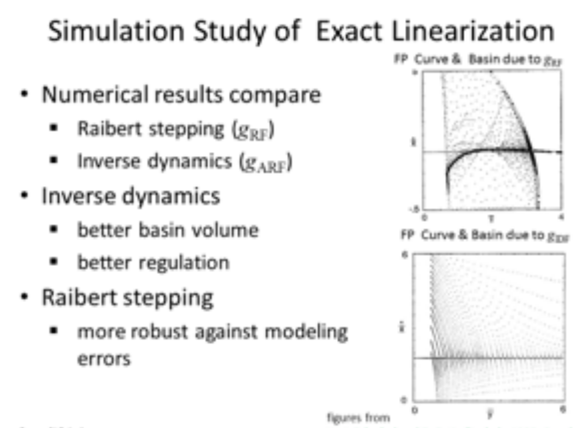
Week 10 – SLIP Stepping Controllers

- Closed form expression for stepping control model
  - exploit conservation laws
  - formalize & exploit symmetry
- Linearized analysis of stepping model fixed point stability
  - shows why & when Raibert stepping works
  - suggests more aggressive (model based) alternative stepping law

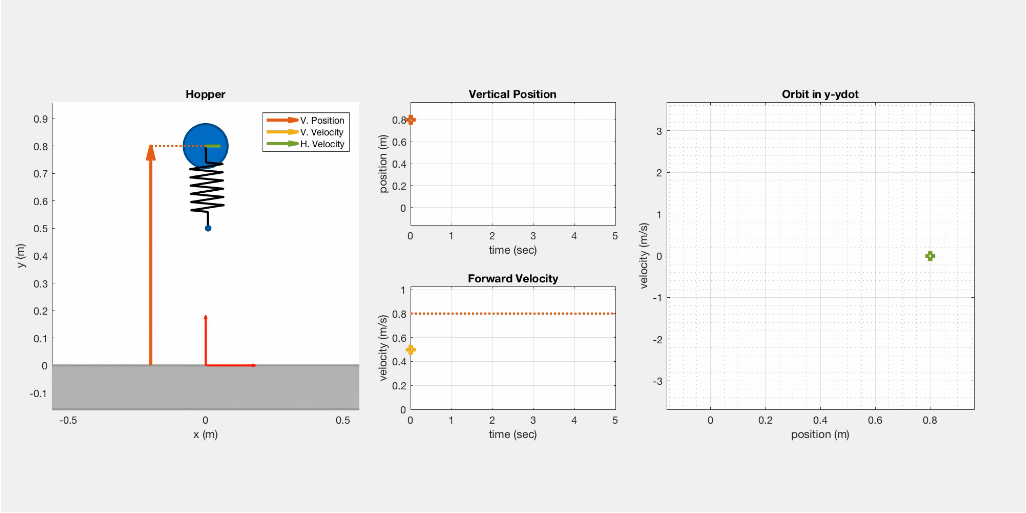




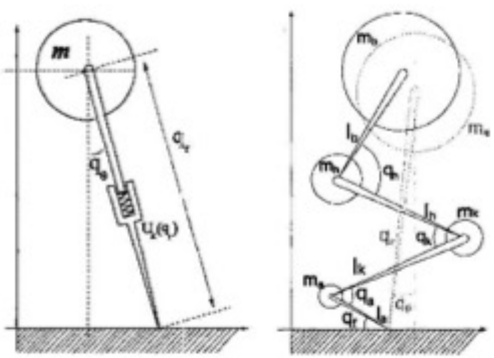




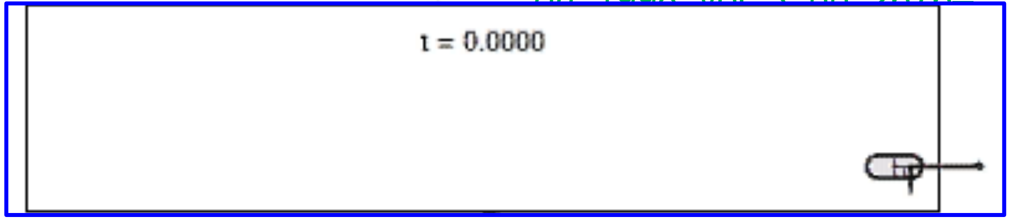
Week 11: Project #3: Higher DoF Systems



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

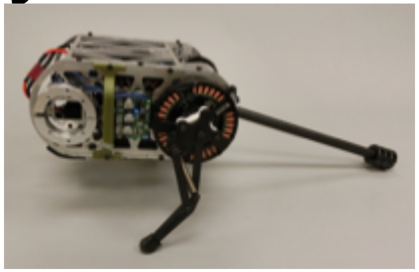


U. Saranli, W. J. Schwind, and D. E. Koditschek, "Toward the control of a multi-jointed, monoped runner," in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, 1998, vol. 3, pp. 2676



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. 4568–4569

Week 12 – Project #4: Jerboa Robot



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.

- 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. 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 monoped,” in Robotics Research, Springer, 2018, pp. 269–285.

edX Robo4 Mini MS – Locomotion Engineering

Week 1 – Unit 1

Big Picture and Motivation

Video 1.2

Segment 1.1.2
Overview of the Week

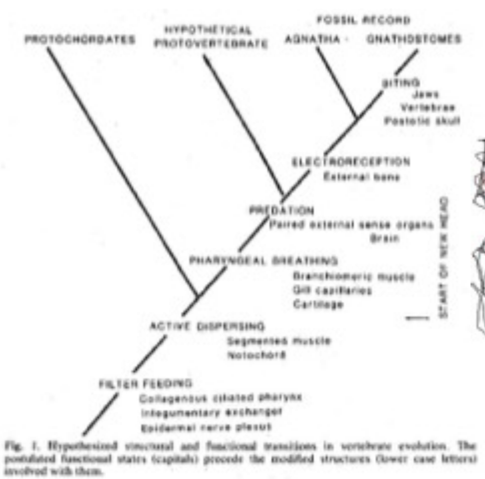
Daniel E. Koditschek
with
Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos
University of Pennsylvania
September, 2017

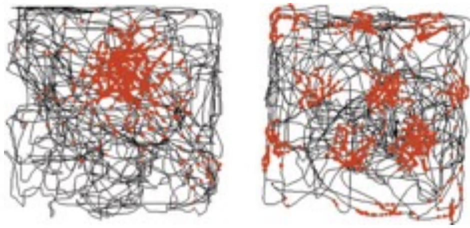
Principled Bioinspiration

- 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

[Alex Dunkel (Maky) - Own work]

T. Libby, A. M. Johnson, E. Chang-Siu, R. J. Full, and D. E. Koditschek, "Comparative Design, Scaling, and Control of Appendages for Inertial Reorientation," IEEE Transactions on Robotics, vol. 32, no. 6, pp. 1380–1398, Dec. 2016.



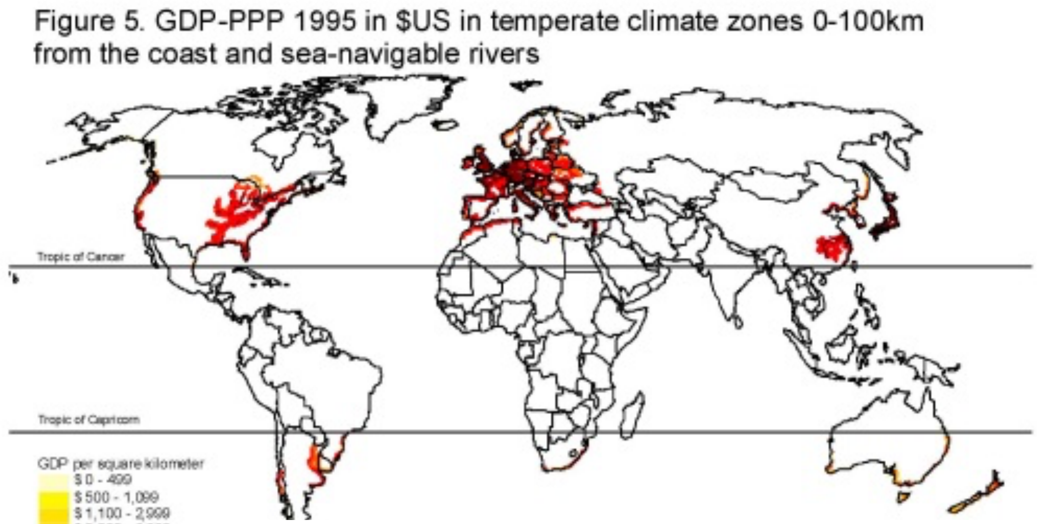


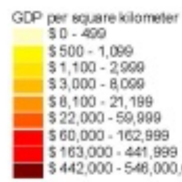
E. I. Moser, E. Kropff, and M.-B. Moser, "Place cells, grid cells, and the brain's spatial representation system," *Neuroscience*, vol. 31, no. 1, p. 69, 2008

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

Compelling Need

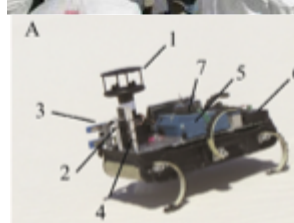
- Ground Mobility
  - for daily human affairs
  - for human [disasters]
  - and for human exploration





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.

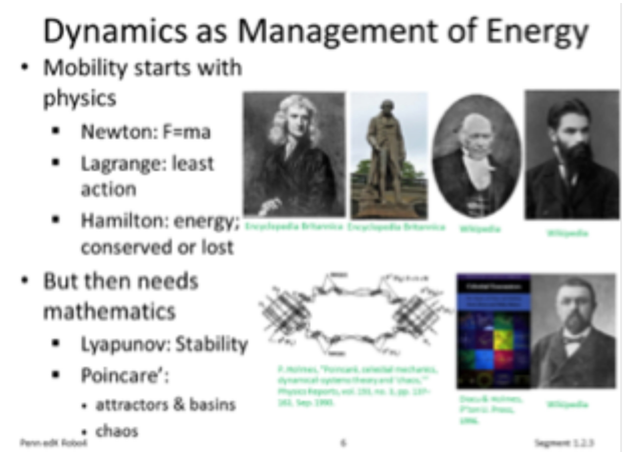
"'Scorpion' robot mission inside Fukushima reactor aborted," Phys.Org, 16-Feb-2017. [Online]. Available: https://phys.org/news/2017-02-scorpion-robot-mission-fukushima-reactor.html.

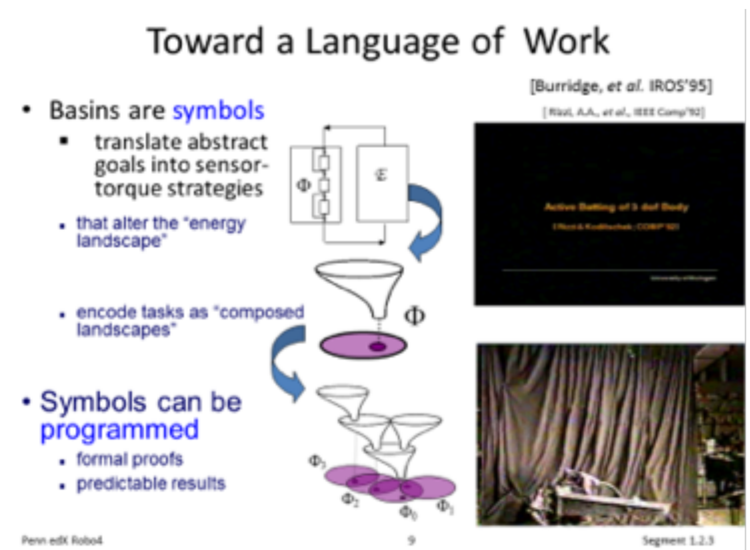


F. Qian et al., "Ground robotic measurement of aeolian processes," Aeolian Research, vol. 27, pp. 1–11, Aug. 2017.

Principled Engineering

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





edX Robo4 Mini MS - Locomotion Engineering:

Week 1 – Unit 2

Locomotion in Machines and Animals

Video 1.3

Segment 1.2.1

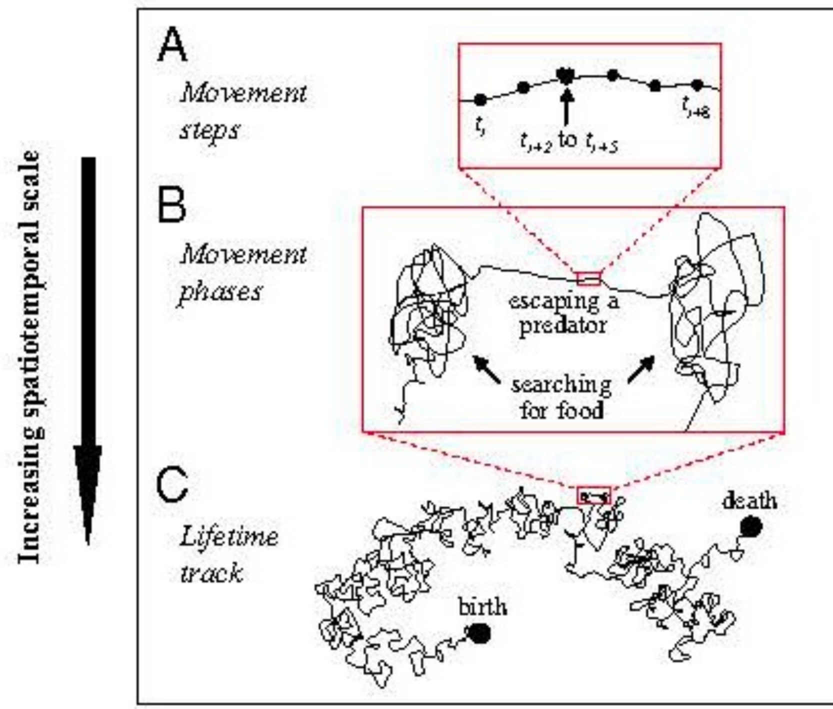
Need for Mobility

Daniel E. Koditschek
with
Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos
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

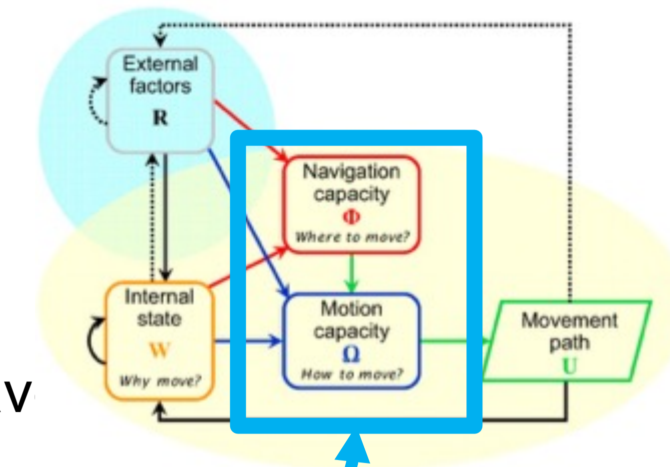


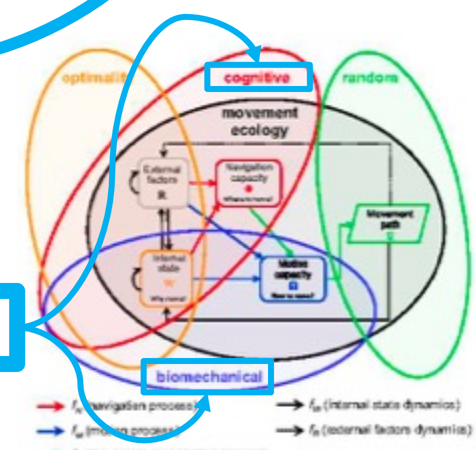
[R. Nathan, W. M. Getz, E. Revilla, M. Holyoak, R. Kadmon, D. Saltz, and P. E. Smouse, "A movement ecology paradigm for unifying organismal movement research," *Proceedings of the National Academy of Sciences*, vol. 105, no. 49, pp. 19052–19059, 2008.]

Why Do Animals Move?

our focus:
synthetic versions

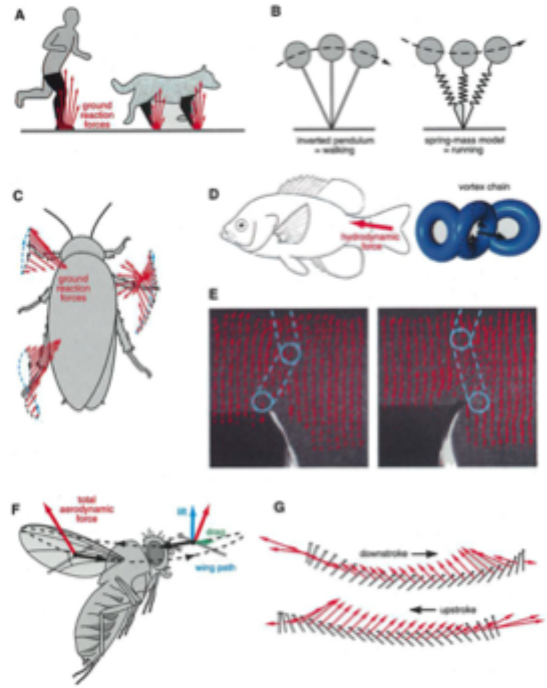
- Movement Ecology [Nathan et al., PNAS’08]
  - must understand at many scales
    - limbs over seconds
    - bodies over minutes
    - places over days
    - migrations over years
  - basic components of study
    - external (environment) & record of trav (paths)
    - motivational & evolutionary drivers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





[R. Nathan, et al. ” *Proceedings of the National Academy of Sciences*, 2008, op. cit.]

How Do Animals Move?

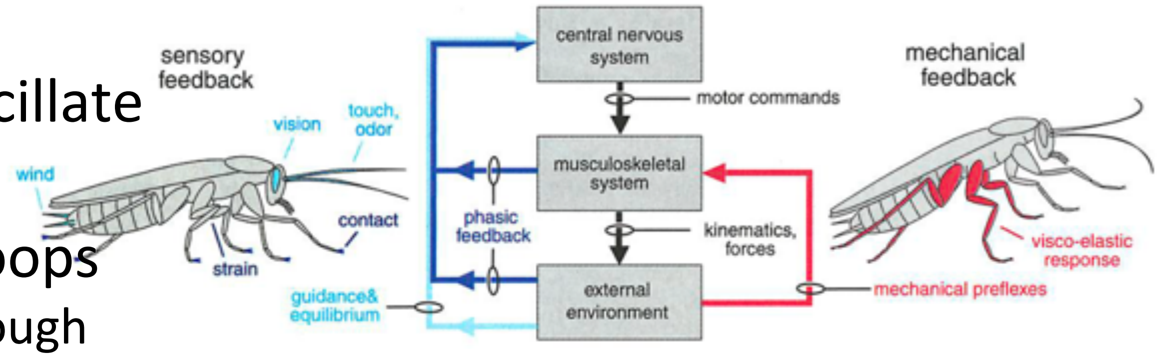


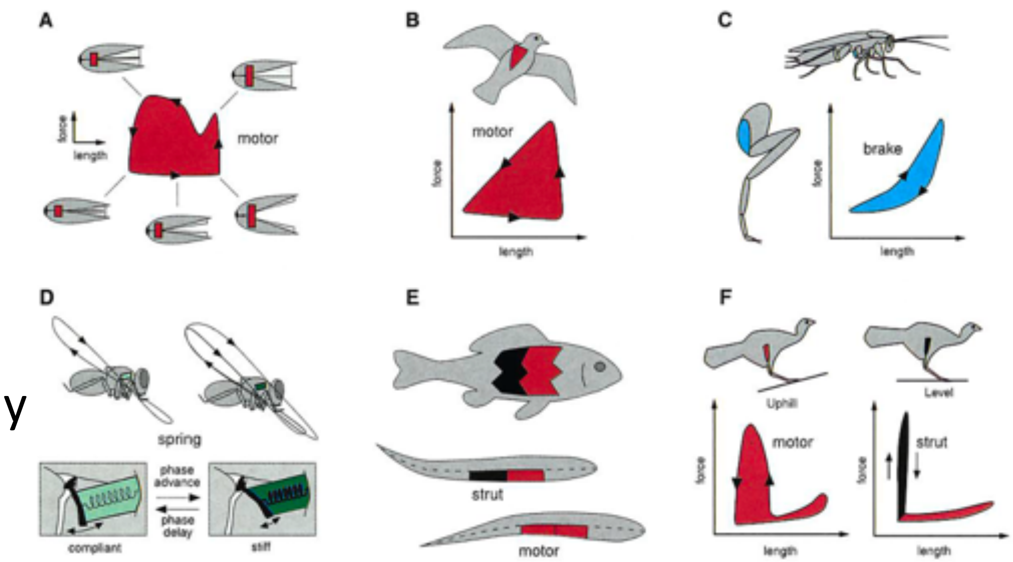
- Newton says
  - body accelerates due to force
  - of reaction against environment
  - carried by appendages
- Now begins a long, unfinished story
  - appendages must oscillate
  - in tight coordination

[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

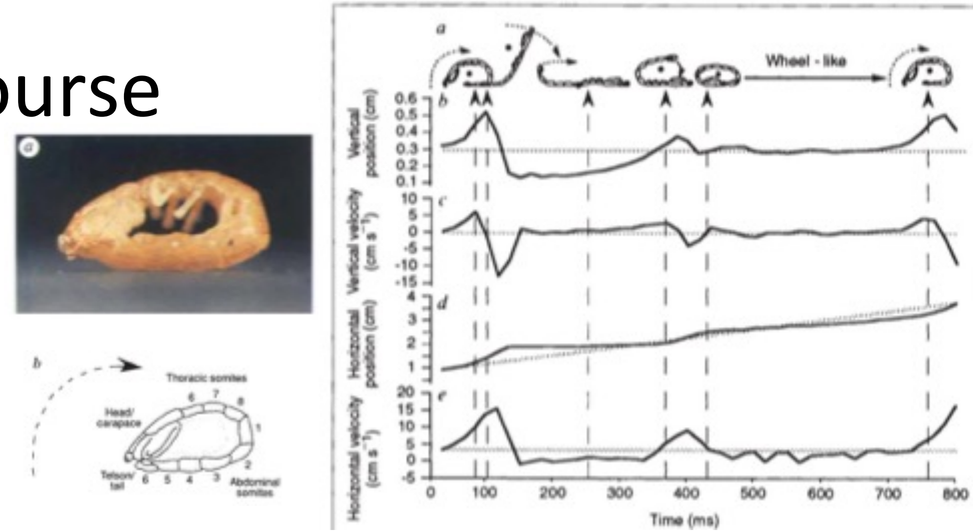




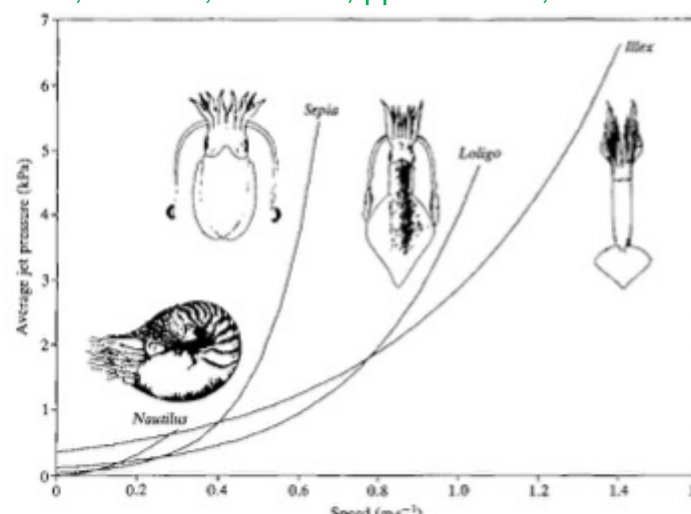
[M. H. Dickinson, et al., *Science*, 2000, op. cit..]

How Don’t Animals Move?

- Animals inspire this course
  - limbed mobility
  - body-based sensing
- On land
  - they stride
  - no wheels?
    - molecular motors
    - mantis shrimp
- In liquid
  - they slither or swim
  - no jets?
    - squid (“just hearts set free”)
    - inefficient to contain reaction mass



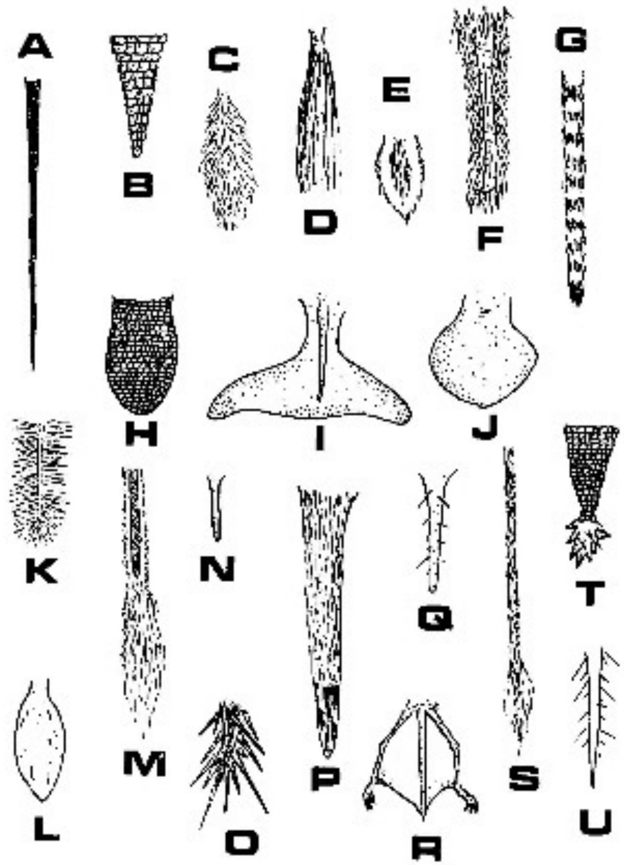
[R. Full, K. Earls, M. Wong, and R. Caldwell, “Locomotion like a wheel?,” *Nature*, vol. 365, no. 6446, pp. 495–495, Oct. 1993]



[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.]

[Alex Dunkel (Maky) - Own work]

["American Beaver" by Steve from washington, dc]

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.]

edX Robo4 Mini MS - Locomotion Engineering:

Week 1 – Unit 2

Locomotion in Machines and Animals

Video 1.4

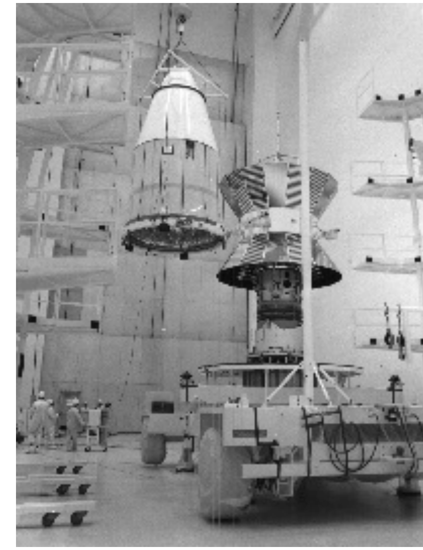
Segment 1.2.2

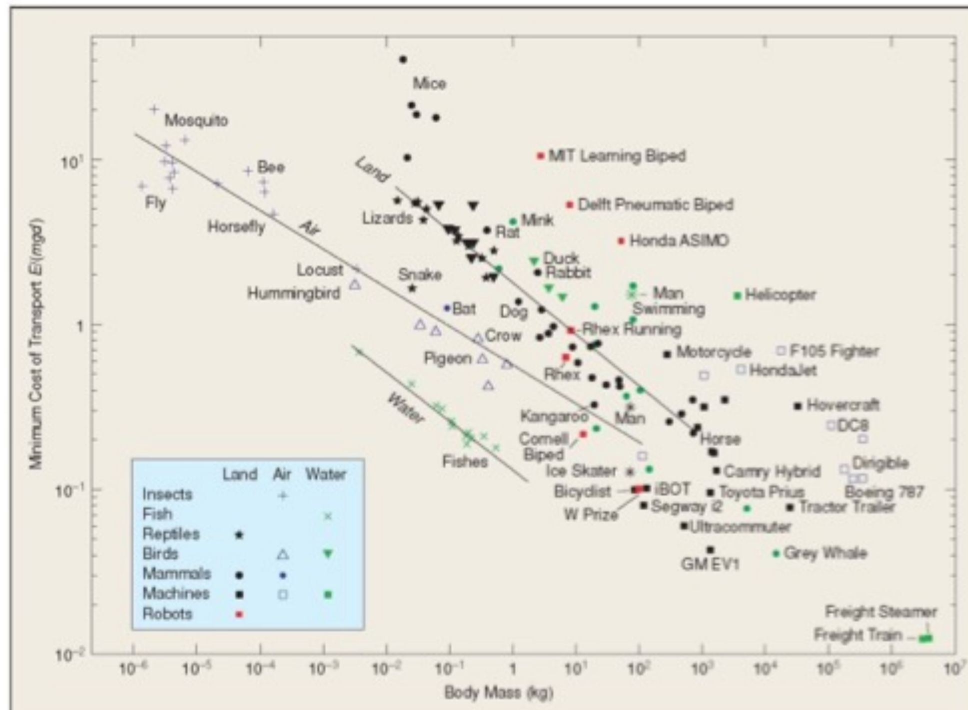
Bioinspiration

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/ = 0.000234[c](#))
  - more load: MSC Oscar (~200,000 m^3)
- Animals – generalists
  - e.g., efficiency
    - specific resistance: Energy/load-distance $= \int$ Power/mass-speed dt
  - unmatched on general terrain

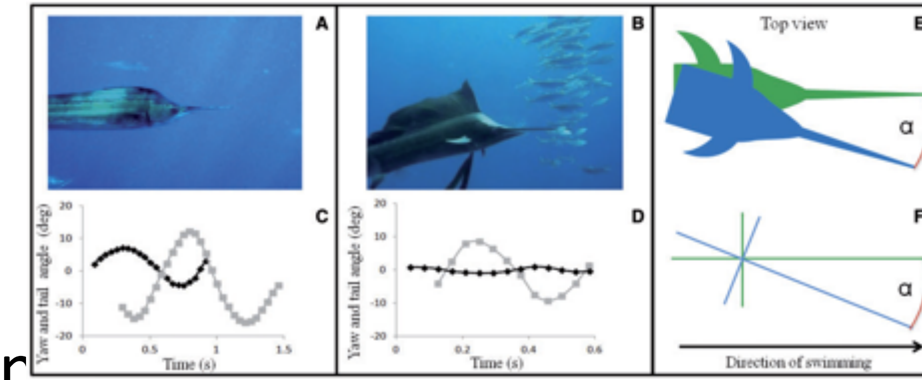




[A. D. Kuo, "Choosing Your Steps Carefully," *IEEE Robotics & Automation Magazine*, vol. 14, no. 2, pp. 18-29, Jun. 2007]

Machines Move Better?

- Machines – specialists
- Animals – generalists
  - cheaper on general terrain
  - at least as agile
    - Porsche: 12 m/s^2 ¼ 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,

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”

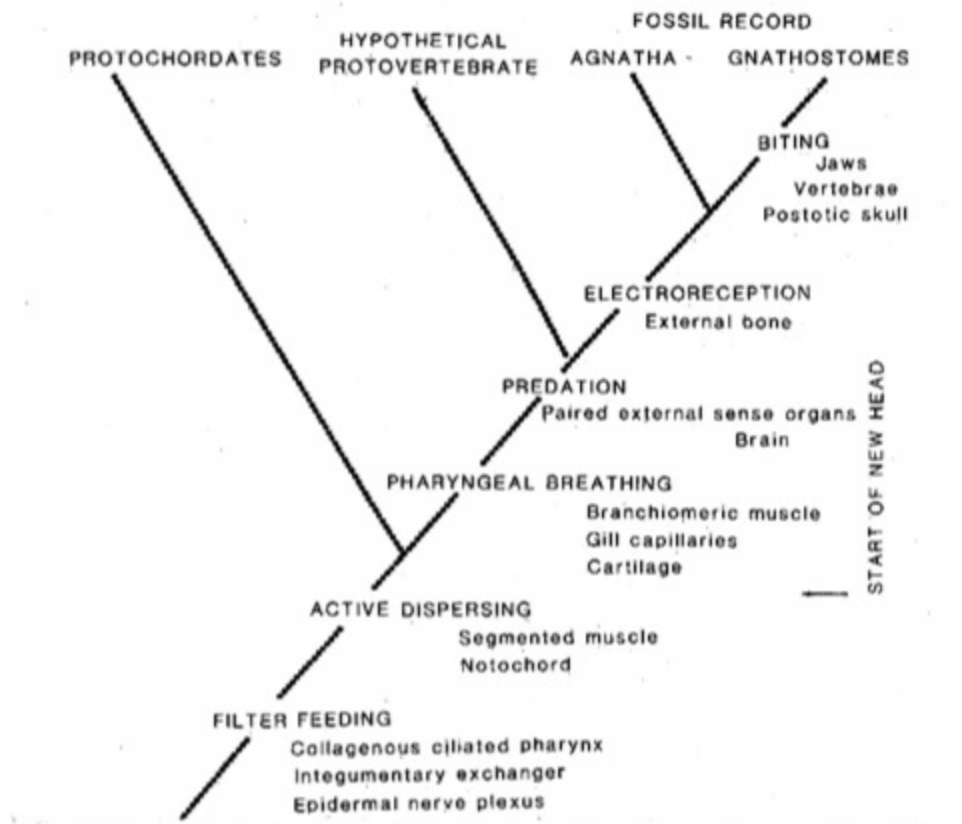
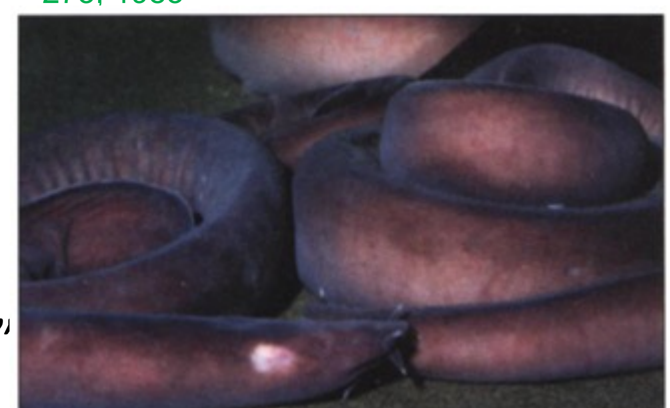


Fig. 1. Hypothesized structural and functional transitions in vertebrate evolution. The postulated functional states (capitals) precede the modified structures (lower case letters) involved with them.

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

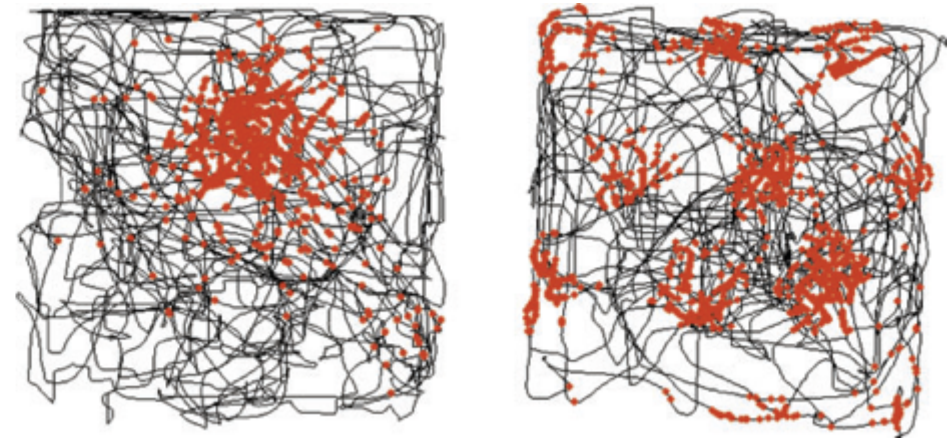


First Vertebrates may have resembled the Hagfish

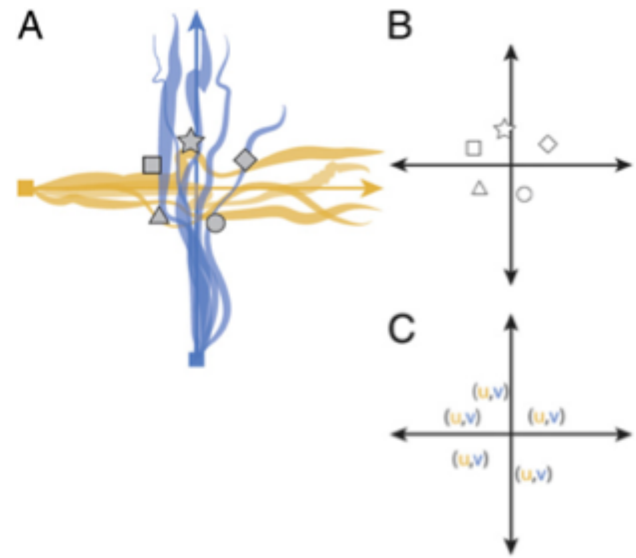
C. Zimmer, “In Search of Vertebrate Origins: Beyond Brain and Bone,” *Science*, vol. 287, no. 5458,

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

edX Robo4 Mini MS – Locomotion Engineering

Week 1 – Unit 2

Locomotion in Machines and Animals

Video 1.5

Segment 1.2.3

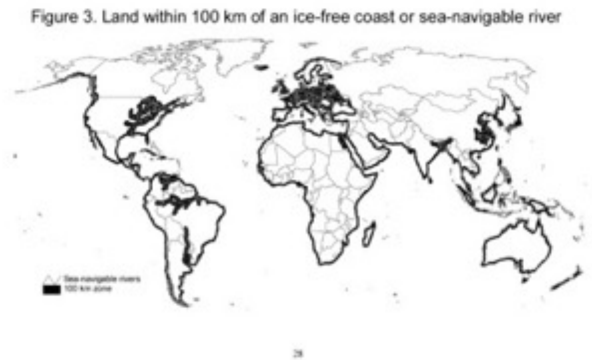
Legged Mobility

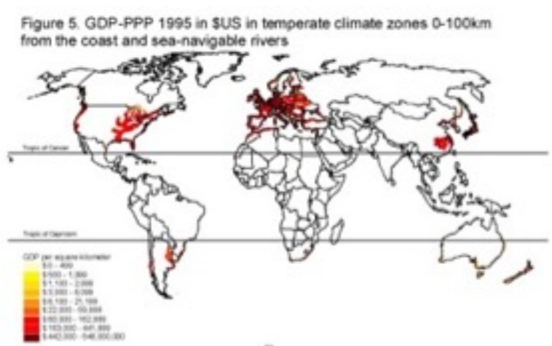
Daniel E. Koditschek
with
Wei-Hsi Chen, T. Turner Topping and Vasileios Vasilopoulos
University of Pennsylvania
September, 2017

Ground Mobility – Where Humans Live

- Navigable, temperate earth ecozones
  - 8% world's inhabited landmass
  - 50% world's economic output
- Inhospitable environments
  - construction, mining, …
  - disaster

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.





[US MSHA]

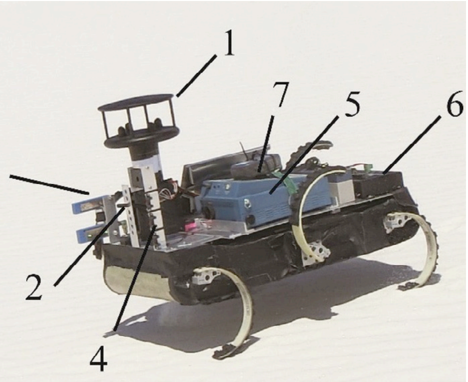
Rick Bowmer, Reuters

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.



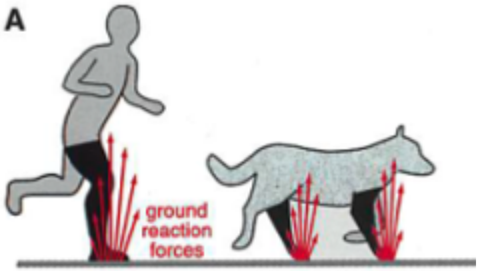
F. Qian et al., "Ground robotic measurement of aeolian processes," Aeolian Research, vol. 27, pp. 1–11, Aug. 2017.

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

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



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

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.

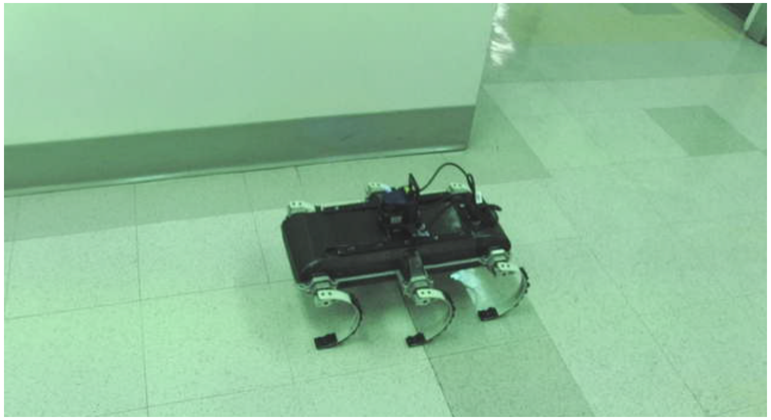
A. M. Johnson and D. E. Koditschek, “Toward a vocabulary of legged leaping,” in *IEEE Int. Conf. Rob. Aut.*, 2013, pp. 2553–2560

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

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

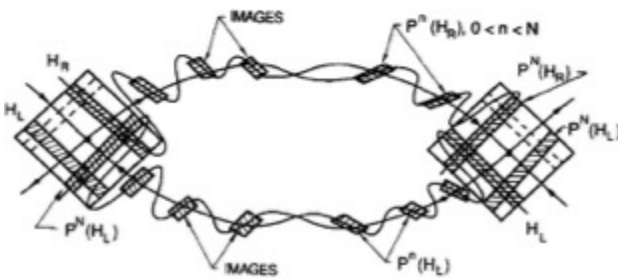
Encyclopedia Britannica

Encyclopedia Britannica

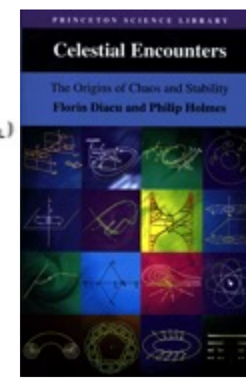
Wikipedia

Wikipedia

- But then needs mathematics
  - Lyapunov: Stability
  - Poincare':
    - attractors & basins
    - chaos



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

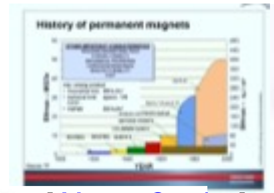


Diacu & Holmes, P'ton U. Press, 1996.

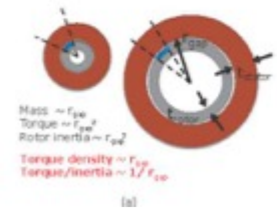
Wikipedia

Energy Exchange: Topics Not Covered

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

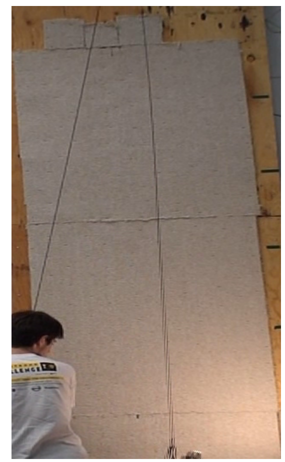


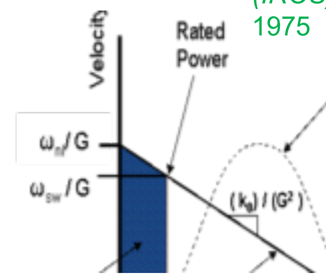
[Maxon Catalog]



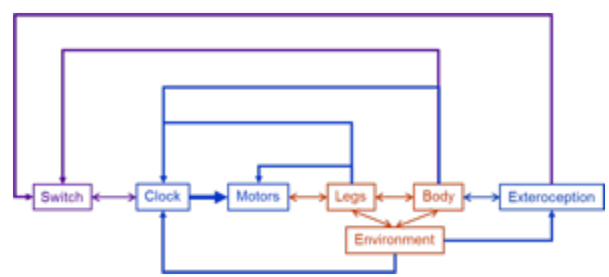
S. Seok, A. Wang, D. Otten, and S. Kim, "Actuator design for high force proprioceptive control in fast legged locomotion," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct., pp. 1970–1975

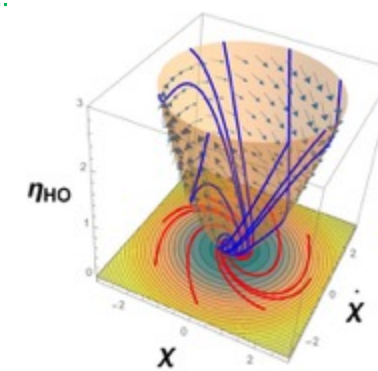
Dickinson, et al., *Science*, 2000, Op. Cit.





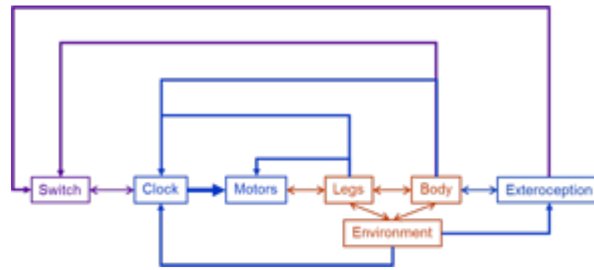
G. A. Lynch, J. E. Clark, P.-C. Lin, and D. E. Koditschek, "A bioinspired dynamical vertical climbing robot," *The International Journal of Robotics Research*, vol. 31, no. 8, pp. 974–996, Jul. 2012.

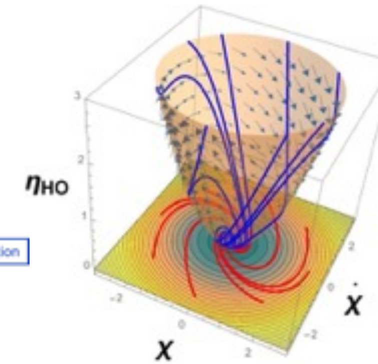




Programming the Exchange of Energy

- 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



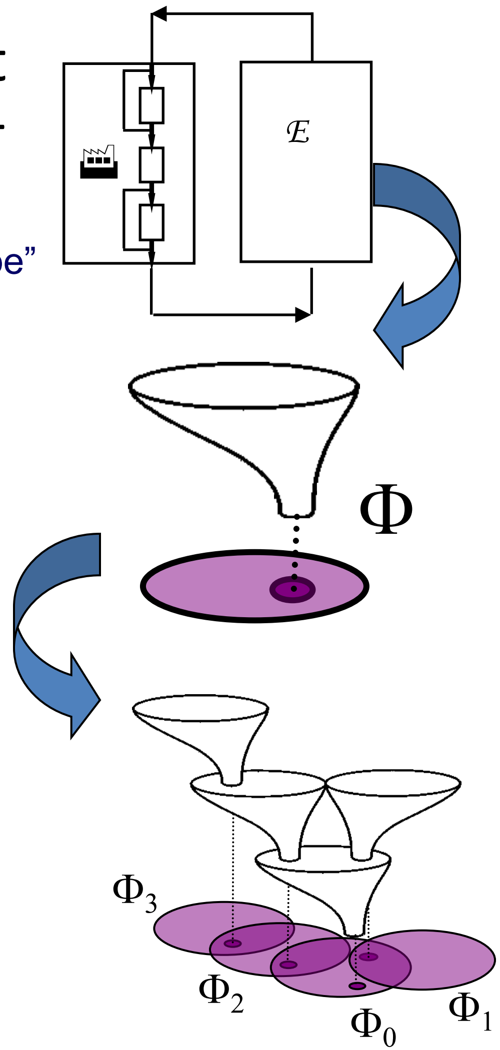


A. De and D. E. Koditschek, "Averaged anchoring of decoupled templates in a tail-energized monoped," in Robotics Research, Springer, 2018, pp. 269–285.

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]