Bio-inspired Design of Systems

A workshop for undergraduate researchers

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This is an attempt to draw attention to instances in nature that spark our interest in "how things work". Understanding these examples from a combination of physical, mathematical, biological, and engineering perspectives can lead to handsome dividends in the form of novel designs for systems that work well. It is important to note that the path from curiosity to understanding, inspiration and invention is not a linear one.

Outline

This workshop will explore the idea that nature has evolved specific and conserved solutions for certain problems that, when properly investigated using physical and mathematical reasoning, can be translated to engineering systems.

Borrowing the language of computer engineers, we will discuss this in terms of hardware design, software design, and hardware-software co-design, as illustrated in three specific biological contexts, and associated engineering applications.

We will allow room for some fun hands-on exploration of ideas, present a few equations, and end with a session of discussions.

1(a). Discuss **the flight video by John Maynard Smith**, and the problem of longitudinal flight stability.

1(b). What do we learn from 1(a)? The right hardware (tail) solves the problem.

1(c). Resulting engineering designs. The joint strike fighter design imitates raptors. RAPTOR –DVD show (1 hr).

2(a). Discuss the flight videos of moth (with and without vibratory gyroscope antennae) from the laboratory of **Thomas Daniel** (University of Washington).

2(b). What do we learn from 2(a)? The right sensing and its exploitation in sensorimotor feedback loops (algorithms) solve the problem.

   The early work of Pringle on halteres in *Diptera* (mentioned by Maynard Smith) discusses another solution found in nature.

2(c). Resulting engineering designs – MEMS gyroscopes. These have antecedents in earlier design (the hemispherical resonant gyroscope, the tuning fork gyroscope). Think of application to the **Ballbot.**

   Unifying physical principle here is that of exploiting the **Coriolis Effect** – mention example of ball set rolling on a turntable. Use gyroscopes from home, including the electrically driven ones and the gyro in a cylinder. Write down equations.

3(a). Discuss the roller racer and plasma car (with videos), **mimicking snake-like undulatory locomotion**.

3(b). What do we learn from 3(a)? Configuration and control can be co-designed.

3(c). Inspiration – not just hardware but also software (sensorimotor signal processing algorithms).

   Underlying physical principle here is that of locomotion exploiting constraints.

4. Future – flapping wing vehicles on planet MARS?

5. Other topics – molecular motors.

6. HOMEWORK Assignment. - How does a bat capture prey in the dark?

Three topics

- The tail
- Insect gyroscope
- Undulatory locomotion

(1) The tail

- John Maynard Smith discusses the problem of longitudinal flight stability (30 min.) (http://www.vega.org.uk/video/programme/84)

- We learn that the right hardware (tail) solves the problem.

- Related engineering designs: the joint strike fighter design imitates raptors. Raptor video (DVD) from PBS (1 hour show).

John Maynard Smith (engineer-biologist) 1920-2004
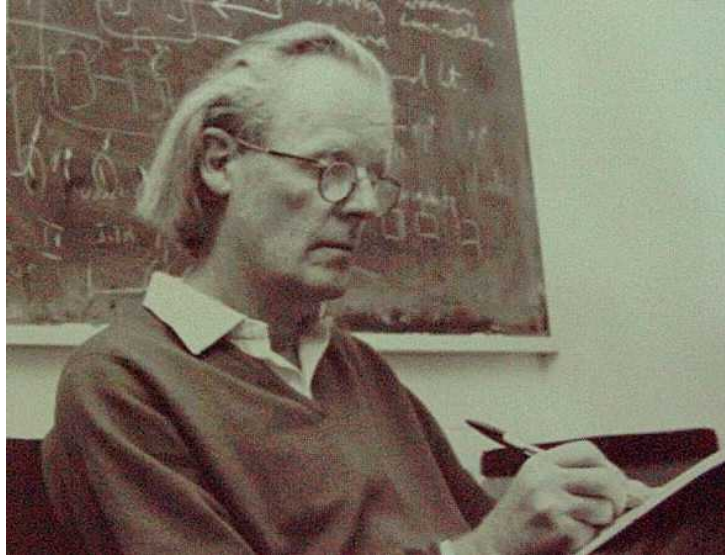
J. Maynard Smith and G.R.Price (1973). *Nature*, **246**:15-18.
J. Maynard Smith (1982). *Evolution and the Theory of Games*, Cambridge U. Press.

R.A. Fisher, William Donald Hamilton, John Maynard Smith all addressed fundamental questions in biology – what is the genetic basis for 1:1 sex ratio? why certain behavioral strategies prevail?, etc.

John Maynard Smith (who trained as an aeronautical engineer at Trinity College, Cambridge, and designed aeroplanes during WW II before starting afresh in biology), and George Price, formulated Evolutionary Game Theory in their famous 1973 paper. A key concept of the theory was that of an evolutionarily stable strategy (ESS). It was anticipated in John Nash's thesis (Non-cooperative Games, 1950, Mathematics Department, Princeton University) in two paragraphs that did not find their way into Nash's journal publications.

(2) Insect Gyroscope

- Flight videos of moth (with and without vibratory gyroscope antennae) from the laboratory of Thomas Daniel (University of Washington).

- We learn that the right sensory signal, and its exploitation in sensorimotor feedback loops (algorithms), solve the problem of flight stabilization. The early work of Pringle on halteres in *Diptera* (mentioned by Maynard Smith) discusses another solution found in nature.

- Related engineering designs – MEMS gyroscopes. These have antecedents in earlier design (the hemispherical resonant gyroscope, the tuning fork gyroscope).

- Unifying physical principle here is that of exploiting the Coriolis Effect (see equations). Hands-on gyroscopes.

Hawkmoth and its Gyroscope

Movies from Professor Daniel's lab (University of Washington, Seattle); supplementary material for the paper

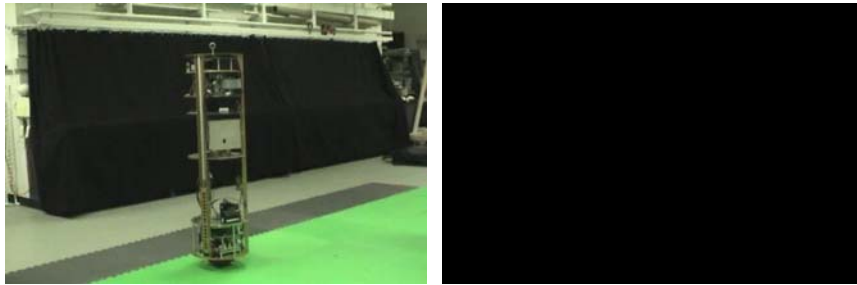Sane S., Dieudonne A., Willis M., and Daniel T., *Science*, 315:863-866 (2007)

http://www.sciencemag.org/cgi/content/abstract/315/5813/863

(1)   Intact antennae

(2)   Detached antennae

(3)   Re-attached antennae

Here we show how feedback from sensing elements is essential. In the case of the hawkmoth, the antennae appear to function as (vibratory) gyroscopes.

Ballbot and Stability (CMU)

See more extensive presentation at
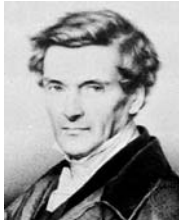http://www.youtube.com/watch?v=7KPOOUsNRe4

In this project, led by Dr. Ralph Hollis and Dr. George Kantor, a 3D version of the inverted pendulum problem is solved using feedback.

Rotating frames and forces

Acceleration in lab frame of a particle Q in rotating frame

$$\ddot{q} = B(\ddot{Q} + 2\Omega \times \dot{Q} + \Omega \times (\Omega \times Q) + \dot{\Omega} \times Q)$$

inertial

centrifugal
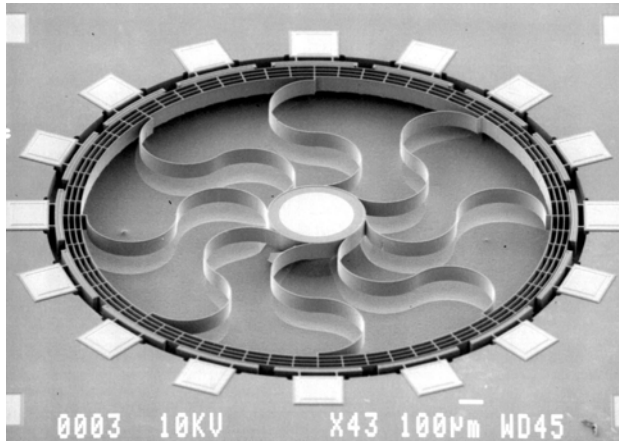
coriolis

Gaspard-Gustave de Coriolis
1792-1843

NASA - GSFC

Sense rotation by sensing coriolis force

Vibratory MEMS gyroscope

From University of Michigan group and F. Ayazi at Georgia Tech

http://en.wikipedia.org/wiki/Vibrating_structure_gyroscope and
http://www.bosch-esperience.co.uk/uk/language1/flash/videos/the_falling_box.html

(3) Undulatory Locomotion

- The roller racer and plasma car (with videos), mimicking lamprey-like undulatory locomotion.

- We learn that configuration and control can be co-designed (in novel ways). The environment matters.

- Software – sensorimotor signal processing algorithms.

- Rectification principle

Roller Racer

Lamprey

United States Patent

Hendricks

[15] 3,663,038

[45] May 16, 1972

[54] **VEHICLE WITH COMBINATION STEERING, BRAKING AND PROPULSION MEANS**

[72] Inventor: **William E. Hendricks**, Wichita, Kans.

[22] Filed: **Apr. 6, 1970**

[21] Appl. No.: **25,762**

[52] U.S. Cl.................................**280/218, 280/87.0, 188/5**
[51] Int. Cl...**B62m 29/00**
[58] Field of Search 280/87.01, 87.02, 87.03, 87.04,
280/87.05, 88, 218, 7.1, 7.15, 7.12, 263, 47.17;
188/2, 5, 20, 119

[56] **References Cited**

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3,345,080	10/1967	Schneiderman	280/87.01
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881,450	11/1961	Great Britain	280/87.02

Primary Examiner—Kenneth H. Betts
Attorney—Robert E. Breidenthal

[57] **ABSTRACT**

A vehicle of a very low profile and very high stability, wherein an integral seat constitutes the vehicle frame. A pair of laterally spaced wheels are mounted on the rear of the seat, and an elongated arm is pivoted intermediate its ends to the front of the seat about a vertical axis, and a dirigible wheel is mounted on the arm rearwardly of the vertical axis. A footrest is secured to the arm forwardly of the vertical axis, whereby a rider can swing the arm to steer the vehicle and also cause propulsion thereof. A brake is pivotally mounted on the arm, with handle actuating means being provided therefor which can be employed to control the brakes and/or swinging movement of the arm. Alternate movement of the arms, legs, and body to the right and left of the desired steering direction coupled with twisting movement of the body results in effecting propulsion of the vehicle in a manner somewhat analogous to the propulsion of a boat by a sculling oar. One version of the vehicle includes a single U-shaped bar to constitute a footrest and handles, and this version includes provision for releasably latching the brake from its breaking condition.

38 Claims, 12 Drawing Figures

14

"While the manner in which the rider can operate and cause the vehicle 10 to be self-propelling can be and is hereinafter described in detail, the actual mechanism or theory of operation may be only partially understood and may even be erroneous, and while such theory is set forth, it is not desired to be bound by such theory of operation, **as it is possible to make, use, and enjoy the vehicle of this invention without knowledge of or understanding the correct theory of operation whatever it may be**."

- William E. Hendricks, US Patent 3,663,038 (1972)
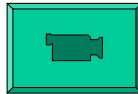
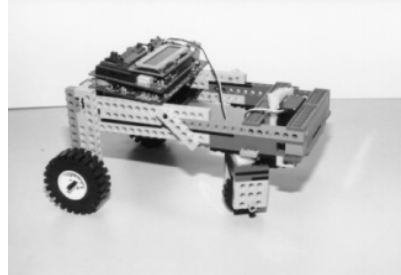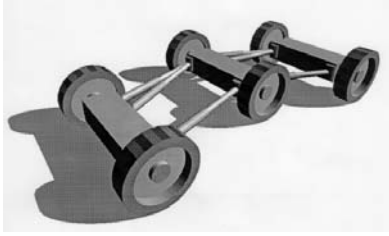# Roller Racer & friends

Plasma car

Roller Racer Movies

Sean -straight line motion
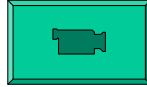
Sameer - circular arcs and figure eight

Roller Racer Prototypes

Nonholonomic Integrator & Rectification Principle
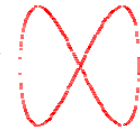
R. W. Brockett

$$\dot{x} \quad = \quad u$$

$$\dot{y} \quad = \quad v$$

$$\dot{z} \quad = \quad xv \ - \ yu$$

$$\langle \dot{z} \rangle \quad = \quad \frac{2 \ Area}{T}$$

Average rate of growth in z

Lissajous figure

The roller racer achieves locomotion by rectification of the oscillatory input (at the handle bars). The details of this process constitute a rich story in mechanics and control theory. But the essentials can be understood by the above simplified version, the nonholonomic integrator (of Roger W. Brockett).

When the control signals u and v are chosen to be sinusoids then the x and y variables trace a Lissajous figure. In the example shown, x = sin(t) and y = cos(2t).

The z variable oscillates but also has a DC component which has the average growth rate given by the "area rule" above, where the "Area" is that of the Lissajous figure.

Questions?