Coupling of Locomotion Control and Sensing in Biological Systems
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Motivation: Active Sensing in Biology

- Halteres in flies [photo: wikipedia]
- Head bobbing in birds [www.reinhold-necker.de]
- Vibrissae system in rodents [photo: wikipedia]
- Surging/casting behaviour in plume tracking [photo: wikipedia]
Beyond Active Sensing: the Hawkmoth *Manduca sexta*

- The actuation required for locomotion in the Hawkmoth enables sensing
  - Abdomen-based pitch control
  - Wing stroke kinematics
- Both enable gyroscopic sensing through induced Coriolis forces and strain sensing
- Actuators achieve simultaneous control and sensing goals

![Hawkmoth Manduca sexta hovering](image)

[Credit: Daniel Lab, UW Biology Department]
Outline

Nonlinear Observability
Abdomen Control
Wake Sensing
Wing Flapping
Conclusion
Given an analytic control affine system:

$$\dot{x} = f(x, u) = f_0(x) + \sum_{i=1}^{m} f_i(x)u_i \quad y = h(x)$$

Take derivatives of output, assuming $u(t)$ analytic function of time:

$$Y = \begin{bmatrix} y^{(1)} \\ y^{(2)} \\ \vdots \\ y^{(n-1)} \end{bmatrix} = \begin{bmatrix} L_f h \\ L_f^2 h \\ \vdots \\ L_f^{n-1} h \end{bmatrix}$$

Then $Y$ is a polynomial function of $u^{(k)}, k = 0, \ldots, n - 2$, with coefficients that are analytic functions of $x$. 
Nonlinear Observability Analysis (cont’d)

Theorem (Nonlinear Observability\(^1\))

The nonlinear system is locally observable at \(x_0\) iff \(dY = \frac{\partial}{\partial x} Y\) has rank \(n\) at \(x_0\), and the first \(n - 1\) derivatives determine local observability.

- Actuation alters the relative observability of each state
- Properties of \(dY\) give measure of observability
  - e.g., \(\|dY\|_F\) gives measure of region of attraction for Newton’s method
- Use \(dY\) to design optimal control and sensor placement algorithms

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Observability via Linearization About Trajectory

Linearize nonlinear system about \((x^0(t), u^0(t))\) to get LTV system:

\[
\dot{x} = A(x^0(t), u^0(t))\dot{x} \\
\dot{y} = C(x^0(t))\dot{x}
\]

Compute output energy:

\[
\|\dot{y}(t)\| = \dot{x}_0^T \int_{t_0}^{t_1} \Phi^T(\tau, t_0)C^T(x^0(\tau))C(x^0(\tau))\Phi(\tau, t_0)\,d\tau \dot{x}_0
\]

\[
= \dot{x}_0^T W(t_1, t_0)\dot{x}_0
\]

**Theorem (LTV Observability)**

The LTV system is observable and the NL system is locally observable about \((x^0, u^0)\) iff \(W(t_1, t_0)\) has rank \(n\).
Observability Gramian as a Measure of Observability

- Eigenvalues of $W$ measure observability of each mode (eigenvectors)
- $\lambda_{\min}(W)$ is Euclidean distance to singular matrices (unobservability)
- $\kappa(W)$ gives shape of observation (estimation uncertainty) ellipsoid
- Proportional to FIM for iid sensor noise, inverse of estimation covariance
Deforming Airframe Control in the Hawkmoth

- Abdomen pitch control mechanisms
  - CG location
  - Inertial redirection of lift vector
- Encoded yaw & roll rate information
  - Lateral Coriolis forces
  - Strain sensing on abdomen
System Abstraction

- Goal: demonstrate capability to detect yaw rates from abdominal deflections
- Abstracted as a pendulum on a rotating base:
  - Rigid in pitch direction
  - Flexible in lateral $y_p$ direction
  - Base is rotated in yaw
- Flexibility modeled using Euler-Bernoulli beam
Results of Abdomen Study

- Abdomen motion required for pitch control and required for yaw/roll rate observability.
- Robotic abstraction of abdomen used to demonstrate yaw rate estimation.

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Wake Sensing from Wing Kinematics

- Animals may use various sensors to detect flow disturbances
  - hairs on bats
  - strain sensing on insects
  - lateral line on fish
- Using flow velocity sensors, can vortices be detected?
- Where should the sensors be placed for best observability?
Observability-Based Sensor Placement

- Discretize sensor space

- Define sensor activation function $\alpha_i \in \{0, 1\}$

- Results in convex optimization problem with $\ell_1$ sparsity:

$$
\max_{\alpha} \quad \lambda_{\min}(W(\alpha)) - c \|\alpha\|_1
$$

subject to $0 \leq \alpha \leq 1$
Optimal Sensor Placement Results

- Optimal sensor sets yield better UKF performance than 99% of randomly sampled sets
- Optimal sensors found in pairs near trailing edge, correlate well with findings of bat study

Wake estimation error for random and optimal sensor sets

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Gyroscopic Sensing in Hawkmoth Wings

- Similar to fly halteres and antennae in moths, the wings may serve as gyroscopic sensors.
- Wings are covered in hundreds of strain-like sensors.
- How might observability tools inform role of strain sensors?

Locations of campaniform sensilla on a hawkmoth wing [Brad Dickerson, UW Biology]

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Reduced-Order Modelling

Wing Properties
- Experiment apparatus for material properties estimation [Combes & Daniel]

Finite Element Model
- First Mode Shape of FEM
- Thin airfoil aerodynamics using local deformed wing shape

Stroke Kinematics
- Fit of Measured Wing Kinematics [Nakata & Liu]

Simulated Flapping
- Simulated flapping cycle
Locomotion control and sensing are tightly coupled in many flying and swimming animals.

Observability tools give insight into these systems:

- What information sensors can encode
- How actuation enhances sensing capabilities

The Hawkmoth *Manduca sexta* hovering
[Credit: Daniel Lab, UW Biology Department]
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