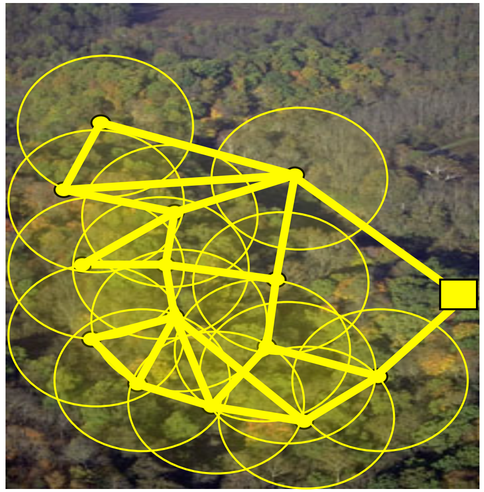
Analysis and Control of Flapping Flight: from Biological to Robotic Insects



Luca Schenato

Robotics and Intelligent Machines Laboratory

Department of EECS

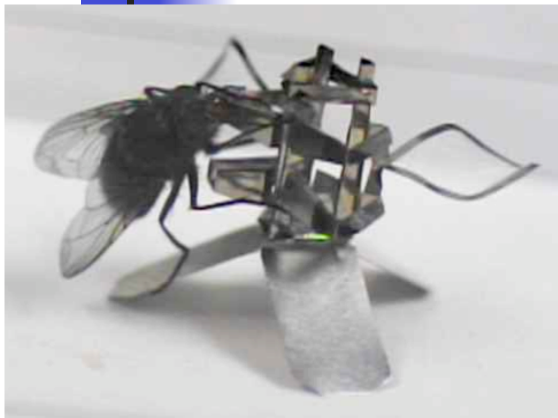
University of California at Berkeley

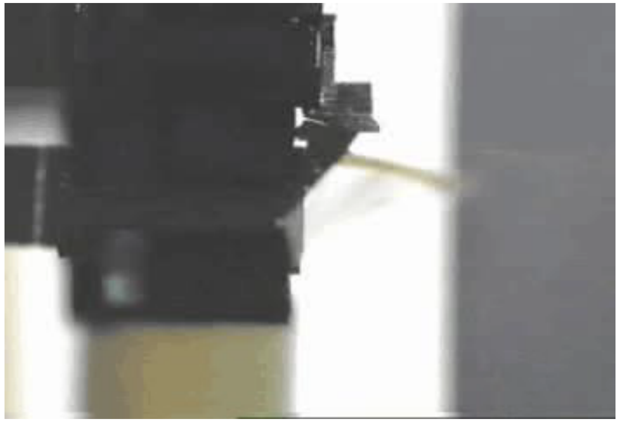
Biomimetic Flying Insects

- Overview and motivations
- True insect flight (Biomimetics)
- Averaging theory
- Flapping flight control

Micromechanical Flight Insect Project* (MFI)

*MURI-ONR





- **Objective**: 10-25mm (wingtip-to-wingtip), autonomous flapping flight, solar-cell powered, piezoelectric actuation, biomimetic sensors
- **Applications:** surveillance, search & rescue in hazardous and impenetrable environments
- **Advantages:** highly manoeuvrable, small, inexpensive
- **Interdisciplinary:** 4Dept (Bio,EE,ME,CS,Material S.), 6 profs., 10 students

Motivating Questions:

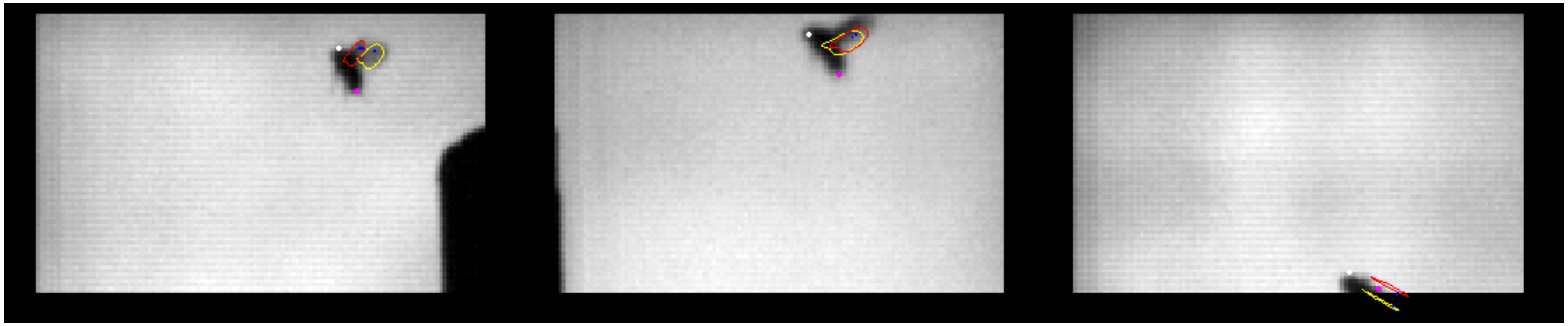
- **Biological perspective:**
  - How do insects control flight ?
  - Why are they so maneuverable ?
- **Engineering perspective:**
  - How can we replicate insect flight performance on MFIs given the limited computational resources?
  - How is flapping flight different from helicopter flight ?
- **Control Theoretic perspective:**
  - What’s really novel in flapping flight from a control point of view ?

Contribution:

- **Biological perspective:**
  - Constructive evidence that flapping flight allows independent control of 5 degrees of freedom
- **Engineering perspective:**
  - Averaging theory and biomimetics simplify control design
  - Periodic proportional feedback sufficient to stabilize several flight modes
- **Control Theoretic perspective:**
  - Flapping flight as biological example of high-frequency control of an underactuated system

Previous work: biological perspective

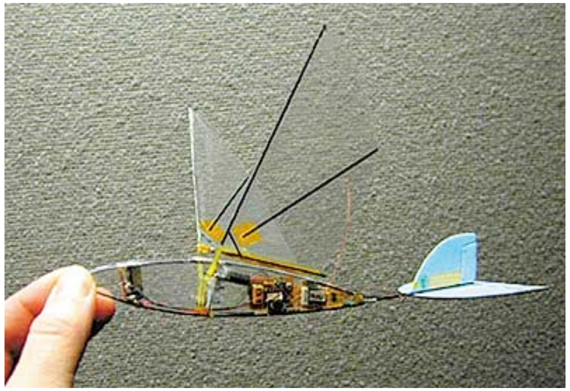
Courtesy of S. Fry



- Seminal work by C. Ellington and M. Dickinson for insect aerodynamics (80-90s)
- Correlation available between flight maneuvers and wing motions
- Partial evidence that insect can control directly 5 degrees of freedom out of the total 6

Previous work: Micro Aerial Vehicles (MAVs)

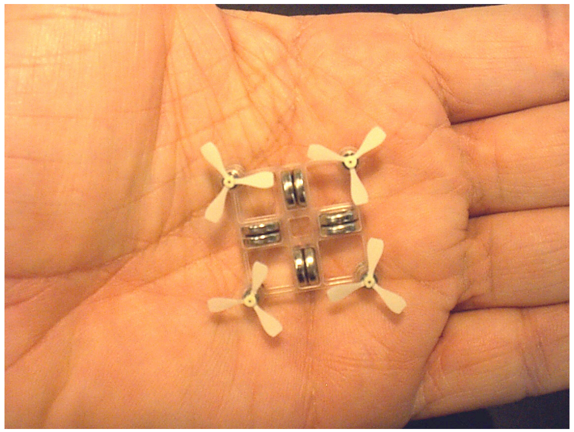
Microbat at Caltech



Entomopter at GeorgiaTech

Black Widow by Aerovinment Inc.

Mesicopter at Stanford



Previous work: control theory

- **Fish locomotion:**
  - [Mason, Morgansen, Vela, Murray, Burdick 99-03]
    - Underactuated systems
    - Averaging theory
- **Anguilliform locomotion (eels):**
  - [McIsaacs 03, Ostrowski 98]
    - Symmetry
    - Averaging theory
- **Flapping flight**
  - … ?

Periodic motion of appendages is rectified into locomotion

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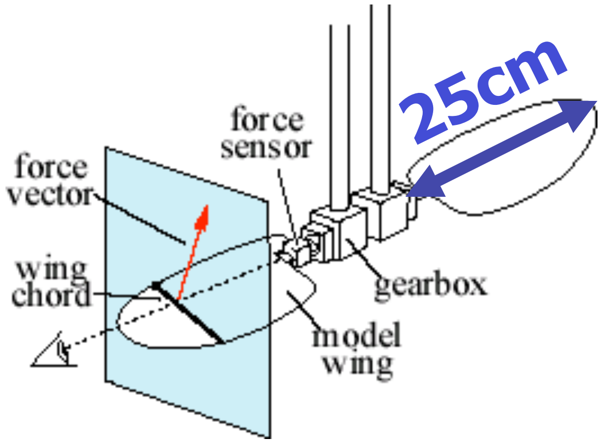
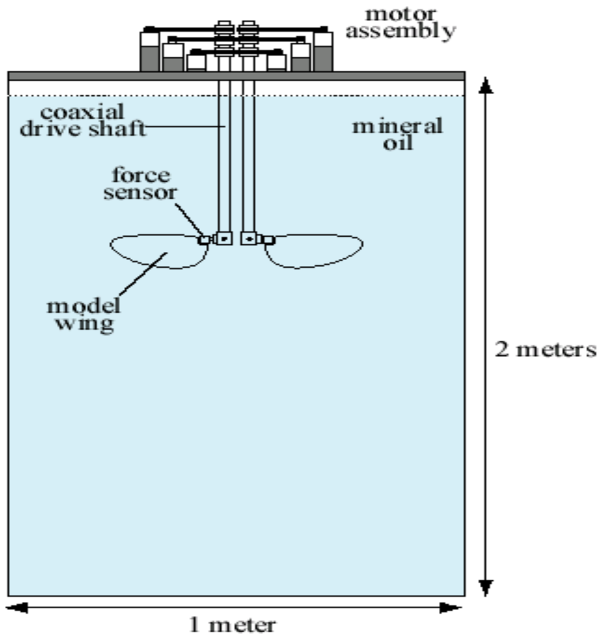
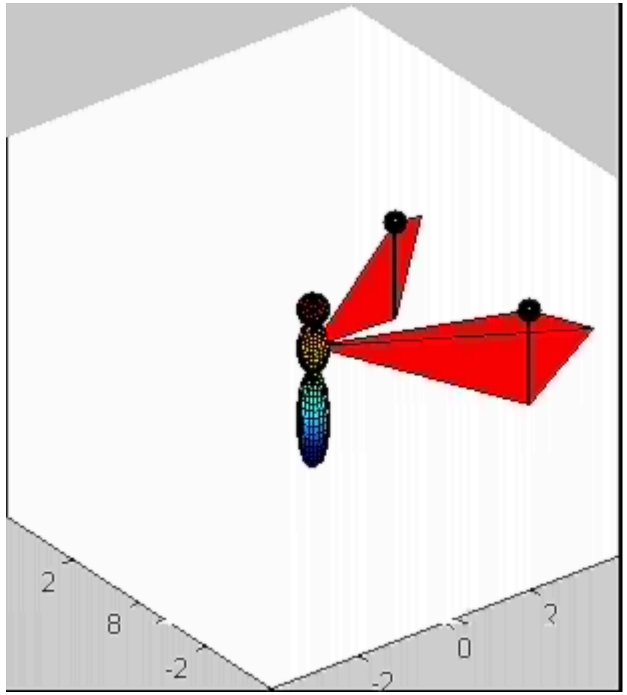
....The Bumblebee Flies Anyway

Unsteady state aerodynamics at low
Reynolds Number Re≈ 100-1000



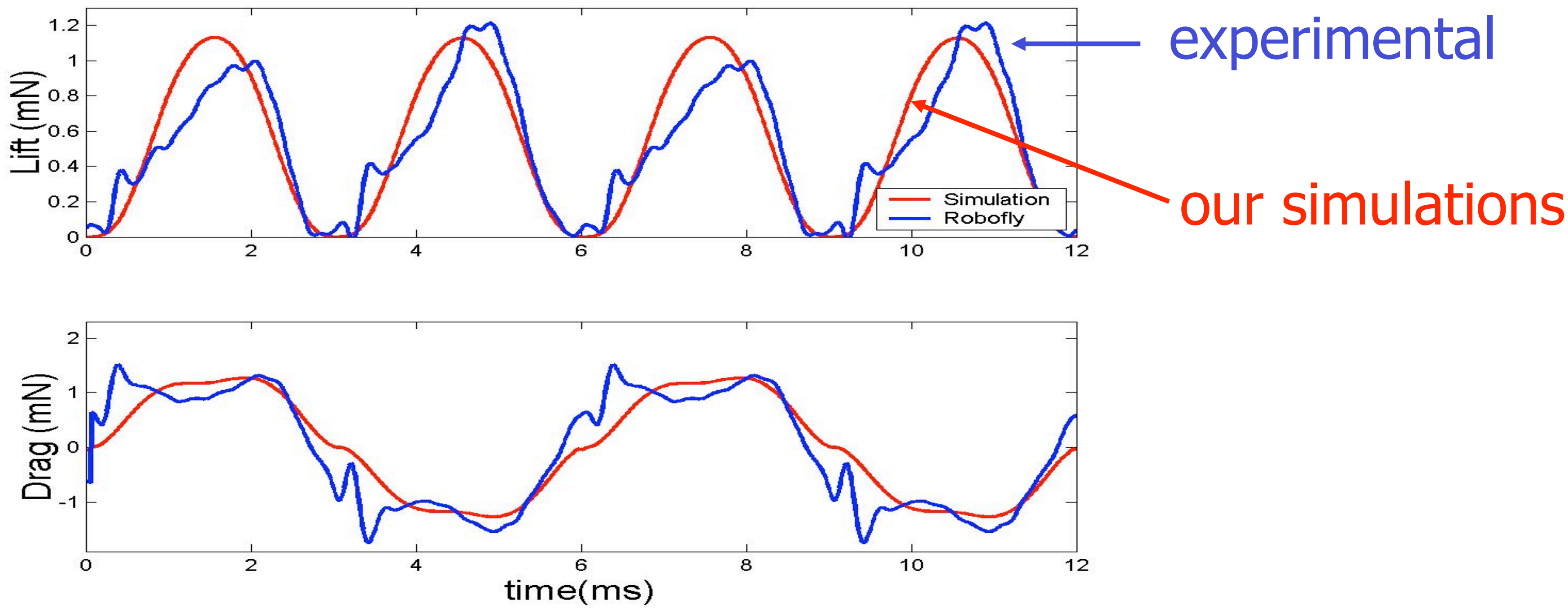




Courtesy of M.H. Dickinson and S. Sane

Aerodynamic Mechanisms:

Experimental data are courtesy of M.H. Dickinson and S. Sane



Delayed Stall

$$F_N = a\,V^2 \sin\alpha$$

Rotational lift

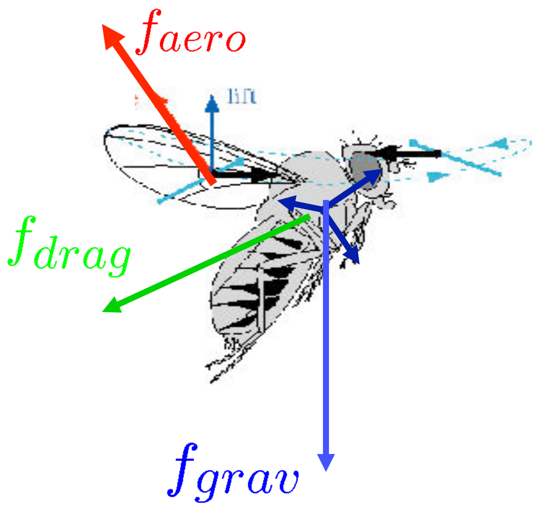
$$F_N = c\,V\dot{\alpha}$$

Wake Capture

Insect Body Dynamics

Rigid body motion equations

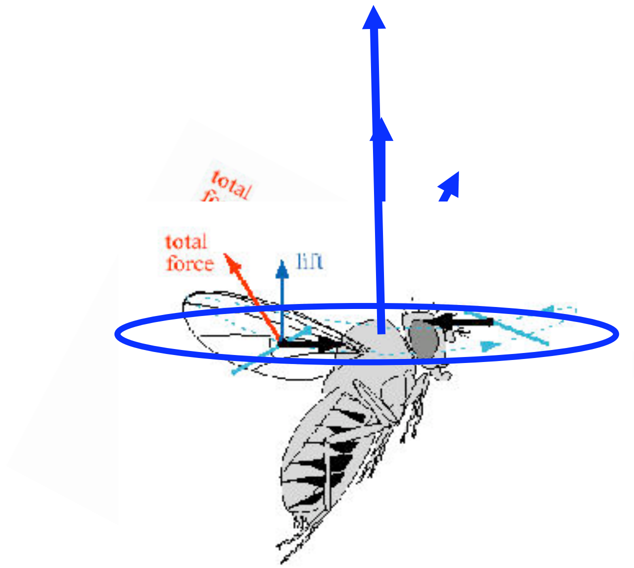
$$
\begin{aligned}
\dot{p} &= v^f \\
\dot{v}^f &= \frac{1}{m} R f^b_{aero} - g - \frac{c}{m} v^f \\
\dot{R} &= R\widehat{\omega}^b \\
\dot{\omega}^b &= I_b^{-1}(\tau^b_{aero} - \omega^b \times I_b \omega^b)
\end{aligned}
$$



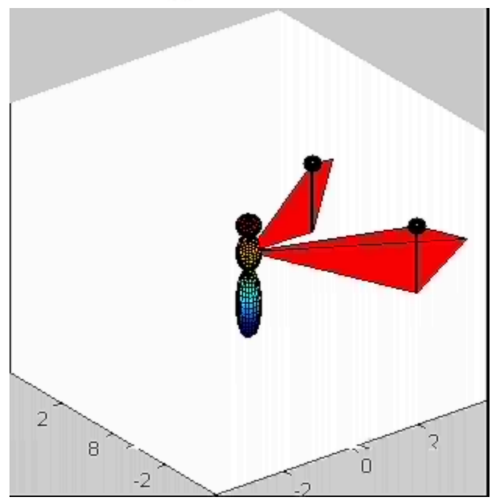
$p \in \mathbb{R}^3$	–	position
$v^f \in \mathbb{R}^3$	–	lin. velocity w.r.t fixed frame
$R \in SO(3)$	–	rotation matrix
$\omega^b \in \mathbb{R}^3$	–	ang. velocity w.r.t. body frame

Insects and helicopters

- **Analogies:**
  - Control of position by changing the orientation
  - Control of altitude by changing lift

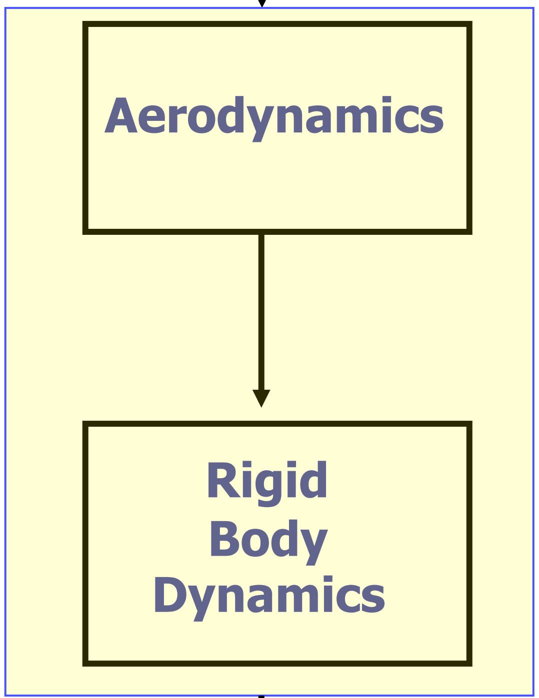


- **Differences:**
  - Cannot control forces and torques directly since they are coupled time-varying complex functions of wings position and velocity



Dynamics of insect

Wing motion $\phi_l(t), \phi_r(t)$ $\varphi_l(t), \varphi_l(t)$ **Input u**



$$
\begin{aligned}
\dot{p} &= v^f \\
\dot{v}^f &= \frac{1}{m} R\, \mathbf{f}_a(u) - g - \frac{c}{m} v^f \\
\dot{R} &= R\widehat{\omega}^b \\
\dot{\omega}^b &= I_b^{-1}(\boldsymbol{\tau}_a(u) - \omega^b \times I_b \omega^b)
\end{aligned}
$$

Insect motion $p(t)$ $R(t)$ **Output x**

Biomimetic Flying Insects

- Overview and motivations
- True insect flight (Biomimetics)
- Averaging theory
- Flapping Flight Control

Averaging Theory:

- If forces change very rapidly relative to body dynamics, only **mean** forces and torques are important

$$f_a^b(t) = \begin{bmatrix} \bar{f}_x \\ \bar{f}_y \\ \bar{f}_z \end{bmatrix} + \begin{bmatrix} \tilde{f}_x(t) \\ \tilde{f}_y(t) \\ \tilde{f}_z(t) \end{bmatrix}$$

$$\tau_a^b(t) = \begin{bmatrix} \bar{\tau}_x \\ \bar{\tau}_y \\ \bar{\tau}_z \end{bmatrix} + \begin{bmatrix} \tilde{\tau}_x(t) \\ \tilde{\tau}_y(t) \\ \tilde{\tau}_z(t) \end{bmatrix}$$

Mean forces/torques **Zero-mean forces\torques**

Averaging Theory (Russian School '60s):

x: Periodic system

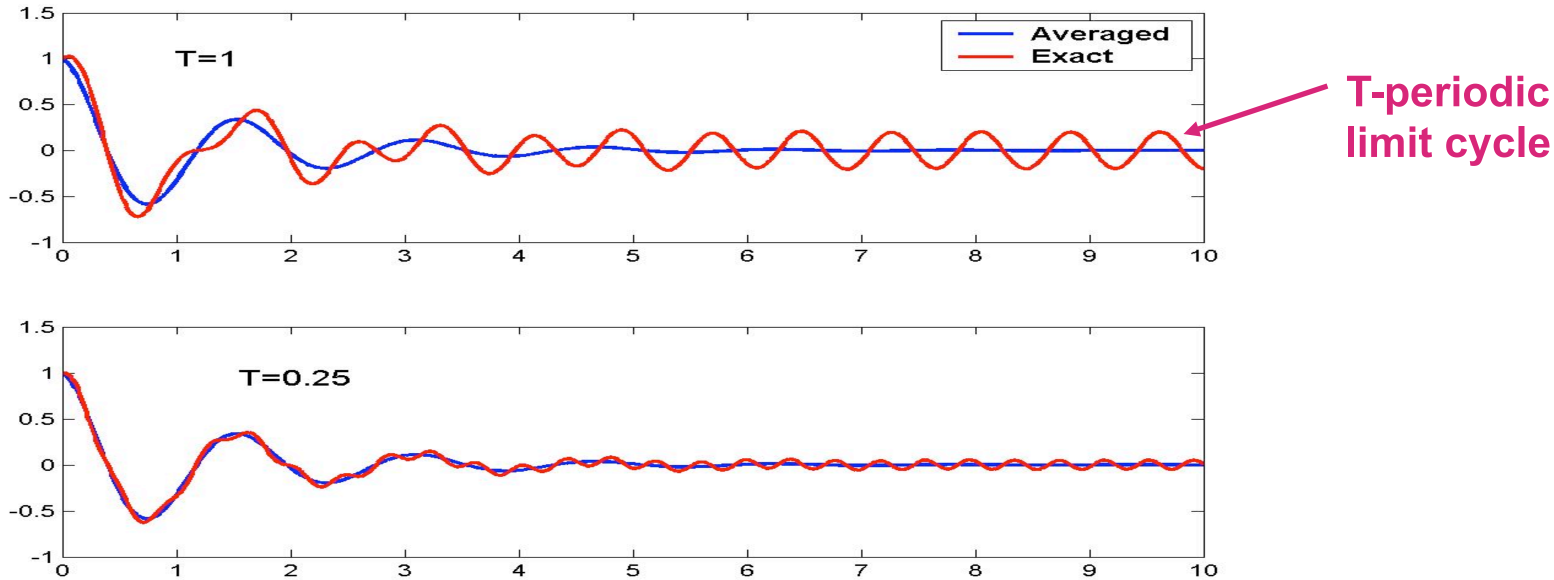
$$\dot{x} = f(x,t)$$

$$f(x,t) = f(x,t+T)$$

x_{av}: Averaged system

$$\dot{x}_{av} = \bar{f}_{av}(x_{av})$$ ← Exponentially stable

$$\bar{f}_{av}(x) \triangleq \frac{1}{T}\int_0^T f(x,\tau)d\tau$$



Averaging: systems with inputs

Original problem . *Find a feedback law* $g(x)$ *such that the system*

$$\begin{aligned} \dot{x} &= f(x,u) \\ u &= g(x) \end{aligned}$$

is asympotically stable.

New Problem . *Find periodic input* $u = w(v,t)$ *and a feedback law* $h(x)$*such that the averaged system*

$$\begin{aligned} \dot{x} &= \bar{f}_{av}(x,v) \\ \bar{f}_{av}(x,v) &= \frac{1}{T}\int_0^T f(x,w(v,\tau))d\tau \\ v &= h(x) \end{aligned}$$

is asymptotically stable.

virtual inputs

Why ? 3 Issues

New Problem 1. *Find periodic input* $u = w(v,t)$ *and a feedback law* $h(x)$ *such that the system*

$$\begin{aligned} \dot{x} &= \bar{f}_{av}(x,v) \\ \bar{f}_{av}(x,v) &= \frac{1}{T}\int_0^T f(x,w(v,\tau))d\tau \\ v &= h(x) \end{aligned} \qquad (1)$$

is asymptotically stable.

Virtual inputs (→ v)

- How do we choose the T-periodic function w(v,t) ?
- How can we compute $\bar{f}_{av}(x,v) = \frac{1}{T}\int_0^T f(x,w(v,\tau))d\tau$?
- How small should the period T be?

Advantages of high frequency: a motivating example

$$\begin{cases} \dot{x} & = & u^2 - 1 \\ \dot{y} & = & u \end{cases}$$

1 Input: u
2 Degrees of freedom: (x,y)
Want (x,y) → 0 for all initial conditions

- Origin (x,y)=(0,0) is NOT an equilibrium point
- # degs of freedom > # input available (independently controlled)

Advantages of high frequency: a motivating example

Input is distributed differently

$$\begin{cases} \dot{x} = u^2 - 1 \\ \dot{y} = u \end{cases}$$

1 Input: u
2 Degrees of freedom: (x,y)
Want (x,y) → 0 for all initial conditions

$+$

$$u = w(v,t) = v_1 + v_2 \sin \frac{t}{T}$$

⇩

$$\begin{cases} \dot{\bar{x}} \approx v_2 - \sqrt{2}\,\bar{v}_2^2 - 1^2 - 1 \\ \dot{\bar{y}} \approx v_1 \end{cases} \quad \begin{cases} v_2 = \sqrt{2} - \bar{x} \\ v_1 = -\bar{y} \end{cases}$$

Two linear independent virtual input: v_1, v_2 !!!!

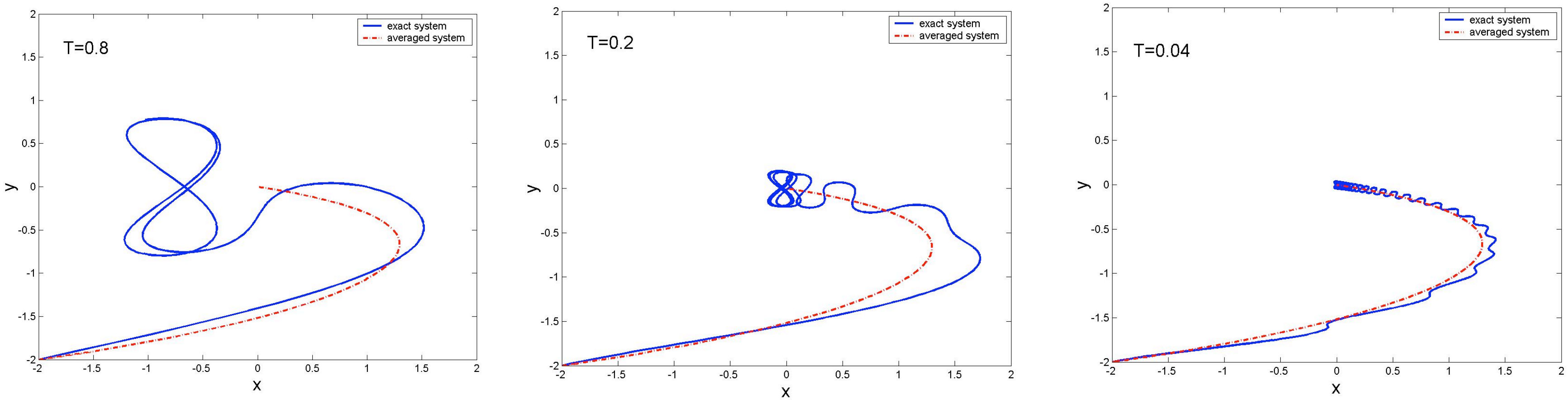
Advantages of high frequency: a motivating example

Closed loop system

$$\begin{cases} \dot{x} = u^2 - 1 \\ \dot{y} = u \\ u = -y + (\sqrt{2} - x)\sin\frac{t}{T} \end{cases}$$

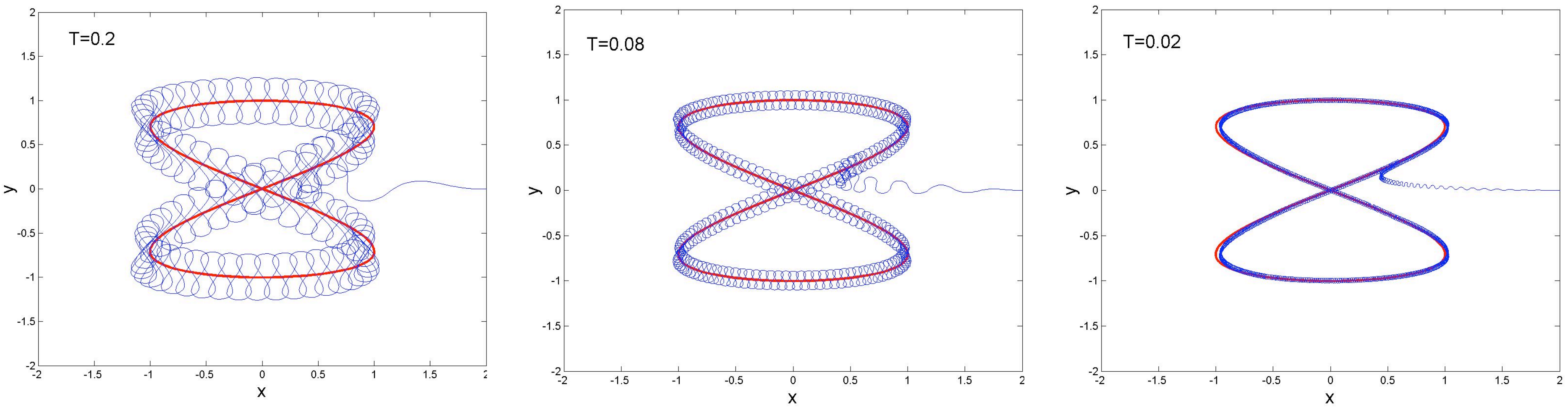
Averaged Closed loop system

$$\begin{cases} \dot{\bar{x}} = \bar{y}^2 + 0.5(\sqrt{2} - \bar{x})^2 - 1 \\ \dot{\bar{y}} = -\bar{y} \end{cases}$$



Tracking "infeasible" trajectories

$$\begin{cases} \dot{x} & = & u^2 - 1 \\ \dot{y} & = & u \\ u & = & -(y - \sin(2t)) + (\sqrt{2} - (x - \sin(t))\sin\frac{t}{T} \end{cases}$$



Advantages of averaging

1. Increases # of (virtual) inputs
2. Decouples inputs
3. Approximates infeasible trajectories

Back to the 3 Issues

- How do we choose the T-periodic function w(v,t) ?
  - Geometric control [Bullo00] [Vela 03] [Martinez 03] ...
  - BIOMIMETICS : mimic insect wing trajectory
- How can we compute $\bar{f}(x,v) = \frac{1}{T}\int_0^T f(x,w(v,t))dt$?
  - For insect flight this boils down to computing mean forces and torques over a wingbeat period:
- How small must the period T of the periodic input be?
  - Practically in all insect species wingbeat period T is small enuogh w.r.t insect dynamics

Biomimetic Flying Insects

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The 3 Issues

- How do we choose the T-periodic function u=w(v,t) ?

- How can we compute $\bar{f}(x,v) = \frac{1}{T}\int_0^T f(x,w(v,t))dt$?

- How small must the period T of the periodic input be?

Flight Control mechanisms in real insects

- Kinematic parameters of wing motion have been correlated to observed maneuvers **[G. Taylor, *Biol. Rev.* 99]**
  - Stroke amplitude:
    - Symmetric change → climb/dive
    - Asymmetric change → roll rotation
  - Stroke offset:
    - Symmetric change → pitch rotation
  - Timing of rotation
    - Asymmetric → yaw/roll rotation
    - Symmetric → pitch rotation
  - Angle of attack
    - Asymmetric → forward thrust

Parameterization of wing motion

$$u = w(v, t) = g_0(t) + G(t)v$$

Stroke amplitude

Offset of stroke angle

Stroke angle

$$\begin{aligned} u_{1,i} &= \frac{\pi}{3}\cos(wt) + v_1 \frac{\pi}{6}\cos(wt) + \frac{\pi}{15} v_2 \\ u_{2,i} &= \frac{\pi}{4}\sin(wt) + v_3 \frac{\pi}{4}\sin^3(2wt) \end{aligned}$$

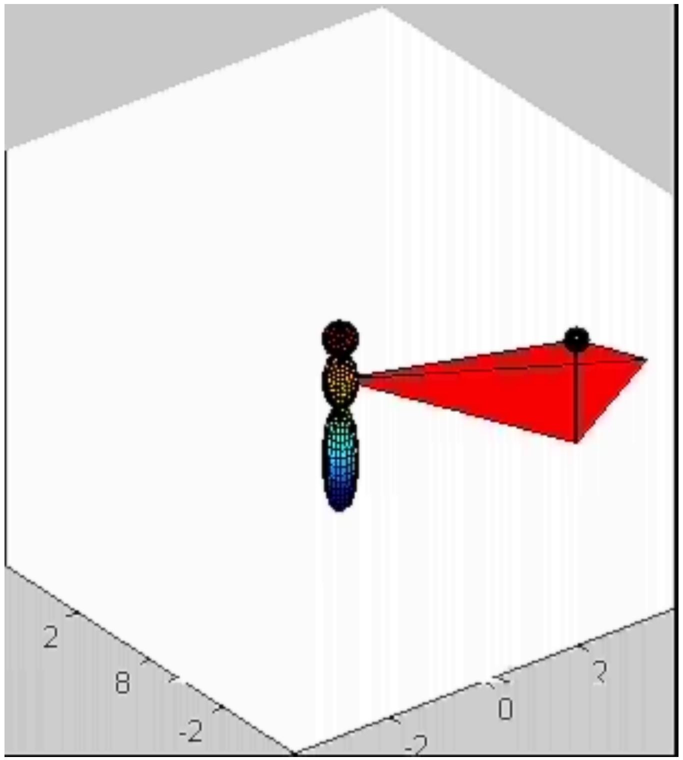
$(i \in \{l, r\})$

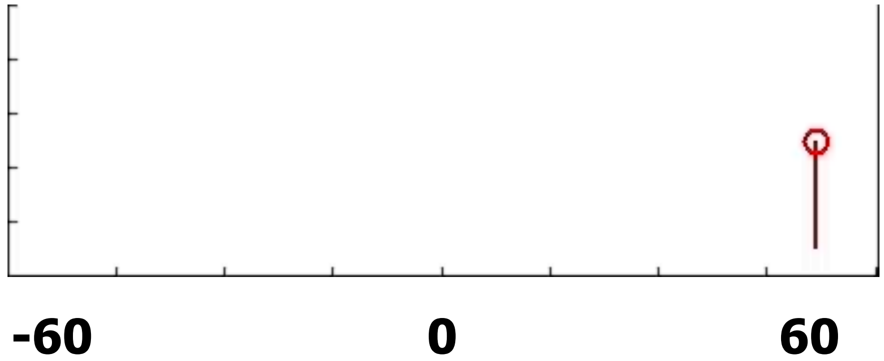
Rotation angle

Timing of rotation

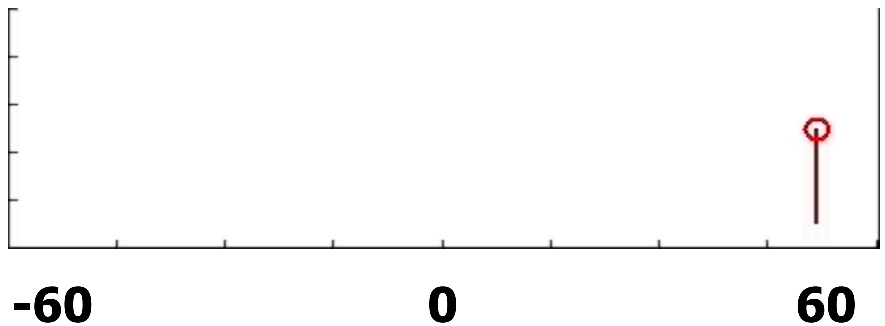
Parameterization of wing motion

$$
\begin{aligned}
u_{1,i} &= \frac{\pi}{3}\cos(wt) + v_1 \frac{\pi}{6}\cos(wt) + \frac{\pi}{15} v_2 \\
u_{2,i} &= \frac{\pi}{4}\sin(wt) + v_3 \frac{\pi}{4}\sin^3(2wt)
\end{aligned}
$$





$v_1 = 1$ $v_1 = 0$ $v_1 = -1$



$v_3 = 1$ $v_3 = 0$ $v_3 = -1$

Back to the 3 issues

- How do we choose the T-periodic function w(v,t) ?
- How can we compute $\bar{f}(x,v) = \frac{1}{T}\int_0^T f(x,w(v,t))dt$?
- How small must the period T of the periodic input be?

Mean forces/torques map

Independent control of 5 degrees of freedom

$$|v_i| \leq 1 \begin{bmatrix} \bar{f}_x \\ \bar{f}_y \\ \bar{f}_z \end{bmatrix} \approx \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + 0.2mg \begin{bmatrix} v_3^l + v_3^r \\ 0 \\ v_1^l + v_1^r \end{bmatrix}$$

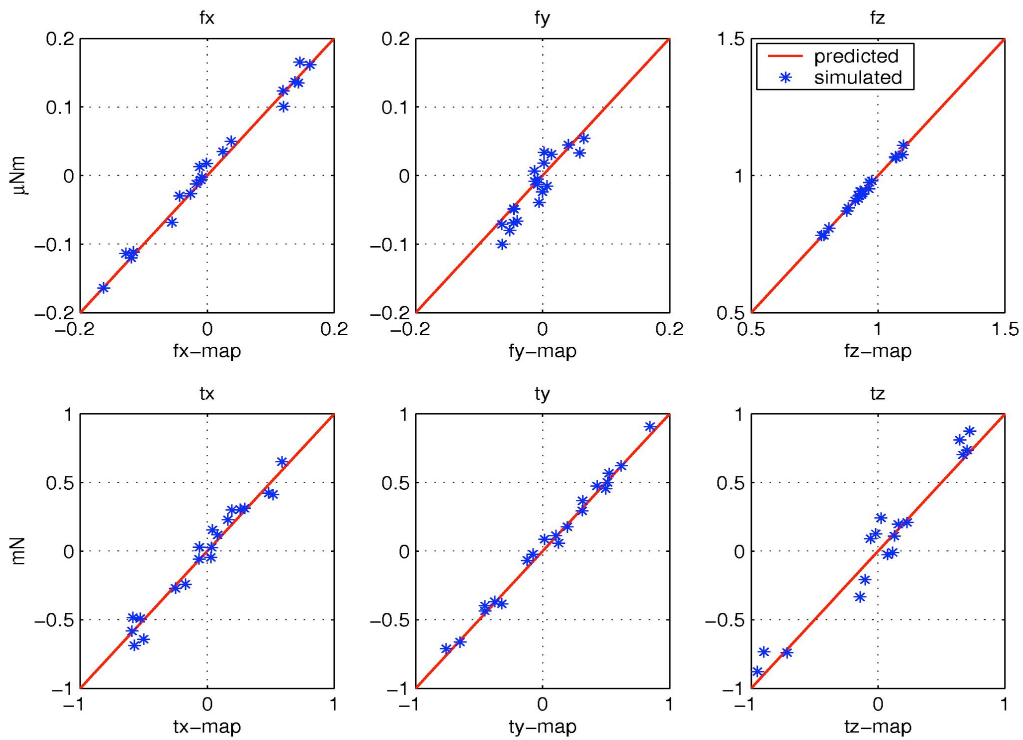
$$\begin{bmatrix} \bar{\tau}_x \\ \bar{\tau}_y \\ \bar{\tau}_z \end{bmatrix} \approx 0.2mgL \begin{bmatrix} v_1^l - v_1^r \\ v_2^l + v^r \\ v_3^l - v_3^r \end{bmatrix}$$

Wing length

Mean forces/torques map

$$\begin{bmatrix} \bar{f}_x \\ \bar{f}_y \\ \bar{f}_z \end{bmatrix} \approx \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + 0.2mg \begin{bmatrix} v_3^l + v_3^r \\ 0 \\ v_1^l + v_1^r \end{bmatrix}$$

$$\begin{bmatrix} \bar{\tau}_x \\ \bar{\tau}_y \\ \bar{\tau}_z \end{bmatrix} \approx 0.2mgL \begin{bmatrix} v_1^l - v_1^r \\ v_2^l + v^r \\ v_3^l - v_3^r \end{bmatrix}$$

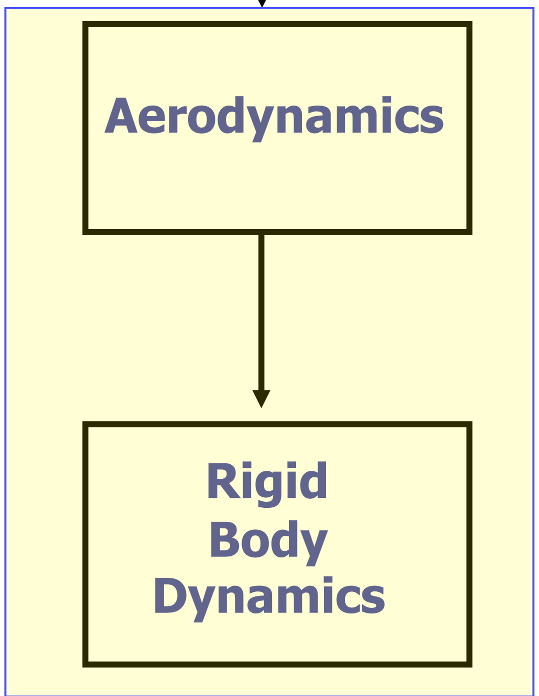


Dynamics of insect revised

Input u

$\phi_l(t), \phi_r(t)$

$\varphi_l(t), \varphi_l(t)$



Output x

$p(t)$

$R(t)$

Before averaging

After averaging

$$
\begin{aligned}
\dot{p}_m &= v^f \\
\dot{v}_m^f &= \frac{1}{m} R \begin{bmatrix} \tilde{v}_1 \\ 0 \\ \tilde{v}_2 \end{bmatrix} - g - \frac{c}{m} v^f \quad f \\
\dot{R}_m &= R \widehat{\omega}^b \\
\dot{\omega}_m^b &= I_b^{-1} \left(\begin{bmatrix} \tilde{v}_3 \\ \tilde{v}_4 \\ \tilde{v}_5 \end{bmatrix} - \omega^b \times I_b \omega^b \right)
\end{aligned}
$$

$b\omega^b)$

$$v = Kx$$

- **Hovering**
- **Cruising**
- **Steering**

Proportional periodic feedback

BIOMIMETICS

Wings trajectory

Kinematic parameters

$$u = g_0(t) + G(t)v$$

Averaging
LQG ,H_∞ ,...

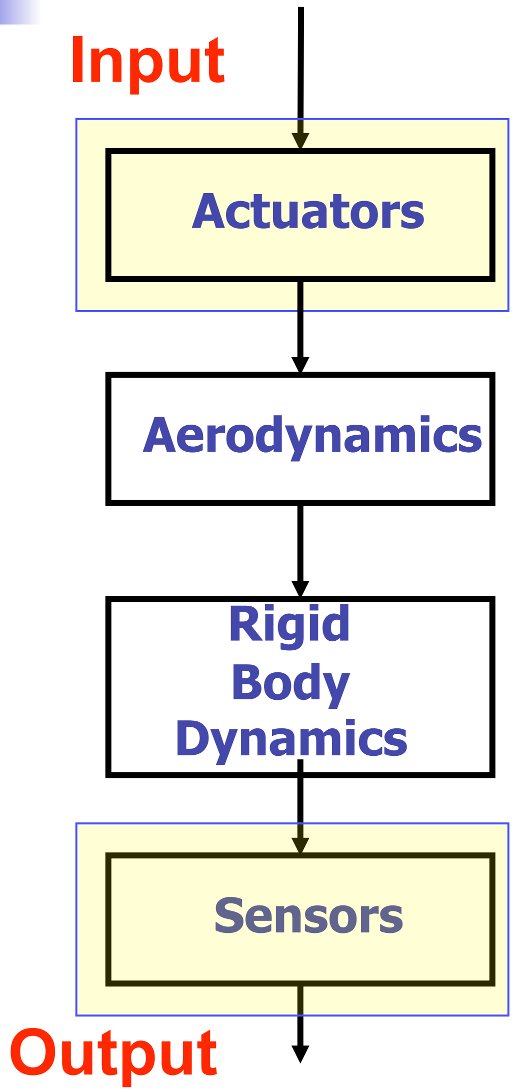
Insect position

$$v = Kx$$

$$u = g_0(t) + \tilde{G}(t)xx$$

Periodic proportional feedback

Insect Dynamics: realistic model



$V_{1,l}(t), V_{2,l}(t)$
$V_{1,r}(t), V_{2,r}(t)$

Input voltage to actuators

$\phi_l(t), \phi_r(t)$
$\varphi_l(t), \varphi_l(t)$

Wing kinematics

$p(t)$
$R(t)$

Insect position

$\widehat{p}(t)$
$\widehat{R}(t)$

Sensor measurements

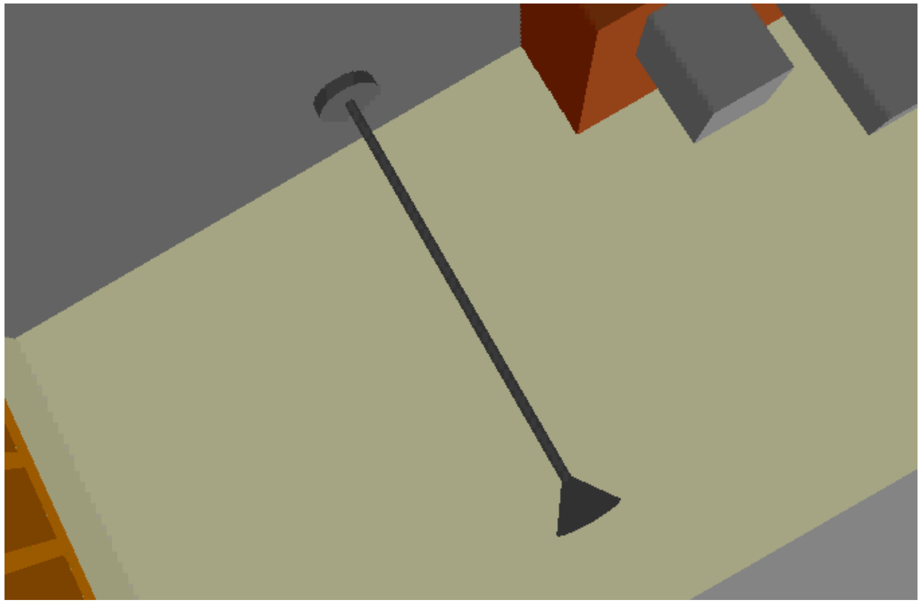
Proportional periodic feedback

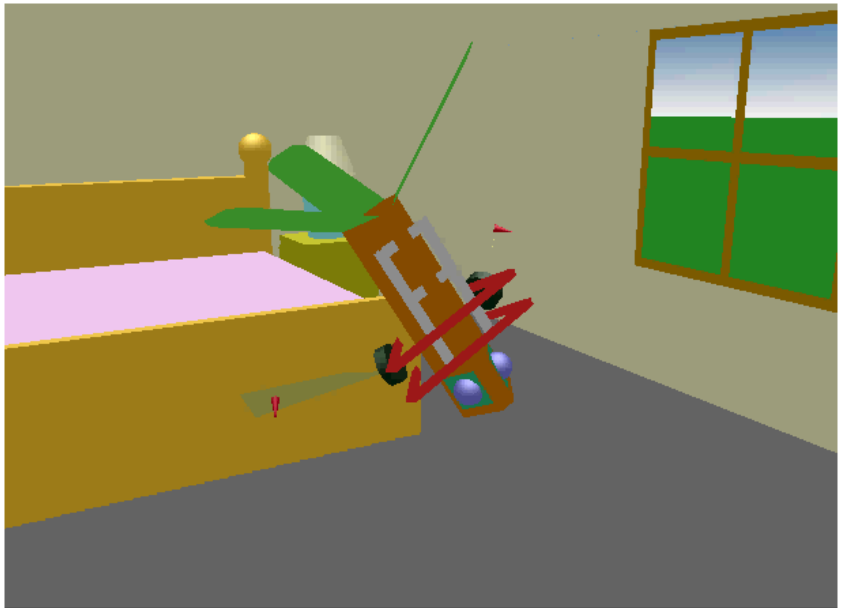
Output from sensors

Input voltages to actuators

$$\begin{bmatrix} V_{1,l}(t) \\ V_{2,l}(t) \\ V_{1,r}(t) \\ V_{2,r}(t) \end{bmatrix} = h(t) + \tilde{H}(t) \begin{bmatrix} y_c \\ y_1^o \\ y_2^o \\ y_x^h \\ y_y^h \\ y_z^h \end{bmatrix}$$

Simulations w/ sensors and actuators: Recovering





Summarizing …

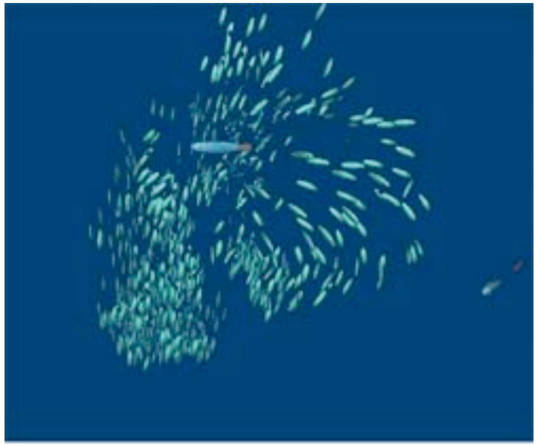
- **Biological perspective:**
  - Flapping flight allows independent control of 5 degrees of freedom
- **Engineering perspective:**
  - Averaging theory and biomimetics simplify control design
  - Periodic proportional feedback sufficient to stabilize several flight modes
- **Control Theoretic perspective:**
  - Flapping flight as biological example of high-frequency control of an underactuated system

What's next ?

Bird flocks

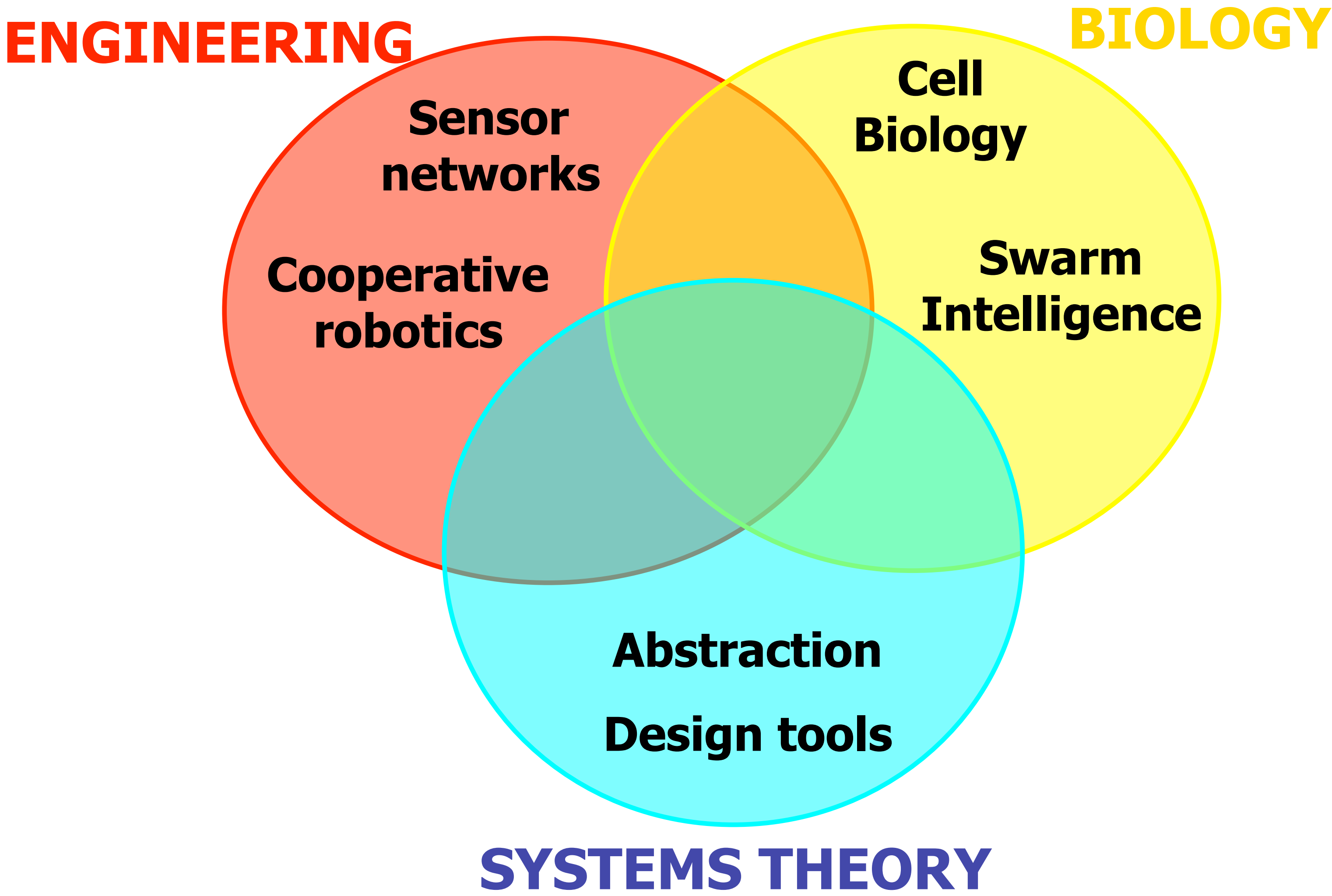
Insect swarms

Fish schools



- **Fundamental questions:**
  - How local feedback and communication give rise to global behavior ?
  - How is information extracted and propagated over the network ?
  - How spatial and temporal correlation is exploited ?

Research agenda: networks of systems



Publications:

- **Analysis and Control of flapping flight: from biological to robotic insect**, Ph.D. dissertation, 2003

- **Attitude Control for a Micromechanical Flying Insect via Sensor Output Feedback** with **W.C Wu, S. Sastry**, IEEE Trans Rob.&Aut., Feb 2004

- **Flapping flight for biomimetic robotic insects: Part I - System modeling** with **W.C Wu, X. Deng S. Sastry**, submitted to IEEE Trans. Robotics

- **Flapping flight for biomimetic robotic insects: Part II – Flight Control Design** with **X. Deng, S. Sastry**, submitted to IEEE Trans. Robotics