Analysis and Control of Flapping Flight: from biological to robotic insects

Ph.D. Dissertation Talk
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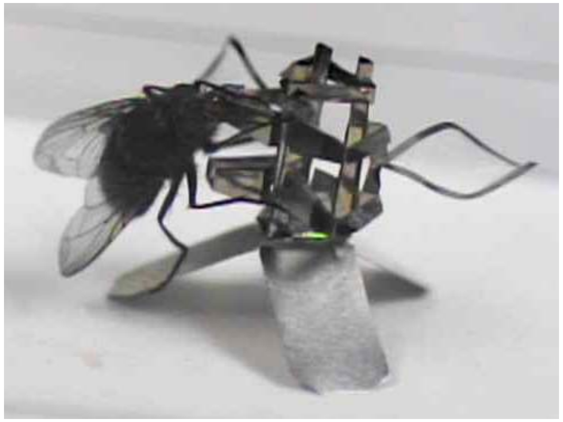
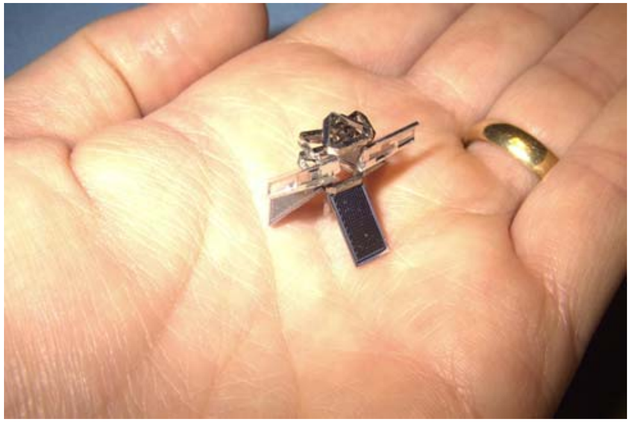
Micromechanical Flight Insect Project (MFI)

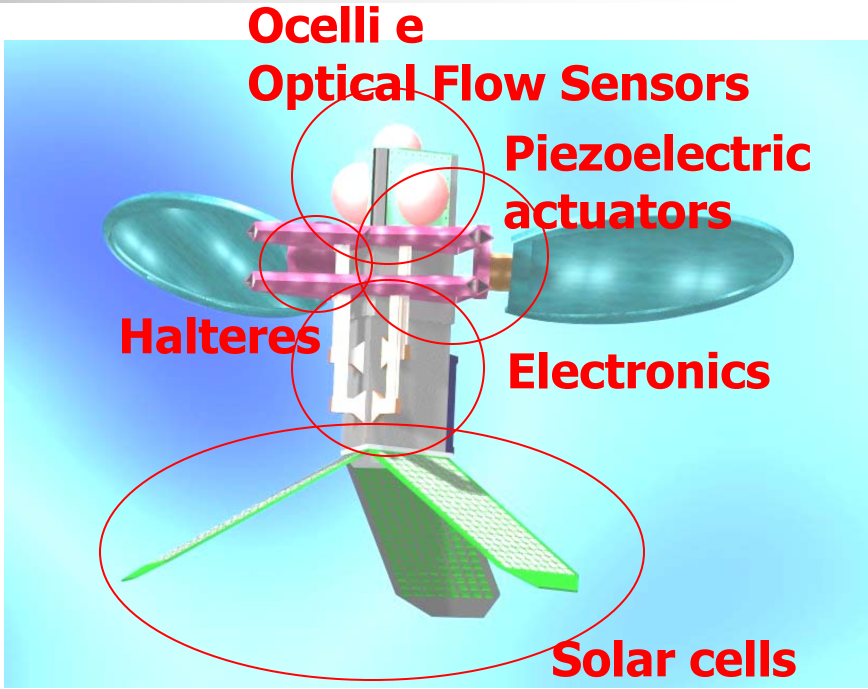




- **Objective**: Development of a micromechanical flying insect (MFI), a 10-25mm (wingtip-to-wingtip) micro air vehicle capable of sustained autonomous flight
- **Applications:** surveillance, search, rescue, map-building and monitoring in hazardous and impenetrable environments
- **Advantages:** highly manoeuvrable, small, inexpensive, swarms of MFIs promise high success rate

MFI Target Specs

- 10-30mm wingtip-to-wingtip
- 100mg weight
- 150Hz wingbeat frequency
- 10-20mWatt power budget from solar cell



Courtesy of MFI group

Micromechanical Flight Insect (MFI)

- **Kickoff:** summer 1998
- **Interdepartmental Project:**
  - 4 departments (EE,ME,Mat Sci,Bio),
  - 5 professors
    - R. Fearing (PI) (EE)
    - M. Dickinson (Bio) (now at Caltech)
    - S. Sastry (EE)
    - T. Sands (Material Sciences) (now at Purdue)
    - K. Pister (EE)
  - 5-8 students/postdocs

Motivating Questions:

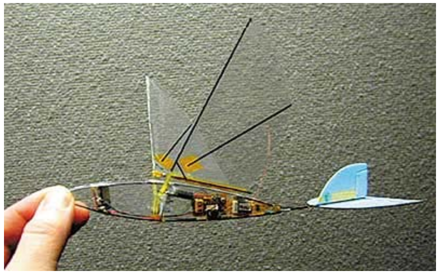
- **Biological perspective:**
  - How many degrees of freedom can be independently controlled in flapping flight ?
  - How do insects control flight ?
- **Technological perspective:**
  - How can we replicate insect flight performance on MFIs given the limited computational resources?
  - Why is flapping flight different from helicopter flight ?
- **Control Theoretical perspective:**
  - What's really novel in flapping flight from a control point of view ?

Previous work: biological perspective

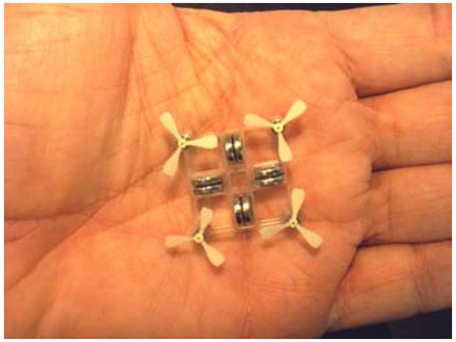
- Seminal work by C. Ellington(80s) and M. Dickinson(90s)
- Aerodynamic mechanisms are now clear
- Correlation available between flight maneuvers and wing motions
- Hierarchical architecture of sensor fusions and neuromotor control
- Some evidence that insect can control 5 degrees of freedom out of the total 6

Previous work: Micro Aerial Vehicles (MAVs)

- **Flapping robots are still at infancy**
  - MFI at U.C. Berkeley
  - Entomopter at GeorgiaTech
  - Microbat at Caltech
  - Microbat by Aerovinment Inc.



- **Microaerial Vehicles:**
  - Black Widow by Aerovinment Inc.
  - Mesocopter at Stanford
  - .....



Previous work: control theory

- **Flapping flight**
  - … ?
- **Fish locomotion:**
  - Caltech group:
    - Underactuated nonholonomic systems
    - Averaging theory

    [Mason, Morgansen, Vela, Murray, Burdick 99-03]
- **Anguilliform Locomotion:**
  - [Ostrowski, Burdick 99]
    - Hyper-Redundant systems
    - Averaging theory

Personal contribution:

- **Biological perspective:**
  - Flapping flight do allow independent control of 5 degrees of freedom (using mathematical models)
- **Technological perspective:**
  - Simple control scheme: proportional period feedback from sensors to actuators input
  - Quantifications of limits of performance
  - Practical methodology (when experimental data available)
- **Control Theoretical perspective:**
  - Rigorous use of averaging theory to explain flapping flight
  - Flapping flight as biological example of high-frequency control of an under-actuated system

Talk overview:

- **Insect Flight Modeling**
  - Aerodynamics
  - Body Dynamics
  - Neuromotor control architecture
  - Flight Control Mechanisms in real insects
- **Averaging theory**
- **Flight control design methodology**
  - MFI toy-model
  - MFI realistic model
  - MFI realistic model + actuators and sensors
- **Conclusions**

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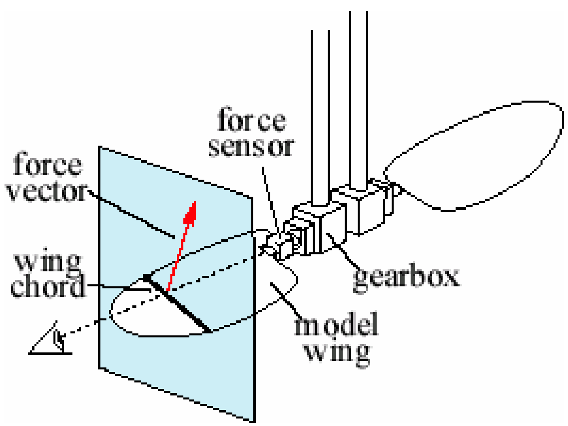
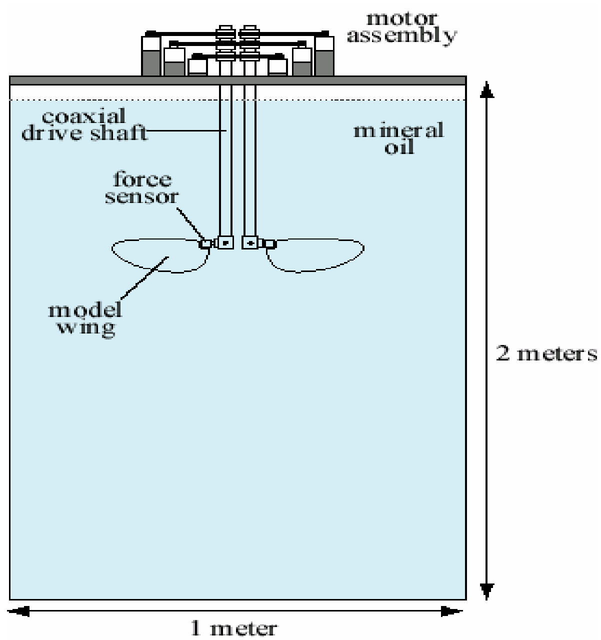
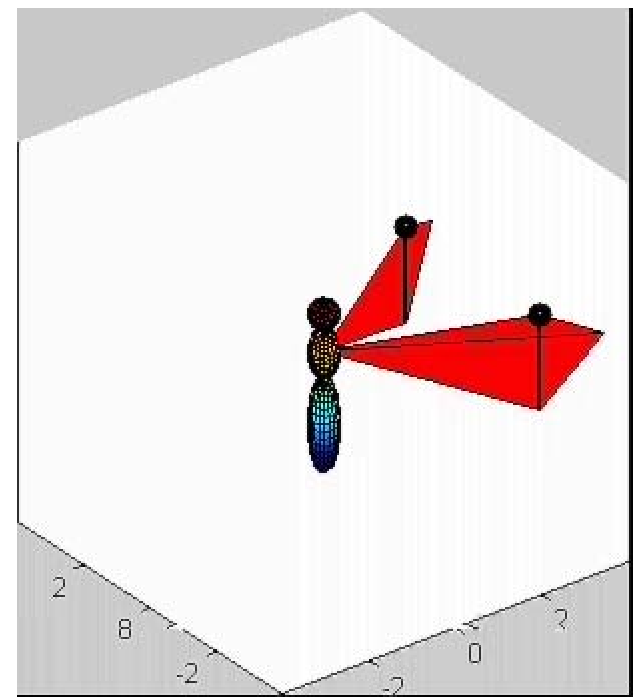
….The Bumblebee Flies Anyway

- **Apparatus:** scaled model of insect wing immersed in a mineral oil talk to replicate the same aerodynamic mechanisms *Re* $\approx$ *100-1000*



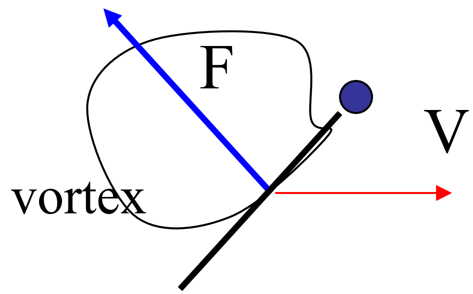


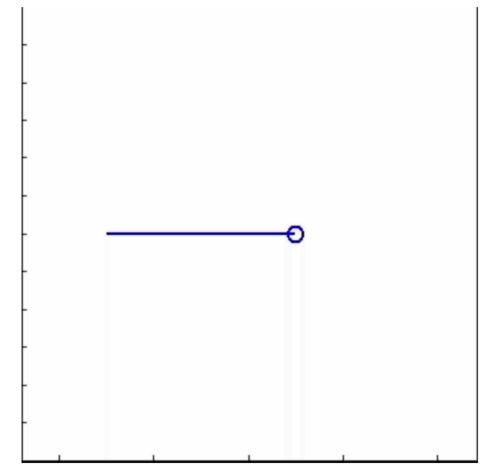


Courtesy of M.H. Dickinson and S. Sane

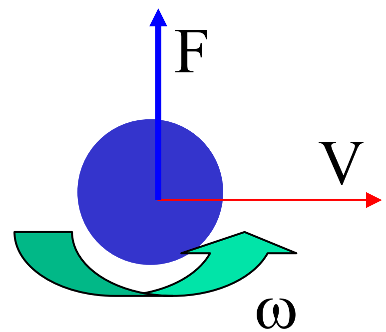
Unsteady-state Aerodynamic Mechanisms

- **Delayed stall:**



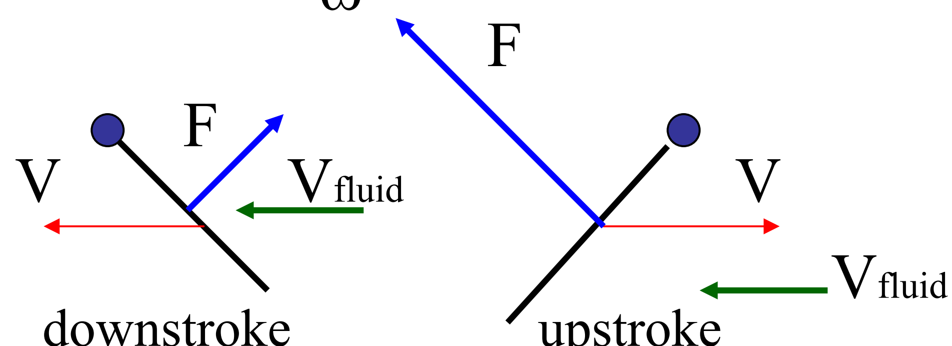


- **Magnus effect**



- **Wake capture**

  $V_{rel}=V_{wing}+V_{fluid}$



Aerodynamic Mechanisms:

- **Delayed stall:**

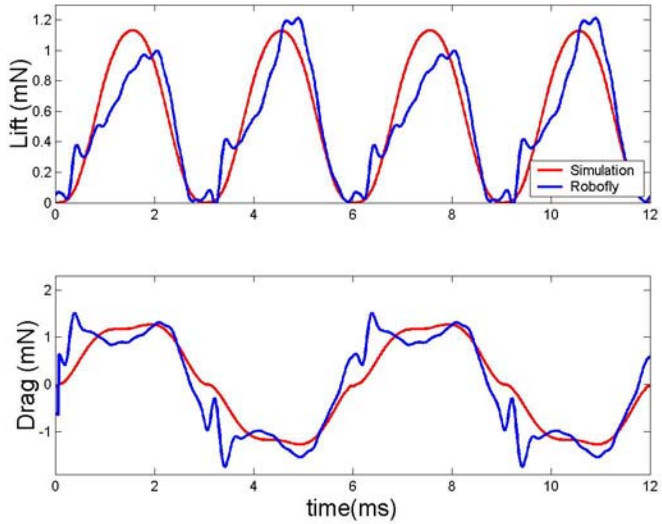
$$F_N = a\, V^2 \sin\alpha$$

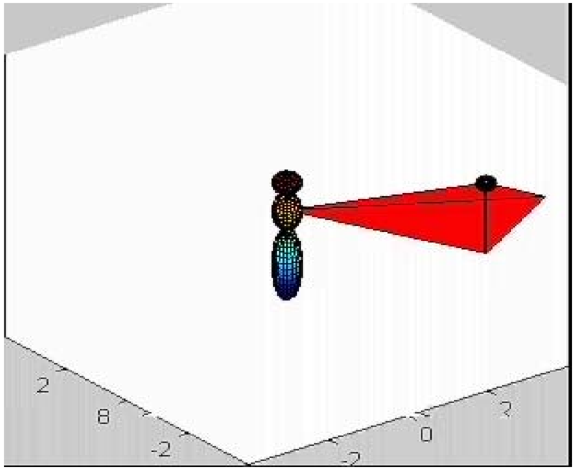
- **Magnus effect**

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

- **Wake capture**

?





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

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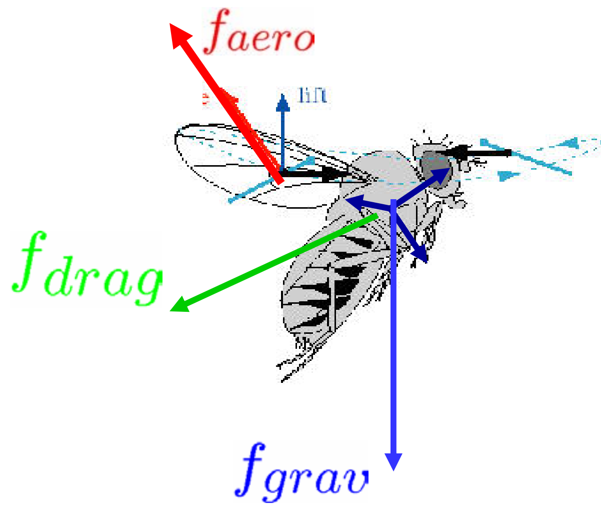
Insect Body Dynamics

- **Hypothesis:** inertial forces from wings can be neglected

Same dynamics as helicopters

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



R(t) **–** Rotation matrix

p **–** position of insect center of mass

Are wings inertial forces important ?

Courtesy of G.C. Walsh
Univ. Maryland, 1991

- **Unlikely:**
  - Wings needs to be shifted forward
  - Wings need to oscillate 90^{o} phased off
  - Given wings-to-body mass ratio, the body oscillation angle is 5-10X larger then the net rotation per wingbeat

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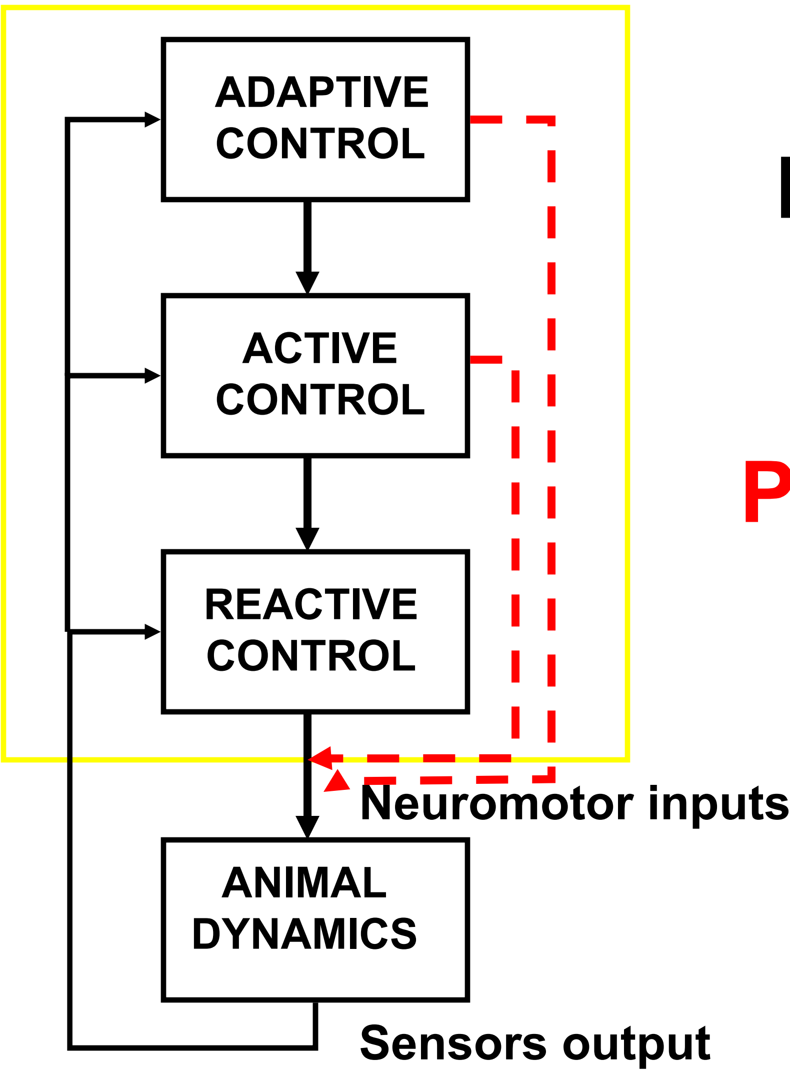
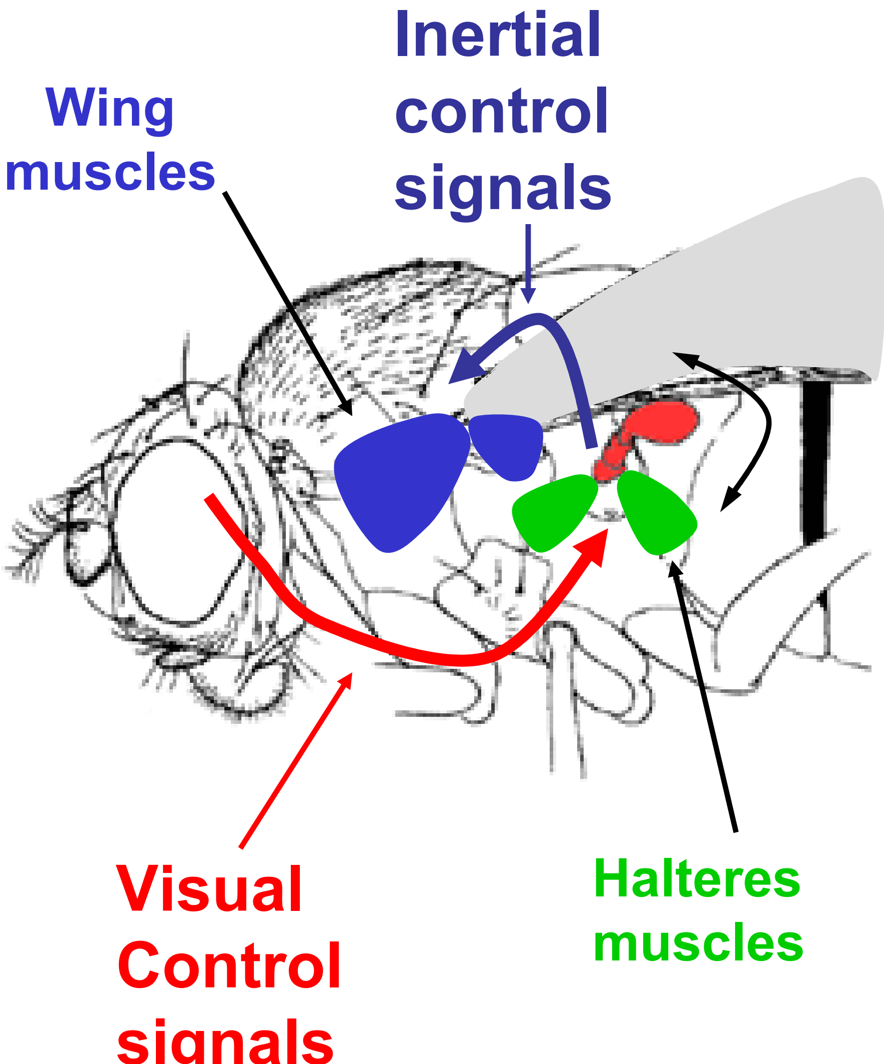
Control architecture in animals



Purely hierarchical

Partially hierarchical

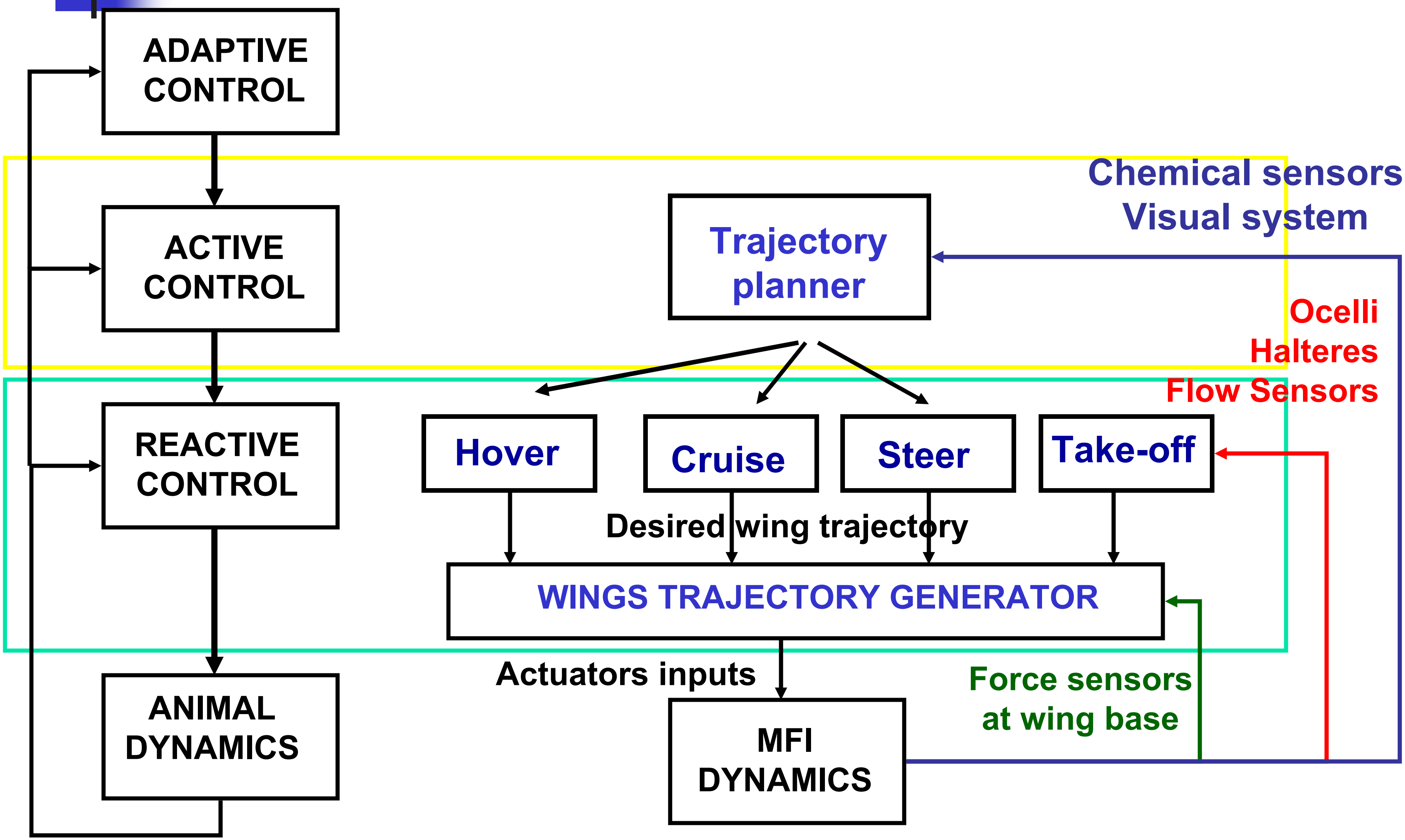
Neuromotor Control in Insects



Visual signals → Halteres muscles → Halteres motion → Wings muscles

External disturbances → Halteres motion

MFI Control Unit



Talk overview:

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  - Neuromotor control architecture
  - **Flight Control Mechanisms in insects and Helicopter**
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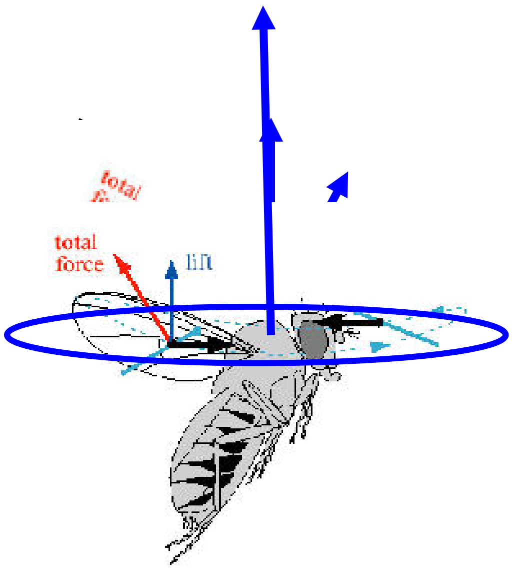
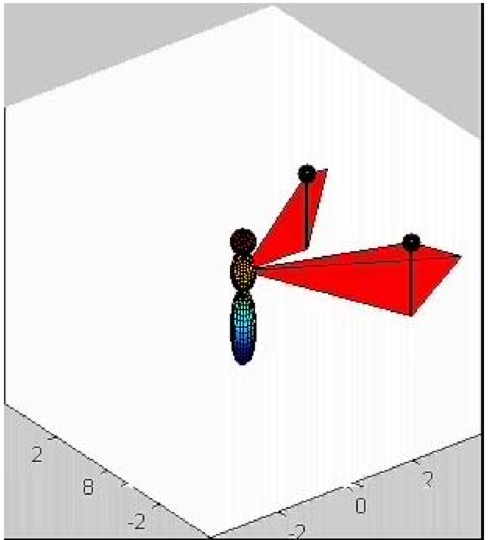
Insects and helicopters

- **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



Flight Control mechanisms in real insects

- Kinematic parameters of wing motion have been correlated to observed maneuvers [Taylor01]
  - 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

Dynamics of insects

$\phi_l(t), \phi_r(t)$ **Stroke angles**

$\varphi_l(t), \varphi_r(t)$ **Rotation Angles (angles of attack)**

↓

Aerodynamics

$$f^b_{aero}(t) = f^b_{aero}(\phi, \dot{\phi}, \varphi, \dot{\varphi})$$

$$\tau^b_{aero}(t) = \tau^b_{aero}(\phi, \dot{\phi}, \varphi, \dot{\varphi})$$

↓

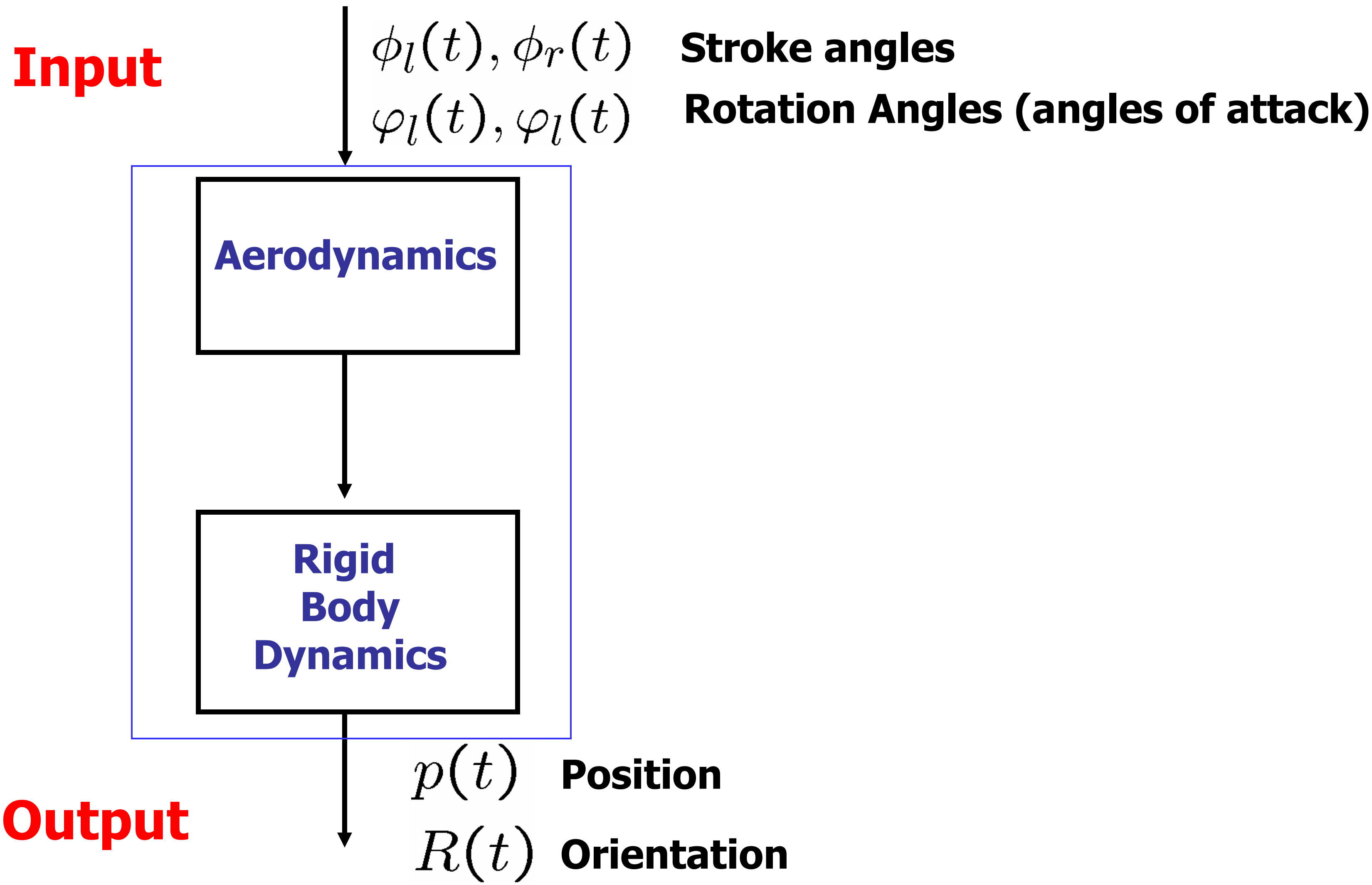
Rigid Body Dynamics

↓

$p(t)$ **Position**

$R(t)$ **Orientation**

Dynamics of insects



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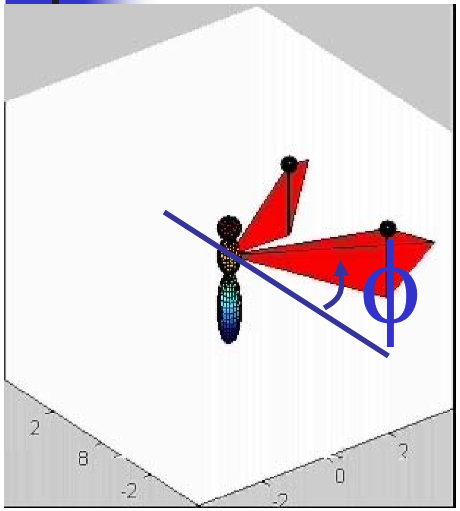
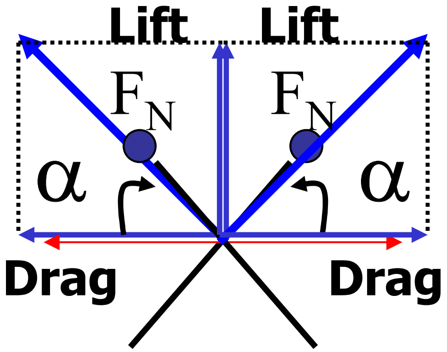
Toy model for insect dynamics





$\alpha = 45^o$

$F_N \propto \dot{\phi}^2$

$$f_a^b = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = A \begin{bmatrix} \dot{\phi_l}|\dot{\phi_l}| + \dot{\phi_r}|\dot{\phi_r}| \\ 0 \\ \dot{\phi_l}^2 + \dot{\phi_r}^2 \end{bmatrix}$$

$$\tau_a^b = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = B \begin{bmatrix} \dot{\phi_l}^2 - \dot{\phi_r}^2 \\ \dot{\phi_l}^2 \phi_l + \dot{\phi_r}^2 \phi_r \\ \dot{\phi_l}|\dot{\phi_l}| - \dot{\phi_r}|\dot{\phi_r}| \end{bmatrix}$$

2 Inputs: (ϕ_l, ϕ_r)

6 Degrees of freedom:
(x,y,z) position
(roll,pitch,yaw) angles

Key ideas:

- Averaging Theory for high frequency periodic systems

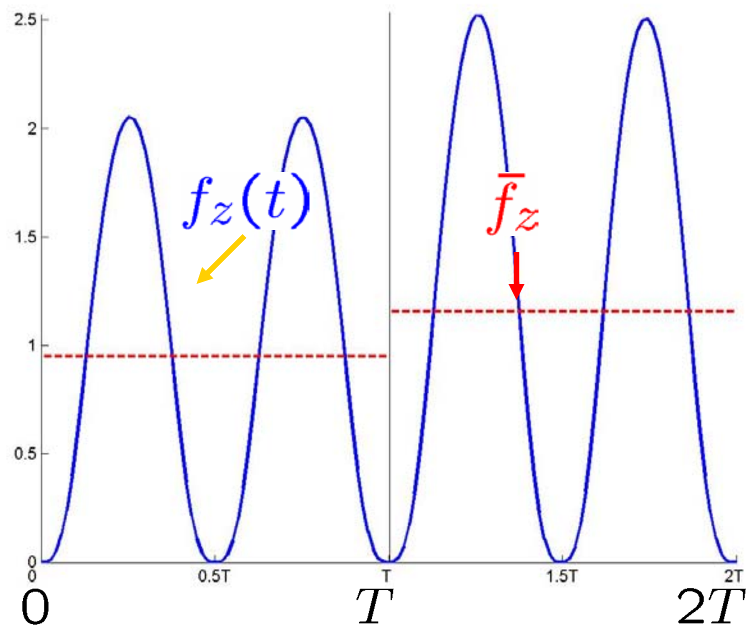
- Biomimetics to teach us how to move wings to generate the desired forces

Averaging Theory:

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

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

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



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

Averaging for linear systems:

System with periodic forcing

$$\dot{x} = f(x,t) = -x + \sin(\tfrac{t}{T})$$

$$x(t) = e^{-t}x_0 + \frac{T}{\sqrt{1+T^2}}\sin(\tfrac{t}{T} - \tan^{-1}(T))$$

$$|x(t) - \bar{x}(t)| \leq kT$$

Averaged system

$$\dot{\bar{x}} = \bar{f}(x) = -\bar{x}$$

$$\bar{f}(x) = \frac{1}{T}\int_0^T f(x,t)dt$$

$$\bar{x}(t) = e^{-t}x_0$$

$$\lim_{t\to\infty} x(t) = x_T(t)$$
$$x_T(t+T) = x_T(t)$$
$$|x_T(t)| \leq kT$$

Averaging Theorem (Russian School '60s):

Periodic system

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

Averaged system

$$\dot{x}_m = \bar{f}(x_m)$$
$$\bar{f}(x) \triangleq \frac{1}{T}\int_0^T f(x,t)dt$$

Theorem:

If origin of

$$\dot{x}_m = \bar{f}(x_m)$$

exponentially stable

⇒

(1) $|x(t) - x_m(t)| \leq kT$

(2) $\lim_{t\to\infty} x(t) = x_T(t)$

$x_T(t+T) = x_T(t)$

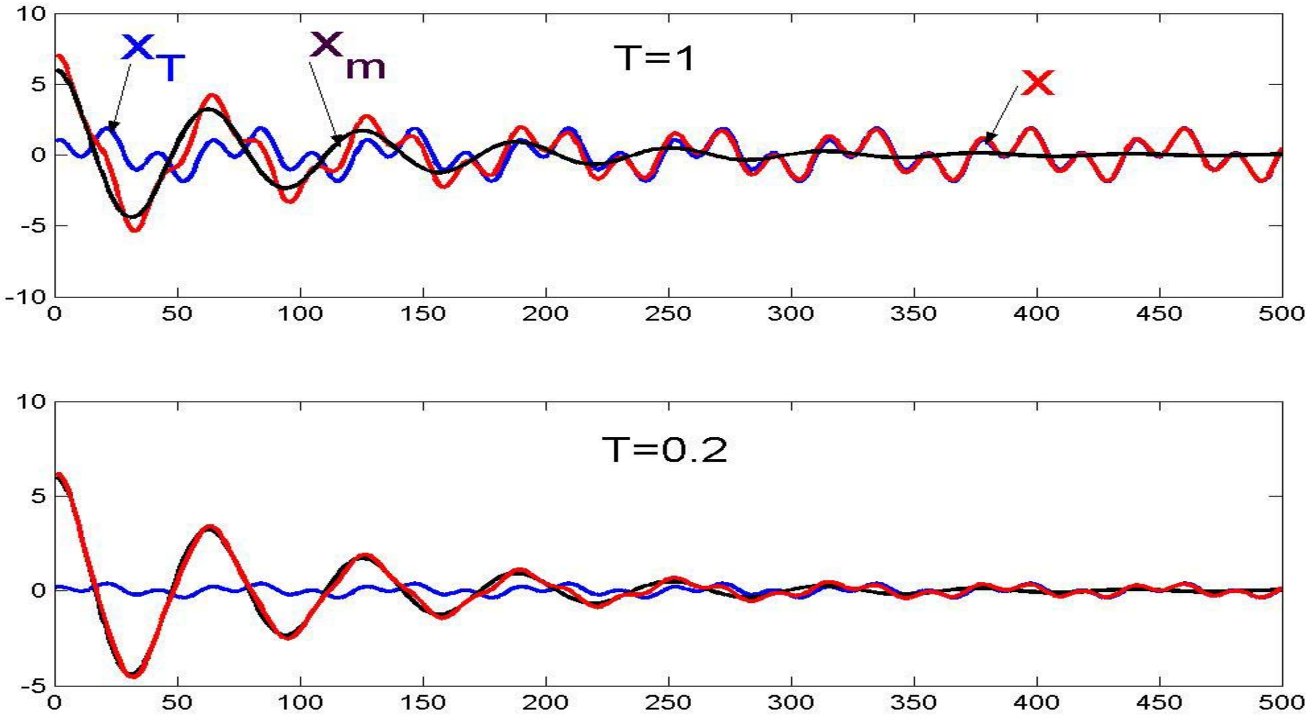
$|x_T(t)| \leq kT$

Averaging Theorem (Russian School '60s):

x: Periodic system

x_m: Averaged system

X_T: Limit cycle



Averaging: system with inputs

Original problem 1. *Find a feedback law* $g(x)$ *such that the system*

$$\begin{aligned} \dot{x} &= f(x,u) \\ u &= g(x) \end{aligned} \quad (1)$$

is asympotically stable.

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

$$\begin{aligned} \dot{x} &= \bar{f}(x,v) \\ \bar{f}(x,v) &= \frac{1}{T}\int_0^T f(x,w(v,t))dt \\ v &= h(x) \end{aligned} \quad (1)$$

is asymptotically stable.

Why doing it ? 3 Issues

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

$$\begin{array}{rcl} \dot{x} & = & \bar{f}(x,v) \\ \bar{f}(x,v) & = & \frac{1}{T}\int_0^T f(x,w(v,t))dt \\ v & = & h(x) \end{array} \qquad (1)$$

is asymptotically stable.

- 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 should the period T of the periodic input

Advantages of High frequency: a toy 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

Advantages of High frequency: a toy 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

+

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

⇩

$$\begin{cases} \dot{\bar{x}} \approx v_2 - \sqrt{2}\, 5 v_2^2 - 1^2 - 1 \\ \dot{\bar{y}} \approx v_1 \end{cases} \qquad \begin{cases} v_2 = \sqrt{2} - \bar{x} \\ v_1 = -\bar{y} \end{cases}$$

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

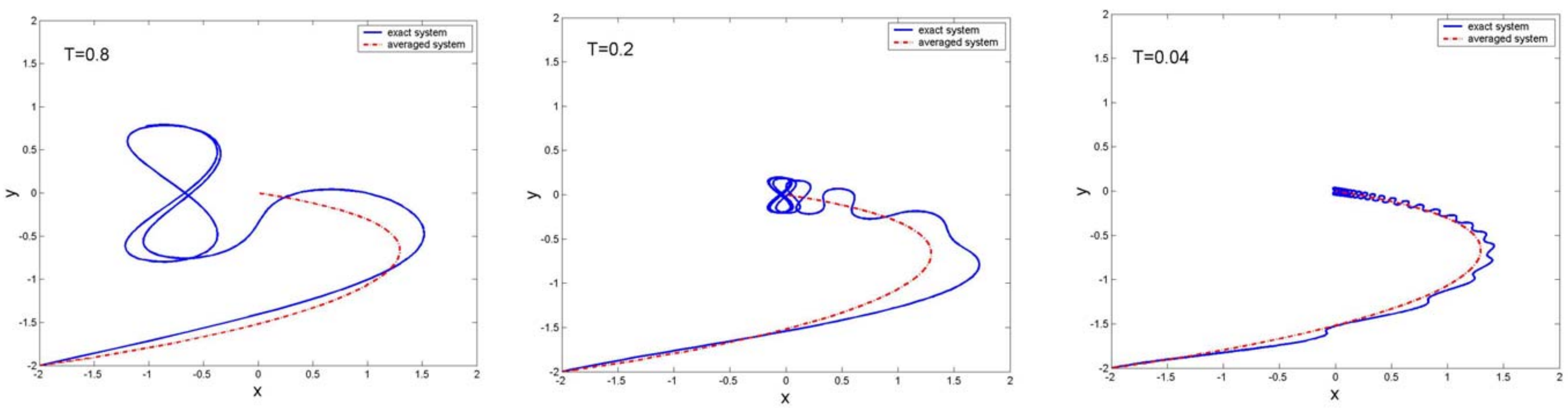
Advantages of High frequency: a toy example

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

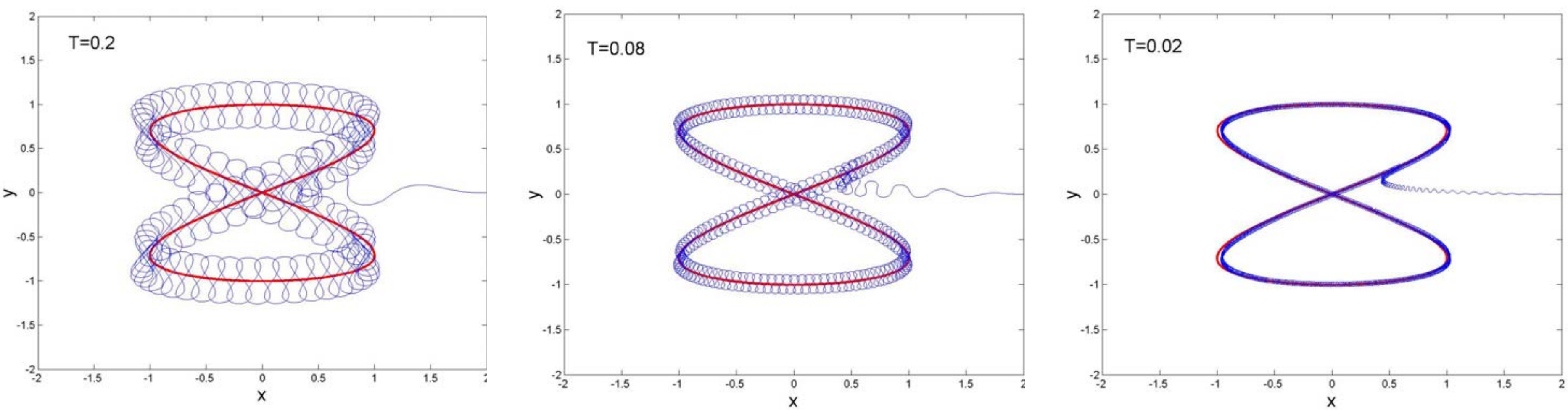
$$\begin{cases} \dot{\bar{x}} &= \bar{y}^2 + 0.5(\sqrt{2} - \bar{x})^2 - 1 \\ \dot{\bar{y}} &= -\bar{y} \end{cases}$$



Tracking: Figure-of-eight

Tracking is very easy to be designed

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



Back to the 3 Issues

- How do we choose the T-periodic function w(v,t) ?
  - Geometric control (read Lie Brackets) [Bullo00][Vela03] ..
  - BIOMETICS: mimic insect wings 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:
    - Simulations
    - Force platform (for example Dickinson's Robofly)
- How small must the period T of the periodic input be?
  - Wingbeat period of all insects is good enough

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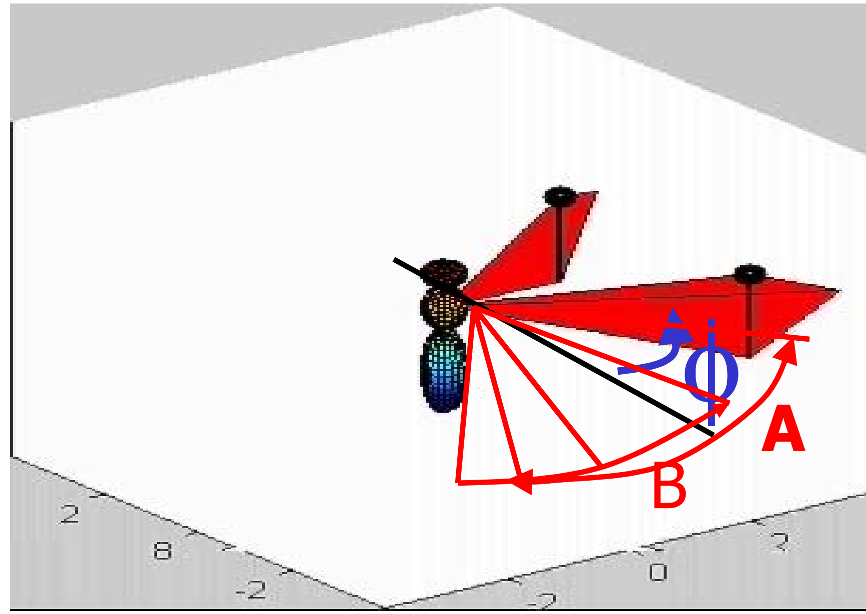
Back to insect toy-model

$$f_a^b = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = a \begin{bmatrix} \dot\phi_l|\dot\phi_l| + \dot\phi_r|\dot\phi_r| \\ 0 \\ \dot\phi_l^{\,2} + \dot\phi_r^{\,2} \end{bmatrix}$$

$$\tau_a^b = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = b \begin{bmatrix} \dot\phi_l^{\,2} - \dot\phi_r^{\,2} \\ \dot\phi_l^{\,2}\phi_l + \dot\phi_r^{\,2}\phi_r \\ \dot\phi_l|\dot\phi_l| - \dot\phi_r|\dot\phi_r| \end{bmatrix}$$

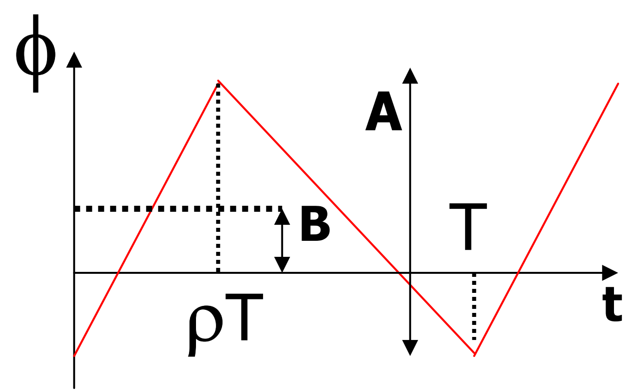


Saw-tooth input

$$u = (\phi_l, \phi_r)$$

$$v = (\rho_l, A_l, B_l, \rho_r, A_r, B_r)$$

$$u = w(v, t)$$



Averaged forces and torques

$$f_a^b(t) = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = a \begin{bmatrix} \dot\phi_l|\dot\phi_l| + \dot\phi_r|\dot\phi_r| \\ 0 \\ \dot\phi_l^{\,2} + \dot\phi_r^{\,2} \end{bmatrix}$$

$$\tau_a^b(t) = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = b \begin{bmatrix} \dot\phi_l^{\,2} - \dot\phi_r^{\,2} \\ \dot\phi_l^{\,2}\phi_l + \dot\phi_r^{\,2}\phi_r \\ \dot\phi_l|\dot\phi_l| - \dot\phi_r|\dot\phi_r| \end{bmatrix}$$

$+$ $(\phi_l, \phi_r) = \text{Saw-tooth motion}$

Symmetric change

$$\bar f_a^b \approx \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + c \begin{bmatrix} (\rho_l - 0.5) + (\rho_r - 0.5) \\ 0 \\ (A_l - A_0) + (A_r - A_0) \end{bmatrix}$$

$$\tau_a^b \approx d \begin{bmatrix} (A_l - A_0) - (A_r - A_0) \\ B_l + B_r \\ (\rho_l - 0.5) - (\rho_r - 0.5) \end{bmatrix}$$

Averaged forces as functions of wings kinematic parameters

Anti-symmetric change

5 **independent** and **decoupled** control of degrees of freedom
Using asymmetric or anti-symmetric wing motion

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- **Conclusions**

Flight Control mechanisms in real insects

- Kinematic parameters of wing motion have been correlated to observed maneuvers [Taylor01]
  - 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

Stroke amplitude

Stroke angle

Offset of stroke angle

$$\phi_i(t) = \frac{\pi}{3}\cos(wt) + v_1 \frac{\pi}{6}\cos(wt) + \frac{\pi}{15} v_2$$

$$\varphi_i(t) = \frac{\pi}{4}\sin(wt) + v_3 \frac{\pi}{4} g(t)$$

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

Guessed function that does the job

$$g(t) = -\frac{\pi}{15}\sin^3(\tfrac{1}{2}wt)$$

Timing of rotation

Rotation angle

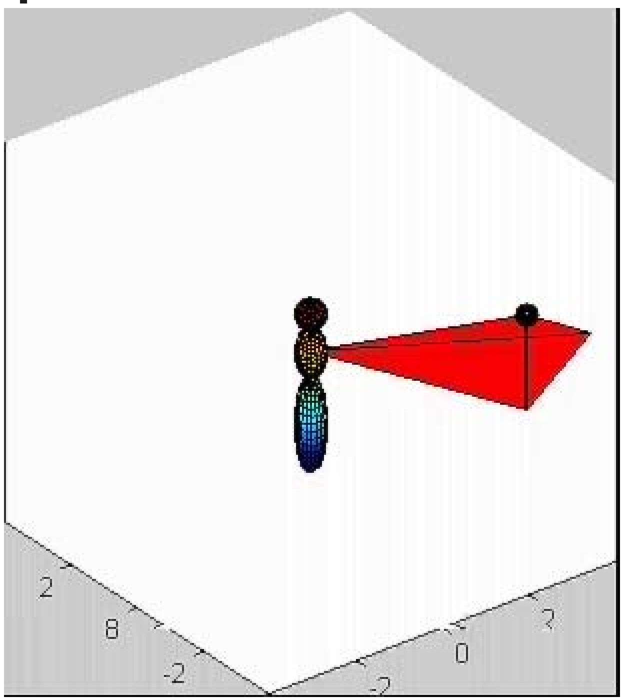
$u = (\phi_l, \varphi_l, \phi_r, \varphi_r)$ **Wings angles**

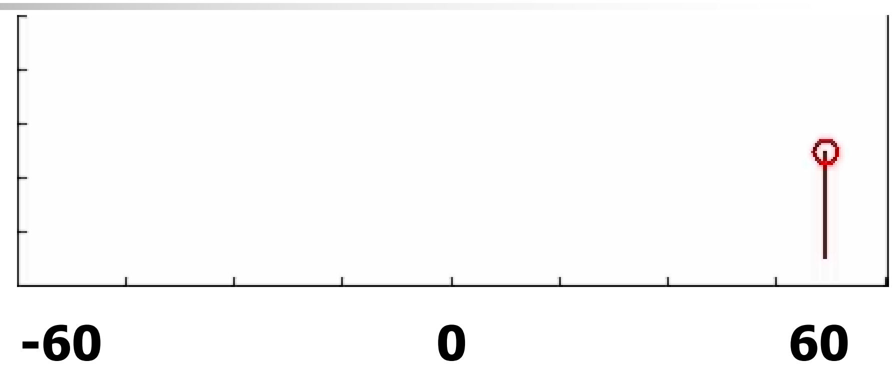
$v = ((v_1, v_2, v_3)_l, (v_1, v_2, v_3)_r)$ **Wing Kinematic paramaters**

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

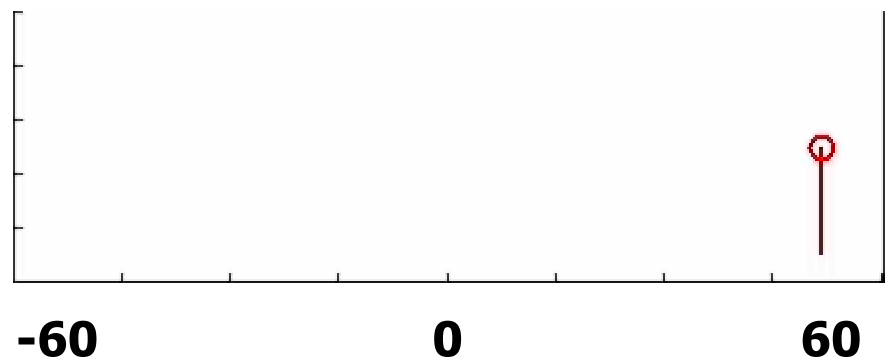
$g_0(t)$, $G(t)$
T-periodic functions

Parameterization of wing motion





$v_1 = 1$ $\quad v_1 = 0$ $\quad v_1 = -1$



$v_3 = 1$ $\quad v_3 = 0$ $\quad v_3 = -1$

$$\begin{aligned}\phi_i(t) &= \frac{\pi}{3}\cos(wt) + v_1 \frac{\pi}{6}\cos(wt) + \frac{\pi}{15} v_2 \\ \varphi_i(t) &= \frac{\pi}{4}\sin(wt) + v_3 \frac{\pi}{4} g(t)\end{aligned}$$

Mean forces/torques map

Wings trajectory → $u = g_0(t) + G(t)v$ ← Kinematical parameters

Independent control of 5 degrees of freedom

$$|v_i| \leq 1$$

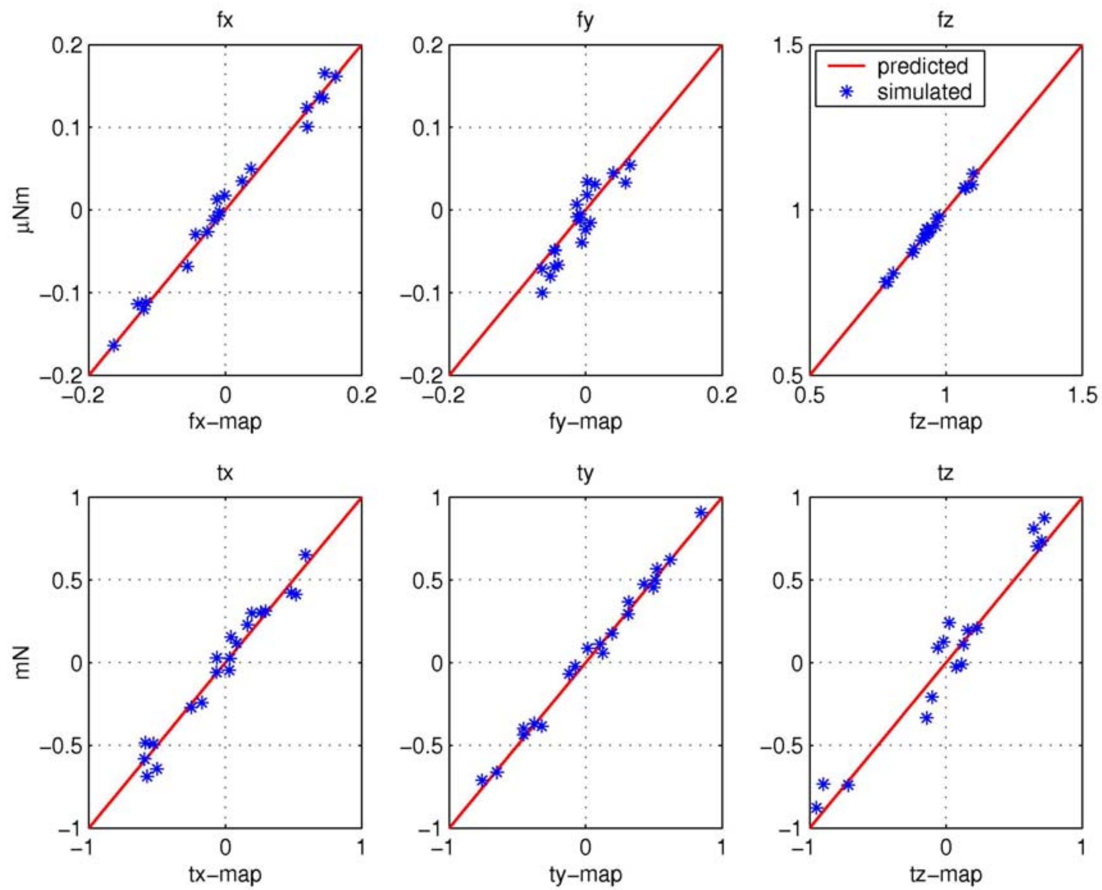
$$\begin{bmatrix} \bar{f}_x \\ \bar{f}_y \\ \bar{f}_z \end{bmatrix} \approx \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + 0.2mg \begin{bmatrix} v_1 \\ 0 \\ v_3 \end{bmatrix}$$

$$\begin{bmatrix} \bar{\tau}_x \\ \bar{\tau}_y \\ \bar{\tau}_z \end{bmatrix} \approx 0.2mgR \begin{bmatrix} v_4 \\ v_5 \\ v_6 \end{bmatrix}$$

Mean forces/torques map

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

$$\begin{bmatrix} \bar{\tau}_x \\ \bar{\tau}_y \\ \bar{\tau}_z \end{bmatrix} \approx 0.2mgR \begin{bmatrix} v_4 \\ v_5 \\ v_6 \end{bmatrix}$$

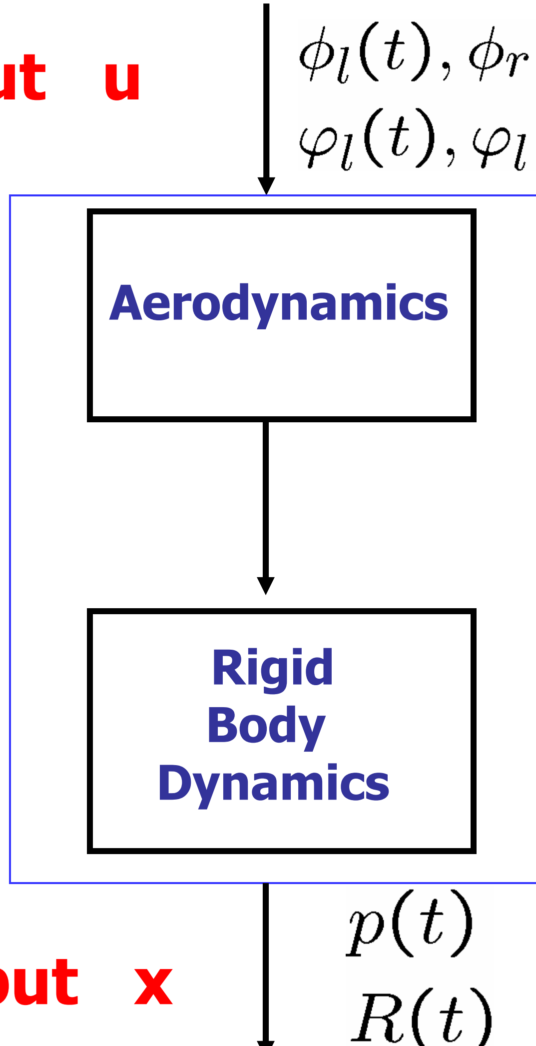


Dynamics of insect revised

Input u

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

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



$p(t)$

$R(t)$

Output x

After averaging

Before averaging

$$\dot{p} \quad \dot{v}^f \quad \dot{R} \quad \dot{\omega}^b$$

$$\begin{aligned}
\dot{p}_m &= v^f \\
\dot{v}_m^f &= \frac{1}{m} R \begin{bmatrix} v_1 \\ 0 \\ v_2 \end{bmatrix} - g \\
\dot{R}_m &= R\widehat{\omega}^b \\
\dot{\omega}_m^b &= I_b^{-1}\left(\begin{bmatrix} v_3 \\ v_4 \\ v_5 \end{bmatrix} - \omega^b \times I_b \omega^b\right)
\end{aligned}$$

Proportional Feedback

$$v = Kx$$

- Hovering
- Cruising
- Steering

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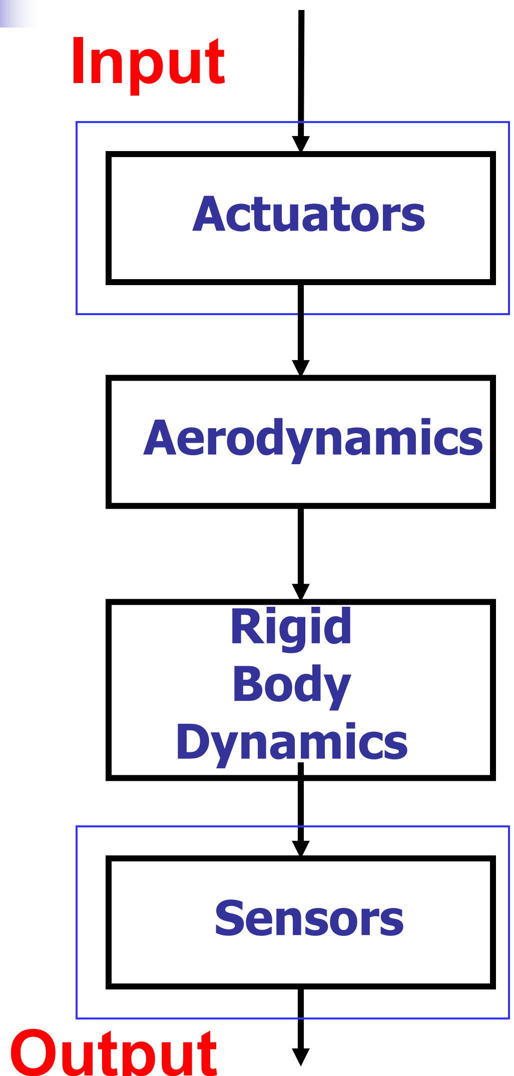
Insect Dynamics: realistic model



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

Input voltage to actuators

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

Wing kinematics

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

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

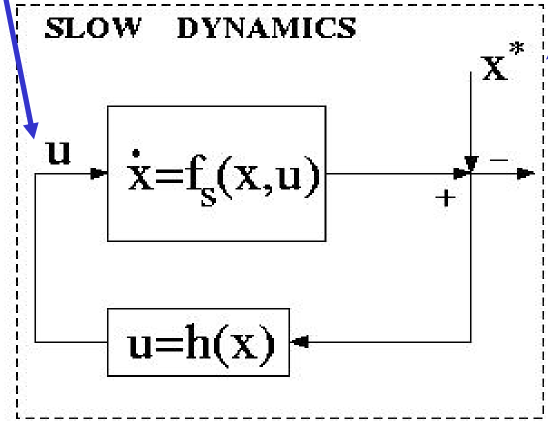
Sensor measurements

Separation of timescale

Wings position

Insect position

Actuators voltage

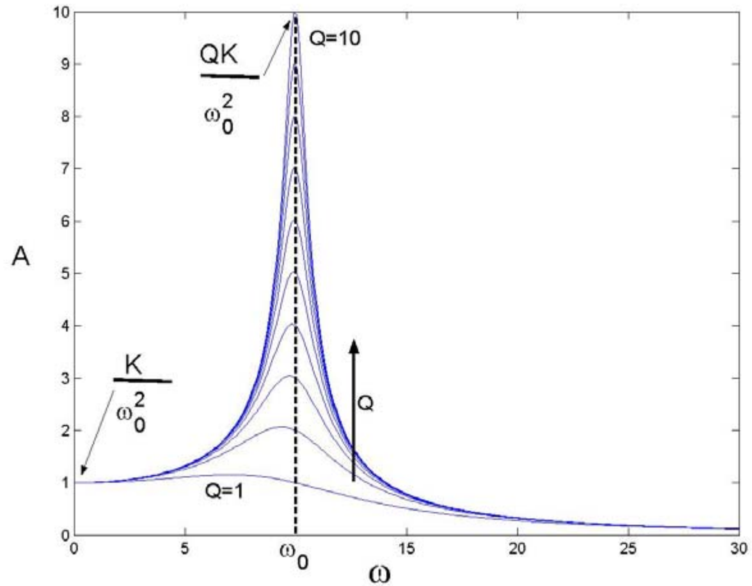


THEOREM: (Extension to [Kokotovic-Khalil 99] work)

If the slow system is slow enough, the cascade system is still stable

The toy model revised

$$\begin{cases} \dot{x} = u^2 - 1 \\ \dot{y} = u \\ \ddot{u} = -\frac{\omega_0}{Q}\dot{u} - \omega_0^2 u + Kv \end{cases}$$



Actuator dynamics:

Q: quality factor

ω_0: resonant frequency

K: static gain

Poles: $\lambda = -\frac{\omega_0}{2Q} \pm j\omega_0$

$$\tau_{decay} = \frac{Q}{\pi}T$$

The toy model revised

$$\begin{cases} \dot{x} &= u^2 - 1 \\ \dot{y} &= u \\ \ddot{u} &= -\frac{\omega_0}{Q}\dot{u} - \omega_0^2 u + Kv \end{cases}$$

Input to fast system

$$v = v_1 \frac{\omega_0^2}{K} + v_2 \frac{\omega_0}{KQ} \sin \omega_0 t$$

Steady state solution of fast system

$$u_T = v_1 + v_2 \sin \omega_0 t$$

Averaged dynamics

$$\begin{cases} \dot{x} &\approx v_2 - \sqrt{2}, \\ \dot{y} &\approx v_1 \end{cases}$$

Stabilizing Input

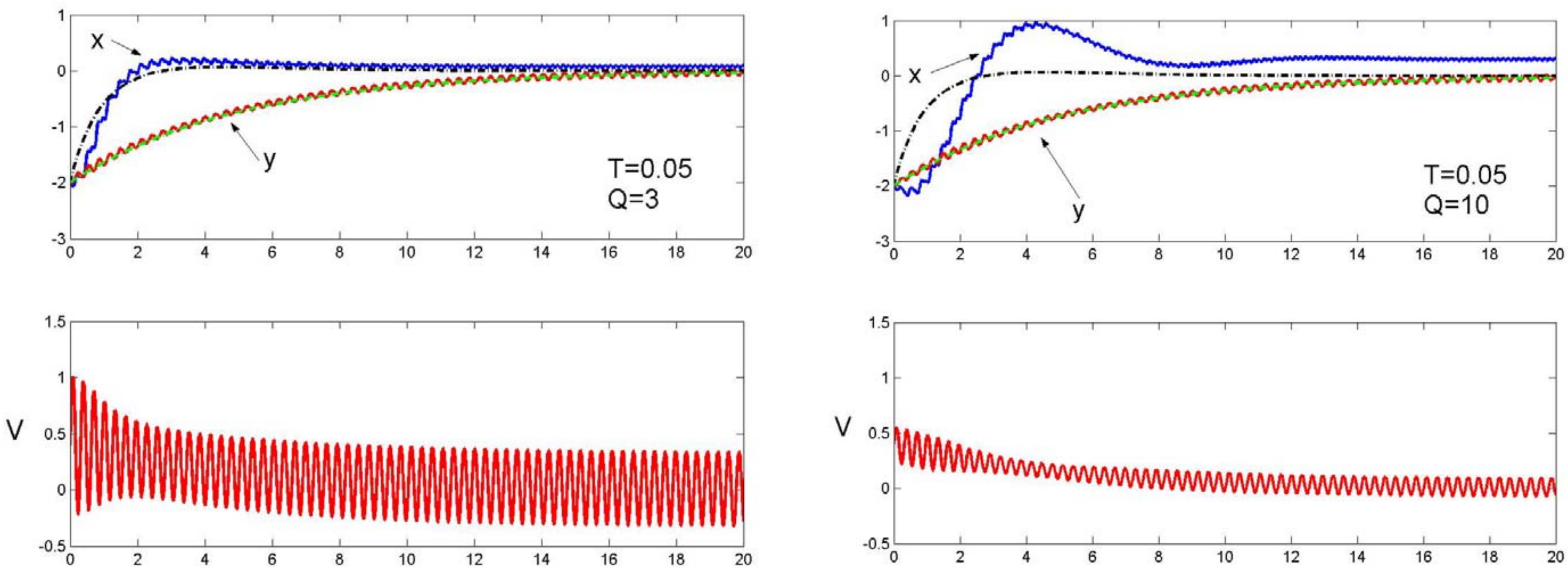
$$\begin{cases} v_2 &= \sqrt{2} - \bar{x} \\ v_1 &= -\bar{y} \end{cases}$$

The toy model revised

$$\begin{cases} \dot{x} &= u^2 - 1 \\ \dot{y} &= u \\ \ddot{u} &= -\frac{\omega_0}{Q}\dot{u} - \omega_0^2 u + Kv \\ v &= -y\,\frac{\omega_0^2}{K} + (\sqrt{2} - x)\,\frac{\omega_0}{KQ}\sin\omega_0 t \end{cases}$$

Close to

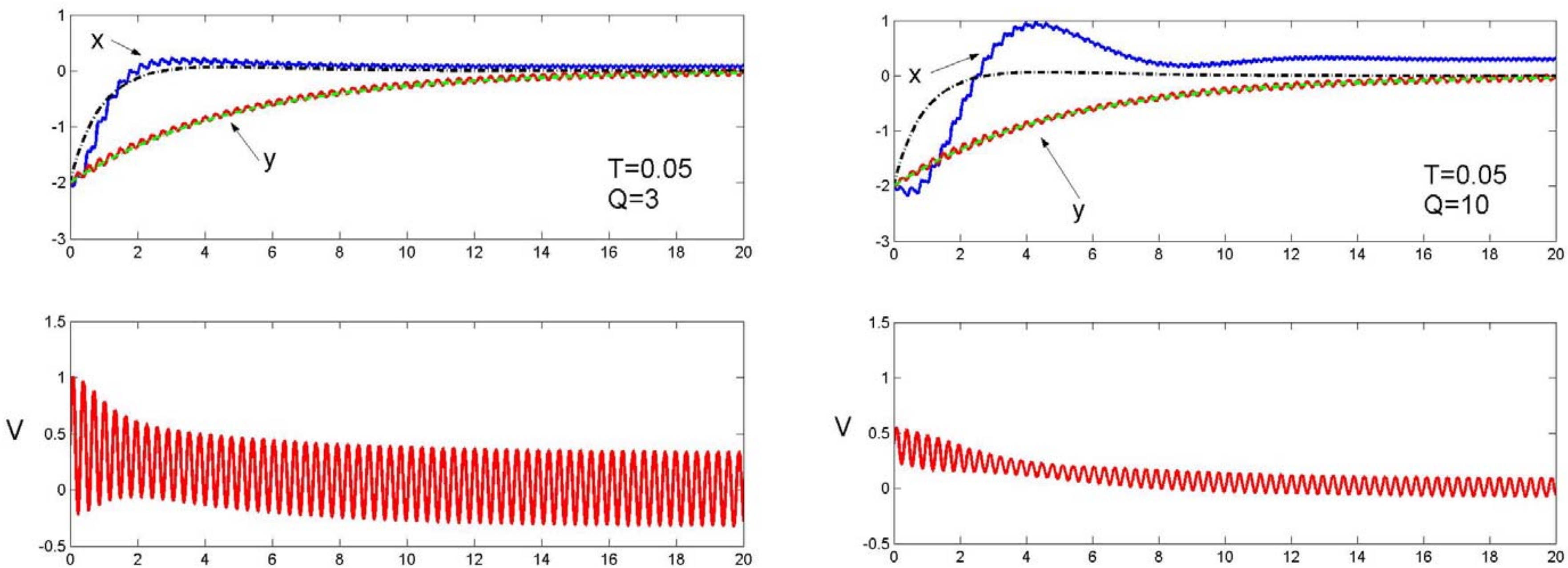
$$\begin{cases} \dot{x} &\approx -x \\ \dot{y} &\approx -y \end{cases}$$



Responsiveness vs input amplitude trade-off

$$\begin{cases} \dot{x} &= u^2 - 1 \\ \dot{y} &= u \\ \ddot{u} &= -\frac{\omega_0}{Q}\dot{u} - \omega_0^2 u + Kv \\ v &= -y\,\frac{\omega_0^2}{K} + (\sqrt{2} - x)\,\frac{\omega_0}{KQ}\sin\omega_0 t \end{cases}$$

$$\tau_{decay} = \frac{Q}{\pi}T$$



MFI actuator dynamics

Stable mechanical system

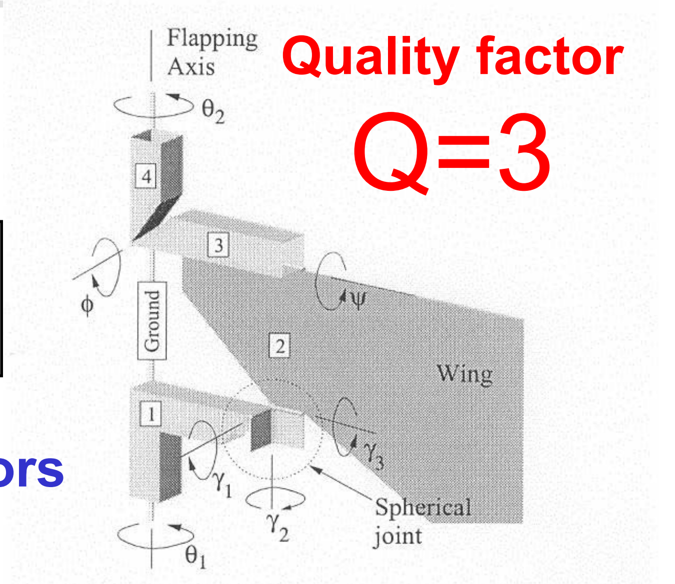
$$M_0 \begin{bmatrix} \ddot{\phi} \\ \ddot{\varphi} \end{bmatrix} + B_0 \begin{bmatrix} \dot{\phi} \\ \dot{\varphi} \end{bmatrix} + K_0 \begin{bmatrix} \phi \\ \varphi \end{bmatrix} = T_0 \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

Wings angles

Input voltage to actuators

$$u = (\phi_l, \varphi_l, \phi_r, \varphi_r)$$
$$V = (V_{1,l}, V_{2,l}, V_{1,r}, V_{2,r})$$

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



Quality factor

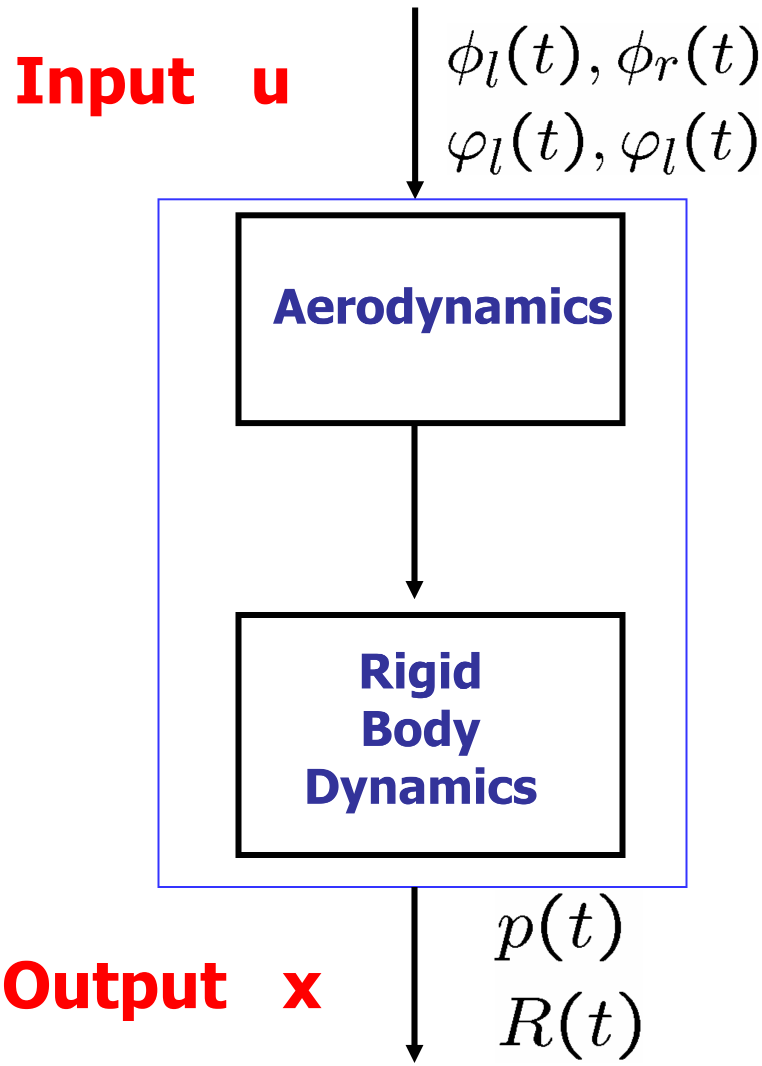
Q=3

Model: courtesy of Srinath Avadhanula

$$V = h_0(t) + H(t)v$$

$h_0(t)$,$H(t)$ obtained by substitution

Dynamics of insect revised



After averaging

$$
\begin{aligned}
\dot{p}_m &= v^f \\
\dot{v}_m^f &= \frac{1}{m} R \begin{bmatrix} v_1 \\ 0 \\ v_2 \end{bmatrix} - g \\
\dot{R}_m &= R\widehat{\omega}^b \\
\dot{\omega}_m^b &= I_b^{-1}\left(\begin{bmatrix} v_3 \\ v_4 \\ v_5 \end{bmatrix} - \omega^b \times I_b \omega^b \right)
\end{aligned}
$$

Proportional Feedback

$$v = Kx$$

- Hovering
- Cruising
- Steering

Proportional periodic feedback

Output from sensors

Input voltages to actuators

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

T-Periodic matrix
T is wingbeat period

Proportional periodic feedback

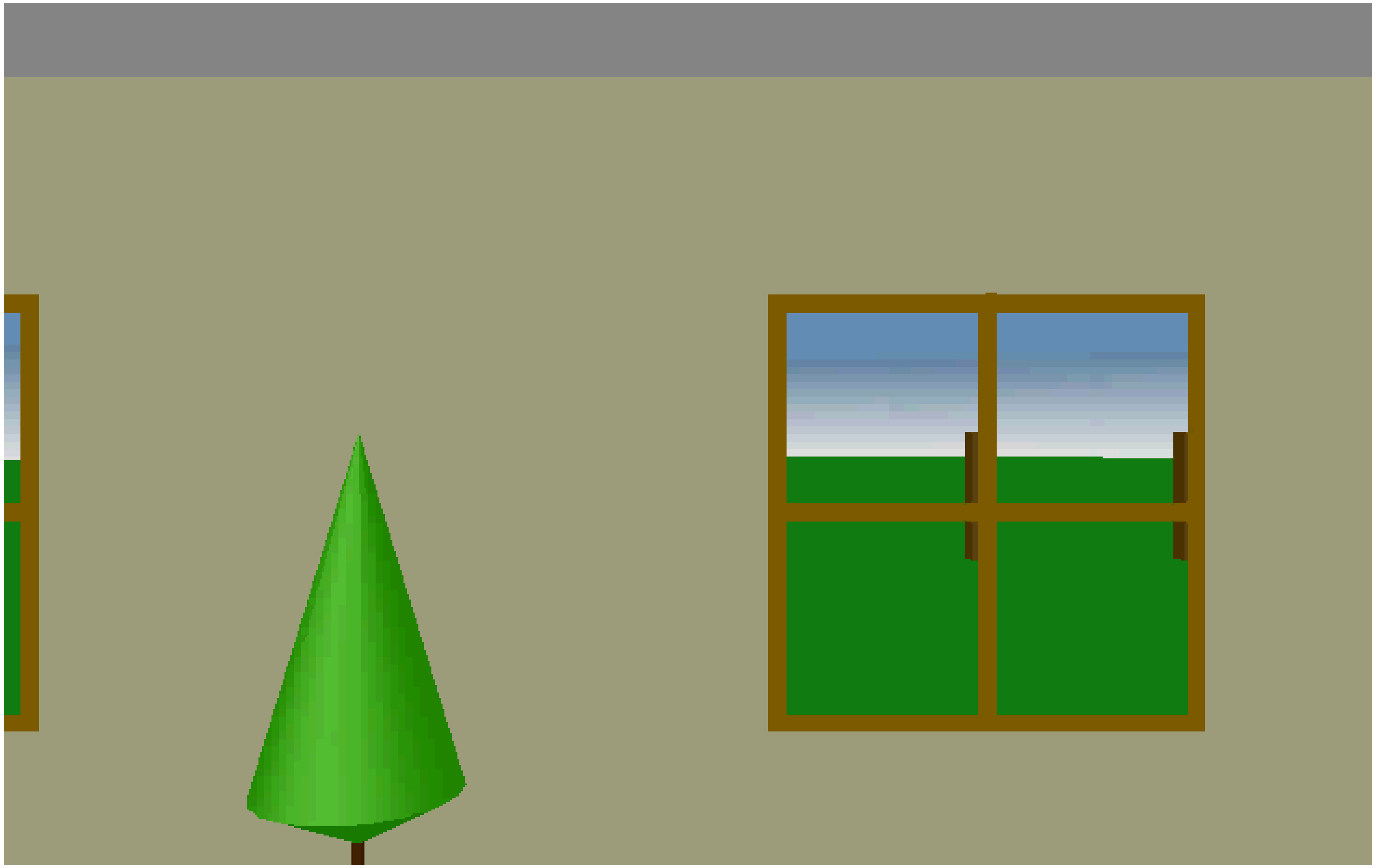
Output from sensors

Input voltages to actuators

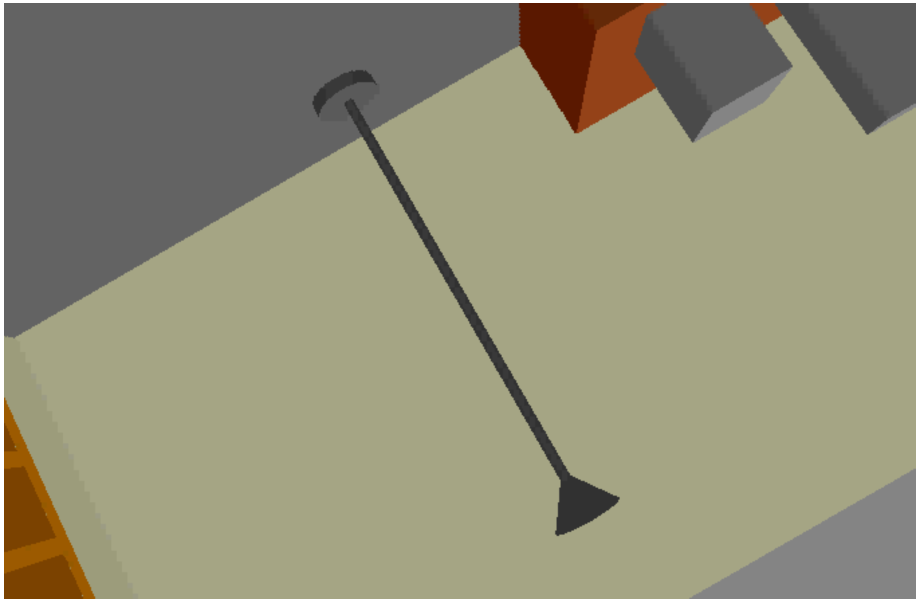
$$\begin{bmatrix} V_{1,l}(t) \\ V_{2,l}(t) \\ V_{1,r}(t) \\ V_{2,r}(t) \end{bmatrix} = h(t) + \tilde{H}(t) \begin{bmatrix} y_c \\ y_1^o \\ y_2^o \\ y_x^h \\ y_y^h \\ y_z^h \end{bmatrix}$$

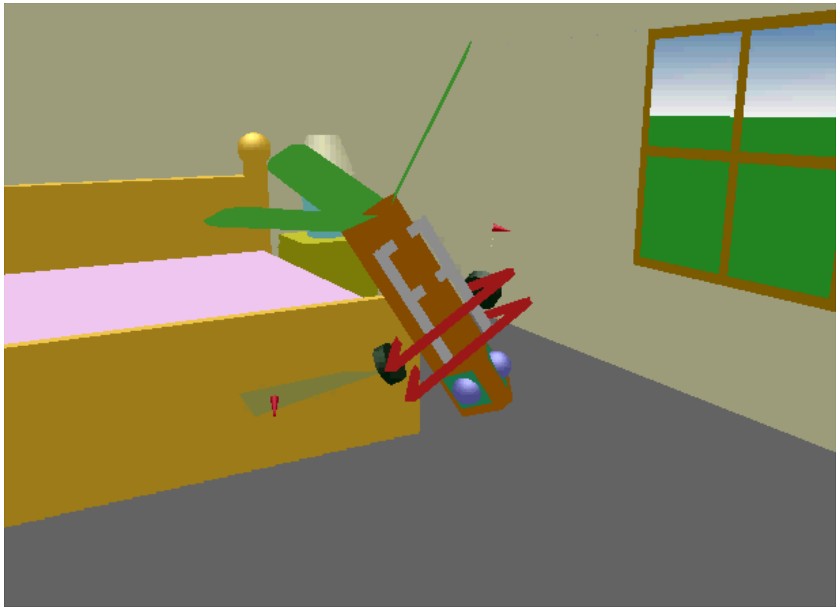
T-Periodic matrix
T is wingbeat period

Simulations w/ sensors and actuators: Steering

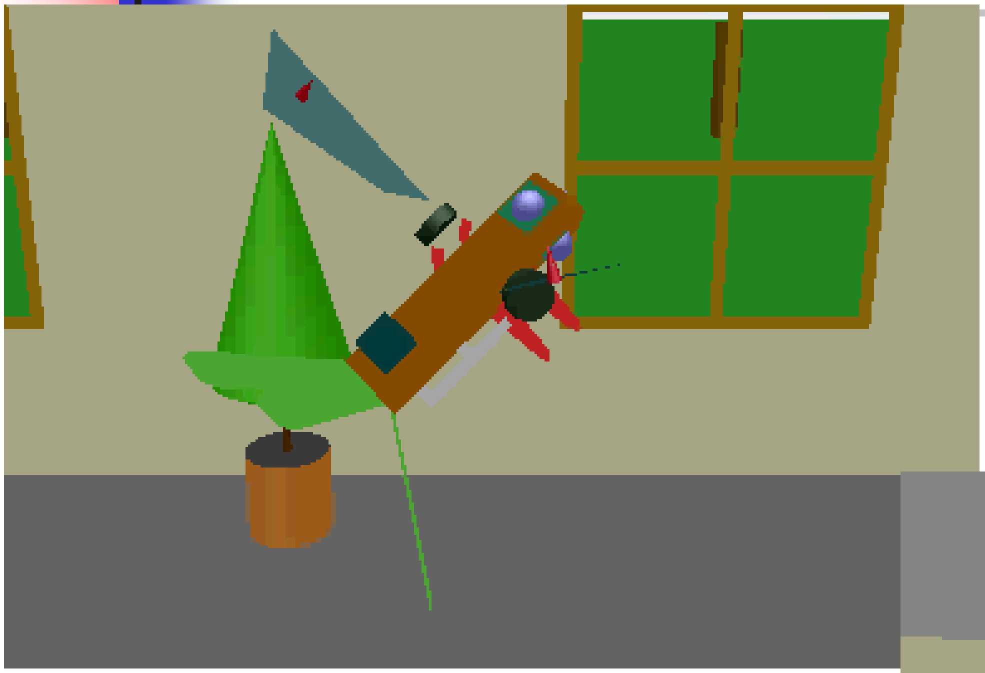


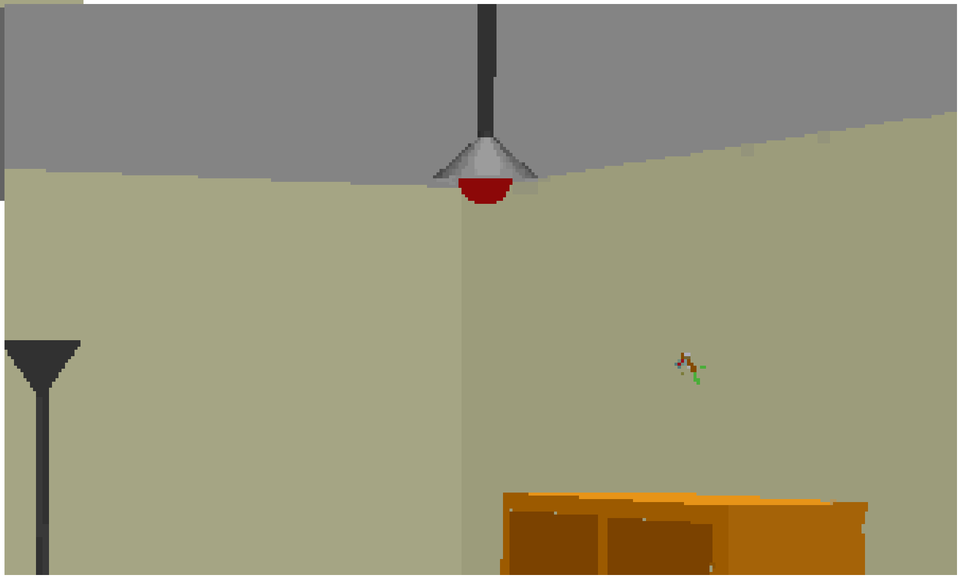
Simulations w/ sensors and actuators: Recovering





Simulations: Hovering





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Personal contribution:

- **Biological perspective:**
  - Flapping flight does allow independent control of 5 degrees of freedom (**using mathematical models**)
- **Technological perspective:**
  - Simple control scheme: proportional period feedback from sensors to actuators input
  - Quantified limit of performance
  - Realistic methodology (when experimental data available)
- **Control Theoretical perspective:**
  - Rigorous use of averaging theory to explain flapping flight
  - Flapping flight as biological example of high-frequency control of an under-actuated system

Future work

- **Biological perspective:**
  - Use experimental data to validate methodology
  - Deeper explorations of design trade-offs:
    - quality factor,
    - actuator stiffness,
    - bandwidth of insect dynamics
- **Technological perspective:**
  - Extension to 1-degree of freedom wing with passive rotation and PWM control
- **Control Theory perspective:**
  - Flapping flight as high frequency control of underactuated system in rigorous terms

Acknowledgments

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X.Deng, W.C. Wu, D. Campolo

Thanks to all MFI group

Project website:

http://robotics.eecs.berkeley.edu/~ronf/mfi.html

Q&A

Thank you

150hz.avi

Video courtesy of Erik Steltz