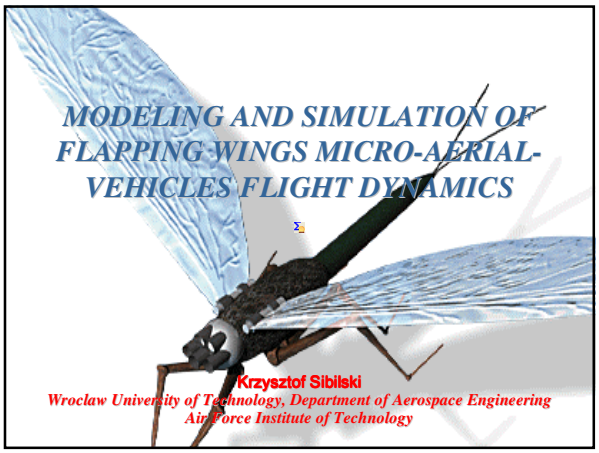


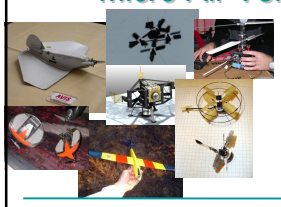
MODELING AND SIMULATION OF FLAPPING WINGS MICRO-AERIAL-VEHICLES FLIGHT DYNAMICS

Krzysztof Sibilski

Wroclaw University of Technology, Department of Aerospace Engineering

Air Force Institute of Technology

Micro Air Vehicle - MAV



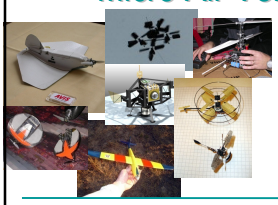
Technical Objectives:

- Develop flight enabling technologies.
- Develop and demonstrate Micro Air Vehicles capable of sustained flight and useful military missions.

Military Relevance:

- Enhanced Situational Awareness for Small Units Operations
  - ***Platoon level asset***
- Enables new missions in emerging warfighting environments
  - ***Urban operations***
- Potential users: Army, Marines, Air Force, Navy, Special Operations Forces

Micro Air Vehicle - MAV



Non Military Relevance:

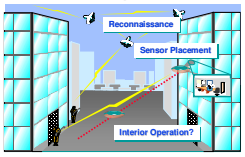
Small air vehicle no larger than 15 cm in any dimension.

- Capable of performing a useful military mission at an affordable cost.

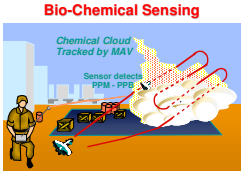
- Outdoor NBC emergency reconnaissance
- Crowd control
- Suspect facilities surveillance
- Snap inspection of pollution
- Road accident documentation
- Urban traffic management
- Search for survivors
- Pipeline inspection
- High risk indoor inspection
- Space exploration

MAV Missions – military application

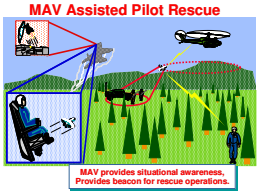
Urban Operations



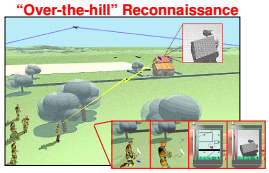
Bio-Chemical Sensing



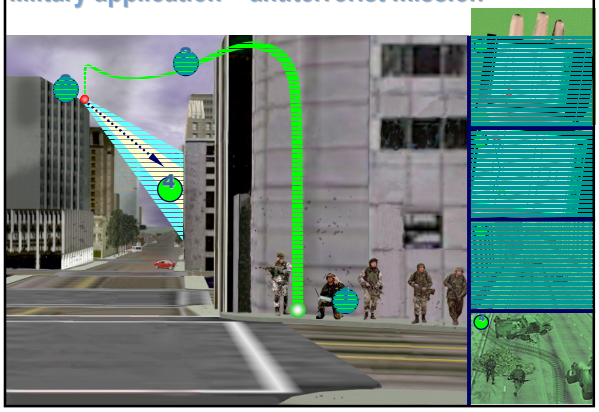
MAV Assisted Pilot Rescue



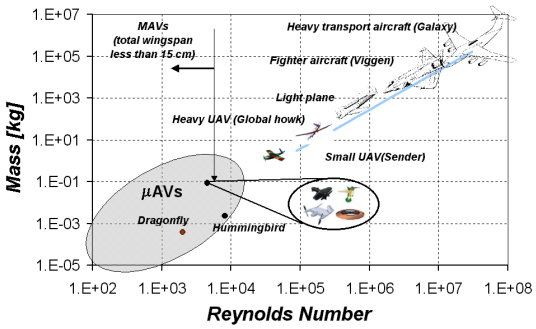
"Over-the-hill" Reconnaissance



Miltary application – antiterrorist mission

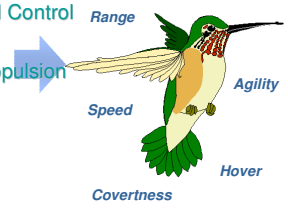


The Micro Air Vehicle Flight Regime Compared to Existing Flight Vehicles



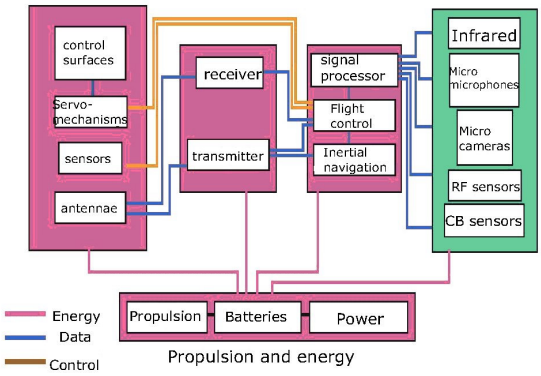
Technical Challenges

- Low Re Aerodynamics and Control
- Lightweight Power and Propulsion
- Autonomy navigation, guidance and control
- Ultra-light sensors and communications



High Degree of Integration and Multifunctionality

Integration of MAV systems



What is Biomimetics?

Biomimetics is the abstraction a good design from Nature.

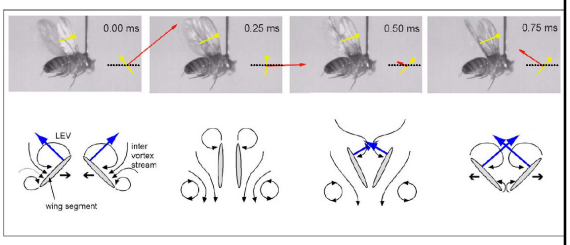
Scientists and engineers are increasingly turning to nature for inspiration. The solutions arrived at by natural selection are often a good starting point in the search for answers to scientific and technical problems. Equally, designing and building bioinspired devices or systems can tell us more about the original animal or plant model.
This lecture is focused on *Bioinspiration & Biomimetics* in design of a new generation of flying vehicles so caaled Micro Aerial Vehicles (MAVs). MAVs are not a toys. MAVs are new generation of autonomous flying robots.
Our research involved:

- the study and distillation of principles and functions found in biological systems flight principles that have been developed through evolution,
- application of this knowledge to produce novel and exciting basic technologies and new approaches to solving scientific problems of fligt.

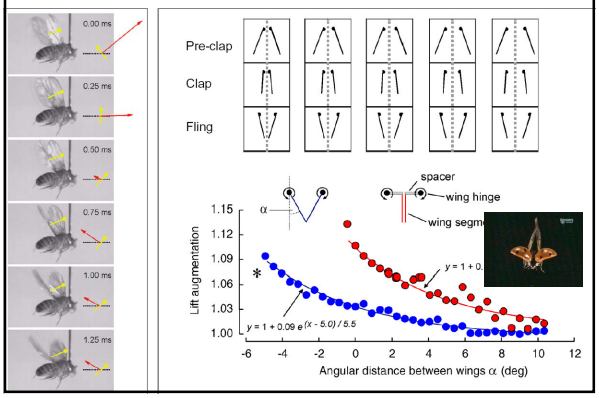
Insects - over 30 000 000 specimens

Aerodynamically, the bumblebee can not fly.
The bumblebee's body is too heavy and its wings span too small !!!
But it does not know that. That is why it flies.

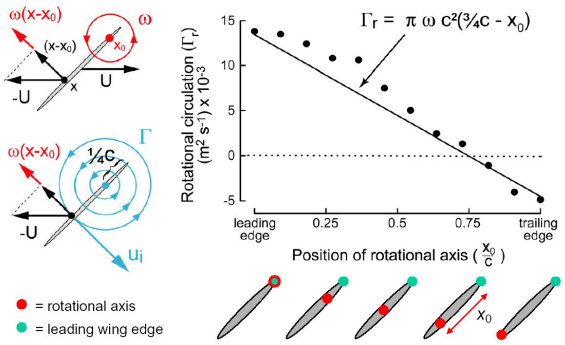
Wais – Fogh mechanism



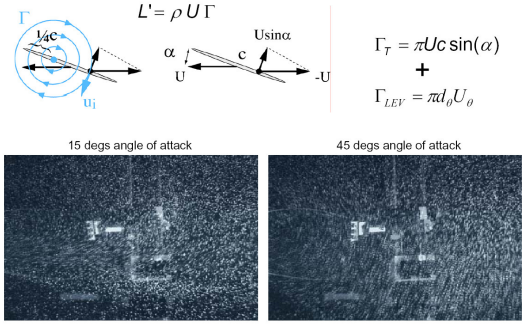
Wais – Fogh mechanism



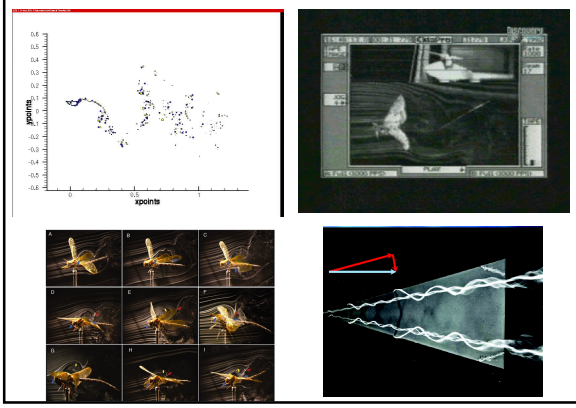
Wings rotation (rotational lift)



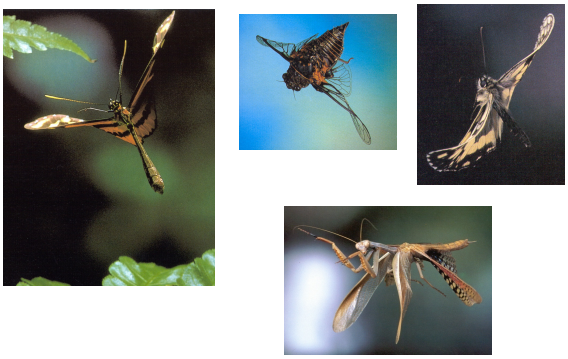
LEX vortex



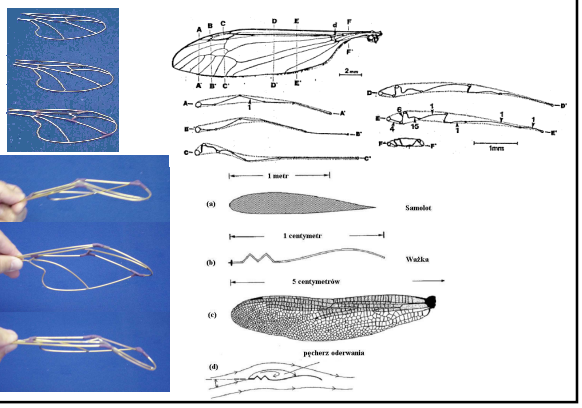
LEX vortex



Insects in flight

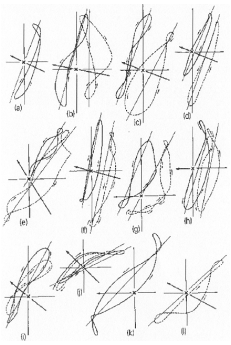


Entomopter & insect wings



Wing Motion

Not simply up and down - much more complex!



Wingtip trajectories

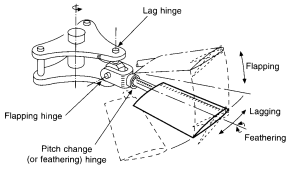
Wing Motion

Can consider as motion as being composed of three different rotations flapping, lagging, and feathering

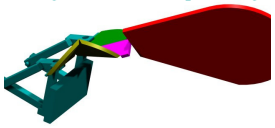
Three Hinges of the Wing Apparatus.

Horizontal (flapping)
Vertical (lagging)
Torsional (feathering)

Helicopter articulated hub

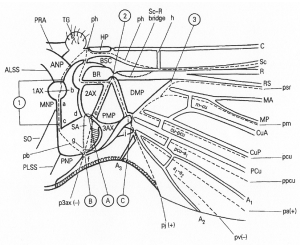


Hinges of an entomopter wing



Each insect hinge occurs at the intersection of a vein and fold

Hinges

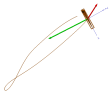


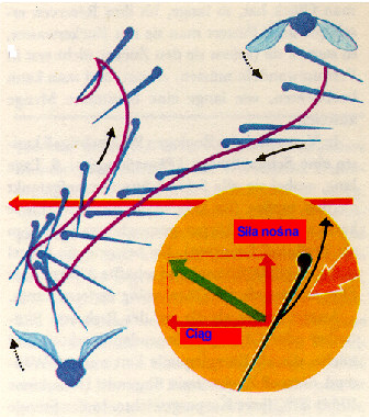
The horizontal hinge - 1
- occurs near the base of the wing next to the first axiliary sclerite
- this hinge allow the wing to flap up and down

The vertical hinge - 2
- located at the base of the radial vein near the second axillary sclerite (2AX)
- responsible for the lagging motion of the wing

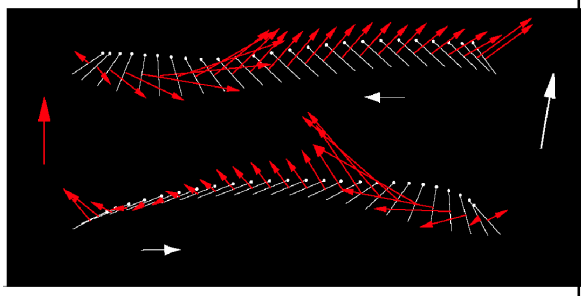
The torsional hinge - 3
- more complicated interaction of sclerite and deformable folds

Insect wings kinematics



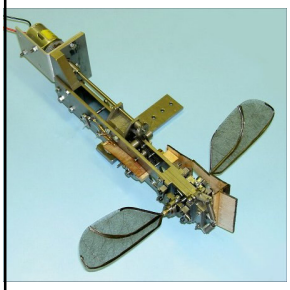


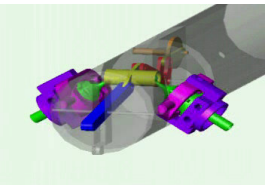
Insect wings kinematics

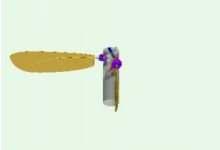


Entomopter's gears

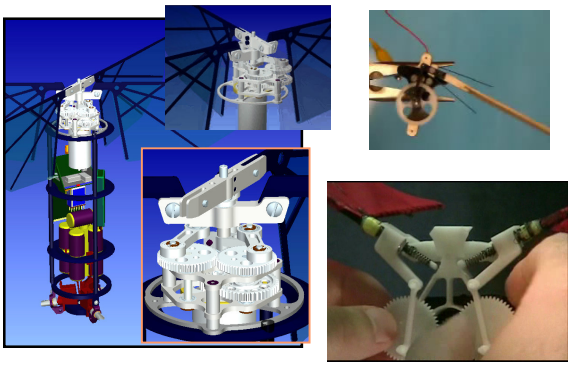
Dr. Zbikowski Cranfield University





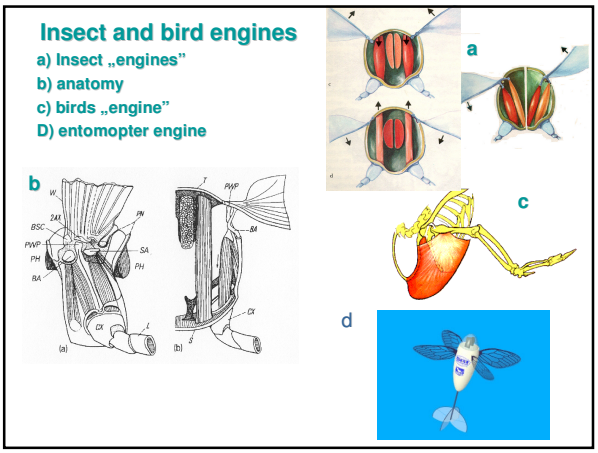


Entomopter gears



Insect and bird engines

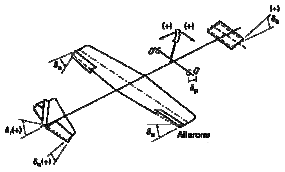
a) Insect „engines"
b) anatomy
c) birds „engine"
D) entomopter engine



Unconventional propulsion – artificial muscels

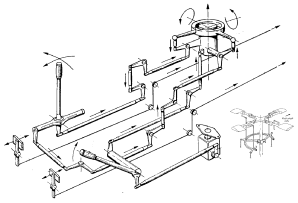
From NASA website

Fixed & rotary wings aircraft aerodynamic controls



Fixed wing aircraft primary aerodynamic controls

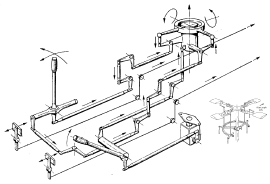
Rotorcraft primary aerodynamic controls

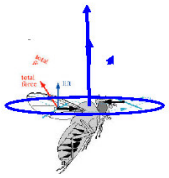


Entomopter vs. Helicopter

Analogies:
-Control by change of thrust position and thrust magnitude

Differences:
- aerodynamic loads are complex function of wings configuration and entomopter velocity

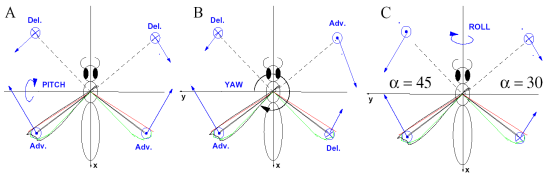




Flight stabilization mechanism

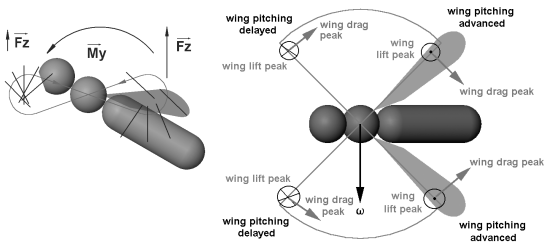
Open loop wing motions that can generate:
(A) pitch, (B) yaw, (C) roll torques.

The arrows represent the instantaneous aerodynamic forces acting on the wings. The circles with a cross or with a dot correspond, respectively to the perpendicular component of the force entering or exiting the stroke plane. Adv. and Del. stand for advanced and delayed rotation, respectively.



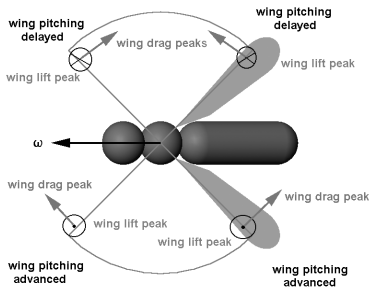
Flight stabilization mechanism

Global pitching moment generated
by different wing pitch reversals on both stroke ends



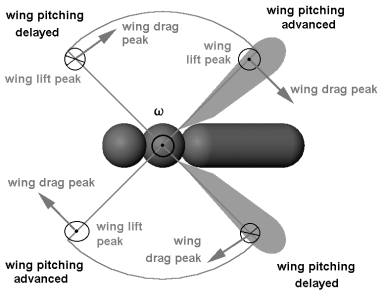
Flight stabilization mechanism

Control in roll

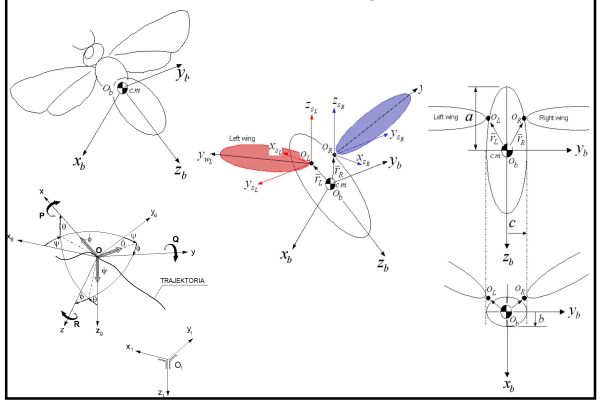


Flight stabilization mechanism

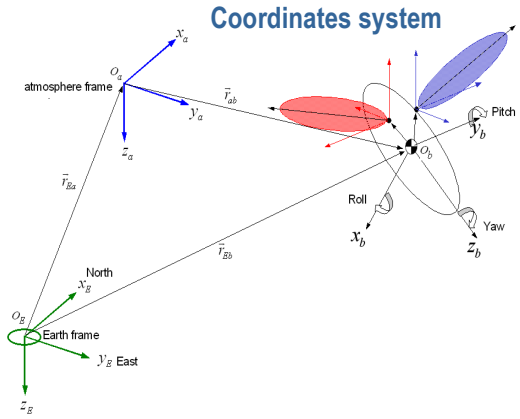
Control in yaw



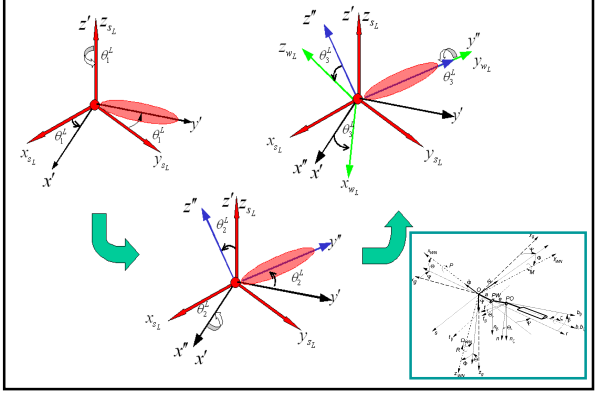
Coordinates system



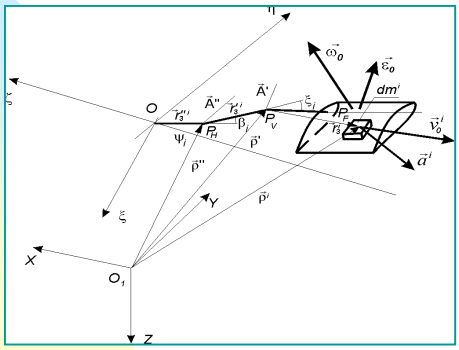
Coordinates system



Coordinates system



Location of points, radius vectors, vectors of velocities and vectors of accelerations



MATHEMATICAL MODEL OF FLAPPING WINGS MAV MOTION

The formalism of analytical mechanics allows to present dynamic equations of motion of mechanical systems in generalised co-ordinates, giving incredibly interesting and comfortable tool for construction of equation of motion of aircraft. An example can be Gibbs-Appel equations. Those equations have the following form:

$$\frac{d}{dt}\left(\frac{\partial S}{\partial \ddot{\mathbf{q}}}\right)=\mathbf{Q} \qquad (1)$$

where: q - is the vector of generalised co-ordinates

$S(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},t)$ **- is so called Appel function, or functional of accelerations**

Functional S for i-th element of the mechanical system is given by the equation:

$$S=\frac{1}{2}\iiint_{V^i}\dot{\mathbf{v}}^i\circ\dot{\mathbf{v}}^i dm^i \qquad (2)$$

where:

$\dot{\mathbf{v}}^i$ **means the vector of absolute acceleration of elementary mass dm^i of i-th body of the considered dynamical system.**

and:

$$\dot{\mathbf{v}}^i=\dot{\mathbf{v}}_0^i+\boldsymbol{\varepsilon}_0^i\times\boldsymbol{\rho}^i+\boldsymbol{\omega}_0^i\times\left(\boldsymbol{\omega}_0^i\times\boldsymbol{\rho}^i\right) \qquad (3)$$

Assuming that:

$$\mathbf{r}^i=\mathbf{r}_3^{\prime\prime i}+\mathbf{r}_3^{\prime i}+\mathbf{r}_3^i \qquad (4)$$

and:

$$\mathbf{M}^i=\begin{bmatrix} m^i\mathbf{I} & m^i\tilde{\mathbf{r}}^{iT} \\ m\tilde{\mathbf{r}}^i & \mathbf{J}_O^i \end{bmatrix} \qquad (5)$$

$$\mathbf{h}^i=\begin{bmatrix} m^i\tilde{\boldsymbol{\omega}}_0+m^i\tilde{\boldsymbol{\omega}}_0{}^2\mathbf{r}^i \\ m^i\tilde{\mathbf{r}}^i\tilde{\boldsymbol{\omega}}\mathbf{v}_0^i+\tilde{\boldsymbol{\omega}}_0\mathbf{J}_O^i\boldsymbol{\omega}_0 \end{bmatrix} \qquad (6)$$

where: m^i - mass of the i-th element, $\mathbf{J}_O{}^i$ tensor of inertia of the *i*-th element,
$\boldsymbol{\omega}_0$ - vector of the angular velocity,
$\mathbf{v}_0{}^i$ - vector of the velocity of the *i*-th element,

where if $\mathbf{a}=\left[a_\xi, a_\eta, a_\varsigma\right]^T$ **than** $\tilde{\mathbf{a}}=\begin{bmatrix} 0 & -a_\varsigma & a_\eta \\ a_\varsigma & 0 & -a_\xi \\ -a_\eta & a_\xi & 0 \end{bmatrix}$

The term (2) can be expressed in the following matrix form:

$$S^i=\frac{1}{2}\left[\dot{\mathbf{v}}^i+\left(\mathbf{M}^i\right)^{-1}\mathbf{h}^i\right]^T\mathbf{M}^i\left[\dot{\mathbf{v}}^i+\left(\mathbf{M}^i\right)^{-1}\mathbf{h}^i\right] \qquad (7)$$

Defining matrixes for all *k* bodies of the system:

$$\mathbf{M}=diag\left[\mathbf{M}^1,\mathbf{M}^2,\ldots\ \ldots,\mathbf{M}^k\right] \qquad (8)$$

$$\mathbf{v}=\left[\left(\mathbf{v}^1\right)^T,\left(\mathbf{v}^2\right)^T,\ldots\ \ldots,\left(\mathbf{v}^k\right)^T\right]^T \qquad (9)$$

$$\mathbf{h}=\left[\left(\mathbf{h}^1\right)^T,\left(\mathbf{h}^2\right)^T,\ldots\ \ldots,\left(\mathbf{h}^k\right)^T\right]^T \qquad (10)$$

Functional S for the whole mechanical system is given by the equation:

$$S=\frac{1}{2}\left(\dot{\mathbf{v}}+\mathbf{M}^{-1}\mathbf{h}\right)^T\mathbf{M}\left(\dot{\mathbf{v}}+\mathbf{M}^{-1}\mathbf{h}\right) \qquad (11)$$

Assuming that q is vector generalised coordinates of mechanical system, the relations between q and v are given by equation:

$$\mathbf{v}=\mathbf{D}(\mathbf{q},t)\dot{\mathbf{q}}+\mathbf{f}(\mathbf{q},t) \qquad (12)$$

hence:

$$\dot{\mathbf{v}}=\mathbf{D}(\mathbf{q},t)\ddot{\mathbf{q}}+\boldsymbol{\varphi}(\mathbf{q},\dot{\mathbf{q}},t) \qquad (13)$$

where:

$$\boldsymbol{\varphi}=\dot{\mathbf{D}}\dot{\mathbf{q}}+\dot{\mathbf{f}}$$

Therefore the Appel function can be expressed by following relation:

$$S(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},t)=\frac{1}{2}\left(\mathbf{D}\ddot{\mathbf{q}}+\boldsymbol{\varphi}+\mathbf{M}^{-1}\mathbf{h}\right)^T\mathbf{M}\left(\mathbf{D}\ddot{\mathbf{q}}+\boldsymbol{\varphi}+\mathbf{M}^{-1}\mathbf{h}\right) \quad (14)$$

Assuming, that:

$$\mathbf{M}_g=\mathbf{D}^T\mathbf{M}\mathbf{D} \quad \text{and} \quad \mathbf{h}_g=\mathbf{D}^T(\mathbf{M}\boldsymbol{\varphi}+\mathbf{h})$$

and remembering, that:

$$\mathbf{D}\left(\mathbf{D}^T\mathbf{M}\mathbf{D}\right)^{-1}\mathbf{D}^T=\mathbf{M}^{-1}$$

the equation (14) can be expressed in the form:

$$S(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},t)=\frac{1}{2}\left(\ddot{\mathbf{q}}+\mathbf{M}_g^{-1}\mathbf{h}_g\right)^T\mathbf{M}\left(\ddot{\mathbf{q}}+\mathbf{M}_g^{-1}\mathbf{h}_g\right) \quad (15)$$

Vector of generalised co-ordinates has following form

$$\mathbf{q}=[x_c,y_c,z_c,\Phi,\Theta,\Psi,\beta_R,\beta_L,\zeta_R,\zeta_L,\theta_R,\theta_L]^T \quad (16)$$

vector of quasi-velocities can be expressed by the following equation

$$\mathbf{w}=[u,v,w,p,q,r,\dot{\beta}_R,\dot{\beta}_L,\dot{\zeta}_R,\dot{\zeta}_R,\dot{\theta}_R,\dot{\theta}_L]^T \quad (17)$$

For the holonomic dynamical system the relation between generalized velocities $\dot{\mathbf{q}}=[\dot{q}_1,\dot{q}_2,.....\dot{q}_n]^T$ and quasi velocities $\mathbf{w}=[w_1,w_2,.....w_3]^T$ is following:

$$\dot{\mathbf{q}}=\mathbf{A}_T(\mathbf{q})\mathbf{w} \quad (18)$$

The matrix $\mathbf{A}_T$ has a construction:

$$\mathbf{A}_T=\begin{bmatrix}\mathbf{A}_G & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{C}_T & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{I}\end{bmatrix} \quad (19)$$

From (18) we have the following relation:

$$\ddot{\mathbf{q}}=\mathbf{A}_T(\mathbf{q})\dot{\mathbf{w}}+\dot{\mathbf{A}}_T\mathbf{w} \quad (20)$$

Finally, the Appel function has following form:

$$S^*(\mathbf{q},\mathbf{w},\dot{\mathbf{w}},t)=\frac{1}{2}\left(\dot{\mathbf{w}}+\mathbf{M}_w^{-1}\mathbf{h}_w\right)^T\mathbf{M}_w\left(\dot{\mathbf{w}}+\mathbf{M}_w^{-1}\mathbf{h}_w\right)$$

where $\mathbf{M}_w(\mathbf{q})=\mathbf{A}_T^T\mathbf{M}_q\mathbf{A}_T$, and: $\mathbf{h}_w(\mathbf{q},\mathbf{w})=\mathbf{A}_T^T\left(\mathbf{M}_q\dot{\mathbf{A}}_T+\mathbf{h}_q\right)$

Gibbs-Appel equations of motion, written in quasivelocities has the following form:

$$\left(\frac{\partial S^*}{\partial\dot{\mathbf{w}}}\right)^T=\left[\frac{\partial S^*}{\partial\dot{w}_1},.....,\frac{\partial S^*}{\partial\dot{w}_k}\right]^T=\mathbf{M}_w(\mathbf{q},t)\dot{\mathbf{w}}+\mathbf{h}_w(\mathbf{q},\mathbf{w},t)=\mathbf{Q}^*(\mathbf{q},\mathbf{w},t) \quad (21)$$

Mathematical model for nonlinear flight simulation

$$\mathbf{M}\dot{\mathbf{V}}+\mathbf{M}\left(\dot{\mathbf{J}}_\Omega+\mathbf{J}_\Omega\mathbf{J}_\Omega\right)\mathbf{R}_C+\mathbf{M}\mathbf{J}_\Omega\dot{\mathbf{R}}_C+\mathbf{M}\mathbf{J}_\Omega=\mathbf{F}+\mathbf{G}$$

$$\mathbf{J}_B\dot{\boldsymbol{\Omega}}+\mathbf{J}_B^R\dot{\mathbf{O}}_R+\mathbf{J}_B^L\dot{\mathbf{O}}_L+\left(\mathbf{J}_s+\mathbf{J}_S^w+2\mathbf{J}_\Omega\mathbf{J}_S+\dot{\mathbf{J}}_S^w\right)\mathbf{V}+$$
$$+\left(\dot{\mathbf{J}}_B^R+\mathbf{J}_\Omega\mathbf{J}_B^R\right)\mathbf{O}_R+\left(\dot{\mathbf{J}}_B^L+\mathbf{J}_\Omega\mathbf{J}_B^L\right)\mathbf{O}_L+\mathbf{J}_\Omega\mathbf{J}_B\boldsymbol{\Omega}=\mathbf{M}_0+\mathbf{R}_C\times\mathbf{G}$$

where: $\mathbf{M}=m\mathbf{I}$, m – mass of MAV, $\mathbf{I}$ – unit matrix,
$\mathbf{F}=[F_x, F_y, F_z]^T$ – vector of aerodynamic forces,
$\mathbf{M}_0=[L,M,N]^T$ – vector of aerodynamic moments,
$\mathbf{V}=[U,V,W]^T$ – velocity vector;
$\boldsymbol{\Omega}=[P,Q,R]^T$ – vector of angular velocity,
$\mathbf{O}_R=\left[P-\dot{\beta},Q+\dot{\theta},R\right]^T$ - vector of right wing angular rates,
$\mathbf{O}_L=\left[P+\dot{\beta},Q+\dot{\theta},R\right]^T$ - vector of left wing angular rate;
$\mathbf{R}_c=[x_c, y_c, z_c]^T$ vector of the center of mass

Mathematical model for nonlinear flight simulation

$$\mathbf{J}_\Omega=\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix} \qquad \mathbf{J}_S=\begin{bmatrix}0 & -S_z & S_y\\ S_z & 0 & -S_x\\ -S_y & S_x & 0\end{bmatrix}$$

S_x, S_y, S_z - static moments of entomopter without wings;
$\mathbf{J}_S^w$ - matrix of static moments of MAV's wing;
$\mathbf{J}_B$ - inertial moment of MAV without wings;
$\mathbf{J}_B^R$, $\mathbf{J}_B^L$ - inertial moments of right and left wing.

The control vector is defined as follows:

$$\mathbf{u}=\left[\beta,\phi,\omega,\psi\right]^T$$

where: β - flapping angle of wings;
ϕ - feathering angle of wings,
ω - frequency of wing motion respect to the body;
ψ - phase shifting between feathering and flapping;
and: $\beta=\beta_0\sin\omega t,\quad \phi=\phi_0\sin(\omega t+\psi)$

Mathematical model for nonlinear flight simulation

In those equations:

$$F_x=\frac{1}{2}\rho V_0^2SC_x(C_L(\alpha,\mathbf{u}),C_D(\alpha,\mathbf{u})),$$

$$F_y=\frac{1}{2}\rho V_0^2S\,C_y(C_L(\alpha,\mathbf{u}),C_D(\alpha,\mathbf{u})),$$

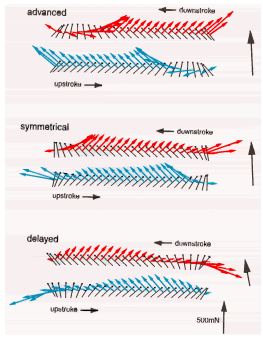
$$F_z=\frac{1}{2}\rho V_0^2S\,C_z(C_L(\alpha,\mathbf{u}),C_D(\alpha,\mathbf{u})),$$

$$M_{0x}=\frac{1}{2}\rho V_0^2SbC_l(\alpha,\mathbf{u}),\qquad M_{0y}=\frac{1}{2}\rho V_0^2SbC_m(\alpha,\mathbf{u}),$$

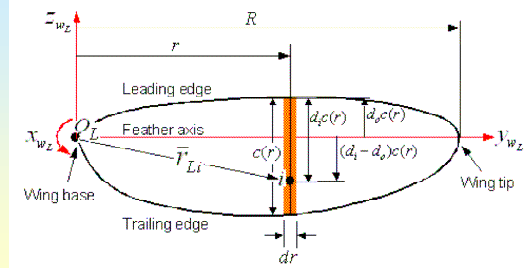
$$M_{0z}=\frac{1}{2}\rho V_0^2SbC_n(\alpha,\mathbf{u}).$$

Distribution of instantaneous forces along a wingbeat cycle:

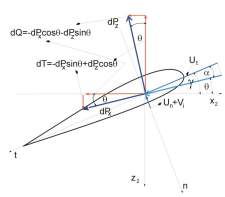
- Important to stabilise the flight.
- Fundamental kinematic parameters:
  - flapping angle of wings β,
  - feathering angle of wings ϕ
  - frequency of wing motion respect to the body ω,
  - phase shifting between feathering and flapping ψ,
  - mean stroke η,
  - angle of attack α
- Large and impulsive forces at the wing reversals.



Aerodynamic model - Blade Element Method (BEM)



Modeling of aerodynamic loads steady state model - BEM



$$\Delta T_i = -\Delta P_{xi}\sin\theta_i + \Delta P_{zi}\cos\theta_i \quad \Delta Q_i = -\Delta P_{xi}\cos\theta - \Delta P_{zi}\sin\theta_i$$

$$\theta = \gamma - \alpha$$

$$\Delta P_{xi} = \frac{1}{2}\rho c_i U^2 C_{xi}(\alpha_i)\Delta b_i \qquad \Delta P_{zi} = \frac{1}{2}\rho c_i U^2 C_{zi}(\alpha_i)\Delta b_i$$

$$\alpha_i = \arctan\left(\frac{U_{si} - V_i}{U_{si}}\right)$$

$$U_{si} = (\cos\beta\cos\zeta + \sin\beta\sin\theta\sin\zeta)U_M + (\cos\beta\sin\zeta - \sin\beta\sin\theta\cos\zeta)V_M + (-\sin\beta\cos\theta)W_M +$$
$$+\left((-\cos\theta\sin\zeta)P + \cos\theta\cos\zeta Q - \sin\theta R - \dot{\zeta}\sin\theta\right)z_3 +$$
$$+\left((\sin\beta\cos\zeta - \cos\beta\sin\theta\sin\zeta)P + (\sin\beta\sin\zeta + \cos\beta\sin\theta\cos\zeta)Q + \cos\beta\cos\theta R + \dot{\gamma} + \dot{\zeta}\cos\theta\cos\beta\right)y_3$$

$$U_{ni} = (\sin\beta\cos\zeta - \cos\beta\sin\theta\sin\zeta)U_M + (\sin\beta\sin\zeta + \cos\beta\sin\theta\cos\zeta)V_M + \cos\beta\cos\theta W_M +$$
$$+\left((\cos\beta\cos\zeta + \sin\beta\sin\theta\sin\zeta)P + (\cos\beta\sin\zeta - \sin\beta\sin\theta\sin\zeta)Q - \sin\beta\cos\theta R + \dot{\theta}\cos\beta - \dot{\zeta}\cos\theta\sin\beta\right)z_3 +$$
$$-\left(-\cos\beta\sin\zeta P + \cos\theta\cos\zeta Q - \sin\theta R - \dot{\zeta}\sin\delta\right)x_3$$

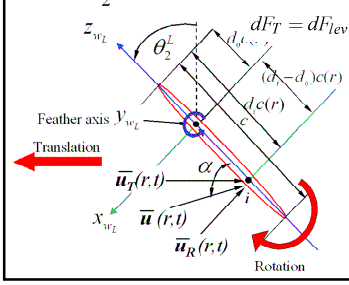
Aerodynamic model – quasi unsteady approach

$$dF_{steady} = \frac{\rho}{2} C_F(\alpha)\,|\bar{u}_T(r,t)|^2 c(r)dr,$$

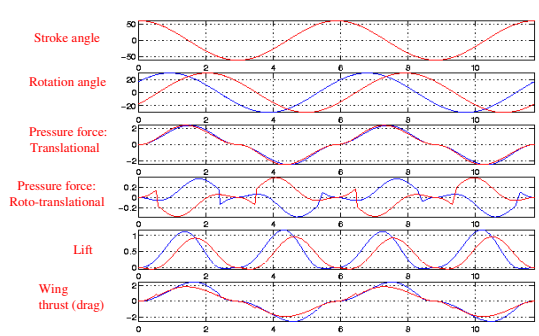
$$dF_T = dF_{steady}(\dot{\theta}_1^L) + dF_{unsteady}(\dot{\theta}_1^L, \dot{\theta}_3^L, \ddot{\theta}_1^L, \ddot{\theta}_3^L),$$

$$dF_{lev+rot} = \frac{\rho}{2} C_1(\alpha)|\bar{u}(r,t)|^2 c(r)dr,$$

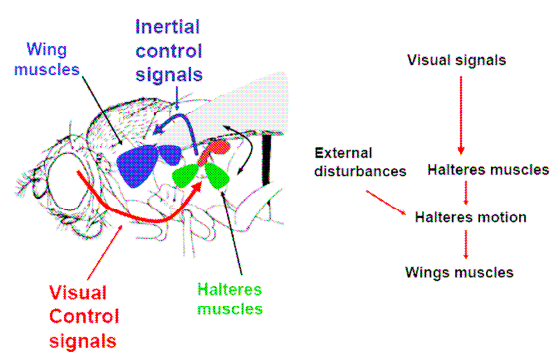
$$dF_T = dF_{lev+rot} = C_1 dF_1 + dF_2(C_1, C_2),$$



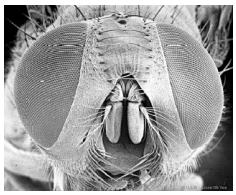
BEM: results of simulations

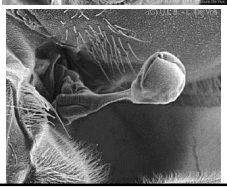


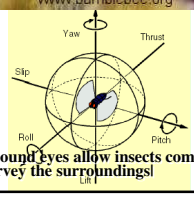
Neuromotor Control in Insects



Flight-related sensors of the housefly *Musca domestica*:
- the large compound eyes dominate the head;
- ocelli are three light-sensitive sensors on top of the head;
- halteres appear on the thorax and beat in anti-phase to the wings, sensing rotary motion

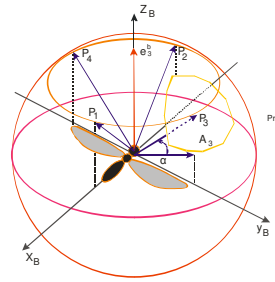


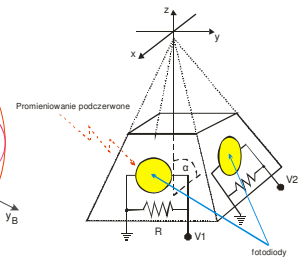




compound eyes allow insects completely to survey the surroundings

Ocelli like light-sensitive sensors applied to stabilization of MAV flight

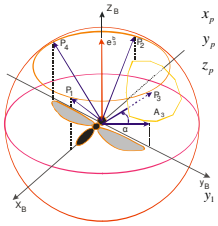




Four photoreceptors are fixed with respect to the insect's body frame

Schematics of ocelli design

Ocelli and halters like light-sensitive sensors applied to stabilization of MAV flight



$$x_p = r\sin\theta\cos\psi \qquad P_1^b = \left[\sqrt{1-h^2}, 0, h\right]^T, P_2^b = \left[-\sqrt{1-h^2}, 0, h\right]^T$$

$$y_p = r\sin\theta\sin\psi \qquad P_3^b = \left[0, \sqrt{1-h^2}, h\right]^T, P_4^b = \left[0, -\sqrt{1-h^2}, h\right]^T$$

$$z_p = r\cos\theta$$

$$I(P) = I(\psi,\theta) = I(\theta) \qquad y_1 = I(P_1^a) - I(P_2^a)$$

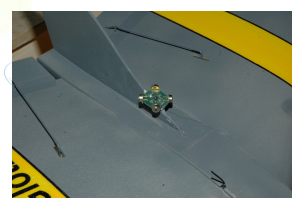
$$\theta_1 < \theta_2 \Rightarrow I(\theta_1) > I(\theta_2) \qquad y_2 = I(P_3^a) - I(P_4^a)$$

$$y_1 = \tilde{I}(hr_{33}) + r_{31}\sqrt{1-h^2}\frac{d\tilde{I}(\xi_1)}{d\theta} - \left[\tilde{I}(hr_{33}) - r_{31}\sqrt{1-h^2}\frac{d\tilde{I}(\xi_2)}{d\theta}\right]$$

$$F_l(t) = -[2m\sin\alpha f_1(t)]\omega_x + [2m\cos\alpha f_1(t)]\omega_y - [2mf_2(t)]\omega_z$$

$$F_r(t) = +[2m\sin\alpha f_1(t)]\omega_x + [2m\cos\alpha f_1(t)]\omega_y + [2mf_2(t)]\omega_z$$

Ocelli like light-sensitive sensors applied to stabilization of MAV flight (Paparazzi autopilot)



Stabilization of hovering flight - Nonlinear Inverse Dynamics (NID) approach

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})\mathbf{u} \qquad \mathbf{y} = \mathbf{h}(\mathbf{x})$$

$$\mathbf{u} = \mathbf{D}^{-1}(\mathbf{x})\left[\mathbf{v} - \mathbf{N}(\mathbf{x})\right] \qquad \mathbf{v} = \mathbf{P}_0\mathbf{y}_z - \sum_{j=0}^{r-1}\mathbf{P}_j\mathbf{y}^{(j)}$$

$$\mathbf{D} = \begin{bmatrix} L_{\mathbf{G}1}L_{\mathbf{T}}^{r_1-1}\mathrm{h}_1, & \ldots, & L_{\mathbf{G}1}L_{\mathbf{T}}^{r_1-1}\mathrm{h}_1 \\ \ldots & \ldots & \ldots \\ L_{\mathbf{G}1}L_{\mathbf{T}}^{r_m-1}\mathrm{h}_m, & \ldots, & L_{\mathbf{G}m}L_{\mathbf{T}}^{r_m-1}\mathrm{h}_m \end{bmatrix}$$

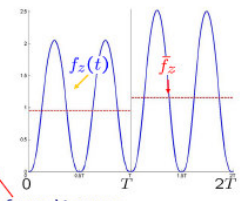
$$L_{\mathbf{F}}\mathrm{h} = \nabla\mathrm{h}\,\mathbf{F} \qquad \mathbf{N}(\mathbf{x}) = [L_{\mathbf{F}}^{r_j}\mathrm{h}_j(\mathbf{x})]$$

Averaging Theory:

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

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

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



Mean forces/torques Zero-mean forces\torques

Averaging: system with inputs

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

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

is asympotically stable.

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

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

is asymptotically stable.

How doing it ? 3 Issues

- How do we choose the T-periodic function w(v,t) ?
  - Geometric control
  - 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
- How small must the period T of the periodic input be?
  - Wingbeat period of all insects is good enough

Parameterization of wings motion

$$\dot{\mathbf{x}} = f(\mathbf{x},\mathbf{u}) = s(\mathbf{x}) + S(\mathbf{x})\,\mathrm{w}(\mathbf{u},\dot{\mathbf{u}})$$

$$\mathrm{w}(\mathbf{u},\dot{\mathbf{u}}) = \begin{bmatrix} \mathbf{F}_a^b(\mathbf{u},\dot{\mathbf{u}}) \\ \mathbf{M}_a^b(\mathbf{u},\dot{\mathbf{u}}) \end{bmatrix}$$

$$\dot{\bar{\mathbf{x}}} = \bar{f}(\bar{\mathbf{x}},\mathbf{v}) =$$

$$= \frac{1}{T}\int_0^T f(\mathbf{x},g(\mathbf{v},t))dt = s(\bar{\mathbf{x}}) + S(\bar{\mathbf{x}})\frac{1}{T}\int_0^T w(g(\mathbf{v},t),\dot{g}(\mathbf{v},t))dt =$$

$$= s(\bar{\mathbf{x}}) + S(\bar{\mathbf{x}})\bar{\mathbf{w}}(\mathbf{v})$$

Parameterization of wings motion

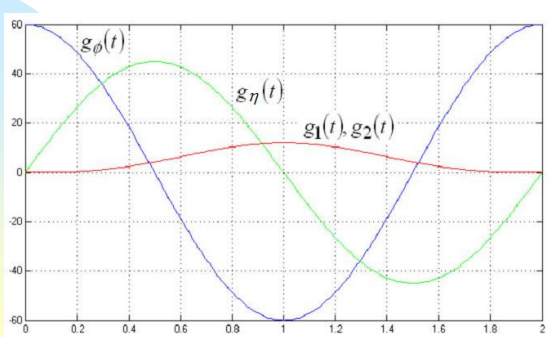
$$\bar{w}(\mathbf{v}) = \frac{1}{T}\int_0^T w(g(\mathbf{v},t),\dot{g}(\mathbf{v},t))dt$$

$$\phi(\mathbf{v},t) = g_\phi(t) + \mathbf{v}_1 g_1(t) \qquad \eta(\mathbf{v},t) = g_\eta(t) + \mathbf{v}_2 g_2(t)$$

$$g_\phi(t) = \frac{\pi}{3}\cos\left(\frac{2\pi}{T}t\right) \qquad g_\eta(t) = \frac{\pi}{4}\cos\left(\frac{2\pi}{T}t\right)$$

$$g_1(t) = \frac{\pi}{15}\cos\left(\frac{2\pi}{T}t\right) \qquad g_2(t) = g_1(t)$$

Parameterization of wings motion



Hovering flight stabilization - NID aproach

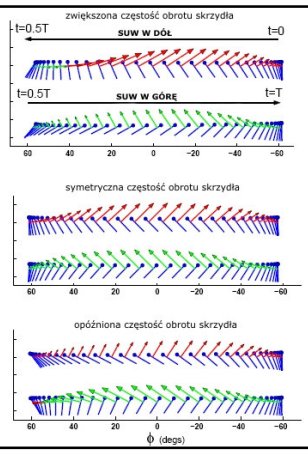
$$\mathbf{u} = (\phi_R, \phi_L, \eta_R, \eta_L)$$

$$\mathbf{v} = (v_1^R, v_1^L, v_2^R, v_2^L)$$

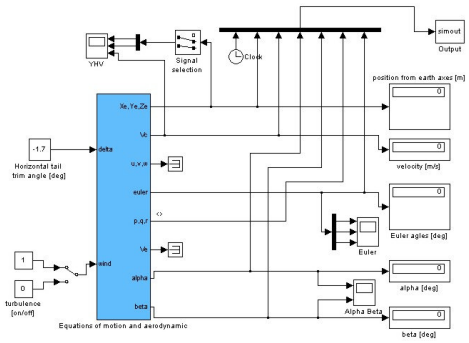
$$\mathbf{u}(v,t) = \mathbf{g_0}(t) + \mathbf{G}(t)\mathbf{v}$$

$$\mathbf{g}_0 = \begin{bmatrix} g_\phi \\ g_\phi \\ g_\eta \\ g_\eta \end{bmatrix}, \mathbf{G} = \begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ 0 & 0 & 0 & g_2 \end{bmatrix}$$

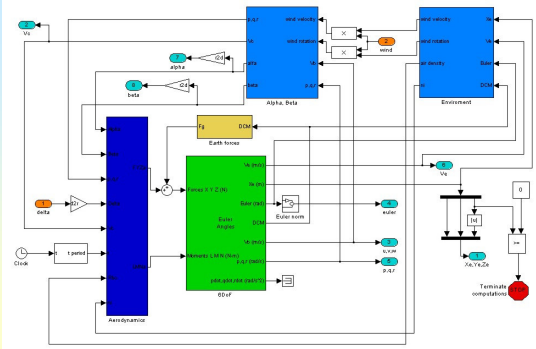
Parametrization of wings motion



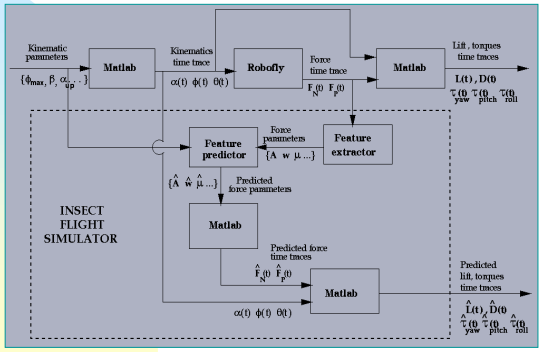
Block diagram of Dynamics Module



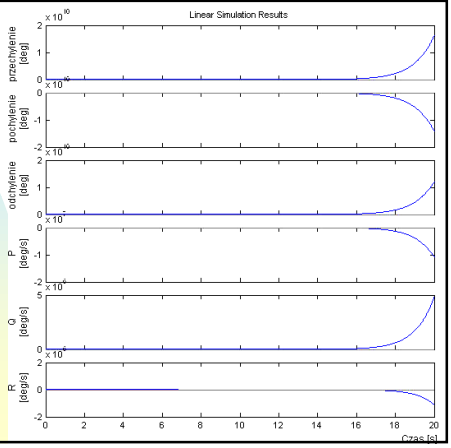
Block diagram of Aerodynamic Module



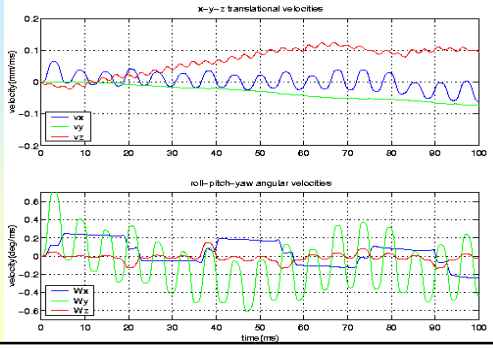
Algorithm Flow Chart:



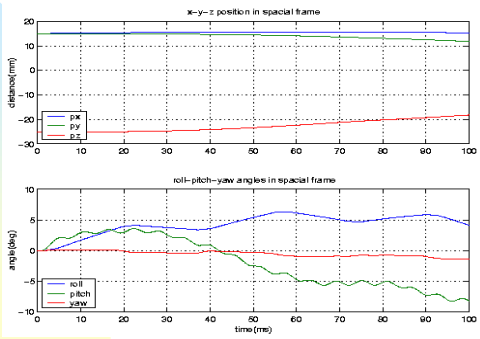
Simulation of hovering flight (uncontrolled motion)



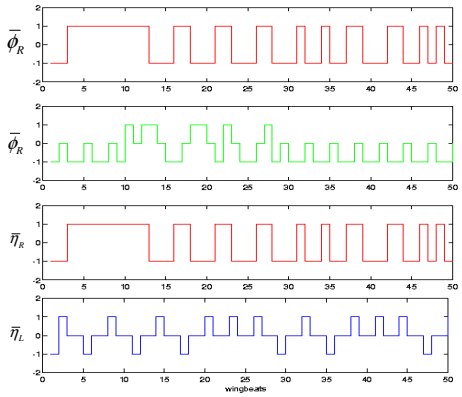
Stabilization of hovering flight (NID)



Stabilization of hovering flight (NID)



Stabilization of hovering flight (NID)



Conclusions

- Fixed wing MAV technology seems to be an almost ready solution for applications requiring high airspeed and long endurance. Microhelicopters can supplement fixed wing designs if hovering is required, but more work has to be done to increase their endurance.
- Concepts entomopters seem to be the most promising, because their successful application would provide high manoeuvrability and efficiency in hover.
- The highly nonlinear nature of the entomopters's mathematical model caused, that the use of linear control schemes is rather impossible. As solution it is possible to apply fuzzy controllers, or genetic algorithms and neural networks.
- The Gur Game, an algorithm for self-optimization and self-organization for distributed nonlinear systems, also can be applied.
- The results demonstrate that flexible membranes improved lift and thrust performance not by maximizing the positive force peaks, but rather by minimizing the negative peaks.
- These performance gains arose from localized areas of the wing during very short time periods of the overall flapping cycle. The physical mechanism for these gains was that wing deformation due to increased flexibility caused a favorable tilting of the overall force vector, thereby reducing the negative force components

… or alternative solution …

„Computer Electronics Meet Animal Brains"

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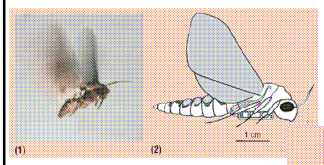

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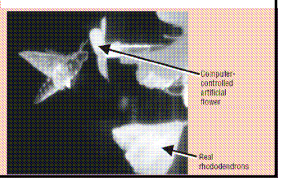

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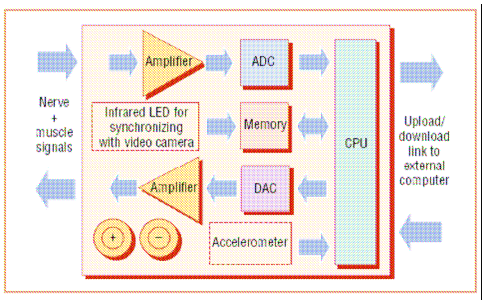

Neurochip functional block diagram. Solid lines show required components, dashed lines show some optional components

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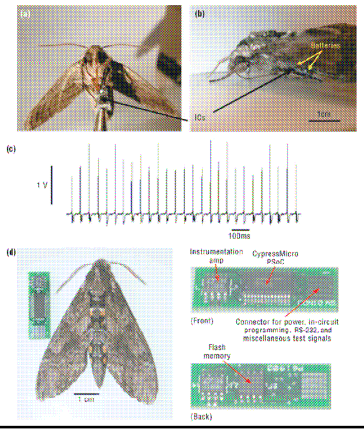

Integrative biology using neurochips. A neurochip can splice into neuromuscular pathways to unravel the internal biological circuitry. Neurochips armed with recording and stimulation channels will help neurobiologists understand the complex interactions among themoth's various neural control systems.