The Micro Air Vehicle Flight Regime Compared to Existing Flight Vehicles

**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 warfare 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.

**MAV Missions – military application**

**Urban Operations**
- Reconnaissance
- Sensor Placement
- MAV Assisted Pilot Rescue
- Provides beacon for rescue operations.

**Bio-Chemical Sensing**
- “Over-the-hill” Reconnaissance
- MAV provides chemical sensing, permits unscheduled sensor placement

**Military application – antiterrorist mission**

**The Micro Air Vehicle Flight Regime Compared to Existing Flight Vehicles**

- Micro (total wing span less than 5 cm)
- UAVs
- Fixed wing (remote operated)
- Light vehicle (remote operated)
- Light plane

**Reynolds Number**
**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**

**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 called 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, mathematically or otherwise 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 flight.

**Insects - over 30 000 000 specimens**

Aerodynamically, the bumblebee cannot 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

Insects in flight

Entomopter & insect wings
Wing Motion
Not simply up and down - much more complex!

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)

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 axillary sclerite
  - this hinge allows 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

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 muscles

Chemically Activated
From NASA website

Fixed & rotary wings aircraft 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

Control in roll

Control in yaw

Coordinates system

Coordinates system
Defining matrixes for all vectors

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

\[ S = \frac{1}{2} \begin{bmatrix} v' + (M')^{-1}h' \\ M' [v' + (M')^{-1}h'] \end{bmatrix} \]

(7)

Defining matrices for all \( i \) bodies of the system:

\[ M = diag [M^1, M^2, \ldots, M^k] \]

(8)

\[ v = \begin{bmatrix} v^1, v^2, \ldots, v^k \end{bmatrix} \]

(9)

\[ h = \begin{bmatrix} h^1, h^2, \ldots, h^k \end{bmatrix} \]

(10)

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

\[ S = \frac{1}{2} \int \nu' + v' \times \nu' \, \mathrm{d}u' \]

(2)

where:

\( v' \) means the vector of absolute acceleration of elementary mass \( \mathrm{d}m' \) of \( i \)-th body of the considered dynamical system.

and:

\[ v' = v'_0 + e'_0 \times p' = \omega'_0 \times [\omega'_0 \times p'] \]

(3)

Assuming that:

\[ v' = v^0_1 + v^0_2 = v^0 \]

and:

\[ M' = \begin{bmatrix} m_1, m_2, \ldots, m_k \end{bmatrix} \]

(5)

\[ h' = \begin{bmatrix} m_1 \omega_1, m_2 \omega_2, \ldots, m_k \omega_k \end{bmatrix} \]

(6)

where: \( m_i \) - mass of the \( i \)-th element, \( \omega_i \) - tensor of inertia of the \( i \)-th element, \( \omega_i \) - vector of the angular velocity, \( v_i \) - vector of the velocity of the \( i \)-th element, \( \omega_i \) - vector of generalised coordinates of mechanical system, \( \nu \) - is the vector of generalised co-ordinates, \( \nu_{f(q_i(q,\dot{q},t))} \) is so called Appel function, or functional of accelerations.

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

\[ S = \frac{1}{2} \int (v + M^{-1}h)(v + M^{-1}h) \]

(11)

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

\[ v = D(q,\dot{q})q + f(q,\dot{q}) \]

(12)

hence:

\[ \dot{q} = D(q,\dot{q})q + \varphi(q,\dot{q}) \]

(13)

where:

\[ \varphi = Dq + f \]
Therefore the Appel function can be expressed by the following relation:

\[
S(q, q, t) = \frac{1}{2} \left[ Dq + \Phi + M^{-1}h \right] M \left[ Dq + \Phi + M^{-1}h \right] \]

(14)

Assuming, that:

\[ M_z = D^2MD \quad \text{and} \quad h_z = D^2(Mp \cdot h) \]

and remembering, that:

\[ D(D^2MD)D^2 = M_2 \]

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

\[
S(q, q, t) = \frac{1}{2} \left[ Dq + M_2h_z \right] M \left[ Dq + M_2h_z \right] \]

(15)

From (18) we have the following relation:

\[
\dot{\mathbf{q}} = A_1(q\dot{w}) + A_2(w) \]

(20)

Finally, the Appel function has following form:

\[
S'(q, w, w, \cdot) = \frac{1}{2} \left[ Dw + M_2h_z \right] h_z \left[ Dw + M_2h_z \right] \]

where $M_z(q) = A_1(q)S + A_2(w)$

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

\[
\frac{\partial S'}{\partial w} = \frac{\partial S'}{\partial w} - \frac{\partial S'}{\partial w} = M_z(q)\dot{w} + h_z(q, w, \cdot) = Q'(q, w, \cdot) \]

(21)

Mathematical model for nonlinear flight simulation

\[
M\dot{V} + M(J_d + J_f J_f)R_c + M(J_d R_c + M J_d)F = G \\
J_d\dot{\Omega} + J_f\dot{\Omega} + (J_d + J_f + 2J_d J_f)\dot{\Omega} + (J_f + J_f J_f)\Omega + J_d J_d \Omega = M_c + R_c \times G \\
\]

where: $M$=m, $m$ – mass of MAV, 1 – unit matrix,

$F$=[$F_x, F_y, F_z$] – vector of aerodynamic forces,

$M_r$=[$M_x, M_y, M_z$] – vector of aerodynamic moments,

$V$=[[$U, V, W$]] – velocity vector,

$\Omega$=[[[0, 0, 0]]] – vector of angular velocity,

$O_x$=[[[P, Q, R]]] – vector of right wing angular rates,

$O_y$=[[[P + Q \theta + R \phi]]] – vector of left wing angular rate;

$R$=[[[x, y, z]]] – vector of the center of mass

In those equations:

\[
F_x = \frac{1}{2} \rho V_0^2 SC_s (C_s(\alpha, \psi), C_D(\alpha, \psi)), \\
F_y = \frac{1}{2} \rho V_0^2 SC_s (C_s(\alpha, \psi), C_D(\alpha, \psi)), \\
F_z = \frac{1}{2} \rho V_0^2 SC_s (C_s(\alpha, \psi), C_D(\alpha, \psi)), \\
M_{\alpha_x} = \frac{1}{2} \rho V_0^2 Sb C_s(\alpha, \psi), \\
M_{\alpha_y} = \frac{1}{2} \rho V_0^2 Sb C_s(\alpha, \psi), \\
M_{\alpha_z} = \frac{1}{2} \rho V_0^2 Sb C_s(\alpha, \psi).
\]
Distribution of instantaneous forces along a wingbeat cycle:

- Important to stabilise the flight.
- Fundamental kinematic parameters:
  - Flapping angle of wings $\beta$.
  - Feathering angle of wings $\phi$.
  - Frequency of wing motion respect to the body $\omega$.
  - Phase shifting between feathering and flapping $\psi$.
- Mean stroke $a$.
- Angle of attack $\alpha$.
- Large and impulsive forces at the wing reversals.

**Aerodynamic model - Blade Element Method (BEM)**

Modeling of aerodynamic loads steady state model - BEM

\[ \Delta T = -\Delta P_w \sin \theta + \Delta P_t \cos \theta \]

**Aerodynamic model – quasi unsteady approach**

\[ dF_{\text{steady}} = \frac{P}{2} C_P(\alpha) \| \mathbf{V}(r,t) \|^2 \mathbf{V}(r,t) dr \]

**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.

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

\[
\begin{align*}
\mathbf{r}_1 &= r \sin \theta \cos \varphi, \\
\mathbf{r}_2 &= r \sin \theta \sin \varphi, \\
\mathbf{r}_3 &= r \cos \theta.
\end{align*}
\]

\[
\begin{align*}
P^e &= [\sqrt{3} a, 0, \pm a], \\
P^p &= [0, a, \pm a].
\end{align*}
\]

\[
I(\mathbf{P}) = I(\mathbf{P}^e) = I(\mathbf{P}^p),
\]

\[
\begin{align*}
\Theta < \Theta^e &\Rightarrow I(\Theta) > I(\Theta^e), \\
\Theta > \Theta^e &\Rightarrow I(\Theta) < I(\Theta^e).
\end{align*}
\]

\[
F_i(t) = [-2m \sin \alpha_i(t)]x + [2m \cos \alpha_i(t)]y - [2m f_i(t)]z,
\]

\[
F_i(t) = +[2m \sin \alpha_i(t)]x + [2m \cos \alpha_i(t)]y + [2m f_i(t)]z.
\]

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

\[
\begin{align*}
\dot{x} &= f(x) + g(x) u, \\
y &= h(x).
\end{align*}
\]

\[
\begin{align*}
u &= D^{-1}(x) [v - N(x)], \\
v &= P v + \sum_{j=0}^{L} P y^{(j)}.
\end{align*}
\]

\[
D = \begin{bmatrix}
L_1 h_1, & \ldots & L_{i_j} h_{i_j} \\
\vdots & \ddots & \vdots \\
L_1 h_m, & \ldots & L_{i_m} h_{i_m}
\end{bmatrix}
\]

\[
L_i h = \nabla h F, \\
N(x) = [L_1 h_1(x), \ldots, L_m h_m(x)].
\]

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

**Averaging Theory:**

- If forces change very rapidly relative to body dynamics, only mean forces and torques determine this body motion.
Averaging: system with inputs

Original problem 1. Find a feedback law $g(x)$ such that the system
\[
\dot{x} = f(x, u) \quad u = g(x)
\]
is asymptotically stable. (1)

New Problem 1. Find periodic input $u = w(v, t)$ and a feedback law $h(x)$ such that the system
\[
\dot{x} = f(x, v) \quad f(v, w) = \frac{1}{T} \int_{0}^{T} f(v, w(v, t)) dt
\]
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 $f$ ?

  - 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

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

\[
w(\mathbf{u}, \mathbf{u}) = \begin{bmatrix} F(\mathbf{u}, \mathbf{u}) \\ M(\mathbf{u}, \mathbf{u}) \end{bmatrix}
\]

\[
\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, v) =
\]

\[
= \frac{1}{T} \int_{0}^{T} f(\mathbf{x}, g(\mathbf{v}, t)) dt = s(\mathbf{x}) + \frac{1}{T} \int_{0}^{T} w(g(\mathbf{v}, t), \mathbf{x}) dt =
\]

\[
= s(\mathbf{x}) + S(\mathbf{x}) \mathbf{w}(\mathbf{v})
\]

Parameterization of wings motion

- $\tilde{\mathbf{w}}(\mathbf{v}) = \frac{1}{T} \int_{0}^{T} w(g(\mathbf{v}, t), \tilde{g}(\mathbf{v}, t)) dt$

- $\phi(\mathbf{v}, t) = g_{\phi}(t) + v_{\phi}(t)$

- $\eta(\mathbf{v}, t) = g_{\eta}(t) + v_{\eta}(t)$

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

- $g_{\eta}(t) = \frac{\pi}{15} \cos\left(\frac{2\pi t}{T}\right)$

- $g_{\phi}(t) = g_{\phi}(t)$

Hovering flight stabilization - NID aproach

\[
\mathbf{u} = (\phi, \phi, \eta, \eta, \xi, \xi, \zeta, \zeta)
\]

\[
\mathbf{v} = (\mathbf{v}, \mathbf{v}, \mathbf{v}, \mathbf{v}, \mathbf{v})
\]

\[
\mathbf{u}(\mathbf{v}, t) = g_{\mathbf{u}}(t) + G(t) \mathbf{v}
\]

\[
g_{\mathbf{u}} = \begin{bmatrix} g_{\phi} \\ g_{\phi} \\ g_{\phi} \\ g_{\phi} \\ g_{\eta} \\ g_{\eta} \\ g_{\xi} \\ g_{\xi} \end{bmatrix}, \quad G = \begin{bmatrix} g_{\phi} & 0 & 0 & 0 \\ 0 & g_{\phi} & 0 & 0 \\ 0 & 0 & g_{\phi} & 0 \\ 0 & 0 & 0 & g_{\phi} \end{bmatrix}
\]
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)
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.
- Microhelicopters can supplement fixed wing designs if hovering is required, but more work has to be done to increase their endurance.
- Concepts of 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' 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"

COMPUTER, January, 2003; Published by the IEEE Computer Society © 2003 IEEE

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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 the moth’s various neural control systems.