Robotic hummingbird: 
Design of a control mechanism for a hovering flapping wing micro air vehicle

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Public PhD defence 
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École polytechnique de Bruxelles
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Flight in nature

Gliding flight

Powered (flapping) flight

Different evolution paths!
History of manned flight

Daedalus & Icarus, Greek mythology

Prisoners “flying” kites in China

DaVinci flying machines

1st manned flight, hot air balloon, Montgolfiers

1st steerable glider, George Cayley

559

1490

1783

1804

1st steerable & powered balloon, Henri Giffard

1st powered flight, Clément Ader

1st controlled & powered flight, Wrights

1st rotary aircraft flight, Paul Cornu

1852

1890

1903

1907

Equivalents nature vs aircraft

High lift devices

- Slotted trailing edge flap (c)
- Split flap (d)
- Trailing-edge flap (a)
- Leading-edge slat (b)

Vortex generators

- a) Protruding digit in a bat wing
- b) Serrated leading edge feather of an owl
- c) Corrugated dragonfly wing

Norberg, 2002
Unmanned Aerial Vehicles
(UAVs, Drones, Remotely Piloted Aircraft)

Advantages over manned aircraft:
• Less payload → smaller, lighter
• No men on-board → operation in risky environments
• Cheaper + cheaper operation

• First developed in 1990s
• Remote / autonomous operation
• On-board camera + live video link
• Payload: cameras, sensors, weapons

General Atomics MQ-1 Predator (1994)
15 m, endurance 24 h, range 1100 km

AeroVironment Wasp (2007)
72 cm, endurance 50 min, range 5 km

Prox Dynamics Black Hornet (2013)
10 cm, endurance 20 min, range 1.6 km

→ Miniaturization
Micro Air Vehicles

- Drones restricted in size and weight
- Operation indoors and outdoors
- Hovering capability

Applications:

→ Potential for flapping wings
Flapping flight

Forward flight

Hovering flight

Hedrick Lab, University of North Carolina

DISCOVERY – Hummingbird Time Warp
http://youtu.be/D8vjtTXgLJw

I. Cohen Group, Cornell University
http://vimeo.com/6362049
Hovering flapping flight

Wing tip trajectory in hover

Hummingbirds

Giant hummingbird 21.5 cm, 24 g, 12 Hz

Bee hummingbird 5 cm, 1.6 g, 80 Hz

Hawk-moth Manduca Sexta 10 cm, 1.6 g, 26 Hz

Fruit fly 0.5 cm, 2 mg, 218 Hz

Damselfly Megaloprepus 19 cm

Images from: www.wikipedia.org, Flickr (Floris van Bruegel, Sergio Quesada)
Lift enhancing mechanisms

Flow topology

Song et al., 2014

Lift enhancing mechanisms

Bomphrey et al. 2009

• Delayed stall of the leading edge vortex

Van den Berg & Ellington, 1997

• Kramer effect (Rotational lift)
• Wake capture
• Clap and fling (some insects)

Sane, 2003

• Wake capture
• Clap and fling (some insects)
Hummingbirds

BBC: Life - Birds
Wing motion control

NATURE - Hummingbirds: Magic in the Air
http://www.youtube.com/watch?v=Hrlr45uGapQ
Fliers with four wings

E. van Wijk & J. Schaap - Flight Artists project, Wageningen University
Flapping wing MAVs

**Tail control**

**DelFly (2005)**
TU Delft, deWagter et al., 2014
18 cm wingspan
20 g, 10-14 Hz

**Four wing designs**

**BionicOpter (2013)**
Festo, Bionic Learning Network
63 cm wingspan
175 g, 15-20 Hz

**Two wing, tail-less designs**

**Harvard RoboBee (2013)**
3.5 cm wingspan
80 mg
120 Hz

**Nano Hummingbird (2011)**
16.5 cm wingspan
19 g
30 Hz

Harvard, Chirarattananon et al., 2014
AeroVironment, Inc. + DARPA
Nano hummingbird

→ The only 2 wing tail-less MAV with on board-power

Developed by AeroVironment, Inc. (5 years)
Financed by DARPA (4 million USD)
**Project goal**

→ Tail-less flapping wing MAV with a single wing pair

<table>
<thead>
<tr>
<th>Wing length (mm)</th>
<th>Mass (mg)</th>
<th>Adapted from: C.H. Greenewalt, Hummingbirds. Dover, 1990.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>80 mg</td>
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</tr>
<tr>
<td>16.5</td>
<td>19 g</td>
<td>Nano Hummingbird</td>
</tr>
<tr>
<td></td>
<td>30 Hz</td>
<td>Our target</td>
</tr>
</tbody>
</table>

3.5 cm wingspan
80 mg
120 Hz

16.5 cm wingspan
19 g
30 Hz

~ 20 cm wingspan
~ 20 g
20 ~ 30 Hz

Chirarattananon et al., 2014

www.avinc.com/nano
Thesis overview

**Goal:** Design a mechanism controlling the flight by wing motion changes

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**THEORETICAL PART**

1. Mathematical modelling
2. Hovering flapping flight stability
3. Control and flight simulation

\[
\begin{bmatrix}
\dot{\mathbf{u}} \\
\dot{\mathbf{q}} \\
\dot{\mathbf{\theta}}
\end{bmatrix} =
\begin{bmatrix}
\dot{\mathbf{\hat{X}_u}} & \dot{\mathbf{\hat{X}_q}} & g \\
\mathbf{\hat{M}_u} & \mathbf{\hat{M}_q} & 0 \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\mathbf{u} \\
\mathbf{q} \\
\mathbf{\theta}
\end{bmatrix} +
\begin{bmatrix}
0 \\
1 \\
0
\end{bmatrix}
\mathbf{\hat{M}_{ext}}
\]

---

**PRACTICAL PART**

4. Flapping mechanism
5. Control mechanism
Flapping mechanism

Flight muscles, Ilustra Media (http://youtu.be/aFdvkopOmw0)

www.faulhaber.com
Flapping mechanism
Flapping mechanism

- Aluminium / steel rivets
- Nylon gears
- Frame + links: 3D printing
- DC Motor
- DM ABS, resolution 16 µm
Flapping motion

Flapping frequency 25 Hz

Photron FASTCAM SA3
2000 fps

Flapping amplitude \( \rightarrow 180^\circ \)
Wing design

BoPET (Mylar)  Polyester (Icarex)  CFRP

DISCOVERY – Hummingbird Time Warp
http://youtu.be/D8vJTXgIJw
Lift measurements

Lift

string

Scale
Lift measurements

\[ \text{Lift} = \text{Sensor 1} + \text{Sensor 2} \]

\[ \text{Moment} = K (\text{Sensor 1} - \text{Sensor 2}) \]
Wing shape evolution

Over 70 designs built and tested
Mechanism evolution

**A:** m = 5.2 g  
(Feb. 2012)

**C2:** Lift = 6.4 g, m = 5.8 g  
(May 2012)

**E2:** Lift = 9.6 g, m = 7.5 g  
(Oct. 2012)

**Take off demonstration:** Motor not in the centre → Guidance
Mechanism evolution

TEST BENCH PROTOTYPES

A: \( m = 5.2 \text{ g} \) (Feb. 2012)

C2: Lift = 6.4 g, \( m = 5.8 \text{ g} \) (May 2012)

E2: Lift = 9.6 g, \( m = 7.5 \text{ g} \) (Oct. 2012)

E4: Lift = 16.1 g, \( m = 10.1 \text{ g} \) (Jan. 2014)

FLIGHT PROTOTYPES

G2: Lift = 9.6 g, \( m = 9.0 \text{ g} \) (Apr. 2013)

J2: Lift = 16.0 g, \( m = 12.5 \text{ g} \) (Jan. 2014)
Uncontrolled prototype

- **Weight:** 12.5 g
- **Wingspan:** 21 cm
- **Power:** off-board

- **Flapping frequency:** up to 24 Hz
- **Lift:** up to 155 mN ≈ 16 g

\[ F_L^* = \text{const} \cdot f^2 \]

\[ f_{\text{take-off}} = 21.5 \text{ Hz} \]
Uncontrolled prototype

- Weight: 12.5 g
- Wingspan: 21 cm
- Power: off-board
- Flapping frequency: up to 24 Hz
- Lift: up to 155 mN ≈ 16 g

→ Flight stability needs to be studied first
Flight stability

Stable flight
   =
Maintaining desired attitude
   (body orientation)

Hovering:
  Roll $\rightarrow$ 0
  Pitch $\rightarrow$ 0
  Yaw $\rightarrow$ Arbitrary
  (constant, or changing
  with finite rate)

Jason Paluck
www.flickr.com/photos/jasonpaluck/4744474530
Mathematical model

Rigid body dynamics (6 DOF) + quasi-steady aerodynamics

1) Vertical dynamics
2) Pitch dynamics
3) Roll dynamics
4) Yaw dynamics

Always stable

Time varying + periodic
Cycle averaging
Linearization in hover

Always stable
Longitudinal flight stability

State space

\[
\begin{bmatrix}
\dot{u} \\
\dot{q} \\
\dot{\vartheta}
\end{bmatrix} =

\begin{bmatrix}
\hat{X}_u & \hat{M}_u & \hat{M}_q \\
0 & 0 & 1
\end{bmatrix}

\begin{bmatrix}
g \\
0 \\
0
\end{bmatrix}

\begin{bmatrix}
u \\
q \\
\vartheta
\end{bmatrix}

+ \begin{bmatrix}
1
\end{bmatrix}

\hat{M}_{ext}
\]

→ characterized by 3 stability derivatives

\[\hat{X}_u < 0, \quad \hat{M}_u < 0\]

\[\hat{M}_u = -K_1 z_W - K_2\]

~ Opposite sign to \(z_W\)

Char. Equation (Root locus form)

\[1 + \frac{\hat{M}_u}{\lambda (\lambda - \hat{X}_u)(\lambda - \hat{M}_q)} = 0\]

\(\hat{M}_u \rightarrow +\infty\)

\(\hat{M}_u \rightarrow -\infty\)
Longitudinal flight stability

Root locus:

\[ 1 + \frac{\dot{M}_u}{\lambda (\lambda - \dot{X}_u)(\lambda - \bar{M}_q)} = 0 \]

1) Wings below COG
2) Wings close to COG (very narrow interval of \( z_w \))
3) Wings above COG

\[ \dot{M}_u = (K_1 z_W) - K_2 \]

\[ \text{dominant term} \]

\[ \dot{M}_u \rightarrow +\infty \]
\[ \dot{M}_u \rightarrow -\infty \]

\[ \text{stable} \]
\[ \text{unstable, divergent} \]

Same situation in lateral system
BUT stable for different wing positions

Whole system unstable
Flight stability in nature

How to Fly Right – Science Take (http://youtu.be/QLhOCIdbV7g)

Flies:
- wings above COG and stable...

Fly responding to a blast wave (http://youtu.be/QH091zFHdQ0)
Flight stability in nature

Stable, because of sensors for feedback:

1) Halteres (bio-gyroscopes)
2) Ocelli
3) Compound eyes

No halteres → unstable

Ristroph et al., 2013
Active stabilization

Halteres (bio-gyroscopes) ➔ Feedback on angular rate

State space model

\[
\begin{bmatrix}
\dot{u} \\
\dot{q} \\
\dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
\hat{X}_u & 0 & g \\
\hat{M}_u & \hat{M}_q - k_q & 0 \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
u \\
q \\
\theta
\end{bmatrix}
\]

Char. Equation (Root locus form)

\[
1 + \hat{M}_u \frac{-g}{\lambda(\lambda - \hat{X}_u)(\lambda - \hat{M}_q + k_q)} = 0
\]

1) Wings below COG ➔ unstable, divergent

2) Wings above COG and sufficient feedback gain

\[
k_q^* > \sqrt{\frac{\bar{M}_u}{\bar{X}_u}} g
\]
No halteres: passive stability can be restored by increasing drag

\[ S_1 \neq S_2, \quad z_1 \neq z_2 \]

\[ X_u = X_{u,Wings} - k_d(S_1 + S_2) \]

\[ M_q = M_{q,Wings} - k_d(S_1 z_1^2 + S_2 z_2^2) \]

\[ M_u = M_{u,Wings} - k_d S_1 z_1 + k_d S_2 z_2 \]

\[ 1 + \hat{M}_u \frac{-g}{\lambda(\lambda - \hat{X}_u)(\lambda - \hat{M}_q)} = 0 \]
Passive stability

Take-off: 1/13 x

- Wings below COG !!!
- Off board power (tether)
- BUT sufficient lift reserve for a radio + battery (2 g)

So far, only 4 projects demonstrated stable flight (actively / passively) in two-winged tail-less MAVs
# Flight stability - conclusion

<table>
<thead>
<tr>
<th></th>
<th>Wings below COG</th>
<th>Wings above COG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inherent stability</strong></td>
<td>Unstable</td>
<td>Unstable</td>
</tr>
<tr>
<td><strong>Active stabilization</strong></td>
<td>Not possible</td>
<td>Possible</td>
</tr>
<tr>
<td>active stabilization with rate feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Passive stabilization</strong></td>
<td>Possible</td>
<td>Possible</td>
</tr>
</tbody>
</table>

- **Wings below COG**: Unstable
- **Wings above COG**: Possible

*Active stabilization with rate feedback*:

- Not possible
- Possible
Flight control by wing motion

NATURE - Hummingbirds: Magic in the Air
http://www.youtube.com/watch?v=Hrlr45uGapQ
Flight control in nature

Roll

Pitch

Yaw

Conn et al., 2011
Flight control in nature

Flight forward & backward via pitch

Flight sideways via roll

DISCOVERY – Hummingbird Time Warp
http://youtu.be/D8vjYTXgUw

N. Boeddeker & J. Zeil,
Australian National University
Control strategy

4 DOF control:

- **Up/down**
  - Control via pitch / roll
  - Forward/backward
  - Sideways
  - Turning

Pitch dynamics ➔ cascade control:

- Speed control
  - \( u_{ref} \)
  - Speed control block (PI)
  - \( \dot{\varphi}_{ref} \)

- Attitude control
  - \( q_{ref} \)
  - Attitude control block (P)
  - \( M \)
  - Pitch dynamics block

\[ \begin{align*}
Z & \rightarrow mg \\
\vartheta & \rightarrow mg \\
\varphi & \rightarrow mg \\
\psi & \rightarrow mg \\
\mathbf{u} & \rightarrow mg \\
\mathbf{w} & \rightarrow mg \\
\mathbf{v} & \rightarrow mg \\
\mathbf{N} & \rightarrow mg \\
\mathbf{L} & \rightarrow mg \\
\mathbf{M} & \rightarrow mg \\
\end{align*} \]
Control results

- Little difference between the original and simplified (cycle-averaged + linearized) model
- Prediction of control moment magnitudes
Control moment generation (2 flapping wings):

2 strategies developed and tested:

- Wing twist modulation via root bar flexing
- Amplitude and offset modulation via joint displacements
Wing twist modulation

Lift force control:

- Reduced lift
- Nominal lift
+ Increased lift

Pitch moment:

Roll moment:

According to Keenon et al. 2012
Wing twist modulation

Manual bar flexing

Pitch moment control

SMA driven bar flexing

Roll moment control

± 4mm → sufficient moments

Short stroke, low bandwidth → different actuators needed
Amplitude & offset modulation

Flapping amplitude and offset can be controlled by displacing these joints.

→ Pitch control

→ Roll control

Left offset servo

Right offset servo

Roll servo

32 mm
Amplitude & offset modulation

- Drive: 8 mm brushless DC (5.2 g)
- Control: 3 x micro-servo (6 g total)
- Wingspan: 21 cm
- Total mass: 21.4 g

Exploded view

- Propulsion DC motor
- Flapping mechanism
- Control mechanism
- Control servos

Faulhaber 0824
3 x HobbyKing 5330

90 mm
32 mm
Amplitude & offset modulation

Hover

Flapping frequency 15 Hz
Photron FASTCAM SA3
2000 fps, shutter 1/10000 s
Combined commands

**Amplitude difference**

- Whole workspace: +/- 24°
- At zero offset: +/- 40°

**Average offset**

- Whole workspace: +/- 12°
- At zero roll: +/- 15°

Flapping frequency ~ 15 Hz
Stable system (~ pendulum), open loop control:
Hovering flapping flight stability

• Pitch and roll dynamics can be characterized by 3 poles each
• The pole configuration depends on the wing position
• If wings are above the COG, angular rate feedback stabilizes the system.

Flapping mechanism

• New 2 stage mechanism with symmetric output has been developed.
• Take off demonstrated.

Control mechanism

• New control mechanism based on flapping amplitude and offset modulation has been developed.
Future work

Mechanical design

• Control mechanism (efficiency, actuators)
• Weight reduction
• Lift production (wings, gearbox, motor)

Control and avionics

• Attitude sensor
• Micro controller
• Radio
• Motor speed controller
• ...

Control mechanism

On-board CPU

Radio control

Attitude sensor (IMU)

Control mechanism

Wings

Flapping mechanism

Battery
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Nicolas Cormond
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