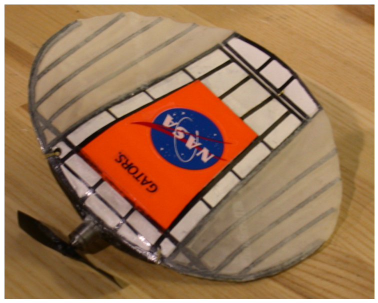
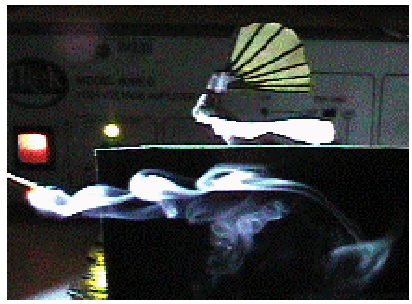
Biologically Inspired Micro-flight Modeling and Control Research





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SAE Aerospace Control and Guidance Systems Committee Meeting
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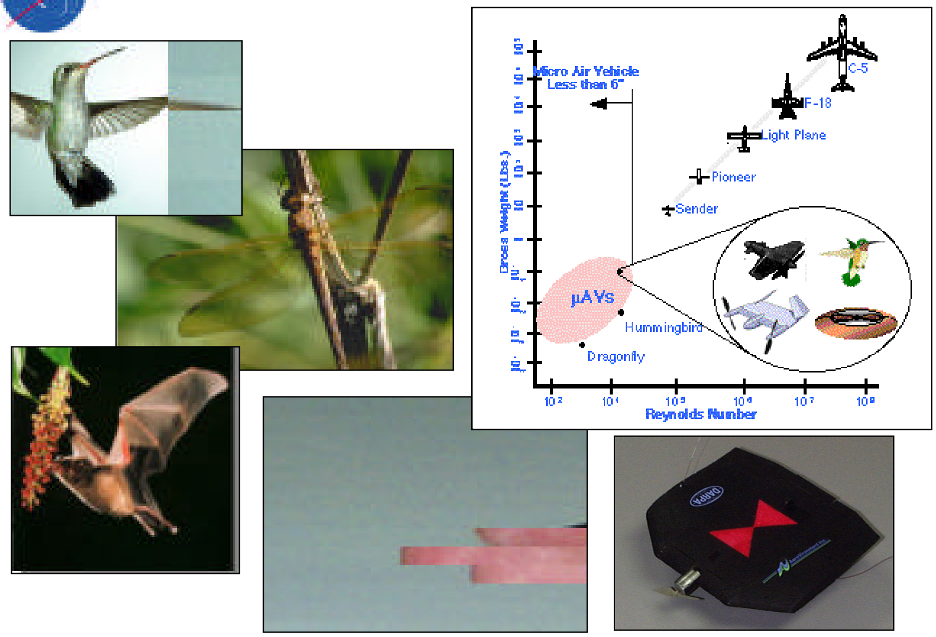
Dynamics & Control of
Biologically Inspired Flight Systems

(Sub-element of *Aircraft Morphing* Project)

- **Explore and exploit flight technologies inspired by biological systems (insects, birds, bats, etc.) to enable new capabilities**
  - **Control of miniaturized flight systems**
  - **Intelligent autonomy and collaborating swarms**
  - **Bird-like agility**
  - **Airmass guidance**
- **Current bio-inspired research activities**
  - **Aeroelastic fixed wing micro aerial vehicles**
  - **Resonance-based flapping flight**
  - **Dynamic soaring**
  - **Biologically inspired geometries**
  - **Muscle-like actuation systems**
  - **Collaborative control**

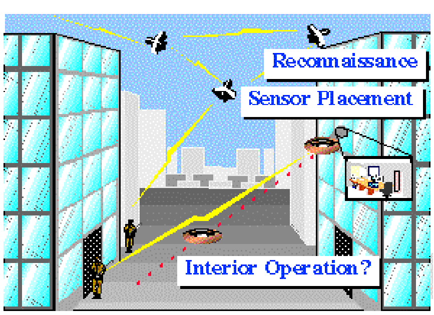
What are Micro Aerial Vehicles?

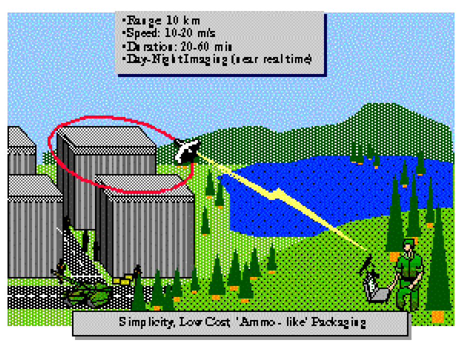


How might Micro Aerial Vehicles be used?

Rapidly Deployable "Eye in the Sky"
- traffic/news/sports
- inspection
- reconnaissance

Delivery/Transmission/Relay
- micro payloads
- communications

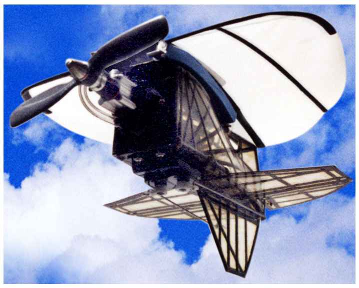




Remote Distributed Sensing
- agriculture/forestry
- atmosphere/weather
- search & rescue

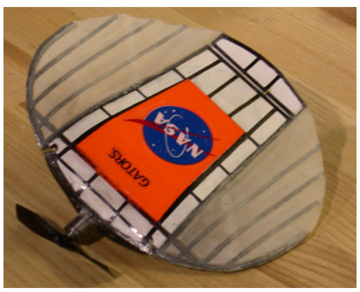
University of Florida MAV

poc: Peter Ifju, ifju@ufl.edu

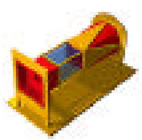


Maximum Dimension	**6 inches**
Empty Weight	**55 grams**
Span	**6 inches**
Wing Area	**20 inches^2**
Mean Chord	**3.3 inches**
Cruise Speed	**10 - 30 mph**
Payload Weight	**~20 grams**

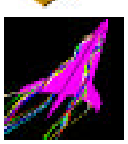
Flexible Latex & Graphite Epoxy Wing



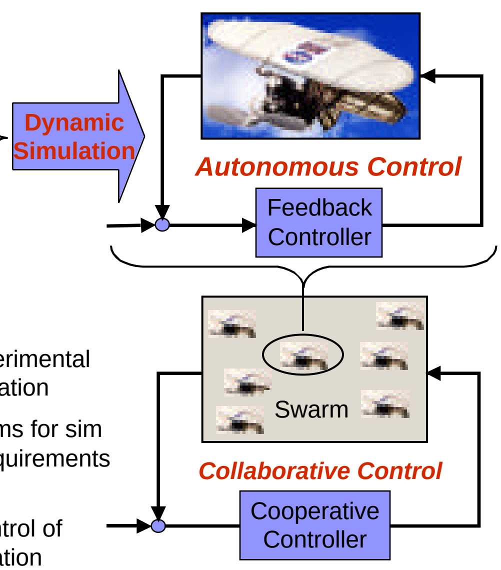
Aeroelastic Fixed Wing MAV



Wind Tunnel and Flight Test



Analytical Aeroelastic Modeling & CFD



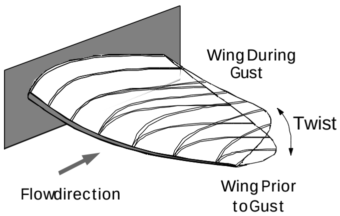
Leverage off of existing design

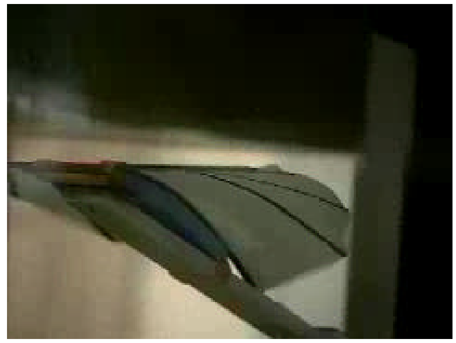
Generate and use analytical and experimental databases to create dynamic simulation

Develop autonomous control algorithms for sim
- Consider sensor and actuator requirements
- Flight test control algorithms

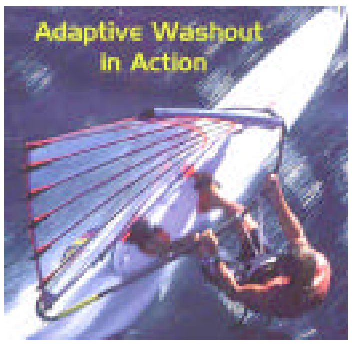
Research swarming / cooperative control of collaborative systems using simulation and flight test

Adaptive Washout





Response to periodic axial velocity perturbations.



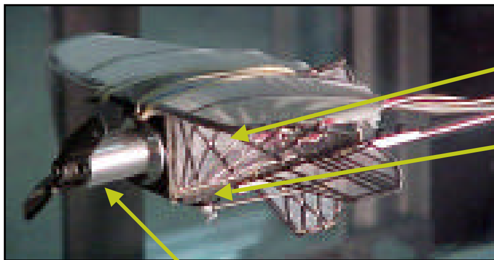
“Chopper”
(U of F Wind Tunnel)

Wind Tunnel Test Objectives

- Establish a capability to perform force/moment, structural deformation, and flow visualization experiments for powered micro aerial vehicles
- Collect static aeroelastic stability and control data for dynamic simulation
  – Forces and moments
  – Variations in elevon deflection, thrust, incidence, speed
- Collect structural deformation data
  – Projection Moire Interferometry (PMI)
  – Videogrammetry
- Identify important flow phenomena
  – Smoke flow
  – Helium bubble visualization

Model Configuration

Basic Aerodynamics Research Tunnel (BART)

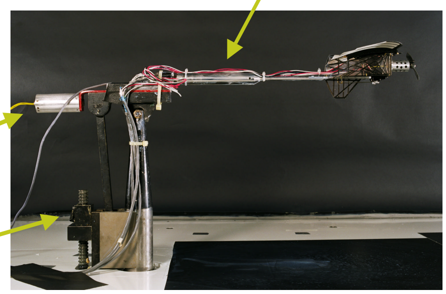


Tilt Sensor (for AoA)

Elevon Servos

Electric Motor
and Mount

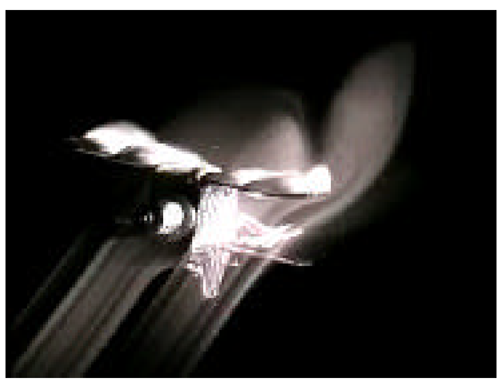
6 Component Balance



Accelerometer
(for AoA)

AoA Motor Drive

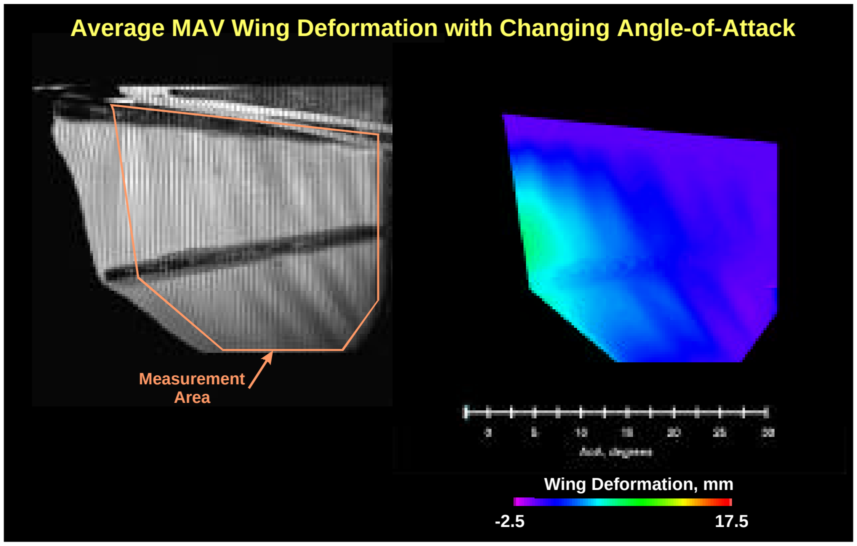
Flow Visualization



q = 1.6 psf (25 mph)
p = 12V (18000+ rpm)
α = 35 degrees

Measuring Wing Shape

poc: Gary Fleming, g.a.fleming@larc.nasa.gov



High-Speed Videogrammetry

poc: Alpheus Burner, a.w.burner@larc.nasa.gov

[click to view movie]

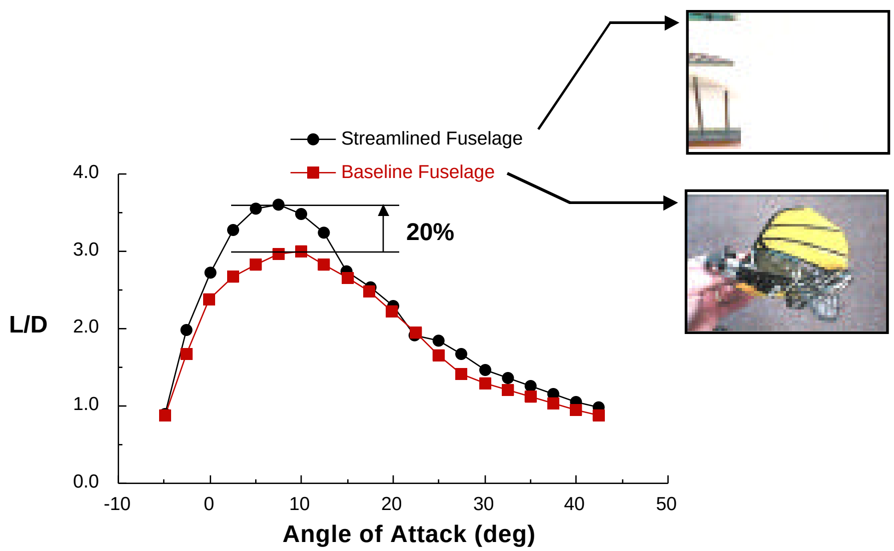
Video Image

[click to view movie]

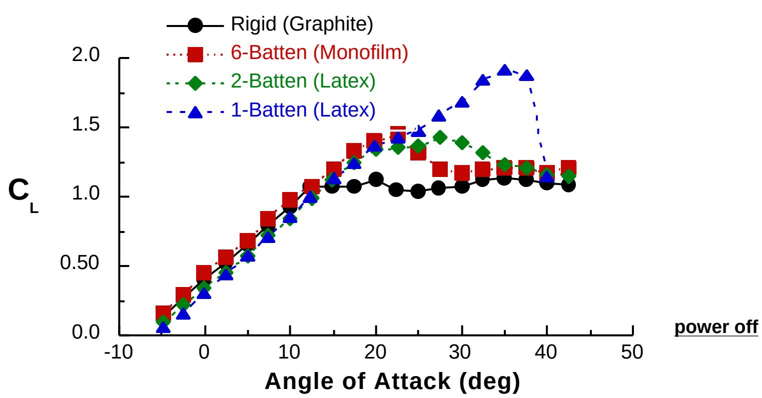
Retro-Reflector Image

Streamlined Fuselage Effect

(q=1.6 psf, power off, 6-batten wing)



Static Aeroelastic Effects (q=1.6 psf)



- **Similar lift curve slopes**

  comparable to other low Reynolds number wings with similar aspect ratio

- **Significant increases in stall angle with increased flexibility**

  stall angles comparable to other low Reynolds number wings with much lower aspect ratio

Stability and Control Properties

(q=1.6 psf, trim power, 2-batten wing)

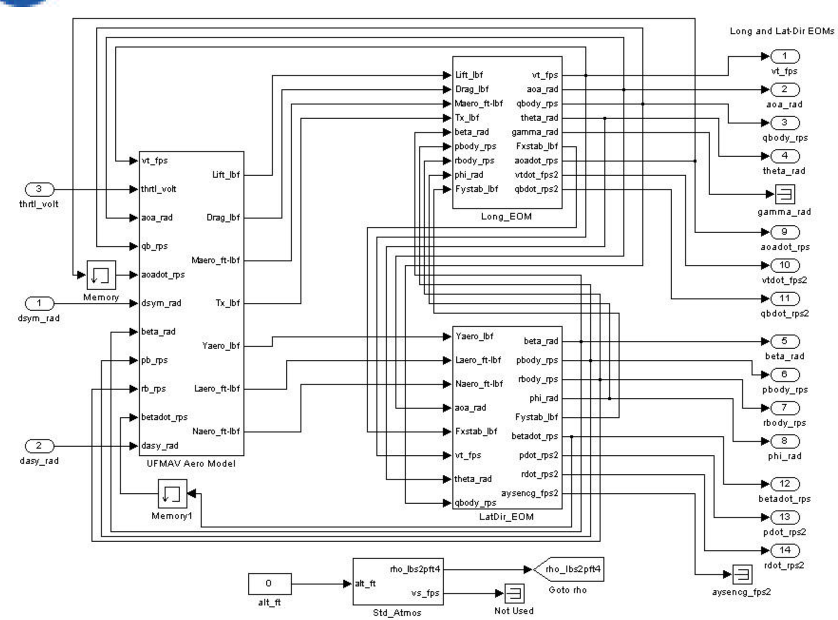
- Static Stability
  - Pitch Stability $C_{m_\alpha} = -0.6$
  - Static Margin $SM \quad \frac{C_{m_\alpha}}{C_{L_\alpha}} = 0.15$
  - Directional Stability $C_{n_\beta} = 0.5$
  - Dihedral Effect $C_{l_\beta} = -0.7$

statically stable in all axes

static derivatives somewhat larger than typical piloted aircraft

- Controllability
  - Symmetric Elevon $C_{L_\delta} = 0.7$, $C_{m_\delta} = -0.4$ $\Big\}$ $\frac{C_{L_\delta}}{C_{m_\delta}} = -1.75$ **characteristic of flying wing**
  - Antisymmetric Elevon $C_{Y_\delta} = -0.10$, $C_{l_\delta} = 0.08$, $C_{n_\delta} = 0.06$

Simulation Structure



Simulation/Vehicle Characteristics

Dynamic Pressure (psf)	Phugoid Mode		Short Period Mode	
	freq. (rad/sec)	damping ratio	freq. (rad/sec)	damping ratio
1.0	0.85	0.44	23.3	0.13
1.6	0.65	0.35	30.2	0.12
2.0	0.67	-0.56	32.6	0.12

- Stable but lightly damped short period mode
- Phugoid unstable at higher speeds

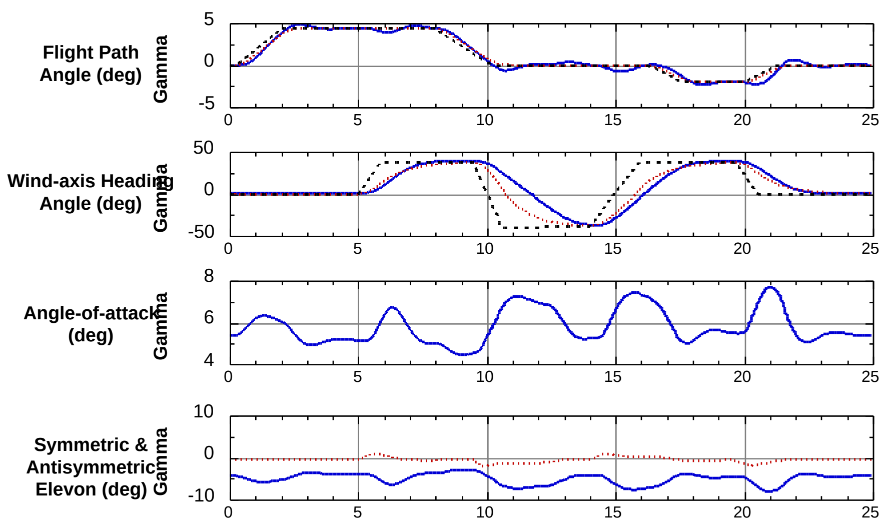
Dynamic Pressure (psf)	Spiral Mode	Roll Mode	Dutch Roll Mode	
	e-value	e-value	freq. (rad/sec)	damping ratio
1.0	-1.04	-27.7	21.1	0.094
1.6	-1.04	-37.3	24.2	0.065
2.0	-1.02	-42.8	25.9	0.050

- All lat-dir modes stable
- Lightly damped dutch roll mode

Dynamic Inversion Controller Performance

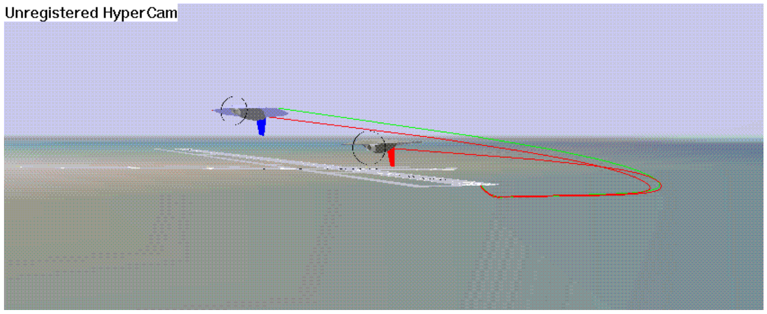
poc: John Davidson, j.b.davidson@larc.nasa.gov

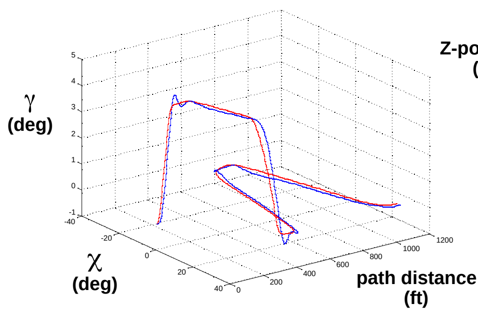
Trajectory #1, I.C.'s : V_t = 37 fps, straight and level trimmed flight

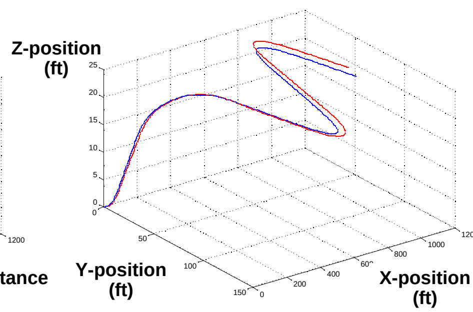


Controller Performance

Trajectory #2







Active Batten Wing

poc: Robert Fox, r.l.fox@larc.nasa.gov

- Objectives
  - Reduce actuator weight
  - Reduce mechanical complexity
  - Enhance controllability
- Biological inspiration
  - Variable wing camber
- Piezo-electric actuator
  - Bi-morph provided limited authority
  - Uni-morph under development
- Issue: limited static deflection amplitude of piezo-actuators

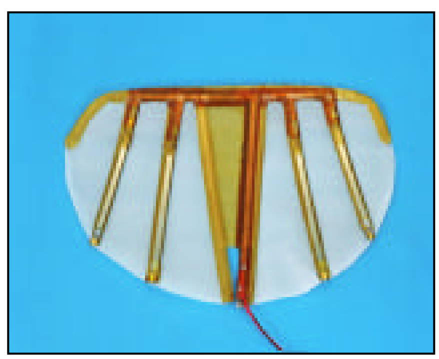
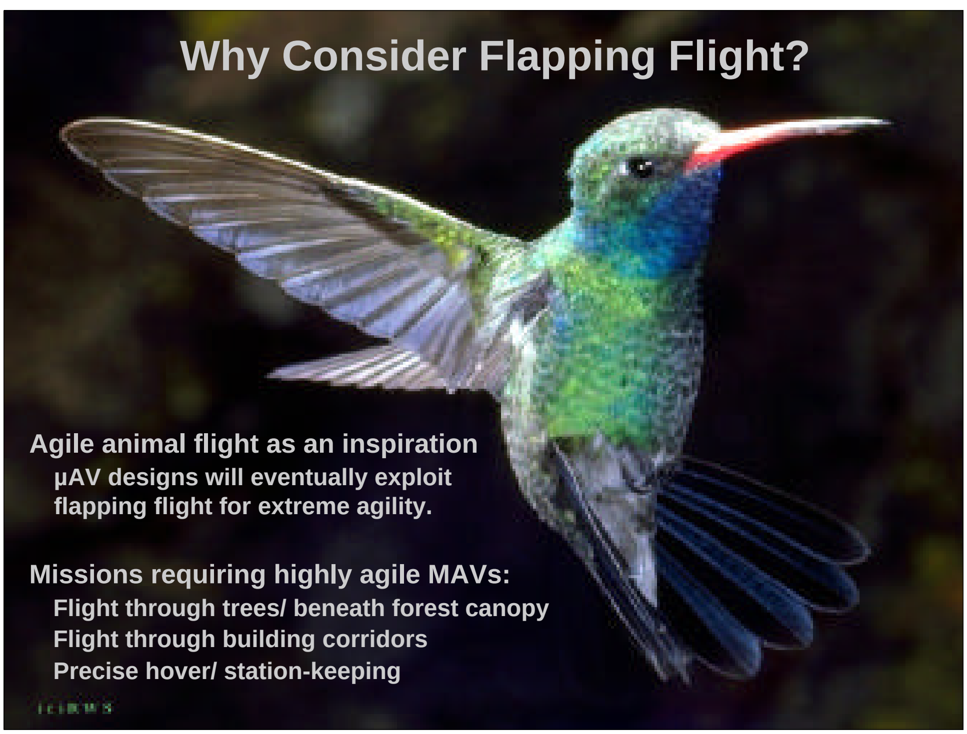


Image-Based Stability Augmentation

poc: Peter Ifju, ifju@ufl.edu

- Locate horizon from on-board camera image
  - Pitch attitude
  - Roll attitude
- Real time algorithm
- Flight tests throughout summer of 2001

Why Consider Flapping Flight?



Agile animal flight as an inspiration

μAV designs will eventually exploit flapping flight for extreme agility.

Missions requiring highly agile MAVs:

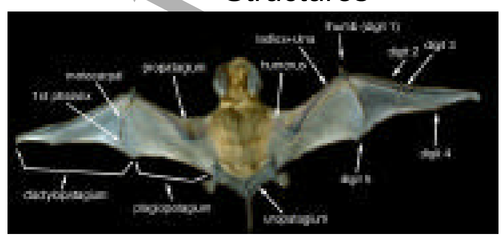
Flight through trees/ beneath forest canopy
Flight through building corridors
Precise hover/ station-keeping

Bio-Inspired Principles from Diverse Examples of Flapping Flight

Flight modes
Wingbeat patterns
Wing design

Sensing

Structures



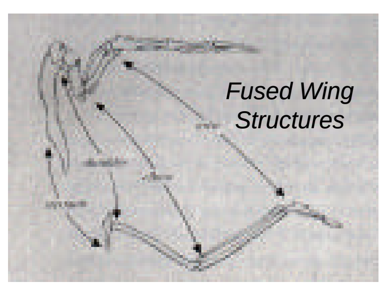
Tractable Flapping Wing Design

Many natural fliers generate lift through resonant excitation of an aeroelastically tailored structure:

Muscle tissue
•
Mode shape
•
Propulsive lift

The humming bird as a starting point:

- the right size
- the right capabilities
- *tractable* example



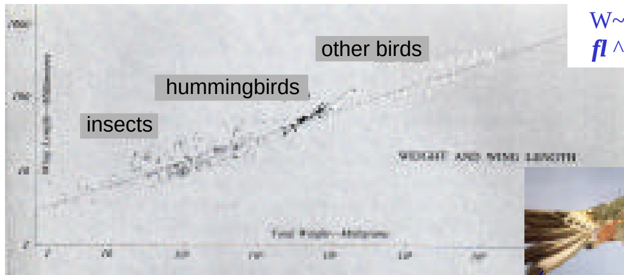
ref: Greenwalt, 1960

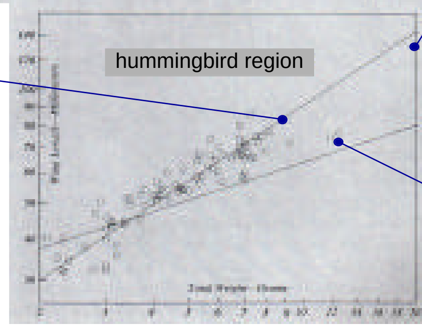
Where to Start?

Scaling relationships

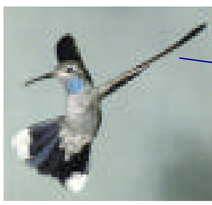
$W \sim l^{(3/2)}$
$f l^{(1.25)} = \text{const.}$

Wing Length vs. Total Weight

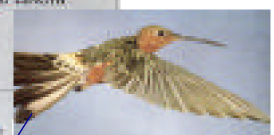




ref: Greenwalt, 1960



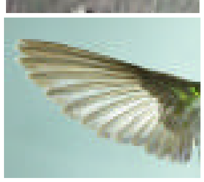
Lampornis Clemenciae (Blue Throat)
Length of wing ~ 8.5 cm
Flapping frequency ~ 23 Hz
Weight ~ 8.4 g



Patagona Gigas (Giant Andean)
Length of wing ~ 12 cm
Flapping frequency ~ 8 -10 Hz
Weight ~ 20 g

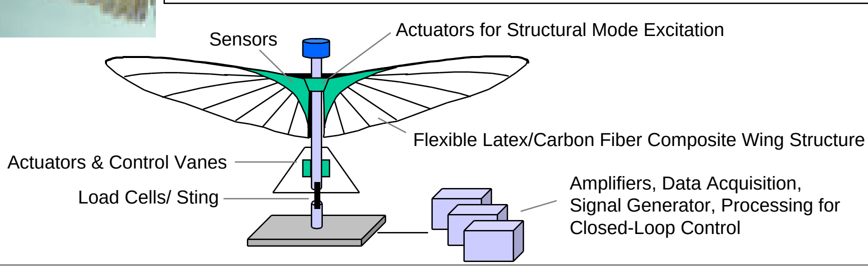
MicroBat (Aerovironment)
Length of wing ~ 7.6 cm
Flapping frequency ~ 20 Hz
Weight ~ 12.5 g

Approach

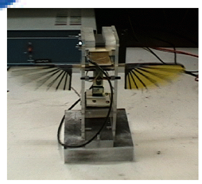
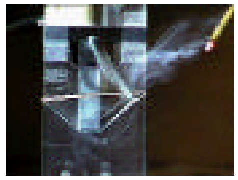


Apply UF MAV structure to planforms inspired by humming bird wing (Chai, 1997 & other zoological references)
Build series of parametric flapping testbeds & simulation models
Excite aeroelastic/structural dynamic modes to produce resonant flapping kinematics (Dickinson, 1999)
Conduct parametric experiments/ refine dynamic simulation models/ develop mechanization & control concepts
- Achieve resonant excitation of parametric wing structures
- Assess/ refine/ collaborate/ generate specifications
- Develop control capabilities

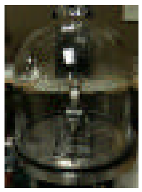
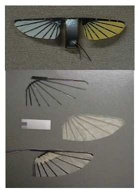
Hardware-in-the-loop flight dynamic simulation & control design



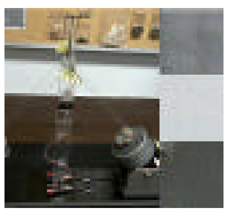
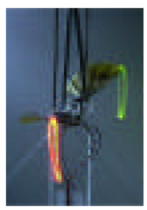
Progression of Resonant Flapping Testbeds

EM Vibration Inducer
- Basic proof-of-concept
- OL frequency sweeps/ resonant frequencies
- Structures/ Materials

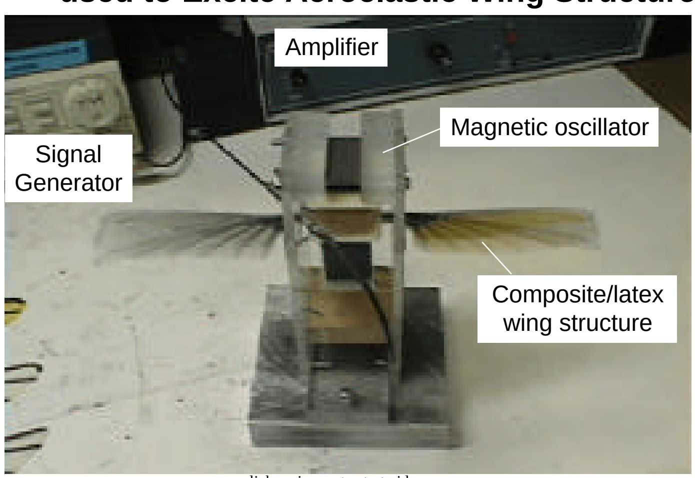



Piezo Ceramic
- Strain rate feedback/ resonant tuner
- Vacuum chamber tests
- Parametrics & flow vis

Dual Shakers
- Wingtip trajectory traces
- 3-DOF shoulder joint
- Control of wing- beat pattern
- Actuator specs

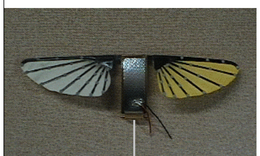
Magnetically-Actuated Resonant Flapping Testbed used to Excite Aeroelastic Wing Structures



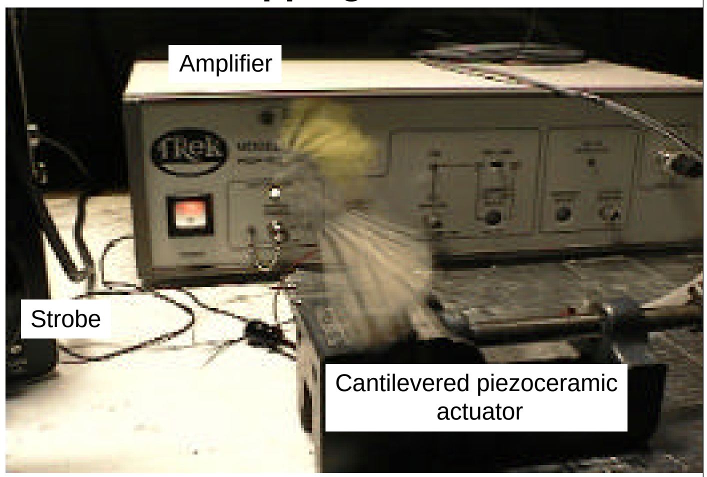
click on image to start video

- Achieved 20 deg flapping arc at ~ 25 Hz (Relatively low flapping amplitude)
- Resonance coincides with humming bird flapping frequency for this size wing
- Kinematics are currently an arbitrary result of cut & try composite layup; Would prefer to specify desired kinematics and solve for required layup
- Generated smoke flow visualization of unsteady aero phenomena

Piezo-Actuated Flapping Testbed



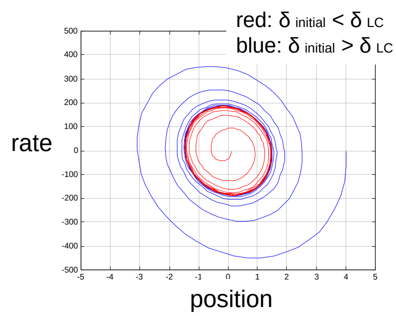
Piezoelectric *thunder* actuator used to excite structural vibration at ~25 Hz

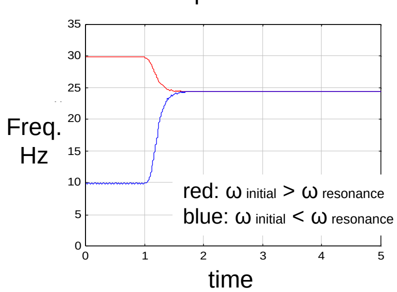


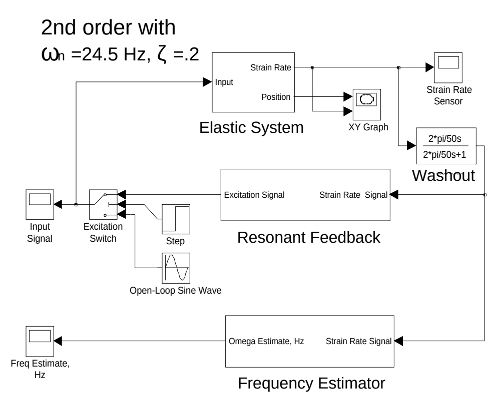
click on image to start video

- Much larger amplitude flapping motions achieved with piezo actuation
- Power consumption: 0.46 W; Blue throat in hover: 0.17 W - 0.34 W
- Flow visualization indicates unsteady vortex structures that are suggestive of “vortex capture” phenomenon exploited by insects as postulated by Dickinson, UC Berkeley (*Science, vol 284, 18 Jun 99*)

Strain-rate Feedback to Produce Limit Cycle Oscillation



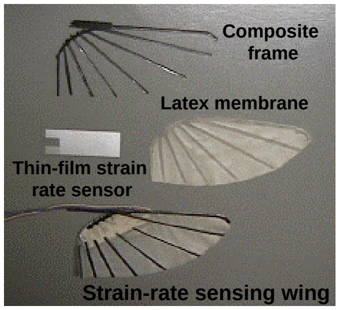




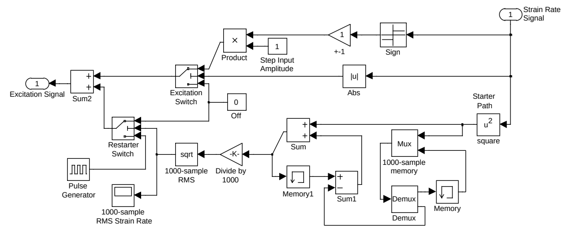
Closed loop system has limit cycle at resonant frequency of aeroelastic wing & actuator system

Bio Inspiration ref: R. Dudley, Biomechanics of Insect Flight

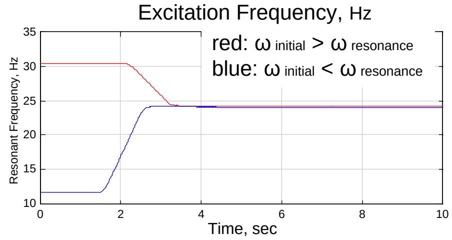
Resonant Tuning using 28 μm PVDF Strain-Rate Sensor



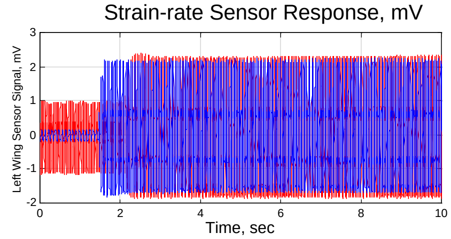
Hardware-in loop controller implemented using dSpace system



Excitation Frequency, Hz



Strain-rate Sensor Response, mV



Response of Resonant Flapping System to Ambient Pressure Variation

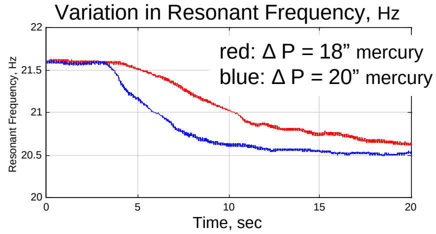
Bell jar enables closed-loop structural dynamic testing under time-varying pressure conditions

Closed-loop system tracks change in modal frequency with pressure variation

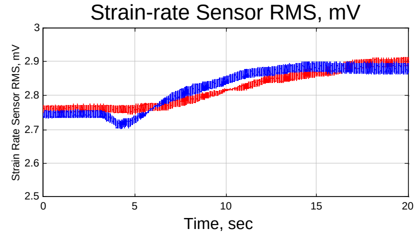
Change in resonant frequency is approximately 1.1Hz for 20 inches of mercury

Resonance tracking using 28 μm PVDF thin-film sensor with flexible wing

Variation in Resonant Frequency, Hz

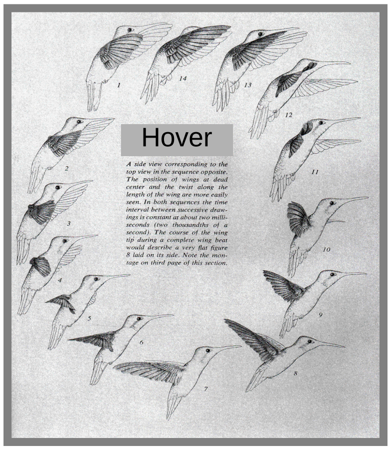


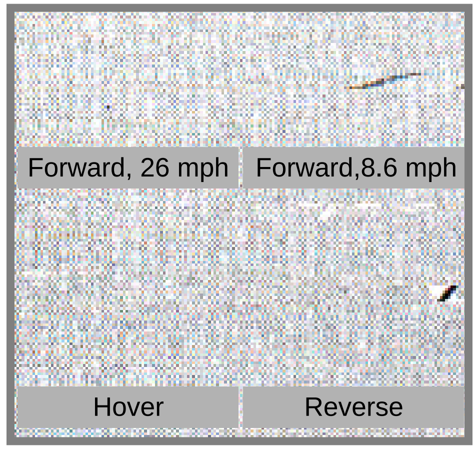
Strain-rate Sensor RMS, mV



Variable Wingbeat Patterns for Agile Flight

ref: Greenwalt, 1960

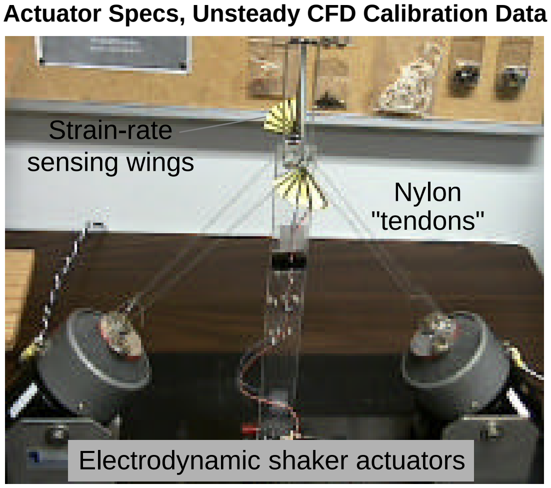


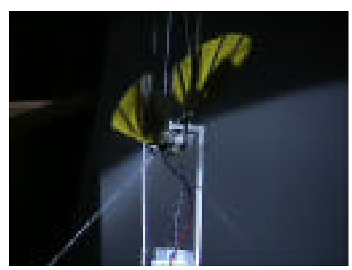


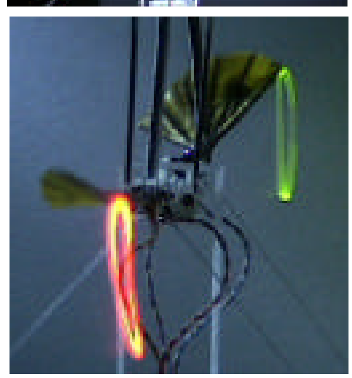
Agility and precision are achieved through coordinated control of resonant wingbeat kinematics and tail effector deployments; flight dynamics and flapping dynamics highly coupled

Shaker-Actuated Flapping Testbed

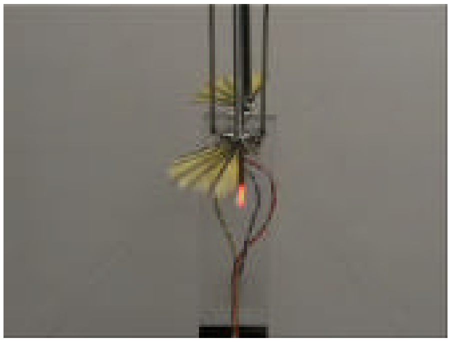
3-DOF Shoulder Joint
Resonant Tuning, Control of Wingbeat Pattern
Large Amplitude Flapping Arc
LEDs Trace Out Wingtip Trajectory
Actuator Specs, Unsteady CFD Calibration Data

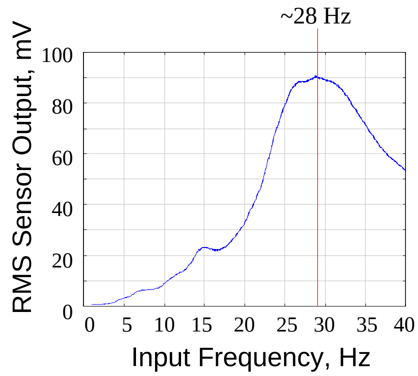






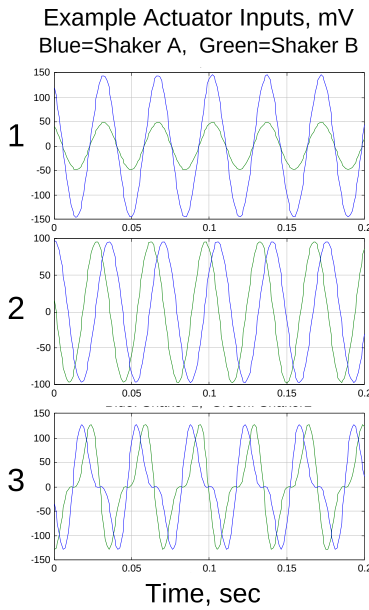
Open-Loop Sinusoidal Input Frequency Sweeps Reveal Resonant Flapping Frequency



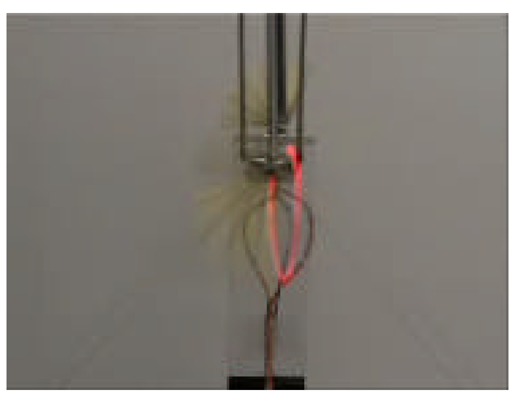


- Output of strain rate sensor is maximized at resonance
- Closed-loop system automatically tunes to this frequency
- Feedback signal can be modified to alter wingtip trajectory

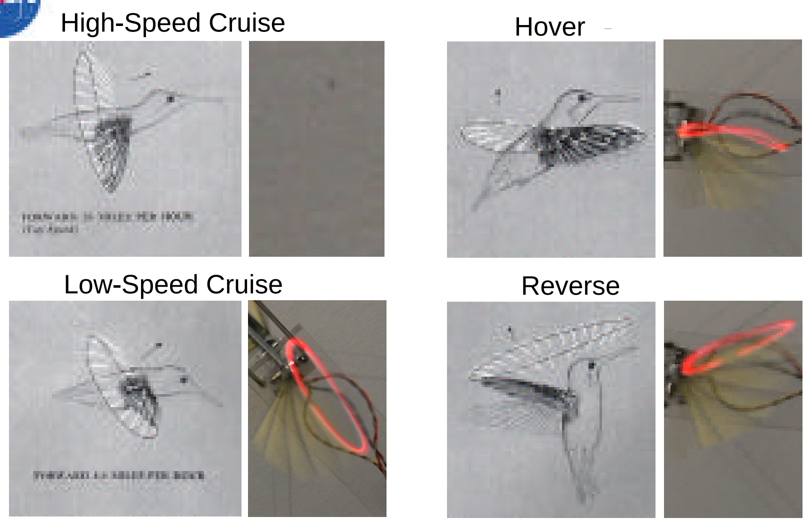
Means of Varying the Wingbeat Pattern



1 Stroke Inclination: vary relative amplitude
2 Ellipse: vary relative phasing
3 Figure 8: superimpose 2nd sinusoid @ 2 x freq. of fundamental resonance

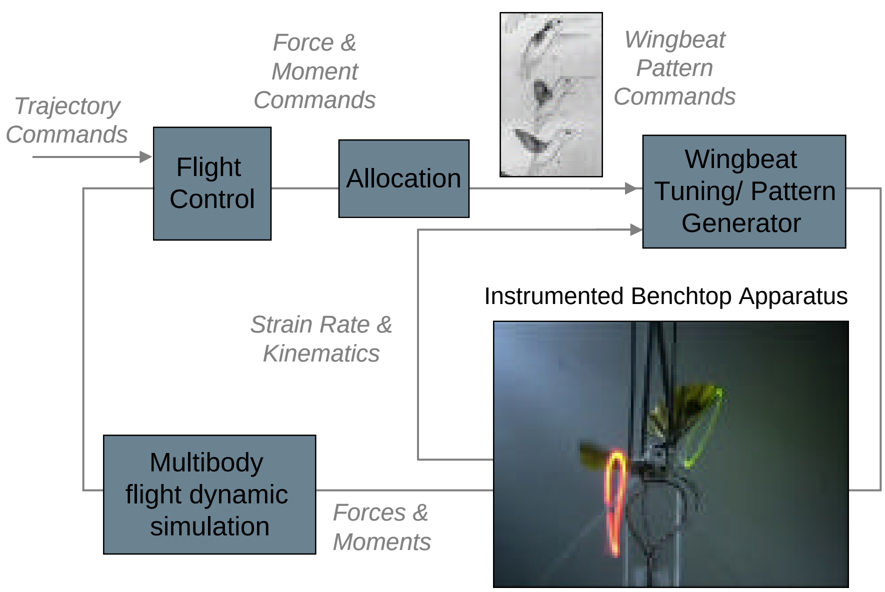


Wingbeat Patterns for Various Flight Modes



Factors to match:
- Wingbeat amplitude
- Strokeplane inclination to body axis
- Approximate wingtip trajectory
- Sense of rotation

Towards Hardware-in-Loop Flight Dynamic Simulation of an Agile Ornithoptic MAV



Outcomes

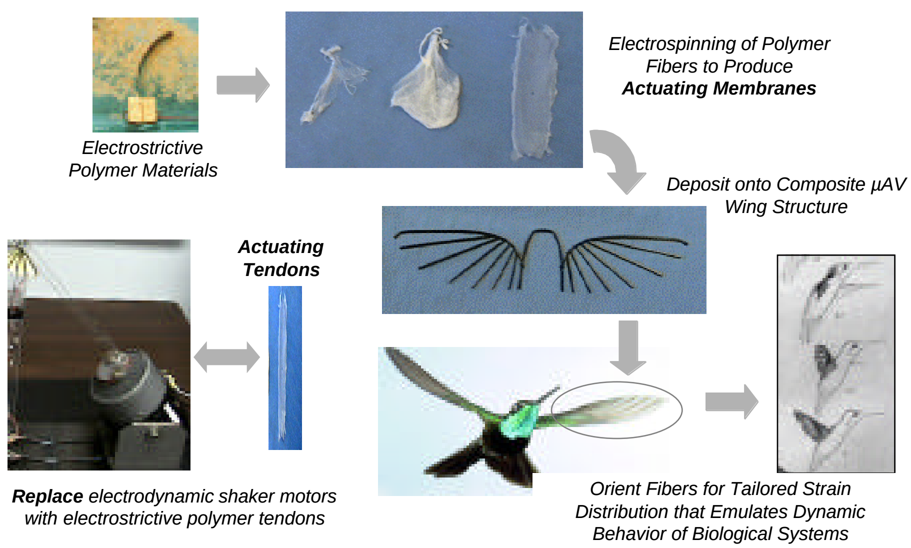
Control concepts for highly agile resonant flapping µAV
- structural concept
- strain rate sensor/ & resonant tuning concept
- wingbeat pattern generator for various flight modes
- agile maneuvering flight controller

Actuator specifications for resonant flapping system
- force, throw, bandwidth requirements
- evaluations of candidates: piezo devices, electrostrictives, SMAs, magnetostrictives

Unsteady CFD calibration data
- quantify wingshape and trajectory
- survey time-varying flow conditions

Application of Synthetic Muscle Tissue to Flapping MAV Airframes

poc: e.j.siochi@, k.j.pawlowski@, j.su@larc.nasa.gov

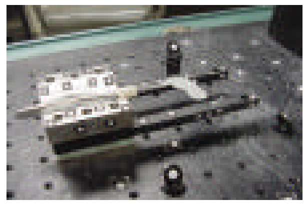


Biologically Inspired Wing Structures

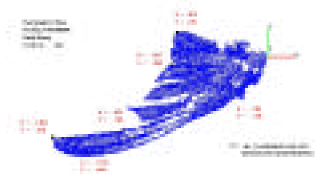
poc: Robert Dudley, r_dudley@utxvms.cc.utexas.edu

Selasphorus Rufus Wing Sample

Advanced Topometric Optical Sensor



Digitized Wing Morphology

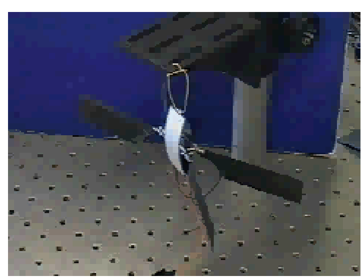


Digitized Wing Sample from UT Austin

- **A**dvanced **T**opometric **O**ptical **S**ensor (ATOS) used to digitally characterize an actual hummingbird wing to obtain morphological specifications (over 9,000 data points)
- Humming bird wing specimen provided by Dr. Robert Dudley of University of Texas at Austin’s Department of Zoology
- Dr. Dudley is currently pursuing studies of humming bird wingbeat kinematics, flight agility, morphology

Ornithoptic µAV Research at Vanderbilt University

poc: Ken Frampton, ken.frampton@vanderbilt.edu



- Smart-materials and miniaturized power electronics have been used at Vanderbilt to create a number of insect-like flight systems designed to produce high-frequency flapping actuation for flexible wings.
- Collaborative research efforts with NASA Langley targeted piezo actuation of resonating wing structures

Unsteady CFD for Flapping Wings

poc: Paul Pao, s.p.pao@larc.nasa.gov

3D Wing Motion Schematic and Flow Solution

Wing Planform types: Sea Gull, Bat

Wing Section = NACA-0009

Semi-span to mean chord ratio = 3.5

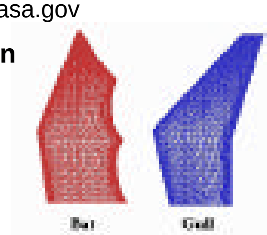
Flapping Amplitude = +/- 0.35 Semi-span

Mean Angle of Attack = 6.0 Deg

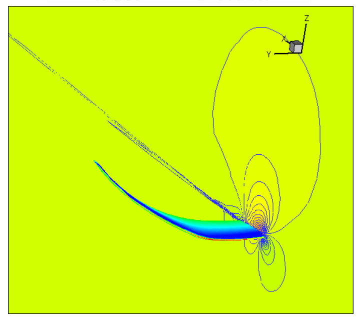
Twist Ratio = 0.70

Reduced Frequency = 0.1 - 0.5

Wing Stroke Plane Angle = 90 Deg



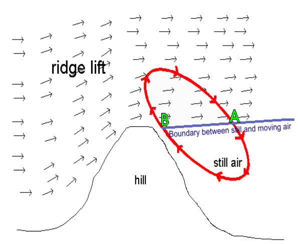
Wing Motion Side View in Ground-Fixed Coordinates



Surface Pressure and Sym Plane Mach #

Other Bio-flight Research at LaRC

- Dynamic Soaring/ Airmass Guidance
  - Dave Cox, d.e.cox@larc.nasa.gov



- Collaborative Control
  - Marty Waszak, m.r.waszak@larc.nasa.gov
- Bio-Inspired Geometries
  - Barry Lazos, b.s.lazos@larc.nasa.gov

HECS Wing

Gull Wing

Questions?