Flapping Wing Flight Using Artificial Muscles

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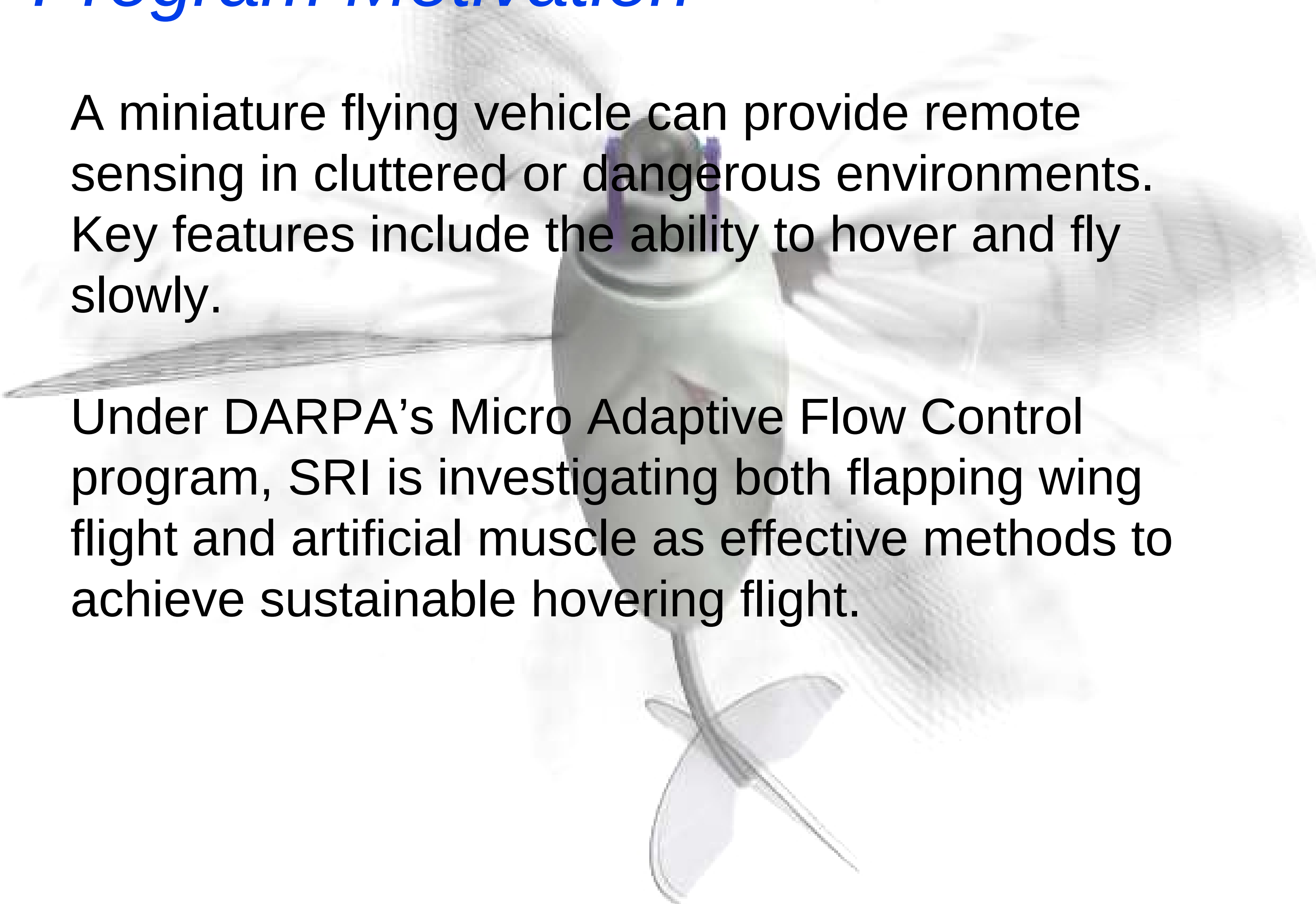
Program Motivation



A miniature flying vehicle can provide remote sensing in cluttered or dangerous environments. Key features include the ability to hover and fly slowly.

Under DARPA's Micro Adaptive Flow Control program, SRI is investigating both flapping wing flight and artificial muscle as effective methods to achieve sustainable hovering flight.

Power Requirements of Hovering Flight

Goal: Convert all of the mechanical energy into a change in the kinetic energy of the air passing through the area.

- **THRUST** = (mass flow rate)(delta velocity as a result of actuator) = 2(mass flow rate)(average air velocity through swept area)

  thrust = $2\rho A v^2$

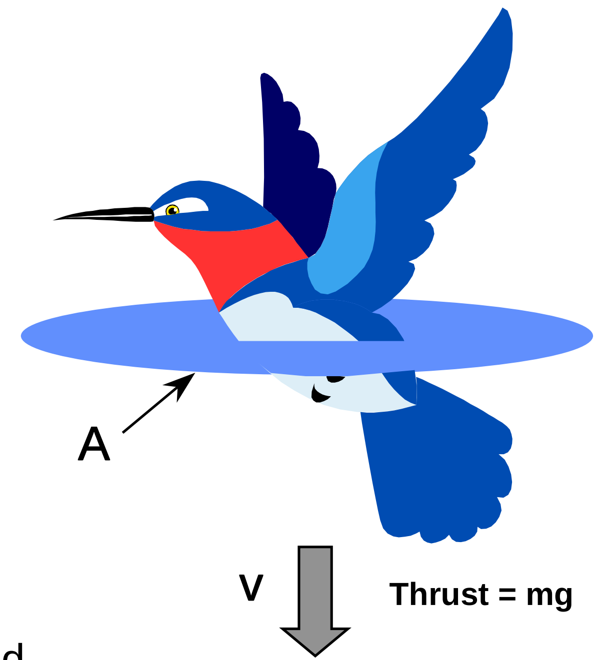
- **POWER** = (thrust)(average air velocity through swept area)

  power = $2\rho A v^3$

- **FOR HOVERING:** thrust = weight of vehicle= mg

- **MINIMUM REQUIRED SPECIFIC POWER =**

  power/m = $[g^{1.5}/(2\rho)^{0.5}][(m/A)^{0.5}]$ (W/g)



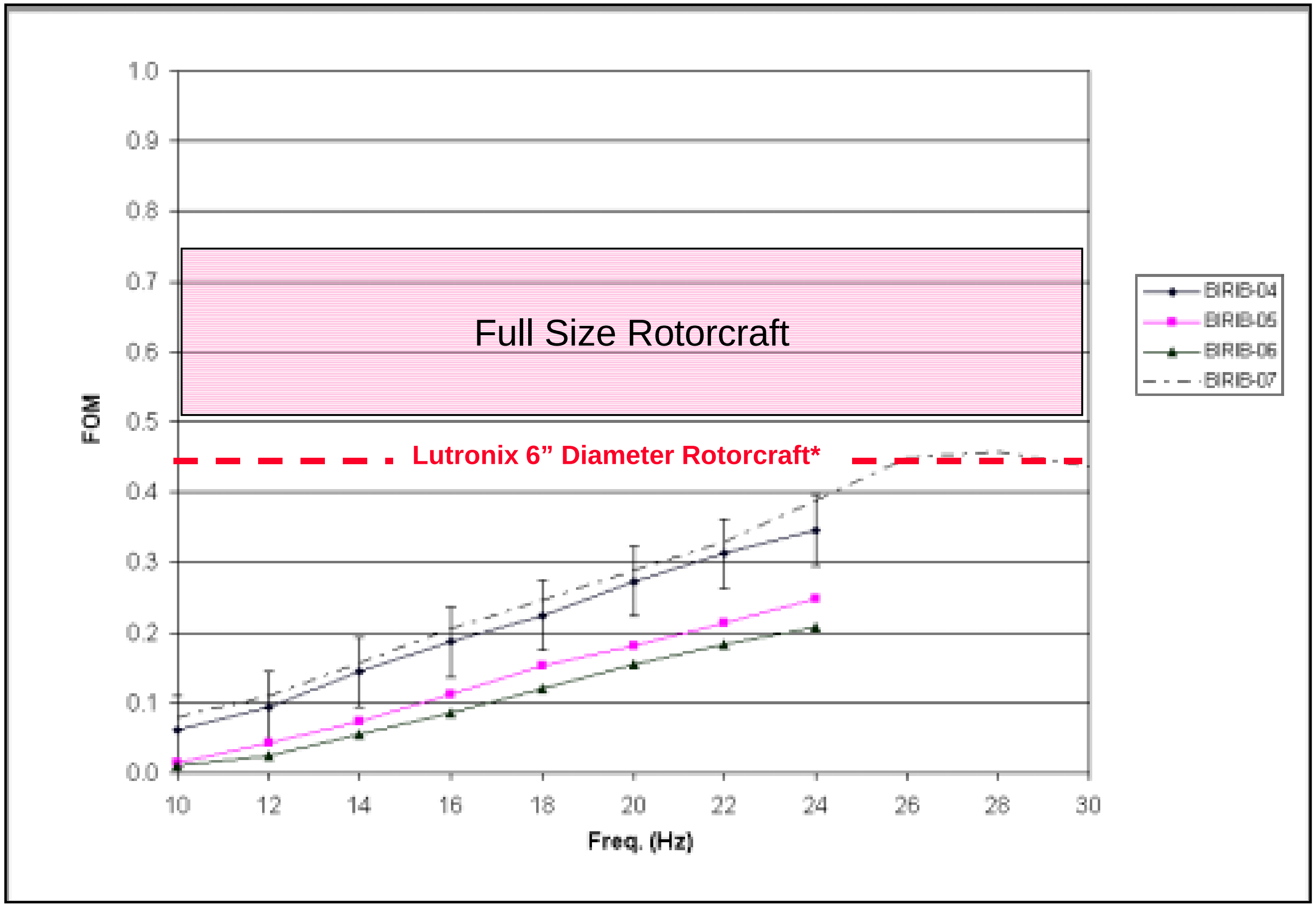
Summary:

•Minimize specific power requirements by minimizing mass and maximizing wingspan (swept area).

•Favor smaller vehicles (since mass $\sim L^3$ and area $\sim L^2$). Specific power requirements $\sim L^{0.5}$

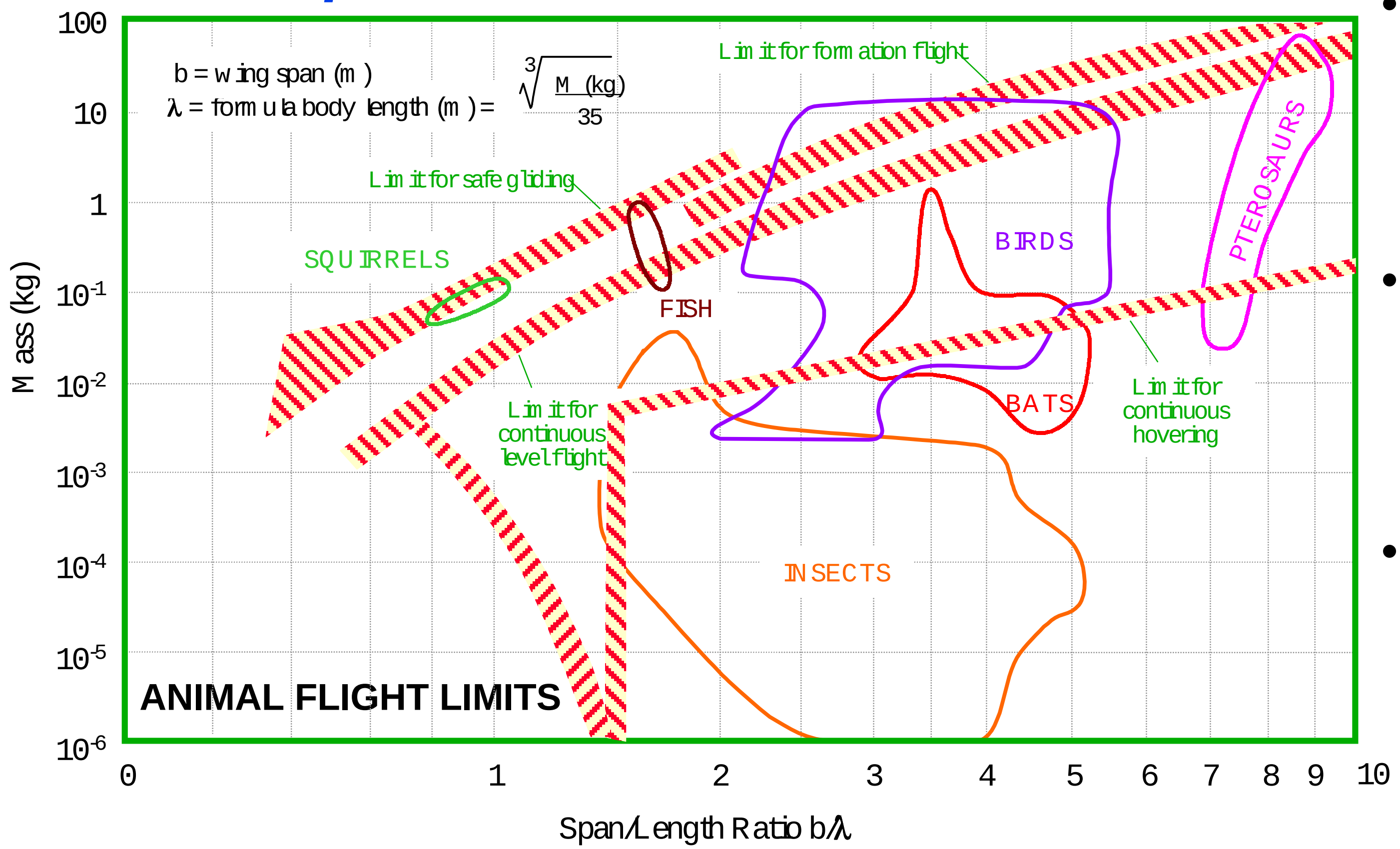
Wing Performance Trends: FOM vs. Flapping Frequency

- Figure of Merit (FOM) is actual thrust-to-power ratio divided by the theoretical maximum for an equivalent swept area.
- Current winged designs perform on par with similarly sized rotor-based designs.
- Future winged designs will presumably surpass small rotors in FOM.



*Lutronix data from Ron Barrett, Auburn University

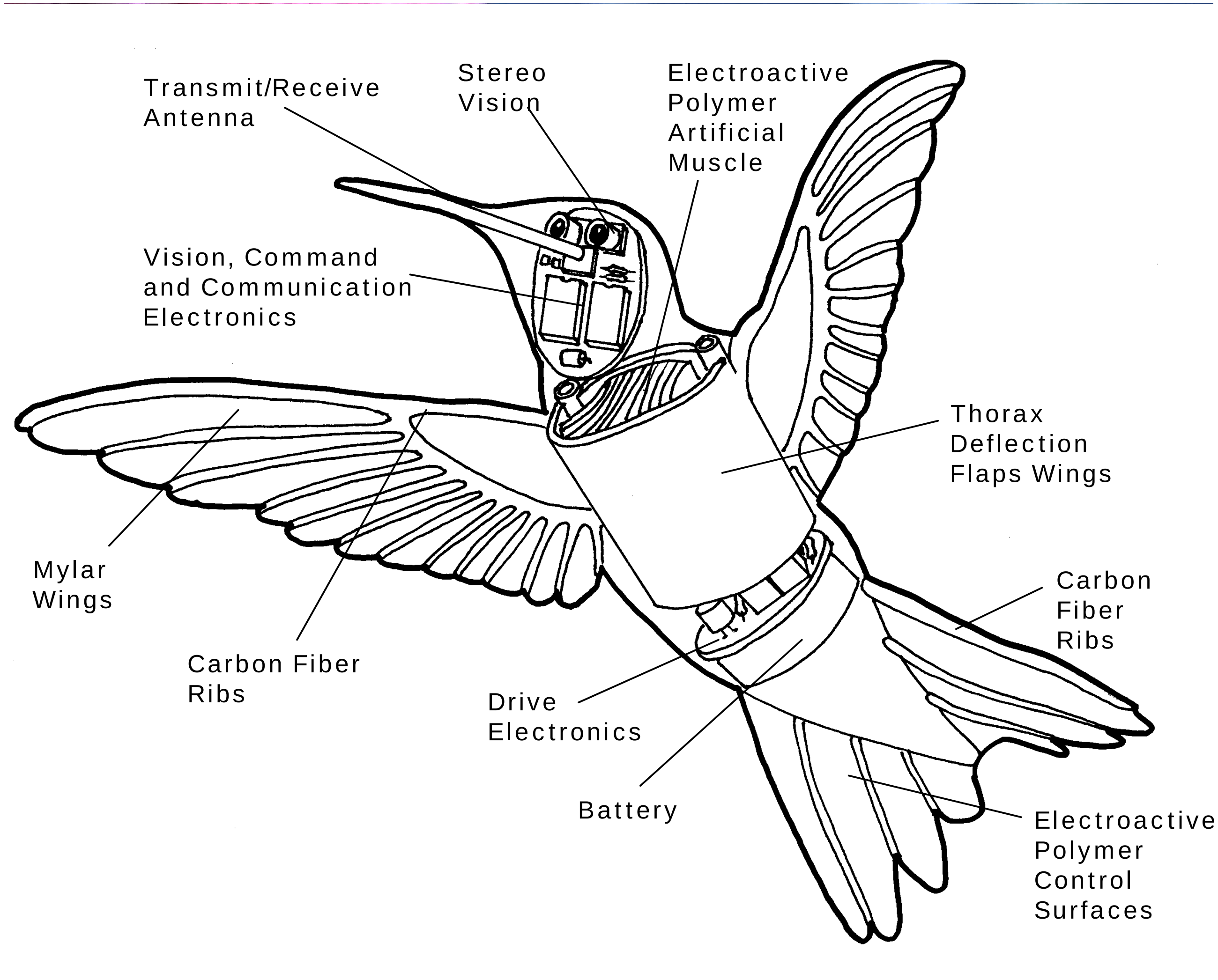
Biological Manifestations of Power Requirements



Source: R.J. Templin, "The Spectrum of Animal Flight," 1998

- Beyond a certain size and mass, sustained flight is not possible
  - Dumbo can't fly
- Continuous hovering requirements limit size and mass further
- What are the biological reasons for the limitations?
  - Available power (specific power of muscle)
  - Wingspan (strength of bones or wing materials)

So Is This What We Want?



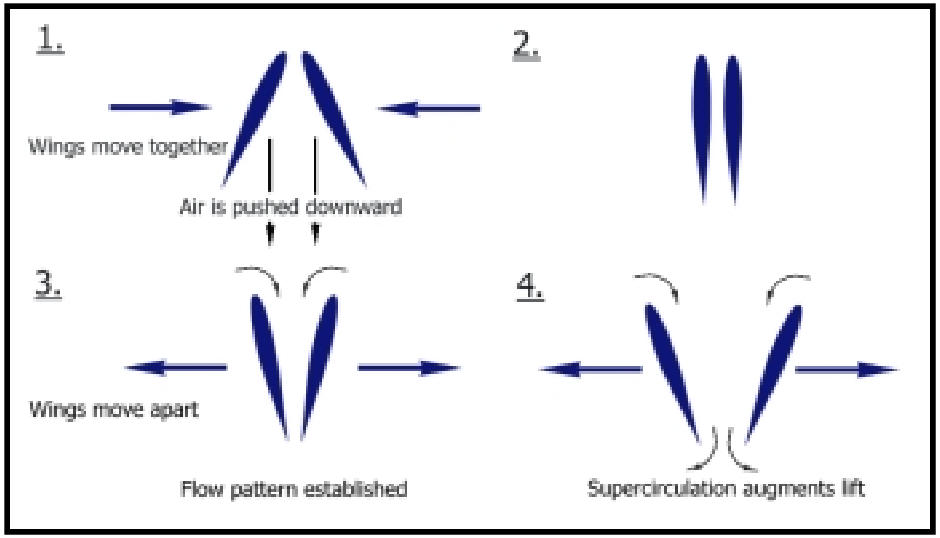
Ruby-throated hummingbirds can fly for 30 hours to cross the Gulf of Mexico, but still hover. Should we imitate them?

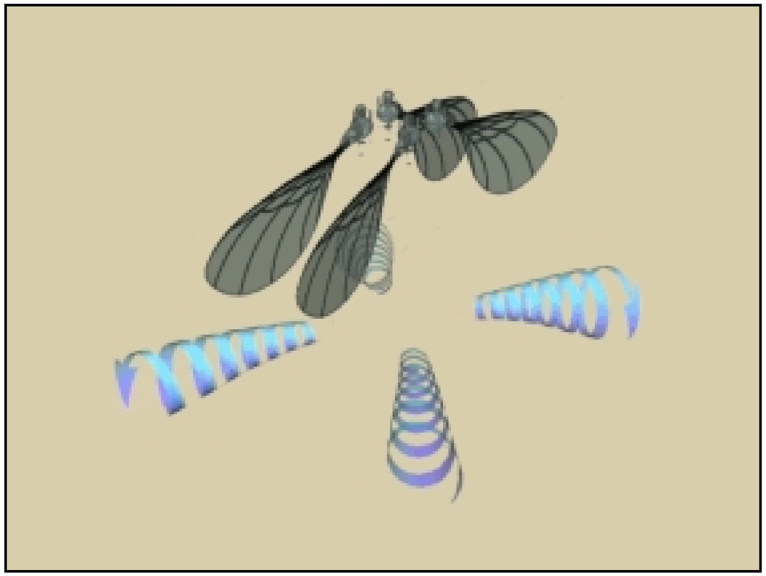
Not necessarily.

Mimicry may give good results, but ideally we want to understand the underlying physical phenomena which enable creatures of this size to fly and hover.

Importance of Unsteady-state Effects in Flapping

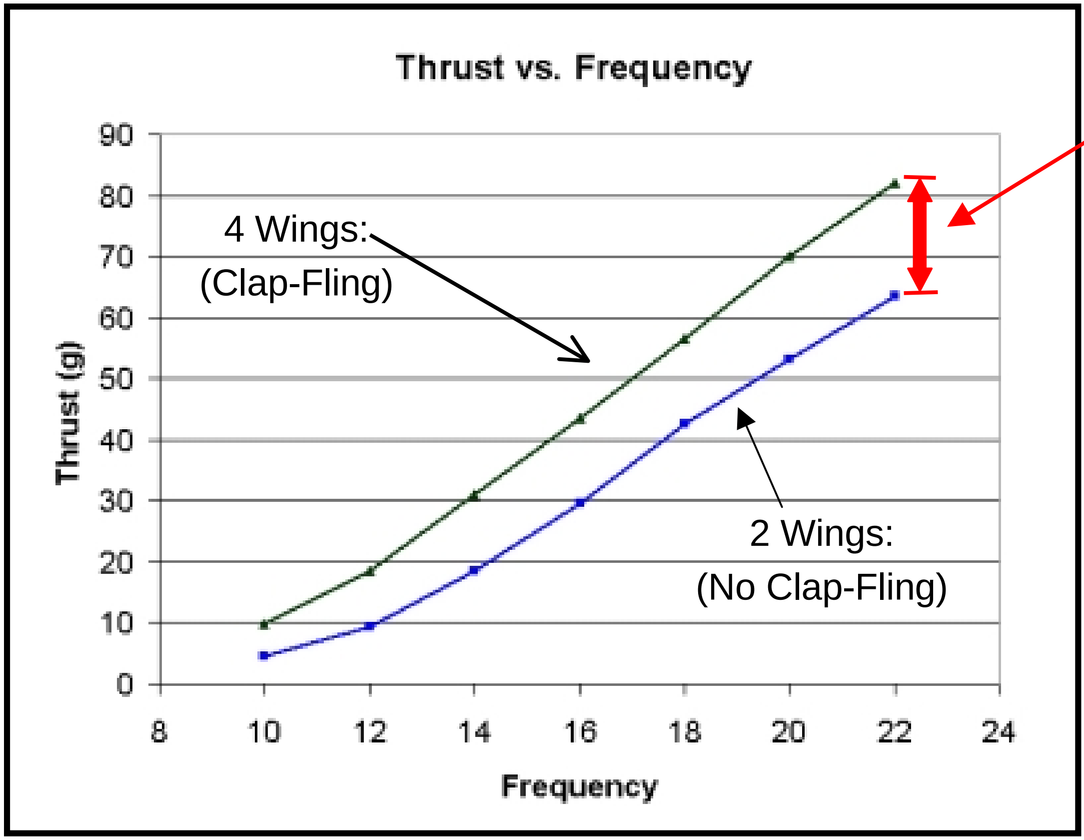
- The “clap-fling” phenomena is used by many birds and insects to increase thrust.





- It has been experimentally shown to offer performance benefits in artificial devices.

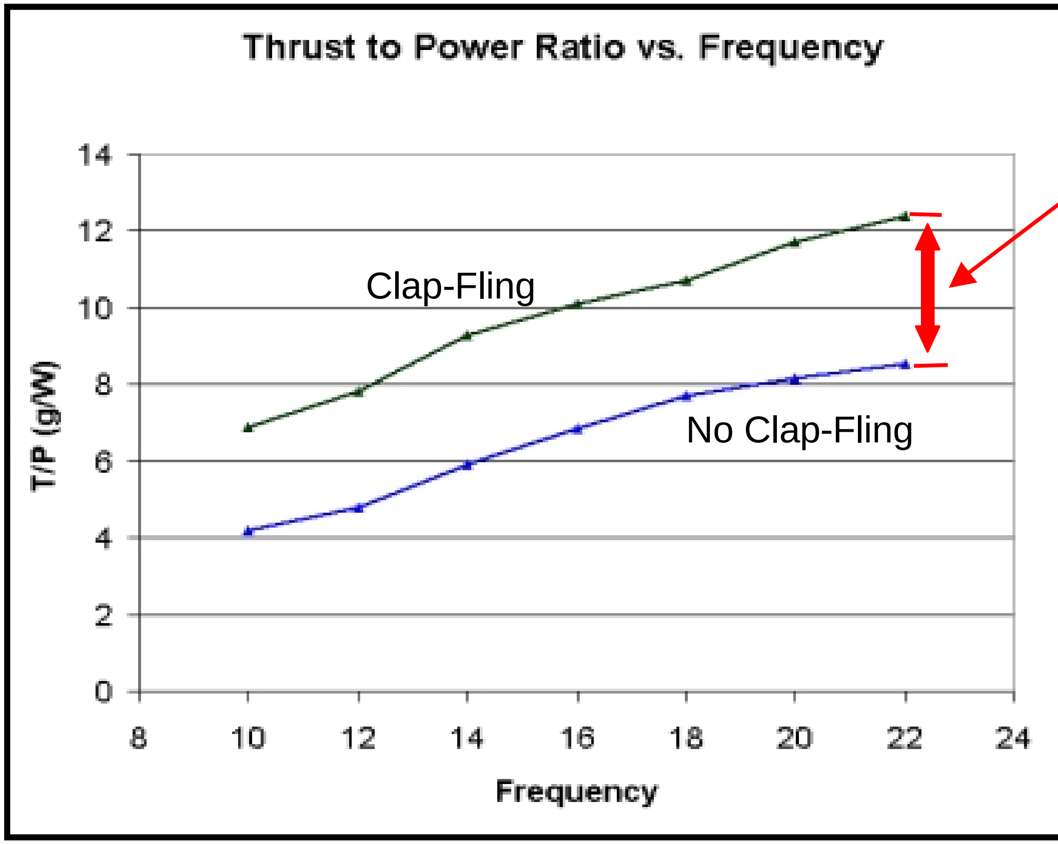
Clap-fling Evaluated: Thrust



BIRIB-04: 76 degree Flapping Amplitude

- 31% increase in thrust due to clap-fling at 22Hz.
- Lower curve represents **TWICE** the thrust from 2 wings that flap opposite one another on the test rig.

Clap-fling Evaluated: Efficiency

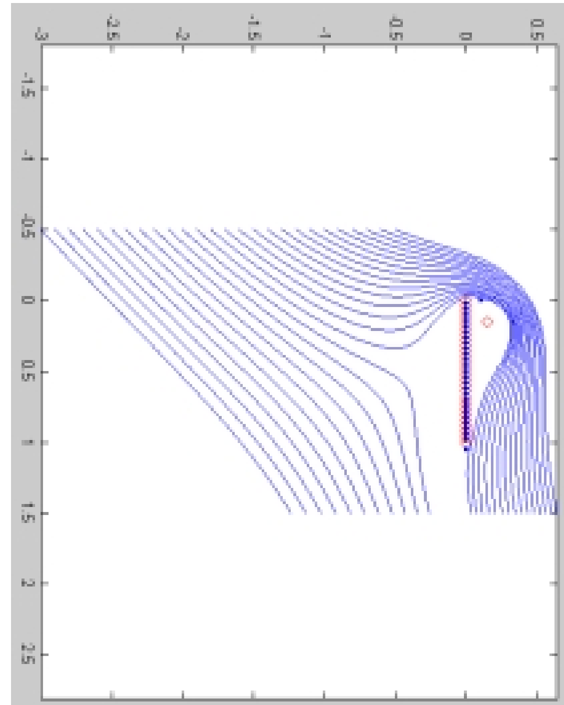


- 51% average increase in thrust-to-power ratio (used in FOM).
- Not only do we have more power, but we have greater efficiency.

Potential Flow Model

← High speed video still

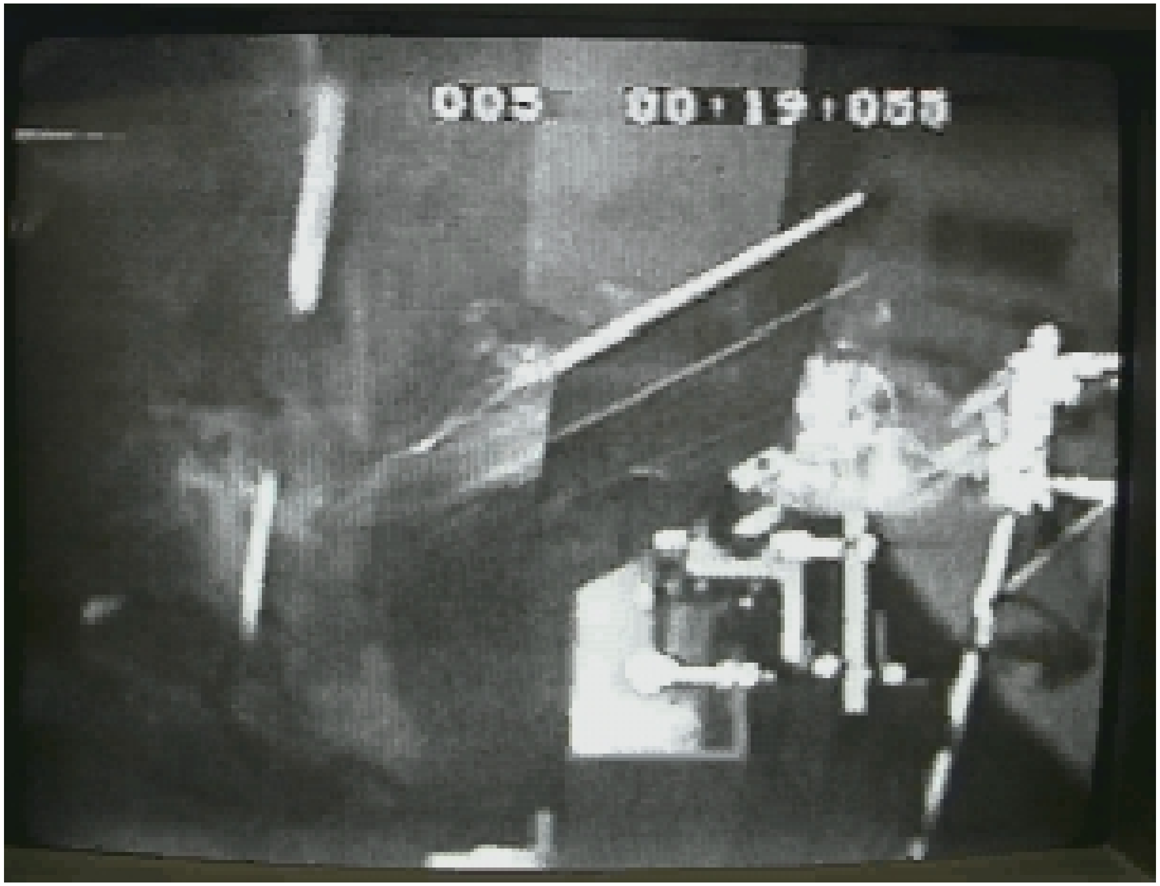
Streamlines about flat plate at 45 ° angle of attack →



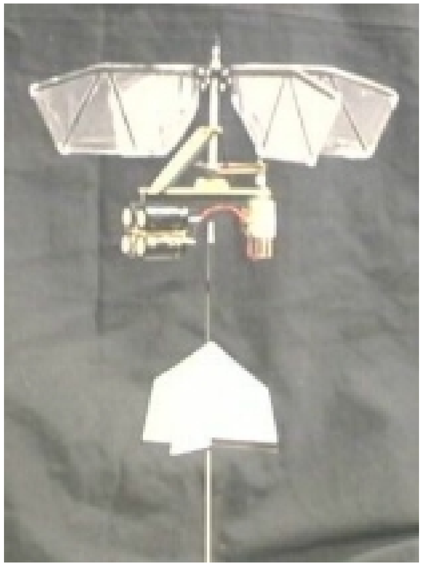
- The leading edge vortex, clap-fling effect and the vortical wake must all be modeled.
- Potential flow used to model complex flows by superposition of simpler flows (vortices, steady flow, sources, sinks).
- Flow visualization data is incorporated into model, which analyzes the aerodynamics.

Experimental Verification

- Parameters of interest will be varied individually and trends examined.
  - Parameters include flapping speed, twisting amplitude, chord length.
- Trends and flow behavior to be incorporated into potential flow model.



Flight Vehicle Development



April 2000: Free Flight Demonstrator

Wing Model: BAT-13

Disk Area (Wing span): 6.75 in

Gross Vehicle mass: 40 g

Power Source: Four 3.3F 2.5 V capacitors in series charged to 14 V

Actuation: WesTechnik DC 5-2.4 coreless DC motor with modified Micro-Mo planetary gear head. (16:1) drive reduction.

November 2000: Radio Controlled Vehicle

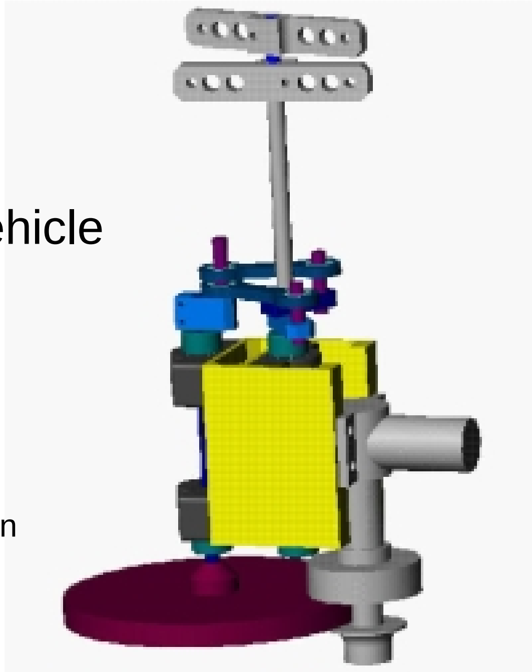
Wing Model: Kite 04

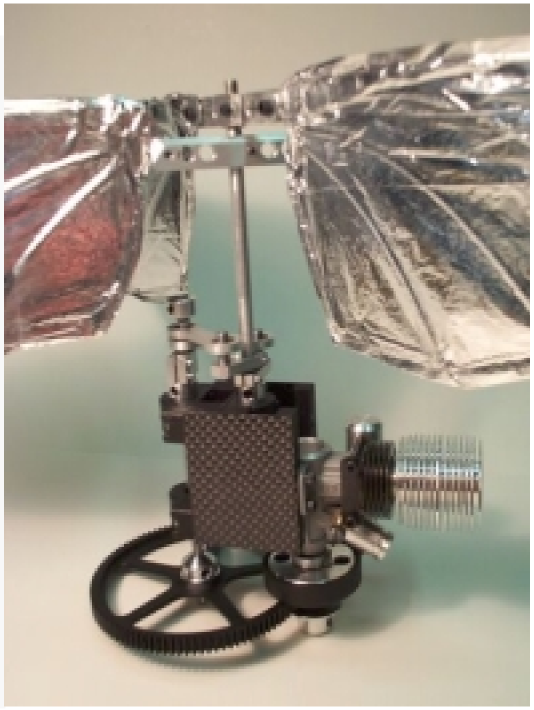
Disk Area (Wing span): 13 in

Gross Vehicle mass: 306 g

Power Source: 1.0 cm^3 Norvel glow fuel engine

Actuation: 4 bar linkages with 11:1 drive reduction





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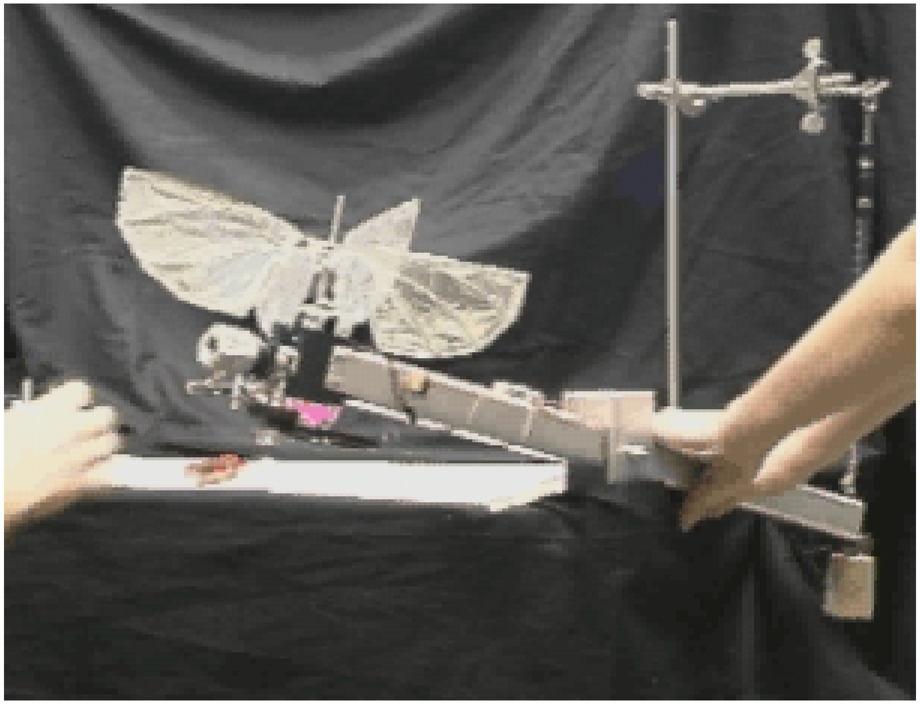
Flight Vehicle Development

- Design Highlights:
  - Utilizes centrifugal clutch to aid starting
  - Operates over 5 minutes on single tank
- Mass Summary:
  - Flight Vehicle (with radio): 261g
  - Fuel: 44g
  - Total: 306g
- Testing Highlights:
  - Operated to 20 Hz
  - Generated >300g of lift on test stand
- Predicted Performance
  - Engine/Wing system predicted maximum speed: 33 Hz
  - Predicted maximum thrust: 350g



Muscles or Motors?

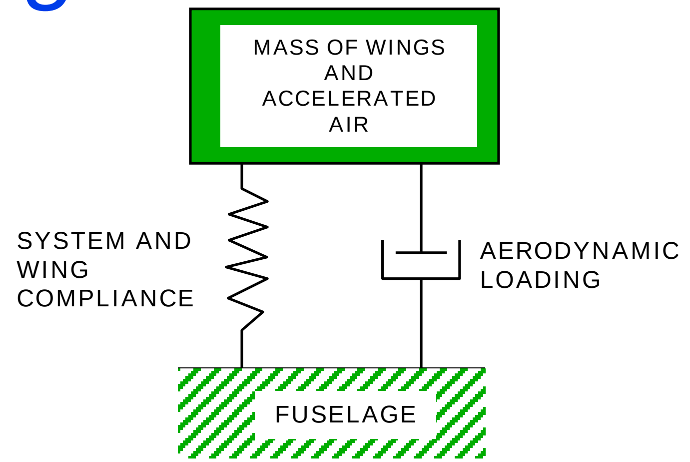
Muscle has higher technical risk, but as lightweight voltage conversion circuitry becomes available, it should be simpler, lighter, lower cost, size scalable, as well as being more efficient, rugged, reliable, and quiet.

- No high speed moving parts or gear reduction. Results in less weight, noise, complexity, and vibration.
- Scales to small sizes better than motors or engines.
- Allows for elastic energy storage (resonant operation).

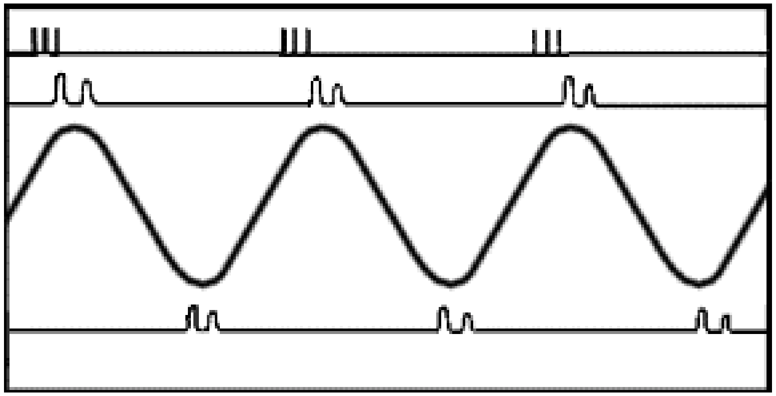
Component	Mass (projected)	Efficiency (projected)
Power conversion/driver circuitry		
Artificial Muscle	2 g	80%
Motor	1 g	90%
Actuator		
Artificial Muscle	5 g	90%
Motor	10 g	75%
Mechanical transmission		
Artificial Muscle	2 g	90%
Motor	5 g	80%
Total Propulsion System		
Artificial Muscle	9 g	65%
Motor	16 g	54%

Elasticity in Flapping Flight

- Resonant operation eliminates “inertial” power required to accelerate and decelerate the wings.
  - Initial results suggest that the inertial power is greater than the aerodynamic power in many fliers.
    - Inertial power is 2 times aerodynamic power in bumble bees (Dudley and Ellington 1990).
    - Inertial power is 4 times aerodynamic power in hummingbirds (Wells 1993).
- Many muscle-like actuators are well-suited to resonant operation due to inherent compliance.



A basic lumped parameter model illustrates the importance of actuating the wings at resonance.



Measurements of wing motion in natural fliers reveals a sinusoidal motion suggesting that of a spring-mass system.

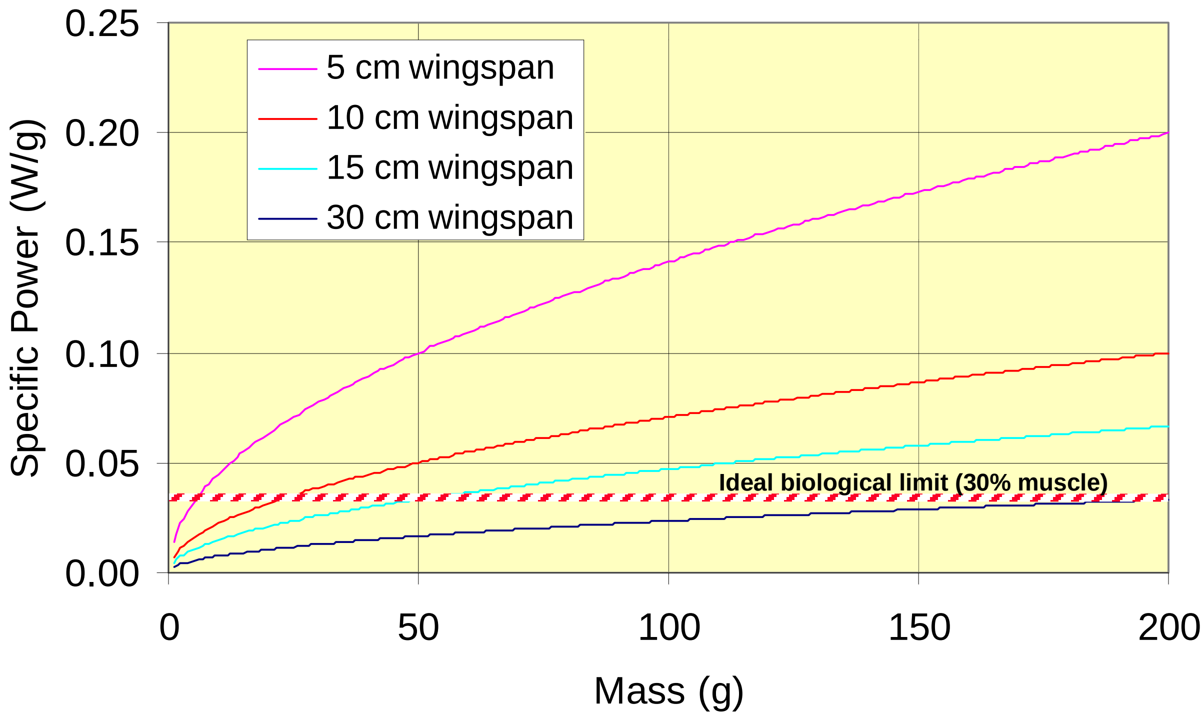
Muscle Power

- Muscle performance is similar across a wide range of creatures.
- 0.1 W/g is a representative power value to use for muscle.
- Assume that about 30% of the creature mass is flight muscle.
  - 0.03 W/g specific power is available.

Creature	Flapping Rate (Hz)	Flight Muscle Specific Power (W/g)	Max. Muscle Strain (%)	Source
Bumble Bee	155	.10	3.1	Josephson 1997
Tobacco Hawkmoth	30	.09	7.9	Stevenson, Josephson 1989
Hummingbird	46	.12	?	Wells 1993
Dragonfly	40	.10	?	(DARPA)

Implications of Physical Limits

- Limitations due to aerodynamics and muscle capabilities constrain the maximum mass capable of hovering.
- Imperfect aerodynamics further limit mass.



Specific power (based on total mass) required to sustain hovering assuming ideal aerodynamics

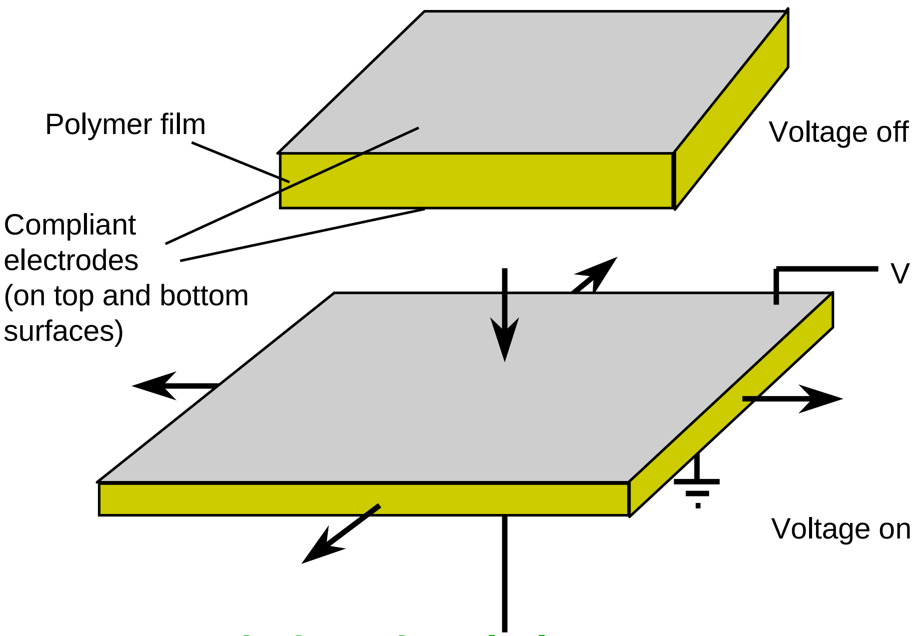
Efficiency

Actuator power requirements are only part of the story. We also must consider actuator efficiency and other factors.

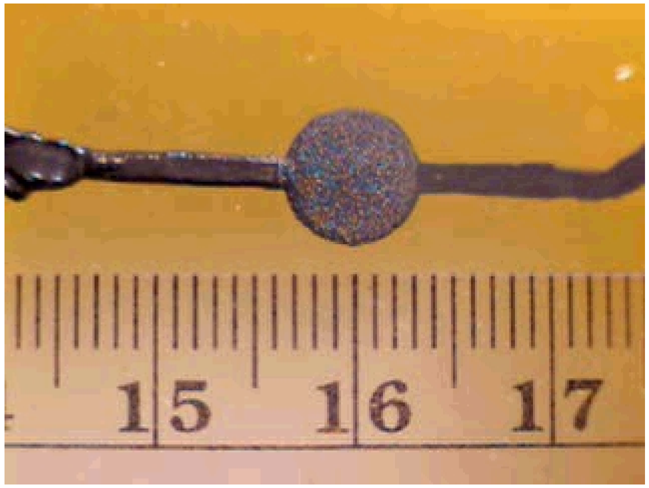
- Muscle efficiencies (chemomechanical) are estimated to be from 10 - 20% for flight muscles (e.g. Josephson, Wells, Dickinson).
- Several "muscle-like" actuator technologies are not viable due to extremely poor efficiencies.
- Electric field activated materials have the most promising overall performance if smart electronics are used to recapture capacitive energy.

Actuator Class	Specific Work	Frequency Response	Efficiency	Voltage	Environmental Factors
Electrochemomechanical (conductive polymers, IPMC)	fair	Poor (size dependant)	Poor <1%	Low	Humidity and temperature dependant
Electric Field Activated (piezoelectric, dielectric elastomers, electrostrictive polymers)	good	good	Fair-Good 10% - 80% depending on electronics	High	
Magnetic Field Activated (magnetostrictive, voice coil, motor)	fair	good	Good 50-80%	Low	
Shape Memory Alloys	excellent	Poor (size dependant)	Poor 2%	Low	Temperature dependant
Biological Flight Muscle	good	good	Fair 10-20%	NA	

Electroactive Polymer Artificial Muscle (EPAM)



Basic functional element



Circular electroded area expands when the voltage is applied

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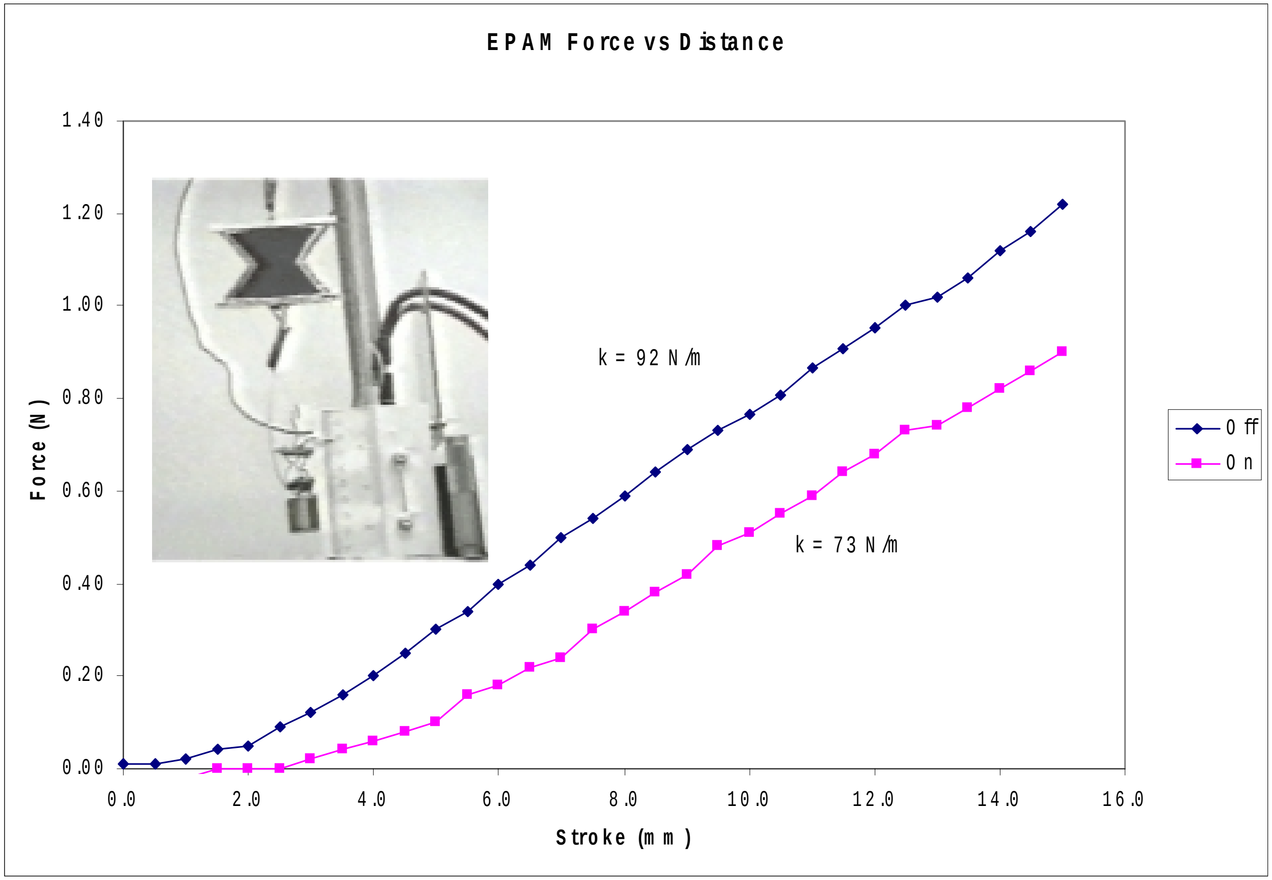
EPAM Performance

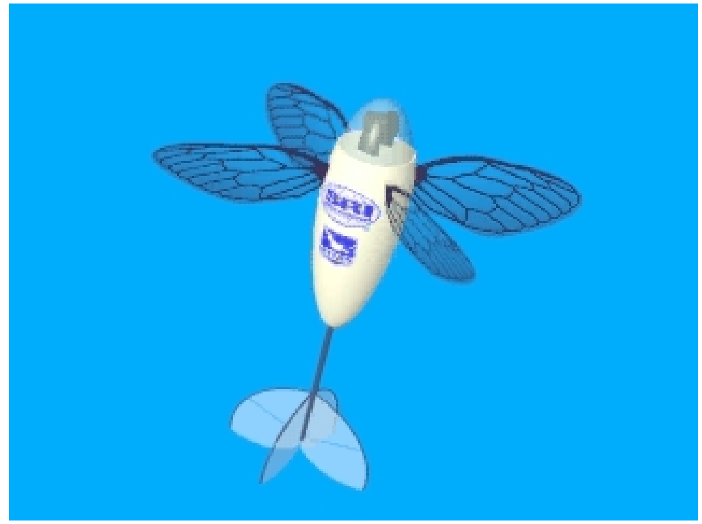
- Quasi-static work loop shows an energy output of about half of that predicted by free stroke vs. force (corrected to same electric field).
- Energy output is dependent on imposed stroke which in turn depends on dynamics of mechanism and aerodynamics.

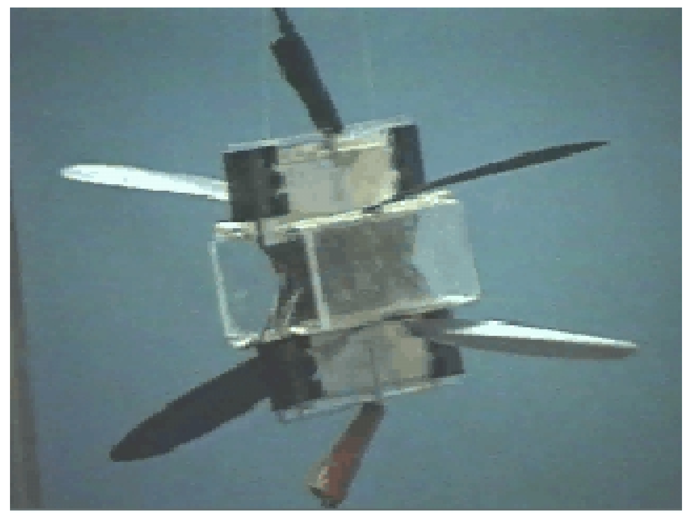


Muscle-Powered Flapping Wing Development

The first prototype proved that the T-flex concept was workable.

- Mechanism works like an insect, moving its wings by deforming the thorax.
- Linkages were inherently simple, being only flexures (living hinges).
- Even a few layers of active muscle resulted in significant wing deflection, especially when exploiting resonance.
- Operation was quiet as predicted.





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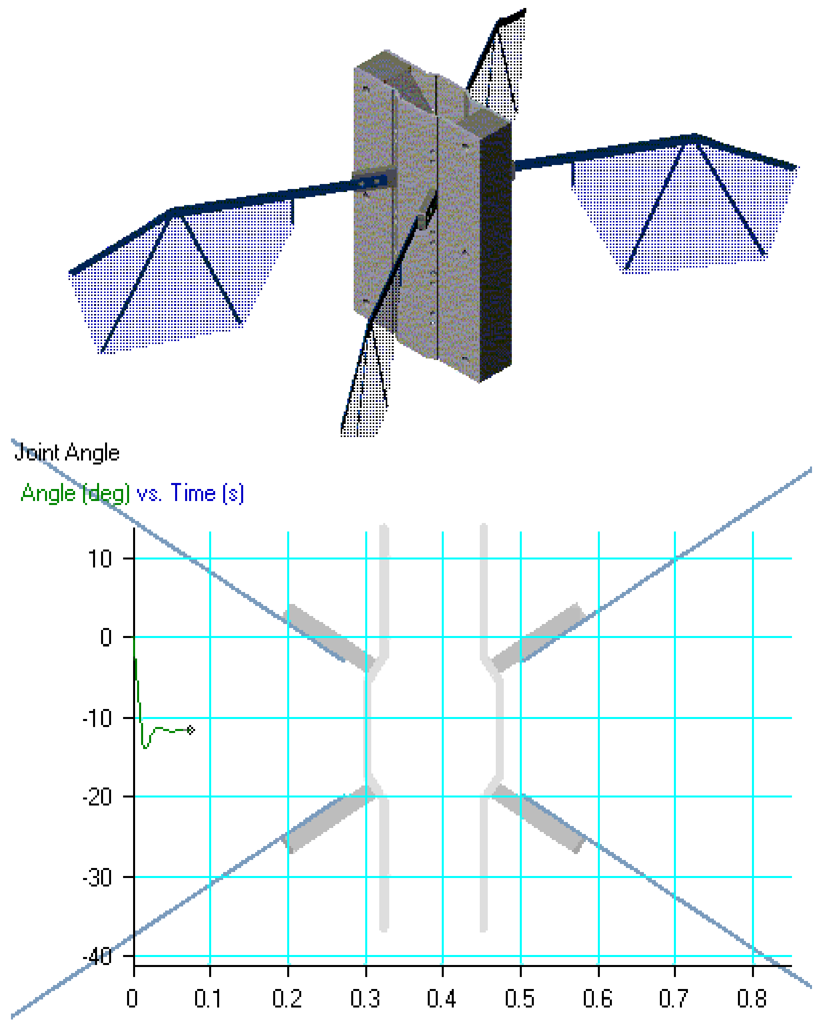
Muscle-Powered Flapping Wing Development

Second iteration design, powered by 10-layer muscle stack, is more compact and lightweight, but has a small flapping amplitude.

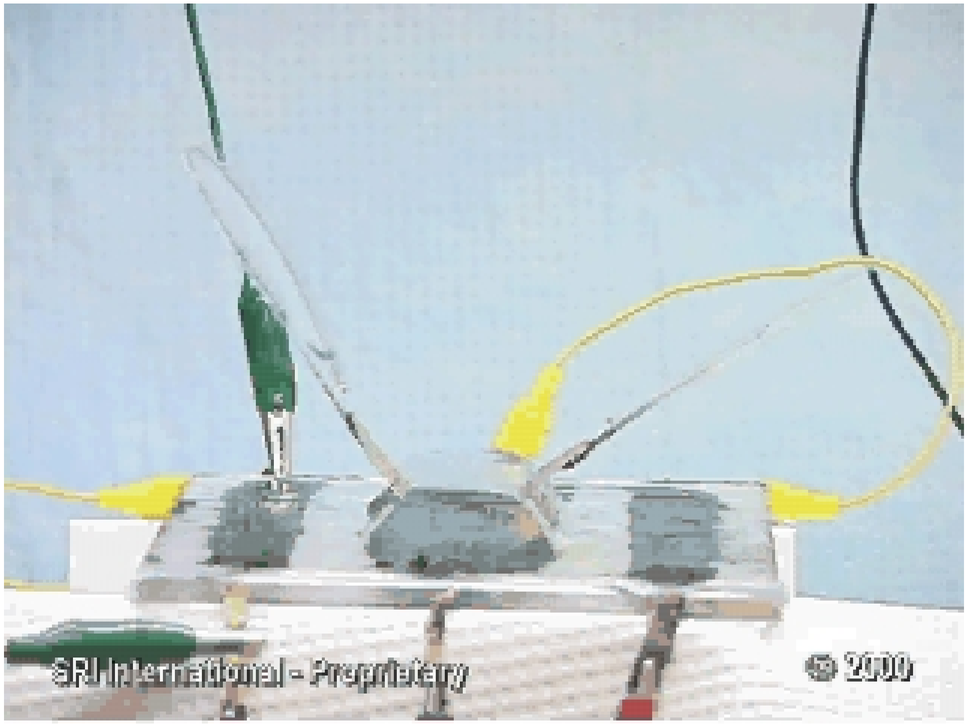
- Used dynamic simulation to analyze problem.
  - Simulation based on quasi-static muscle performance and experimental estimates of mechanism joint stiffness and damping.
- Joint damping and mechanism preload are critical.
  - Body material needs changing.
  - Adding additional muscle layers should improve results by lowering specific damping and properly preloading the mechanism.
- Further modeling will include more accurate aerodynamic loads (from new test rig).



Dynamic simulation of T-flex

Muscle-powered Flapping Wing Development: Future Possibilities

- A new alternate design uses higher strain and energy output acrylic.
- Acrylic is more reliable and easier to fabricate.
- Two-phase stretched film design minimizes problems with creep.
- Issues with acrylic speed of response and efficiency remain.
- Actuator configuration and shape allows for radical new vehicle design.



Acrylic Stretched-film flapping mechanism

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