Making MAVs Move: Power and Propulsion from a Systems and Biological Perspective

Ist US-European Micro-Aerial Vehicle Technology Demonstration and Assessment

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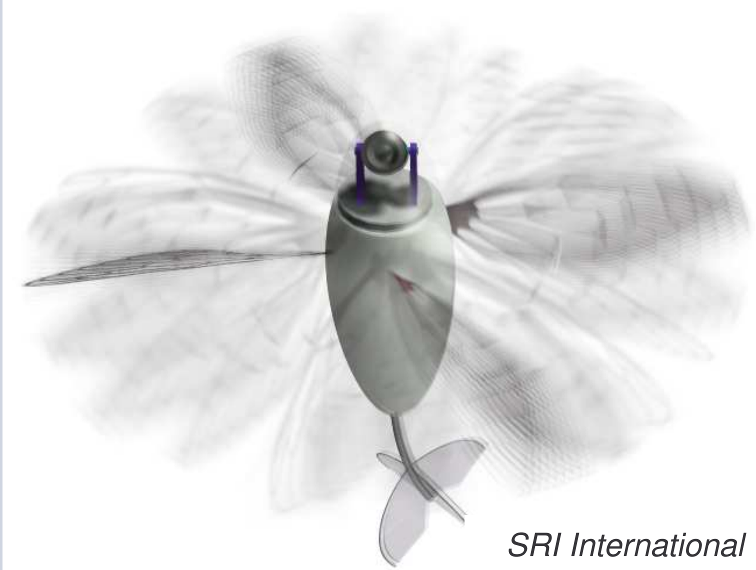
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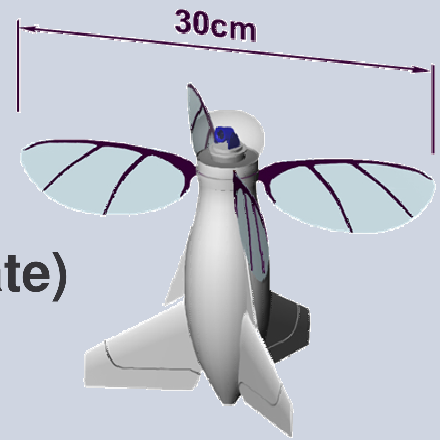
The Dream (<5 years)

Notional MENTOR Vehicle Design

- Backpack-portable “Eye in the Sky” for reconnaissance in cluttered environments
- Both hover and forward flight capable
- Easy to control (teleoperate)
- Quiet!
- >20 Minute flight time, 10 min hover



Possible future mission scenario for a Mentor-type vehicle

The Dream (10+ years)

- "Fly on the Wall" robotic fly for sensing and recon
- Ultra miniature
- Stealthy and Biomimic
- Self recharging (foraging, scavenging) or nuclear
- Mostly autonomous

BBC Animation for National Geographic Explorer

Biomimetic actuation and propulsion may be more than just a dream

Aerodynamics for Dummies: Basic Energy Relations

- **Hovering is the most demanding flight regime and can give us good insight into basic power requirements for flight**

Simple Analysis of Hovering Requirements (assuming perfect aerodynamics)

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

$$\text{thrust} = 2\rho A v^2$$

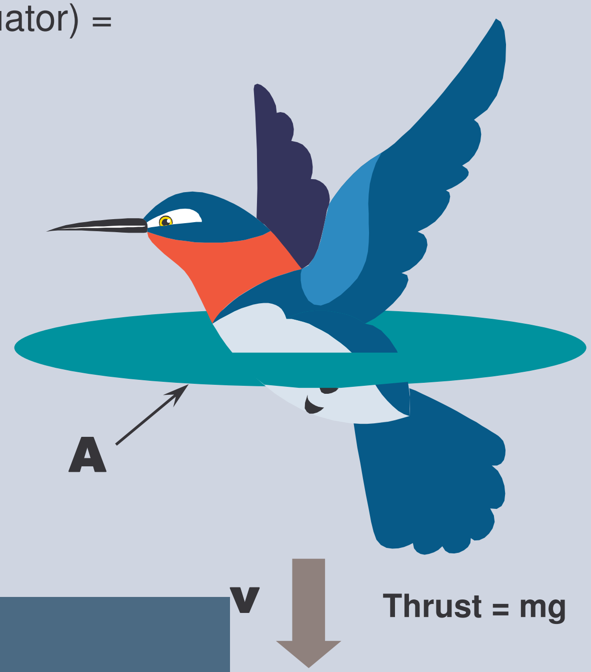
– POWER = (thrust)(average air velocity through swept area)

$$\text{power} = 2\rho A v^3$$

– FOR HOVERING: thrust = weight of vehicle= mg

– MINIMUM REQUIRED SPECIFIC POWER =

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



Conclusions:

- 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 $\sim L^{0.5}$

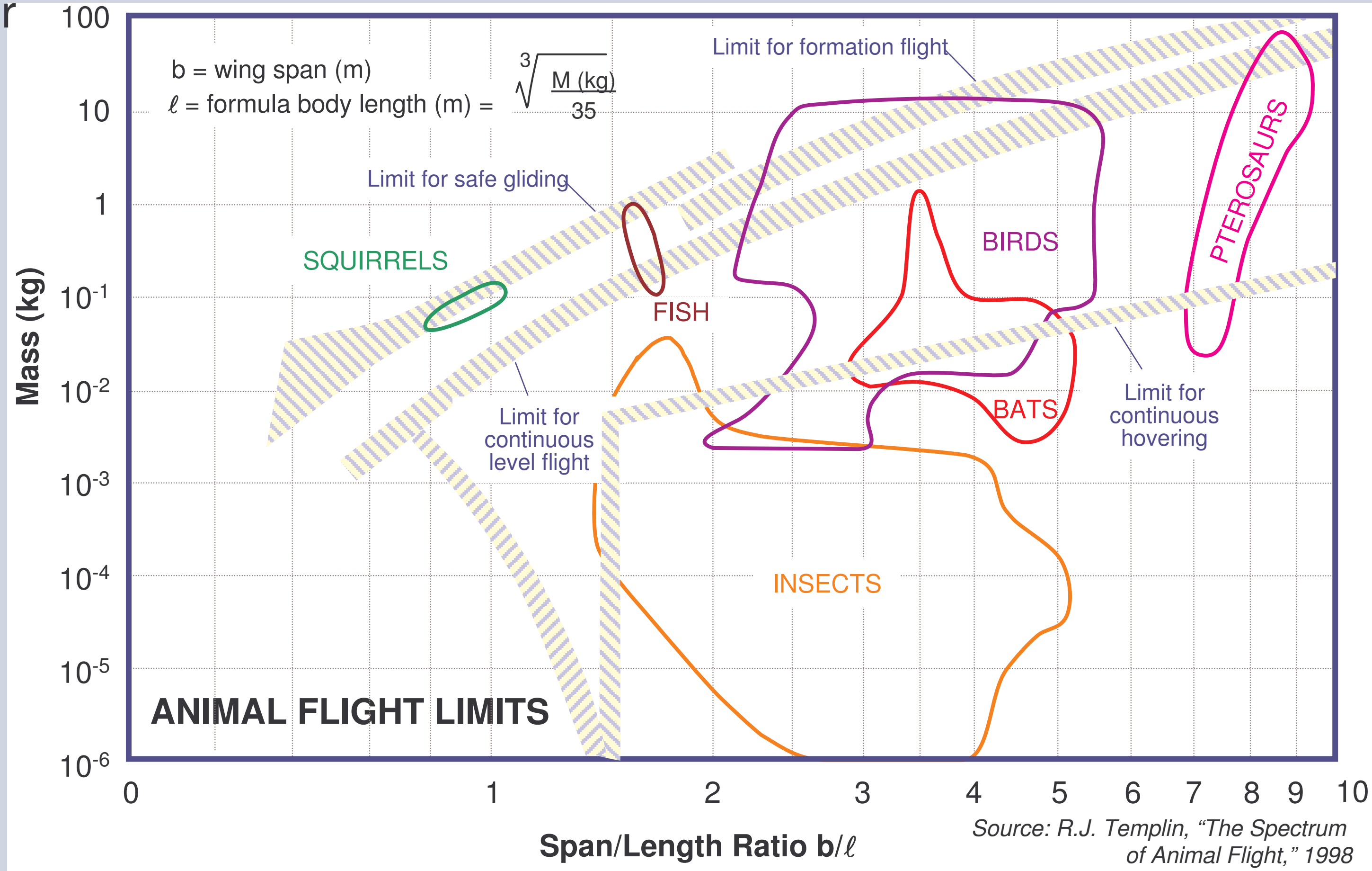
Biological Baseline: Muscle Power

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)

- **Muscle power output is similar across a wide range of creatures.**
  - About 0.1 W/g
  - Battery power for high specific power batteries is similar
- **Assume that about 30% to 70% of the creature mass is flight muscle**
  - 0.03 to 0.07 W/g specific power is available.

Biological Manifestations of Power Requirements

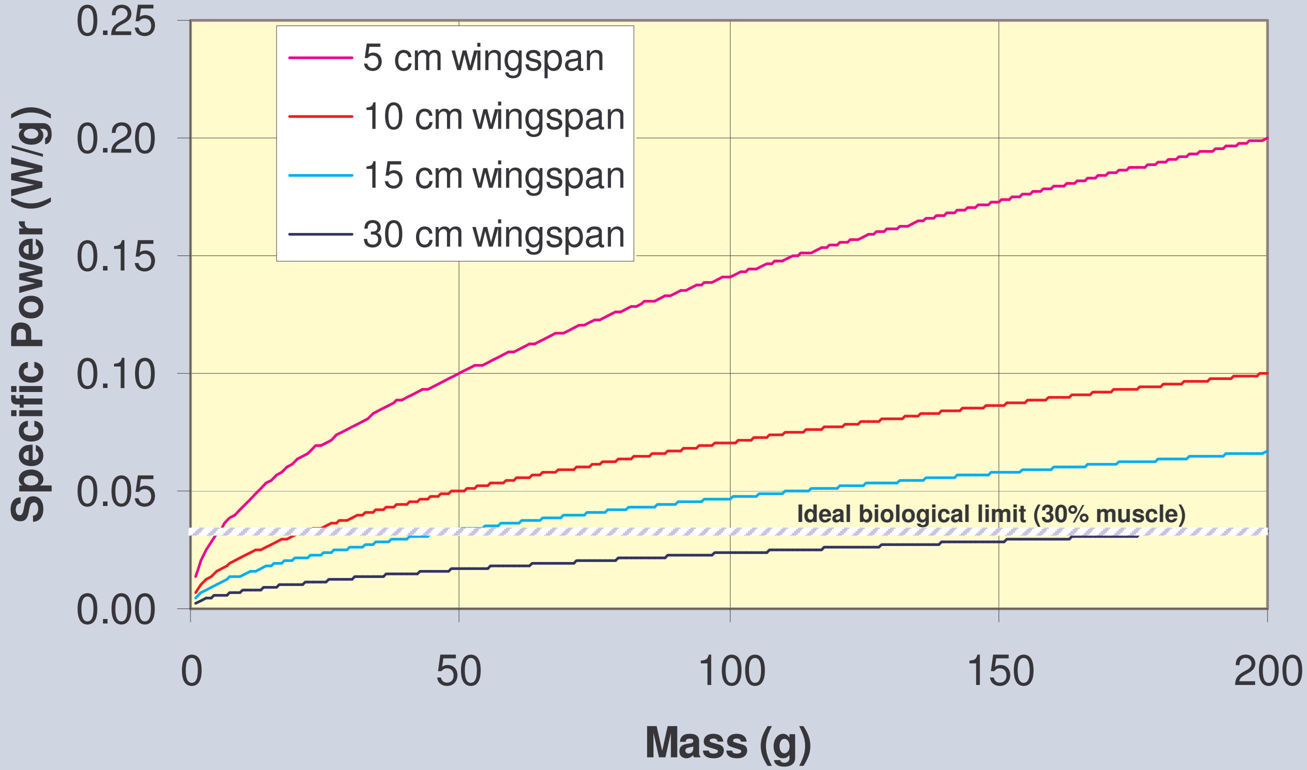
- Beyond a certain size and mass, sustained flight is not possible
- Continuous hovering requirements limit size and mass further
- What are the biological reasons for the limitations?
  - Available power (specific power of muscle)
  - Wingspan (strength of bones or wing materials)



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

Engineering Manifestations of Power Requirements

- Power requirements constrain the maximum mass capable of hovering
- Imperfect aerodynamics further limit mass

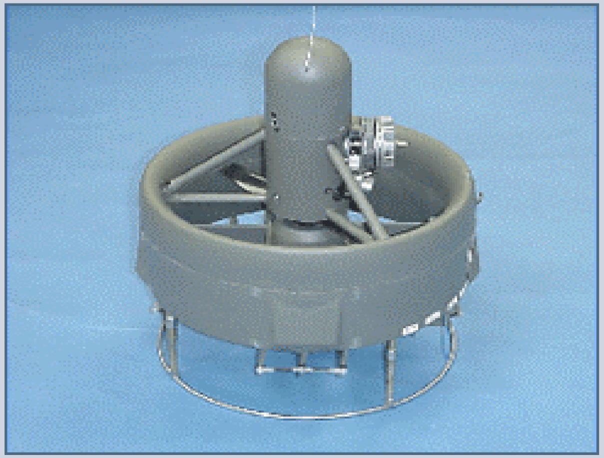


Specific power (based on total mass) required to sustain hovering assuming ideal aerodynamics

Aerodynamics for Birdbrains: Flapping-Wing Propulsion for MAVs?

- **Aerodynamic Efficiency**
  - flapping wings can have large effective "actuator areas" which can producing hovering thrust more efficiently.
  - unsteady effects like dynamic-stall delay and "clap-fling" augment thrust
- **Simple and Robust**
  - low tip speeds and flexible wings can mean less damage or disturbance if collisions occur
- **Stability**
  - a flight vehicle with flapping wings can be easier to stabilize and control than a rotary-wing aircraft.
- **Economy of Design (Multifunctionality)**
  - lifting surfaces and propulsion devices can share a common structure
- **Scalable**
  - aerodynamic benefits and simplicity are more significant at the ultrasmall scales envisioned for future Micro Air Vehicles
- **Stealth**
  - can visually mimic birds, bats or insects.
  - may be quieter (like an owl) or mimic natural sound.

Hummingbirds can cross the Gulf of Mexico non-stop, swoop from a tree to stop on a dime and hover near a flower. Such inspiration from nature suggests that flapping-wing propulsion has many benefits.

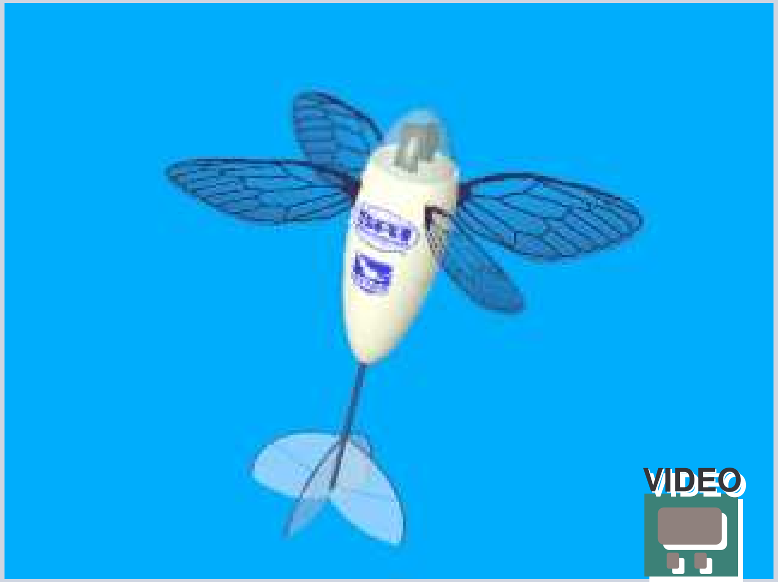


(Source DARPA)

VTOL Ducted Fan
Can Flapping-wing vehicles offer better performance and stealth?

Notional Design Concept of a Hover-capable Flapping-wing MAV – UTIAS Design

- **Ideal for hovering and forward flight**
- **4-Wings (X-wing)**
  - more ‘clap-fling’ and lift augmentation
  - Balanced flapping forces – less vibration
- **One degree-of-freedom actuation**
- **Simple 2-D fabricated wings**
- **Artificial Muscle-based actuation**



“The Double Hummingbird”

Original Notional Design includes the X-wing configuration and artificial muscle actuation

UTIAS

Wing Design: Simple 2D Design

Design Features:

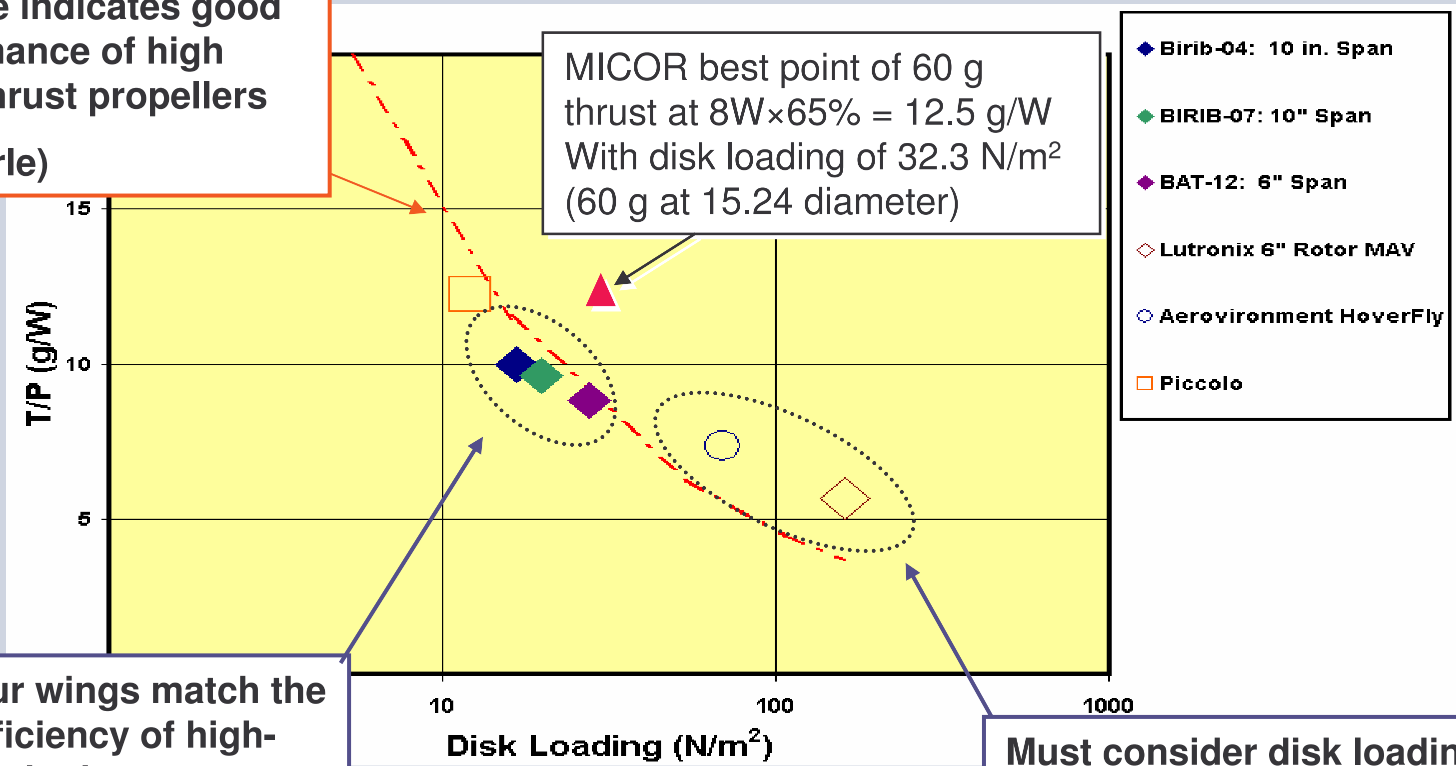
- **Aero-Elastically Tailored:**
  - Stiffness of spar elements custom tailored
  - Wing deforms in response to aerodynamic loads
  - Allows simple, 1 DOF kinematics
- **Rapid Manufacturing and Refinement:**
  - Wings can be batch processed for time effective manufacturing and consistency
  - Constructed from multiple strips of carbon pre-preg
  - Wing stiffness can be modified without re-tooling
  - “Flat” wing is symmetric about vehicle centerline - no right or left-handed wings

Aerodynamic Efficiency: The Key Metric

Red line indicates good performance of high static thrust propellers

(Hepperle)

MICOR best point of 60 g thrust at 8W×65% = 12.5 g/W With disk loading of 32.3 N/m² (60 g at 15.24 diameter)



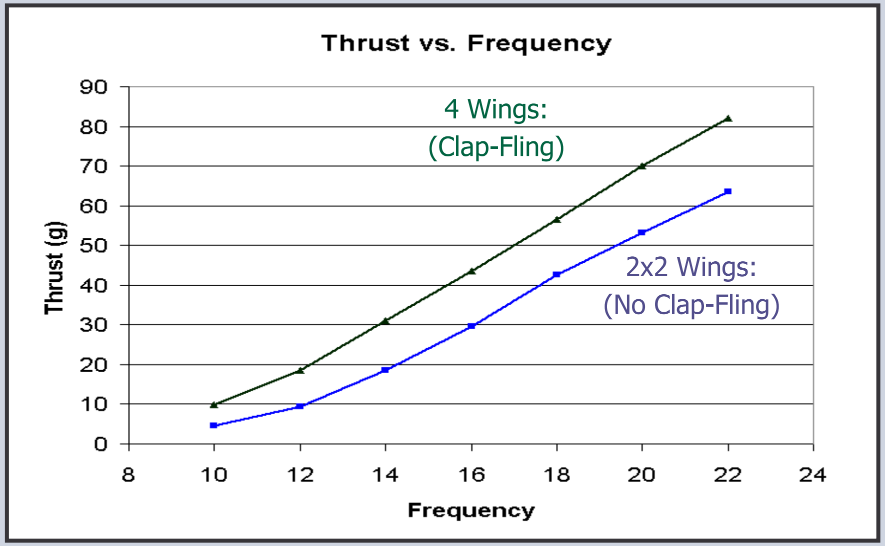
Our wings match the efficiency of high-static-thrust propellers

Must consider disk loading when comparing efficiency to other hovering aircraft

- With limited development effort, flapping-wing flight already seems comparable to best conventional rotorcraft
- Can exceed rotorcraft performance within 1 year?
- Already superior at smaller scales?

Nature's Tricks

- **Flapping wings allow for good aerodynamic efficiency at high disk loading**
  - Dynamic Stall Delay:
    - Local interference effects between wings
    - augment circulation and delay separation
  - Clap-Fling: Nature's After Burner
    - Employed by insects and birds for high thrust maneuvers



Early experiments showed that clap-fling has the effect of increasing both the thrust at given flapping frequency and the T/P ratio for the same disk loading

Mentor: Fuel-burning Radio Controlled Testbed

Vehicle Specifications

Size/Weight:

Weight (Wet):	550 grams
Size - Assembled:	11” x 11” x 14”
Size - Packed :	6” x 6” x 14”

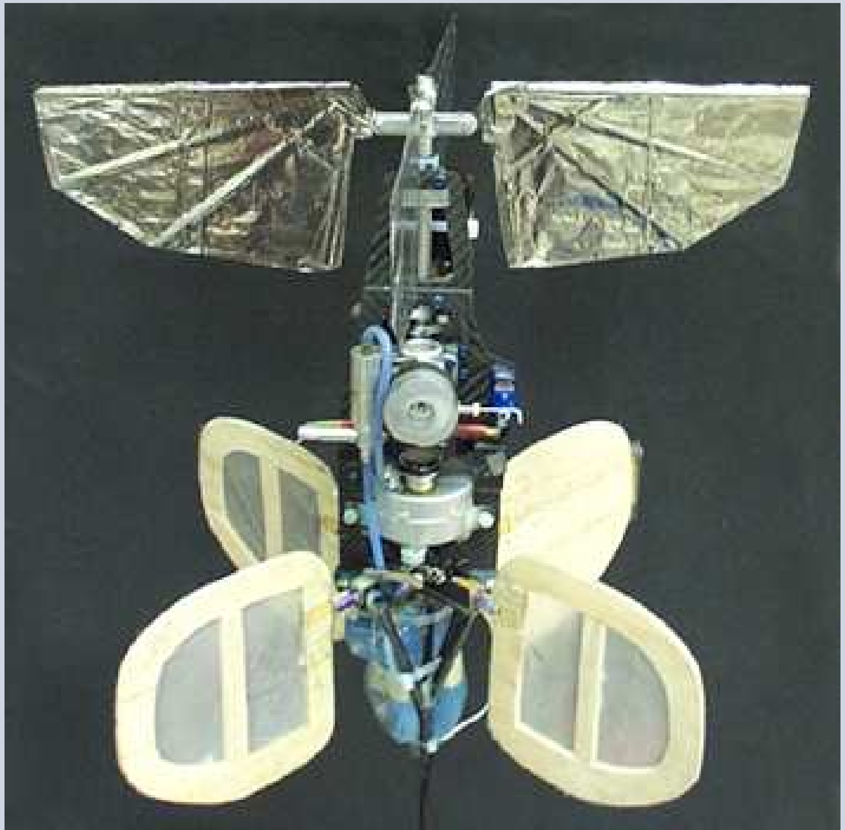
Performance:

Peak Thrust:	590 grams
Thrust to Weight Ratio:	1.07
Thrust/Power Ratio at Hover	5.6 g/W
Hover Duration (100% Power)	8 min. with 50g fuel
Payload Capacity:	30 to 70 grams

Power required (hover): **98 W**

Mass Breakdown:

Power Plant:	= 140 g
Fuel and Tank:	= 75 g
Transmission:	= 80 g
Airframe, & Wings:	= 170 g
Receiver and Batteries:	= 35 g
On-Board PLC Controller With 3- axis Gyros	= 40 g
TOTAL	= 550 g



Mentor
Superfly 2.5

MENTOR – The World's First Hovering Ornithopter

- Vehicle has hovered for more than 1 min
- Routine, stable, hovering flights
- Vehicle carries 6 min of fuel (at hover power)
- Still need to improve altitude control

B O W N

One of the top 100 in *Popular Science's* "Best of What's New" (December 2002)

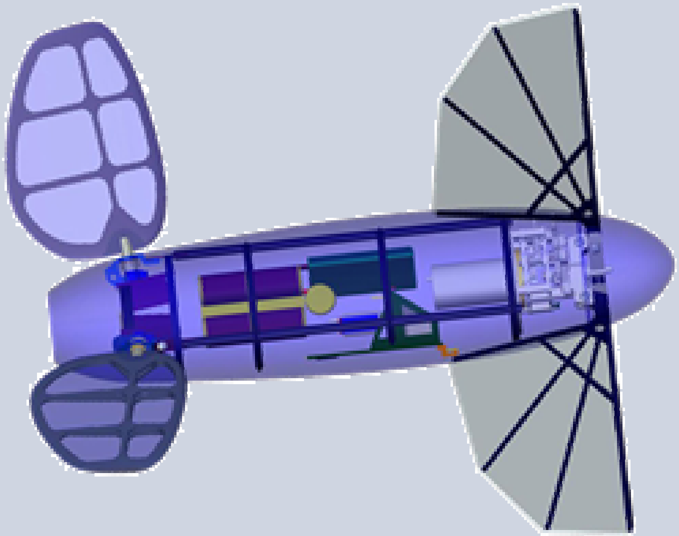
UTIAS

Electric Hovering Flights

- **Short duration hovering flights have been achieved with battery power (NiCad)**
- **Weight savings and specialized batteries can allow much longer range/duration and/or increased payload capacity**
- **Aerodynamic noise due to wing slap is significant**
  - New wing materials and designs can be quieter

Preliminary Verification of Forward Flight Stability

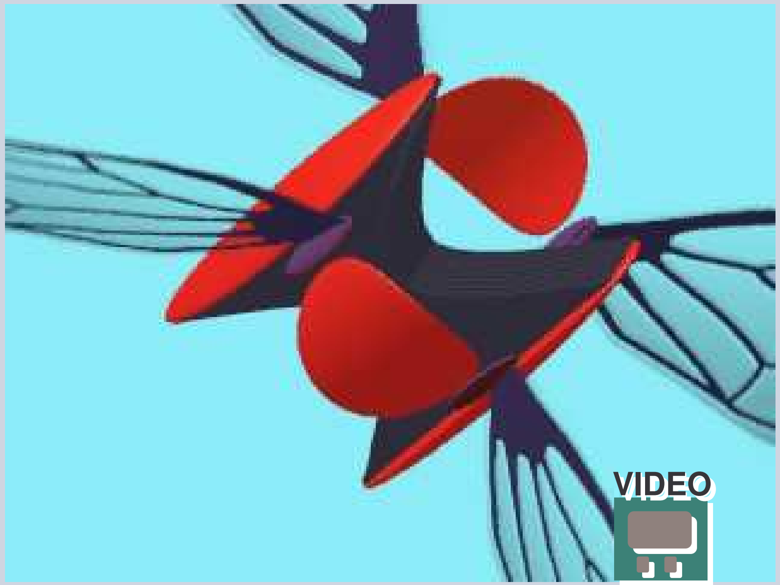
- **Stable forward flight was demonstrated**
  - Active roll stability augmentation
  - Enlarged tail surfaces seen here are not expected to be needed in future versions
  - Electric powered
  - Radio controlled



Better Actuation through Biomimicry?

- Does it make sense to go from energy source to rotary to flapping?
- Can a biologically-inspired actuation mechanism using artificial muscle be better?

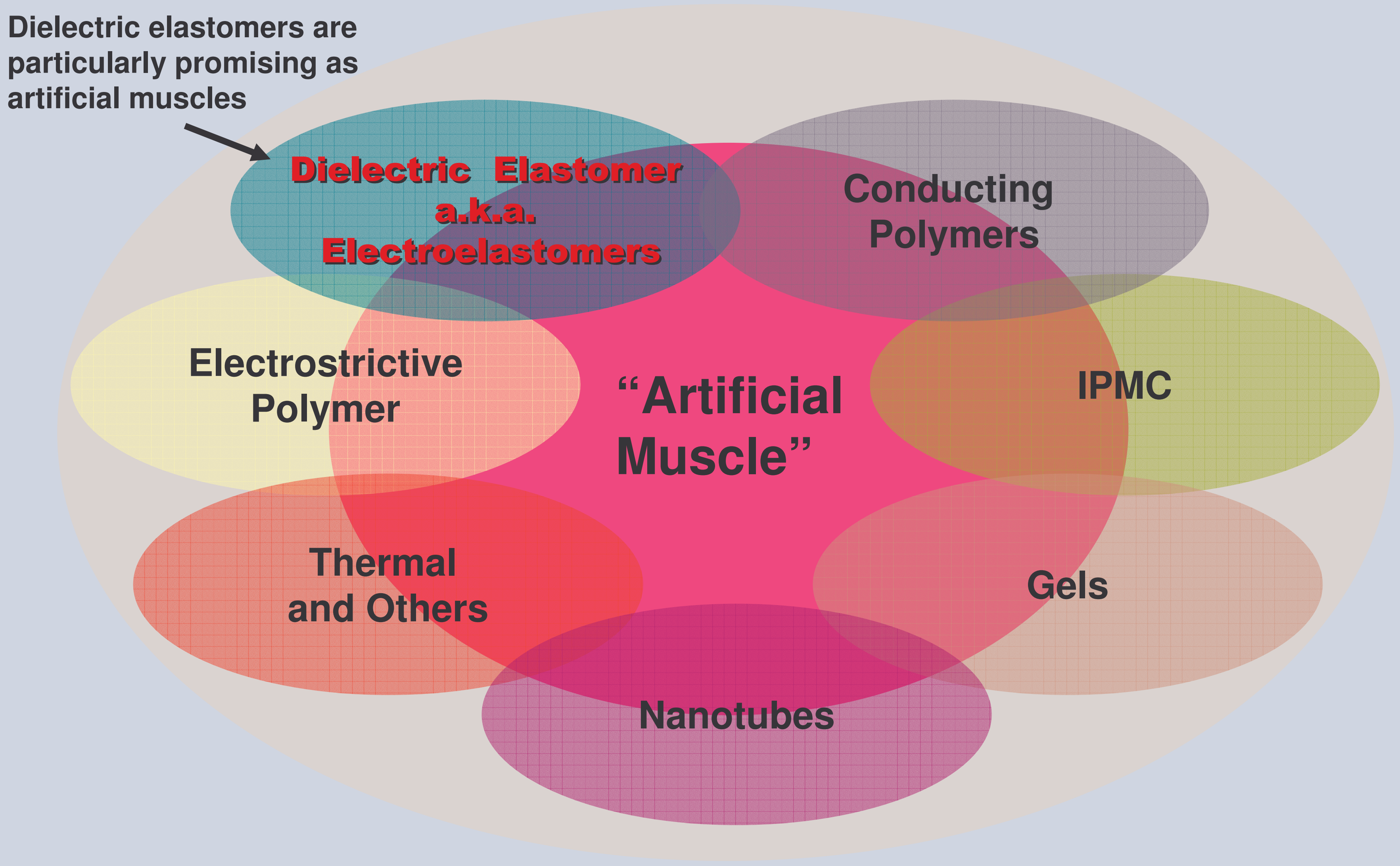
vs



What if we had Muscle-like Actuators

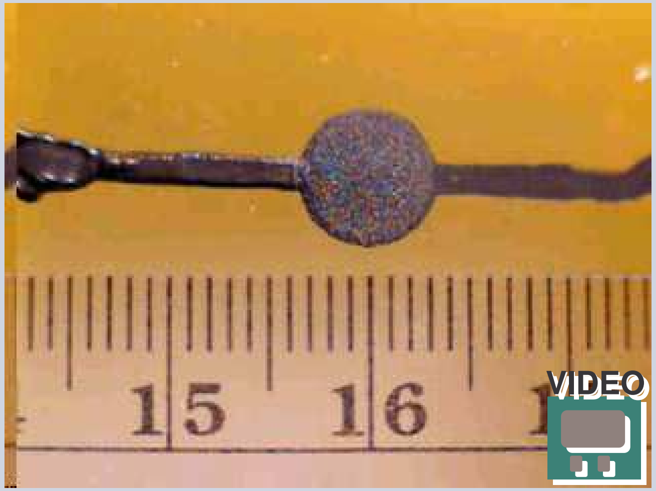
- **Simple, lightweight and efficient direct-drive mechanisms**
- **Quiet!**
- **Inherent elastic energy storage (resonant operation) for greater efficiency**
  - "Springs for Wings" (Alexander, Dickinson)
- **Scale well to smaller sizes unlike electric motors and engines which become less efficient**
- **Low cost**

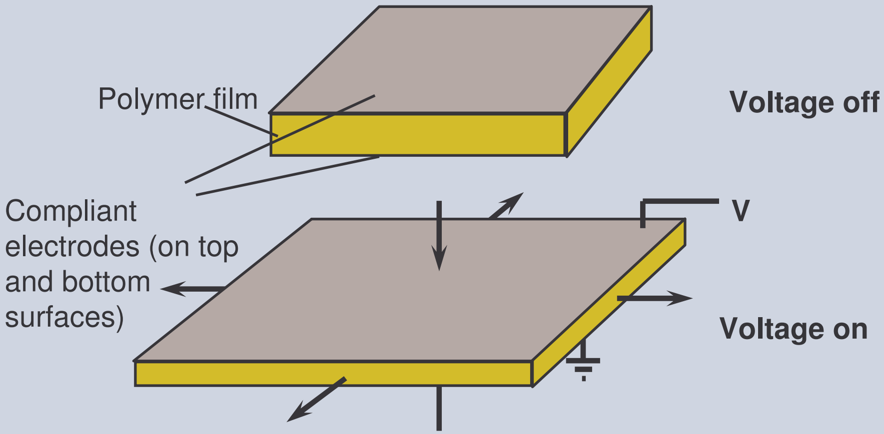
Electroactive Polymer Artificial Muscle



Dielectric Elastomer Artificial Muscle: What is it?

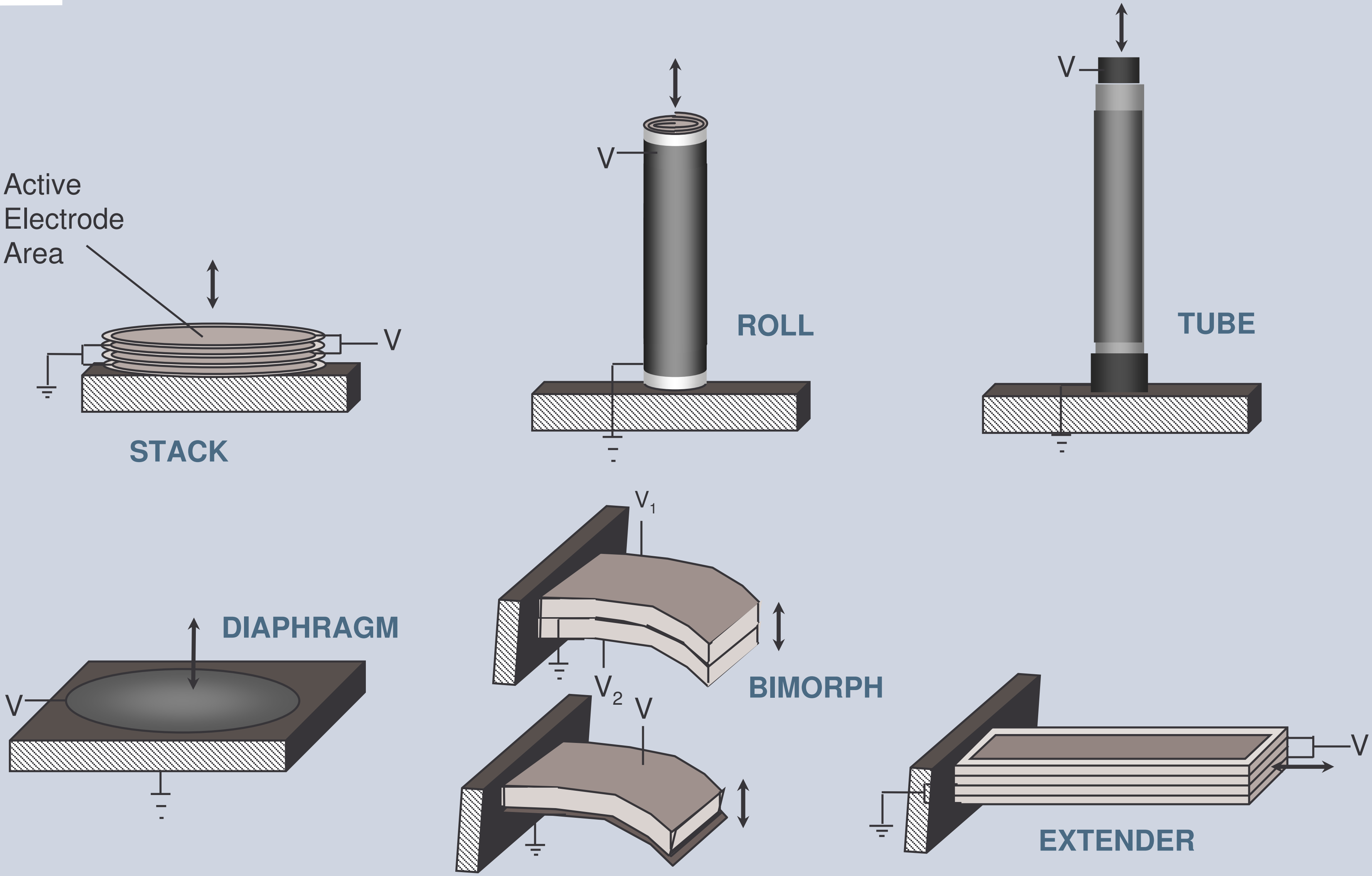
- Polymer film sandwiched between compliant electrodes and acts as as a dielectric (insulator)
- The incompressible polymer expands in area when a voltage is applied
- Similar in operation to piezoelectrics, but with greater than 100x movement





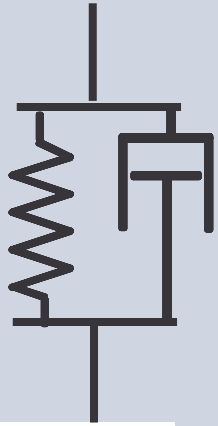
Basic functional element

Many Possible Configurations



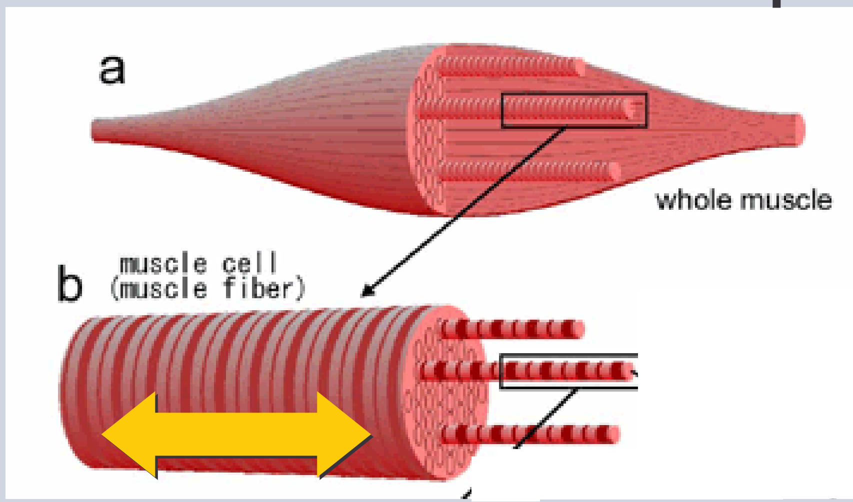
EAPs as Artificial Muscles?

- EAPs can behave a lot like a muscle
- Muscle is a spring-damper system and sensor in addition to a motor



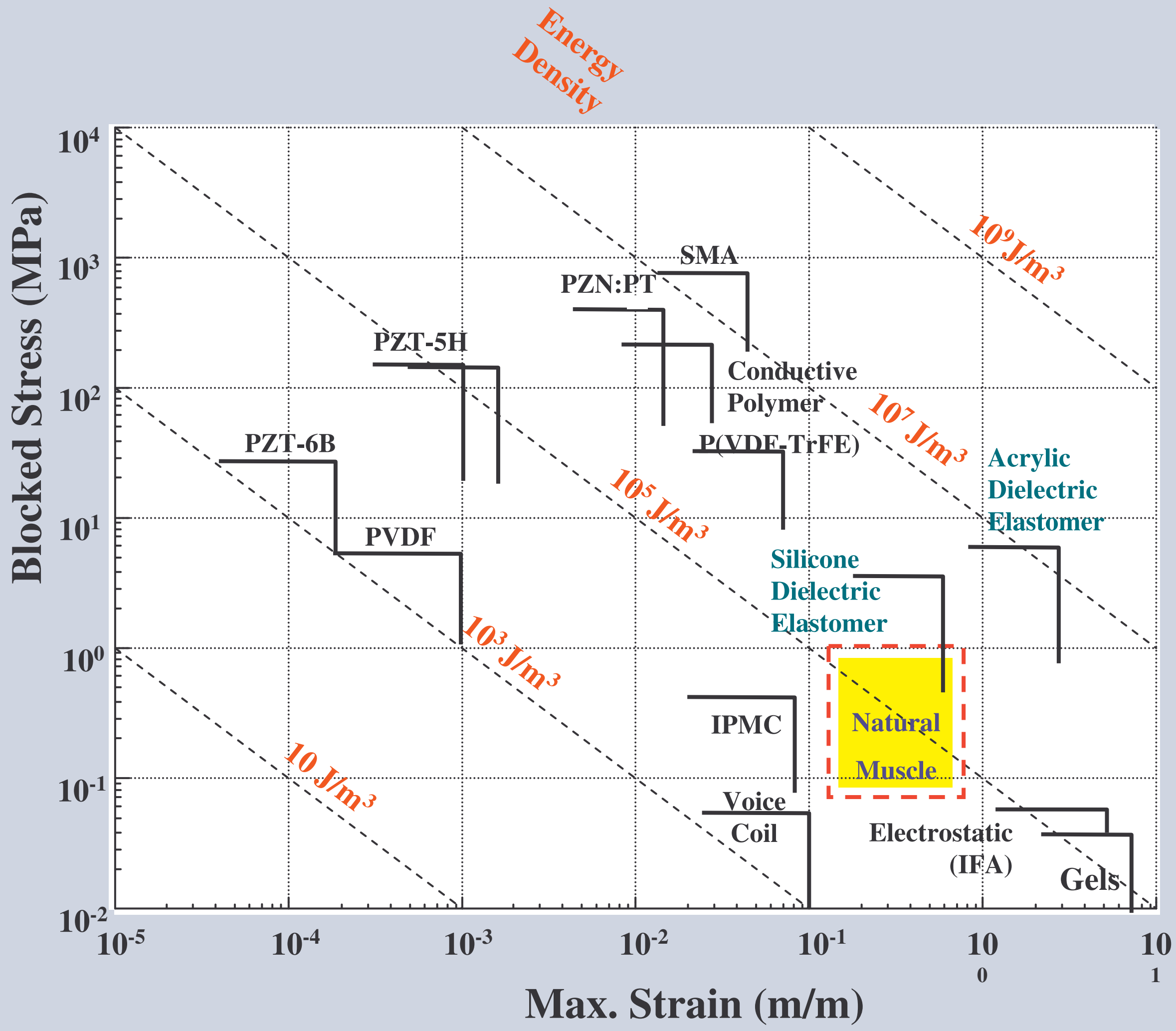
MER Rolled actuator

VIDEO



Natural Muscle

Actuator Performance Comparison - Stress vs. Strain



- Fewer materials have the stress-strain characteristics of natural muscle that allows for simple direct-drive flapping-wing actuation

Source: DARPA and SRI International

Efficiency Matters Too

- Muscle efficiencies (chemomechanical) are estimated to be from 10–20% for flight muscles (e.g., Josephson, Wells, Dickinson).
- Electric field activated materials have the most promising overall performance

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	

Advanced Robots and Prosthetics

- Muscle-like actuation suggests a new generation of highly dexterous anthropomorphic robots or prosthetic devices

EAPs replicate behavior of natural muscles

VIDEO

Full-size skeleton model with "bicep" actuator

VIDEO

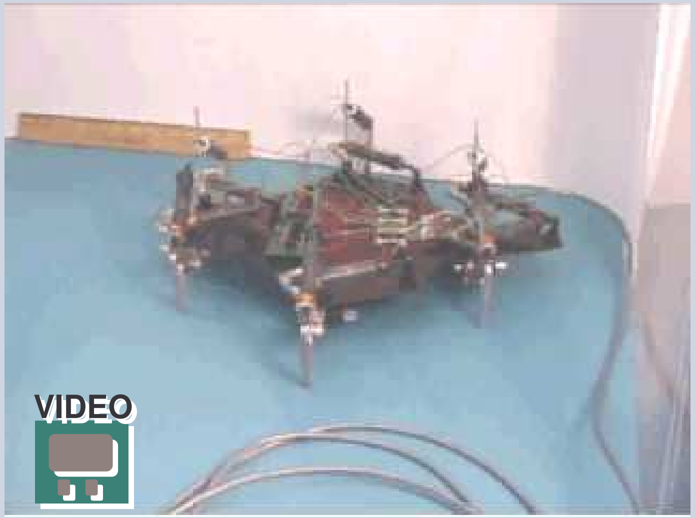
3-fingered hand with tendon driving "forearm" actuators

Insect-like Robots

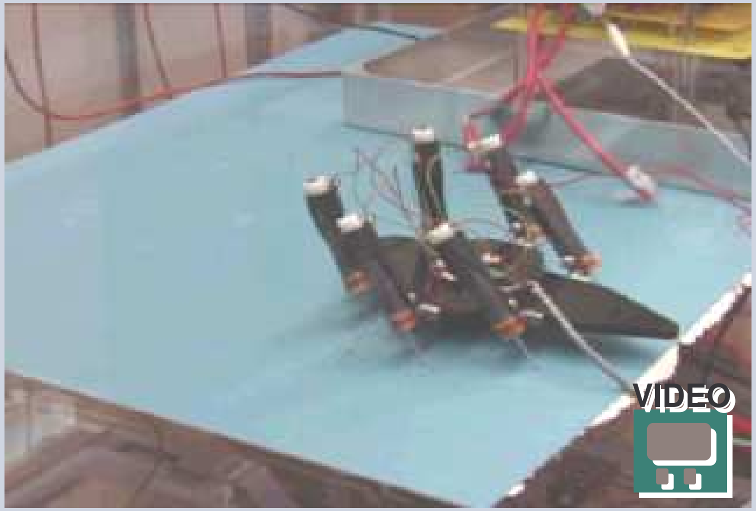
- Goal is to extract key features from biology to create simple yet robust walkers

The Inspiration - robust and mobile

EAPs replicate behavior of natural muscles – even small ones



Flex - ONR Robot



Skitter - DARPA Robot

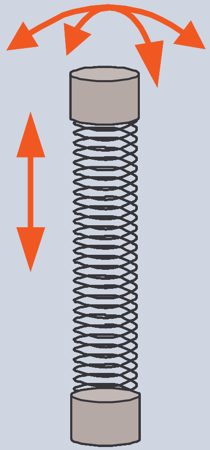
Multi-DOF Rolled Actuators

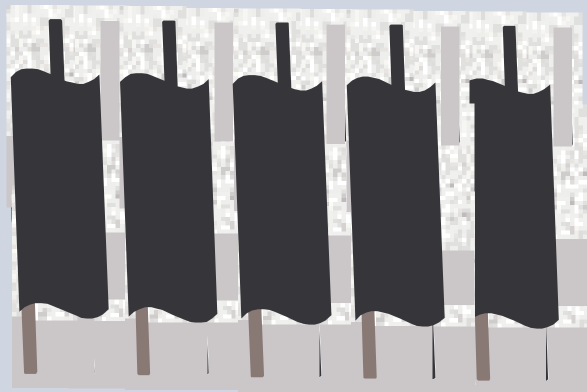
- Multiple-DOF structures with a single monolithic structure by patterning electrodes
- Scalable to insect size

2-DOF Roll

EAP is multifunctional – structure, actuation, and sensing

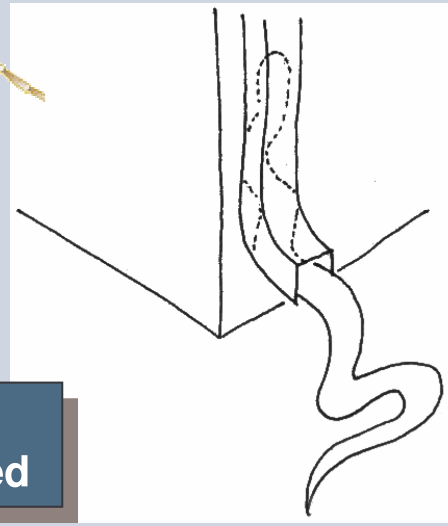
3-DOF Roll





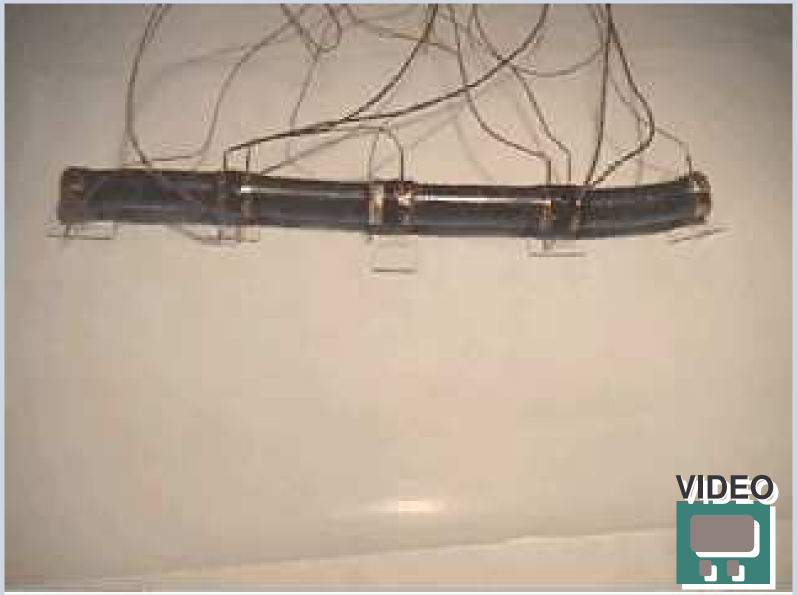
Crawl and Slither

- Multi-DOF actuator can makes a very simple robot structure with biomimetic motions
- Small insect and worm like robots can access almost anywhere or achieve great dexterity



Simple, rugged, highly articulated

MERbot Walker



4-Link “Snake” or “Tentacle”

Dynamic Micro Robots

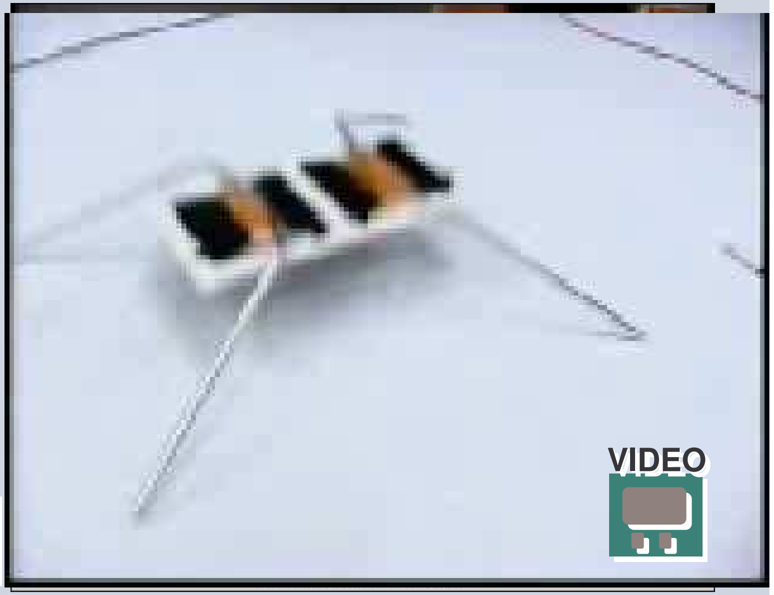
- Beginning to make small robots that can mimic the dynamic gaits of biological creatures like insects

High strain, energy, peak power and compliance of EAPs achieves hopping gait

2D fabrication is simple, scalable and can integrate with electronics – "a robot per day"

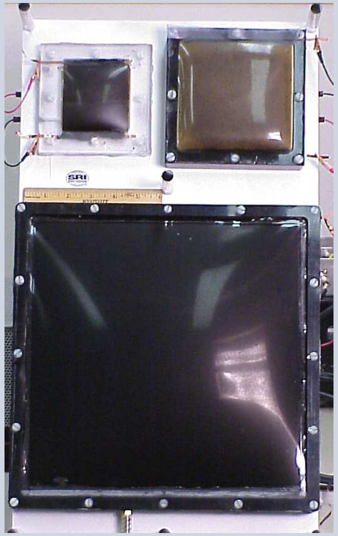
Very preliminary locomotion is impressive

Framed Actuator is the basis of flat simple robots



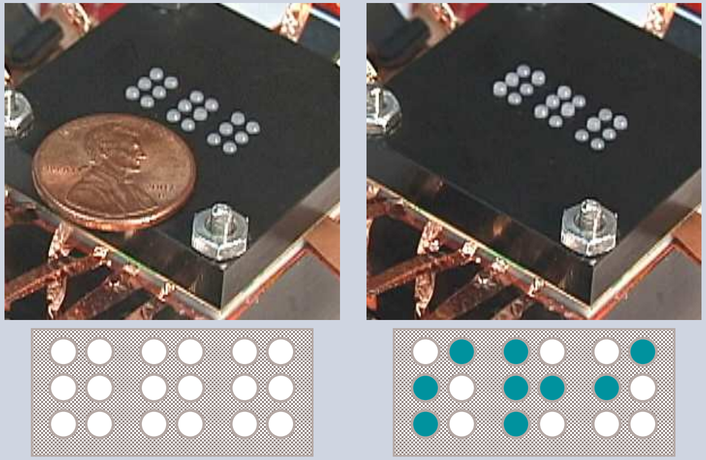
A joint effort with Anita Flynn of MICROPROPULSION

....Pumps and Bumps....



Low-profile, lightweight loudspeakers with no metal

3-cell Proof-of-principle Braille display

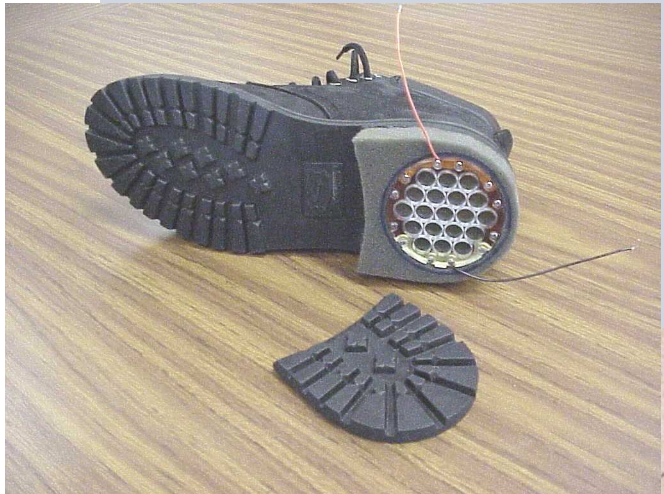


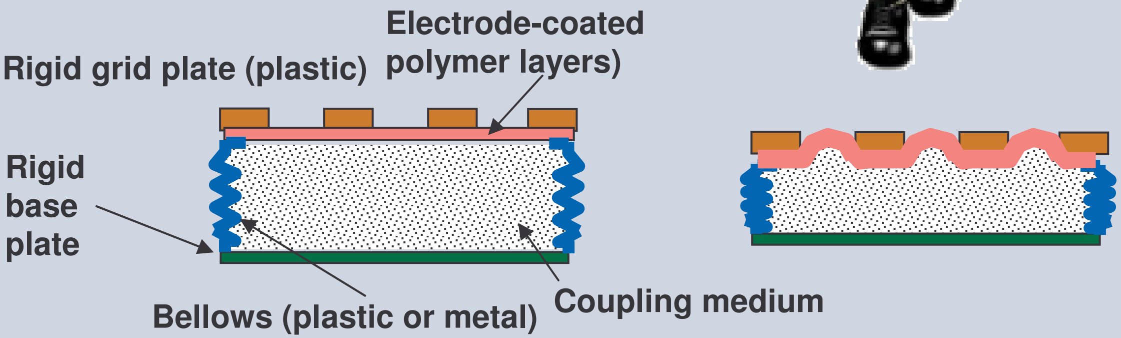
Enhanced Thickness Mode can control surface texture for a variety of applications

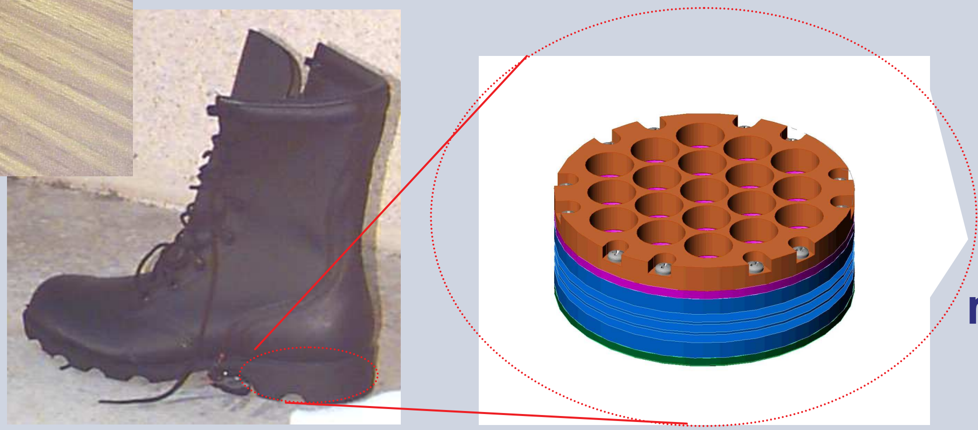
Acrylic diaphragm actuator showing large out-of-plane motion in response to an applied voltage.

DARPA Heel-strike Generator

- Dielectric elastomers operate in reverse as a generator
- Captures “free energy” of walking
- Demonstrated up to 0.8 J per heel strike
- Powered night-vision goggles





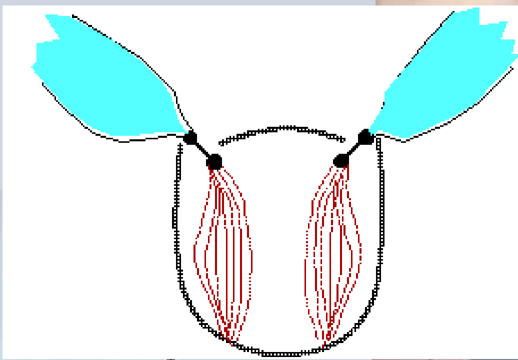


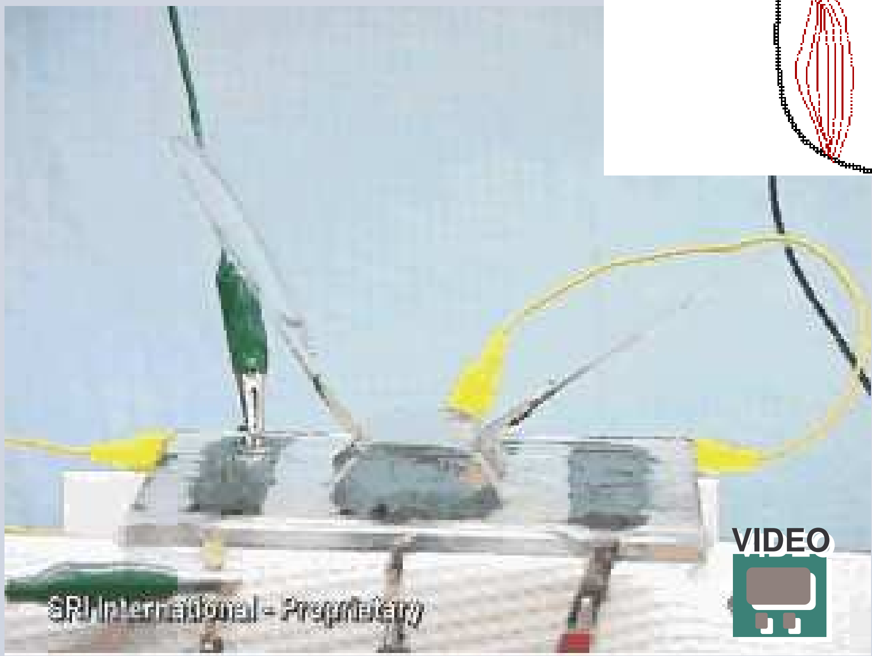
Heel-Strike generators are expected to produce 1W of power under normal walking conditions

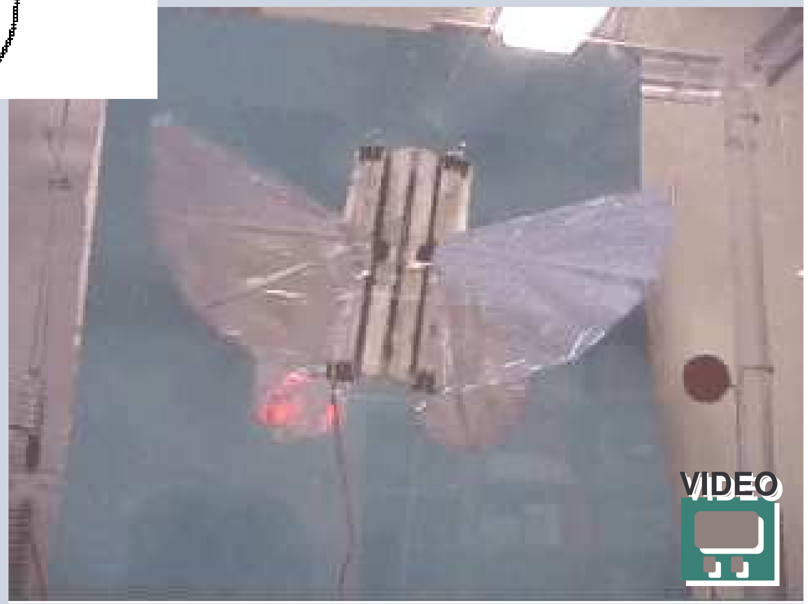
Muscles Mechanisms for Flapping

- Several muscle-based flapping mechanisms were demonstrated
- Simple T-flex mechanisms are inspired by insect flyers

Insect muscles flex the thorax to which the wings are attached







Systems Comparisons

- Biological creatures have good duration
- Fuel-burners are still the best synthetic flyers but battery-powered systems are narrowing the gap because electric actuation can be efficient

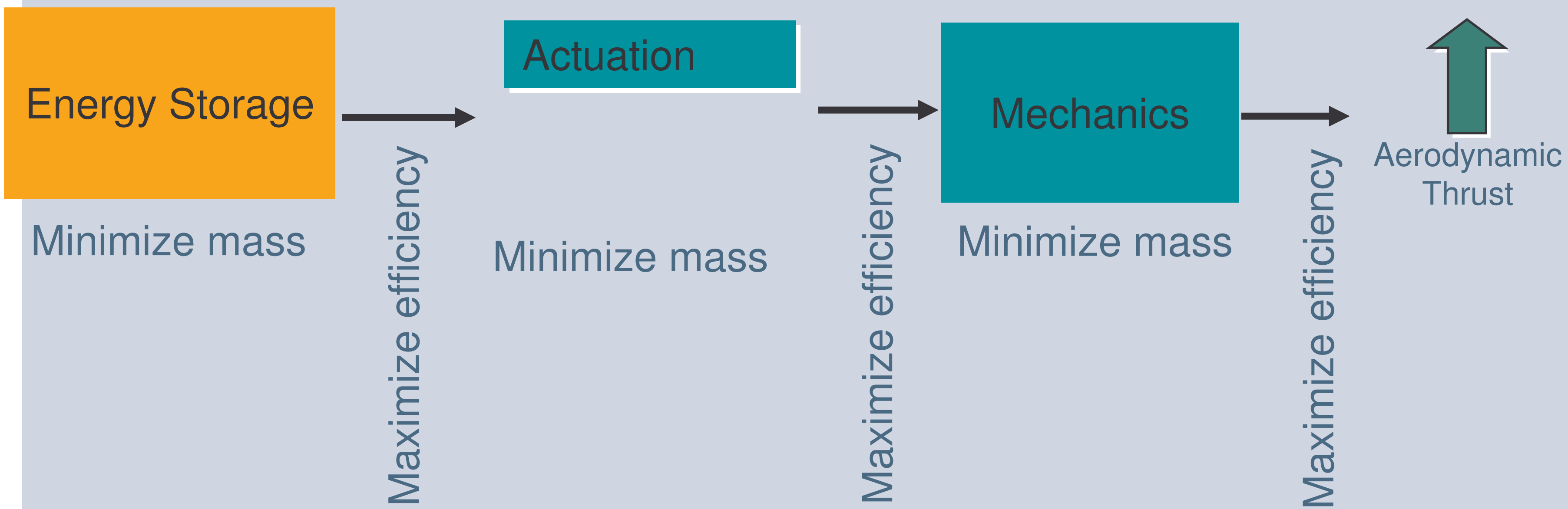
Primary Source	Specific Energy (MJ/kg)	Conversion Efficiency	System Specific Energy (MJ/kg)
Protein (e.g., meat)	4	10% (muscle)	0.4
Carbohydrates (e.g., honey)	15	10% (muscle)	1.5
Fat (e.g., vegetable oil)	36	10% (muscle)	3.6
Hydrocarbon Fuel (e.g., diesel, gasoline)	42	5-20% (engine, turbine or fuel cell/motor)	2.1 to 8.4
Rechargeable Battery (e.g. lithium metal)	0.5	20-80% (motor, piezo or electrostrictor)	0.1 to 0.4
Non-rechargeable Battery (e.g., lithium vinyl chloride)	2.4	20-80% (motor, piezo or electrostrictor)	0.48 to 1.9

Source: H. Tennekes, *The Simple Science of Flight*

Ruby-throated hummingbird crosses the Gulf of Mexico (30 hr flight) without "refueling" suggesting that biological energy sources and muscle can be an efficient system

A Systems Viewpoint

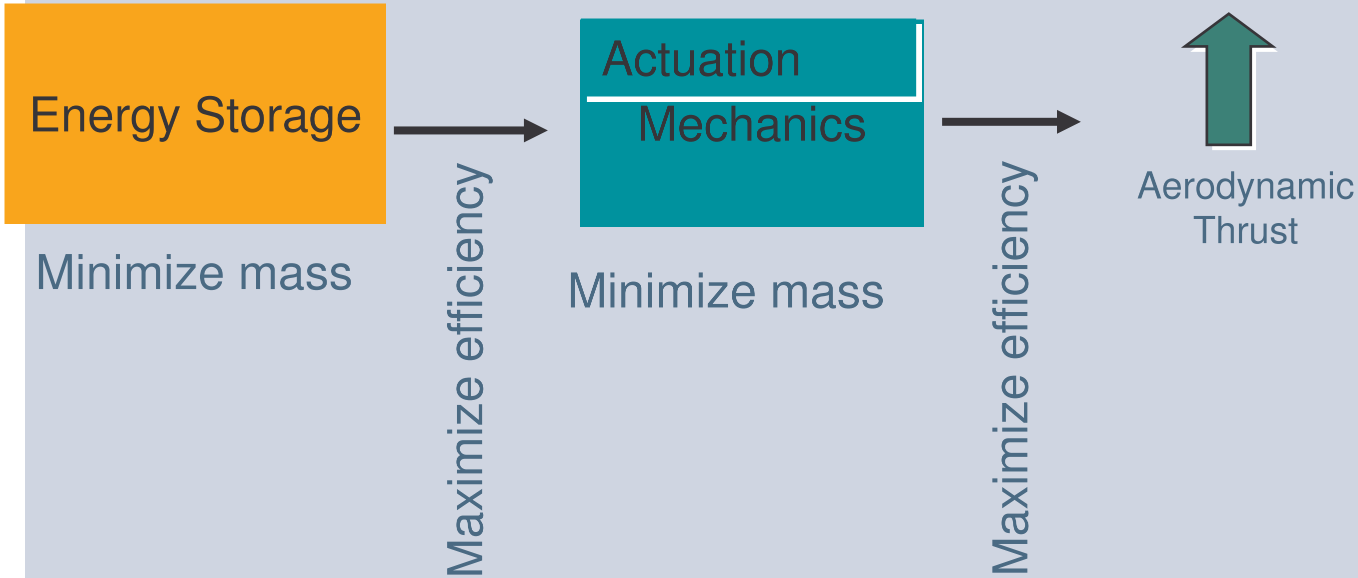
- Many factors determine the best propulsion system
- For longest mission duration and improved performance we wish to minimize mass and maximize efficiency at each step



3 Components

Fuel-burning Muscle?

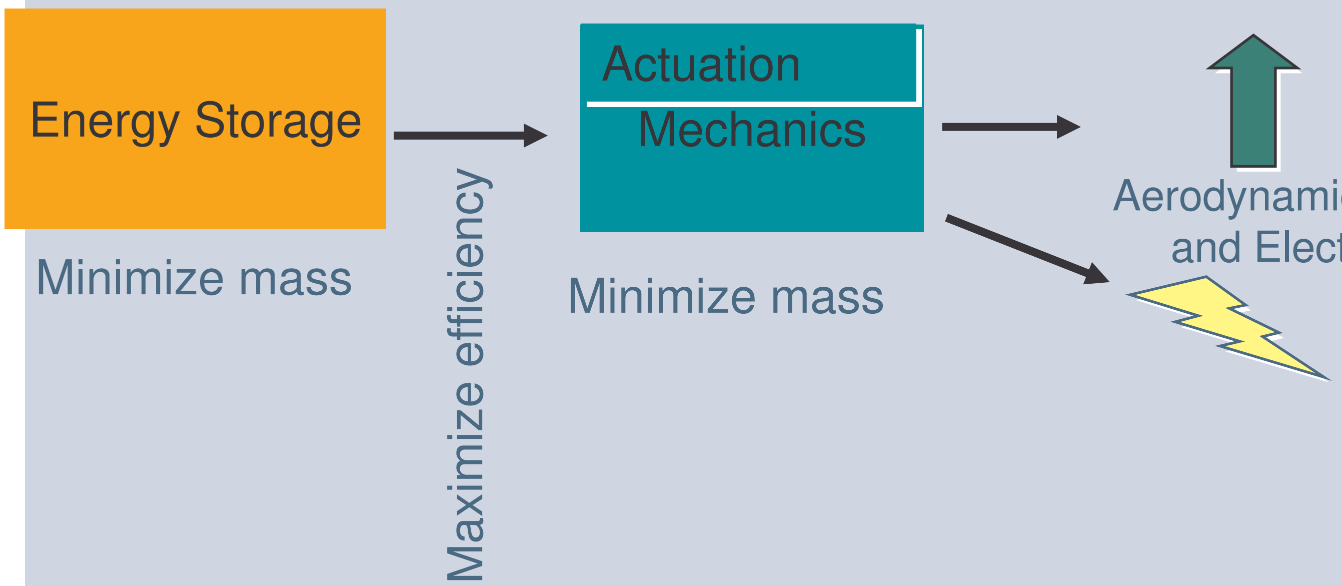
- What if we could go straight from fuel to mechanical motion?
- High energy density of fuel combined with lower mass and greater efficiency than conventional high-speed rotary engine mechanisms
- A natural fit for powering flapping wings



2 Components

Hybrid Power Output: More than Muscle

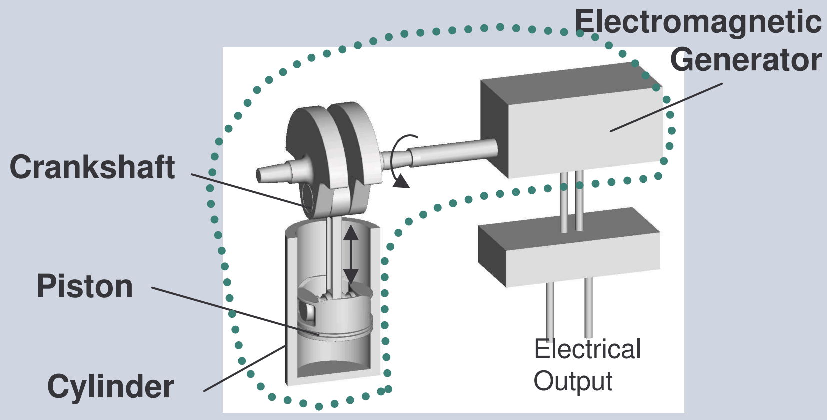
- MAVs (as well as other vehicles and robots) require both mechanical and electrical power
- Polymer engine with EAPs can further eliminate components



2 Components + 2 Outputs

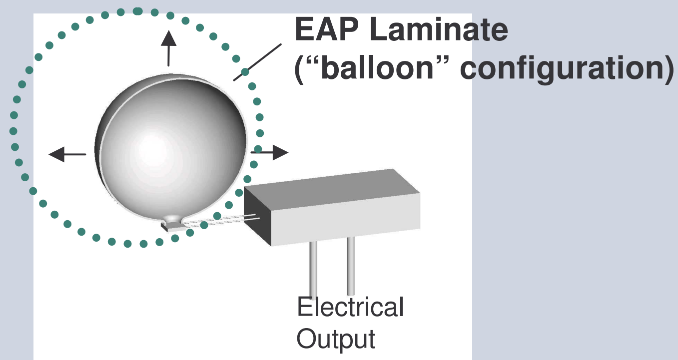
Polymer Engines: General Motivation

- **Expandable polymers replace metal piston-cylinder or turbine**
- **Eliminates many current limitations of small engines:**
  - Excessive heat loss
  - Piston-cylinder leakage
  - Excessive friction losses
  - Opportunity to use resonance and novel thermodynamic cycles
- **Many other advantages**
  - Lightweight; tremendous design flexibility
  - can use EAPs for electricity too (hybrid)
  - Very low cost (disposable engines)
  - Rugged; no tight tolerances or wear surfaces; highly shock tolerant
  - Quiet!



Conventional Generator System

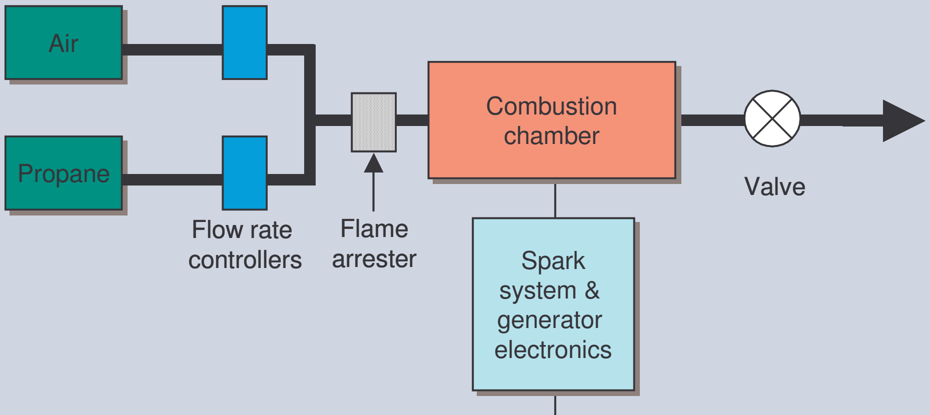
Replaced by

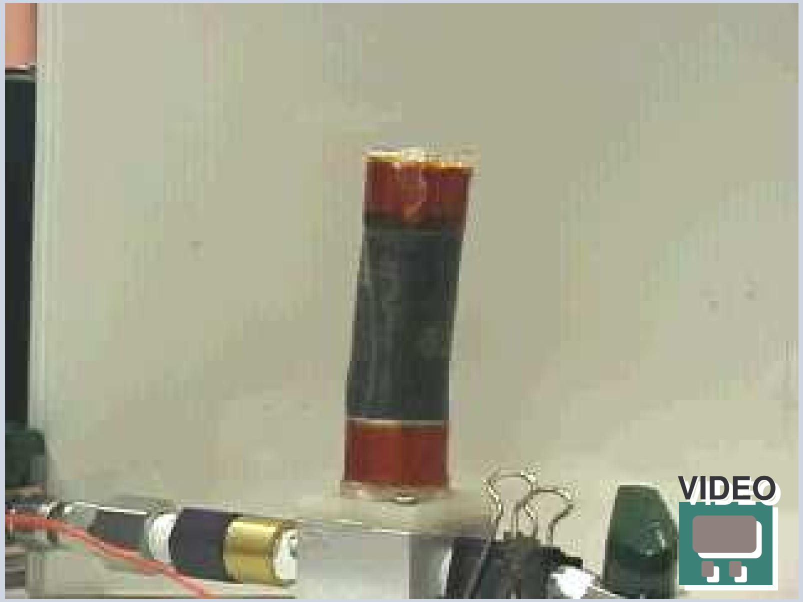


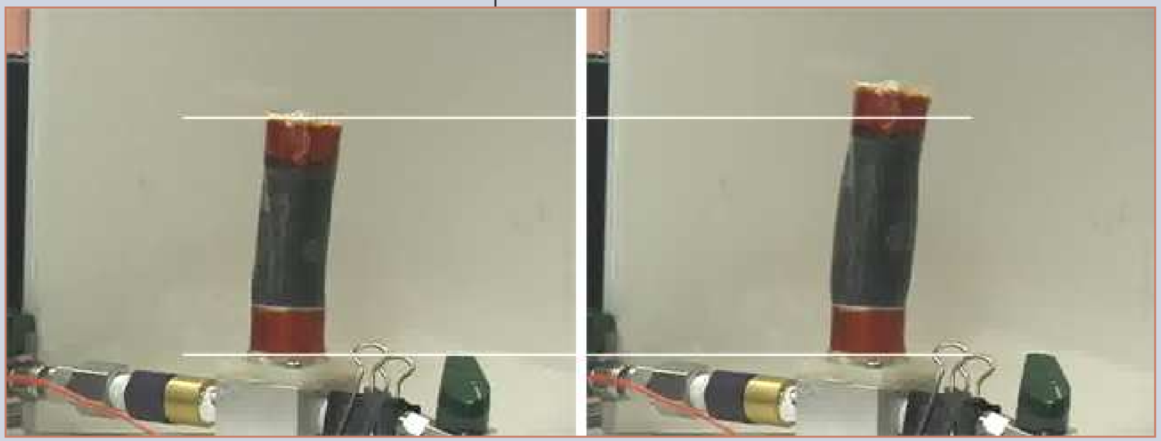
Comparable Polymer Engine System

Polymer Engine: A Fuel-burning Muscle?

- Combustion inside a polymer chamber can reproduce muscle-like motion with minimal mass and complexity



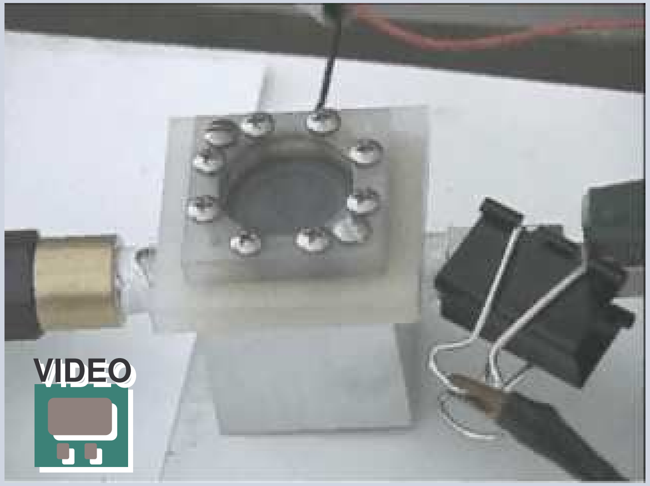




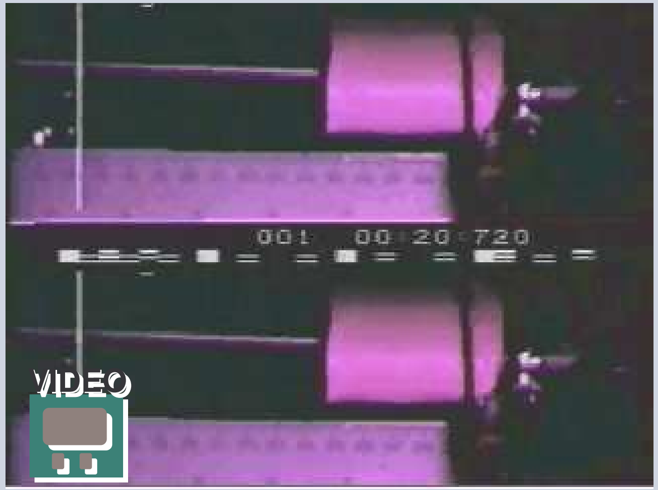
Combustion inside Dielectric Elastomer roll causes linear 23% expansion that could be used for both electrical and mechanical output

Promising Results

- **Polymer engines operated with high temperature combustion gases (>1000 ℃) for over 3 hrs at 3 Hz**
  - Already well beyond energy density of batteries
- **Multiple fuels (butane, propane, hydrogen)**
- **External combustion cycle also demonstrated**
- **Variety of engine configurations demonstrated**
- **Over 10% fuel-to-mechanical efficiency already demonstrated**
  - Better than typical 5% of small engines
- **Significant improvements expected from higher expansion ratios and modified pressure-volume cycles**
- **> 20% efficiency appears feasible**



Diaphragm-based



5 Hz Firing (4X slowed)
Polymer Cylinder

Specific MAV Mission Example

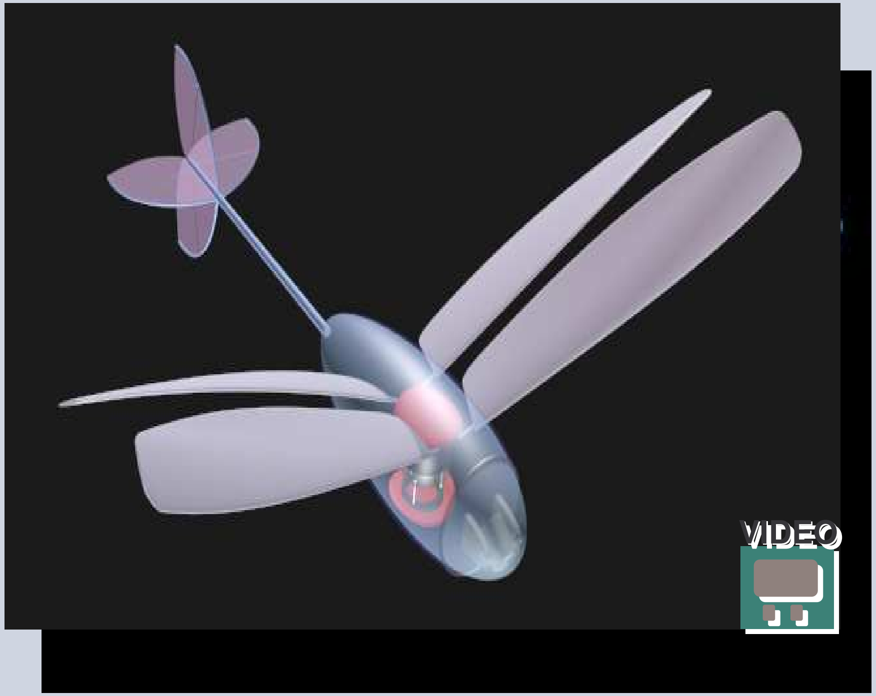
Small Systems Power Plant Comparison (MAV Mission)

	Max System Efficiency (%)	Non-fuel Power Density (W/g)	Subacoustic Operation?	Range of Fuels?	Relative Mission Duration
Polymer Engine	**24**	**3.8**	**Yes**	**Yes**	**4**
Metal Engine + Generator	5.7	1.7	No	Yes	1
Fuel Cell + Electric Motor	24	0.04	No	No	1
Battery + Electric Motor	80	1	Yes	No	1

Systems Solution: Integrated Polymer Engine-Flapping-wing MAV

- Directly couples to flapping-wing flight (no linear-rotary conversion)
- Can also produce electrical energy for navigation, stability, sensors etc. (no mechanical to electrical conversion)
- Lightweight, quiet (low frequency operation), greater overall efficiency

Dragonfly style Flapping-wing MAV with direct-flapping engine



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