Robotic Bees: Operation Overview and Autonomy-Enabling Technologies

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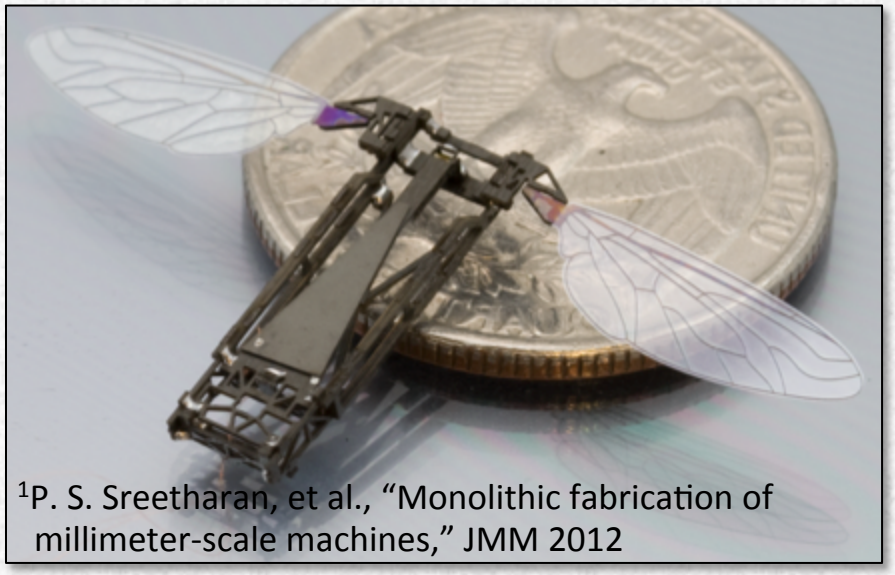
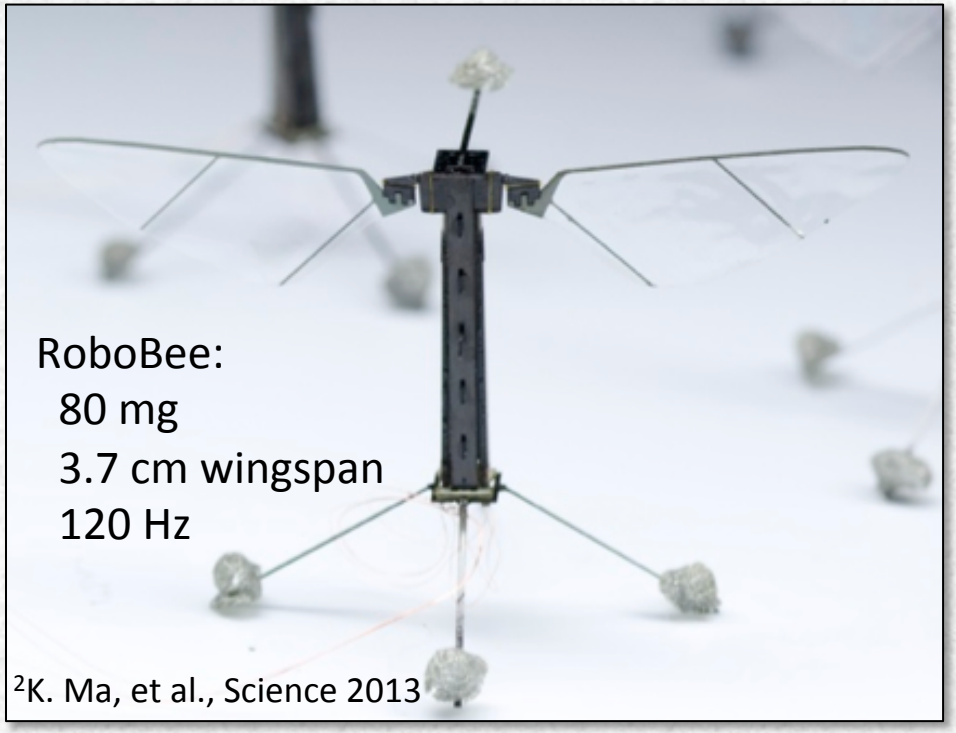
What are RoboBees?

Honey bee: ~100 mg
0.9-2 cm wingspan
200-230 Hz

Hoverfly: ~1-3 cm wingspan
~100-150 Hz



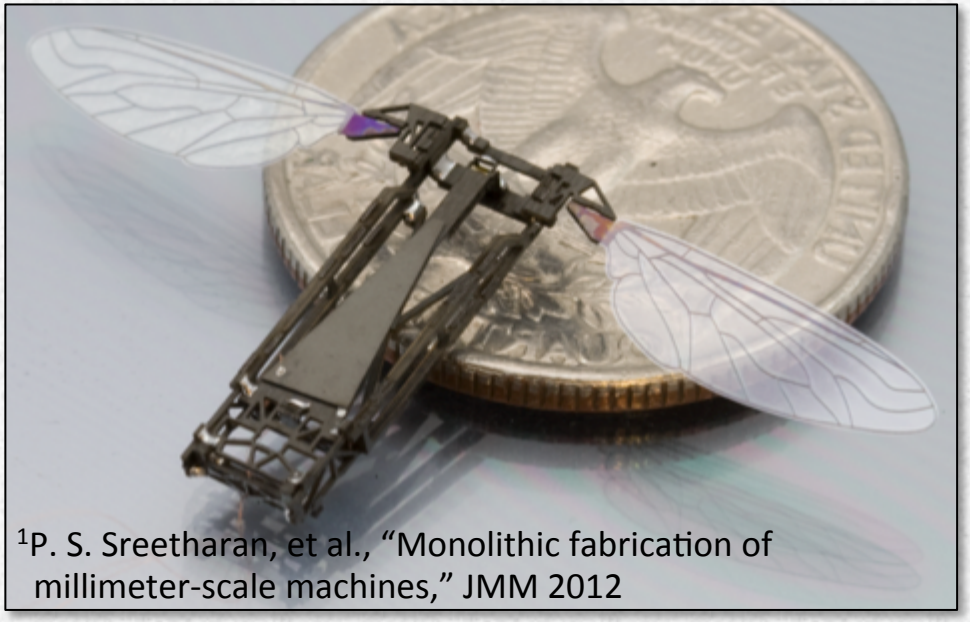
[1]P. S. Sreetharan, et al., "Monolithic fabrication of millimeter-scale machines," JMM 2012



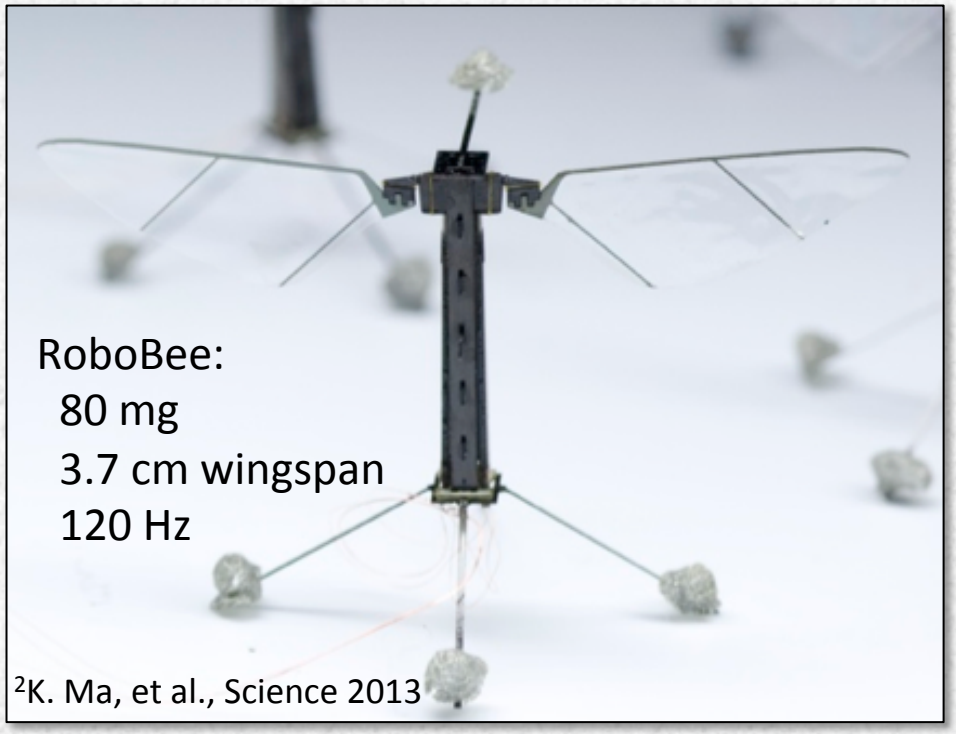
[2]K. Ma, et al., Science 2013

What are RoboBees?

Hoverfly:
~1-3 cm wingspan
~100-150 Hz



[1]P. S. Sreetharan, et al., "Monolithic fabrication of millimeter-scale machines," JMM 2012

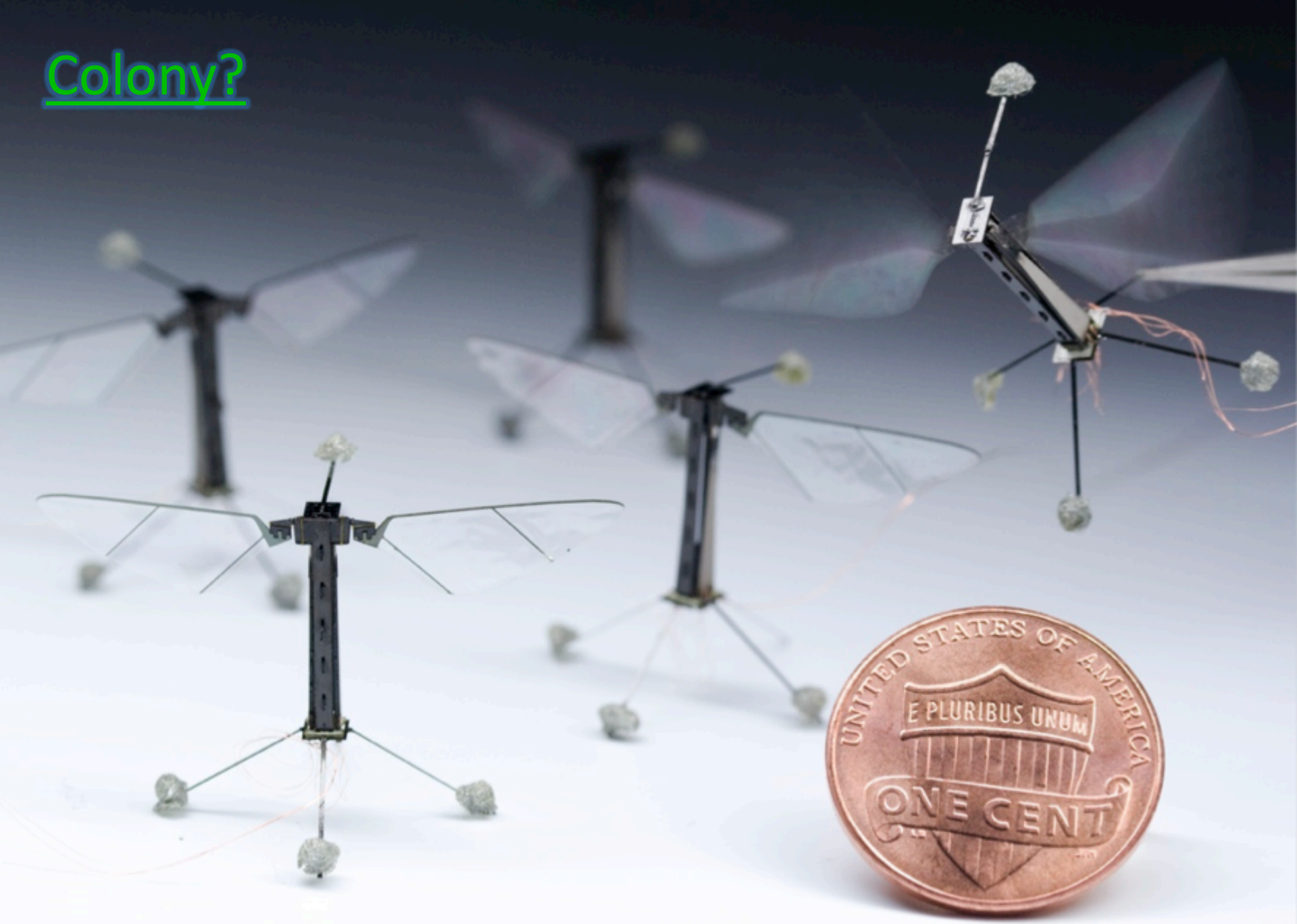


RoboBee:
80 mg
3.7 cm wingspan
120 Hz

[2]K. Ma, et al., Science 2013

Colony?

Colony?



[1]K. Ma, et al., Science 2013

Applications

Crop pollination

Search and rescue

Archaeological excavation

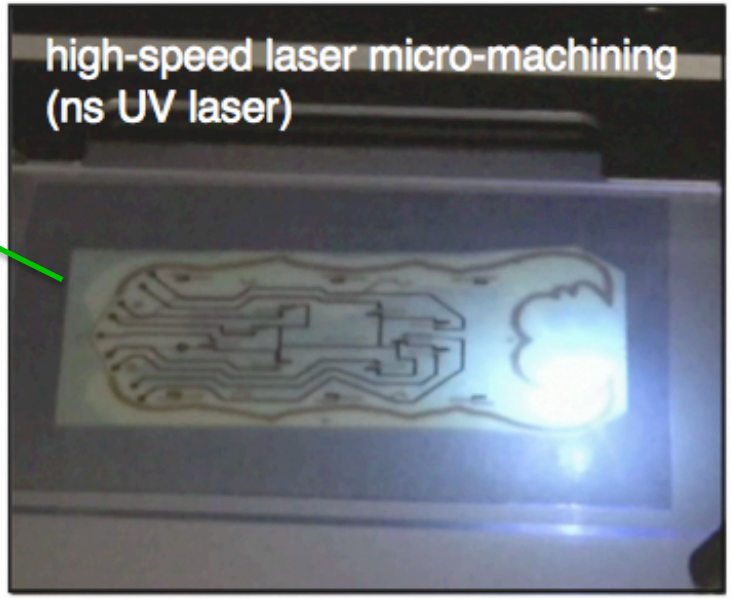
Outline

- Overview
  - Manufacturing process
  - RoboBee operation
- Towards autonomy
  - Sensors
  - Power
  - Actuators
  - Scaling

“Printed-Circuit MEMS” (PC-MEMS) Manufacturing Process:

“Smart Composite Microstructures” (SCM)

1



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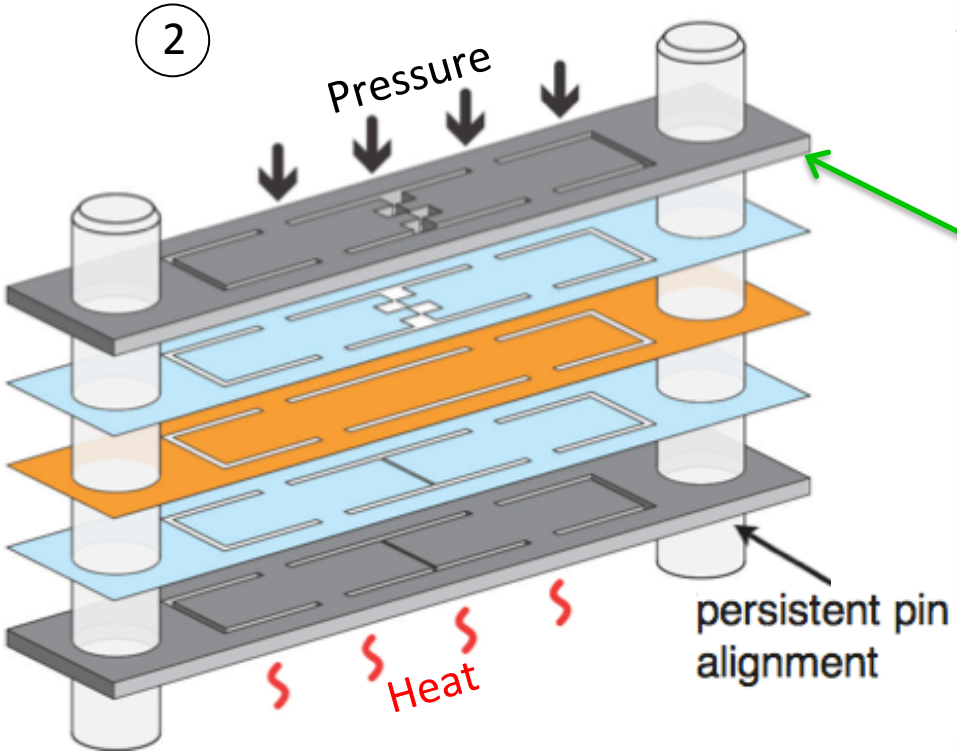

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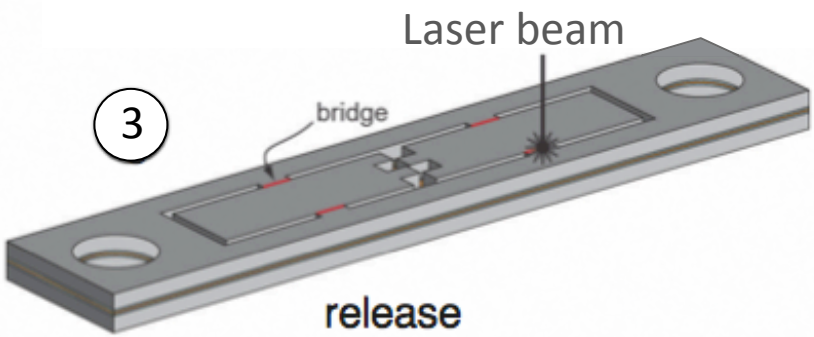

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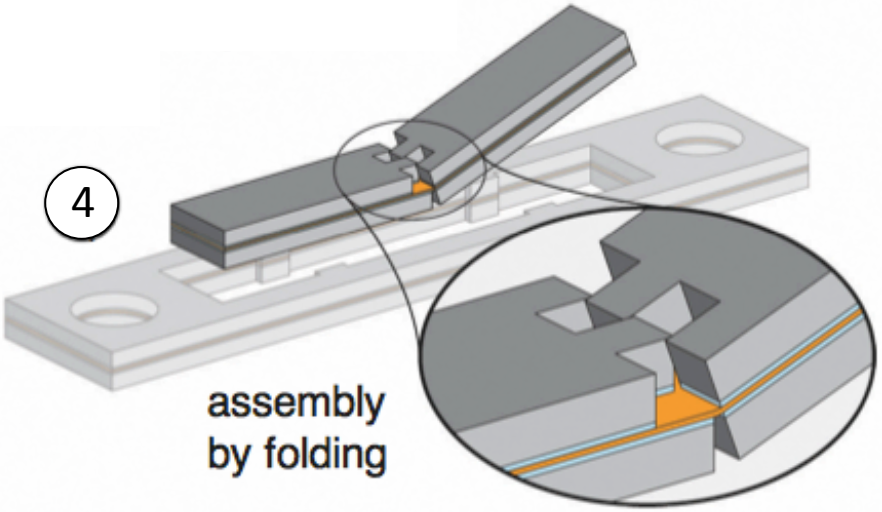
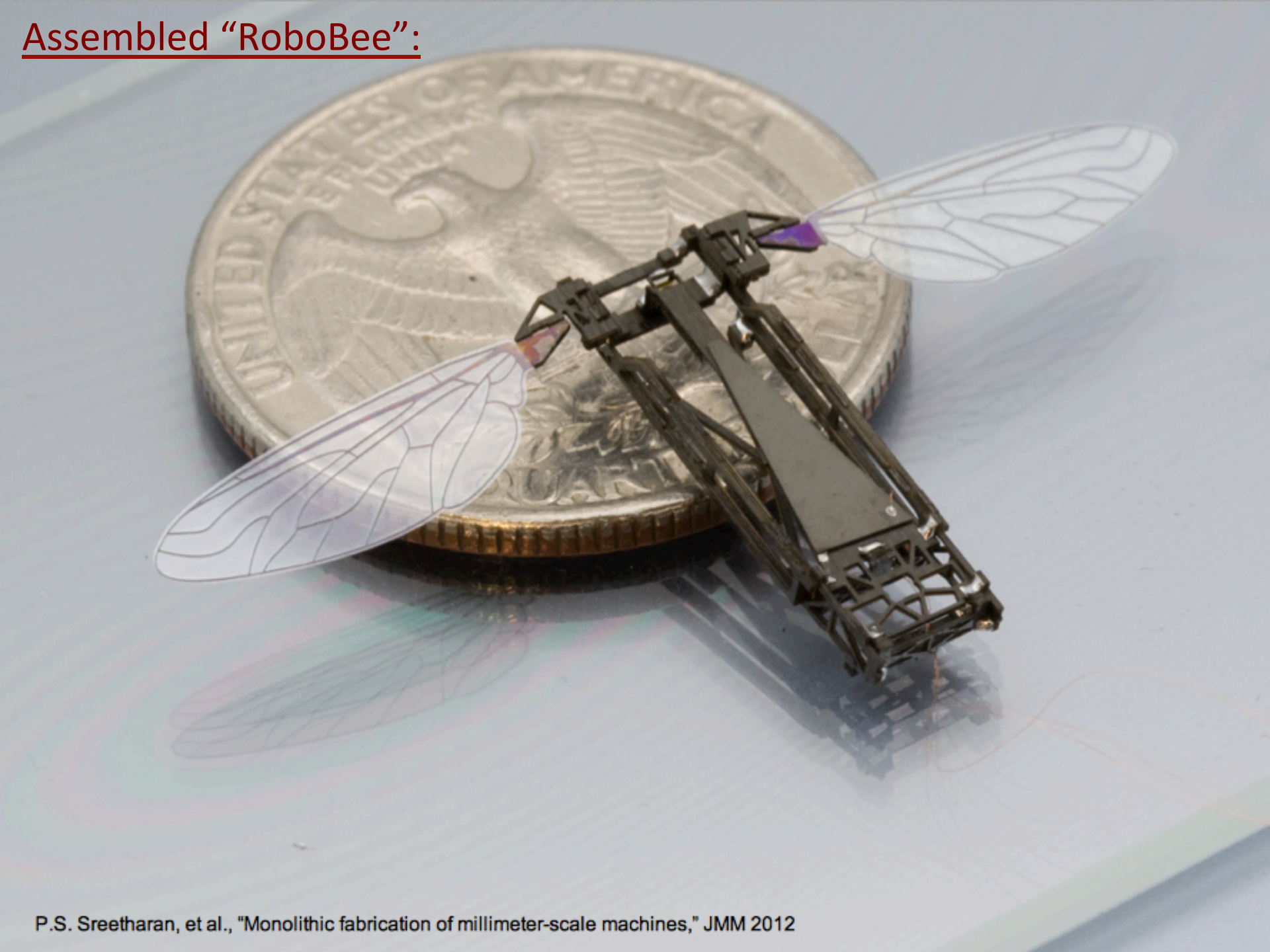
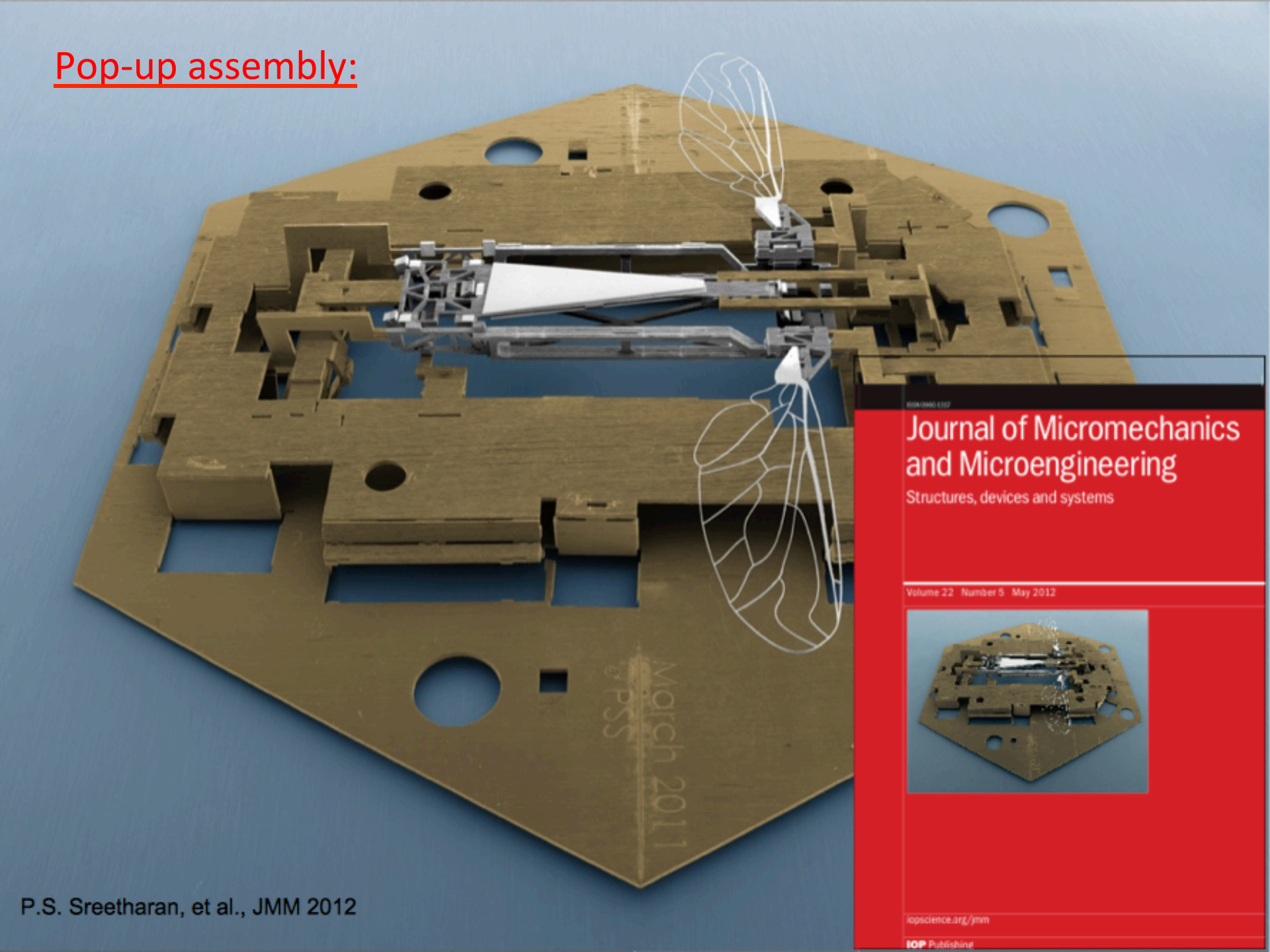


Assembled “RoboBee”:



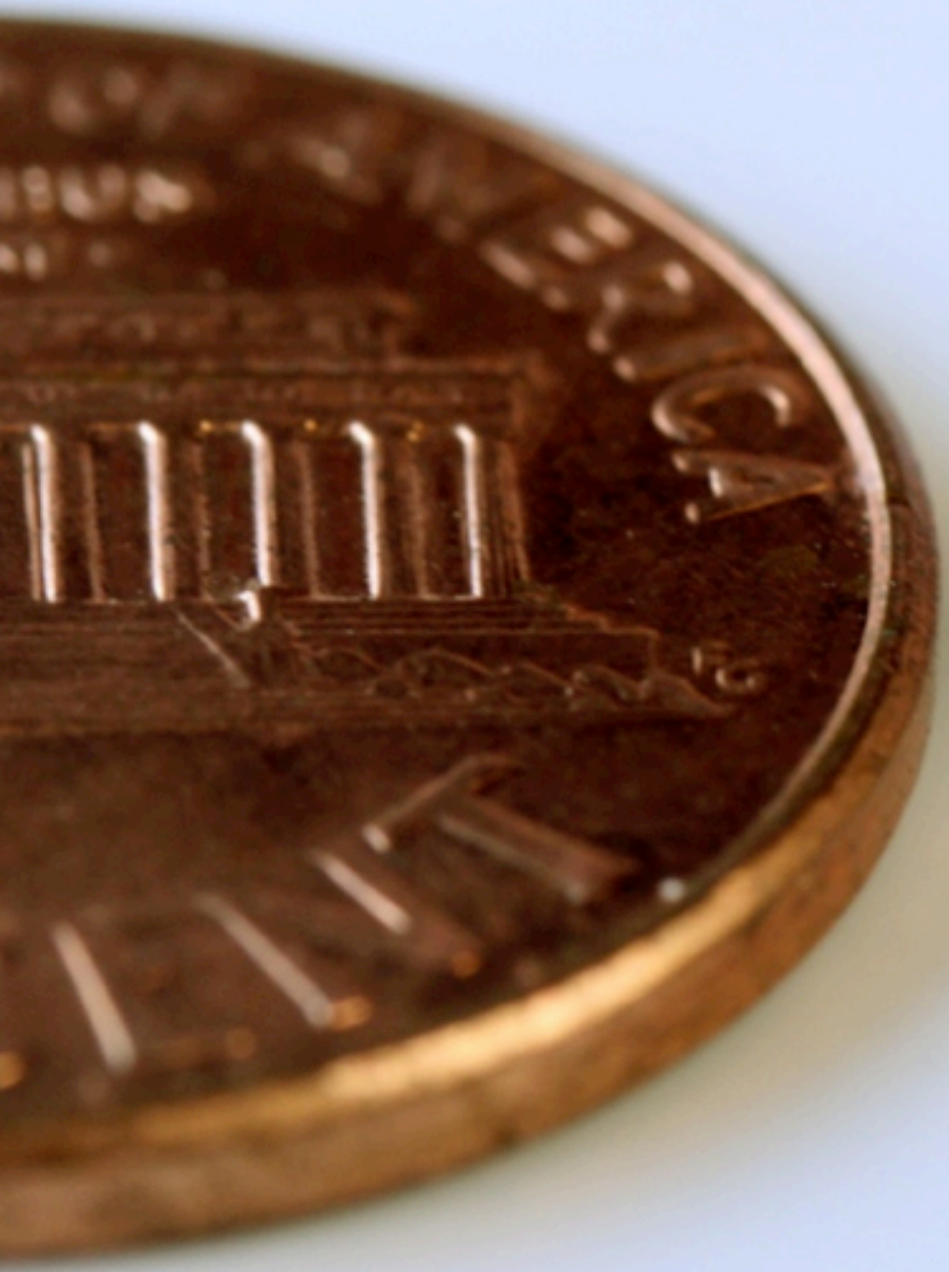
P.S. Sreetharan, et al., "Monolithic fabrication of millimeter-scale machines," JMM 2012

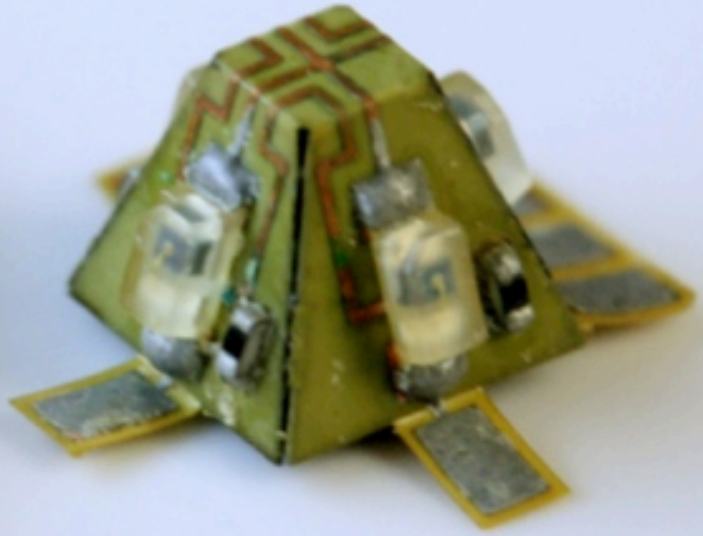
Pop-up assembly:

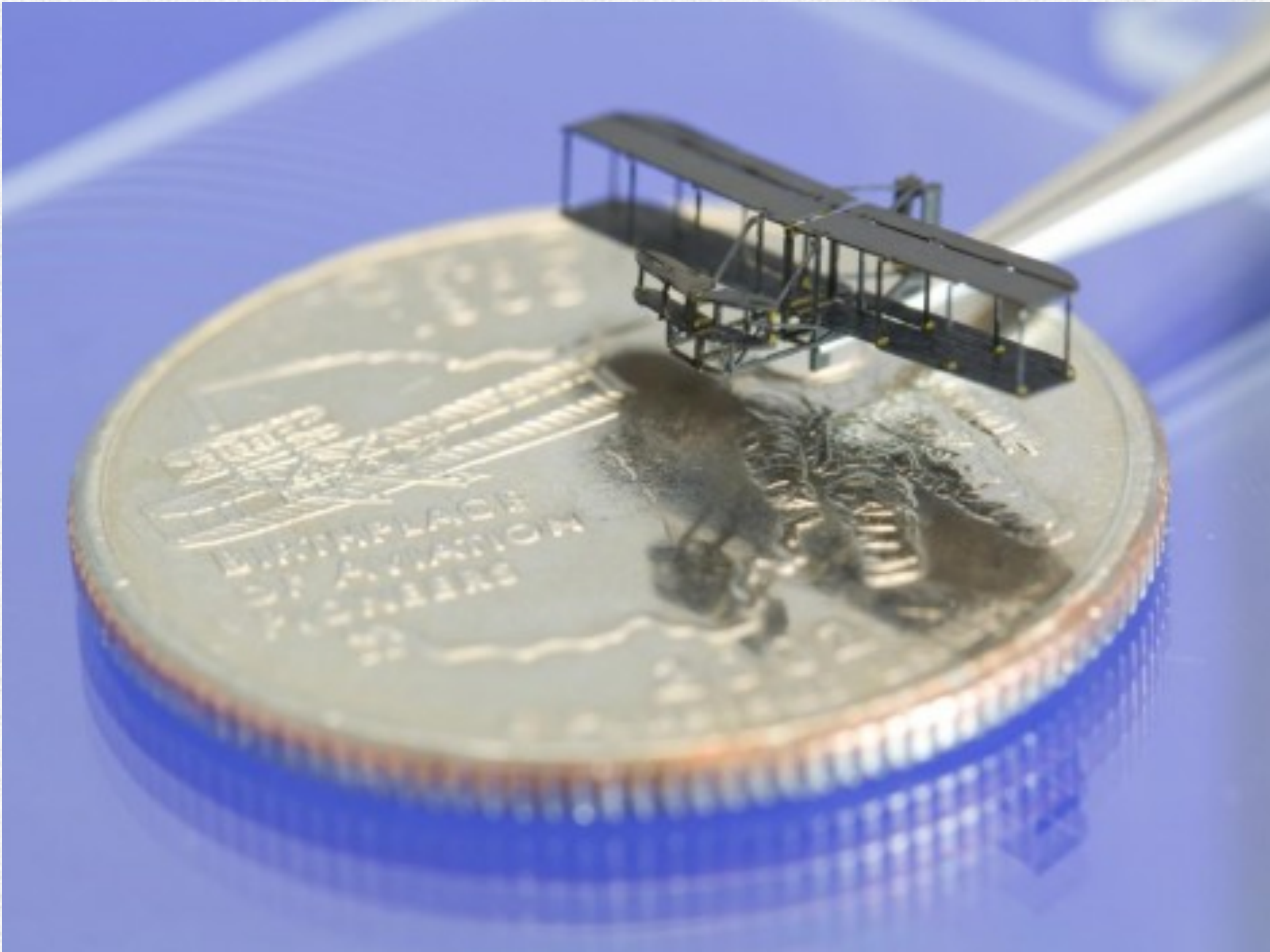


P.S. Sreetharan, et al., JMM 2012

Ocelli:






BIRTHPLACE
OF AVIATION
WRIGHT BROS

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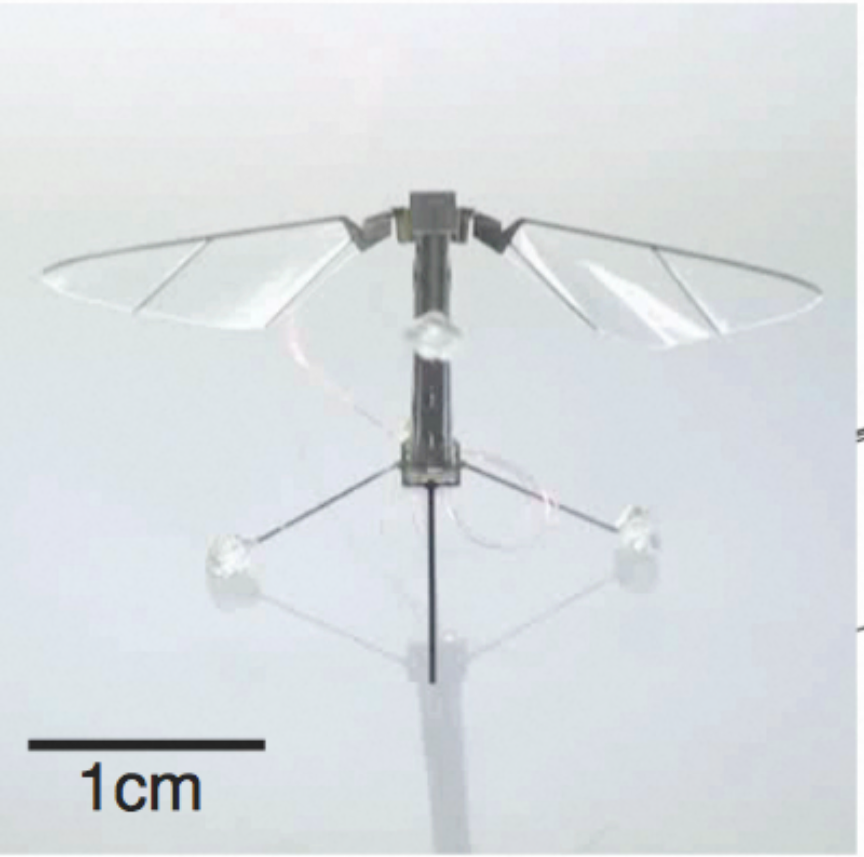
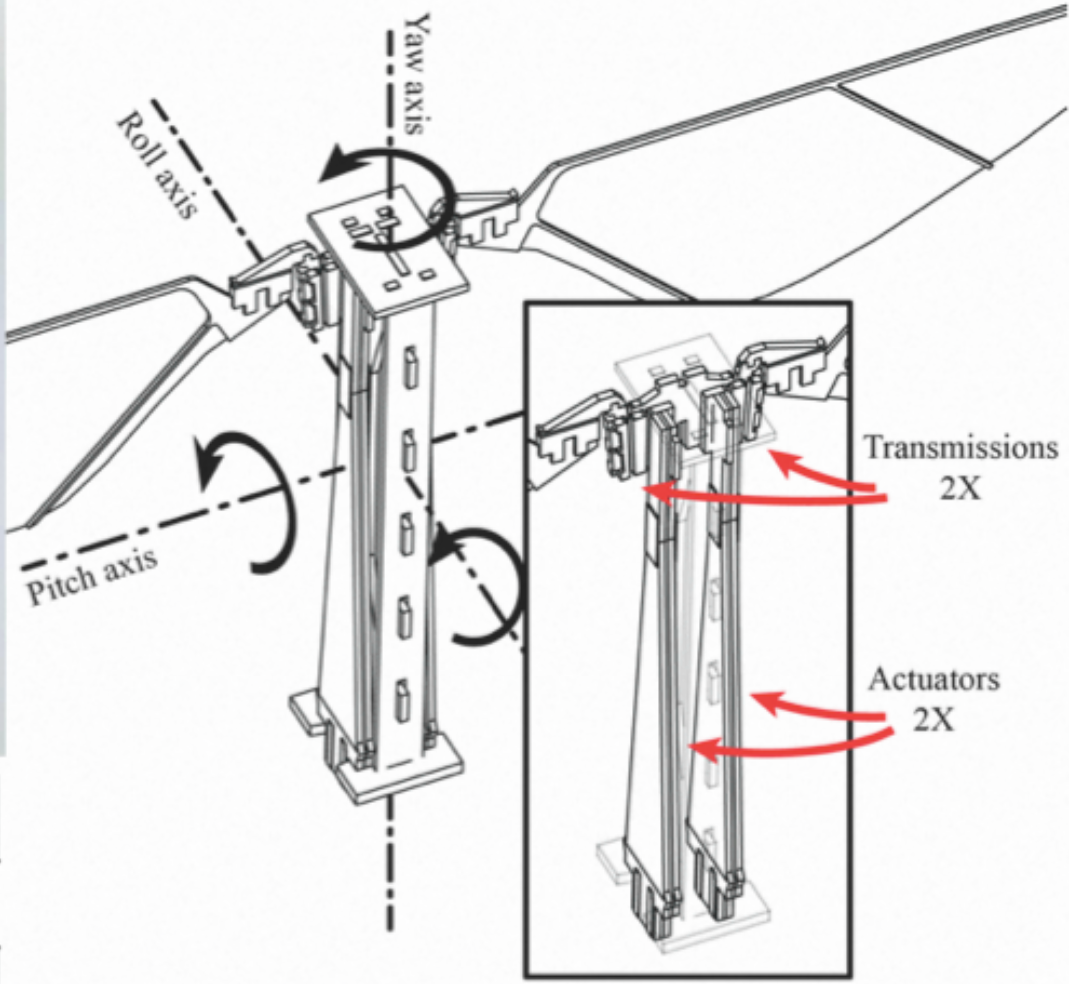
Current design 1: “dual actuator”

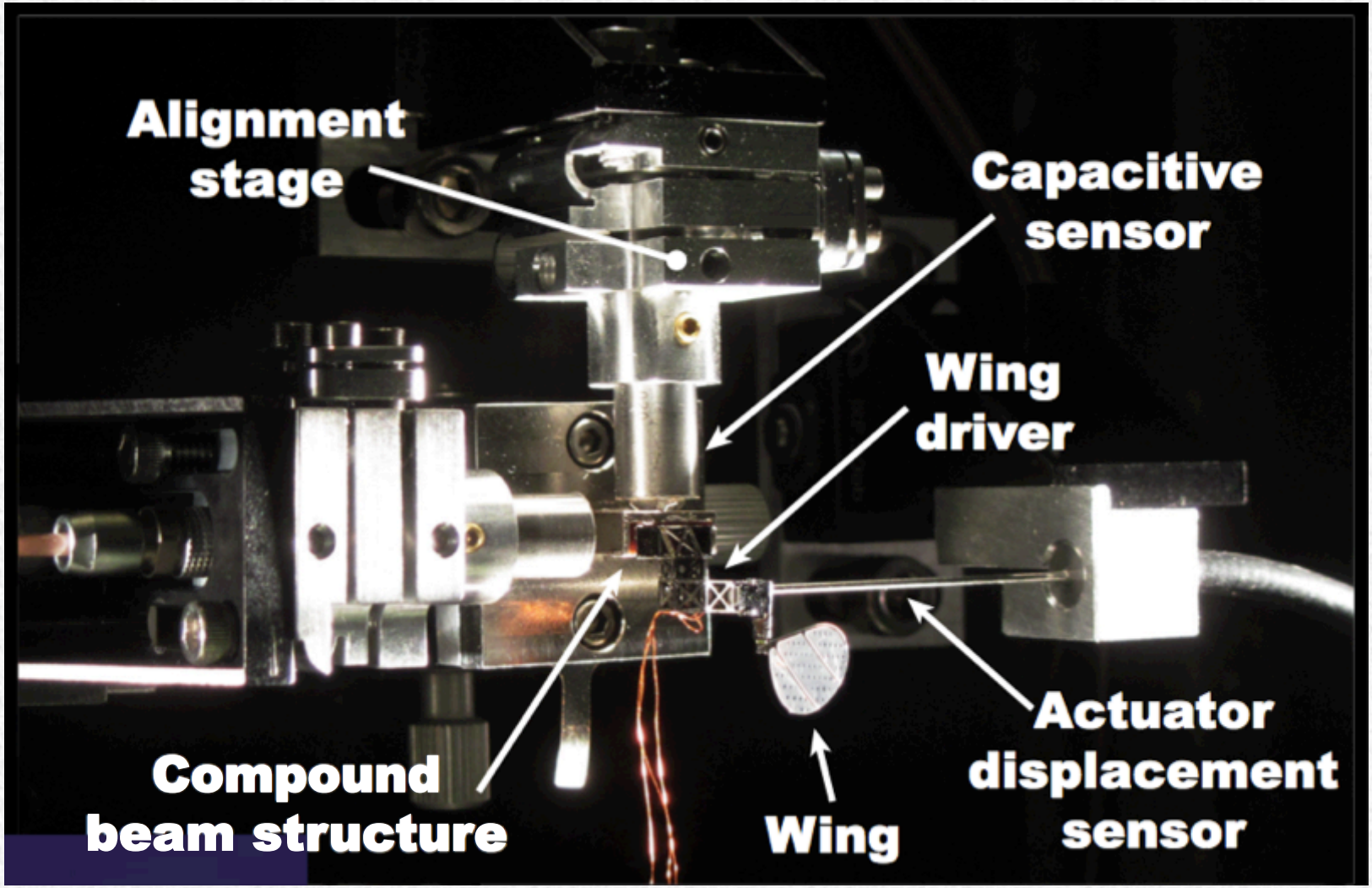




total mass	80mg
total power	~20mW
wingbeat frequency	100-120Hz
Re	~3000

[1]K. Ma and R.J. Wood, IROS 2012

At-Scale Wing-Flapping Characterization



[1]K. Ma, et al., Science 2013

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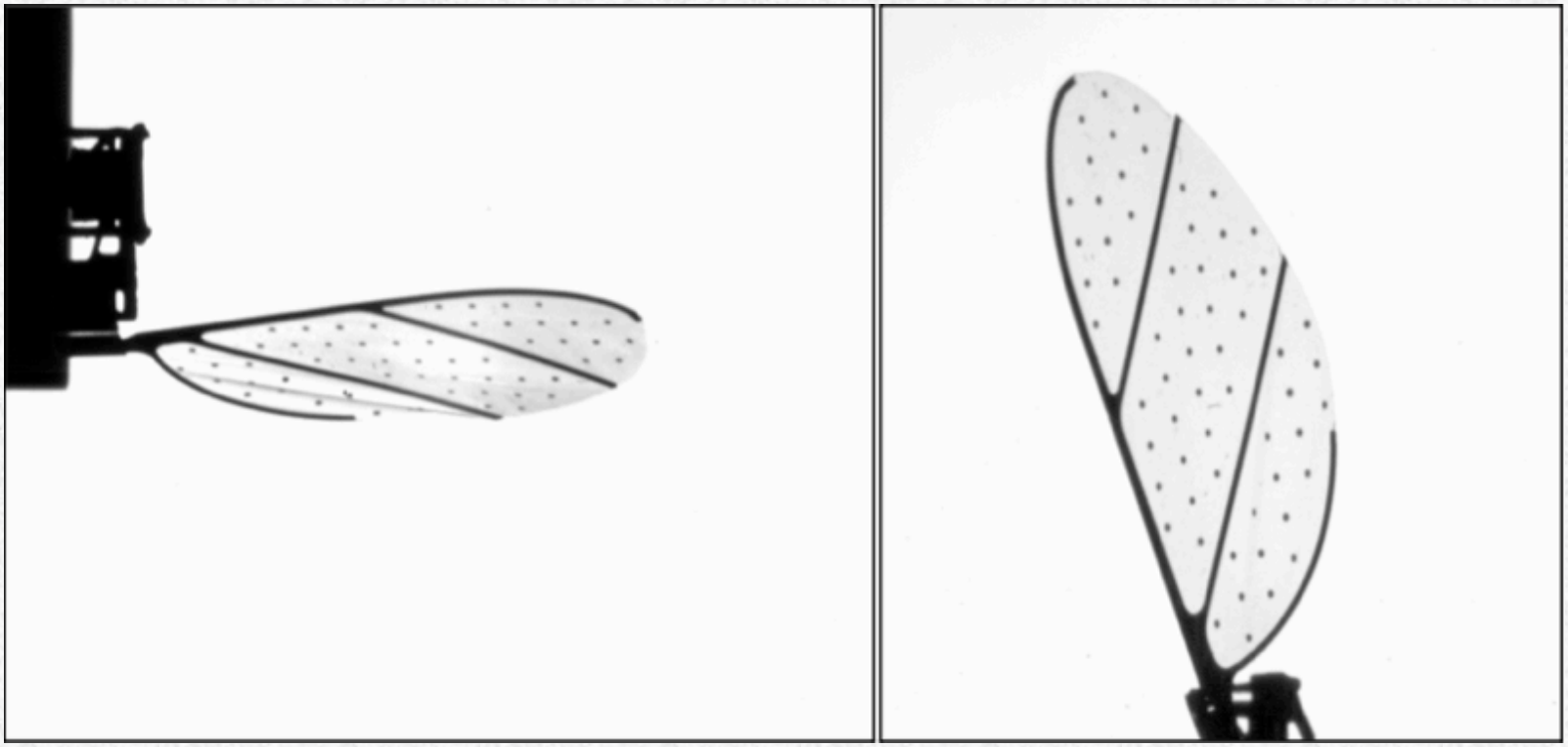
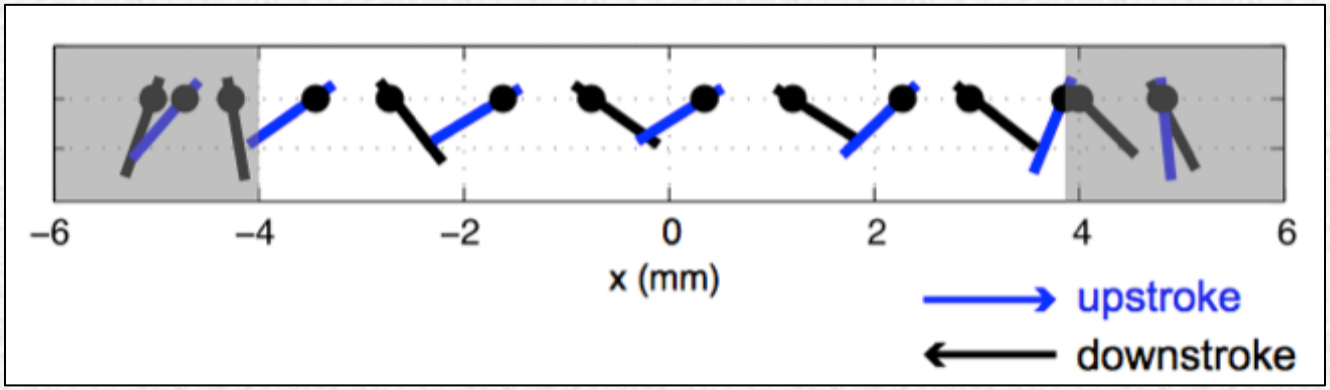
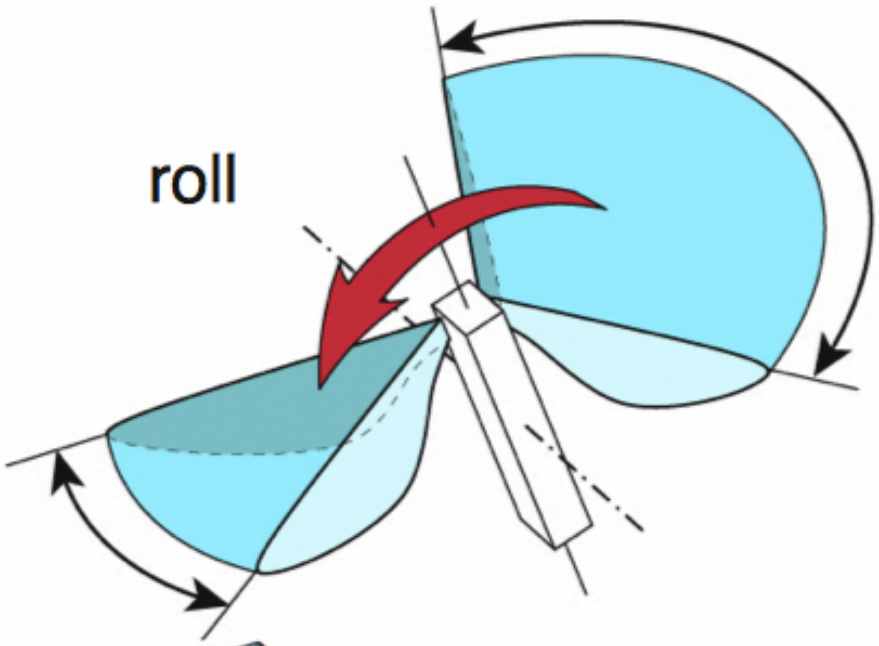
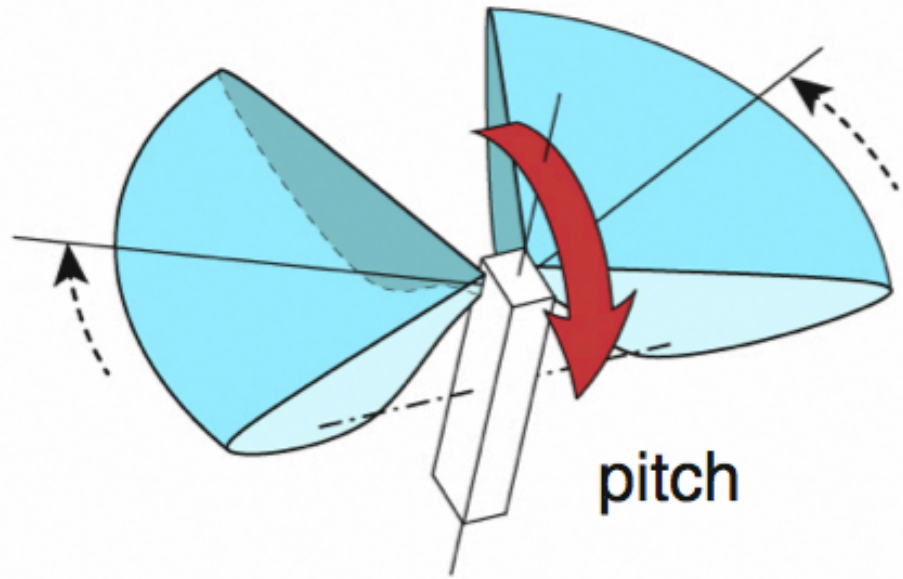


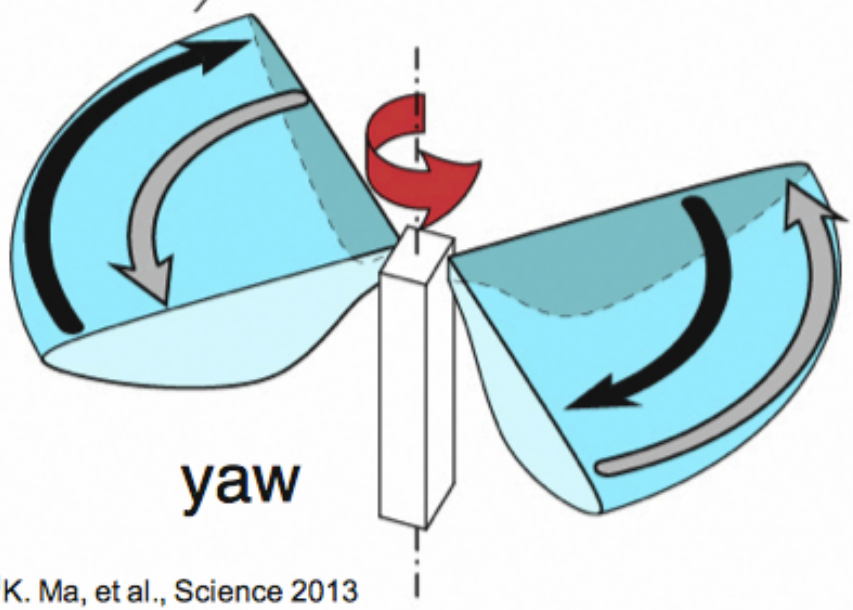


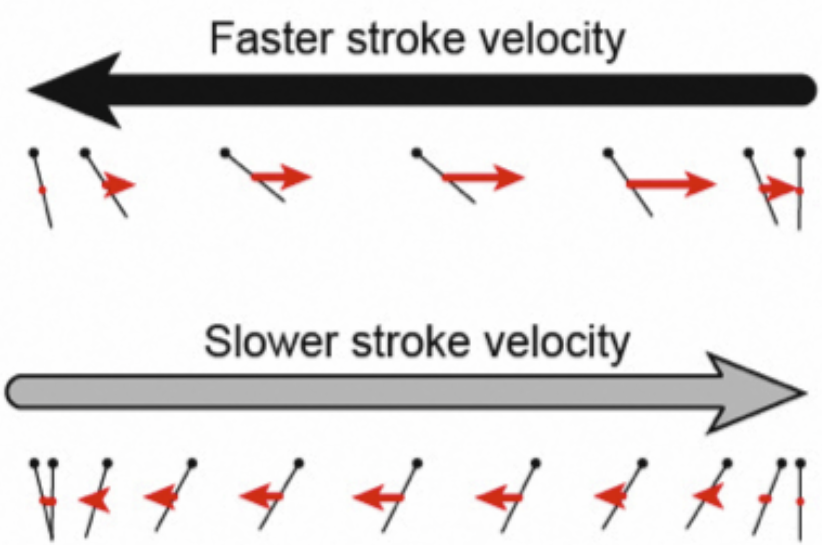
[1]K. Ma, et al., Science 2013

Body torque control



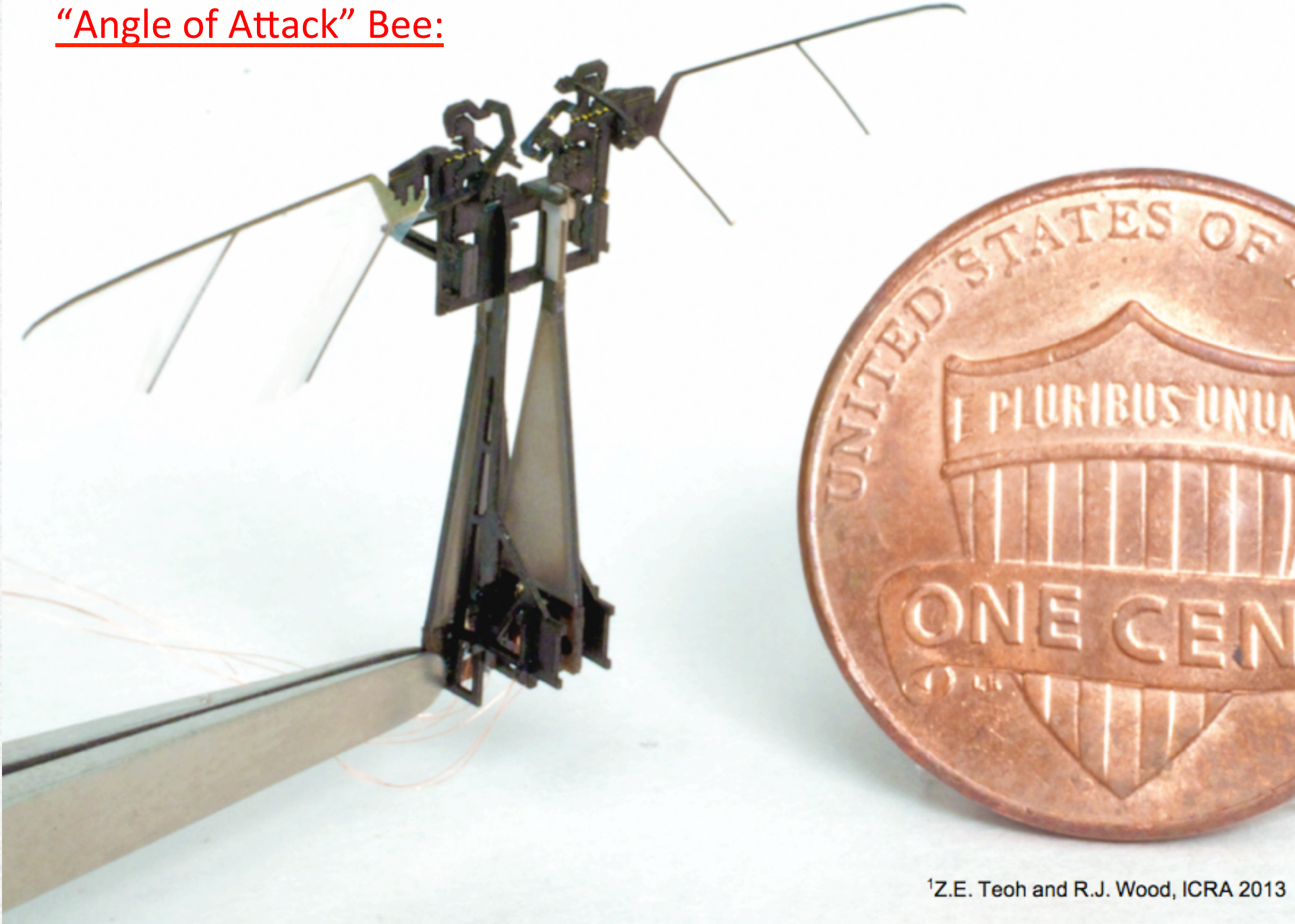




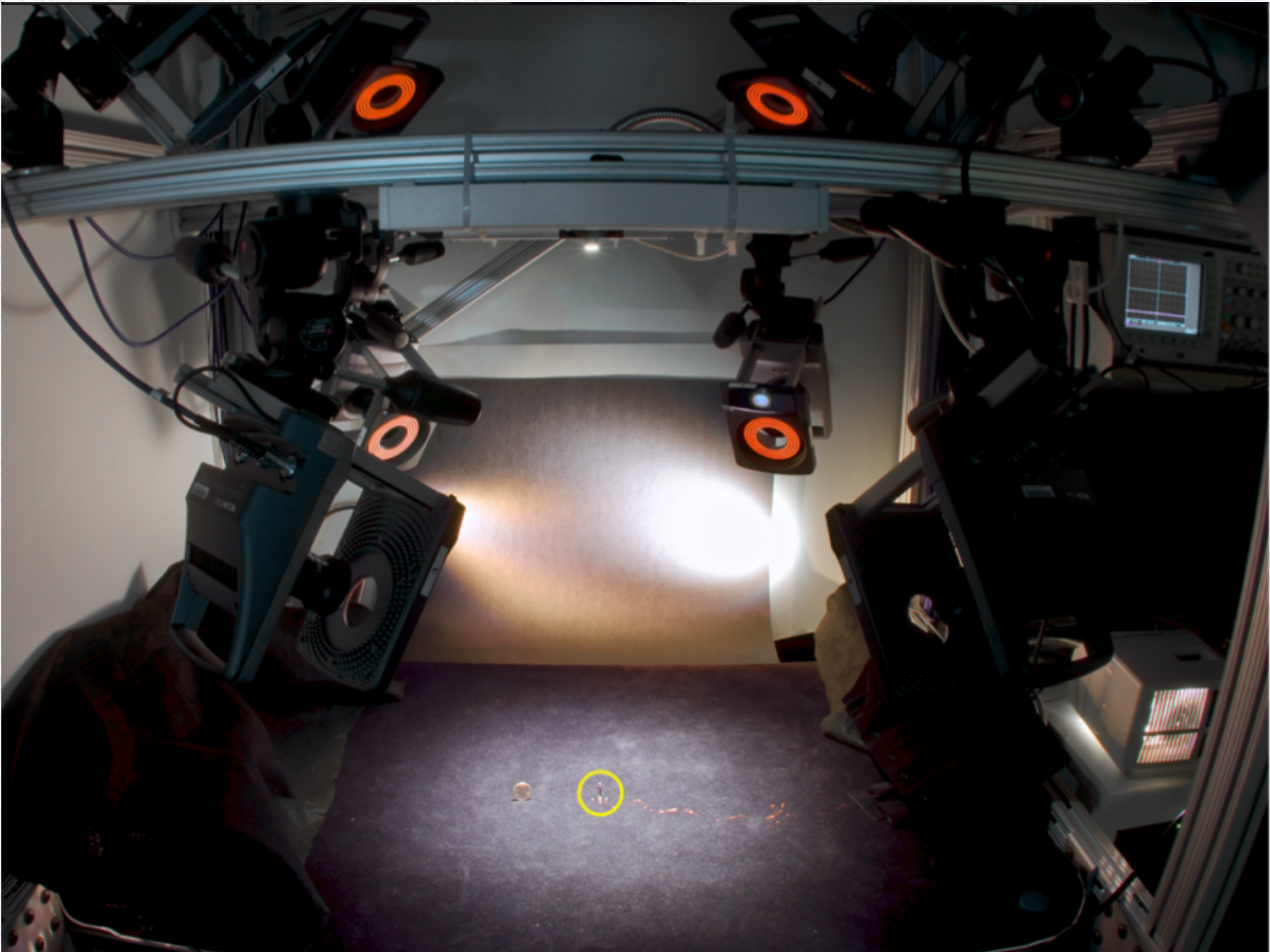


[1]K. Ma, et al., Science 2013

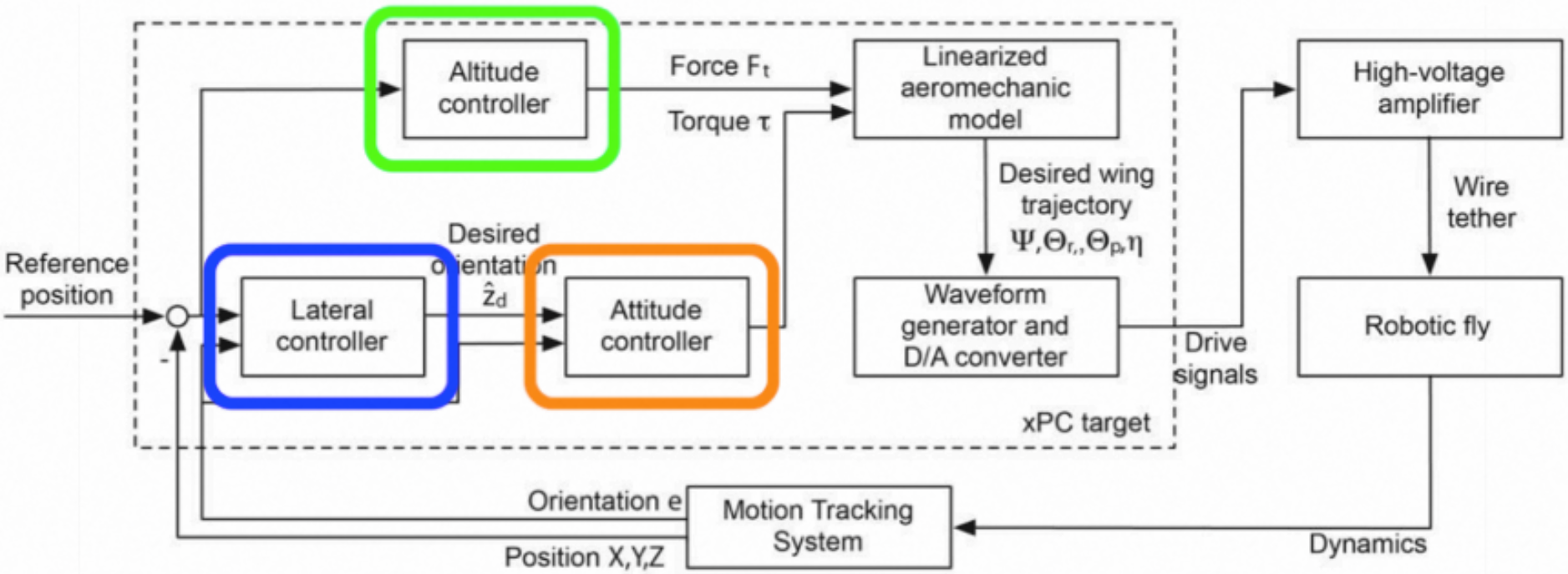
“Angle of Attack” Bee:



[1]Z.E. Teoh and R.J. Wood, ICRA 2013



Control architecture



[1]K. Ma, et al., Science 2013

Hovering

[1]K. Ma, et al., Science 2013

Lateral Maneuver

[1]K. Ma, et al., Science 2013

Aerodynamics of insect flight

Challenges:

1. Intermediate Reynolds number (viscous effects are important)
2. Unsteady aerodynamics...

Incompressible Navier Stokes	Quasi-steady model
$\frac{\partial \bar{V}}{\partial t} + \bar{V}\bar{\nabla}\cdot\bar{V} = \frac{1}{\rho}\bar{\nabla}p + \nu\nabla^2\bar{V}$ $\bar{\nabla}\cdot\bar{V} = 0$ $\bar{F} = \int_{\partial\Omega} \bar{\bar{\tau}}\cdot\hat{n}dl$	$\bar{F}_i = \frac{1}{2}\rho C_i(\alpha)\int_{x_r}^{x_r+R} v^2(r,w)c(r)dr$ $C_L(\alpha) = C_{L_{max}}\sin(2\alpha)$ $C_D(\alpha) = (\frac{C_{D_{max}}+C_{D_0}}{2}) - (\frac{C_{D_{max}}-C_{D_0}}{2})\cos(2\alpha)$

Opportunities/goals:

- RoboBee mean lift coefficient is 0.8 while insect mean C_L is 2x higher
- Autonomous operation requires heavy lift capability and endurance: $(C_L/C_D)_{max}$ and $(C_L^{3/2}/C_D)_{max}$[1]

[1]Whitney and Wood, Bioinspiration & Biomimetics, 2012

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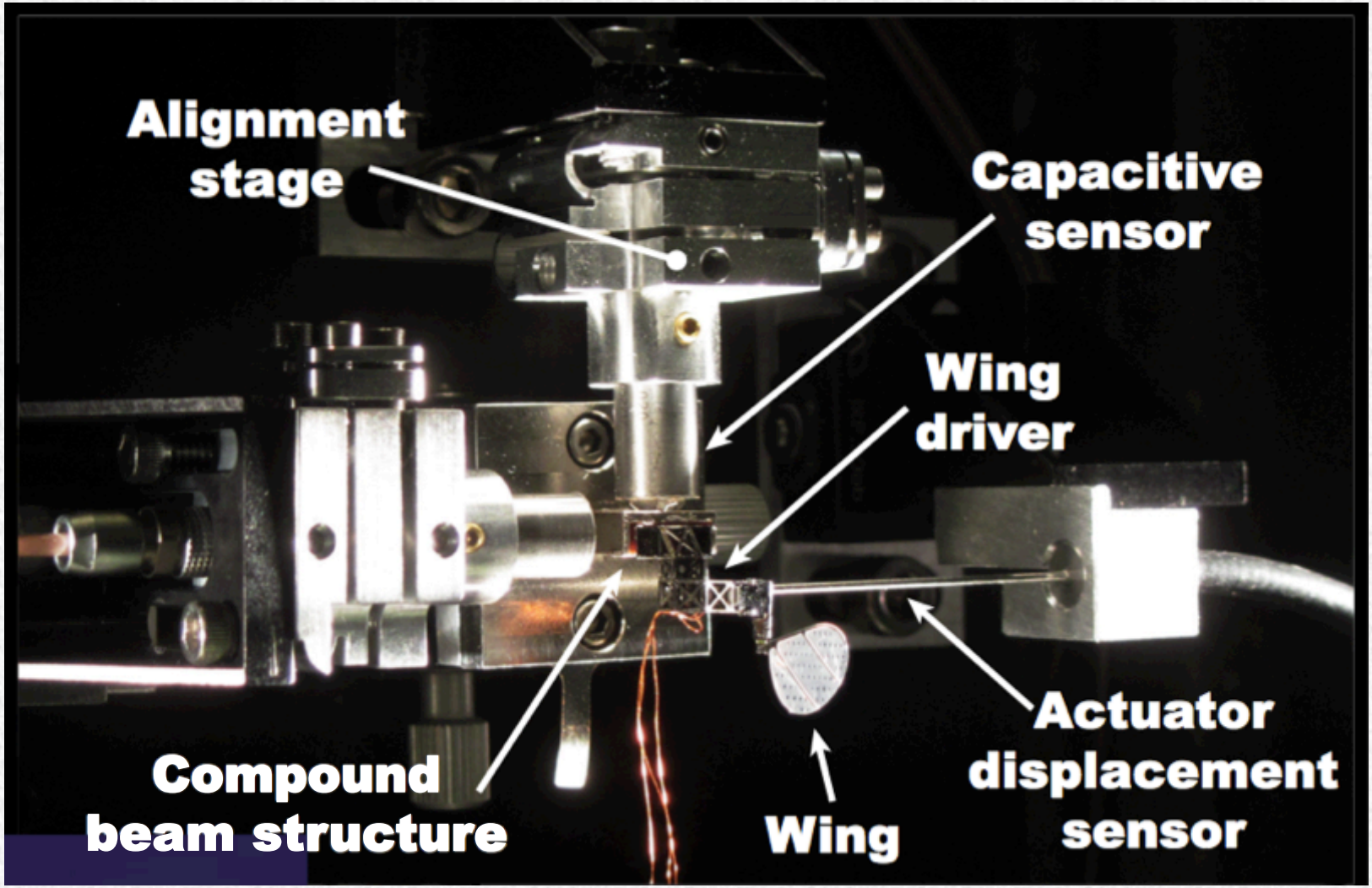

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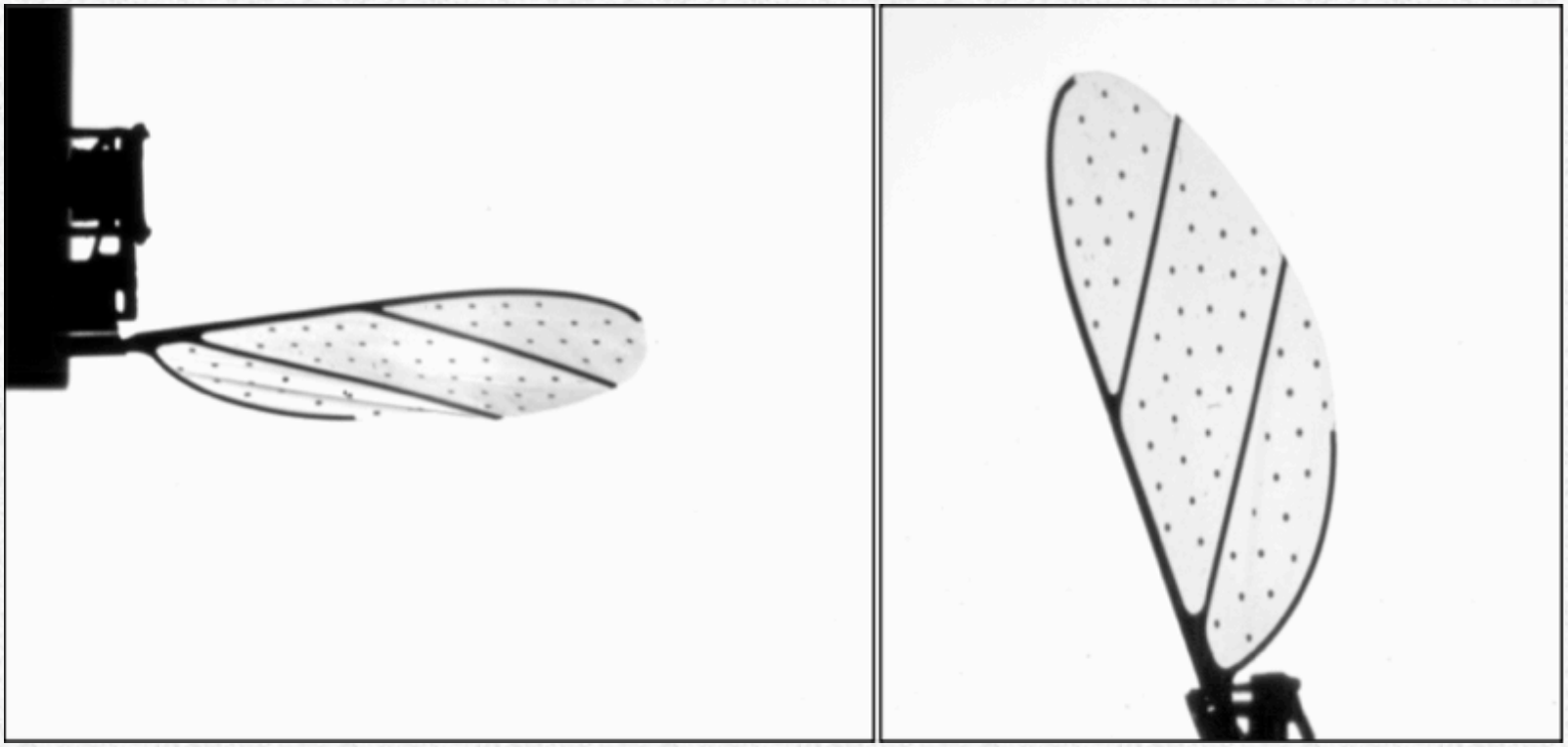

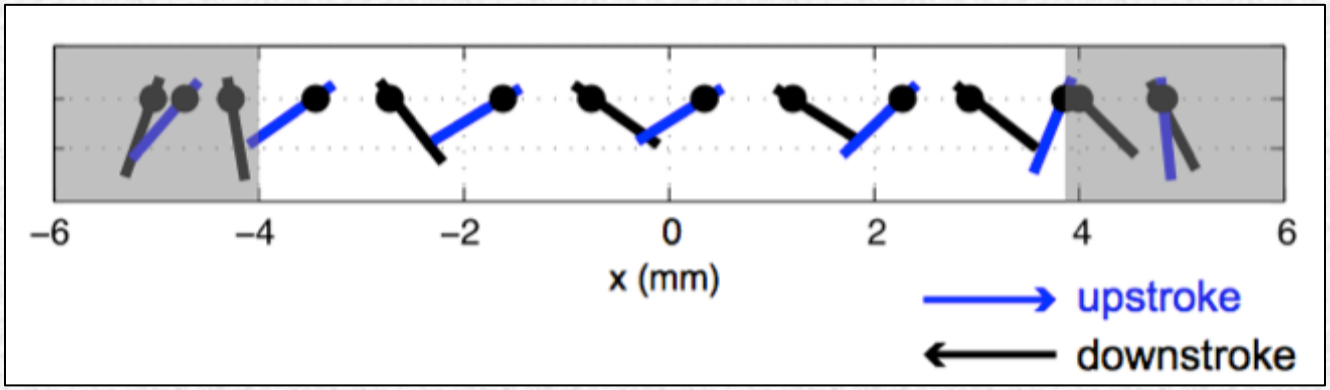

[1]K. Ma, et al., Science 2013

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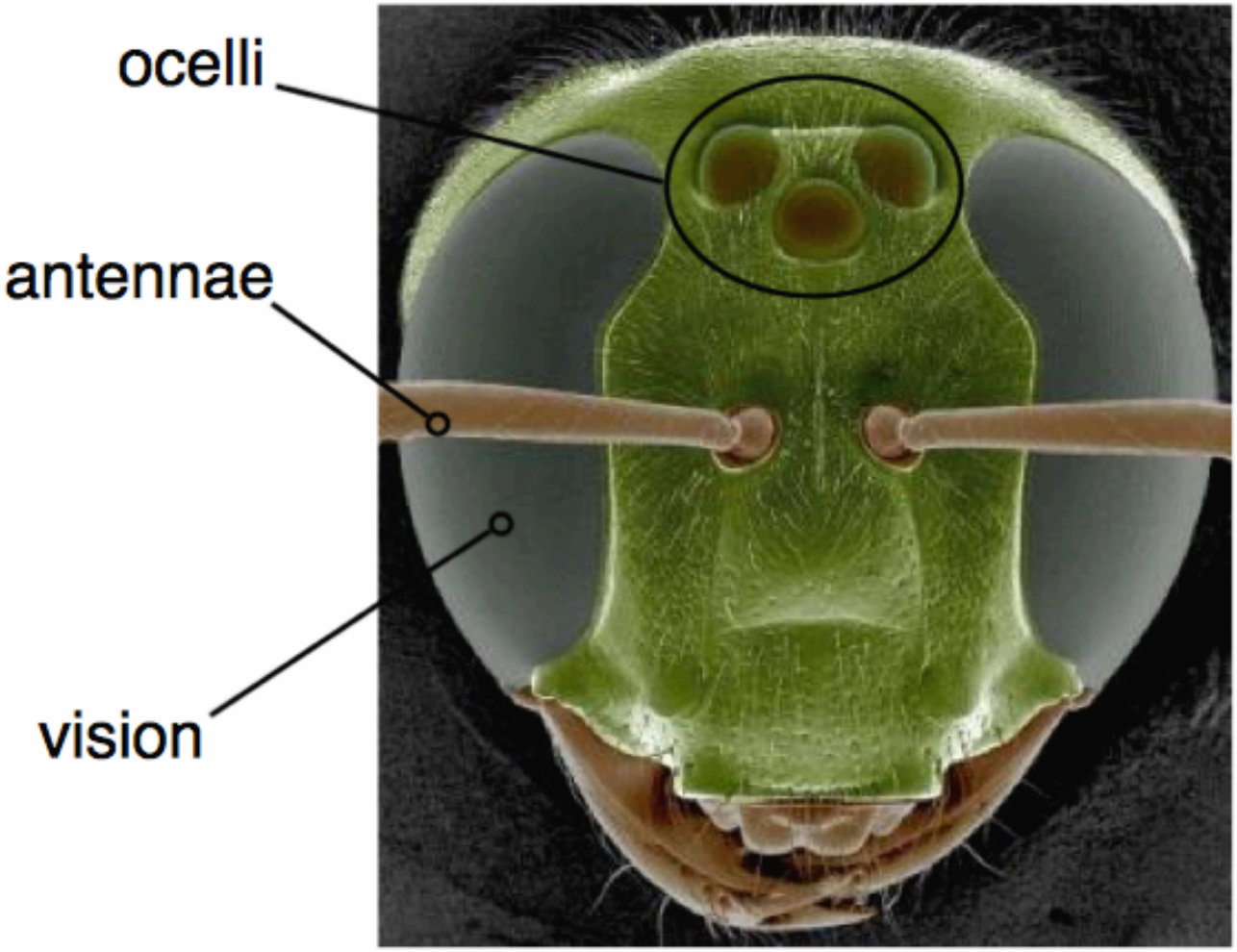
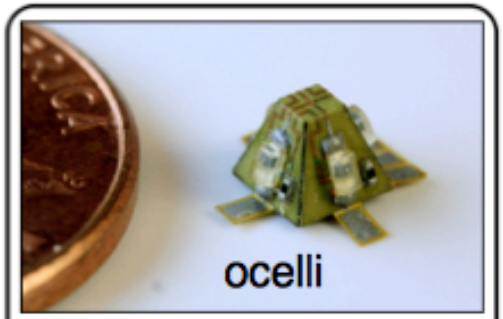
Sensing



Megalopta Genalis
Credit: Lund University, Sweden

non-bioinspired:
- IMU
- magnetometer
- pressure
- range finder

Sensors

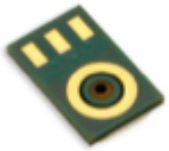


~40 mg

magnetometer
accelerometer
gyroscope

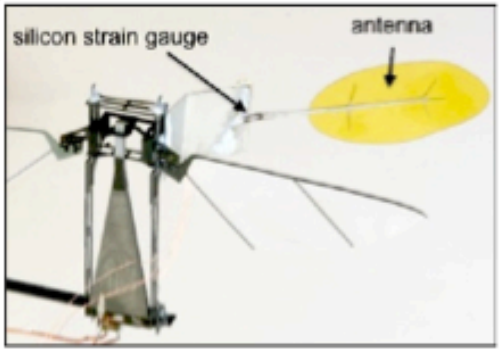
$$\begin{bmatrix} \theta_x \\ \theta_y \\ \theta_z \\ \dot{\theta}_x \\ \dot{\theta}_y \\ \dot{\theta}_z \end{bmatrix} \quad \begin{bmatrix} x \\ y \\ z \\ \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}$$

laser rangefinder

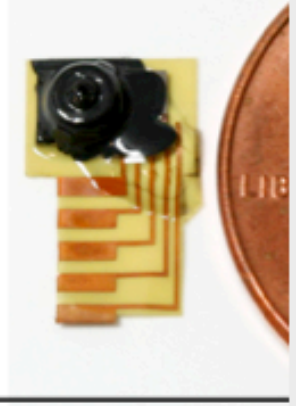


sonar (audio)

pressure



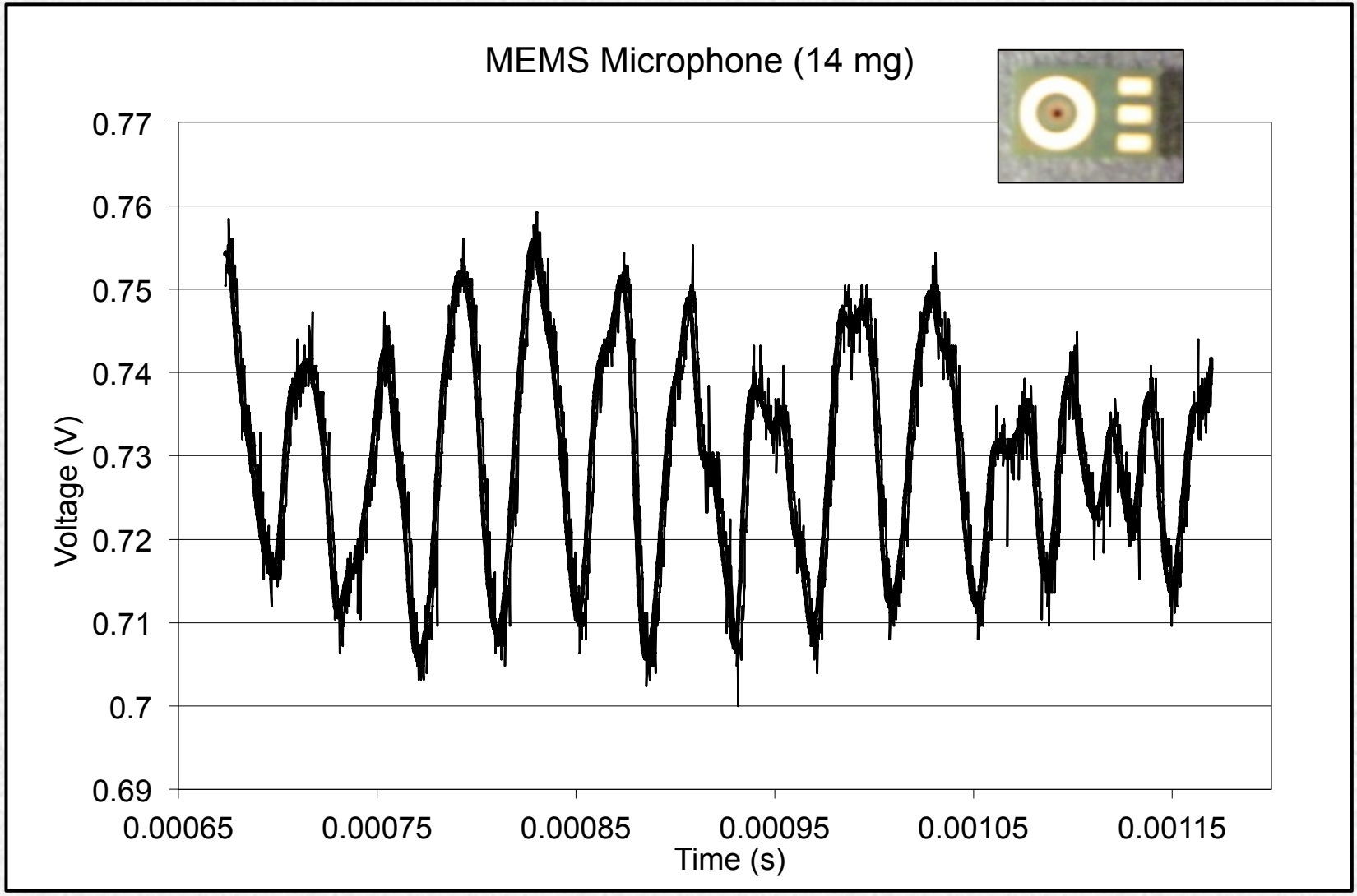
antenna (wind)



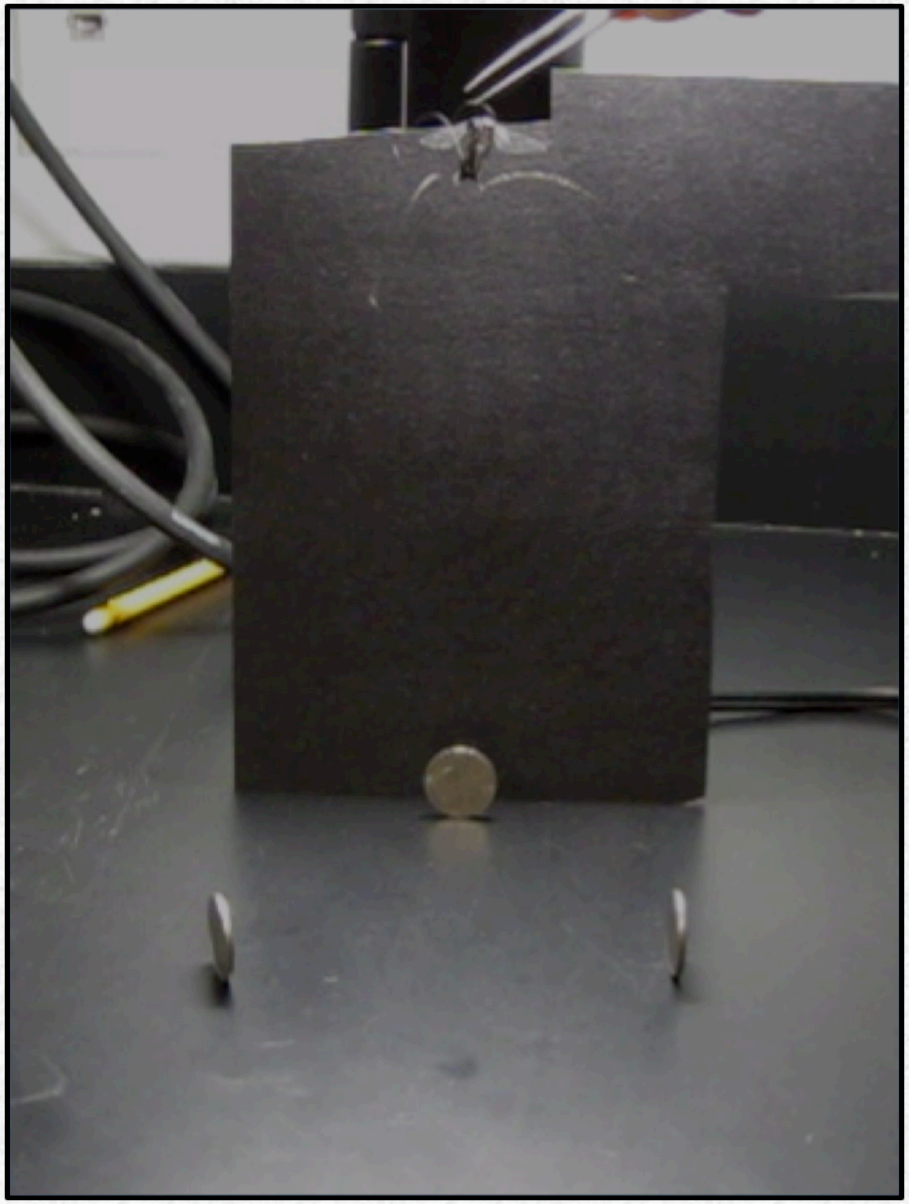
[1]S. B. Fuller, et al., ICRA 2013 [2]P.-E. J. Duhamel, et al., ICRA 2012

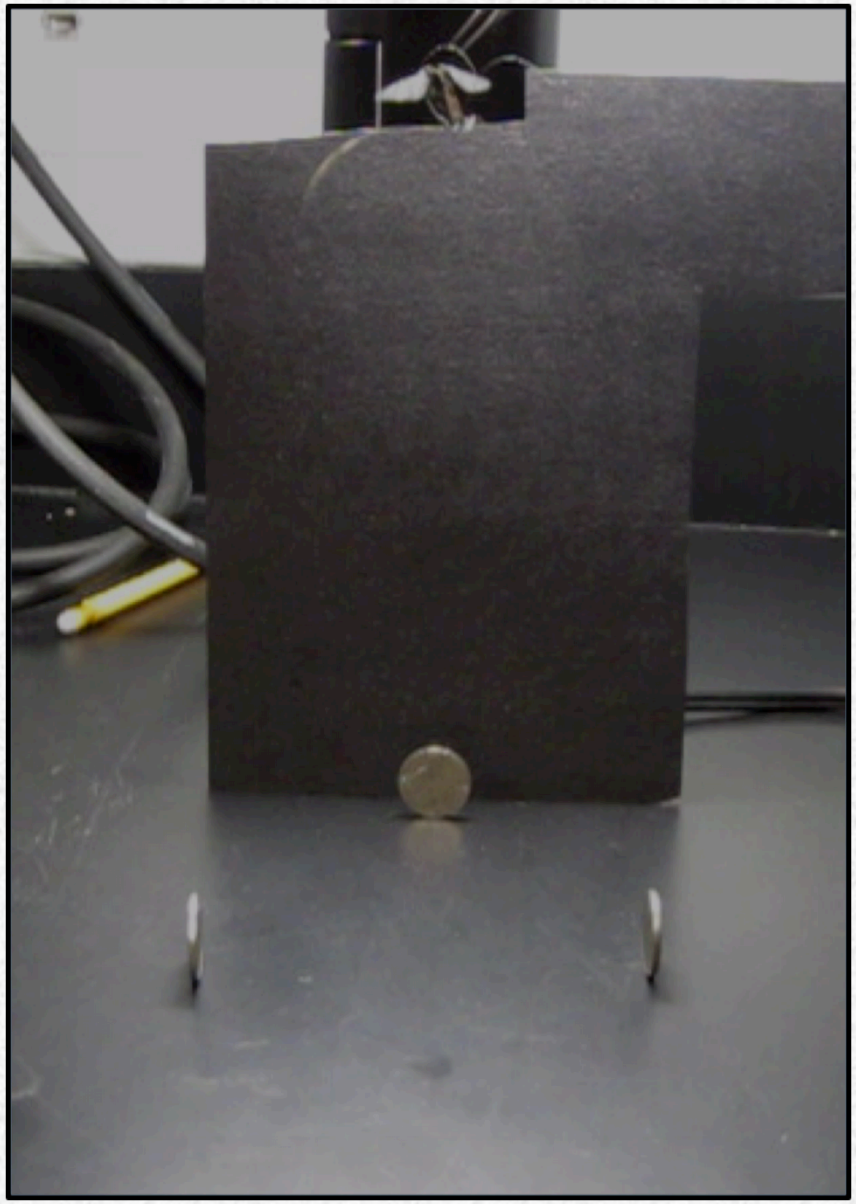
Sensor	Type	Mass	Power	BW	Precision	Remarks
Ocelli[1]	light	22 mg	< 5 mW	100 kHz	2 deg/s	
Gyroscope	MEMS	40 mg	20 mW	200 Hz	1 deg/sec	vibration-sensitive
Accelerometer	MEMS	40 mg	20 mW	200 Hz	0.2 milli-g	
Sonar	audio	14 mg	.4 mW	100 Hz	low	wings as emitters?
Magnetometer	magnetic	16 mg	1 mw	1 kHz	1 deg	magnetic interference?
Pressure	MEMS	30 mg	1 mW	200 Hz	1 m	
Optical flow[2]	CMOS	>100 mg	10-20mW	40 Hz	NA	computation-heavy
Airspeed[1]	PC-MEMS	5 mg	25 mW	100 Hz	10 cm/s	
Laser rangefinder	CMOS	5 mg	1.5 mW	40 Hz	1 cm	needs camera

MEMS Microphone



Landing Gear





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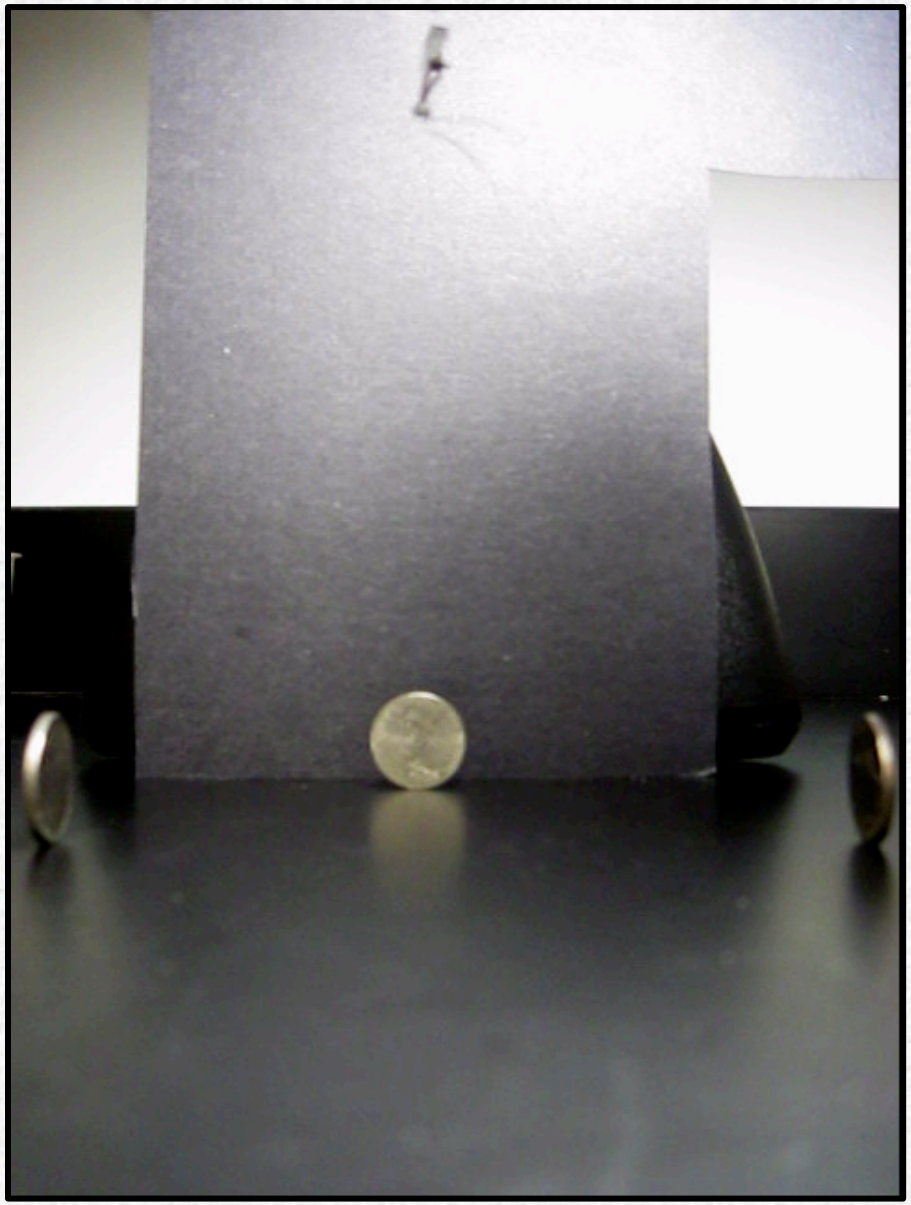

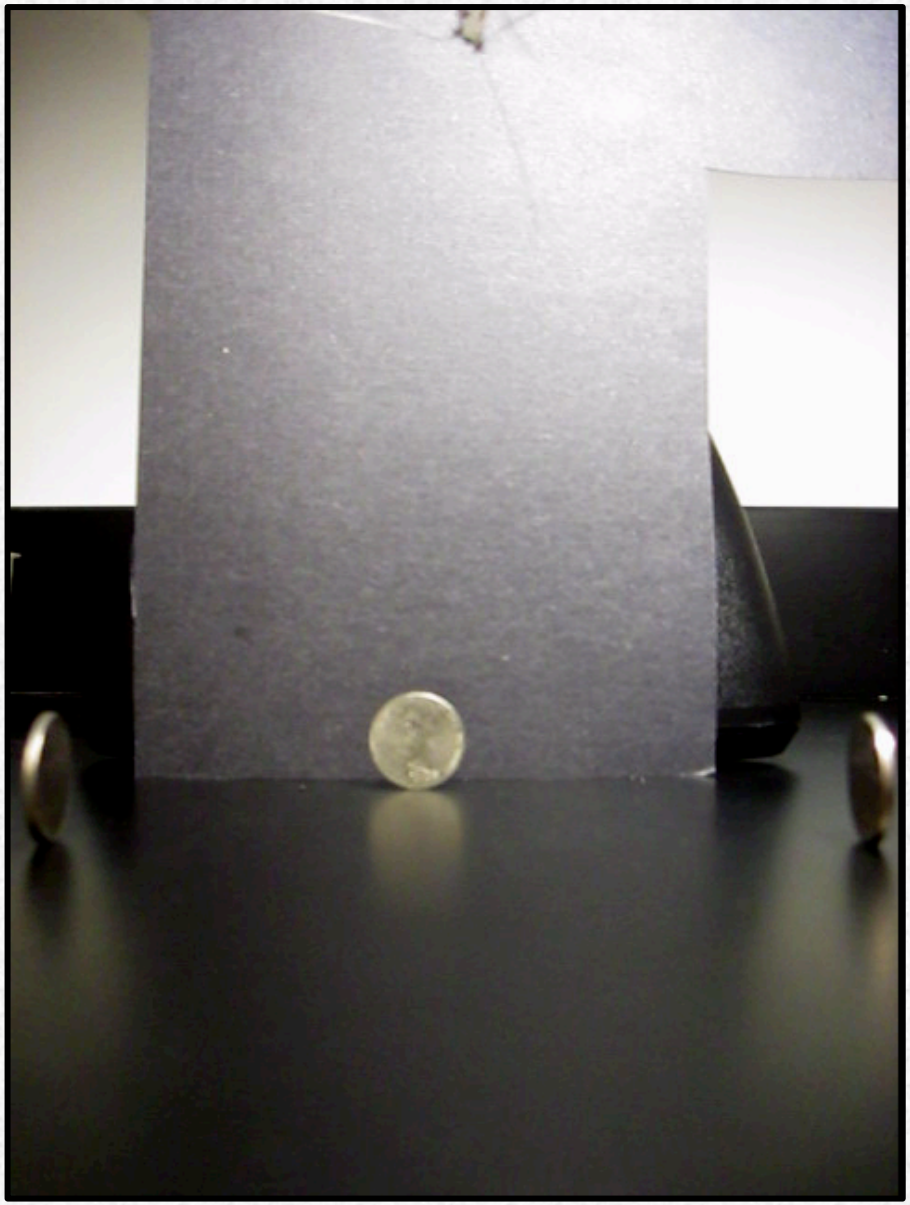

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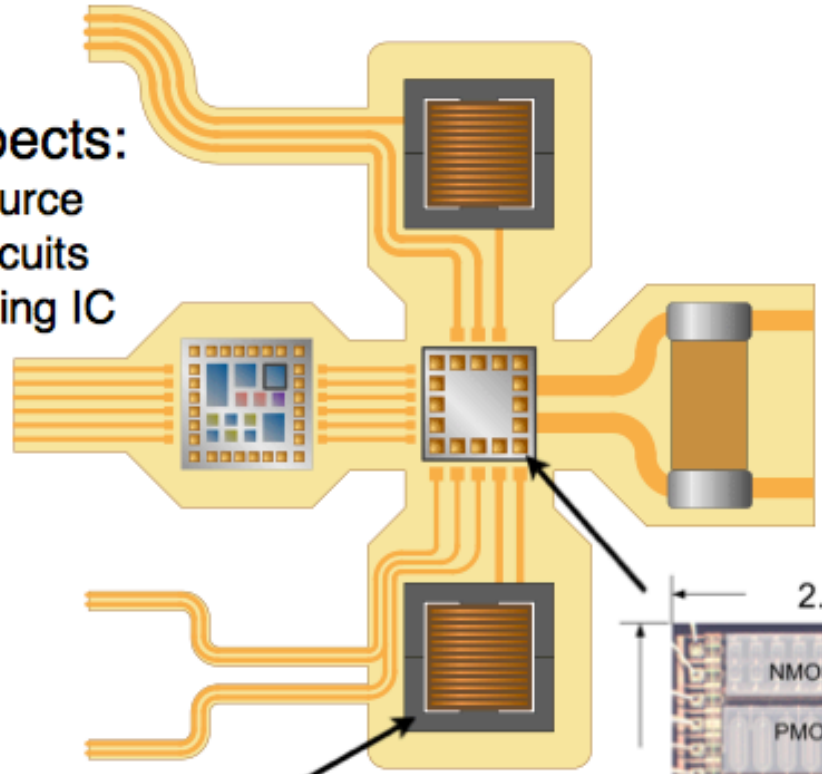
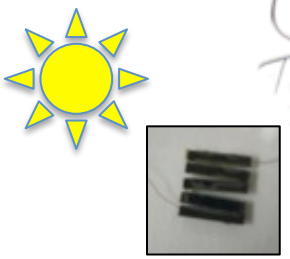
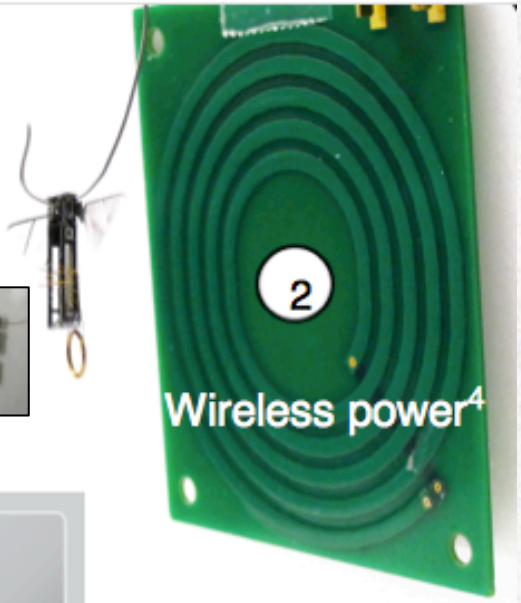
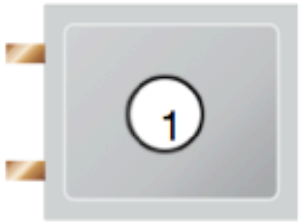
Power architecture

3 key aspects:
1. power source
2. power circuits
3. coordinating IC

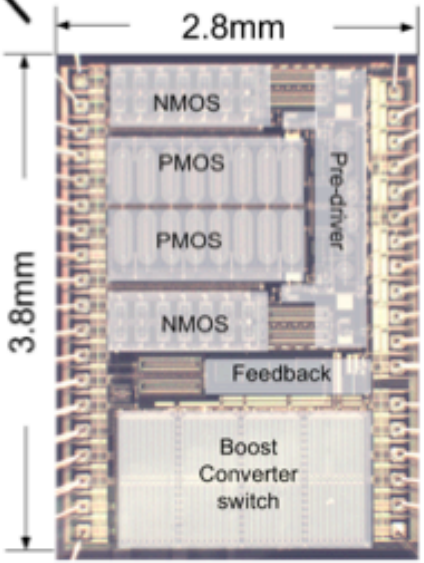




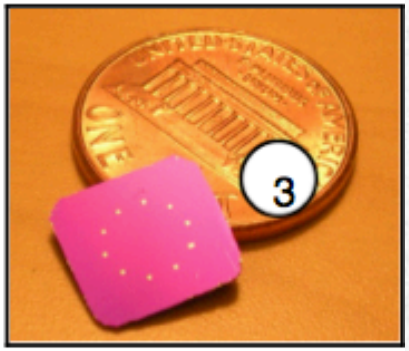




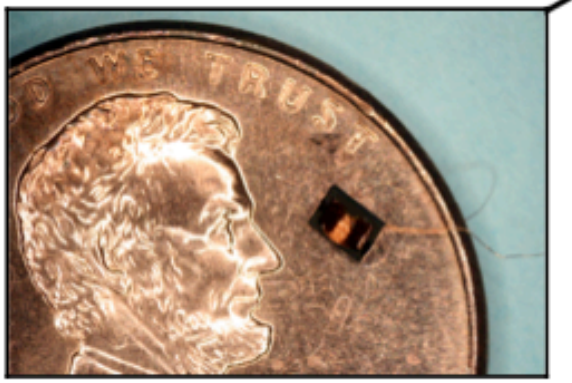
Battery



High voltage IC[2]



Micro fuel cells[3]



Custom magnetic components[1]

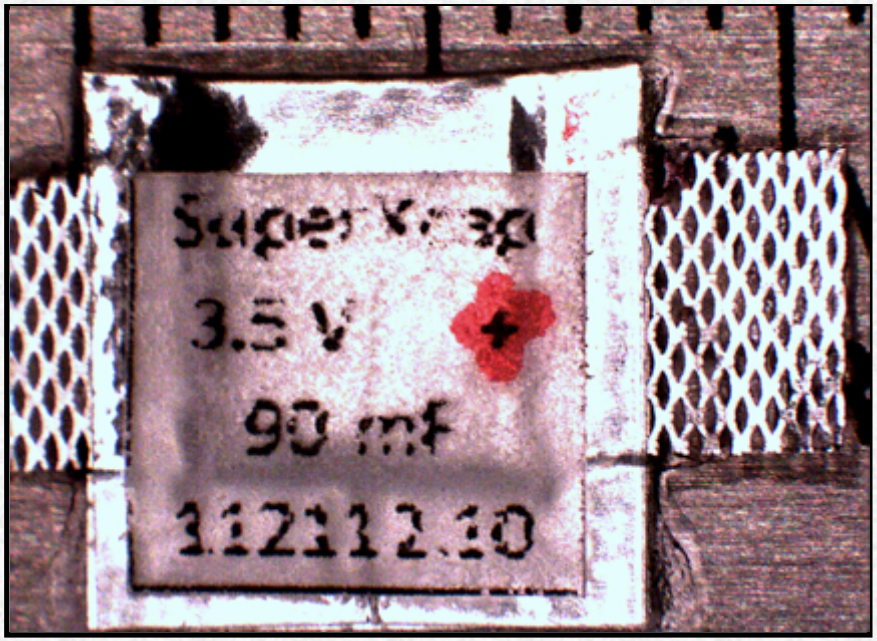
[1]M.Karpelson et al., Sensors and Actuators A, 2011

[2]M. Lok et al., to appear: ECCE, 2013

[3]M. Tsuchiya, B.K. Lai and S. Ramanathan, Nature Nanotechnology, 6, 282, 2011

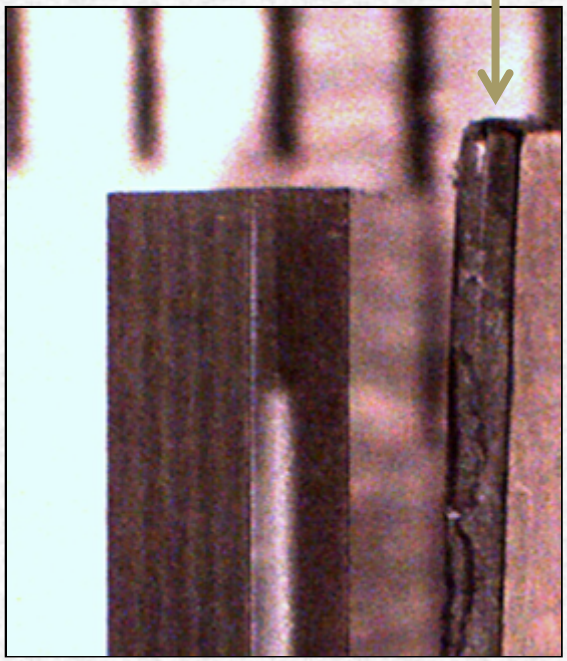
[4]Sample, Meyer, and Smith, IEEE

Other Projects



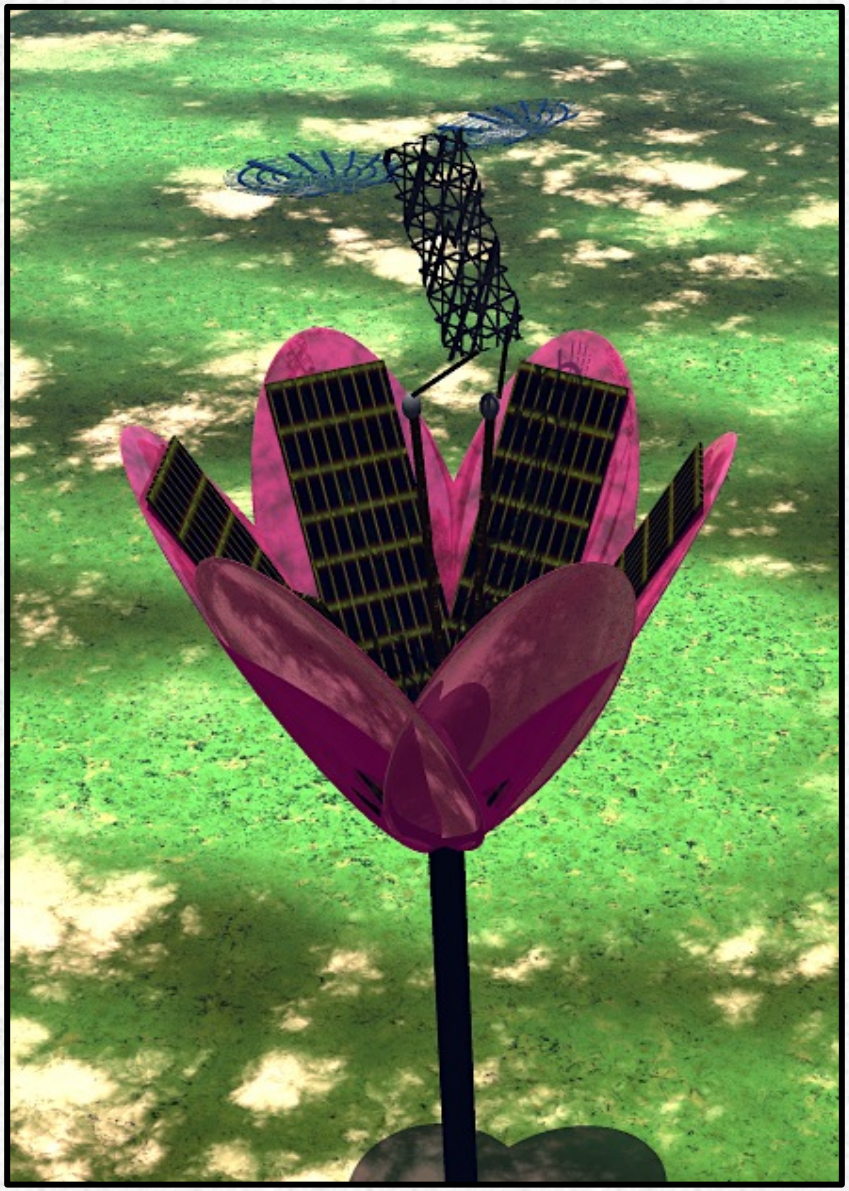
Super Capacitors:
3.5 V, 90 mF, ~60 mg, 0.64 cm²

After polishing

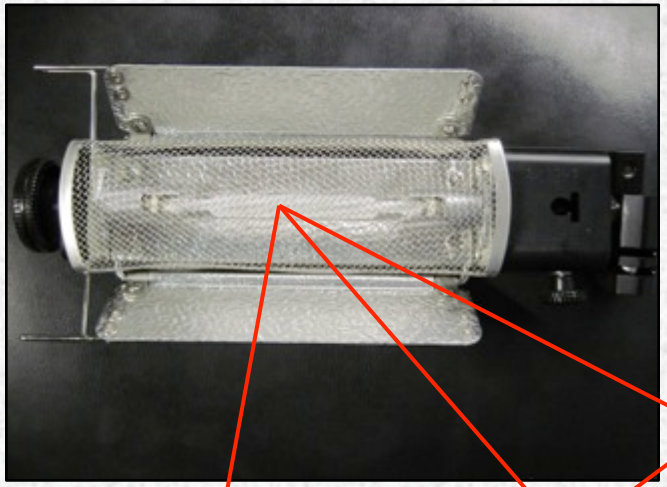


Solar Cells (at one sun):
4.5 V, 5 mA, ~150 mg, 1.65 cm

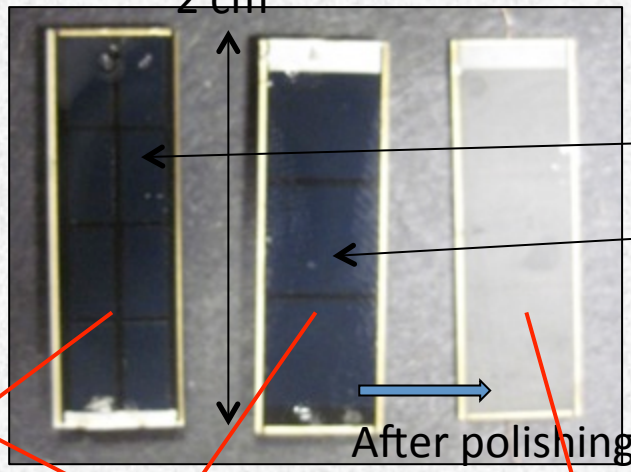
Other Projects



Solar Cells



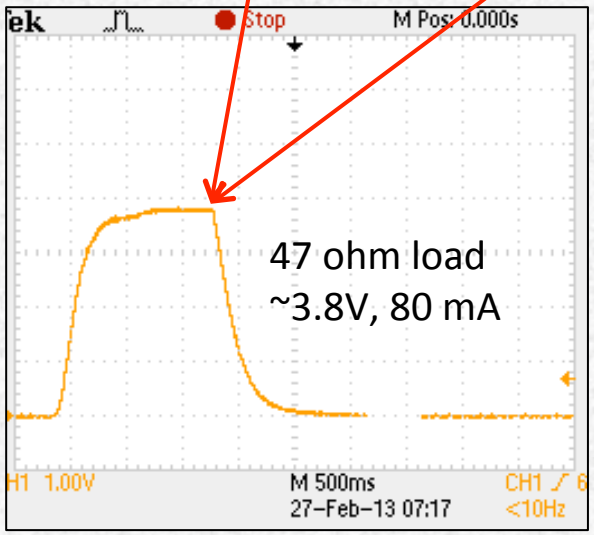
20,000 lumen light source
=> ~20 suns 2 cm away

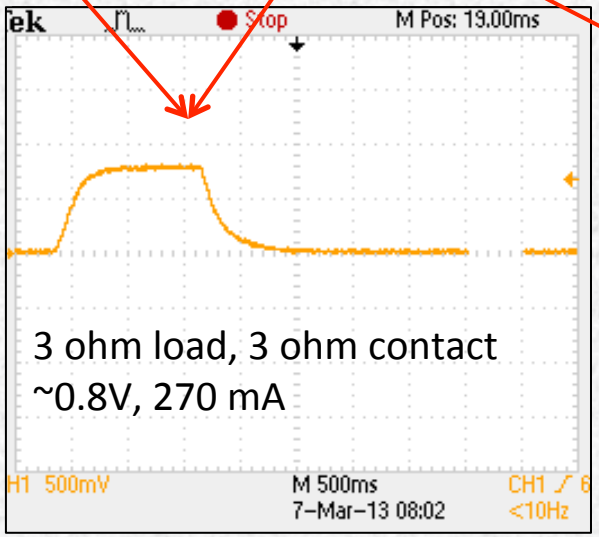


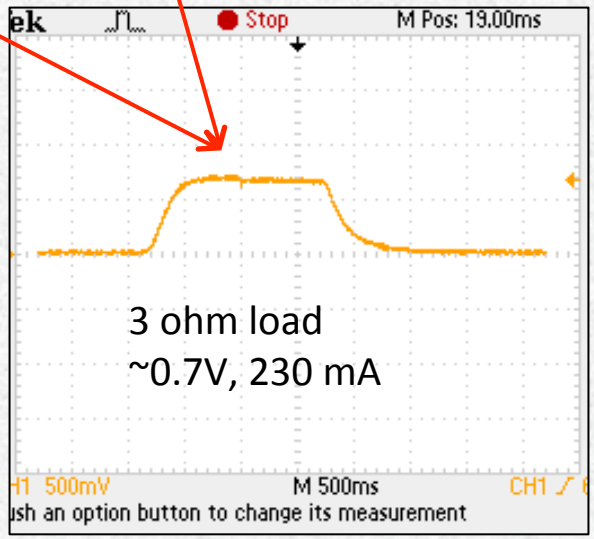
1-sun ratings:

4.5 V, 5 mA

1.5 V, 15 mA







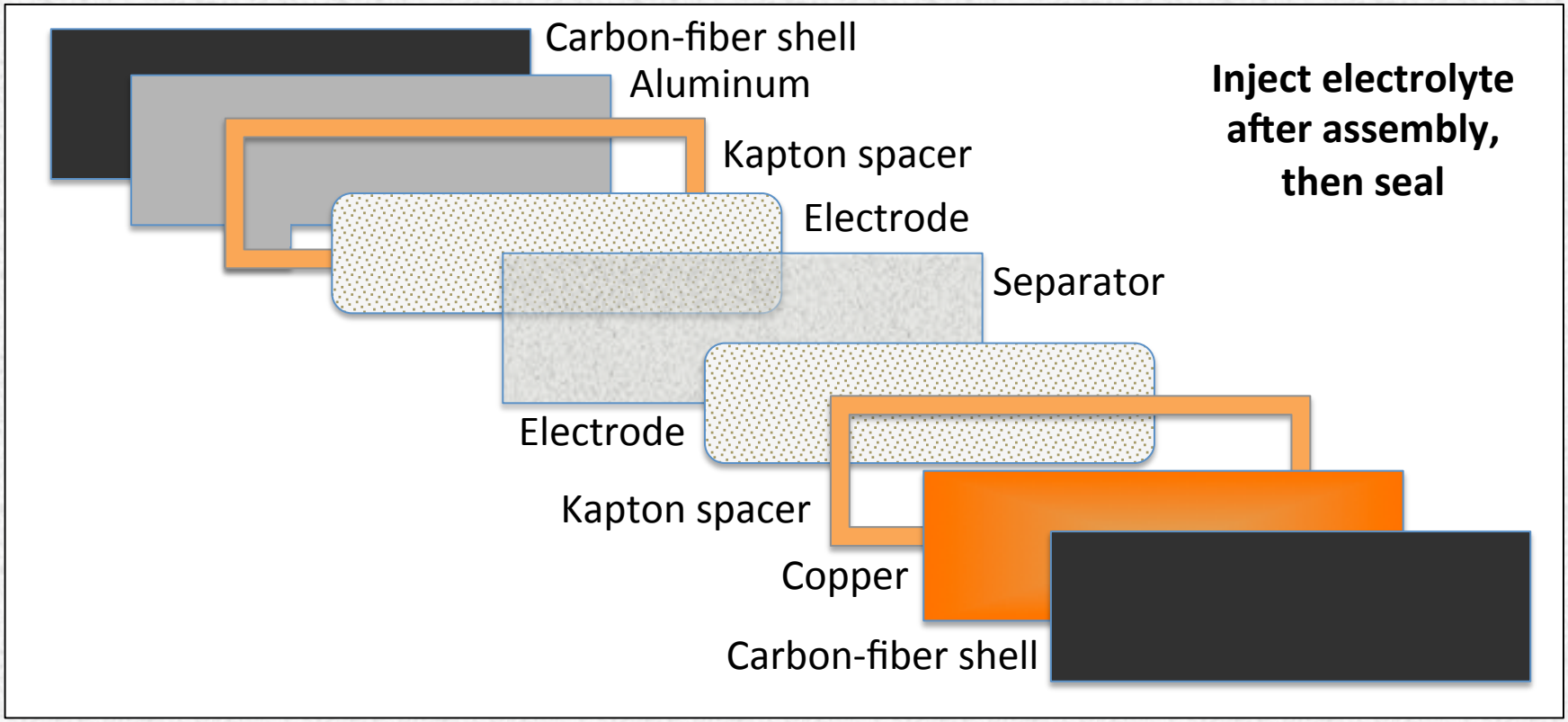
Batteries

- "Best" available commercially:
  - Li-Po thin-film batteries
    - 400 mg, ~1 W for ~1 minute.

- Power density sufficient, but we need it lighter
  - Option 1: cut and reseal
  - Option 2: make our own
    - Collaboration with Belcher lab at MIT

Batteries

- In-house battery manufacturing:
  - Design so that casing of battery is part of the bee's structure
  - Wire internally for higher voltage outputs

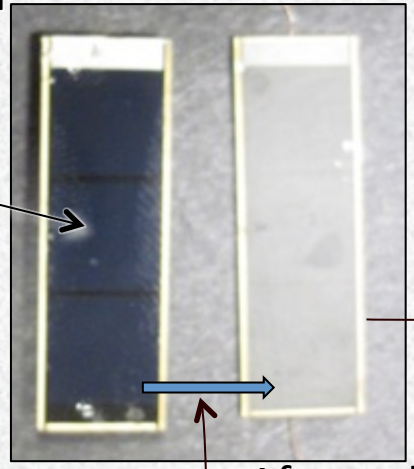


Solar Cells – thickness reduction

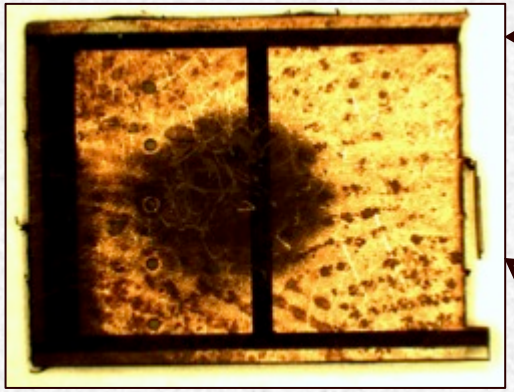
Lapmaster

~2 cm

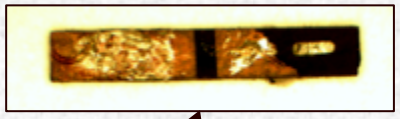
Off-the shelf:
1-sun rating:
1.5 V, 15 mA
~500 mg
0.045 mW/mg



After polishing:
~90 - 100 mg



More polishing, plus cut with laser
6 mm x 6 mm: ~23 mg



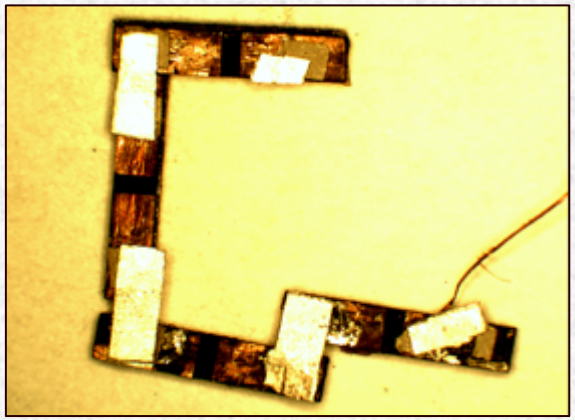
~5 mm x 1 mm
~3-3.5 mg
~0.48 V and ~2.5 mA @ 1 sun

Cut with DPSS laser **~0.37 mW/mg**

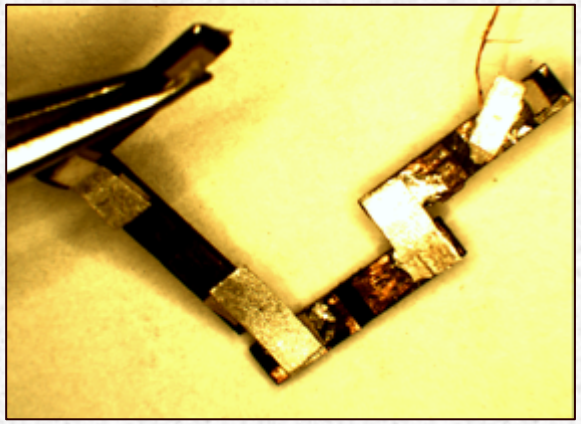
=> Factor of ~8 increase in power density

Solar Cells - wiring

- Wiring the laser-cut cells:
  - Conductive film adhesive, with a bridge of silver-ink coated PVDF



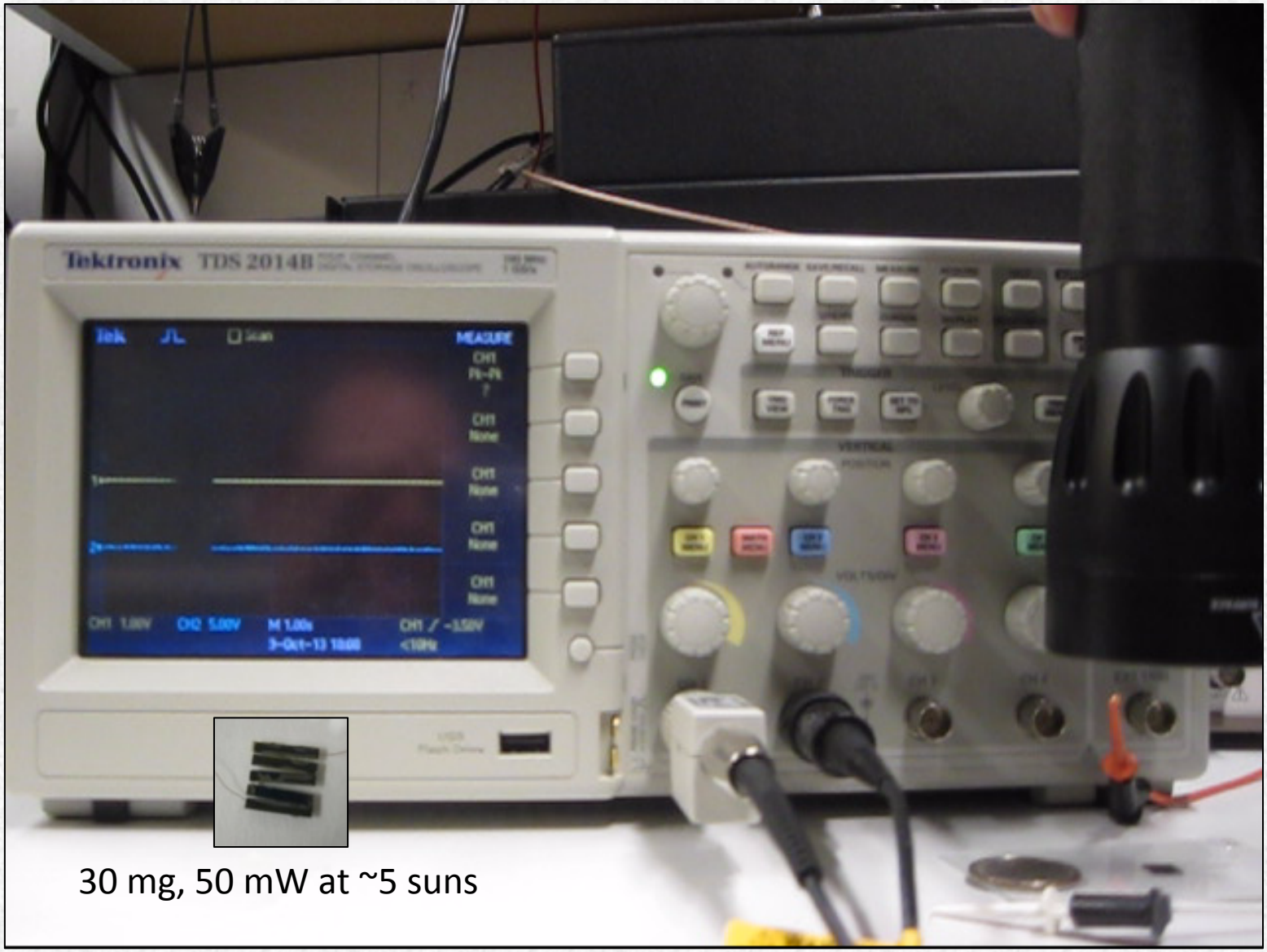
~15 mg



- Makes low resistance (<0.2 ohms), flexible connection

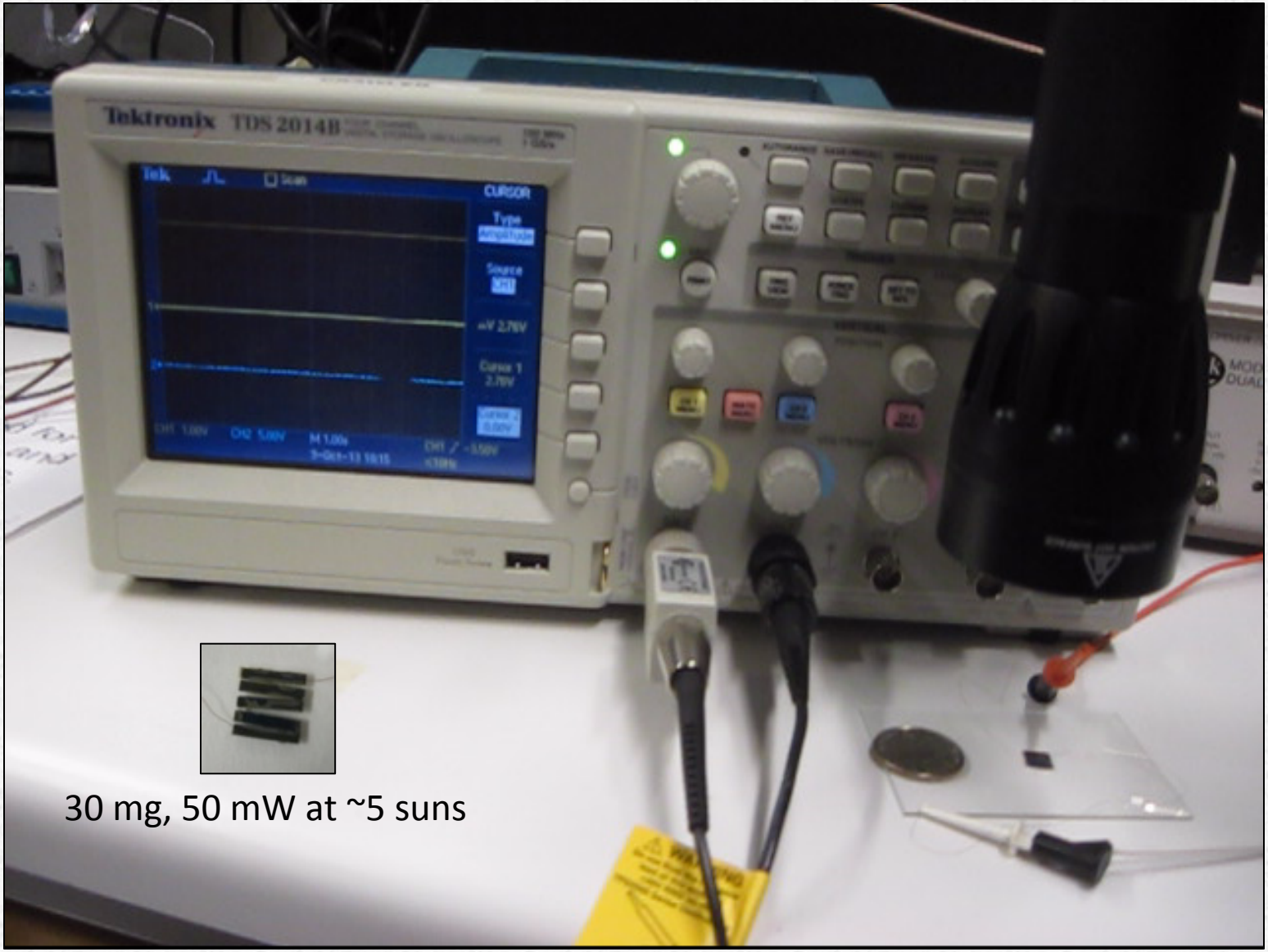
<u>Potential for integration as a structural element</u>

Solar power supply

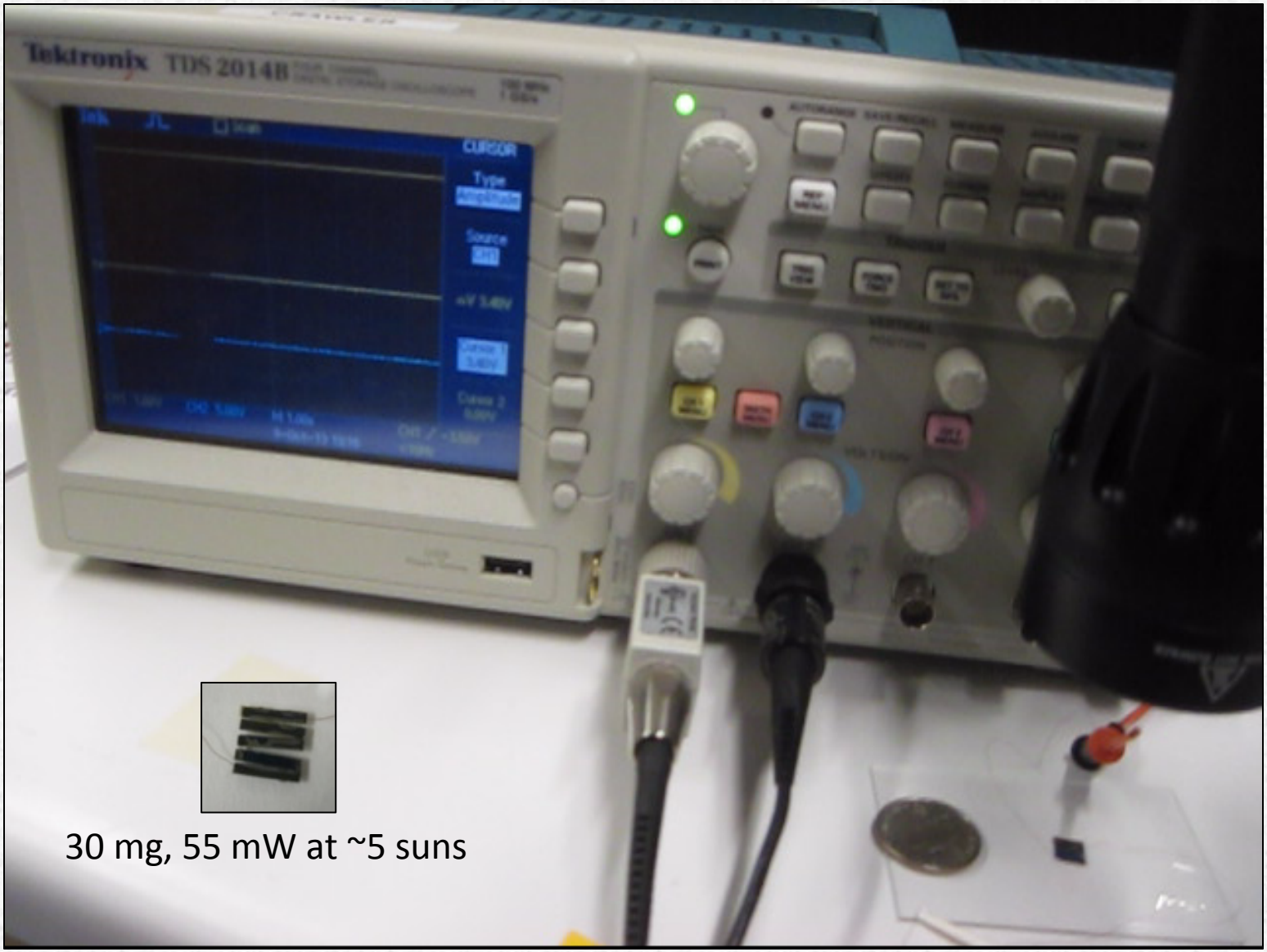


30 mg, 50 mW at ~5 suns

Solar power supply



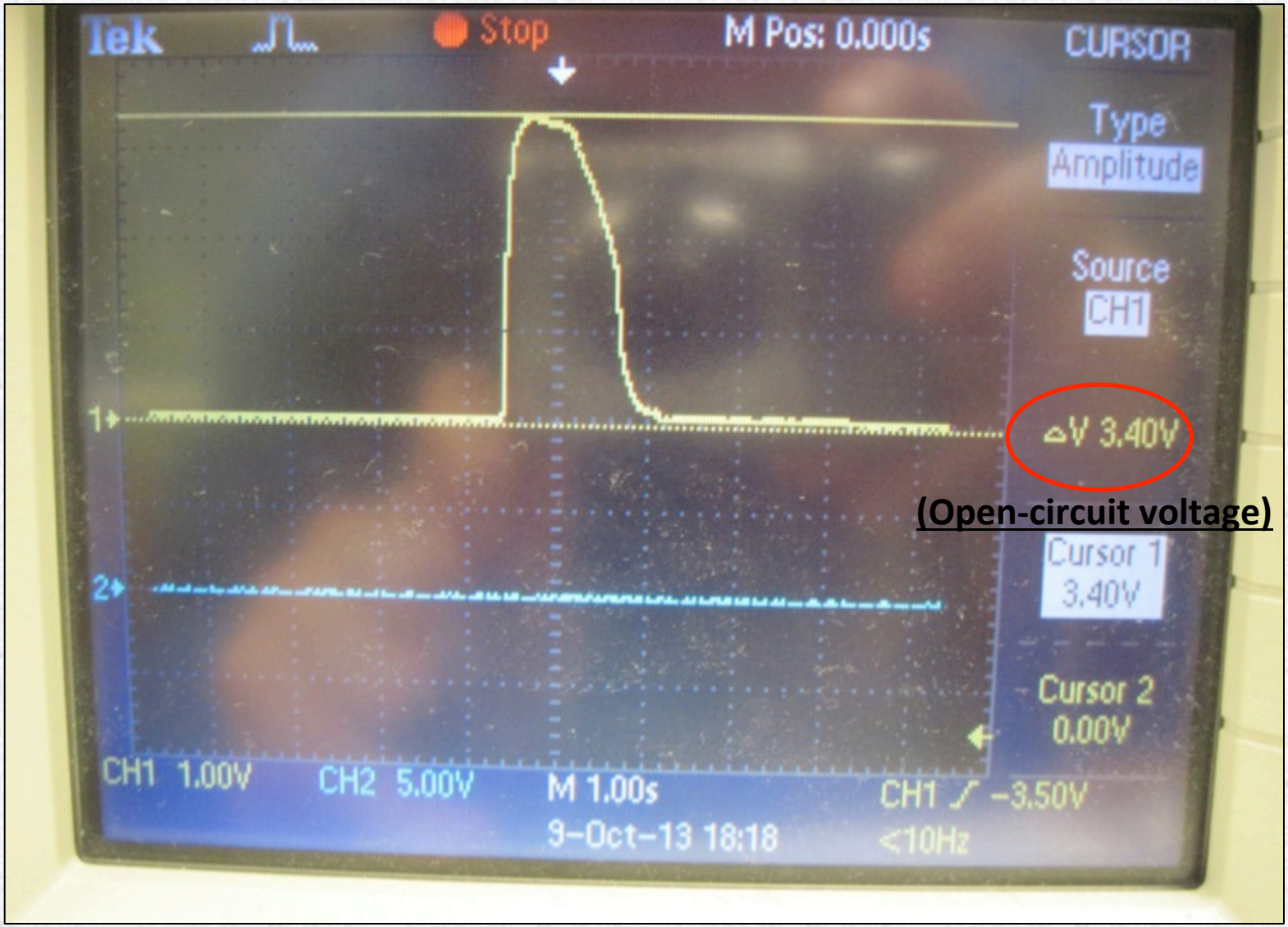
Solar power supply



30 mg, 55 mW at ~5 suns

Solar power supply

Solar power supply

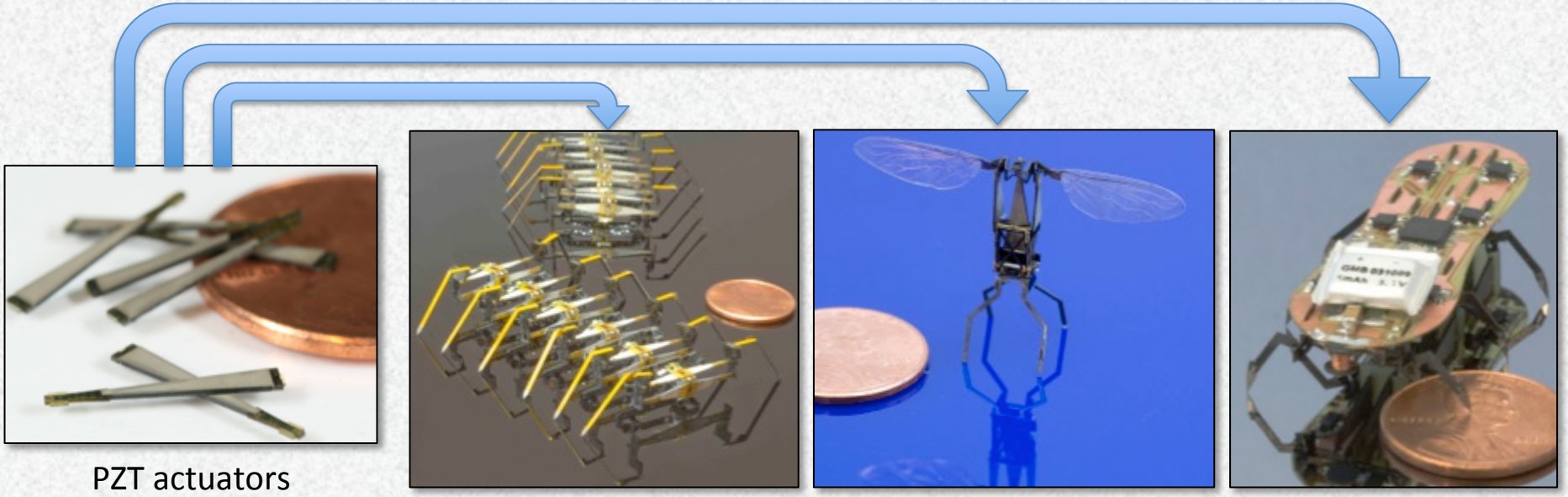


(Open-circuit voltage)

Outline

- Overview
  - Manufacturing process
  - RoboBee operation
- Towards autonomy
  - Sensors
  - Power
  - Actuators
  - Scaling

Actuators for Microrobots



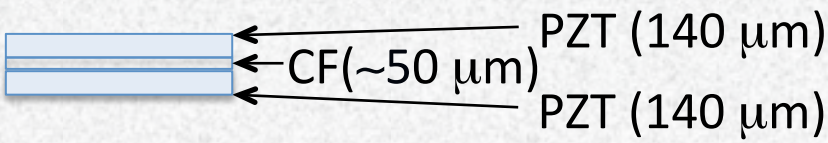
PZT actuators

Centipede Milirobot
(K. Hoffman)

Harvard Robobee
(B. Finio)

HAMR3
(A. Baisch)

- Bimorph cantilever actuators:
  - Symmetric laminate of polycrystalline PZT with central carbon-fiber composite layer:



- Manufacturing:
  - A sheet of the piezoelectric ceramic is first scored utilizing a DPSS Laser, then supported at the score line and cleaved.
- **How can we adjust this process to optimize actuator energy density?**

Actuators for Microrobots

Actuation requirements: moderate strain, large force, high efficiency, high bandwidth, low mass (high power density)

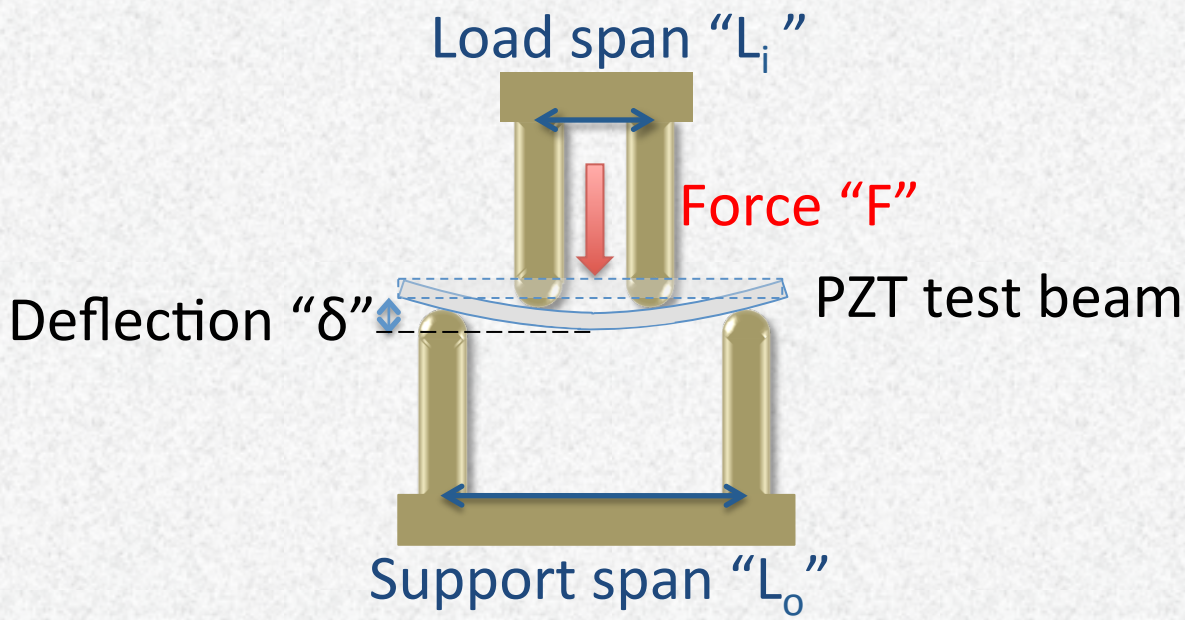
●=*highest*, ◕=*high*, ◐=*moderate*, ◔=*low*, ○=*lowest*

type	example	efficiency	toughness	bandwidth[1]	max. ϵ	max. σ	density
bulk piezo.	PZT-5H[2]	◐	◐	●	○	◕	●
single crystal	PZN-PT[3]	◐	○	●	◐	◐	●
AFC	PZT-5A[4]	◐	◐	●	◐	◐	◐
SMA	Nitinol[5]	○	◕	◐	◐	●	●
IPMC	Nafion[6]	◐	◐	◐	●	◐	◐
EAP	DE[7]	◐	◐	◐	●	◐	◐
electromag.	brushless[8]	◕	NA	◐	NA	NA	●

[1]depends upon structure geometry
[2]from Piezo Systems, http://www.piezo.com
[3]single crystal piezoelectric ceramics
[4]active fiber composites from Advanced Cerametrics, http://www.advancedcerametrics.com
[5]shape memory alloy, http://www.dynalloy.com
[6]from DuPont
[7]dielectric elastomers
[8]for example 0308 brushless DC micro-motor from Smoovy, http://www.faulhaber-group.com

PZT Material Characterization

- **4-point bend tests on PZT beams**
  - 25 mm long, 2 mm wide "b", 140 μm thick "d"

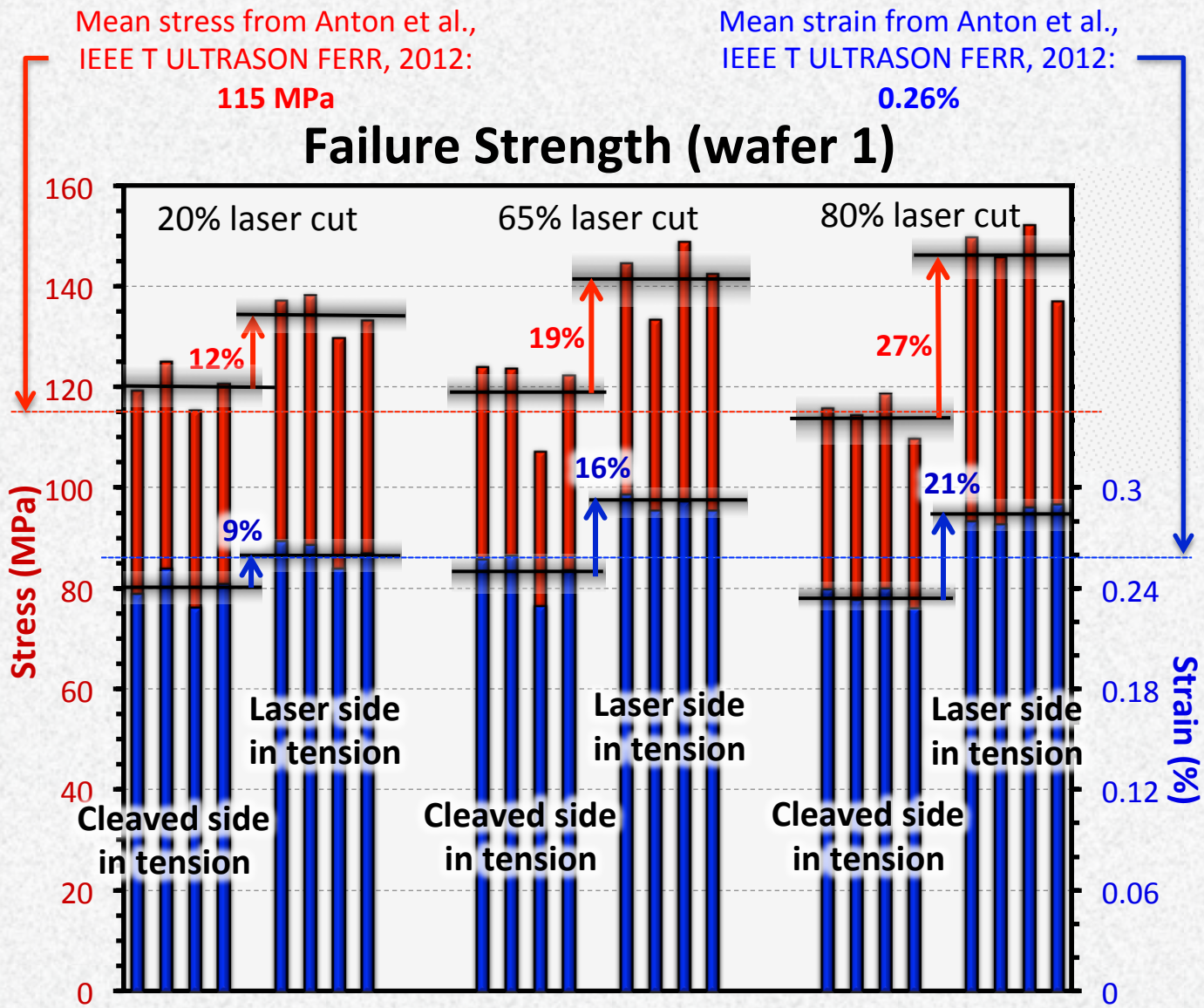


- Maximum stress (σ) and strain (ϵ) at the beam's surface are given by:

$$\sigma = F * 1.5\,(L_o - L_i) / (b\,d^2)$$

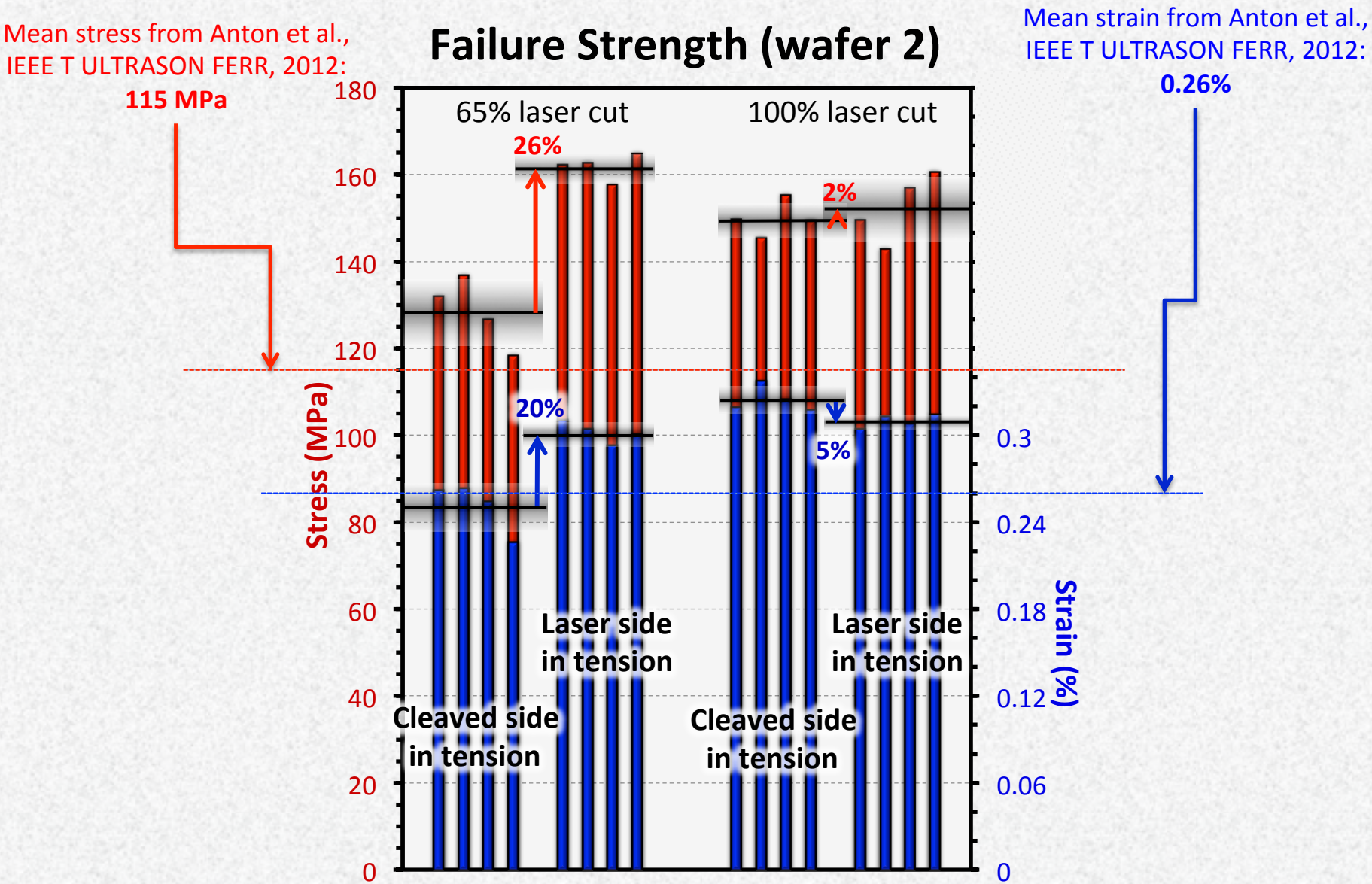
$$\epsilon = \delta * 6\,d / (L_o - L_i)(L_o + 2L_i)$$

PZT Strength Tests



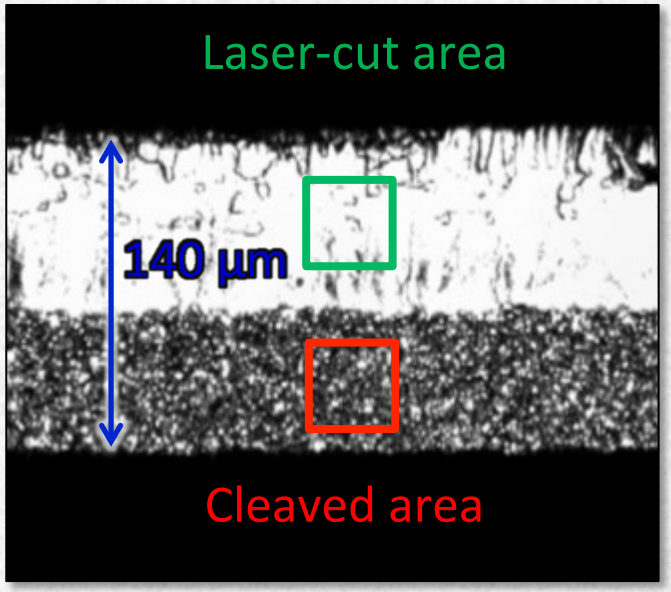
~10% - 25% increase in failure strength is seen when the laser-cut side is in tension.

PZT Strength Tests



PZT Strength Tests

Image showing a cross-section
of 60% laser-cut PZT:



- Average roughness (R_q) decreases from 1.62 µm RMS in the cleaved area to 0.66 µm RMS in the laser-cut area.

  ⇒ This is likely the cause of the increase in failure strength.

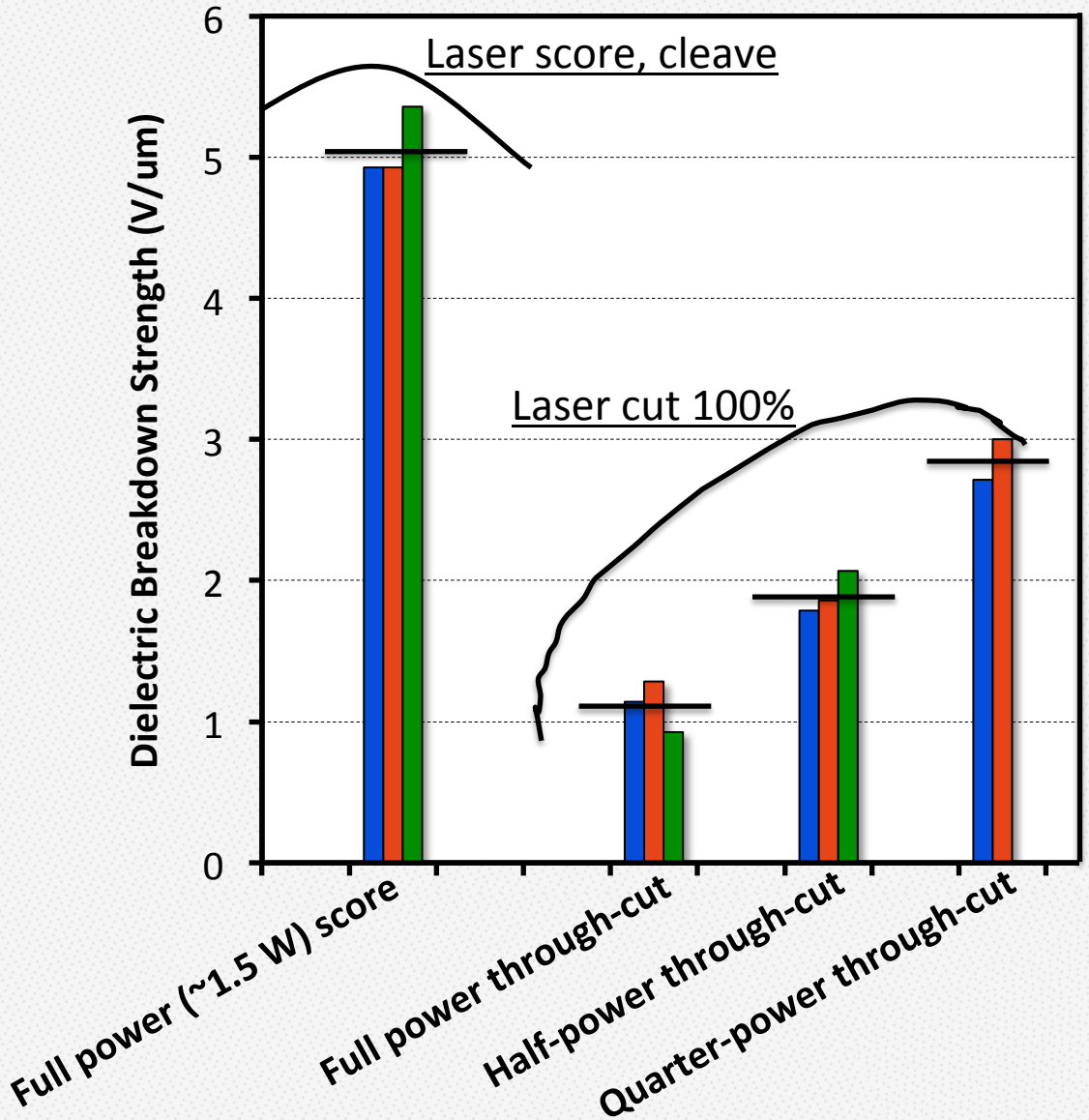
Actuator Manufacturing

- Bending tests indicate that cutting further through the PZT with the laser increases fracture strength
  - However, cutting at 100% power reduces the electrical breakdown strength to ~1 V/um (compare with air: ~3 V/um)
  - This is unchanged after ultrasound

- Solution: reduce power to 20%, increase number of passes
  - For through-cut of 130 um PZT, use 800 passes, stage up 13 ticks (or ~65 um), another 800 passes
  - For through-cut of 60 um PZT, use 400 passes

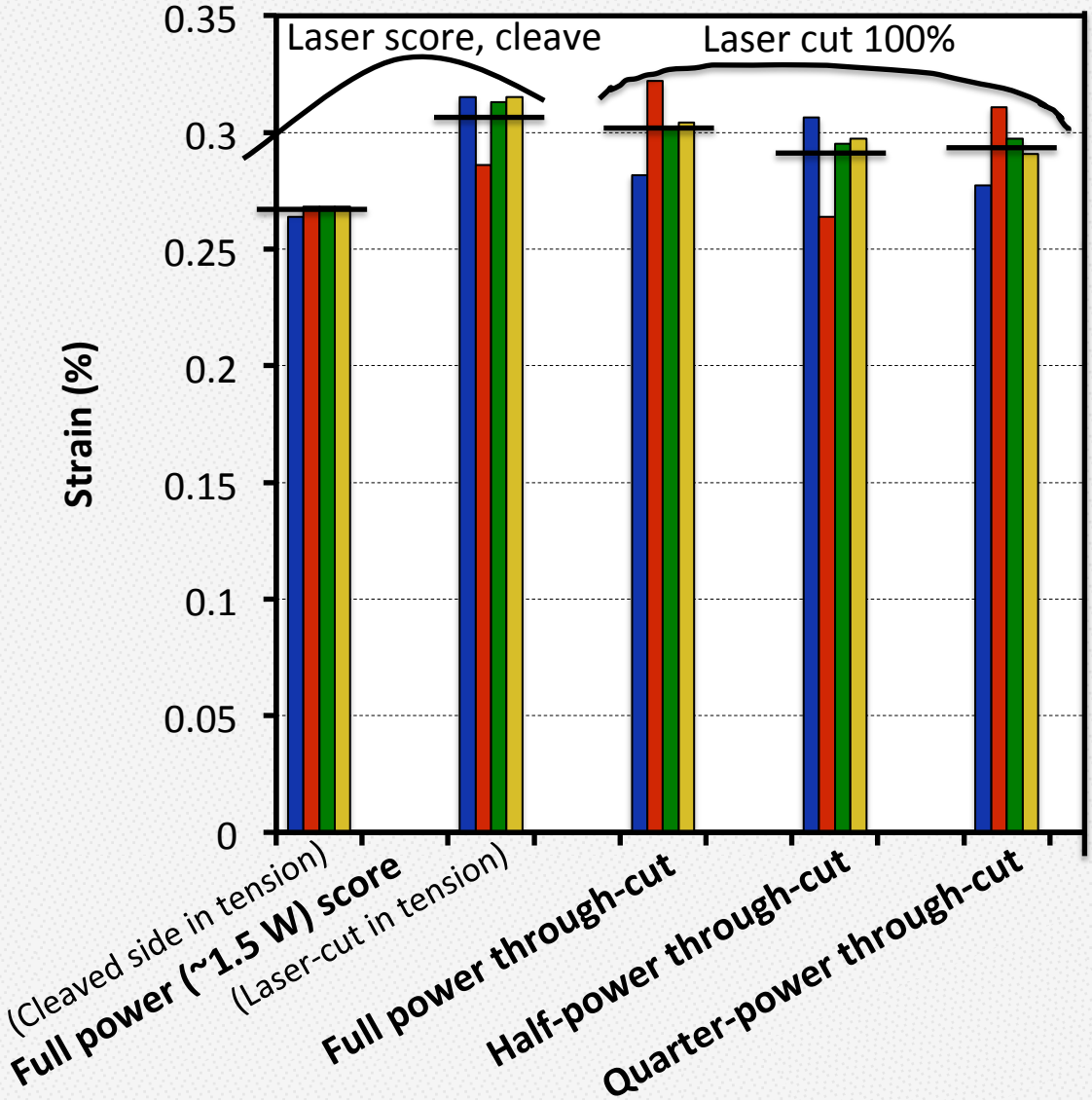
- To increase the electrical breakdown strength beyond that of air:
  - Coat edge with CA glue: ~6 V/um
  - Increase laminating pressure from 7.5 lbs/inch^2 to 15 lbs/inch^2 => some of the resin squeezes out and coats the edges.
  - Parylene: to be determined

PZT laser-cut optimization

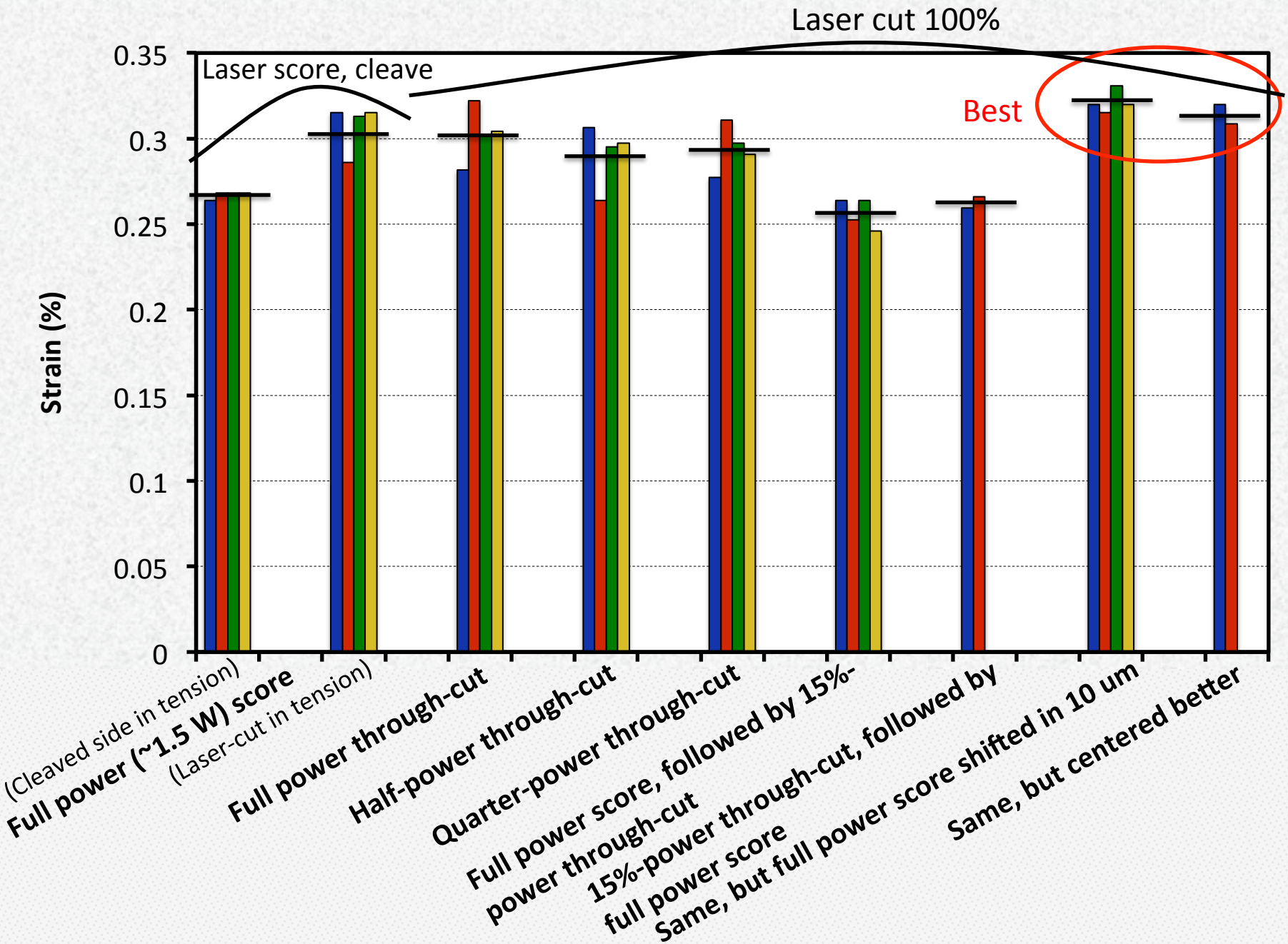


- Laser increases flexural strength, but decreases breakdown strength

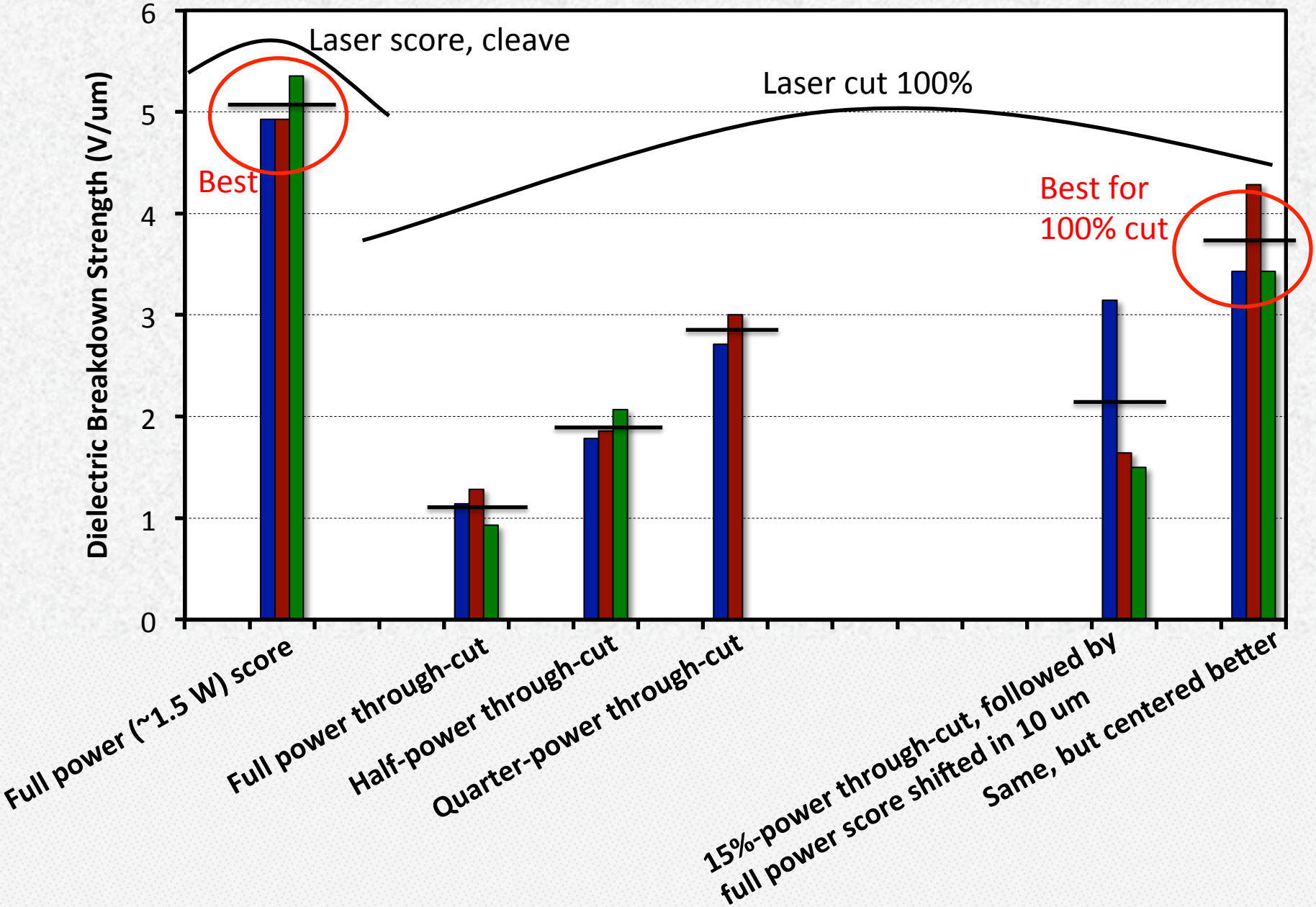
PZT laser-cut optimization



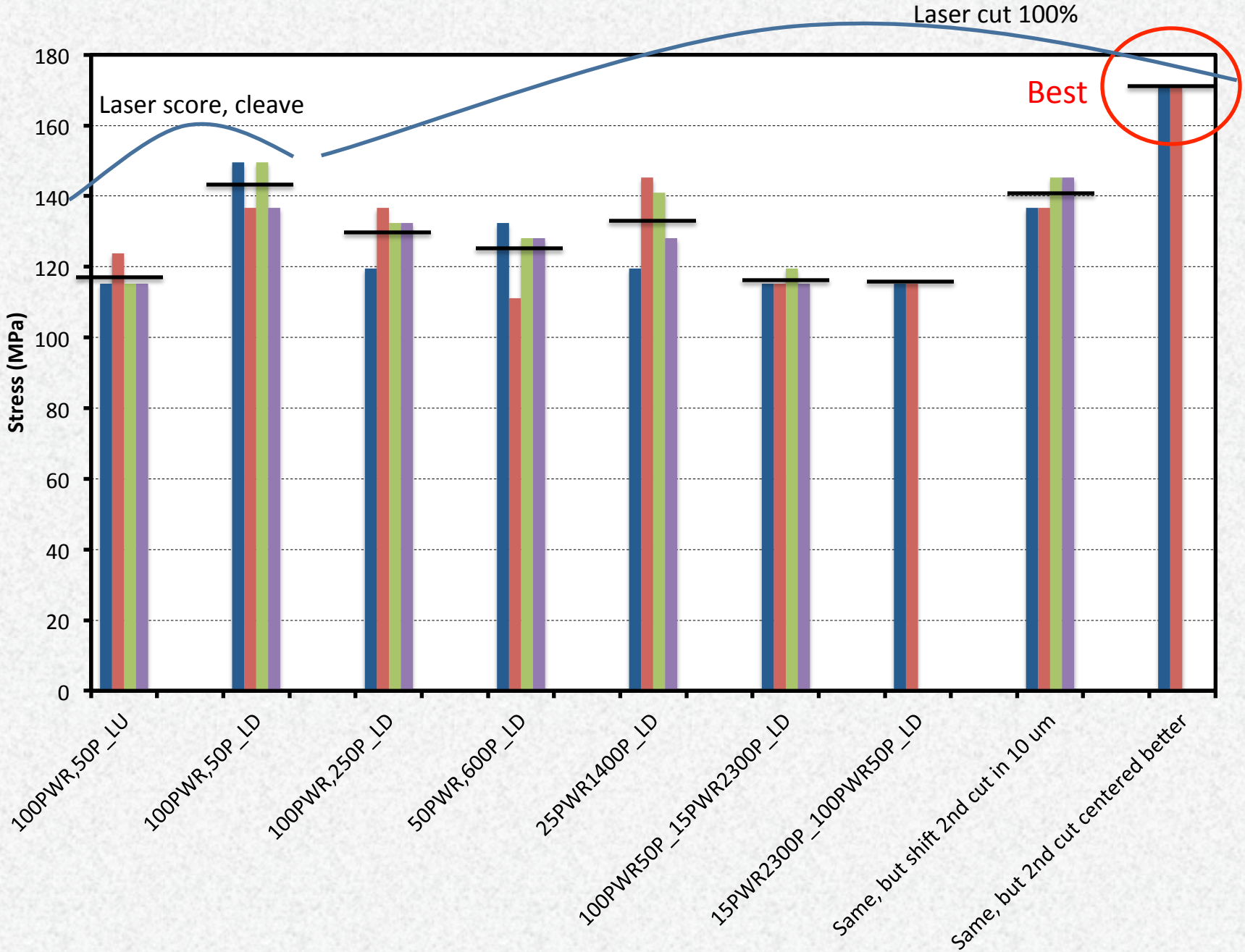
PZT laser-cut optimization



PZT laser-cut optimization

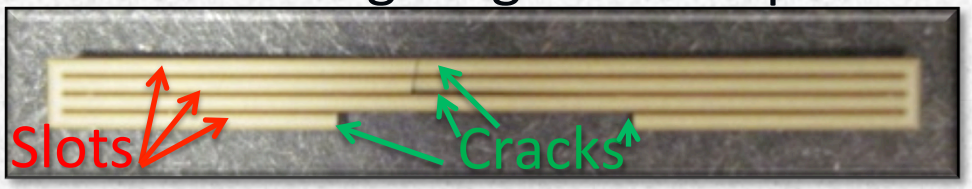


PZT laser-cut optimization



Crack-Arresting Features

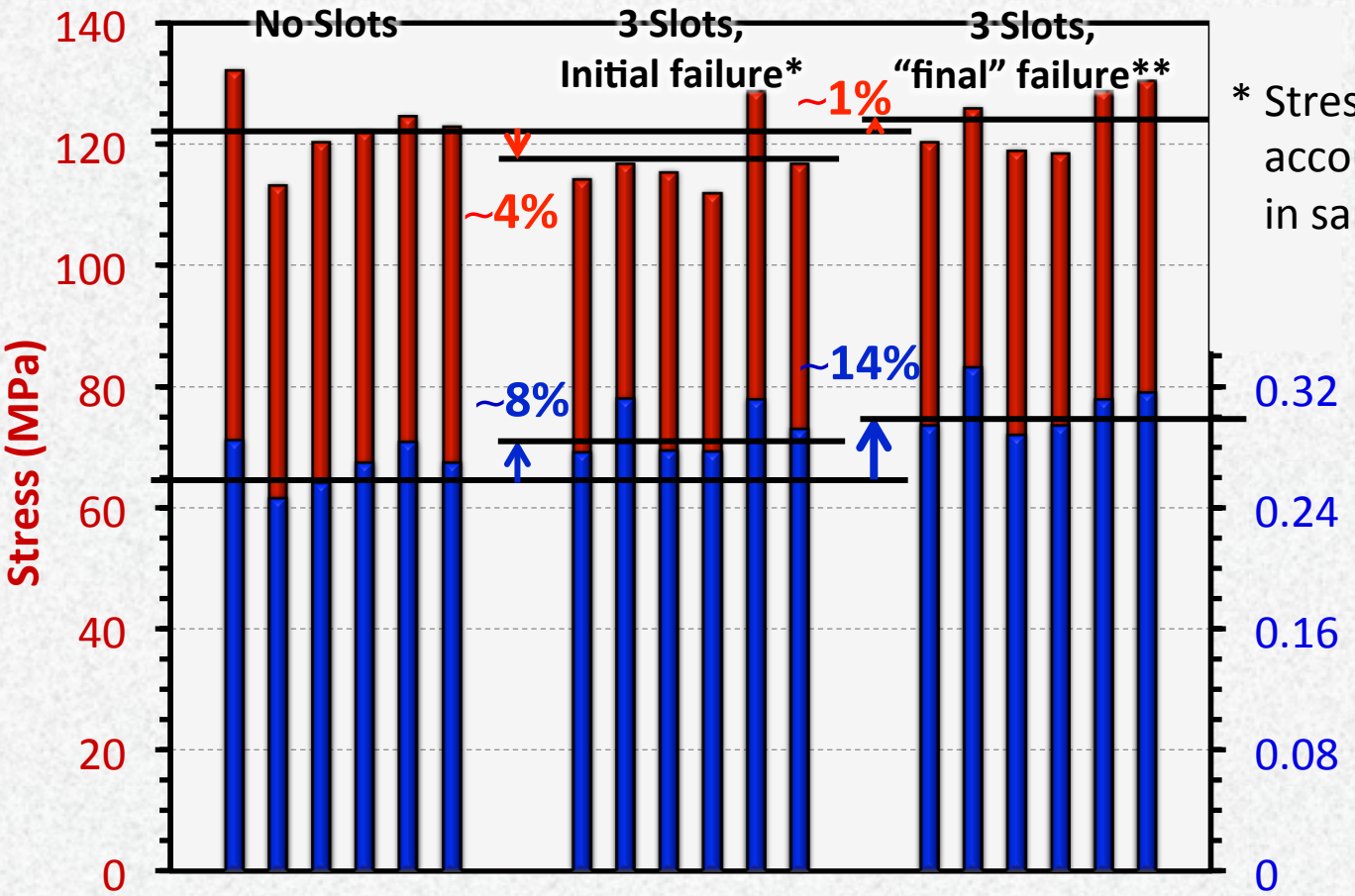
Slots cut along length of sample:



Cracks stopped by the slots

Failure Strength

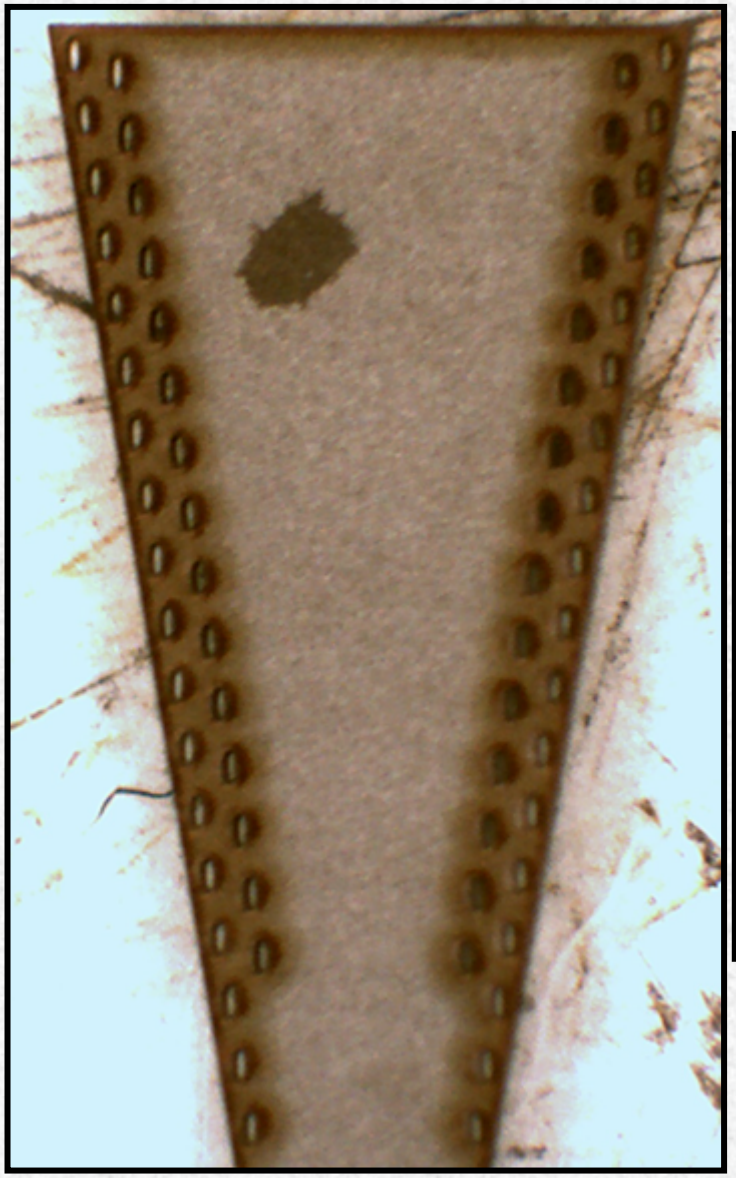
For all samples: Laser side is in tension, outside is ~65% laser cut, slots are ~100% laser cut

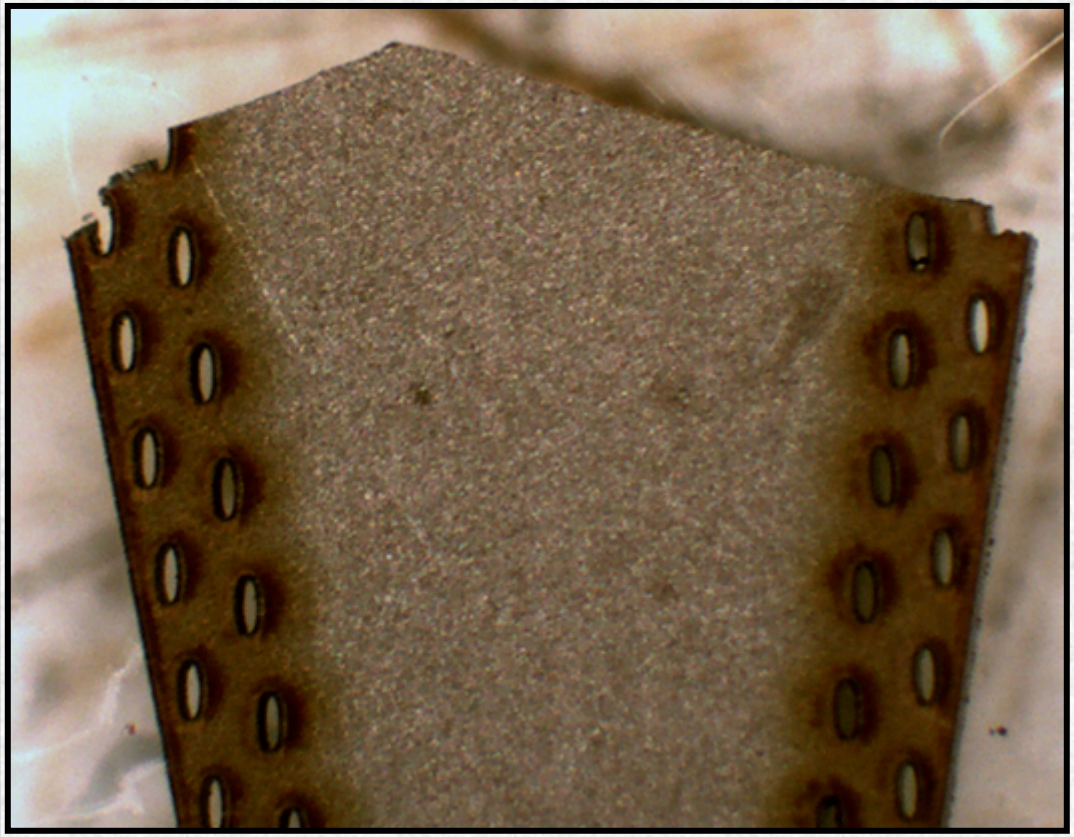


* Stress adjusted to account for reduction in sample width.

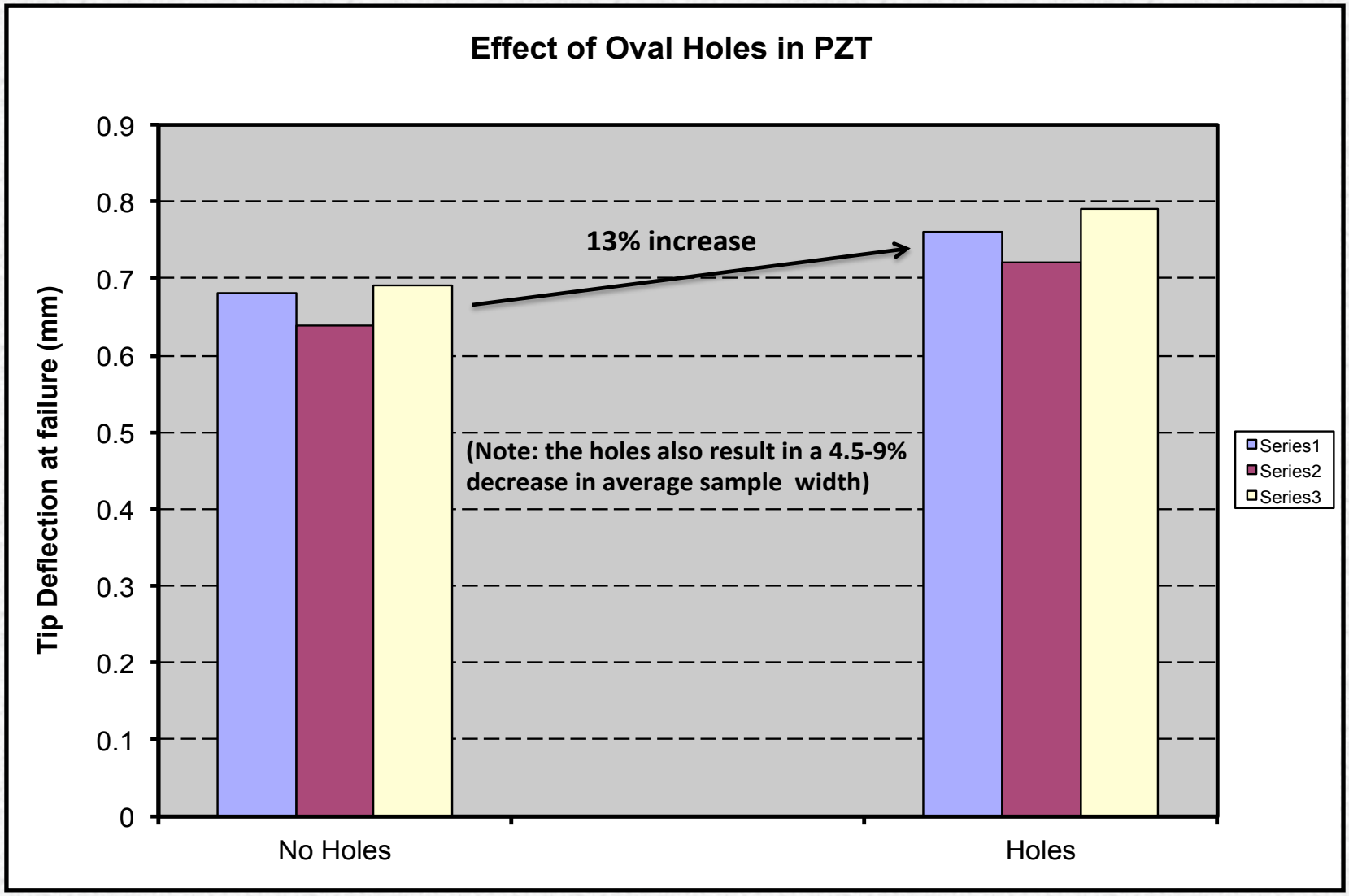
- **Strain at "final" failure ~14% greater for the slotted samples.**

Holes in PZT

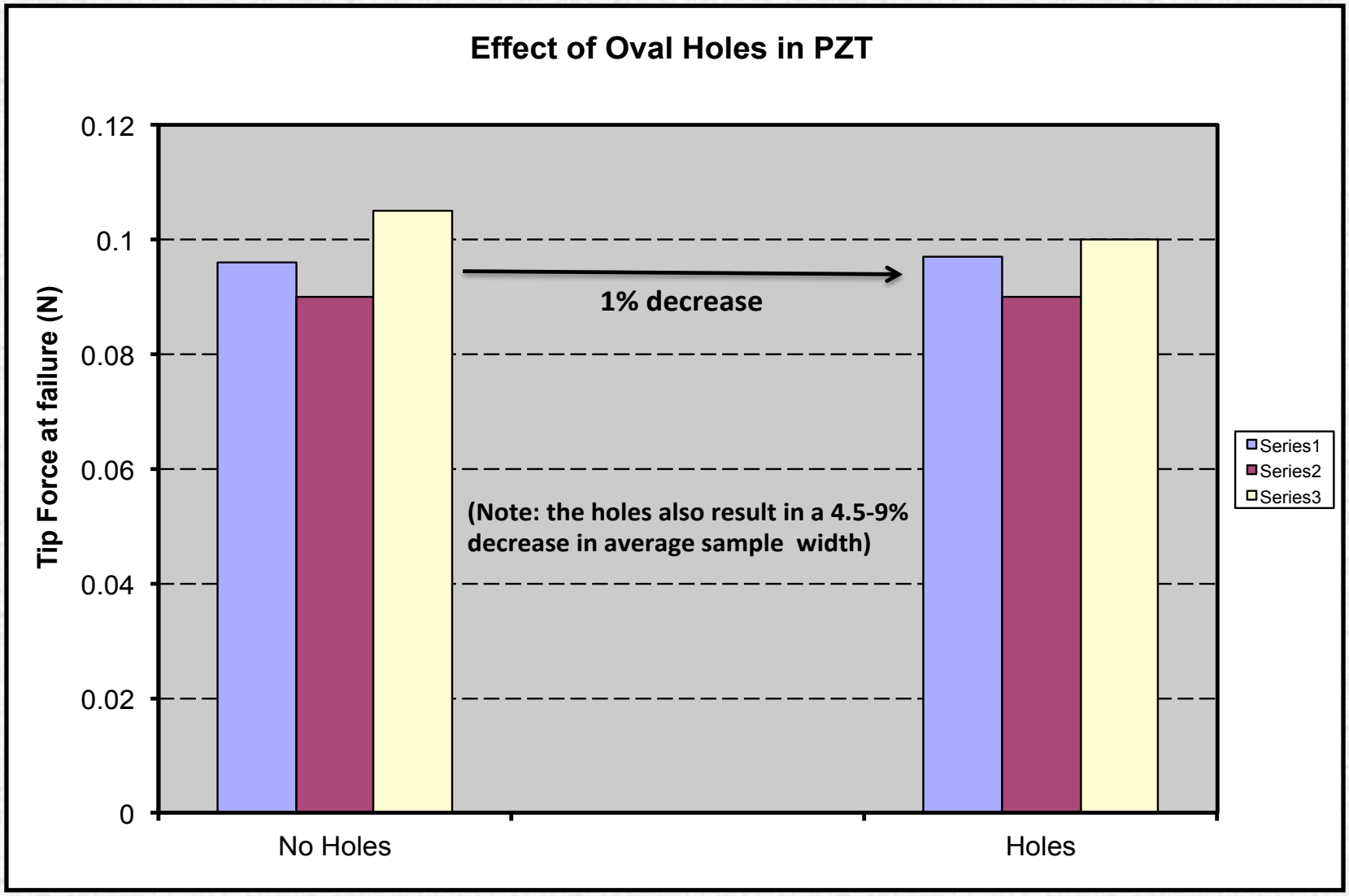




Holes in PZT


Effect of Oval Holes in PZT
Tip Deflection at failure (mm)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
13% increase
(Note: the holes also result in a 4.5-9% decrease in average sample width)
No Holes
Holes
Series1
Series2
Series3

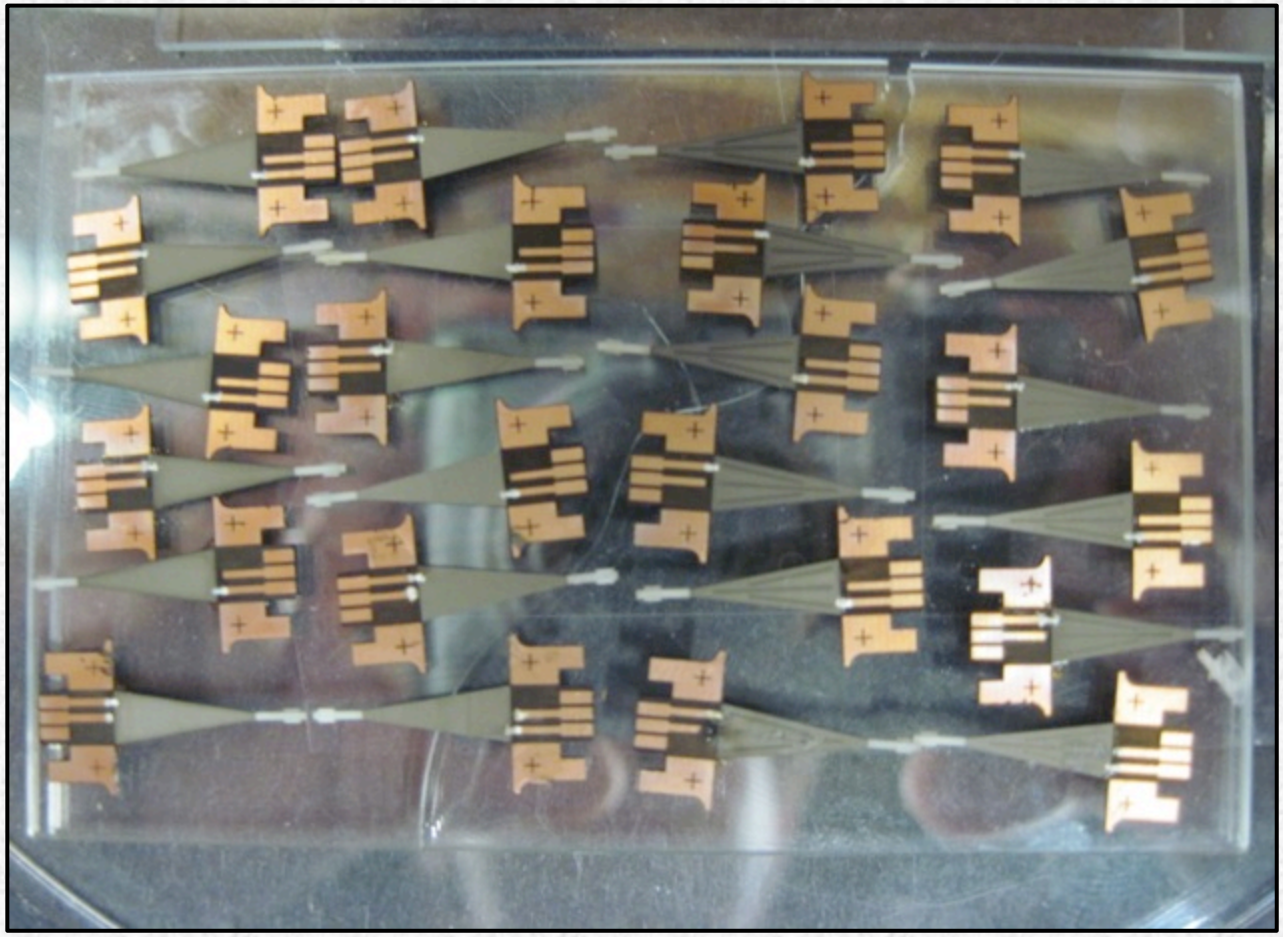
Holes in PZT


Effect of Oval Holes in PZT
Tip Force at failure (N)
0.12
0.1
0.08
0.06
0.04
0.02
0
No Holes
Holes
1% decrease
(Note: the holes also result in a 4.5-9% decrease in average sample width)
Series1
Series2
Series3

Outline

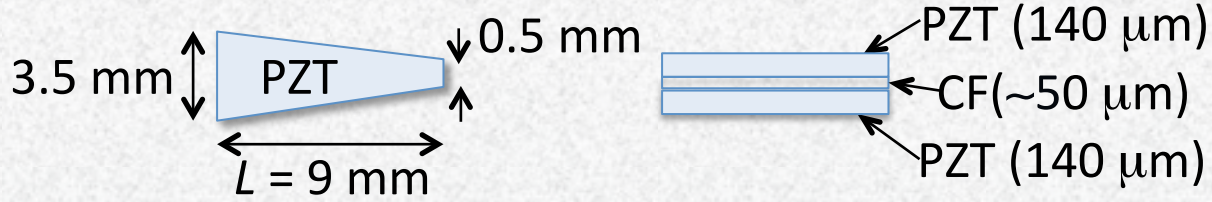
- Overview
  - Manufacturing process
  - RoboBee operation
- Towards autonomy
  - Sensors
  - Power
  - Actuators
  - Scaling

Actuator Testing



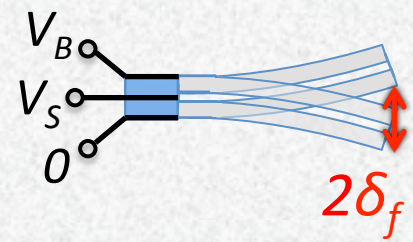
PZT Actuator Characterization

- **Free-deflection tests on PZT actuators**:



- Apply a voltage of the form:

$$V_s(t) = 0.5\,(1 + V_B \sin(2\pi f t))$$

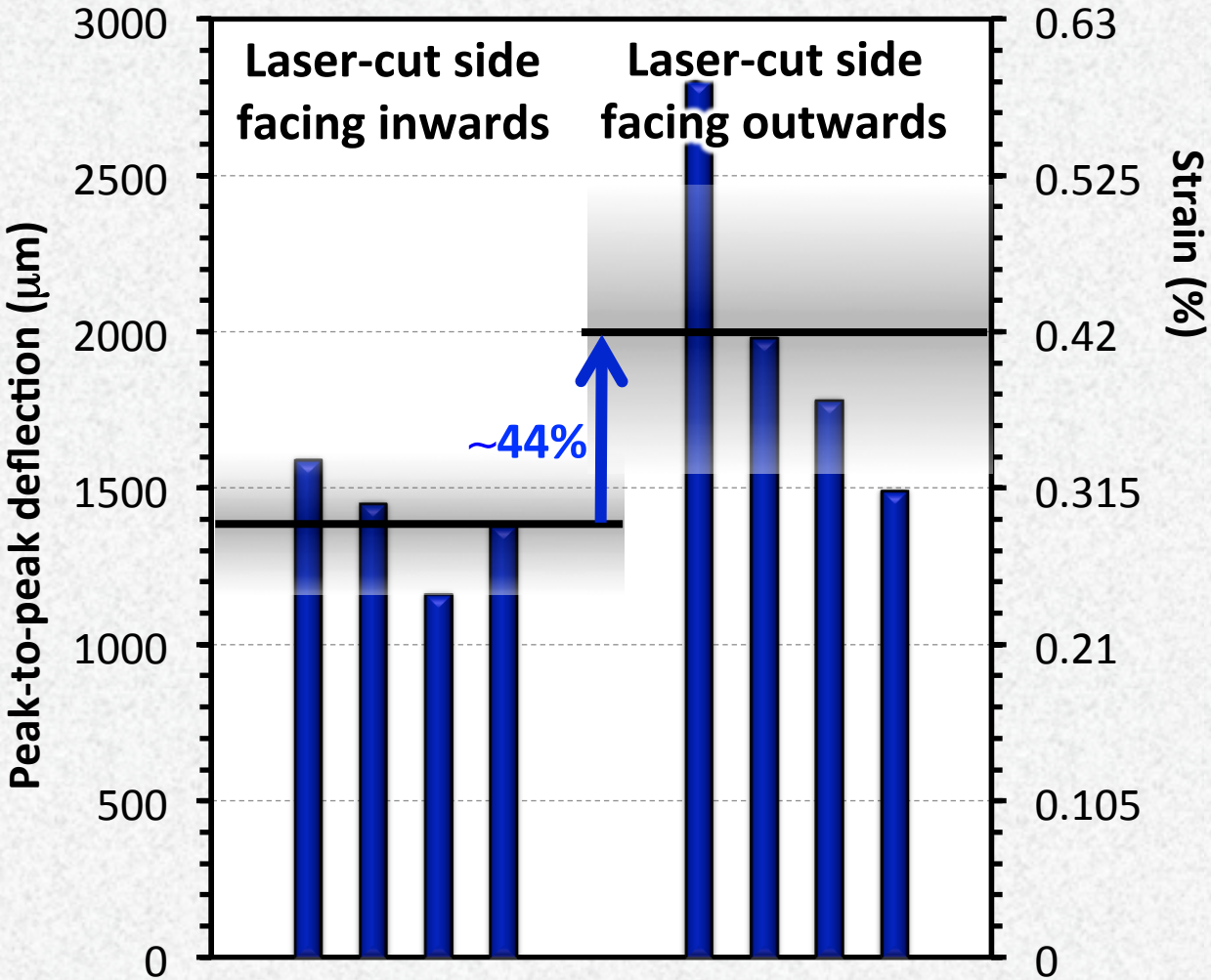


- Max strain (on the surface) is given by:

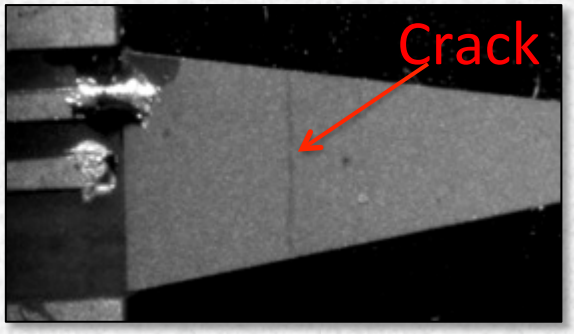
$$\epsilon \approx \delta_f (2t_{PZT} + t_{CF})/L^2$$

Actuator Flexural Strength

• *Edge treatment to allow greater deflection:*



Example of typical failure mode – a transverse crack through the PZT:

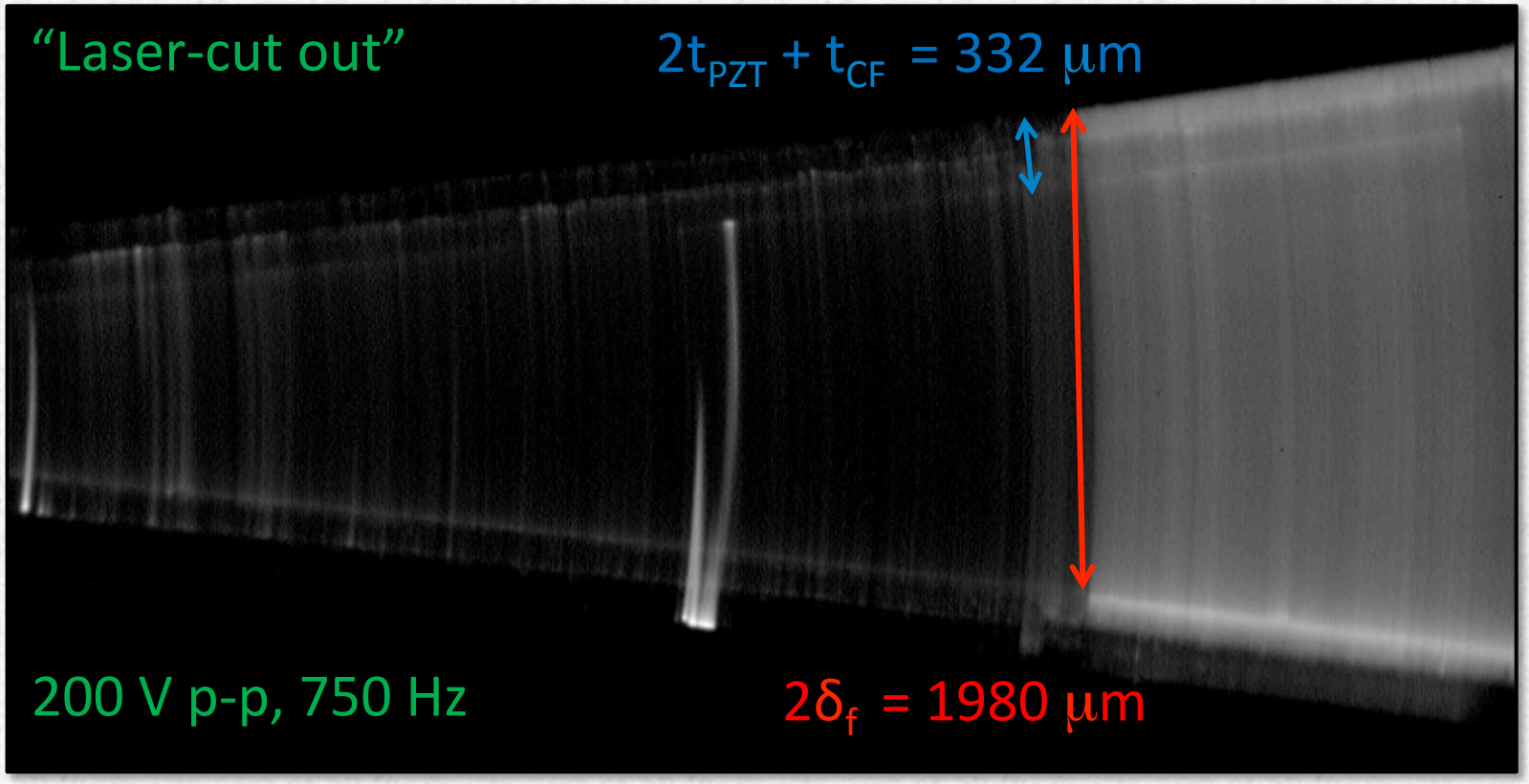


(For all samples: Laser cut is ~65% through the samples, and Vb = 200 V)

- Frequency is increased until failure occurs.

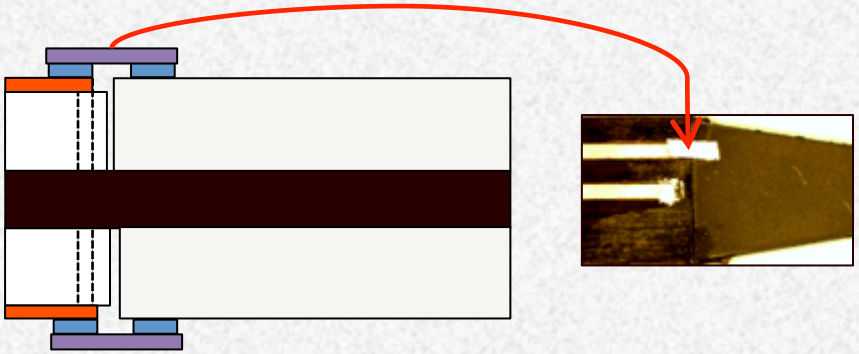
Actuator Flexural Strength

Example of actuator vibration just before failure:



Actuator Manufacturing

- Electrical connections:
  - At high vibration amplitudes/frequencies, the conductive epoxy debonds from the PZT and/or develops cracks
  - Solution: Conductive film adhesive on PZT and copper-clad FR4, with a bridge of silver-ink coated plastic (PVDF in this case)



PZT
15 um Conductive Adhesive (ESP8660 from AI Tech)
Carbon Fiber Composite
Copper-clad FR4
Silver Ink coated PVDF

Outline

- PZT actuators
  - Laser cut optimization
  - Elimination of manual assembly
- Solar power supply
- Intermittent flight vehicle
  - Thrust improvements
  - Stroke & hinge angle code
  - Effect of stops?

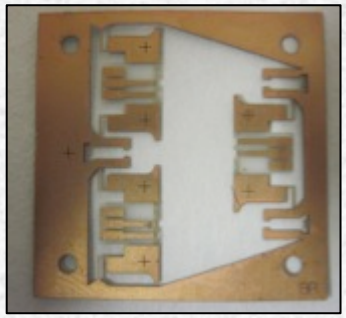
PZT actuator manufacturing

<u>Current process:</u>

Cut PZT (and other materials) separately
Manually place into alignment jig for bonding process
Separate copper etching and conductive epoxy steps required

Laser score & cleave PZT

+



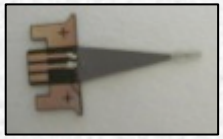
Cut Cu-clad FR 4 with laser, use photoresist mask to wet etch copper

+ etc..

Cut CF and Al2O3 with laser

==>

Manually place PZT and Al2O3 tips into jig, heat + pressure to bond



After release cut and conductive epoxy application

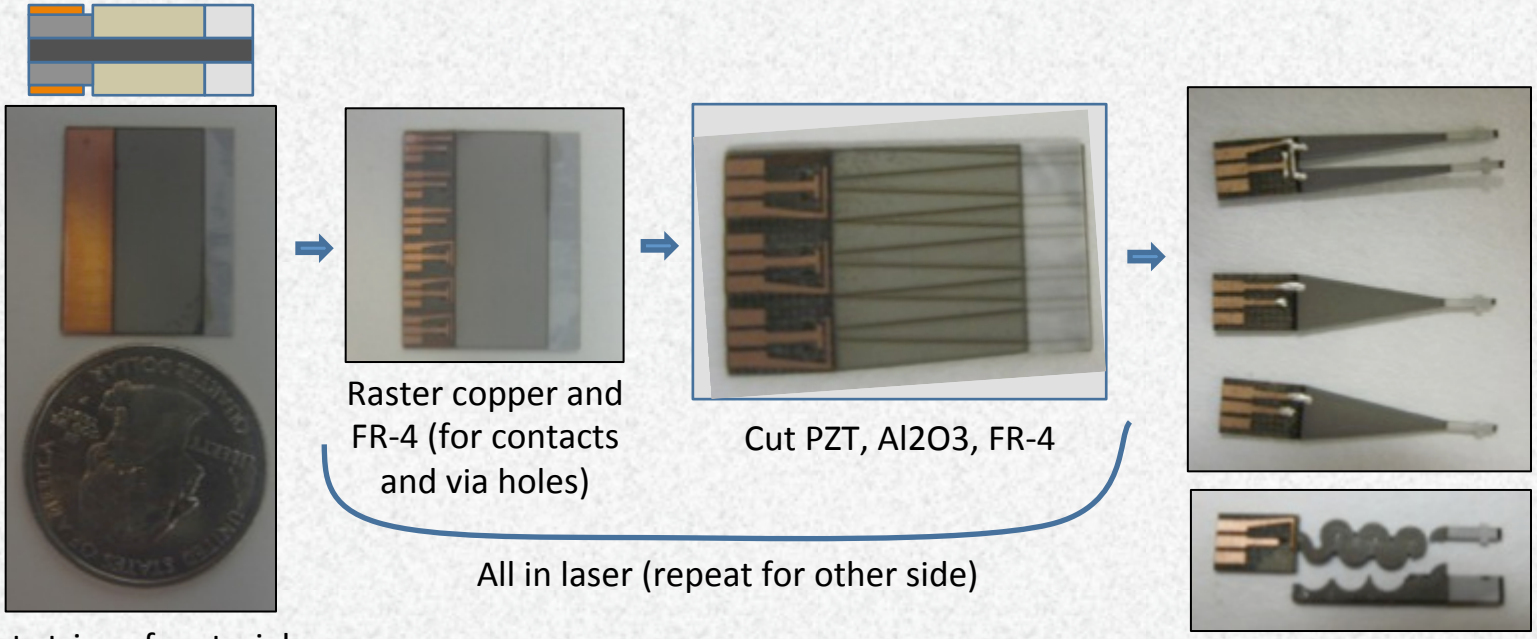
PZT actuator manufacturing

<u>New process – Pre-stacked actuators:</u>

(A) Cut strips of PZT, Al2O3, Cu-clad FR-4, and CF

Bond together

Use laser to cut PZT, Al2O3, FR-4, raster copper, and raster FR-4



Cut strips of materials and bond together

Separate actuators and apply conductive epoxy

Advantages: No manual placement of PZT and Al2O3

All patterning (including copper etching and via holes) done using laser

Disadvantages: Waste half of PZT

Still have conductive epoxy step

Length of actuator fixed from initial stack

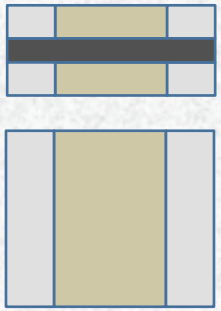
PZT actuator manufacturing

<u>New process – Pre-stacked actuators:</u>

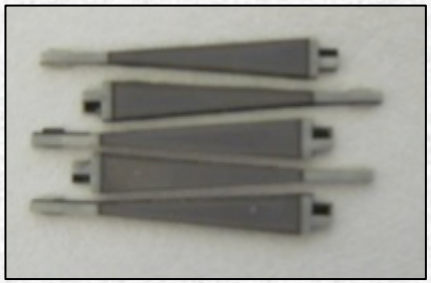
(B) Al2O3 as base as well as tip

Raster Al2O3 without damaging CF

Use electrical "plug" to contact PZT and CF directly



Cut strips of materials
and bond together



Raster Al2O3 (via holes),
cut PZT and Al2O3
[All in laser; repeat for other side]

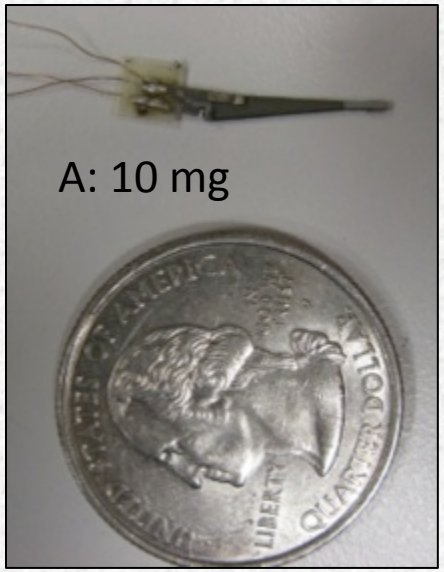
Now no manual assembly at all!

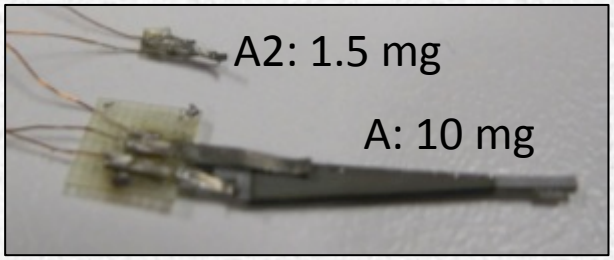
Just make pre-stack, then cut/raster as needed with laser

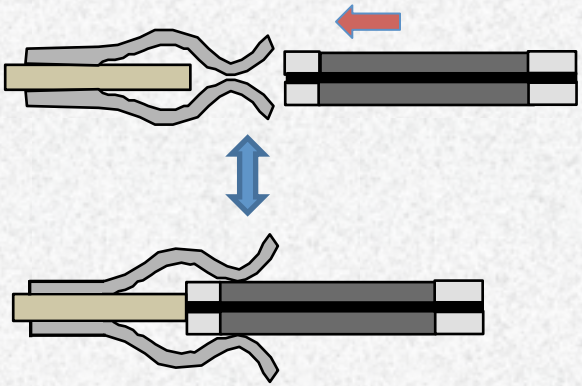
PZT actuator manufacturing

Electrical “plugs”:

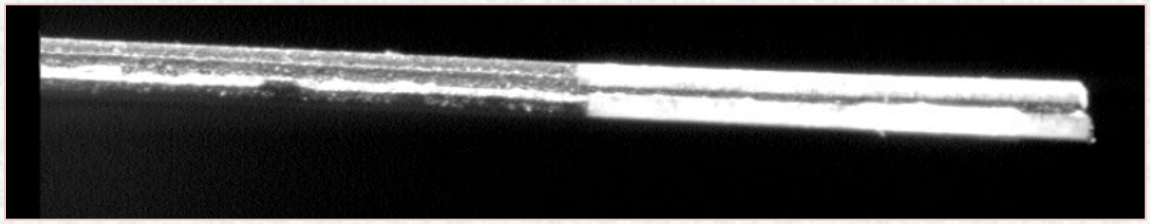
Version A, A2 (manually assembled)





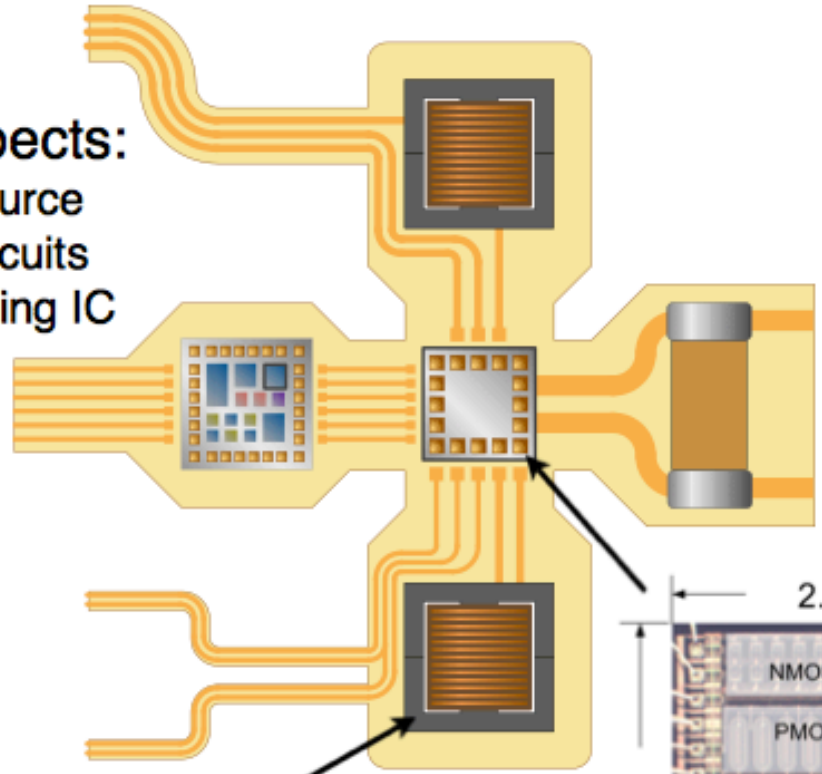


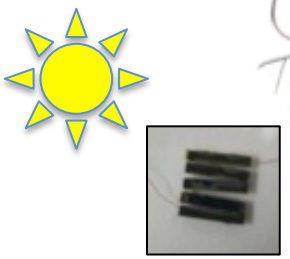
Video:

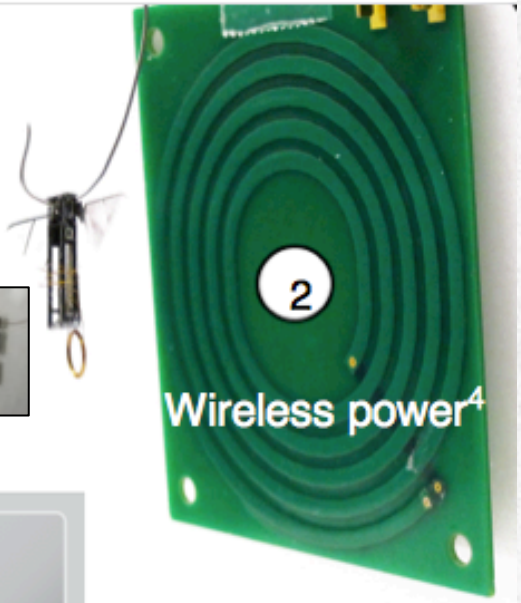


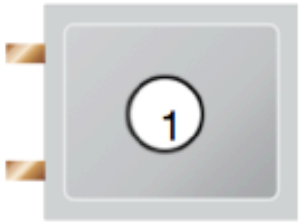
Power architecture

3 key aspects:
1. power source
2. power circuits
3. coordinating IC

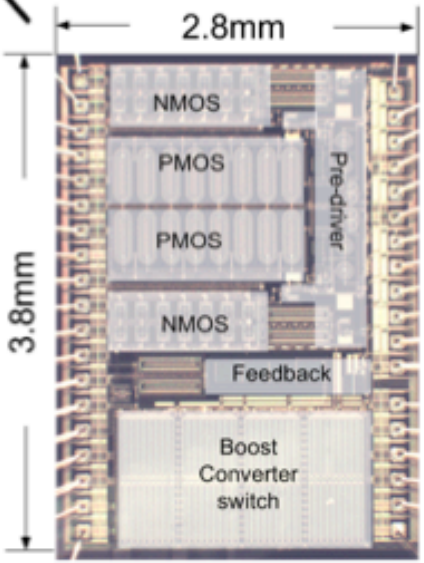




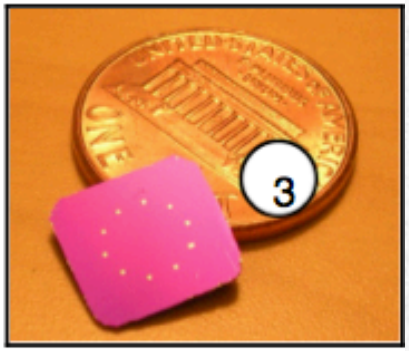




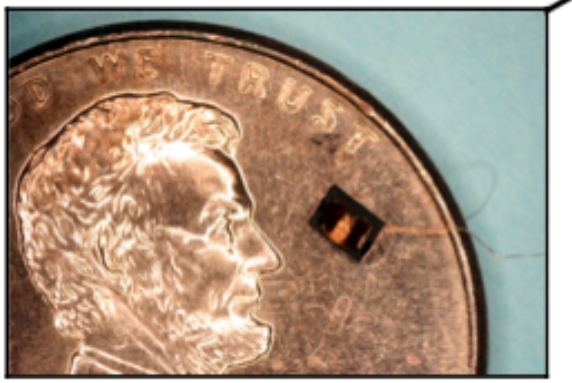
Battery



High voltage IC[2]



Micro fuel cells[3]



Custom magnetic components[1]

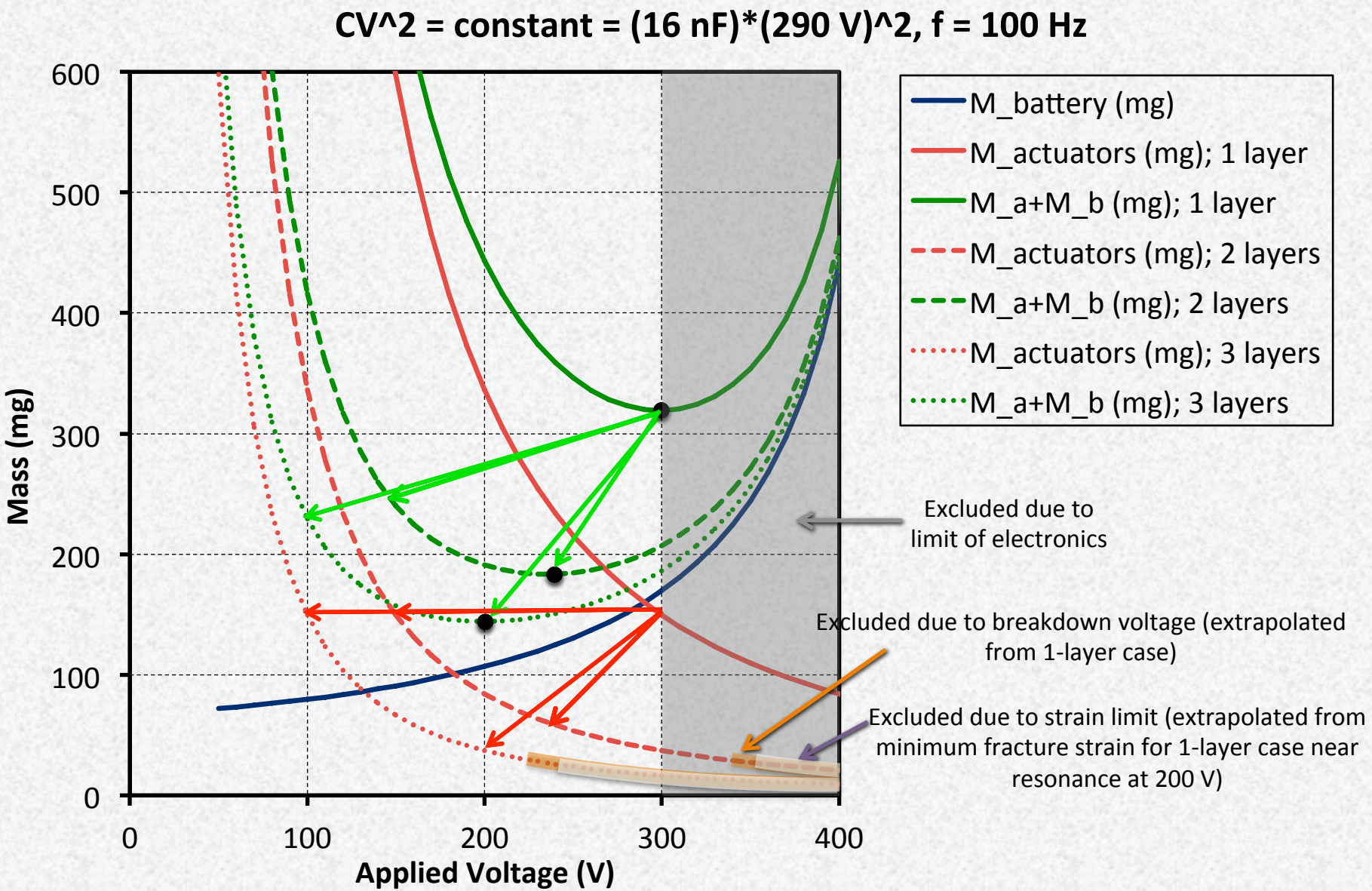
[1]M.Karpelson et al., Sensors and Actuators A, 2011

[2]M. Lok et al., to appear: ECCE, 2013

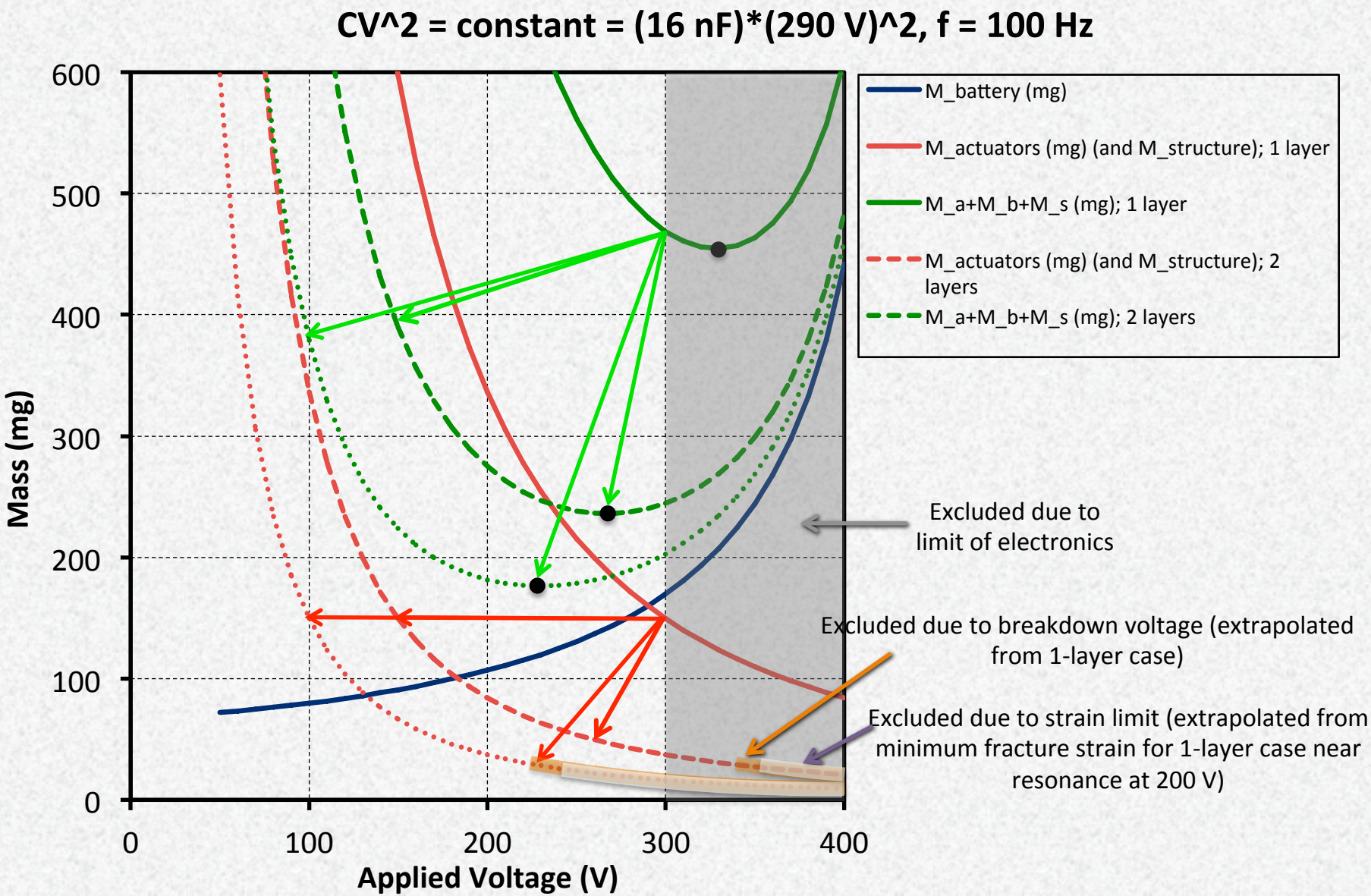
[3]M. Tsuchiya, B.K. Lai and S. Ramanathan, Nature Nanotechnology, 6, 282, 2011

[4]Sample, Meyer, and Smith, IEEE

Finding the optimal drive voltage



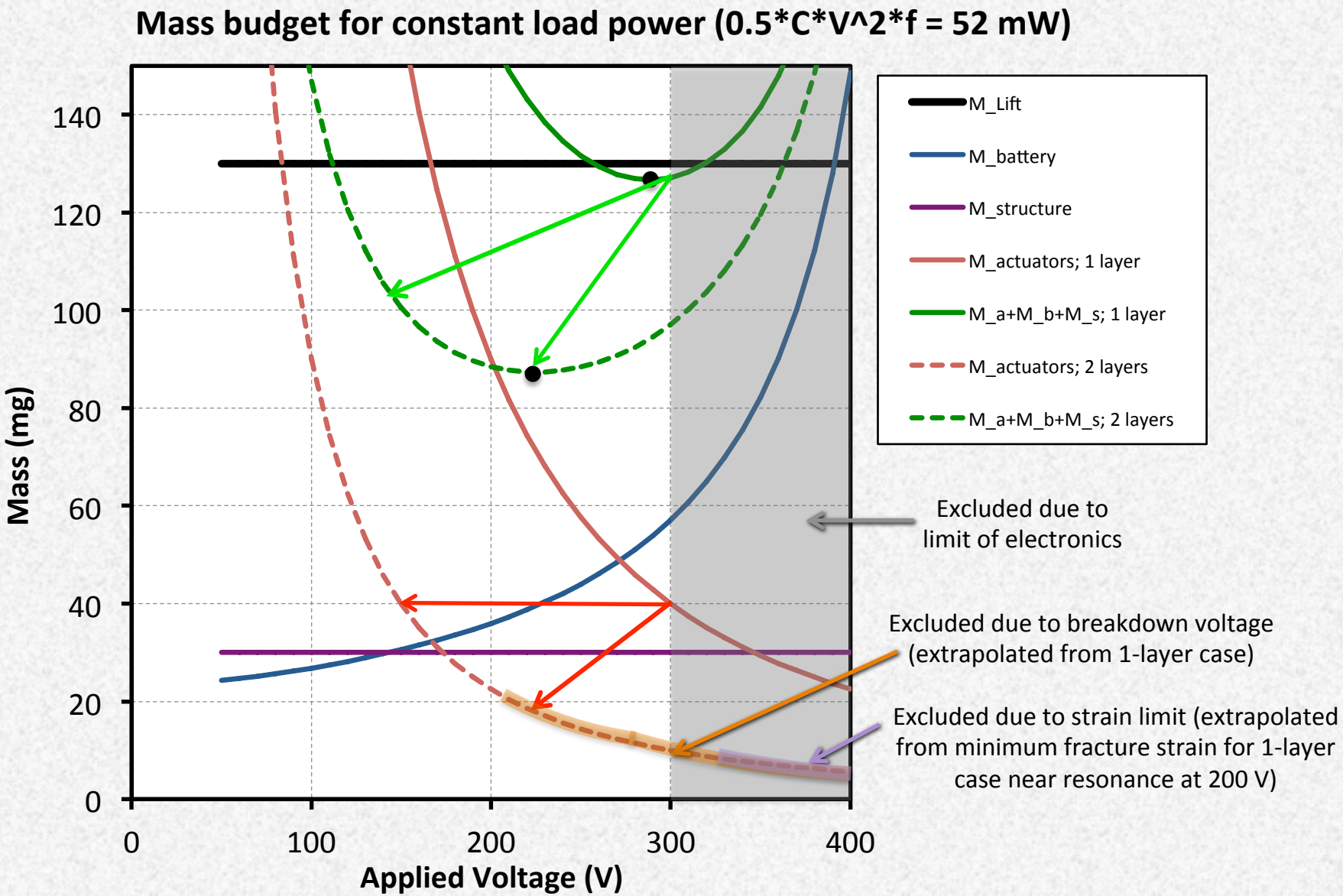
Finding the Optimal Drive Voltage



Outline

- Overview
  - Manufacturing process
  - RoboBee operation
- Towards autonomy
  - Sensors
  - Power
  - Actuators
  - Scaling

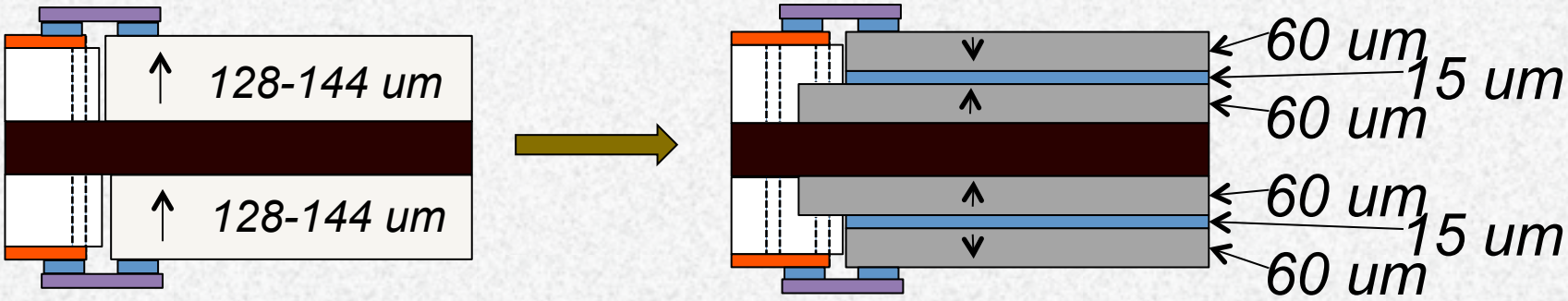
Mass Budget - Drive Voltage Dependence



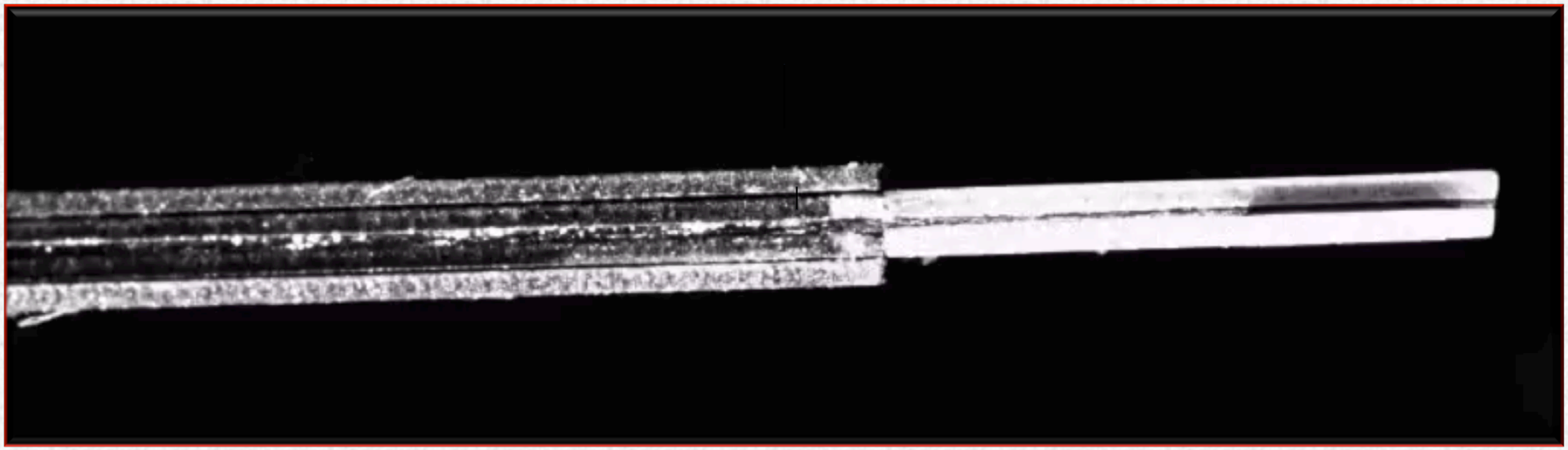
Multi-Layer Actuator

- *Thinner PZT to allow lower actuator voltage:*

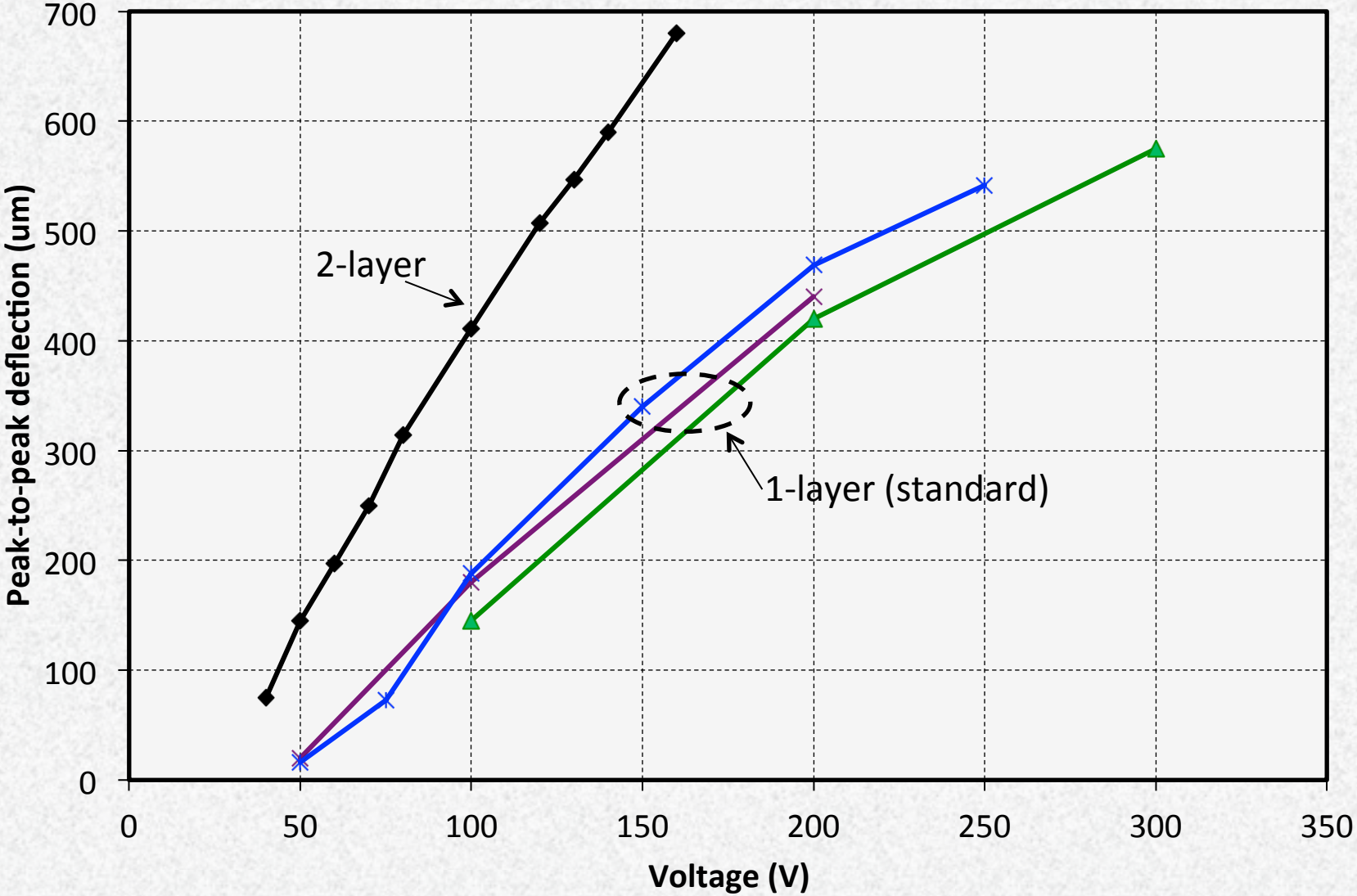
  - *PZT (60 um from B&H Technical Ceramics)*
  - *15 um Conductive Adhesive (ESP8660 from AI Tech)*
  - *Carbon Fiber Composite*
  - *Copper-clad FR4*



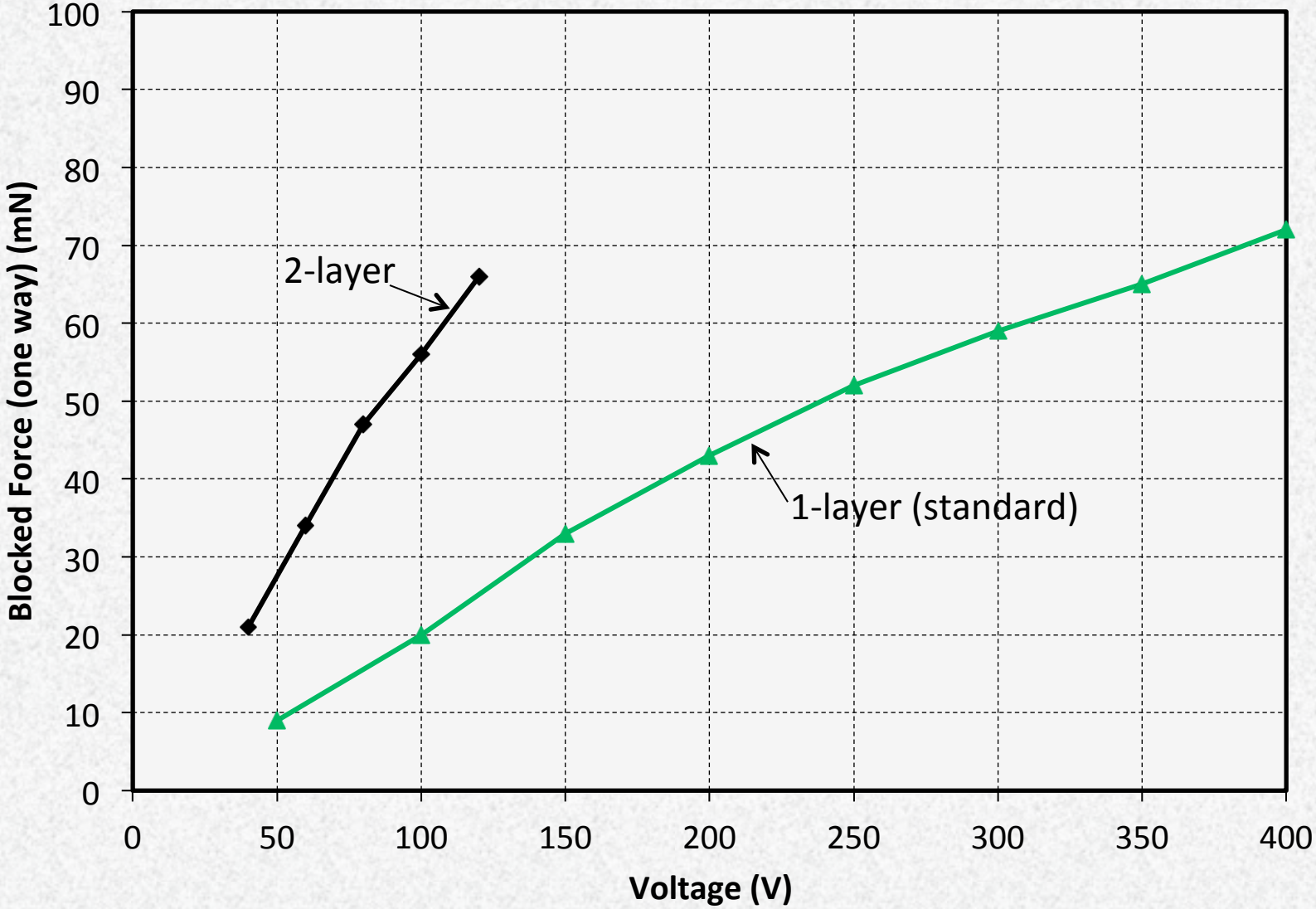
Test of Multilayer Actuator



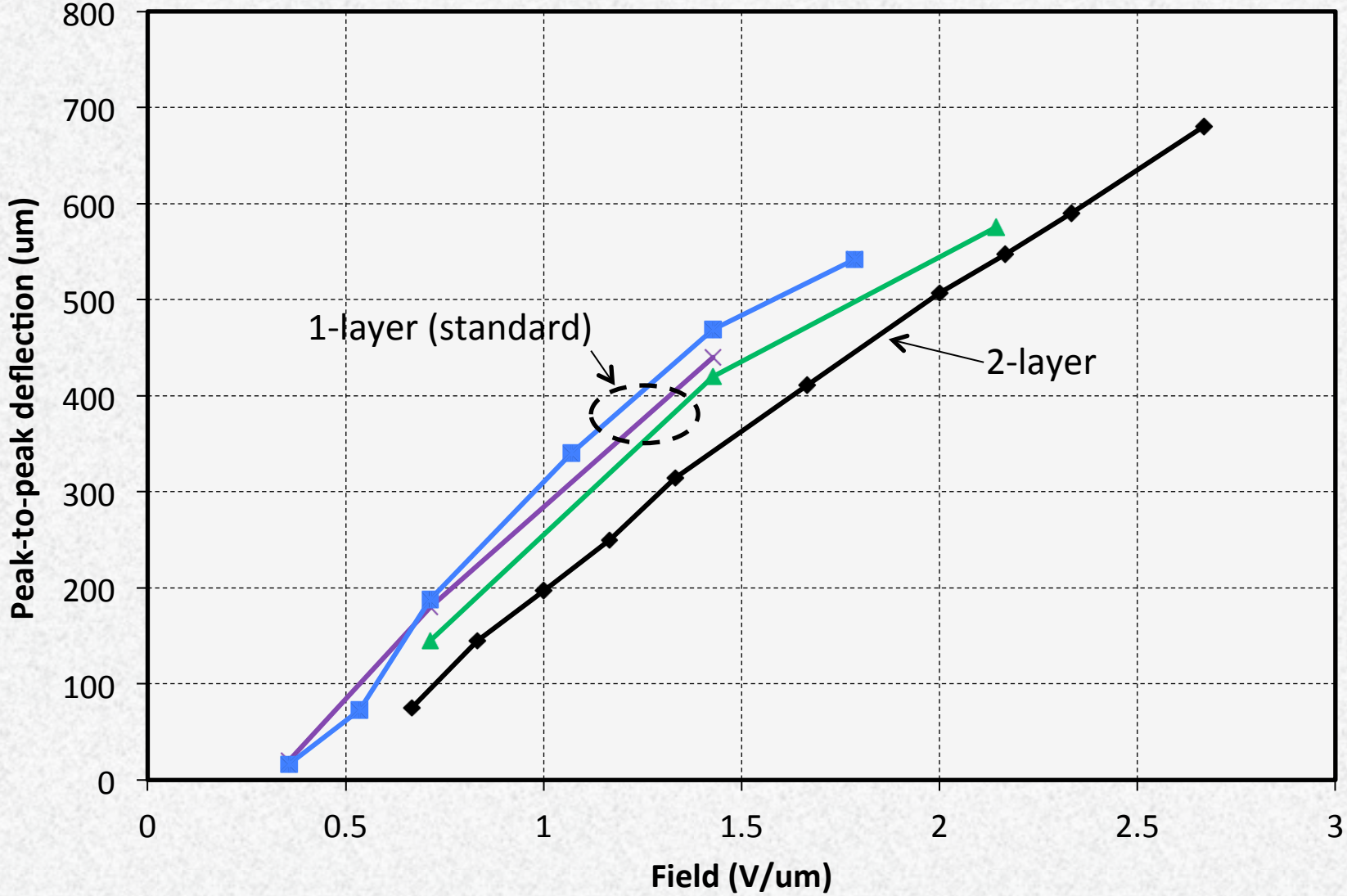
Multi-Layer Actuator



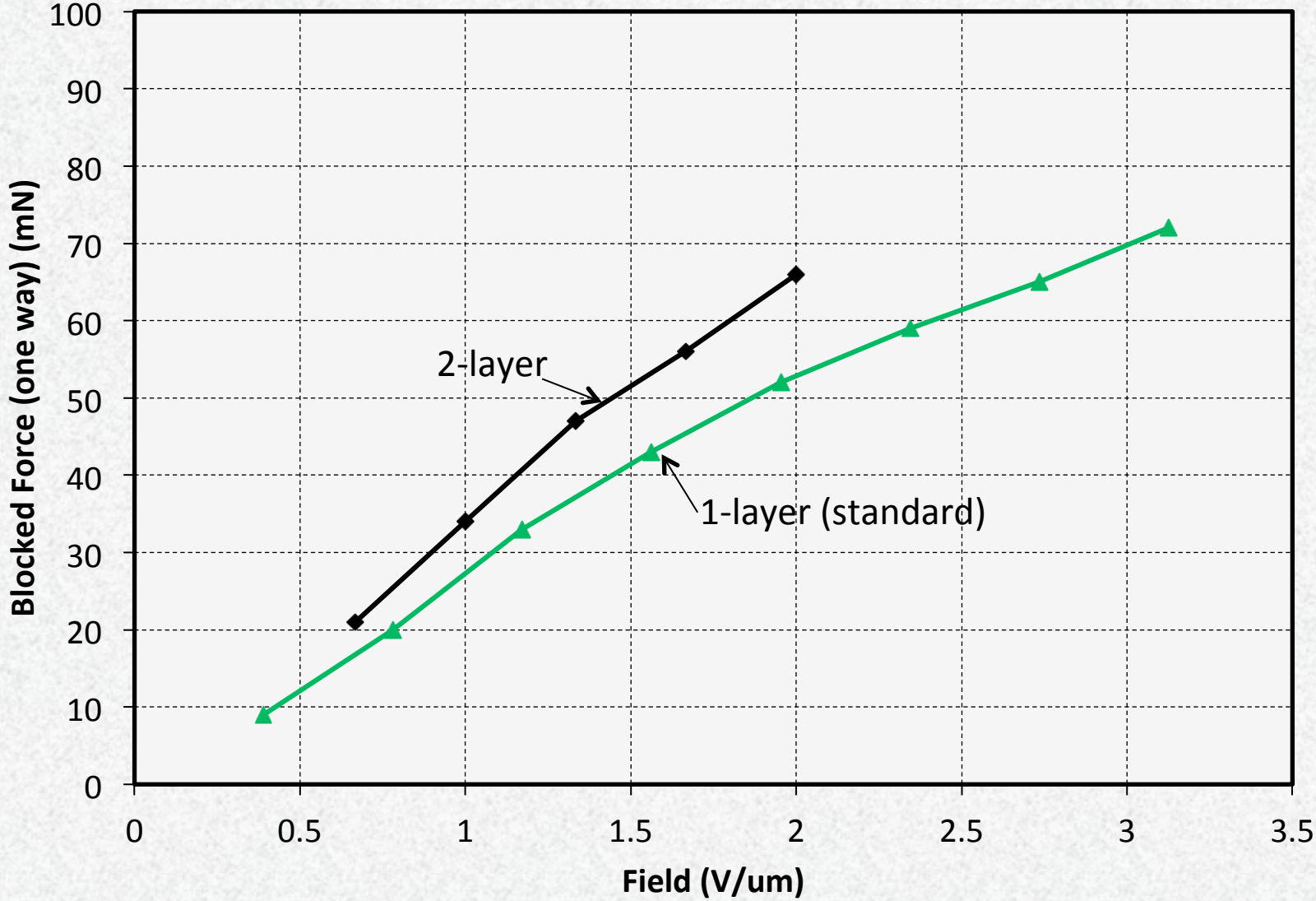
Multi-Layer Actuator



Multi-Layer Actuator



Multi-Layer Actuator



Outline

- Overview
  - Manufacturing process
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  - Sensors
  - Power
  - Actuators
  - Scaling

Scaling Relations for the RoboBee

$$M_L \approx \underbrace{2}_{\text{\# of wings}} * \underbrace{\frac{2\pi^2 \rho_{air}}{g}}_{\text{Constants}} * \underbrace{C_L * \theta_{s,\max}^2}_{\text{Flapping parameters}} * \underbrace{\frac{\hat{r}_2^2}{AR} * R^4}_{\text{Wing parameters}} * \underbrace{f^2}_{\text{Adjustable for scaling}}$$

For the RoboBee (R = 1.5 cm, f = 120 Hz,…), this gives **~160 mg** (measured: **130-150 mg**)
For a larger vehicle (R = 6.7 cm, f = 27 Hz,…), this gives **~4.3 g** (measured: **4 g**)

$$M_A \approx \underbrace{2}_{\text{\# of wings}} * \underbrace{\frac{1}{S_{A,0}}}_{\text{Actuator energy density (J/kgV}^2\text{)}} * \underbrace{2\pi^2 \rho_{air}}_{\text{Constants}} * \underbrace{C_D * \theta_{s,\max}^3}_{\text{Flapping parameters}} * \underbrace{\frac{\hat{r}_2^2 \hat{r}_{cp}}{AR} * R^5}_{\text{Wing parameters}} * \underbrace{f^2 * V^{-2}}_{\text{Adjustable for scaling}}$$

=> Gives **~29 mg** for the RoboBee (actual is **~48 mg**)

$$M_B \approx \underbrace{\frac{4\pi^2 \varepsilon_0 \varepsilon_r \rho_{air}}{\gamma_A t_p}}_{\text{Actuator energy density (J/kgV}^2\text{)}} * \underbrace{\frac{1}{W_B} * \frac{1}{S_{A0}}}_{\text{Constants}} * \underbrace{C_D * \theta_{s,\max}^3}_{\text{Flapping parameters}} * \underbrace{\frac{\hat{r}_2^2 \hat{r}_{cp}}{AR} * R^5}_{\text{Wing parameters}} * \underbrace{f^3 * \frac{1}{\eta(V)}}_{\text{Adjustable for scaling}}$$

M_F = 100-180 mg, M_S = 30 mg

Scaling Relations for the RoboBee

$$M_L \approx \underbrace{2}_{\text{\# of wings}} * \underbrace{\frac{2\pi^2 \rho_{air}}{g}}_{\text{Constants}} * \underbrace{C_L * \theta_{s,\max}^2}_{\text{Flapping parameters}} * \underbrace{\frac{\hat{r}_2^2}{AR}}_{\text{Wing parameters}} * \underbrace{R^4 * f^2}_{\text{Adjustable for scaling}}$$

For the RoboBee (R = 1.5 cm, f = 120 Hz,…), this gives **~160 mg** (measured: **130-150 mg**)
For a larger vehicle (R = 6.7 cm, f = 27 Hz,…), this gives **~4.3 g** (measured: **4 g**)

$$M_A \approx \underbrace{M_L g}_{\text{Lift force}} \underbrace{\frac{1}{S_{A,0} * V^2}}_{\text{Actuator energy density}} * \underbrace{\frac{C_D}{C_L}}_{\text{Drag to lift ratio}} * \underbrace{\theta_{s,\max} \hat{r}_{cp} R}_{\text{Transmission ratio}}$$

Scaling terms: $R^5 * f^2 * V^{-2}$

=> Gives **~38 mg** for the RoboBee (actual is **~48 mg**)

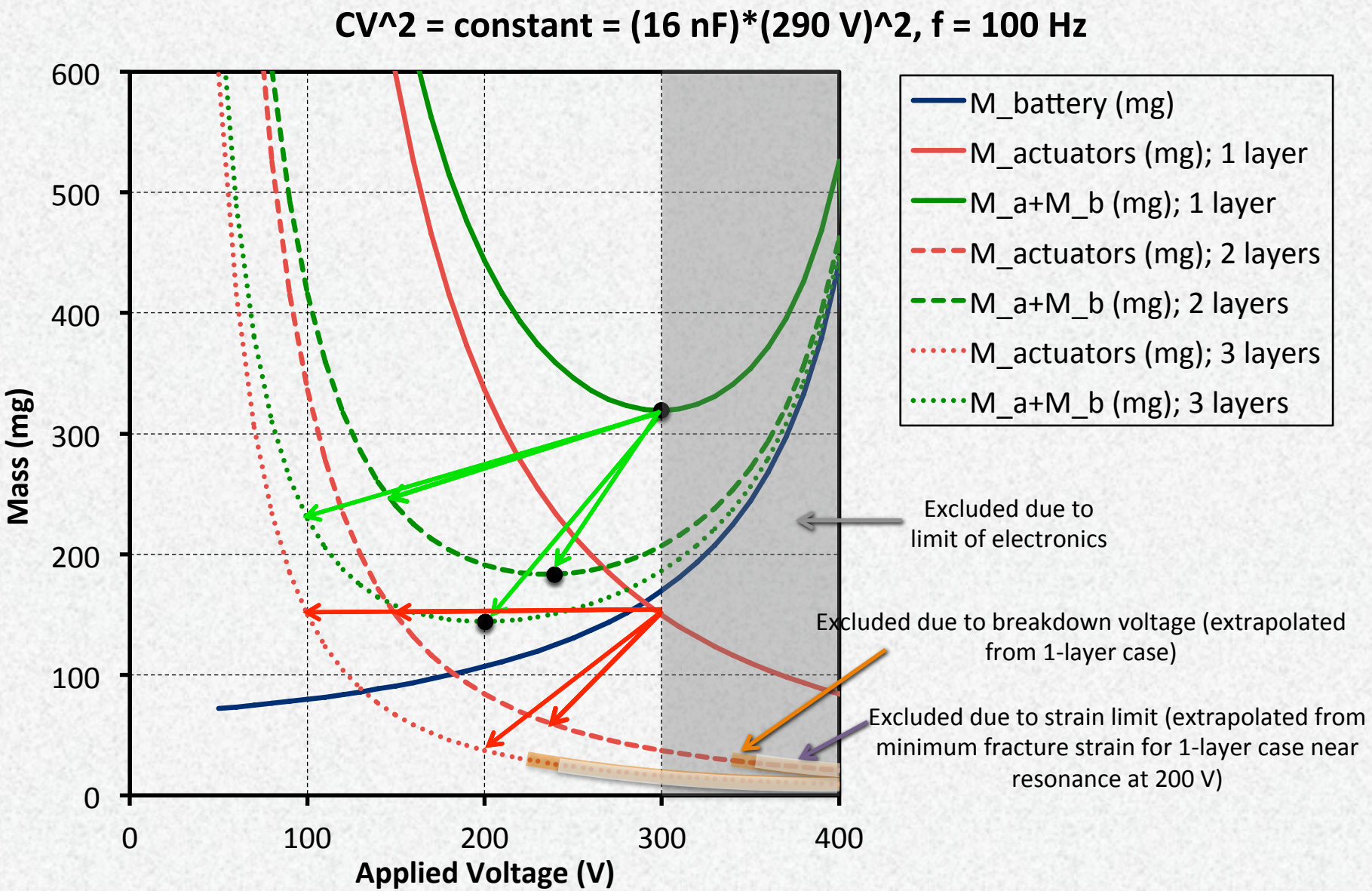
$$M_B \approx \underbrace{M_A * \frac{\varepsilon_0 \varepsilon_r}{\gamma_A t_p} * V^2 * f}_{\text{Actuator power}} * \underbrace{\frac{1}{W_B}}_{\text{Battery power density}} * \underbrace{\frac{1}{\eta(V)}}_{\text{Power electronics efficiency}}$$

Scaling terms: $R^5 * f^3 * \frac{1}{\eta(V)}$

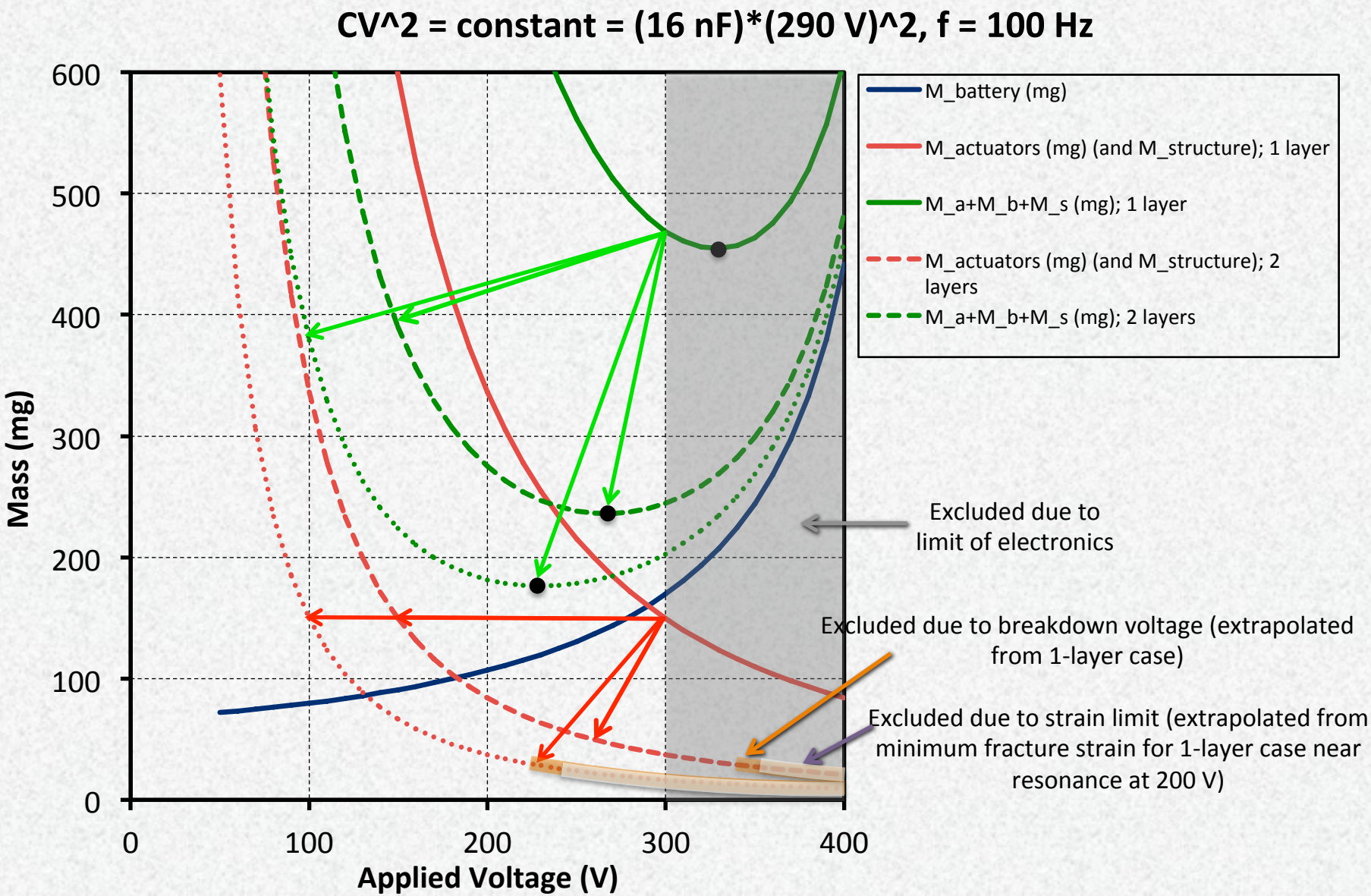
=> Gives **~48 mg** for the RoboBee (actual TBD)

M_F = 100-180 mg
M_S = 30 mg

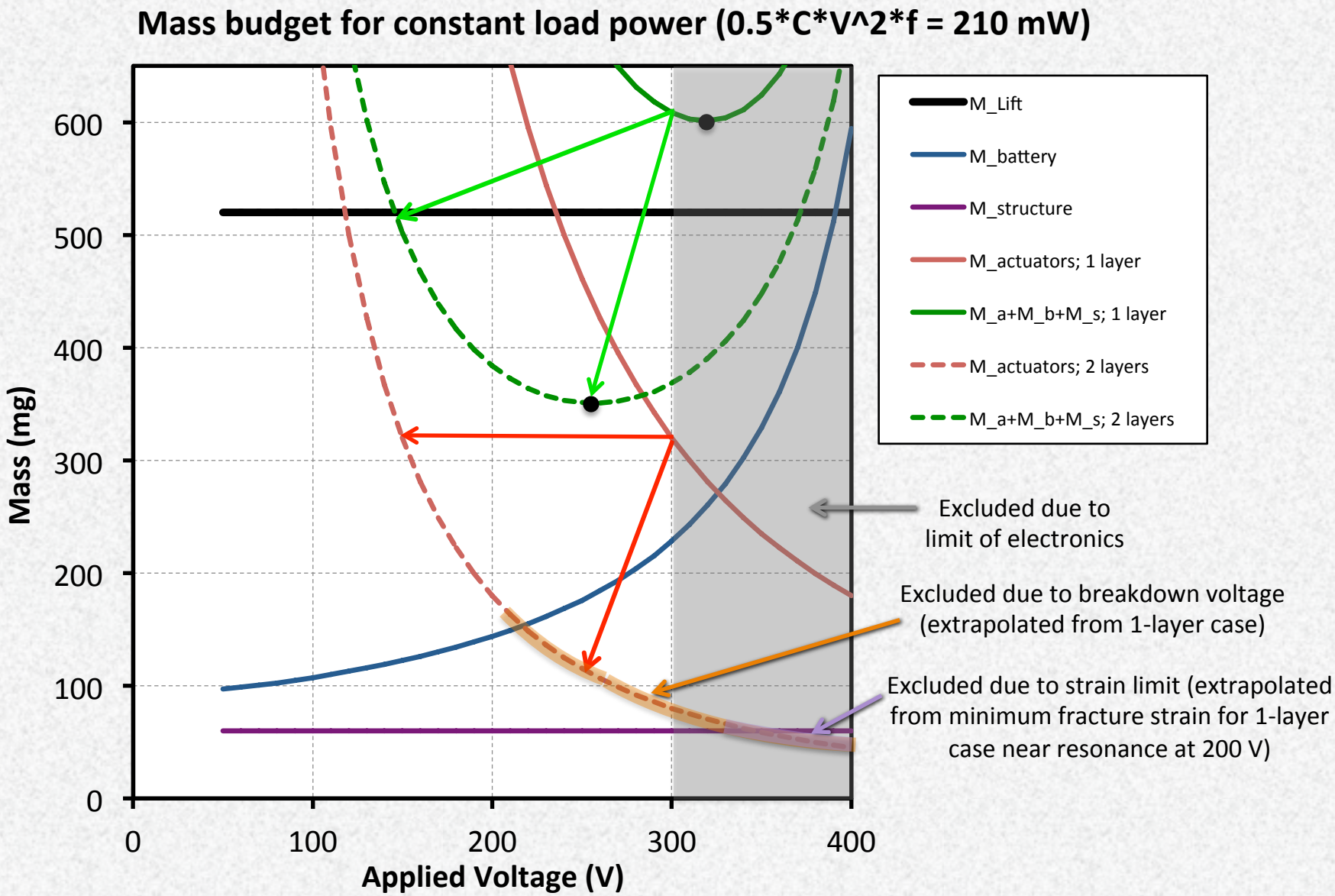
Finding the optimal drive voltage



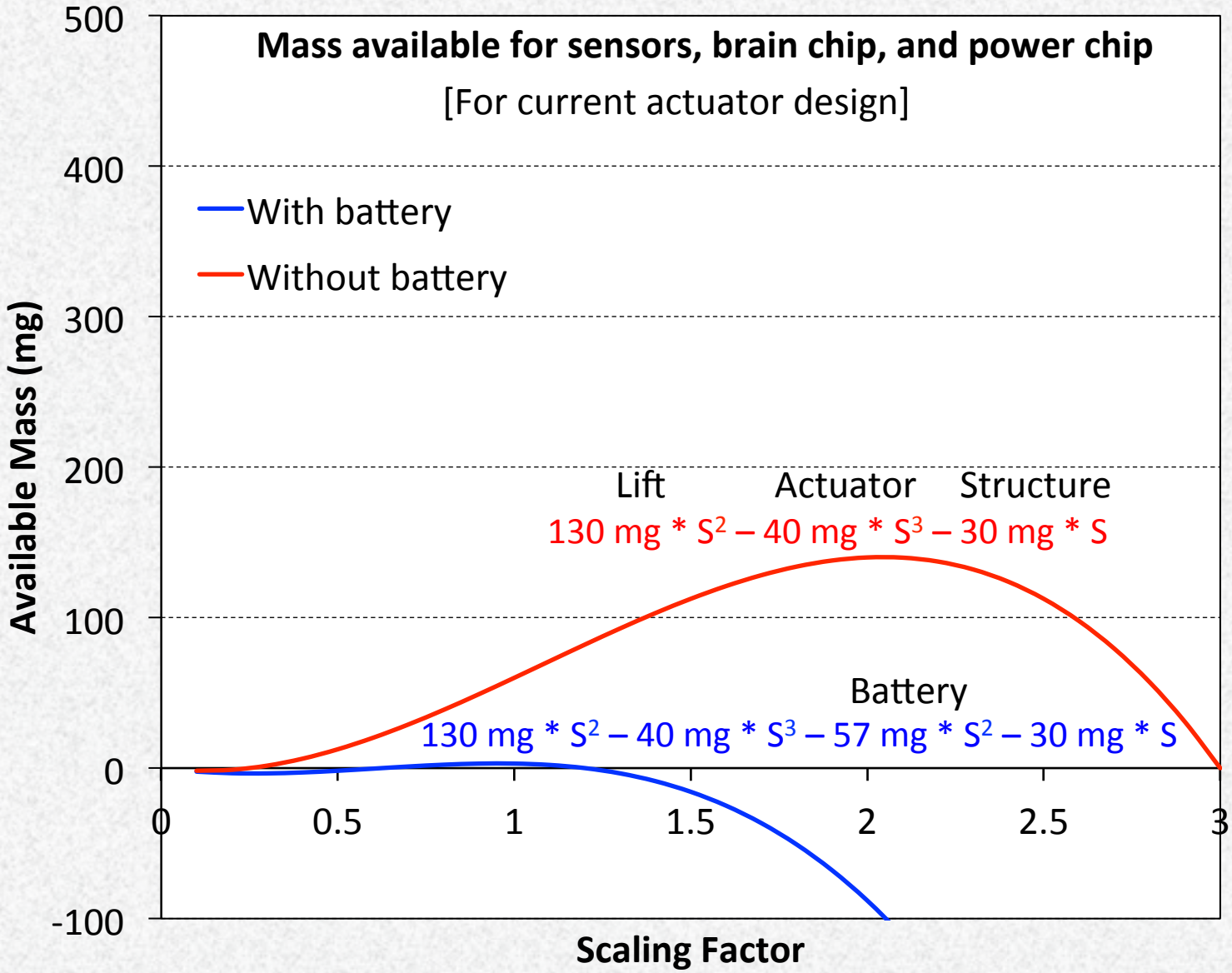
Finding the optimal drive voltage



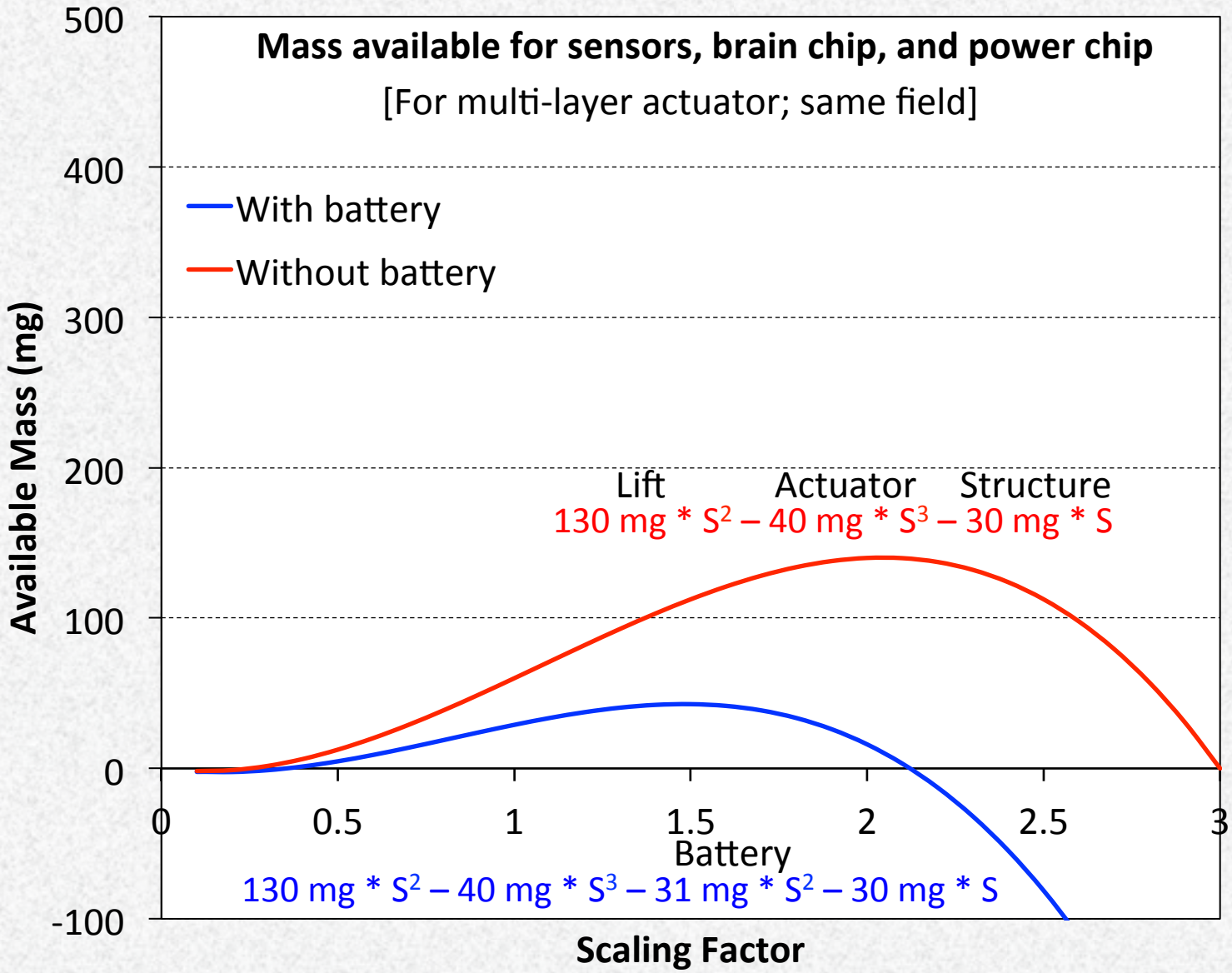
Scaled-up RoboBee



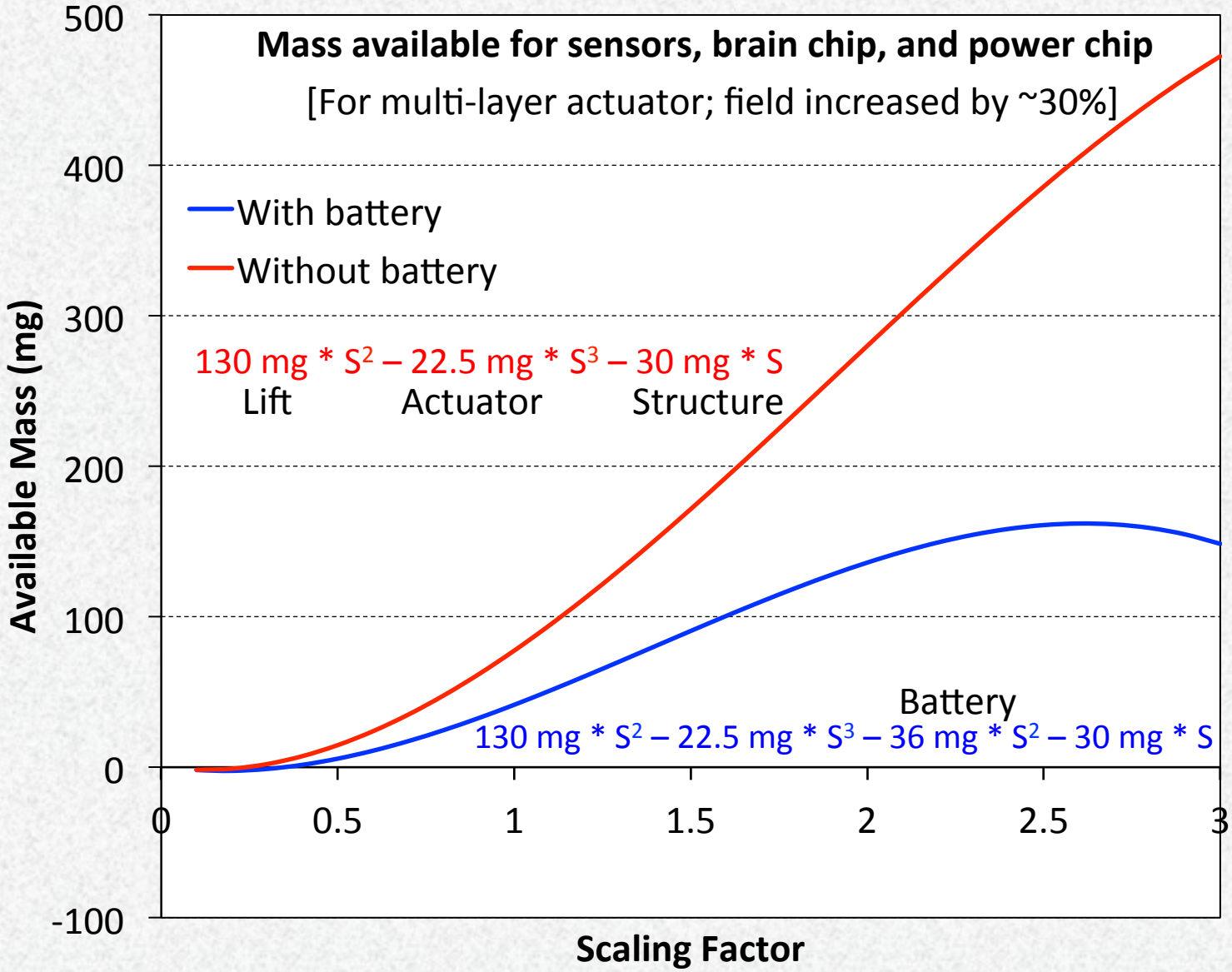
Scaled-up RoboBee



Scaled-up RoboBee



Scaled-up RoboBee



The hovering experiment

- Target Schedule Date: August 31, 2014
- Brain SoC, power electronics, (battery) and sensors mounted on the RoboBee

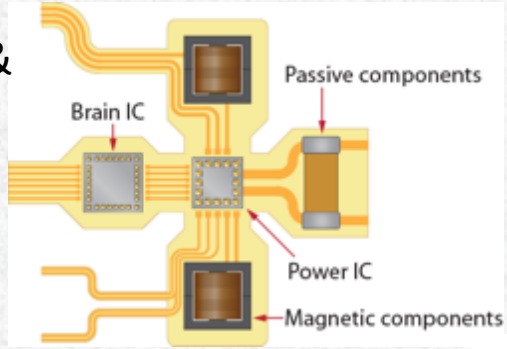
Scaled Up RoboBee

Battery

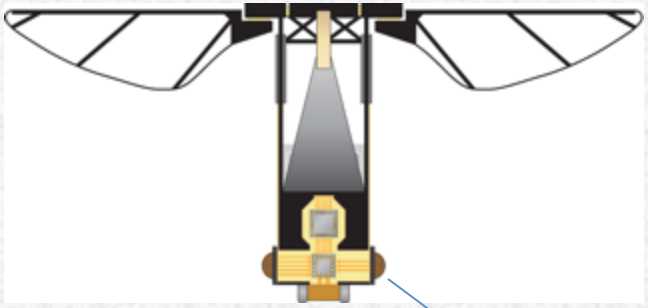
Battery 120 - 160 mg
Cut and reseal, or manufacture

Brain + Power + Sensing 90 – 150 mg
Die thinning, Bare Die Bonding

Brain IC &
Sensors



Power
Electronics



520 mg lift

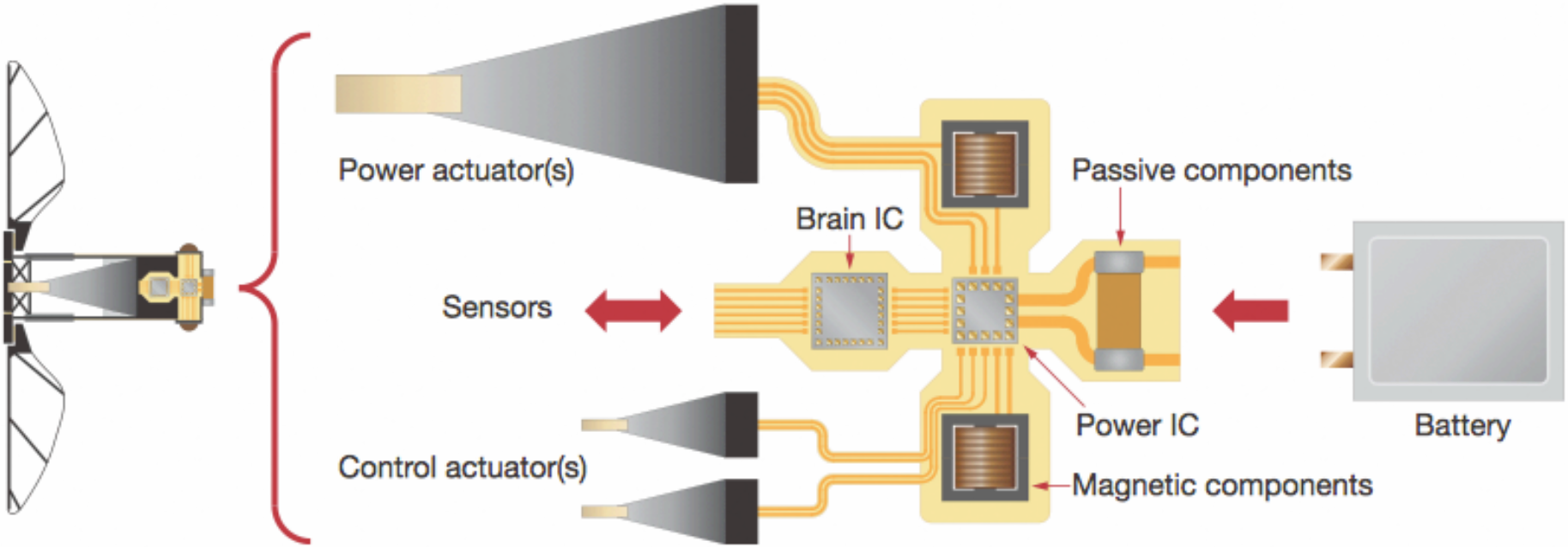
Actuator

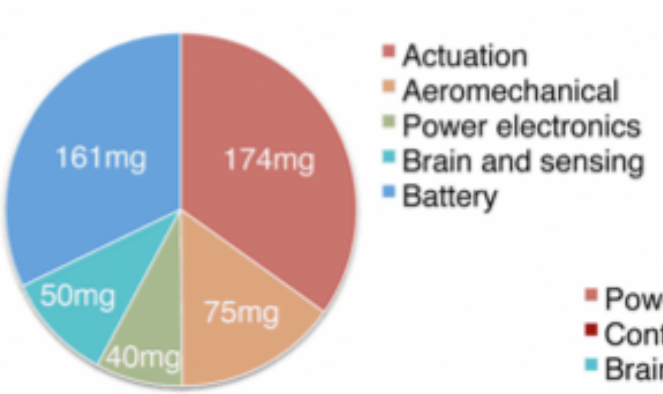
150 – 320 mg

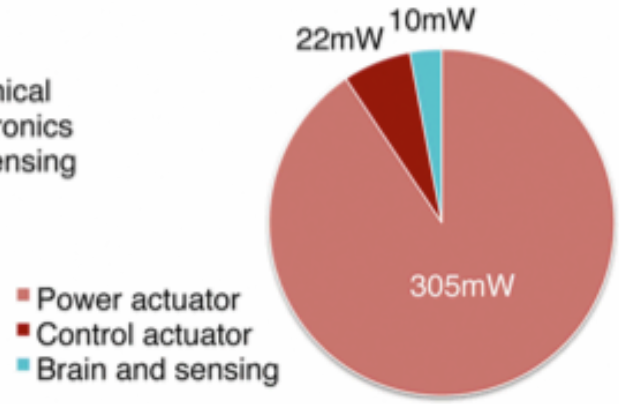
Wings and
Transmission

40 – 160 mg

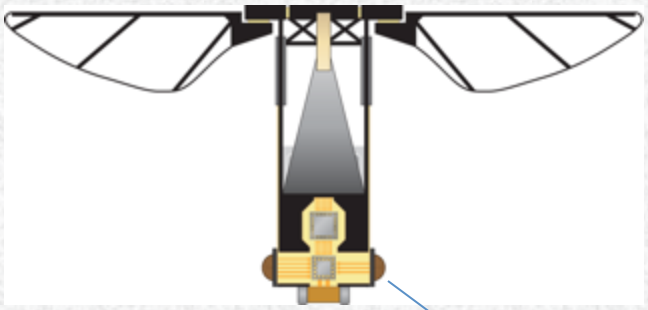
Power and Weight Budget for Scaled-Up RoboBee



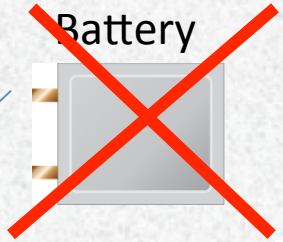




Scaled Up RoboBee

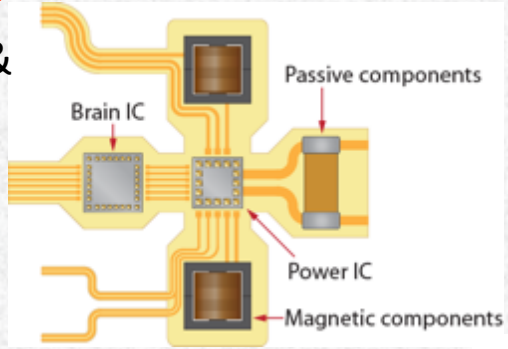


500mg lift



Brain IC &
Sensors

Brain + Power + Sensing 250mg
Die thinning, Bare Die Bonding



Power
Electronics

Actuator

Intrinsic
Weight
250mg

Wings and
Transmission

Power versus Body Design

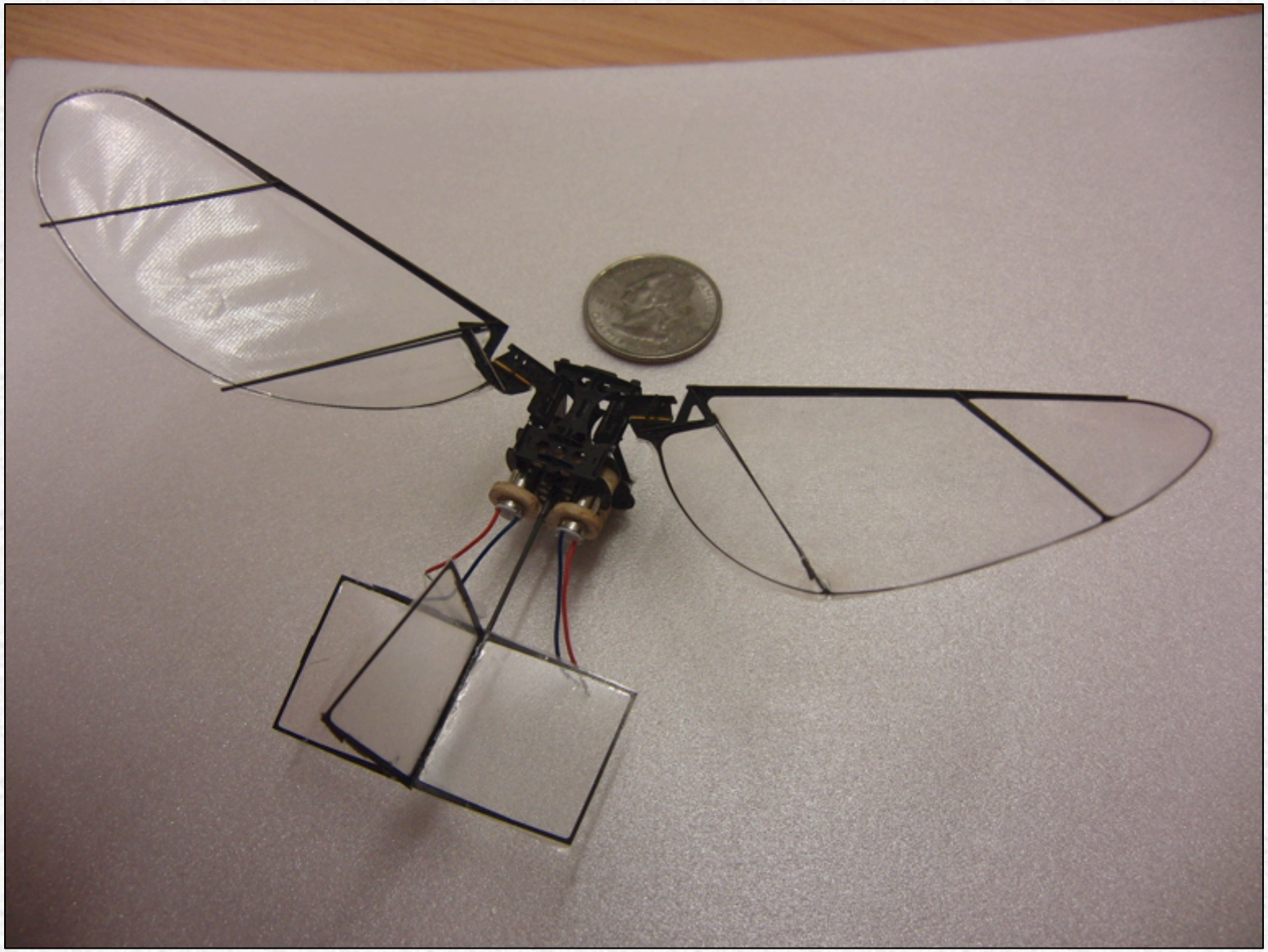
- Lift = f (actuator size, voltage, frequency)
- Weight = f (power electronics topology, actuator size, other bee components)
- Power = f (power electronics topology, actuator size, voltage, frequency)
- Lift > weight ? Is that sufficient?
- If Battery, minimize both weight and power
- We can now explore this design space for single layer and two layers actuators. Noah is currently leading this effort.

Sensor versus Body

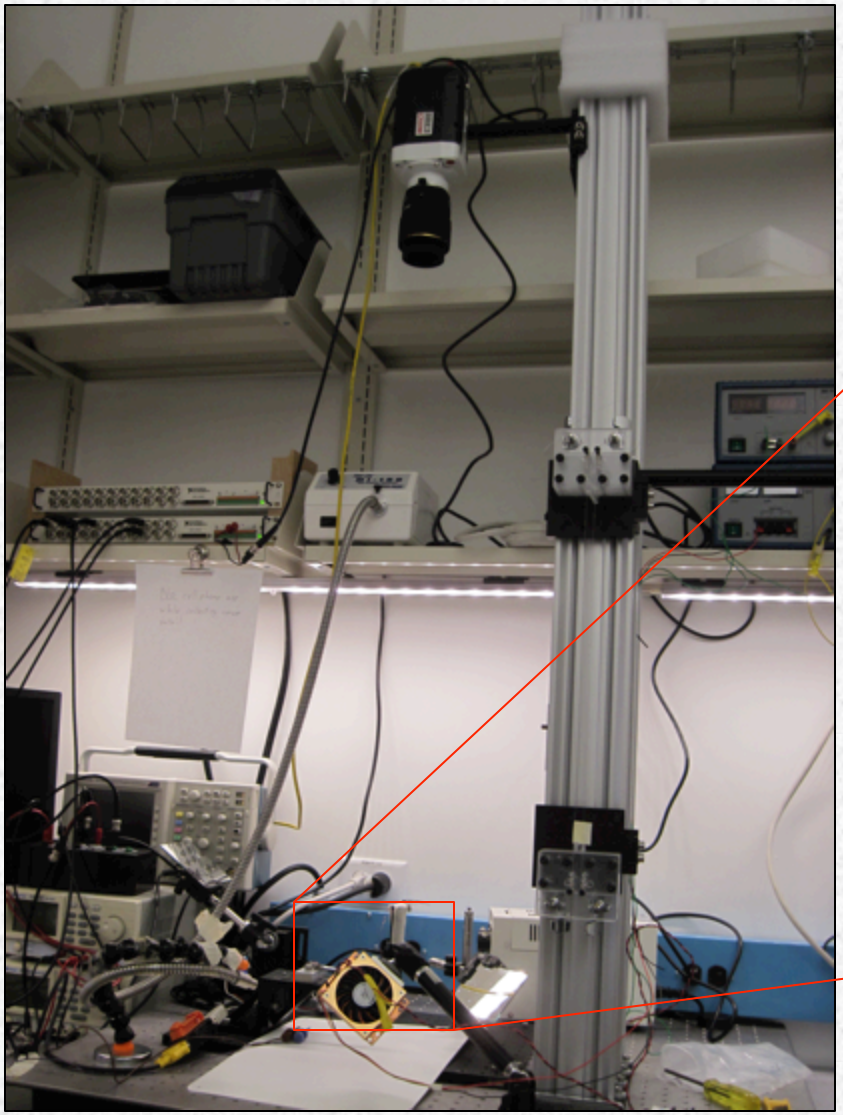
- What are the sensors needed?
  - Optical flow image sensor, gyros …
- How much do they weight?
- Where on the bee should the sensors be mounted?
- What are the control algorithms?
- Timelines for answering these questions?

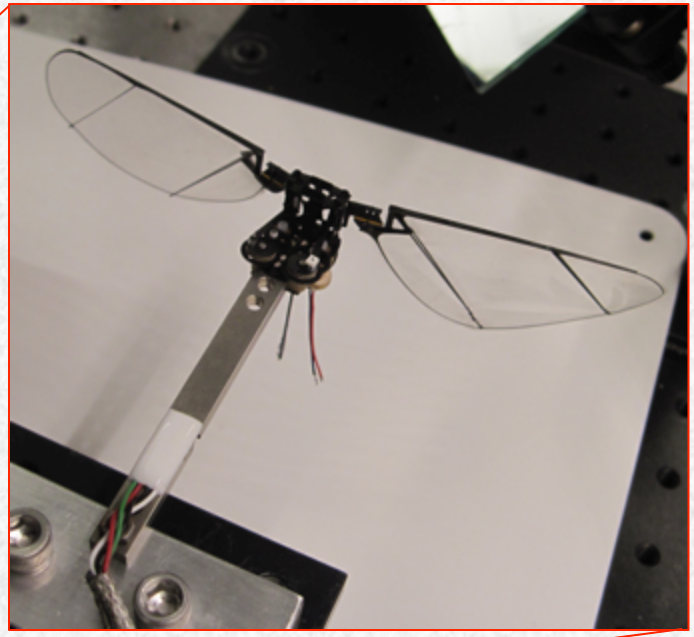
Intermittent flight vehicle

(~5x larger than RoboBee)



Intermittent flight vehicle

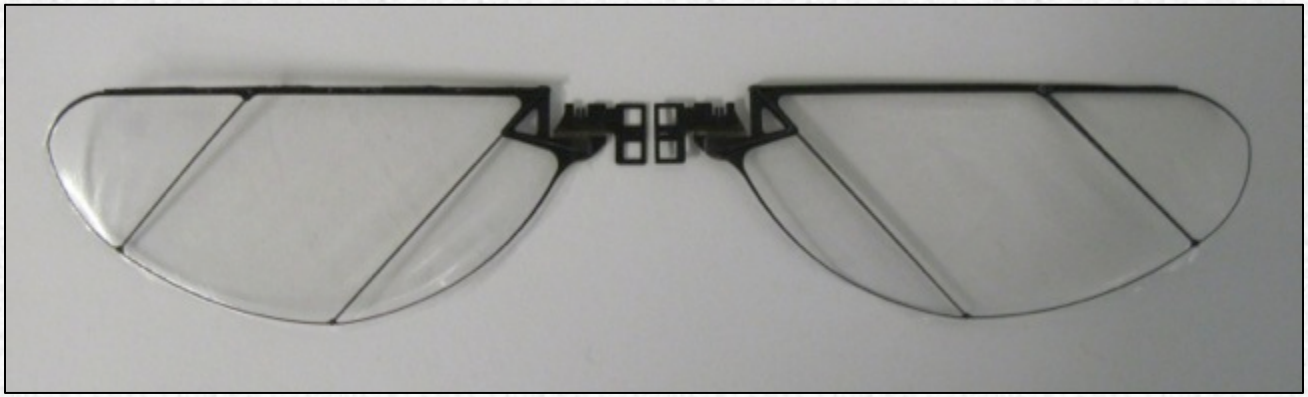




Intermittent flight vehicle

Testing various hinge stiffness and leading edge offsets
=> Optimizing phase offset between stroke and hinge angle

<u>Best so far:</u>



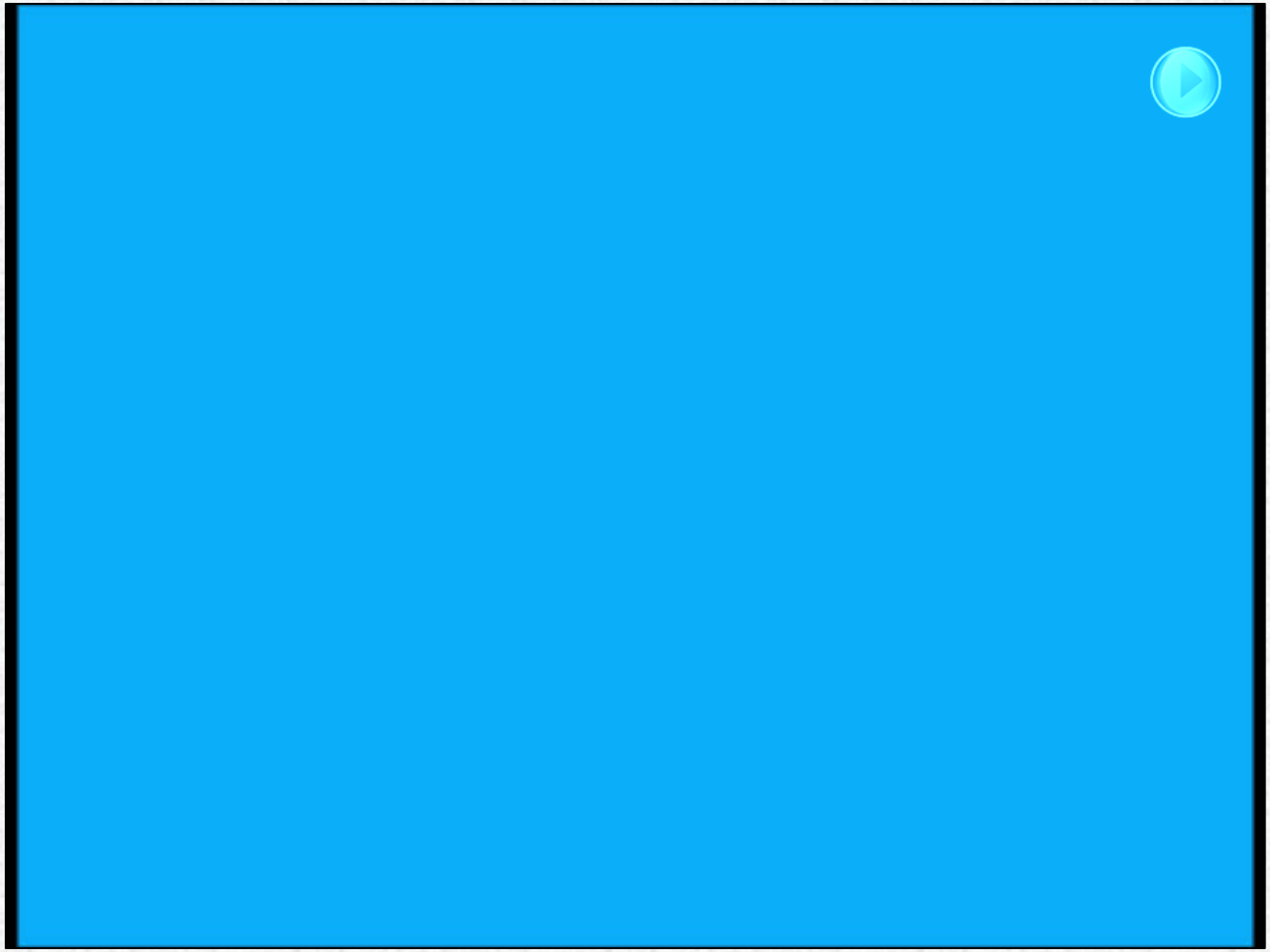
Phase nearly ideal, and thrust is ~2 grams per wing at 27.4 Hz
(compared with initial un-optimized results of ~1 gram per wing)

Hinge: 50 um thick Kapton, 200 um long, 6 mm wide => stiffness ~ $7*10^{-4}$ N*m/rad
Scaling of hinge stiffness is close to L^5*(max stroke angle)^2*f^2 (or Area * velocity^2)
Offset: ¼ of mean wing width

Intermittent flight vehicle

Code to measure stroke and “hinge” angle

- Wing can twist slightly, so code detects angle of two spars separately
- Calculates predicated time-varying thrust using these angles
- Mean value agrees with measured thrust to within ~ 30%



Intermittent flight vehicle

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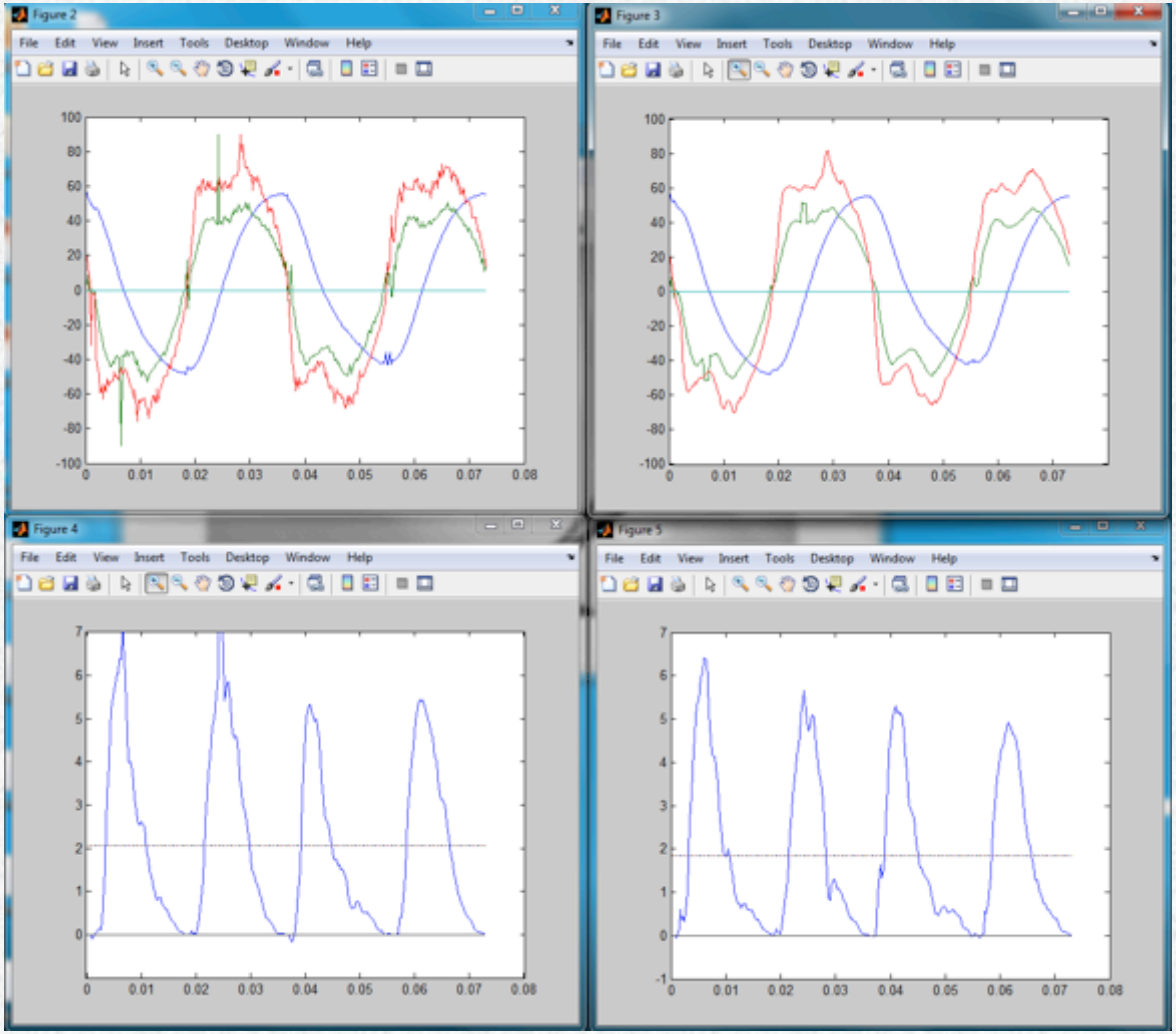

Thanks!

- our sponsors:
  - AFOSR
  - ARL (MAST)
  - DARPA (DSO)
  - Draper Labs
  - NSF (RI, CMMI, CISE, CPS, MRSEC)
  - ONR
  - Wyss Institute for Biologically Inspired Engineering

- more info:
  - micro.seas.harvard.edu
  - wyss.harvard.edu
  - robobees.seas.harvard.edu

Questions?

Robotics at Harvard

Roger Brockett – Controls

Rob Howe – Biorobotics Lab

Radhika Nagpal – Self Org Systems

Conor Walsh – Biodesign Lab

George Whitesides – Soft Robotics

Rob Wood – Microrobotics Lab