MAS836 – Sensor Technologies for Interactive Environments

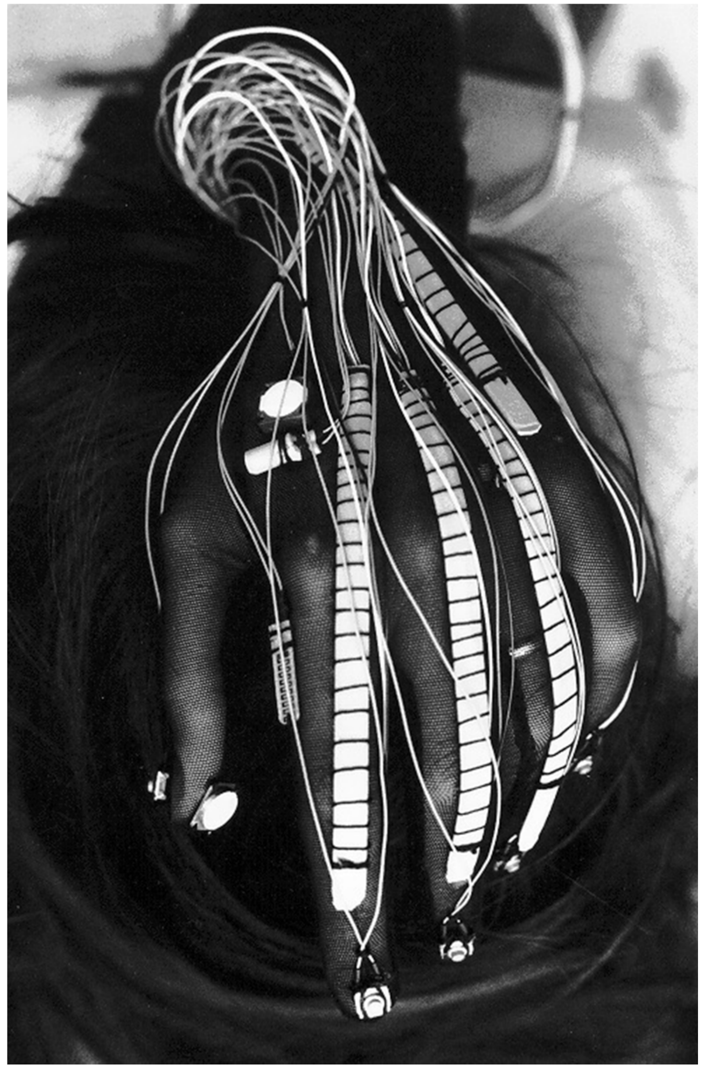
Original images © source unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Lecture 5 – Pressure Sensors Pt. 2 and Piezoelectrics

Some FSR-Bendy-Sensor Gloves

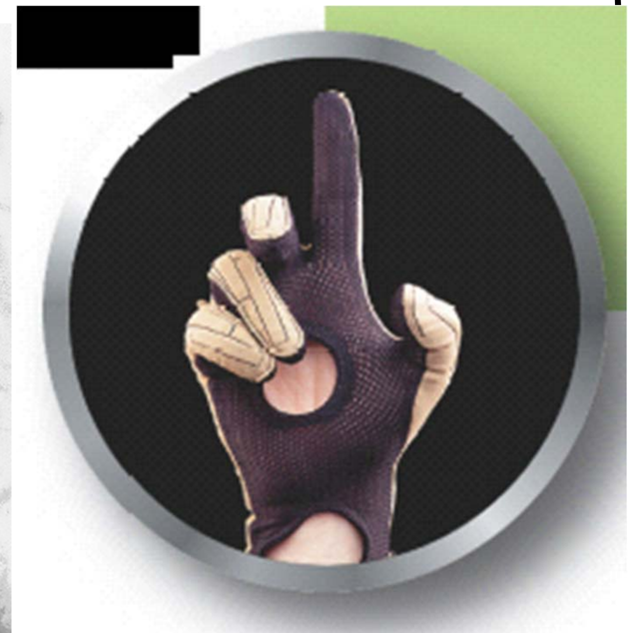
Photo courtesy of Tim Deering on Flickr. CC-BY-NC

Mattel's Power Glove
1989



Courtesy of Laetitia Sonami. Used with permission.

Laetitia Sonami's Lady's Glove
(STEIM, 1997)



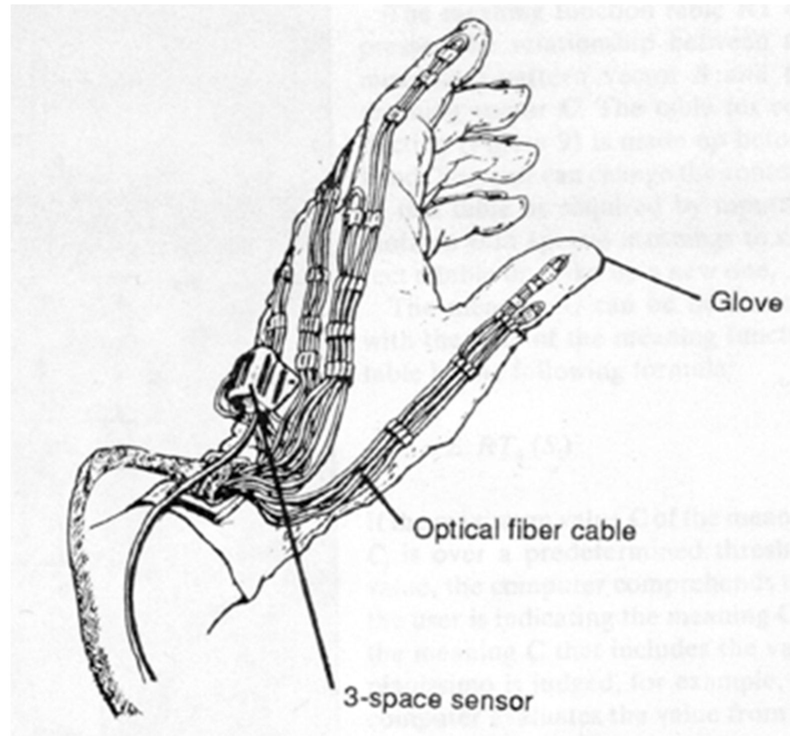
The 22-sensor CyberGlove has three flexion sensors per finger, four abduction sensors, a palm-arch sensor, and sensors to measure flexion and abduction. Each sensor is extremely thin and flexible being virtually undetectable in the lightweight elastic glove.

Courtesy of CyberGlove. Used with permission.

Immersion's Cyber Glove

Data Gloves

5DT Data Glove 16

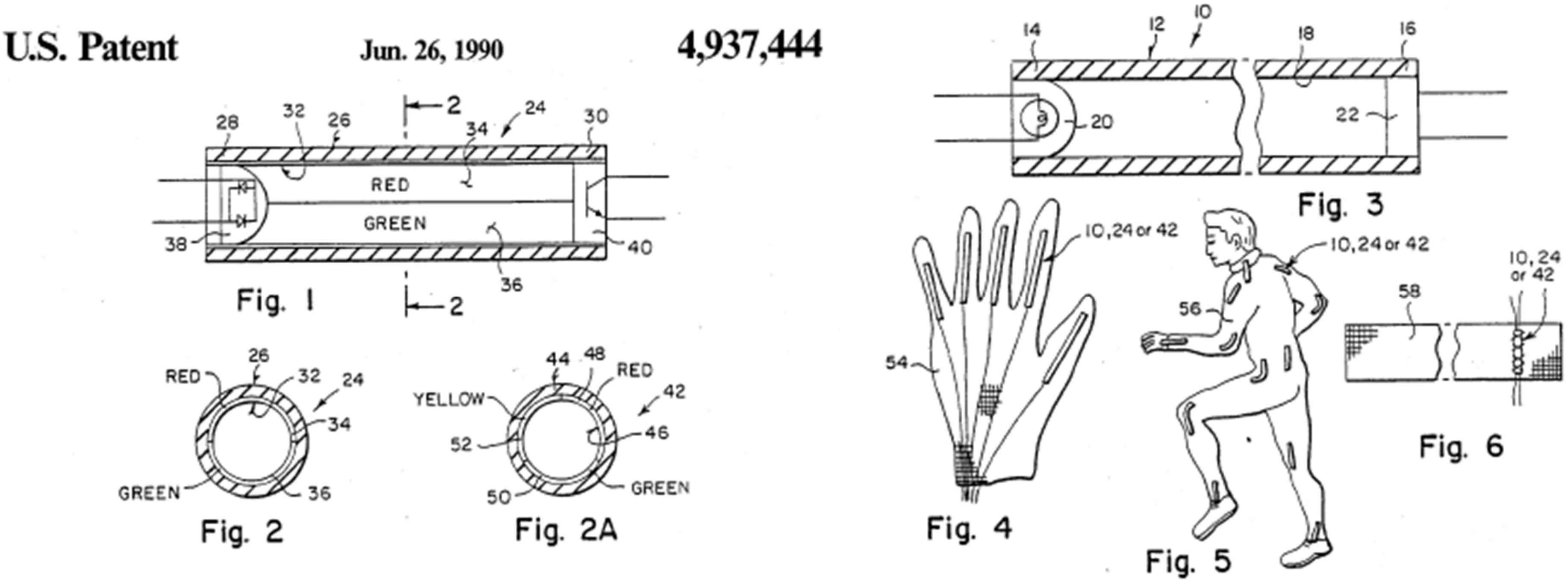


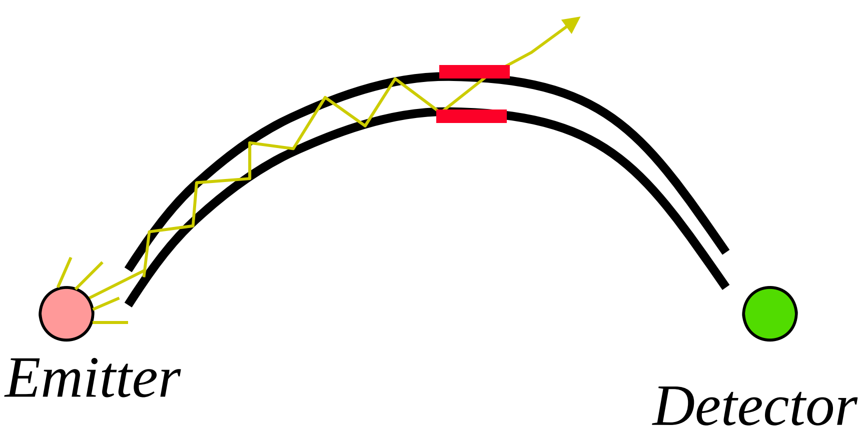
Black stretch lycra
Minimum dynamic range is 8 bits.
Fiber optics based
14 Sensors in total
2 Sensors per finger. Abduction sensors between fingers.

- Abraded-cladding fiber optic bend sensor in the Data Glove

Courtesy of 5DT Inc. Used with permission.

Data Glove by Tom Zimmerman (VPL)





- Cladding of a Graded Index Optical Fiber is abraded at point where sensitivity is desired
- When fiber bent, light leaks out as a function of bend angle
  - Drop in signal at detector
- Patented by Tom Zimmerman (lab alum) at VPL in 1985 & 1990.

Measurand's Shape Tape

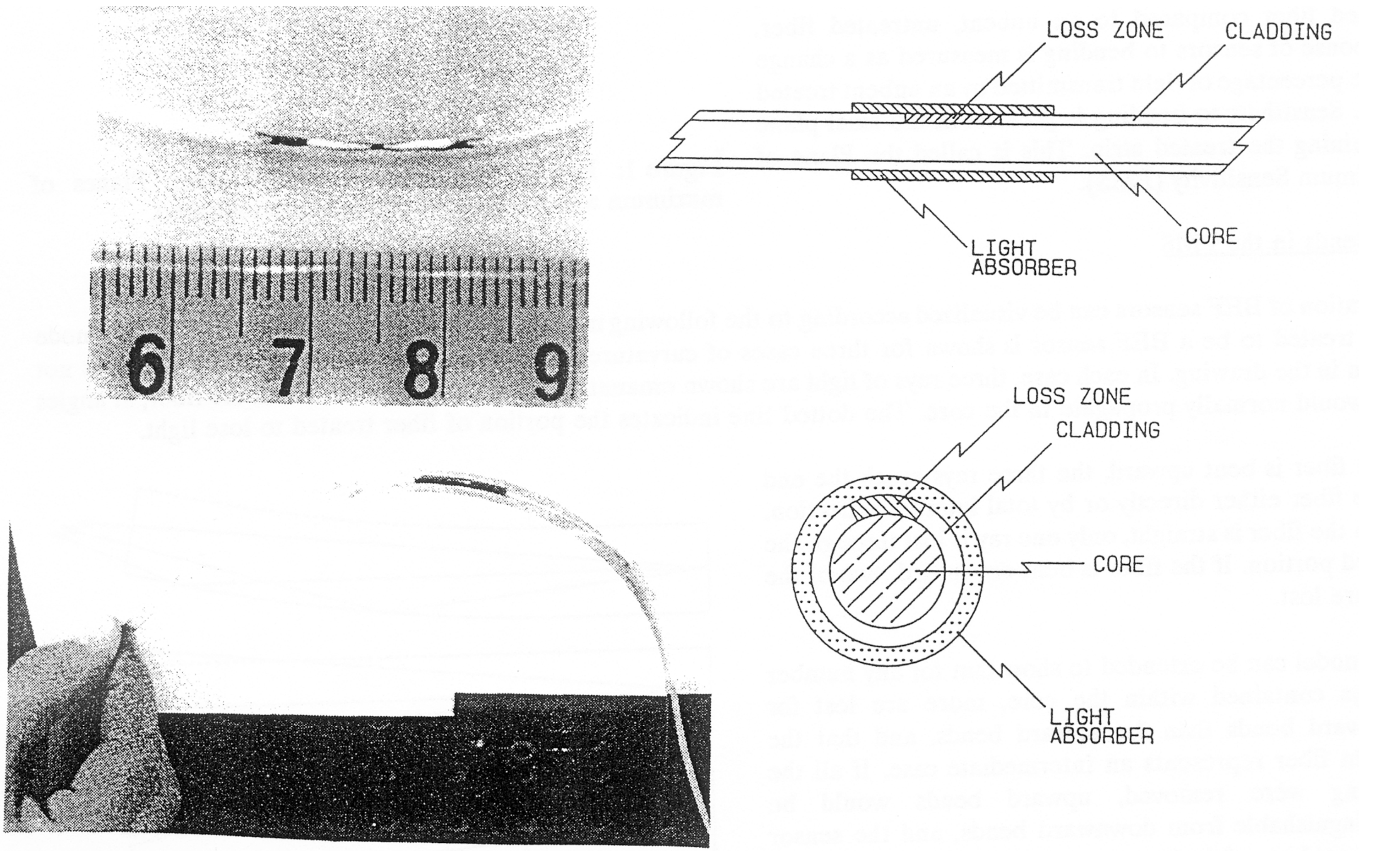
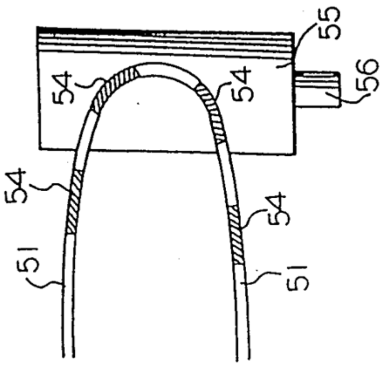


Figure 3: Examples of BEF sensors. Upper left: 200/230 micron BEF, coated with black epoxy over treated zone (scale marks: cm); Lower left: A BEF sensor attached to a thin metal substrate can be bent over large angles.; Right: construction of BEF sensor.

Courtesy of Measurand. Used with permission.

Measurand's Shape Tape



Can pixellate with an array of fibers, with treatment at different locations

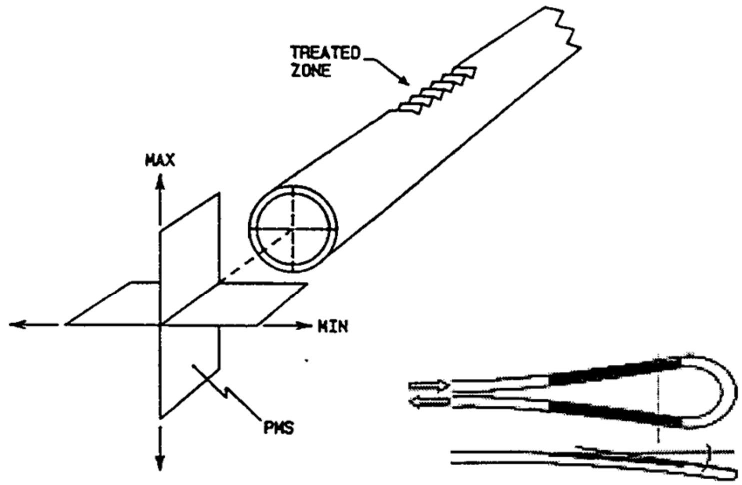
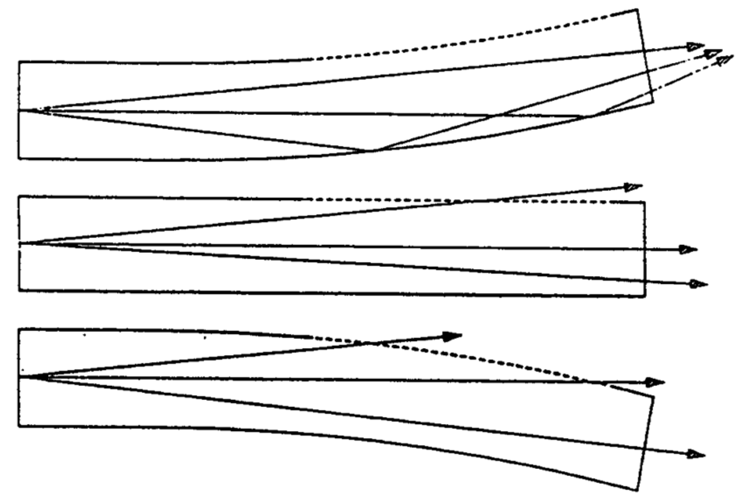


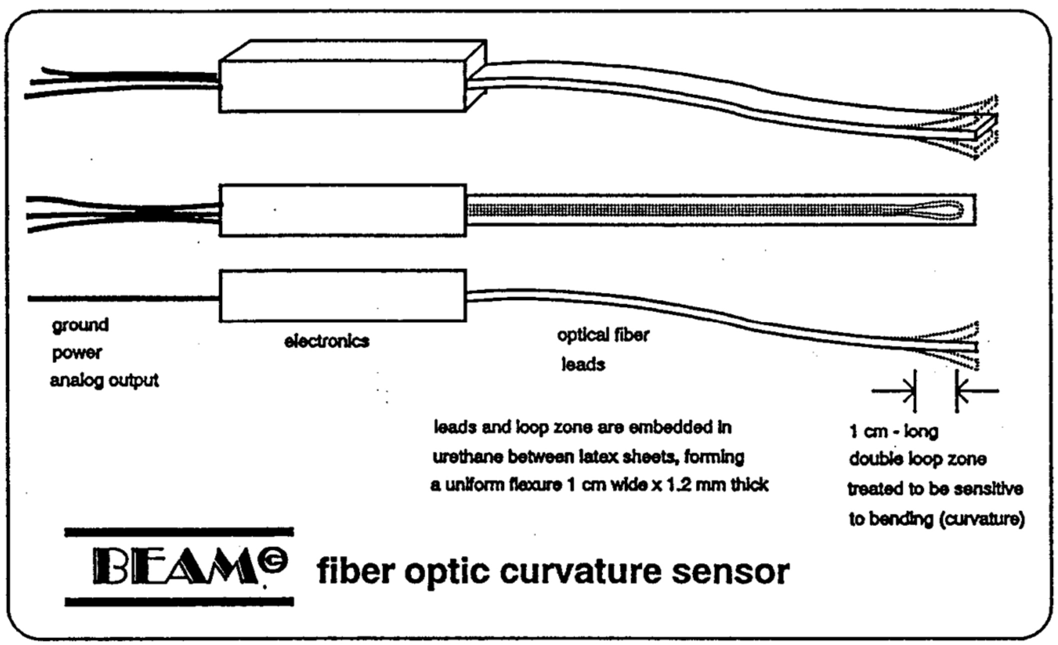
Figure 1: Plastic fiber with a treated strip. Planes of maximum and minimum sensitivity are indicated.

The dotted line indicates the portion of fiber treated to lose light.



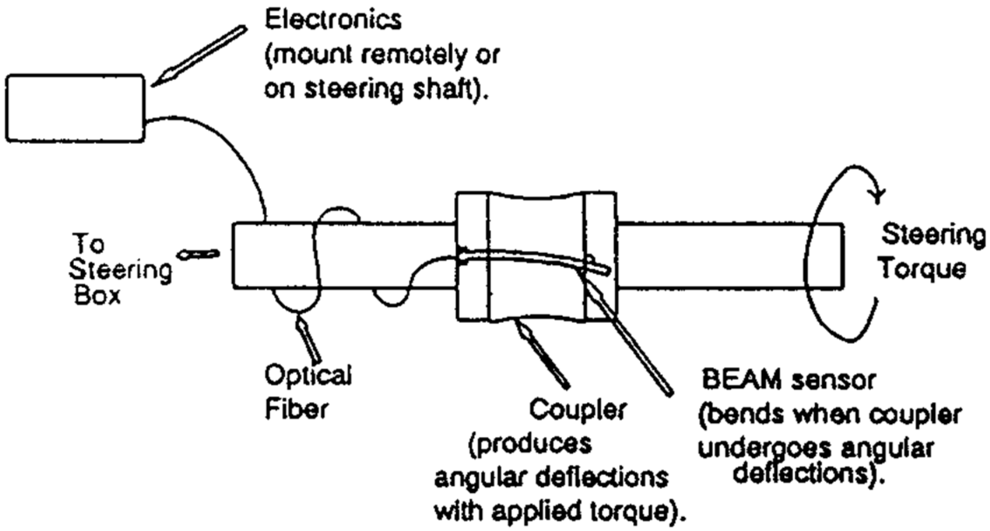
If the fiber is bent upward, the three rays reach the end of the fiber either directly or by total internal reflection. When the fiber is straight, only one ray is lost through the treated portion. If the fiber is bent downward, two of the rays are lost.

This model can be extended to show that for any number of rays contained within the core, more are lost for downward bends than for upward bends, and that the straight fiber represents an intermediate case. If all the cladding were removed, upward bends would be indistinguishable from downward bends, and the sensor would not be useful when straight, the most likely position for embedded fibers.



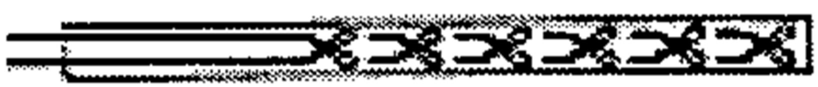
Courtesy of Measurand. Used with permission.

How ShapeTape Measures Twist



Bend fibers near center of strip
Twist fibers near edges

Can also wrap fibers around center?



Courtesy of Measurand. Used with permission.

SHAPE TAPE™ uses paired loops to sense twist and bend along a ribbon substrate. In this case, sums and differences correspond to twist and bend, and there is no control loop used in ordinary applications.

Shape Tape

Characteristics, S1280CS multiplexed ShapeTape™
(Specifications will vary for other lengths, number of sensors, etc.)

Dimensions of tape: 1.3 x 13 x 1800 mm nominal
Dimensions of interface box: 16 x 54 x 168 mm nominal
Operating temperature: -20 to 50 deg c
Sensitive zone: outboard 480 mm contains 16 sensors arranged in 8 pairs
Sensor length: each sensor integrates curvature over a 60 mm portion of the sensitive zone
Sensor pair: each pair resolves bend and twist, using calibration constants
Calibration: Circle, twist, & flat poses yield stored calibration constants
Data: x,y,z and orientation at 16 or more points along sensitive zone, relative to inboard reference end
Calibrated Range of each sensor: ± 40 mm radius bend; ±22.8 deg twist
Safe Bending radius: ± 20 mm radius
Spatial sampling limits: each monotonic (single polarity) curve requires two sensor lengths
Operating range for end of 'U' shape: two elliptical volumes, 160 x 250 mm each.
Endpoint accuracy within operating range and sampling limits: 1-3% of length is a reasonable expectation for postional errors; thus, for the first 100 mm of a tape, the error can be expected to be 1-3 mm, and if the tape is 1000 mm long, the error at the tip can be expected to be 10-30 mm.
Endpoint resolution: 0.3 mm rms, x,y,or z; 0.5 deg, roll, pitch, or yaw
Other locations on tape: errors reduce toward inboard reference end, within range and sampling limits
Maximum data acquisition speed: 110 Hz
Included: Wall mount power supply (60 Hz, 120VAC), serial cable, interface box, and tape

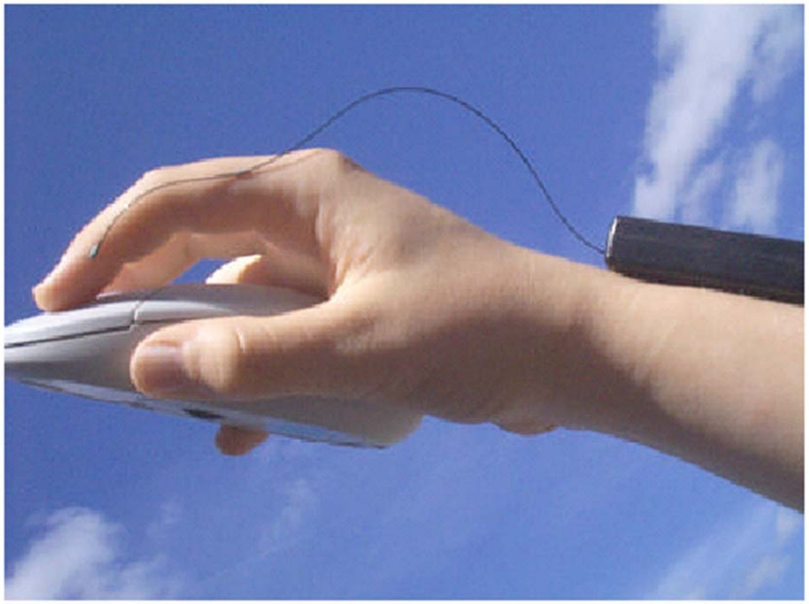
Courtesy of Measurand. Used with permission.

http://www.youtube.com/v/ZMZr1jNDVGY&color1=0xb1b1b1&color2=0xcfcfcf&hl=en_US&feature=player_embedded&fs=1

Shape Tape Products

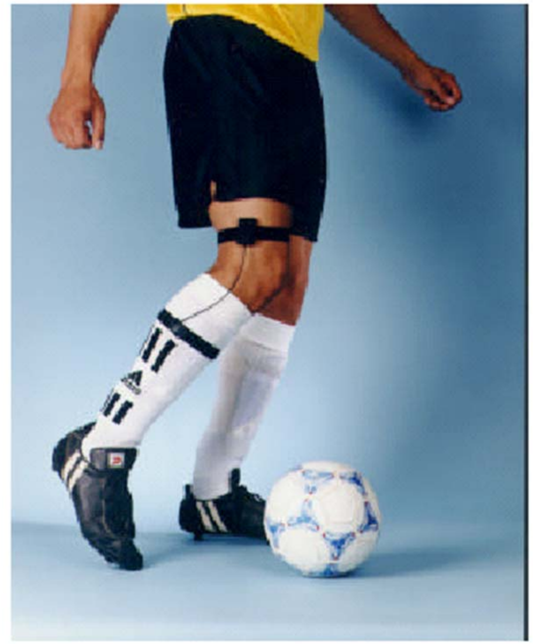
S720 MINIATURE JOINT ANGLE SHAPE SENSOR™

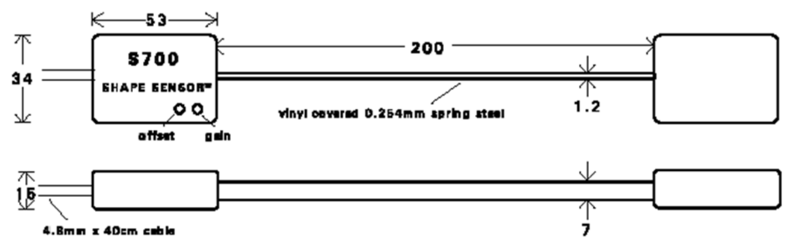
Revision 20020912



S700 JOINT ANGLE SHAPE SENSOR

Revision 20020912





Courtesy of Measurand. Used with permission.

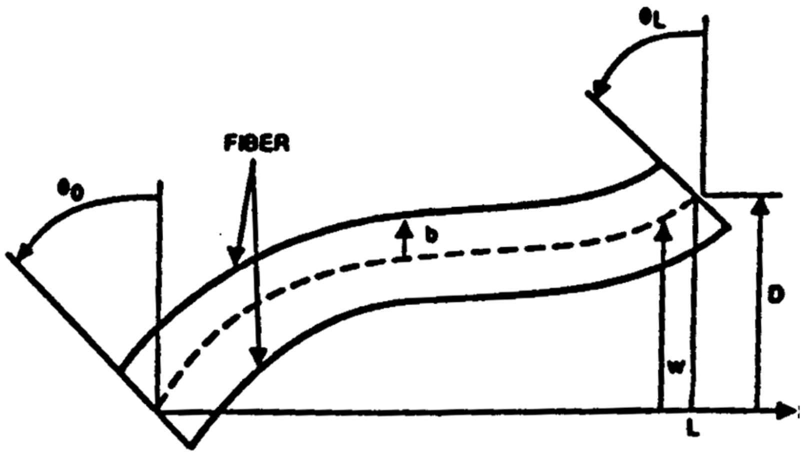
AXIS - Alignment Transfer By Integrated Strain

P = sensor weighting (uniform)

b(x) = half diameter

w''(x) = rod curvature

x = distance along rod



OUTPUT OF INTEGRATING STRAIN SENSOR WITH WEIGHTINGS FUNCTION p(x)

$$-\Delta L \equiv \varepsilon = \int_0^L P\, b(x)\, w''(x)\, dx$$

$$= P\, b(x)\, w'(x)\Big|_0^L - P\, b'(x)\, w(x)\Big|_0^L + \int_0^L P\, b''(x)\, w(x)\, dx$$

If $b(x) = B$

$$\varepsilon = P\,B[w'(L) - w'(o)] = P\,B(\theta_L - \theta_o) \quad \text{(ANGLE OUTPUT)}$$

If $b(x) = K(1 - x/L)$

$$S = -K\,P w'(o) + K\,P/L[w(L) - w(o)]$$

$$= -K\,P(\theta_o - D/L) \quad \text{(DISPLACEMENT OUTPUT)}$$

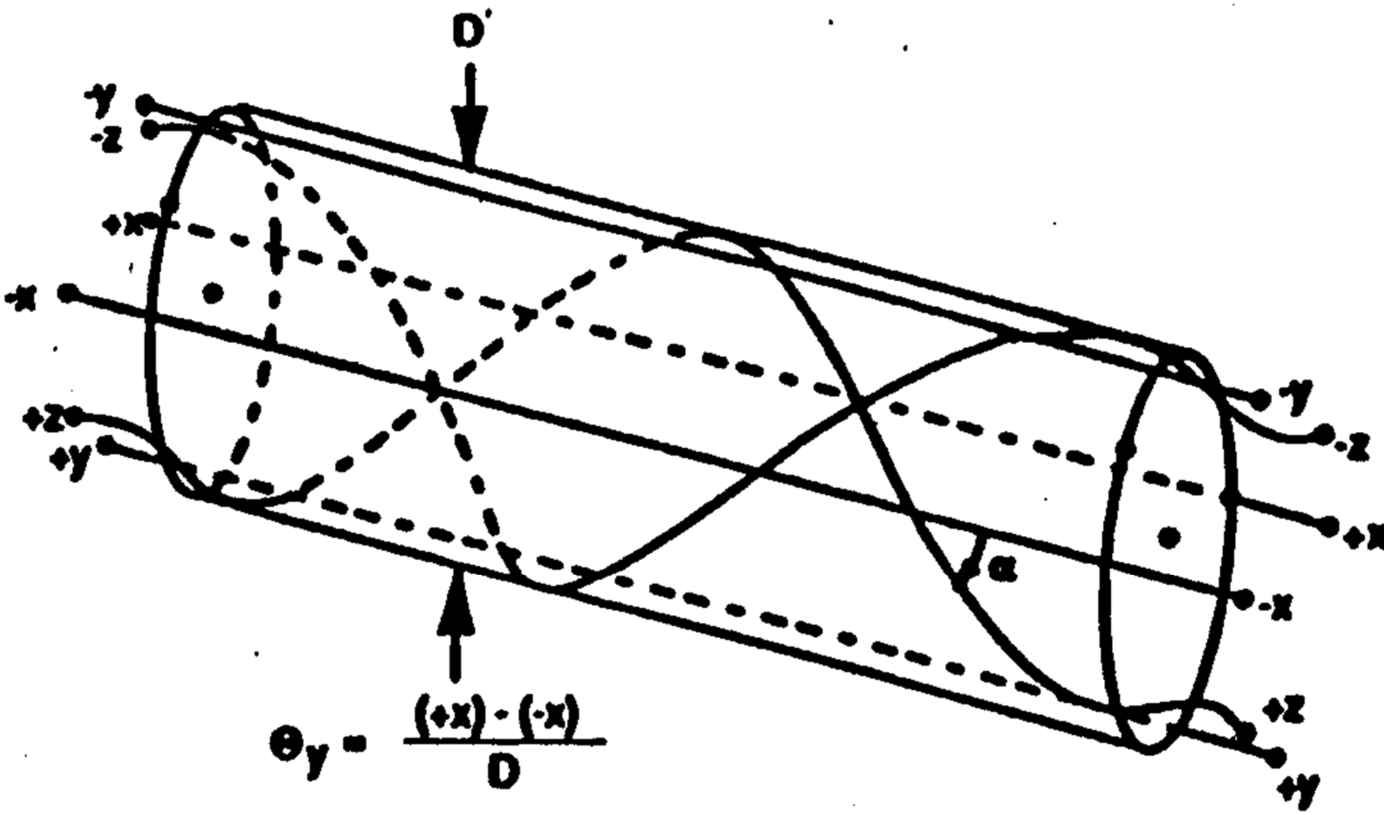
Courtesy of Draper Laboratory. Used with permission.

Figure 1. AXIS Analysis.

- Invented by Len Wilk, Draper Lab
  - US Patent # 4,788,868 (1988)
- Output of a strain-measuring loop draped across a beam depends *only* on the difference between the angles of the ends

Three-Angle measurements with twist

Note: D must be fairly small to avoid snapping measuring fiber or wire



$$\theta_y = \frac{(+x) - (-x)}{D}$$

$$\theta_p = \frac{(+y) - (-y)}{D}$$

$$\theta_r = \frac{(+z) - (-z)}{D} \sin\alpha$$

- Helical windings provide measurement of twist

As shown in Figure 2, a pair of fibers in the (nominally) y z plane will provide a measure of the relative rotation about the x axis (e.g. the pitch angle):

$$\theta p = \Delta Ly / D \quad (2)$$

The pair of fibers in the (nominally) x z plane provide the yaw angle,

$$\theta y = \Delta Lx / D \quad (3)$$

while a clockwise helical fiber compared to a counterclockwise helical fiber provides the roll (twist) angle,

$$\theta r = \Delta Lz \sin\alpha / D \quad (4)$$

where α is the helix angle, D is the diameter separating the pairs of fibers, and ΔL is the difference in length between the fibers of a pair.

Some topological comments are in order. (1) The above configuration will provide the three angles independently given that the magnitude of the angles does not get too large (of order 30 degrees). (2) Bending and twisting that is constrained to one plane can be accommodated to large angles without topological limit. (3) Several rods can be joined in series: if the rods are joined at fixed right angles in cardinal directions, then the fiber pairs, rod to rod, can be joined so as to provide the proper angular transformations; if the rods are constrained to lie in cardinal planes, but at (fixed) arbitrary angles in these planes, and a double set of fibers implemented, the double pairs of fibers can be proportionally combined for proper transformations; with a triple set of fibers, the rods can be at any arbitrary fixed angles, and proportional combinations among the fiber pairs will provide the correct transformations.

Courtesy of Draper Laboratory. Used with permission.

Measurement of displacement with weighting

$$\in = -KBw'(0) + (w(L) - w(0)) = -KB(\theta_0 + D/L)$$

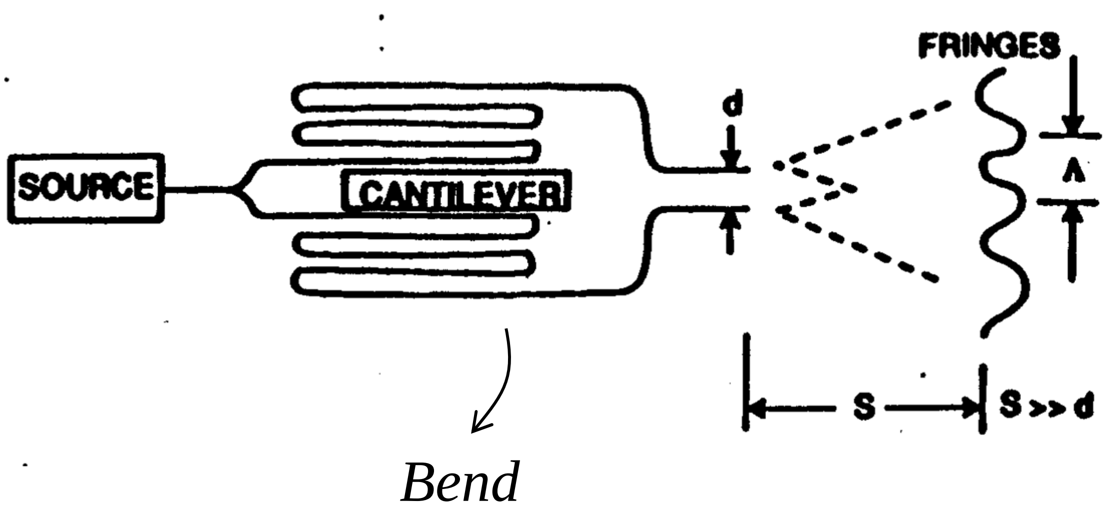
AXIS Interferometric Readout

Thus, we see that angle and displacement of two reference points can be measured by integrating strain sensors. In the case of an optical fiber, the optical phase shift as a function of strain is given by the photoelastic effect

$$\phi(\epsilon) = knL(1+\epsilon) - \frac{kn^3L}{2}\left(\rho_{12} - \nu(\rho_{11}+\rho_{12})\right)\epsilon \quad (5)$$

where $k = 2\pi/\lambda$, n is the refractive index, ν is Poisson's ratio, and ρ_{11} and ρ_{12} are the photoelastic constants. The cable would be instrumented with pairs of integrating strain sensors on opposite sides of the cable, operating in a differential mode.

Single-Axis Interferometer Schematic



Courtesy of Draper Laboratory. Used with permission.

Results in an arcsecond of deflection per fringe

Differential measurement!

Resistive Wire Strain Detection

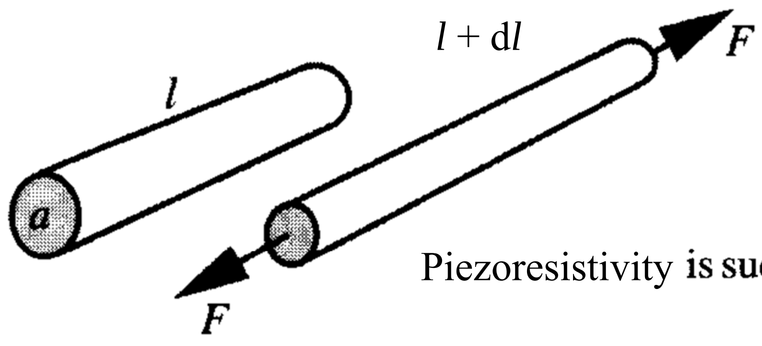


Fig. 3.19. Strain changes the geometry of a conductor and its resistance.

Piezoresistivity is successfully employed in sensors which are responsive to stress, σ:

$$\sigma = \frac{F}{a} = E\frac{dl}{l}, \tag{3.60}$$

Strain (e = dl/l)

where E is Young's modulus of the material and F is the applied force. In this equation, the ratio $dl/l = e$ is called *strain*, which is a normalized deformation of the material.

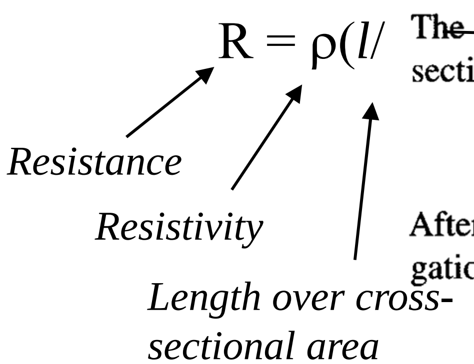


Figure 3.19 shows a cylindrical conductor (wire) stretched by applied force F. The volume v of the material stays constant while the length increases and the cross sectional area becomes smaller. As a result, Eq. (3.54) c[illegible] be rewritten as

$$R = \frac{\rho}{v} l_2. \tag{3.61}$$

After differentiating, we can define sensitivity of resistance with respect to wire elongation:

It follows from this equation that the sensitivity becomes higher for the longer and thinner wires with a high specific resistance. Normalized incremental resistance of the strained wire is a linear function of strain, e, and it can be expressed as

$$\frac{dR}{R} = S_e e, \tag{3.63}$$

Gauge Factor

where S_e is known as the *gauge factor* or *sensitivity* of the strain gauge element. For metallic wires, it ranges from 2 to 6. It is much higher for semiconductor gauges; it is between 40 and 200.

© Springer. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Strain Gauge Patterns

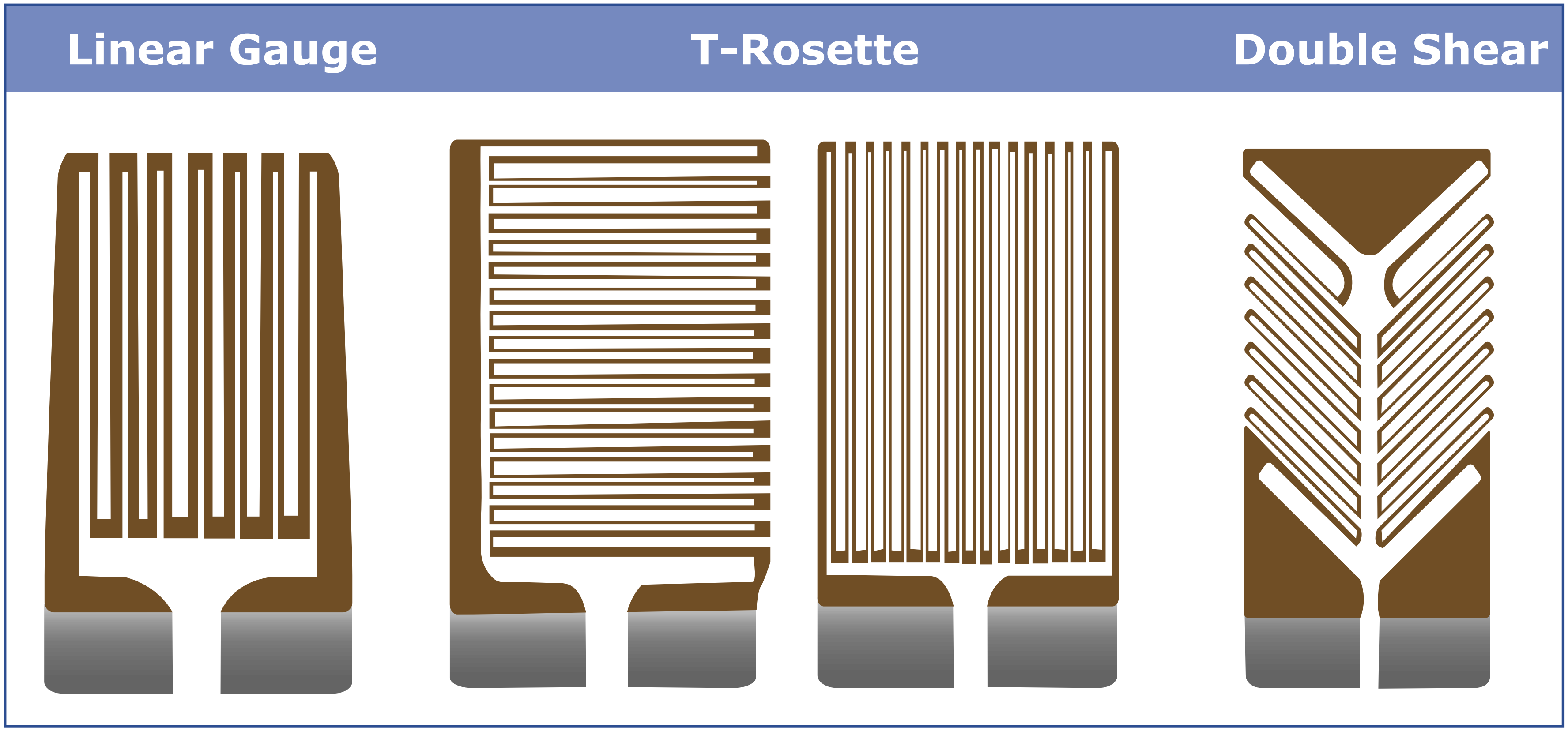
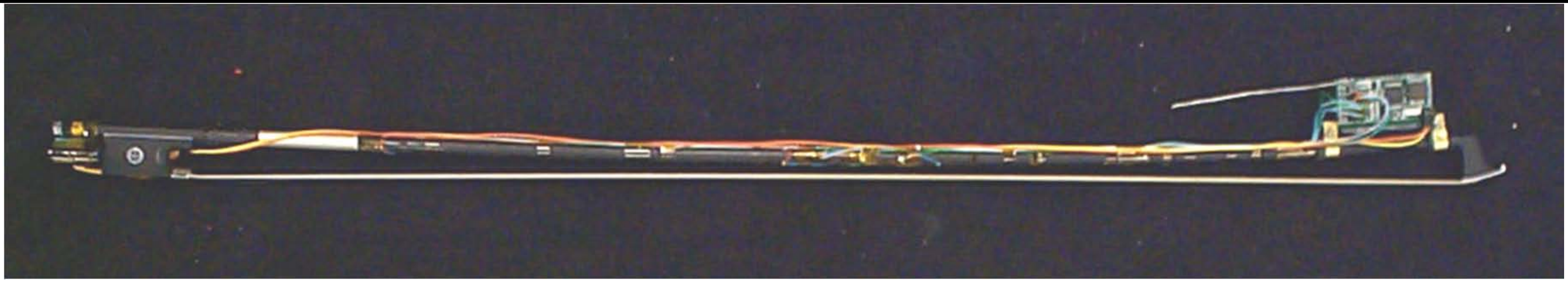
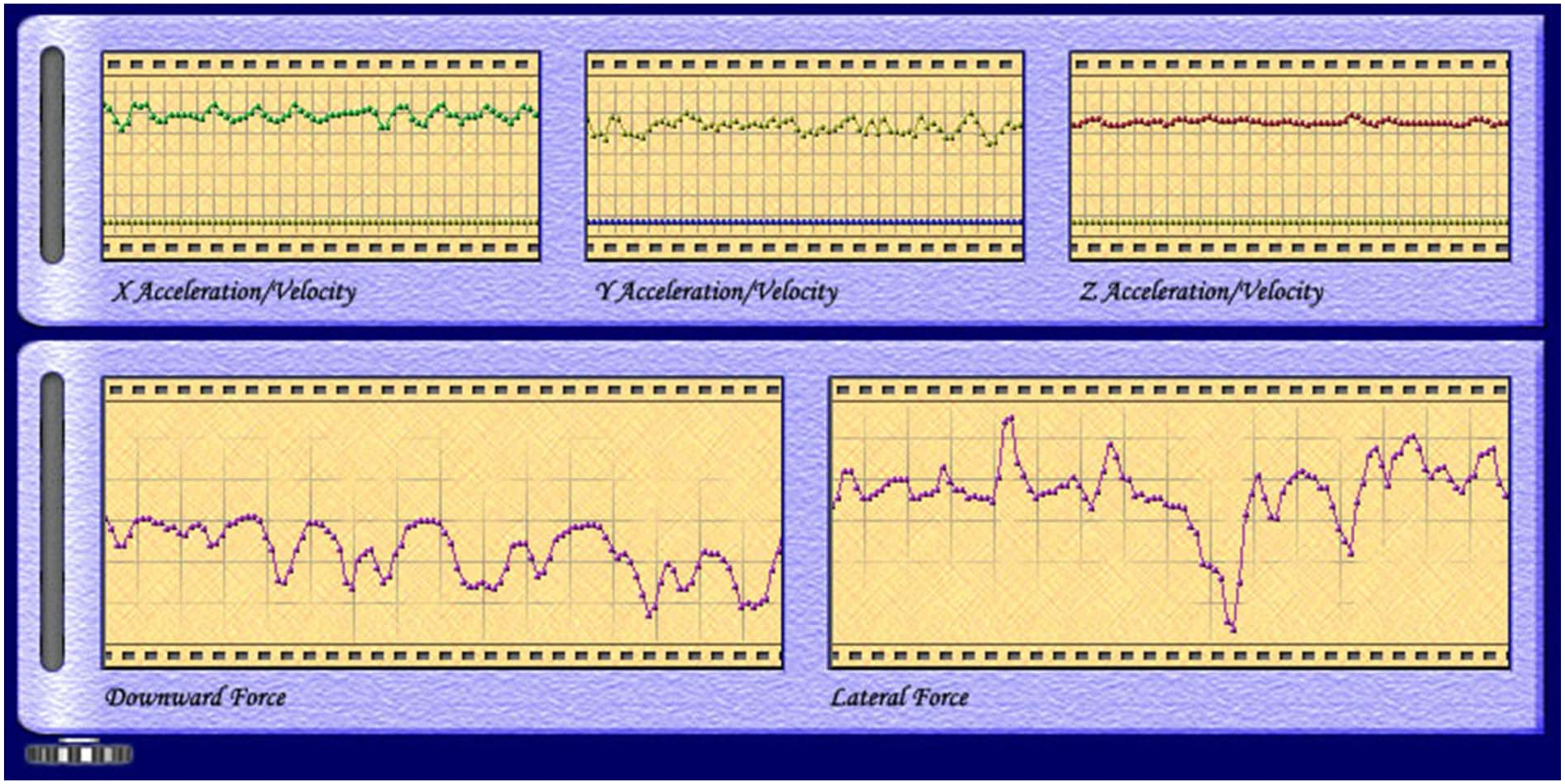


Image by MIT OpenCourseWare.

Strain Gauges want to be bonded onto a hard surface, so they can be forced into strain when the surface is deflected. Soft materials won't strain the gauge enough

Current Work – Diana Young's wireless bow

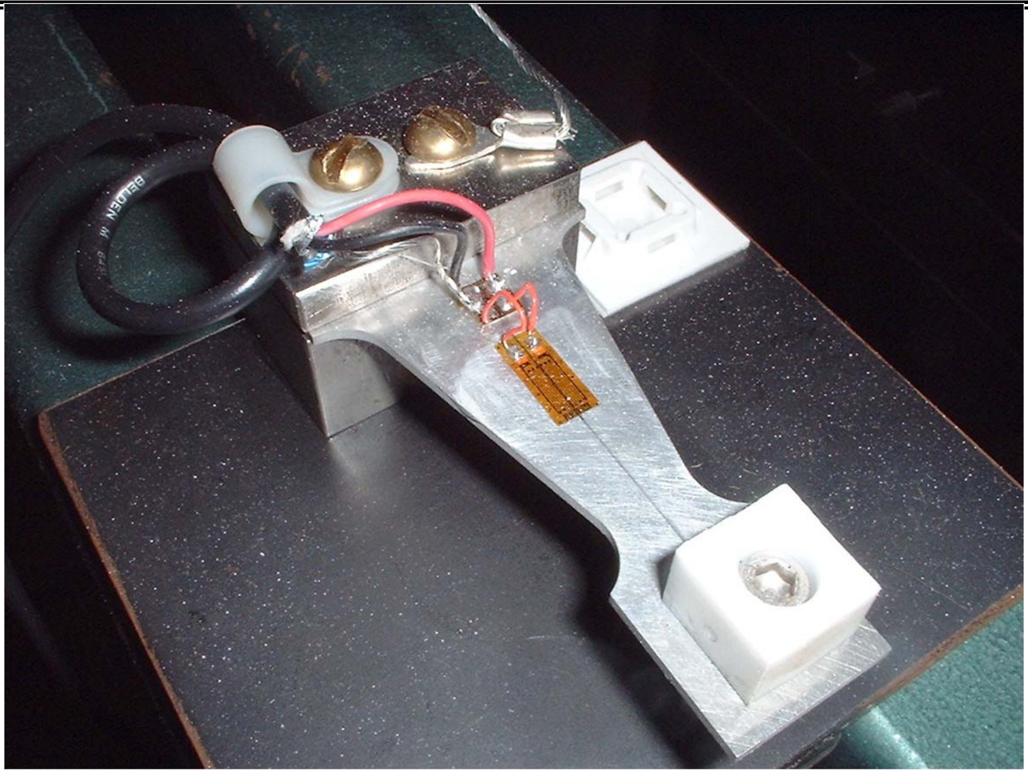




© Diana Young. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

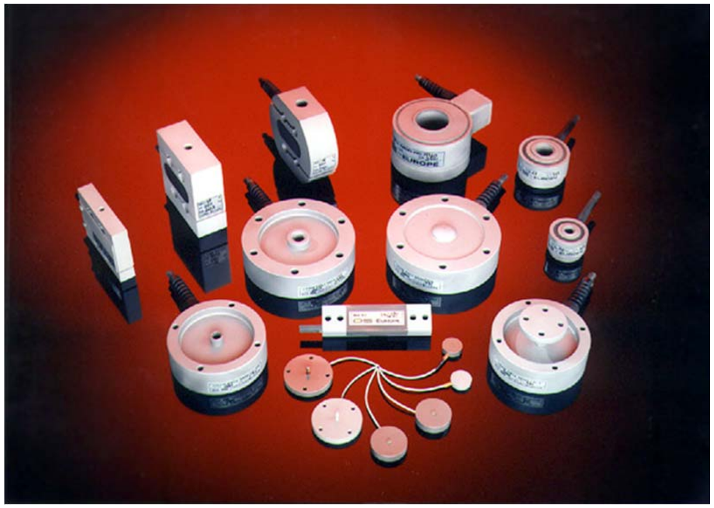
- Strain gauges on bow for bow bend (in x,y) and twist.
- Accelerometers for 3-axis motion
- Capacitive transmitters as before for position

Load Cells



Simple, "naked" load cell from Ohio State

20 Ton load cell for truck weight



Load Cell assortment from DHS

- Bond strain gauge to cantilevered beam
  - Force deflects beam, bends strain gauge, creates signal
- Can be quite accurate
  - Compensate temperature effects

© Unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Silicon Pressure Sensors

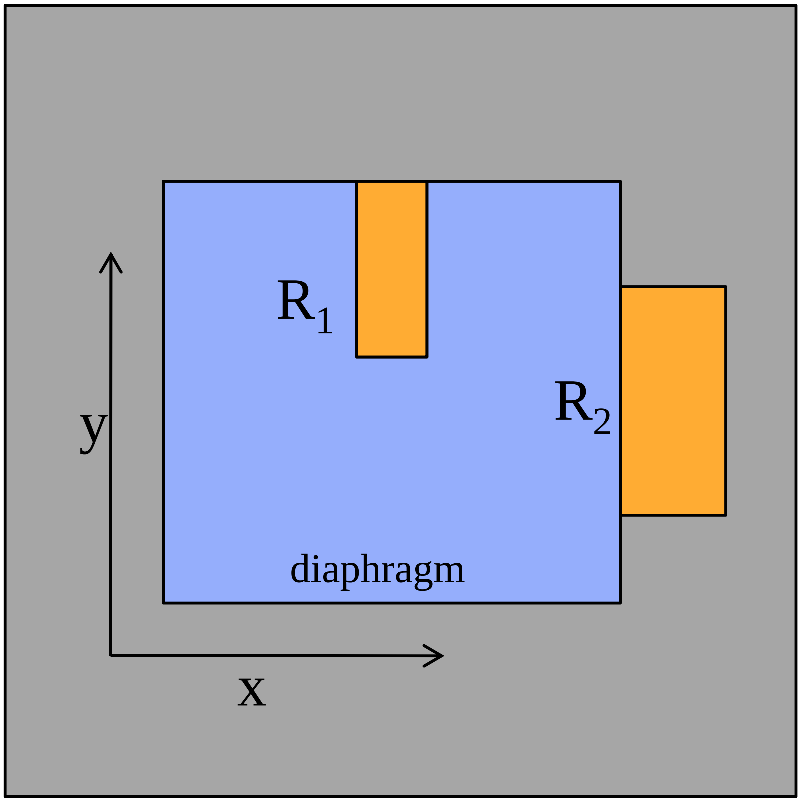
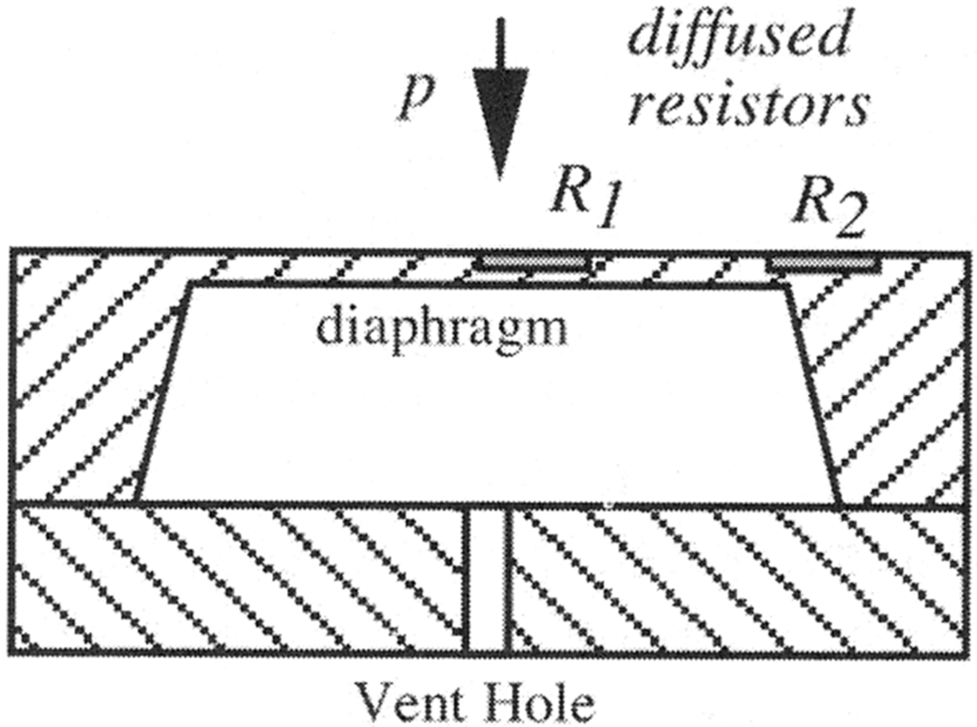


Fig. 10.4. Position of piezoresistors on a silicon



- Piezoresistors diffused onto silicon at R1, R2
  - Boron doping typical…
- Piezoresistors couple into longitudinal & transverse stress
  - Coupling is opposite for each mode
- R1 and R2 essentially subtract in a half-bridge

where π_1 and π_t are the piezoresistive coefficients in the longitudinal and transverse direction, respectively. Stresses in longitudinal and transverse directions are designated σ_1 and σ_t. The π coefficients depend on the orientation of resistors on the silicon crystal. Thus, for p-type diffused resistor arranged in the $\langle 110 \rangle$ direction or an n-type silicon square diaphragm with (100) surface orientation as shown in Fig. 10.4, the coefficients are approximately denoted as [7]

$$\pi_1 = -\pi_t = \frac{1}{2}\pi_{44}. \tag{10.11}$$

A change in resistivity is proportional to applied stress and, subsequently, to applied pressure. The resistors are positioned on the diaphragm in such a manner as to have the longitudinal and transverse coefficients of the opposite polarities; therefore, resistors change in the opposite directions:

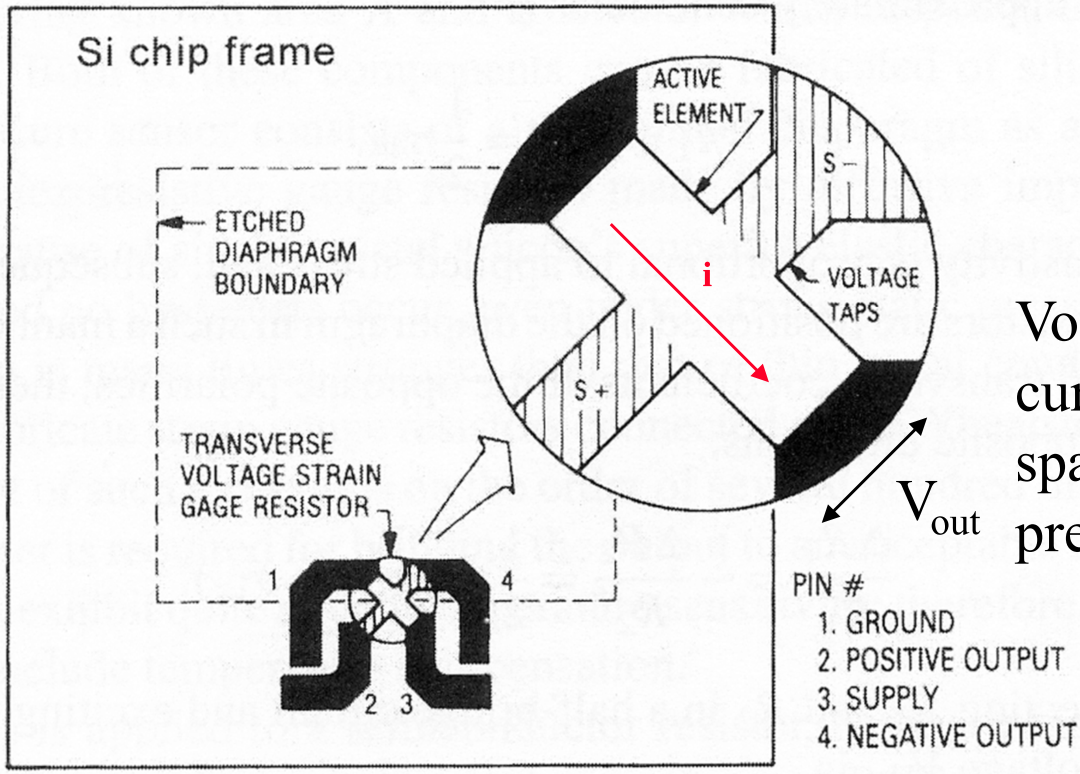
$$\frac{\Delta R_1}{R_1} = -\frac{\Delta R_2}{R_2} = \frac{1}{2}\pi_{44}(\sigma_{1y} - \sigma_{1x}). \tag{10.12}$$

When connecting R_1 and R_2 in a half-bridge circuit and exciting the bridge with E, the output voltage V_{out} is

$$V_{out} = \frac{1}{4}E\pi_{44}(\sigma_{1y} - \sigma_{1x}). \tag{10.13}$$

© Springer. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Motorola MPX Pressure Sensor



Voltage created when current bends due to spatial R gradient from pressure distrubution

© Freescale Semiconductor Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

- Pressure sets up electrical field in non-excited connections (hence voltage)
  – Analogous to Hall effect
  – Essentially already a bridge
  – Everything is on one substrate - simpler T compensation

Pressure Sensors

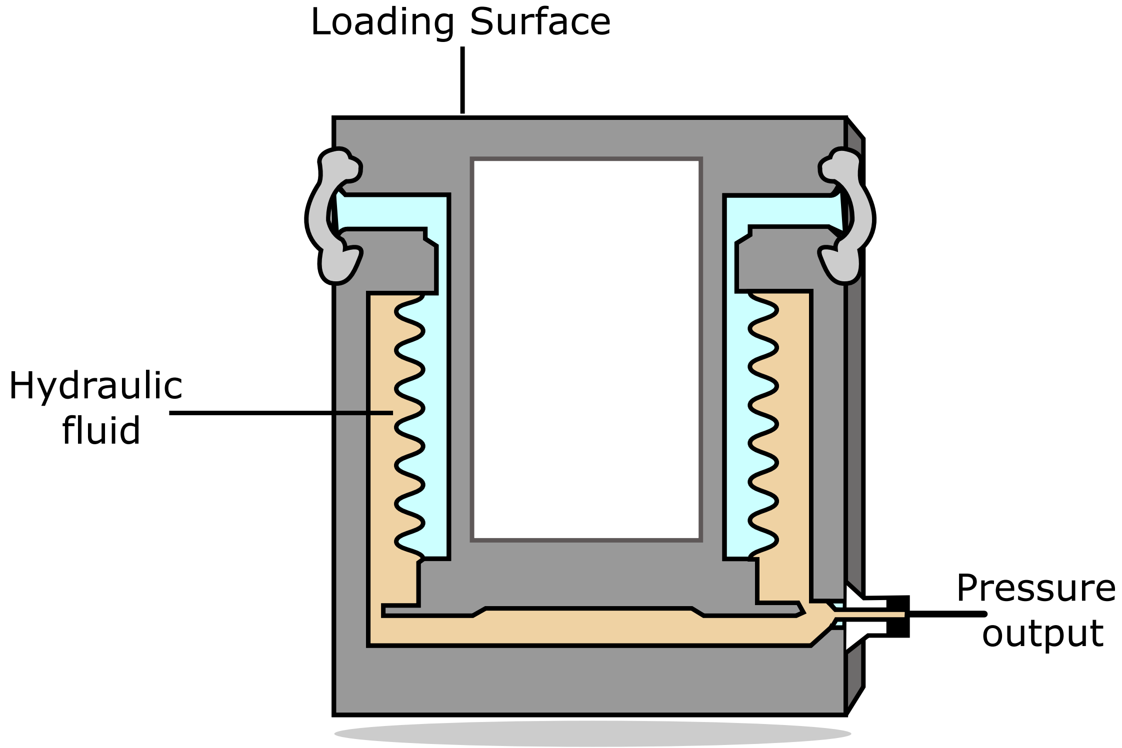


Image by MIT OpenCourseWare.

Photos of various pressure sensors removed due to copyright restrictions.

Hydraulic Load Cell

Link to UW paper on elevators

Many manufacturers: Motorola, MSI, Silicon Designs...

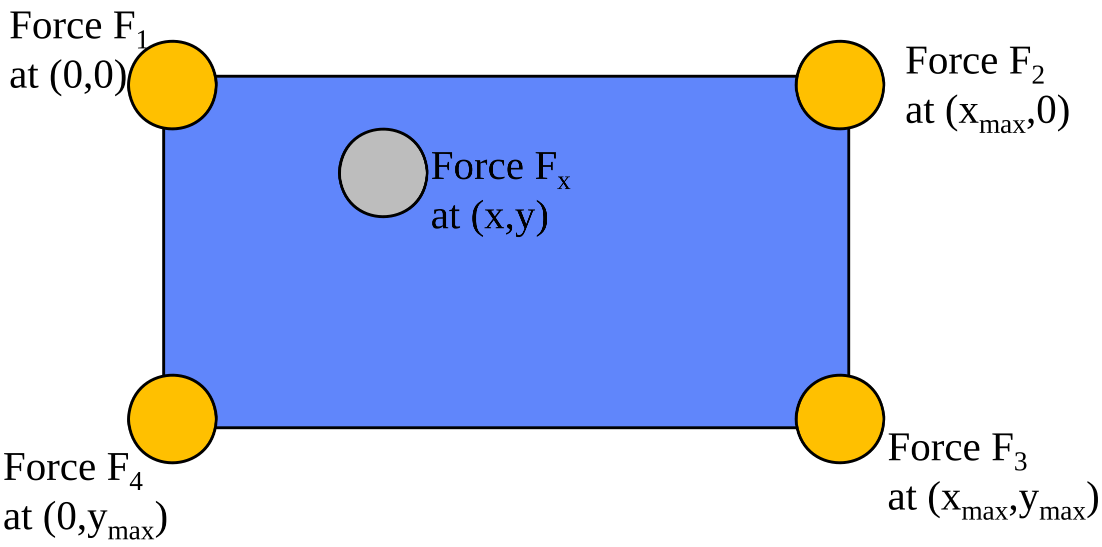
- Absolute and Differential (air or fluid) pressure
  - Back of diaphragm open or closed to the air/medium

UW/Intel Wearable Monitoring

Graph removed due to copyright restrictions.

Brunette, W., Lester, J., Rea, A., and Borriello, G. 2005. Some sensor network elements for ubiquitous computing. In Proceedings of the 4th international Symposium on information Processing in Sensor Networks (Los Angeles, California, April 24 - 27, 2005). Information Processing In Sensor Networks. IEEE Press, Piscataway, NJ, 52.

Force Balance Platform

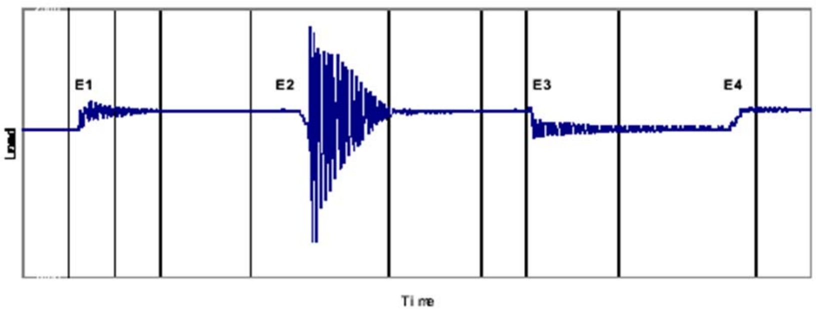


$$F_x = F_1 + F_2 + F_3 + F_4$$

$$F0_x = F0_1 + F0_2 + F0_3 + F0_4$$

$$x = x_{max} \frac{(F_2 - F0_2) + (F_3 - F0_3)}{(F_x - F0_x)}$$

$$y = y_{max} \frac{(F_3 - F0_3) + (F_4 - F0_4)}{(F_x - F0_x)}$$



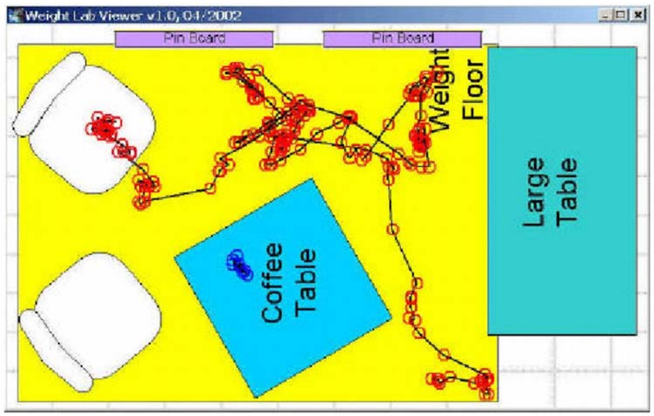


Fig. 8. Weight lab viewer showing a trace on the floor layout of the lab and also some interaction with the table (object put down).

By looking at the dynamic pressure balance on the table, objects on the table can be identified by weight change and tracked by force balance. Ditto for people moving around the floor

Albrecht Schmidt, et al., Ubicomp 2002

http://ubicomp.lancs.ac.uk/smart-its/Weight_Table/weight_table.html

© Albrecht Schmidt. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Piezoelectric References

Cover of "Piezoelectric Ceramics: Principles and Applications", APC International, removed due to copyright restrictions.

- APC International
  - Piezoelectric Ceramics: Principles & Applications
- Websites:
  - MSI Tutorial, Piezo Systems Tutorial

Piezoelectrics

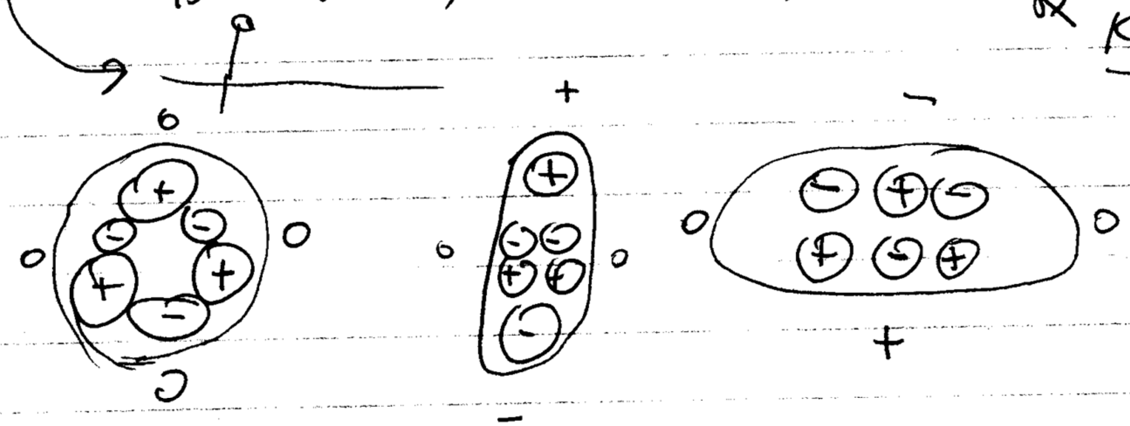
Piezoelectrics

Measure dynamic force

Ferroelectrics

→ Deformations of unit cell produce charge

Crystals (quartz), Ceramics (PZT), Polymers (PVDF) & Kynar

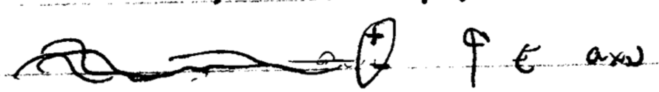


— Crystal lattice gives intrinsic polling

— Ceramics, Polymers need to be polled

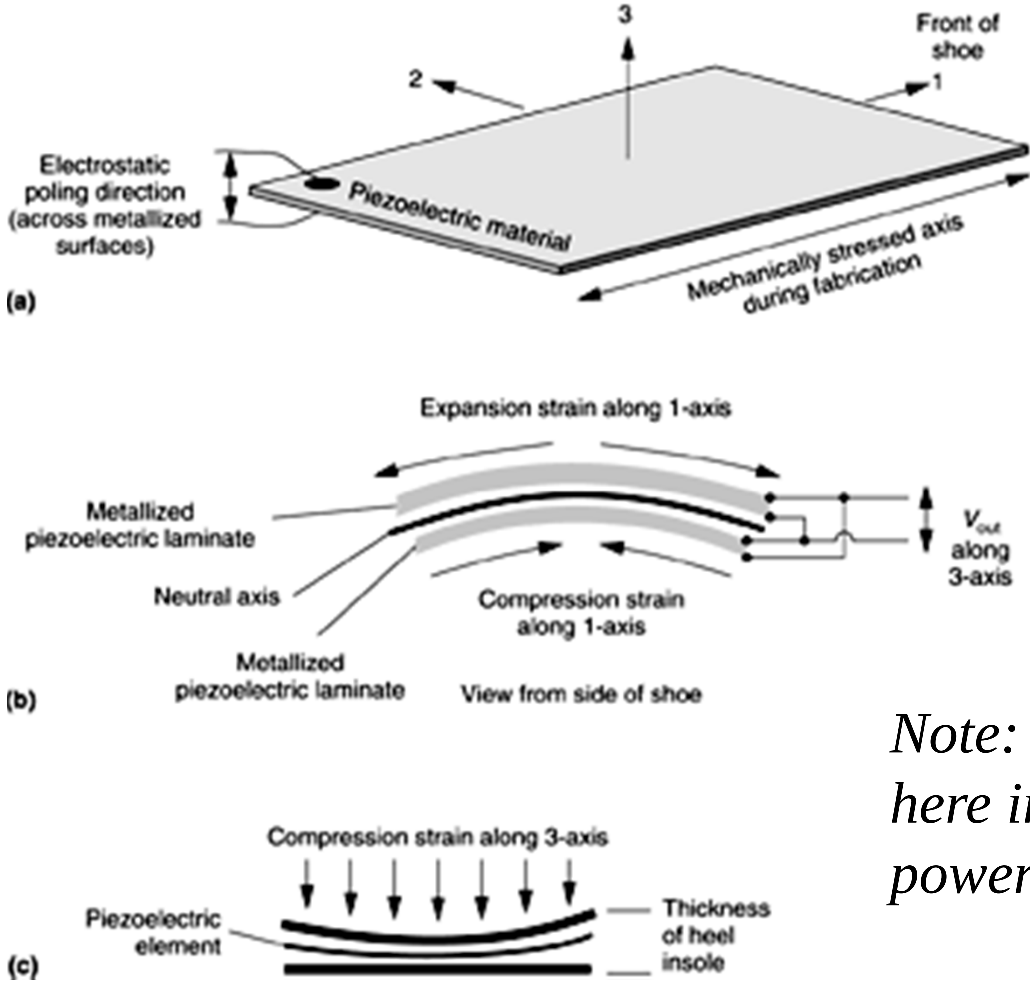
→ $\vec{E}$ field, pulling (foil), Temp (> curie)

→ Foil becomes "semicrystalline homopolymer"



Piezo Axes under Strain

Electrodes aluminized, silver inked, carbon (high strain)



Piezo Strain Coefficients:

d_{31}, d_{32}, d_{33} -> Coulombs/Newton (charge/force)

Piezo Voltage Coeficients:

g_{31}, g_{32}, g_{33} -> Electric Field Strength/Pressure ([V/m]/[N/m²])

$$g_{mn} = d_{mn}/\varepsilon$$

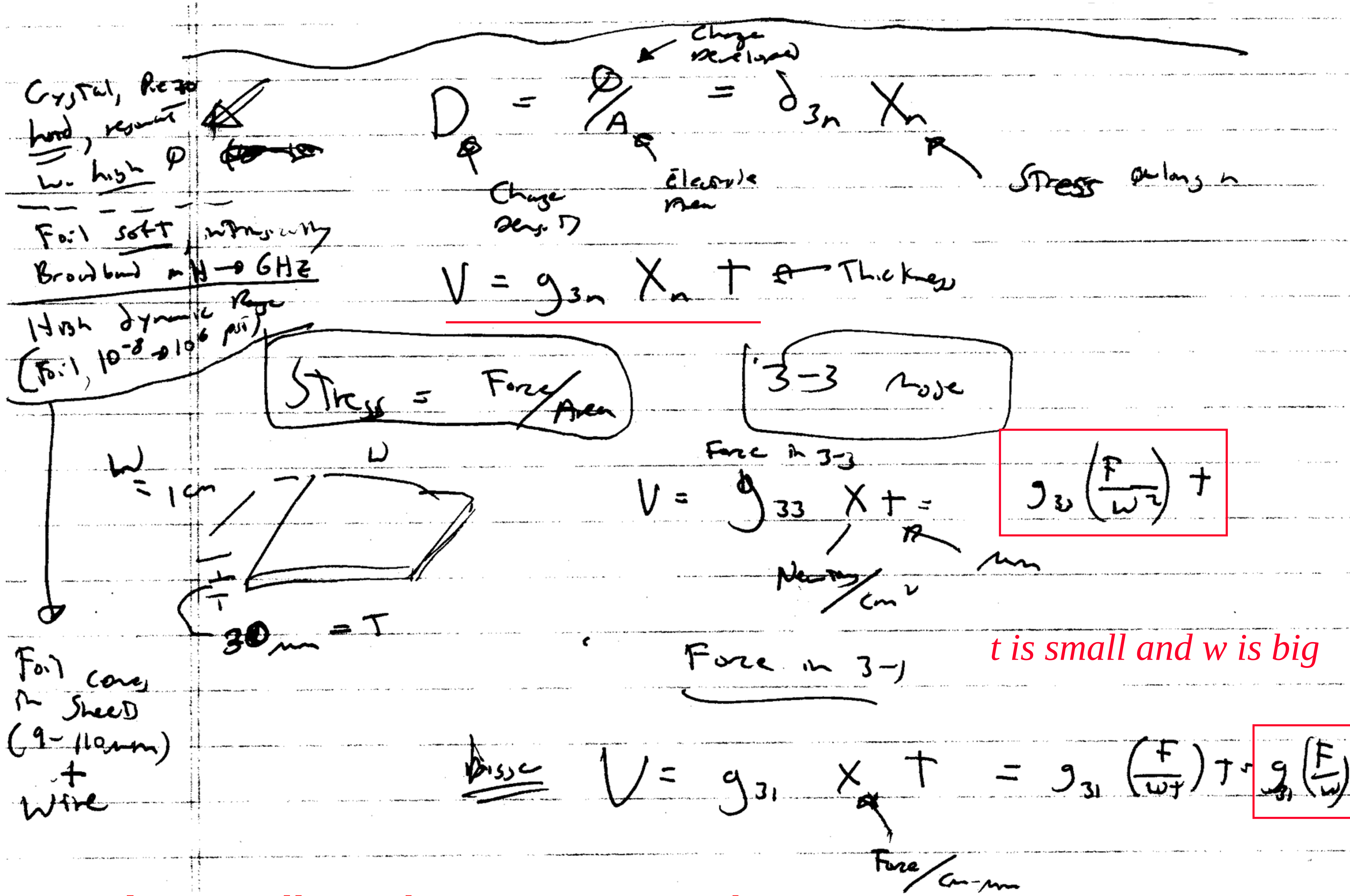
Note: Connected here in parallel for power generation

© Unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Capacitor - charge collection electrodes along 3 axis

In polling process, material heated, electric field applied along 3, strain along 1

Voltage from Strain

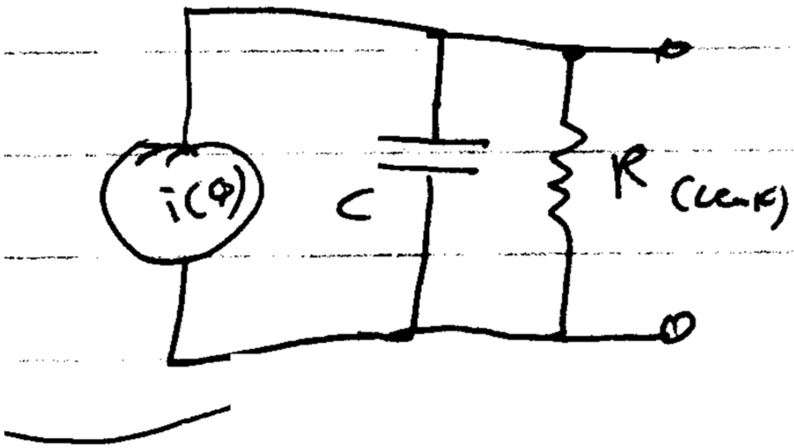


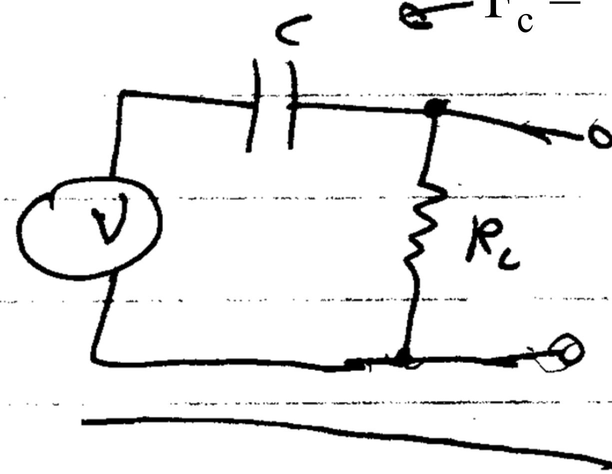
$g_{33}\left(\frac{F}{w^2}\right)T$

t is small and w is big

3-1 mode generally much more responsive than 3-3

Equivalent Circuits



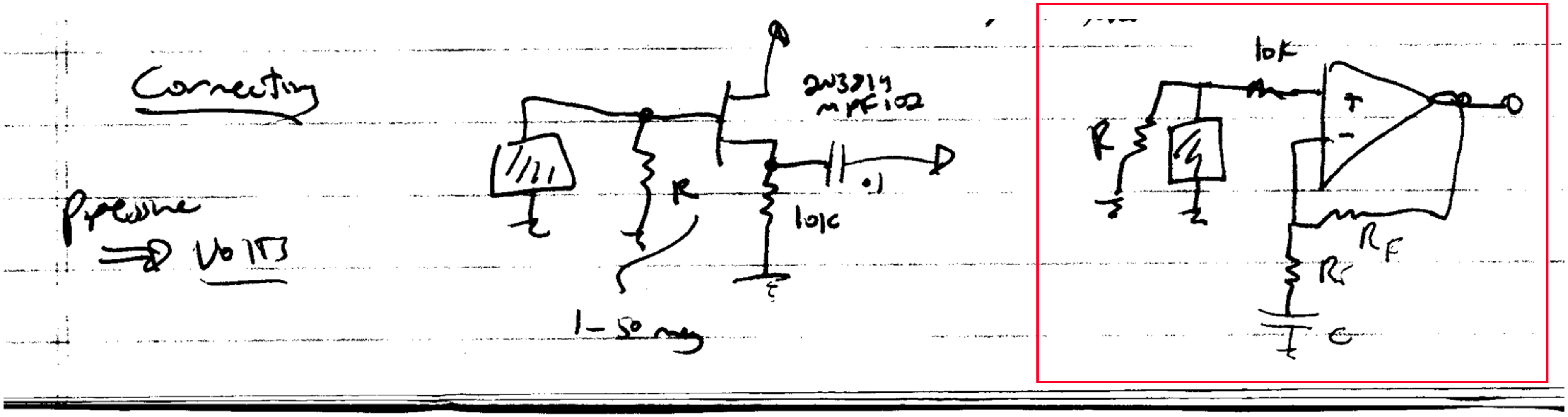


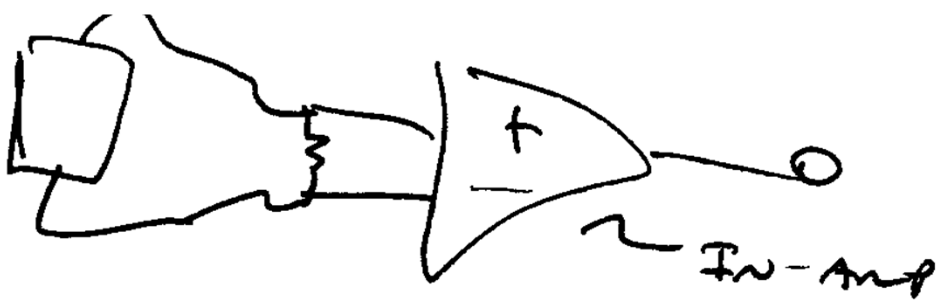
$$F_c = \frac{1}{2\pi R_L C}$$

High and reactive Impedance!

Capacitive Signal Source

Circuits, etc.





Some use charge-sensitive (integrating or transimpedance) amplifiers - e.g., to approximate steady-state pressure

I tend to use high-impedance amplifiers for piezoelectric elements

Piezo Foil (PVDF)

Photos of piezo film sensors removed due to copyright restructions.
See: Measurement Specialties.

Applications

PVDF uses

→ Rugged, easily interfaced, nice signals

~ Dynamic Pressure

[Feet, fingers, furniture, shoes...] ← Morphs

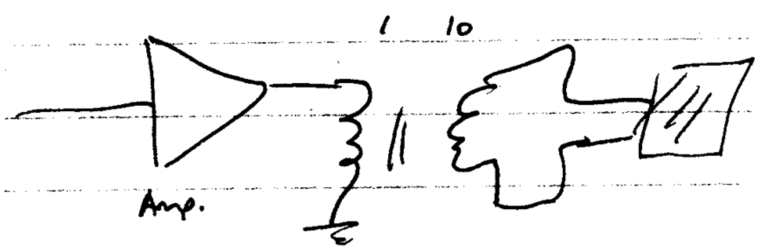
⇒ Acoustic Pickup [Suspension...]

⇒ Sonar

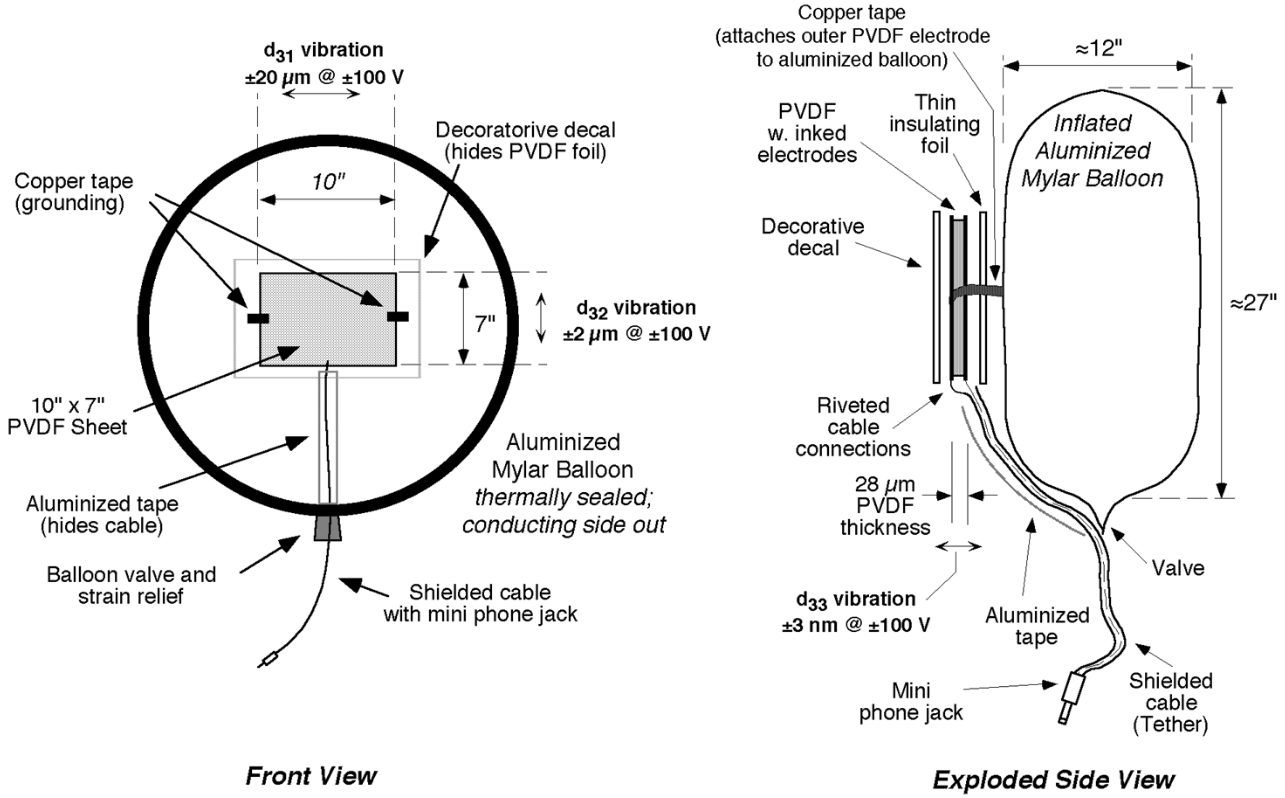
⇒ Distributed Transducer/Array

⇒ Reciprocal ~ Actuator

Thunder

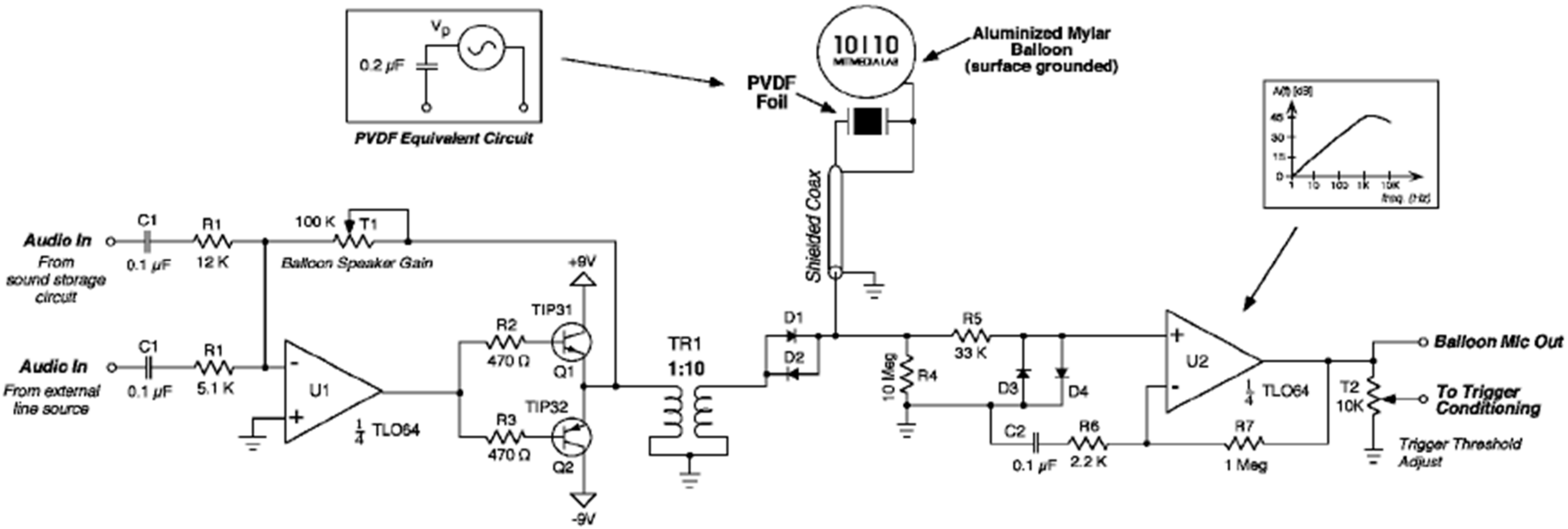


1995 - Interactive Audio Media



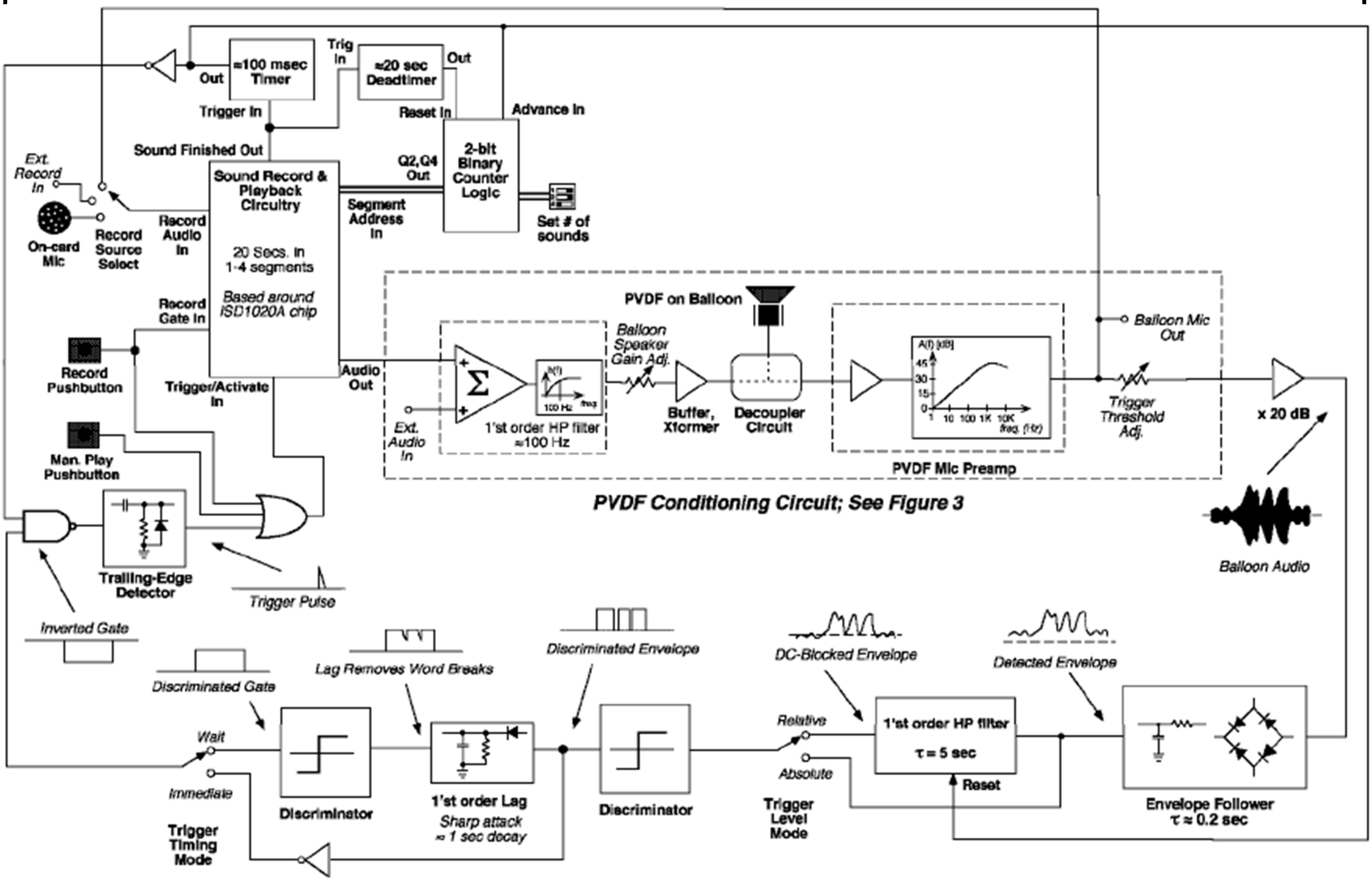
- PVDF strip laminated onto balloon surface forms speaker and microphone
- Simple electronics enable very simple "behavior"
- All over Media Lab for 10'th birthday (60 made)

Balloon Driver/Buffer

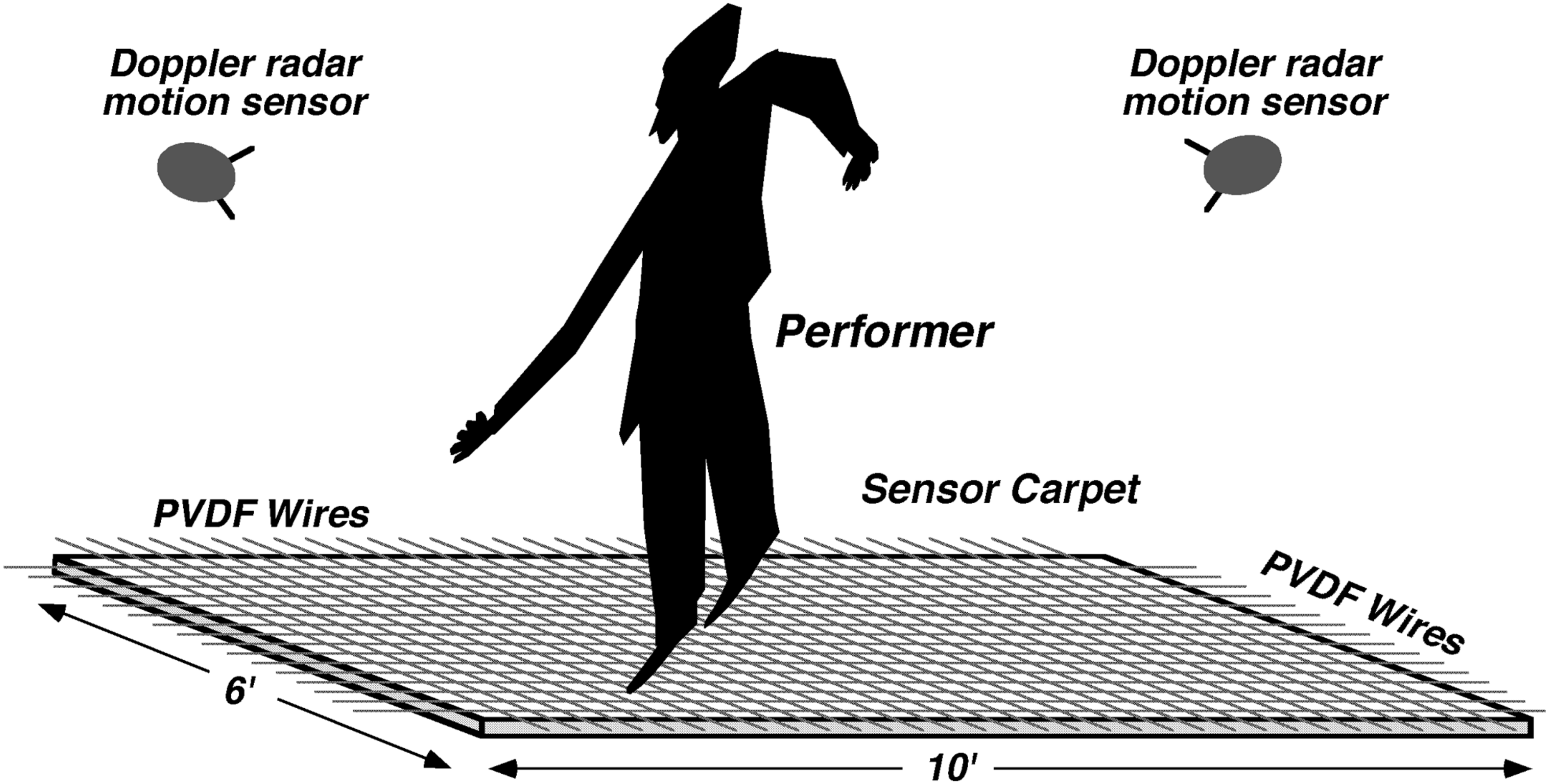


Transformer output boost, diode-based TR switch, and HP input response

All in Analog(!)

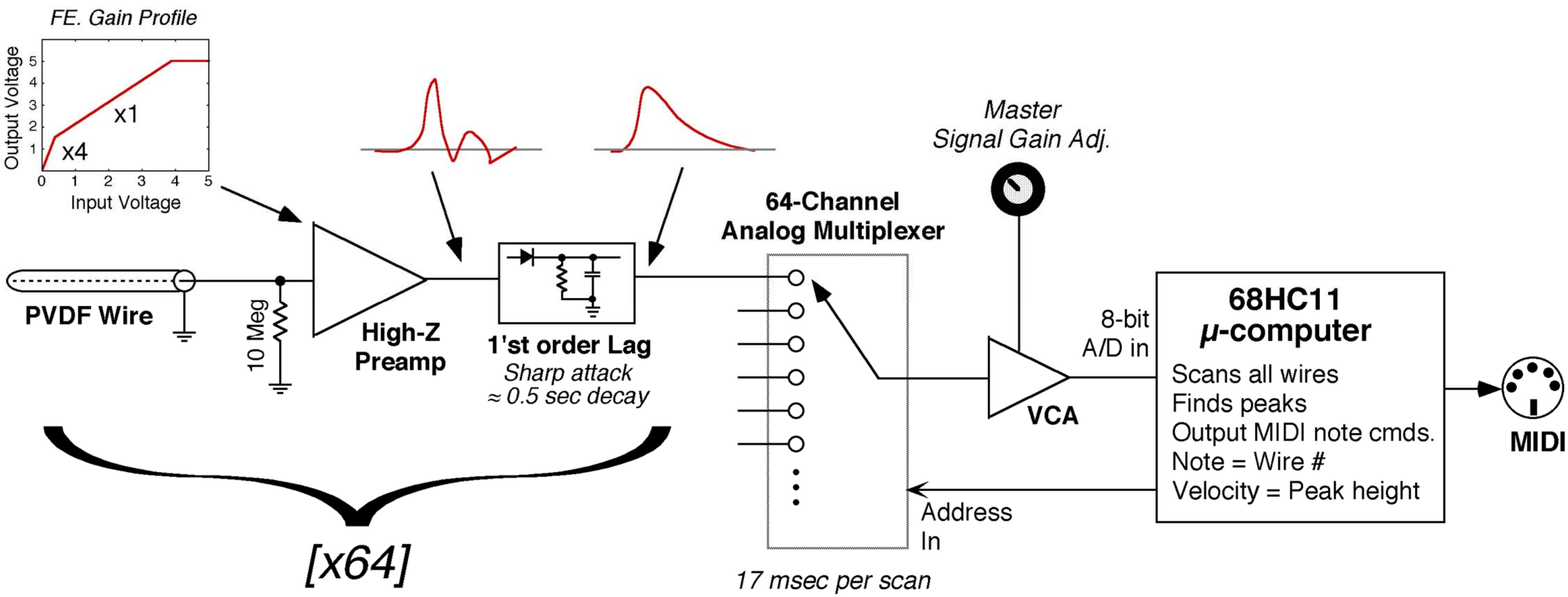


The Magic Carpet



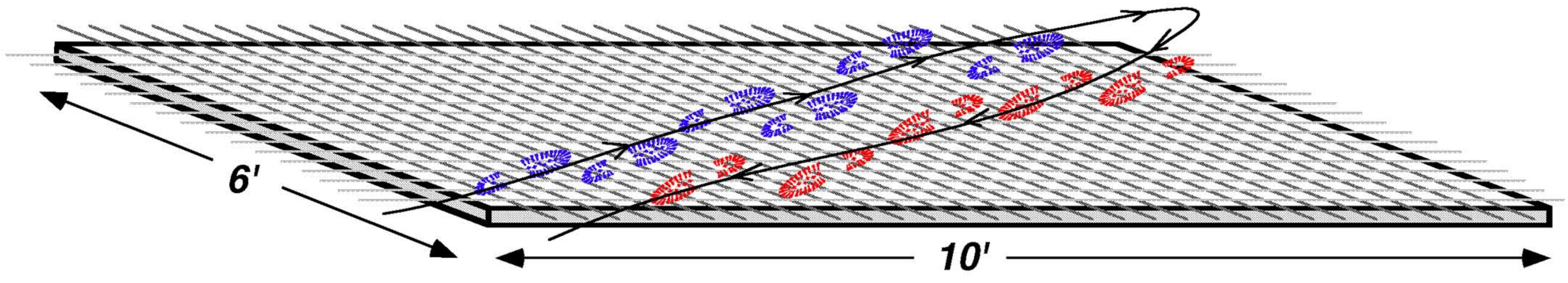
- Foot position, dynamic pressure captured by 4” grid of piezoelectric wire
- Pair of orthogonal Doppler radars measure upper body motion
- Not currently in the Brain Opera...

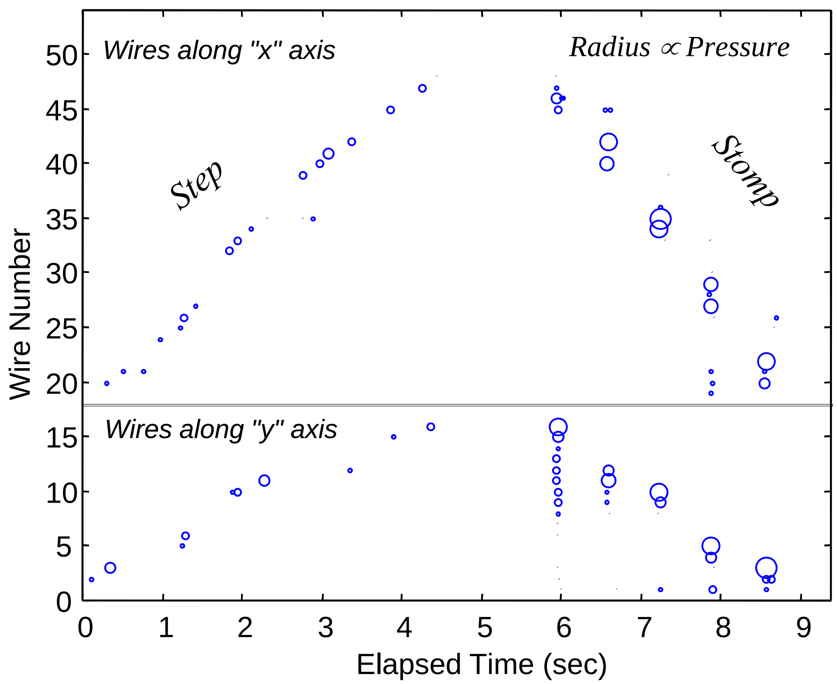
Sensing in the Carpet



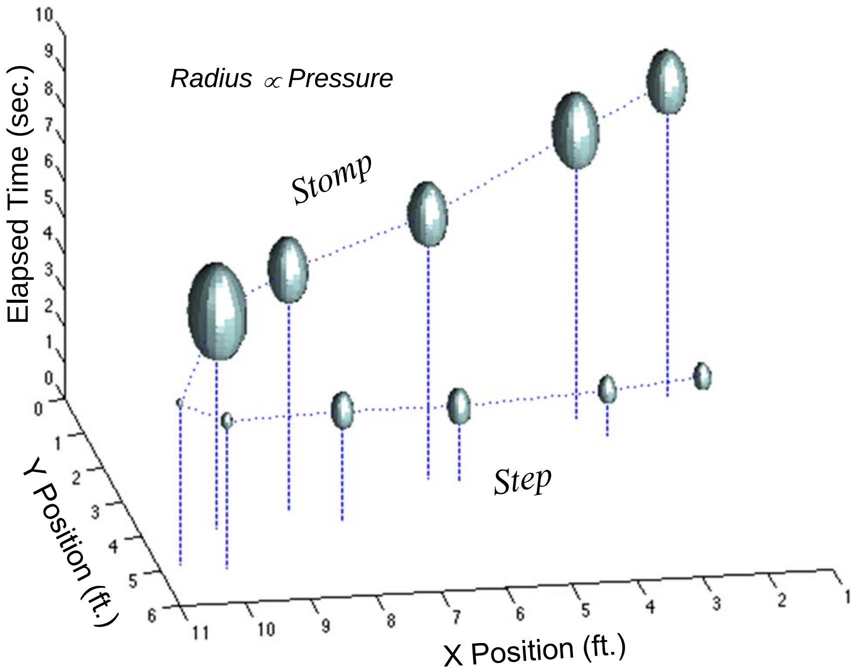
- Up to 64 PVDF wires are sampled at 60 Hz
- MIDI note events generated at every peak
- Simple electronics...

Carpet Data Analysis





Raw data from carpet wires



Data after time clustering

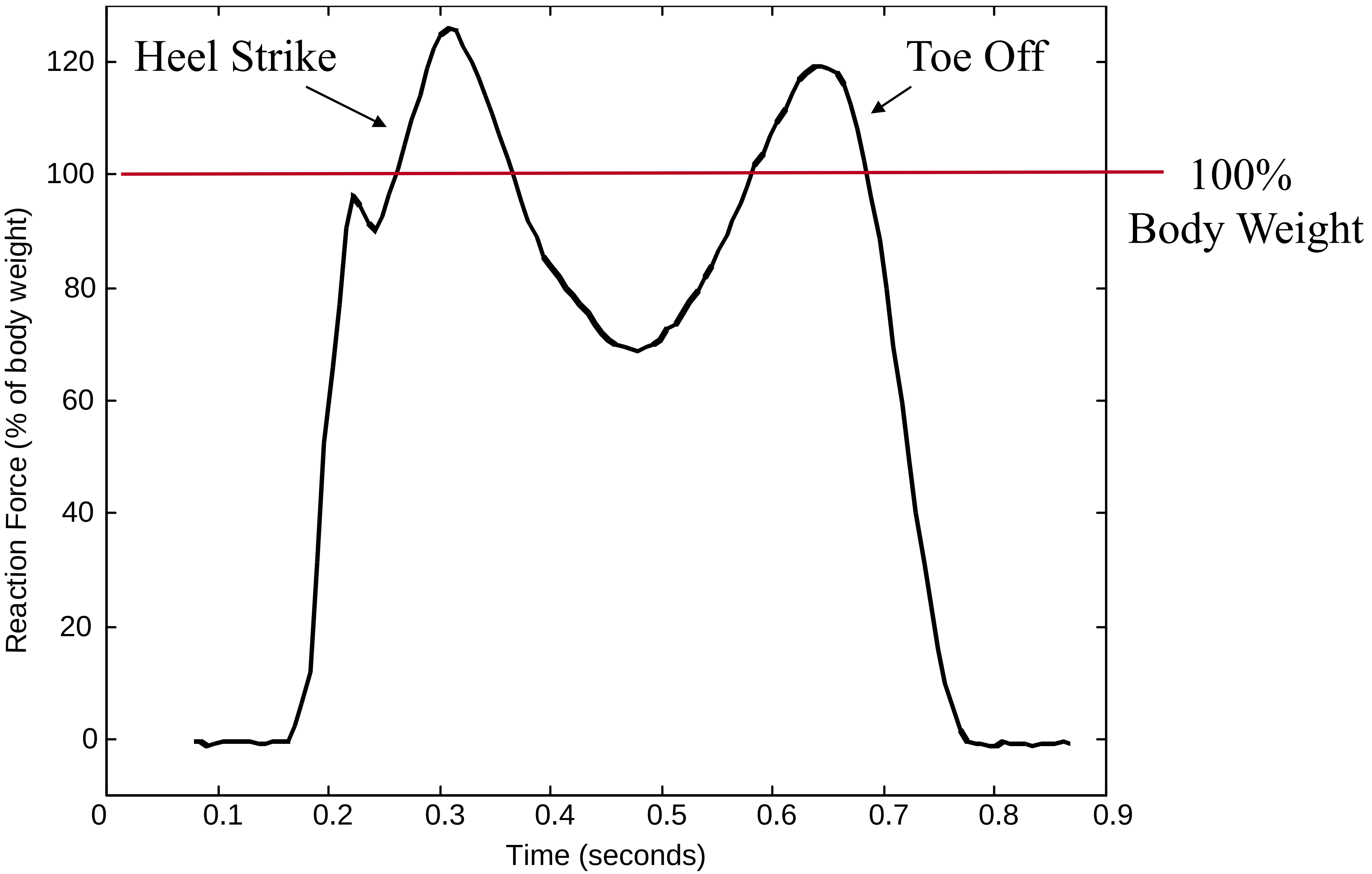
Smart Flooring at the MIT Museum

Stomping Ground

Permanent installation at the MIT Museum, opened 4/30/02

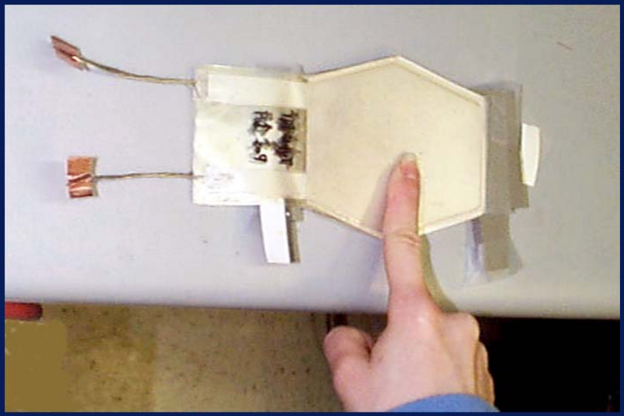
Collaboration with John Maeda's A&C Group (graphics)

Heel Strike



- Force at heel strike and toe off exceeds 100%
  - Heel can compress by 1 cm – Watts possible?

Power Harvesting Insoles - 1998



PVDF Stave

Molded into sole

Energy from bend

$P_{peak} \cong 10$ mW

$\langle P \rangle \cong 1$ mW

"Thunder" PZT

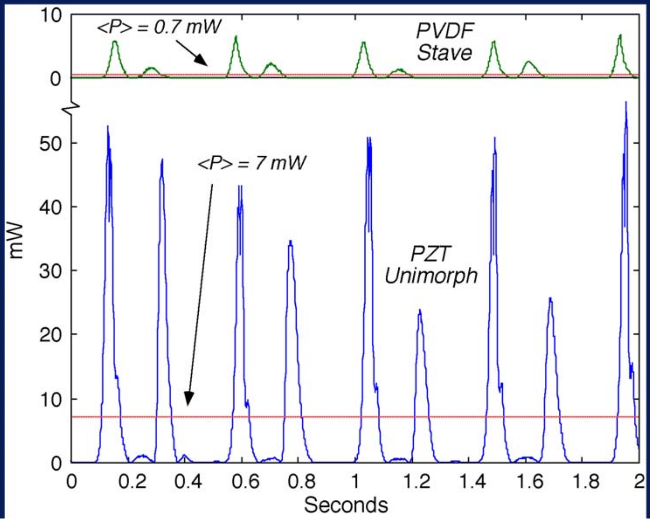
Clamshell Unimorph

Under insole

Pressed by heel

$P_{peak} \cong 50$ mW

$\langle P \rangle \cong 10$ mW



Raw Power

circa 1% efficient

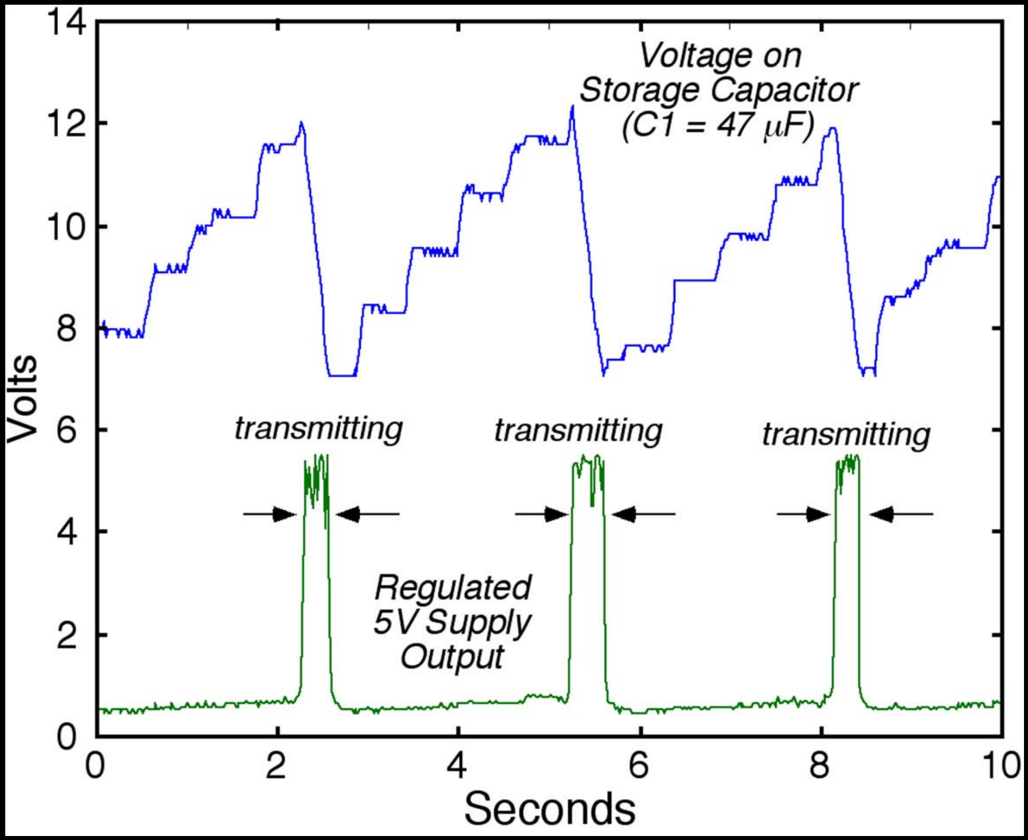
Unnoticable

Responsive Environments Group

MIT Media Lab

1998 IEEE Wearable Computing Conference

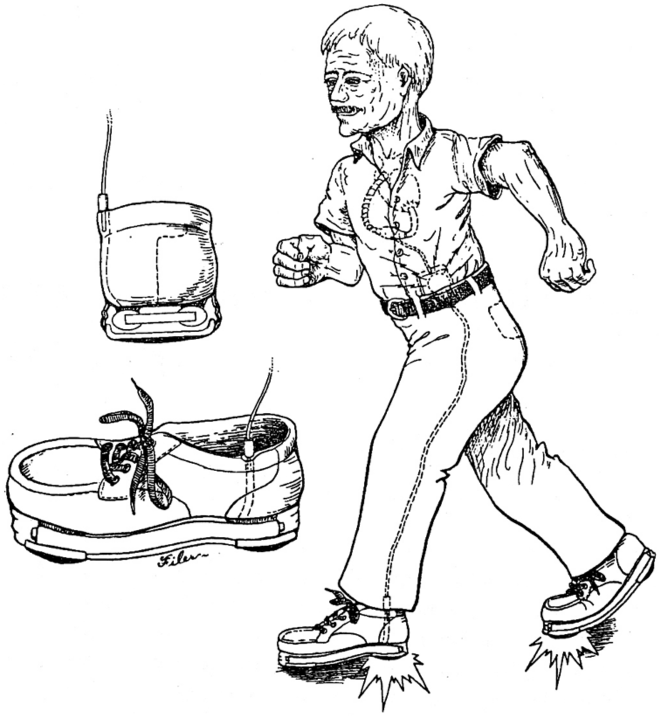
Application: Batteryless RF Tag



- Use Piezo-shoes to charge up capacitor after several steps
- When voltage surpasses 14 volts, activate 5 V regulator
  - Send 12-bit ID 6-7 times with 310 MHz ASK transmitter
- After 3-6 steps, we provide 3 mA for 0.5 sec
  - Capacitor back in charge mode after dropping below output

Responsive Environments Group - MIT Media Lab

Passive Hydraulic Chopping to Excite PZT at Resonance



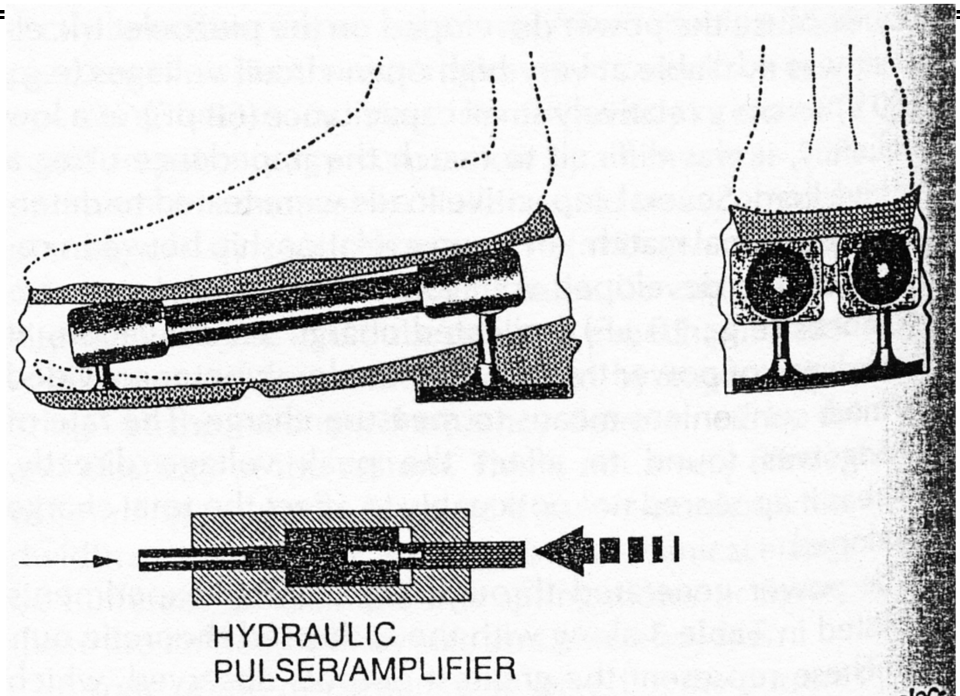
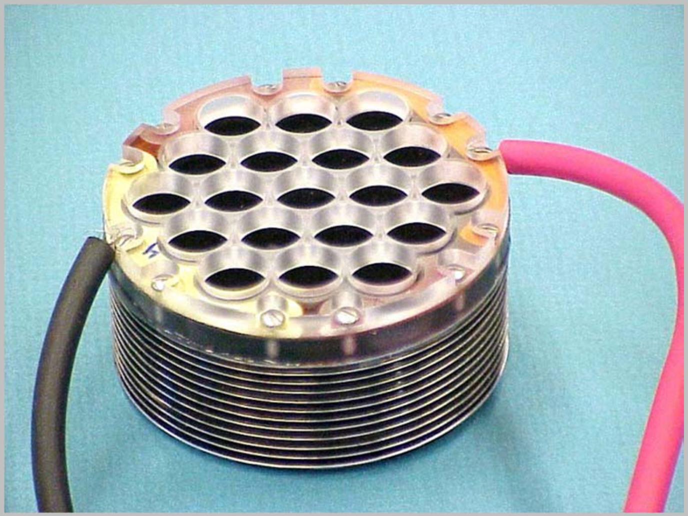


Figure 3. Schematic of shoe generator within midsole. Piezoelectric stack is actuated by hydraulic amplifiers coupled to heel and toe.

© James F. Antaki, PhD. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

- Antaki, et al., 1995
  - Passive hydraulic resonant excitation of piezoceramic stack during heel compression
  - Big, kludgy shoe
    - Developed to power artifical organs
    - Developed order of 0.2 – 0.7 Watt average power
    - 2 Watts from simulated “jogging”

Dielectric Elastomers under the heel

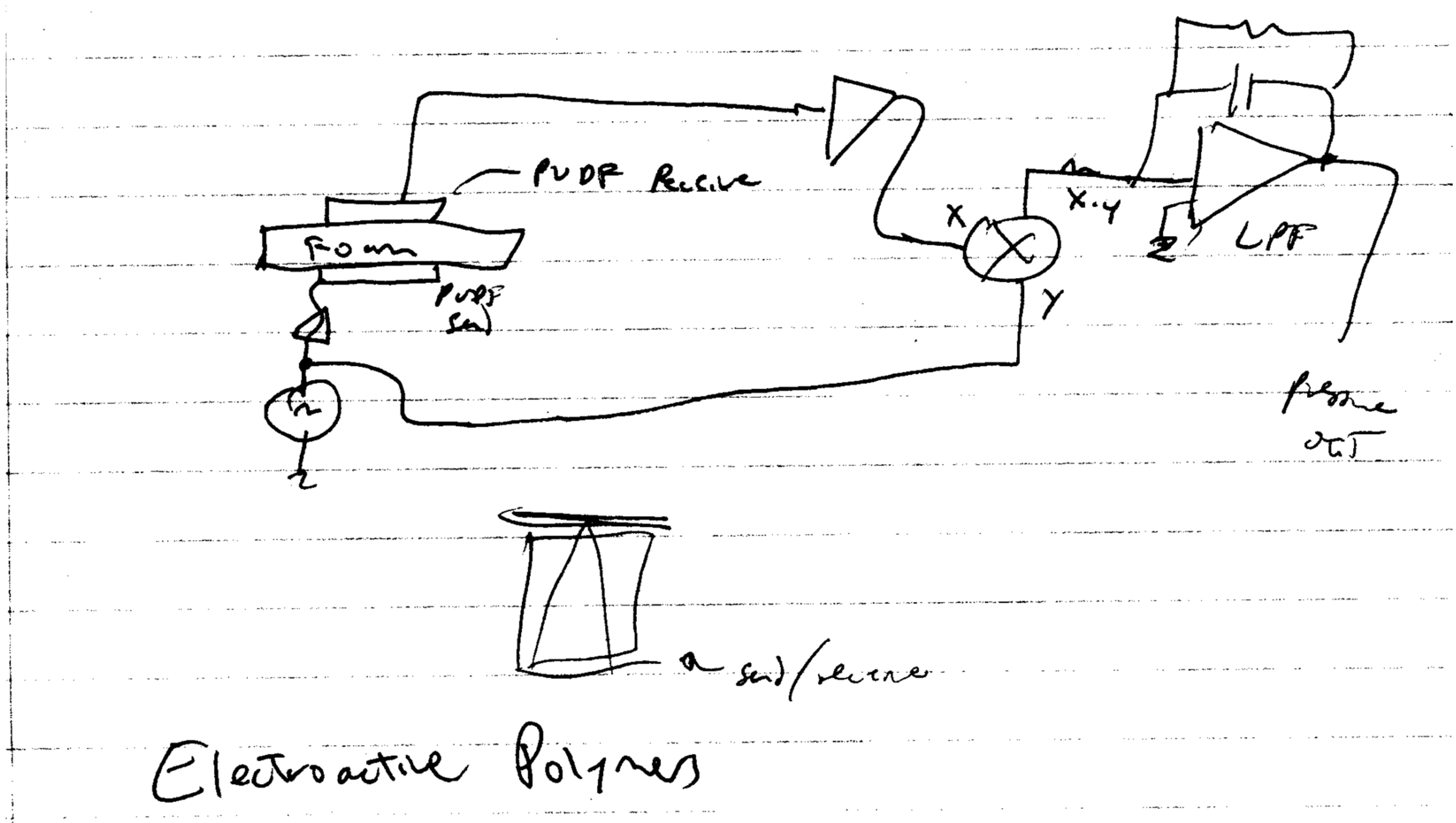


Courtesy of SRI International. Used with permission.

- Electrostatic generator with silicone rubber or flex acrylic elastomer between the plates
  - Placed under heel
  - 2-4 mm of squeeze gives 50-100% area strain
  - 4 kV across them!
  - Saw 0.8 Watt per shoe (2 Hz pace, 3 mm deflection)
  - Estimate that 1 Watt is possible with more deflection

Ron Pelrine, Roy Kornbluh - SRI International

Driven Pressure Sensor



MIT OpenCourseWare
http://ocw.mit.edu

MAS.836 Sensor Technologies for Interactive Environments
Spring 2011

For information about citing these materials or our Terms of Use, visit: http://ocw.mit.edu/terms.