Lecture 4 – Pressure Sensors Pt. 1
Very Basic Digital Noise Reduction

• Remove outliers

• Average the signals
  – Summing $N$ signals results in a resolution improvement of a factor $\sqrt{N}$
  – Provided that measurements are uncorrelated and exhibit Gaussian statistics
  – Must not be quantization limited
    • I.e., you *need* some noise to start with!
    • Note that this is *not* usually true for pickup, which is from a correlated source!
    • Pickup noise can add in phase
      – Linearly!!!
    • L3 BGO story...
Position Encoders

• Displacement
  – Rotary or Linear Potentiometer
  – Linear encoder
    • Optical
    • Magneto-Acoustic
  – Shaft encoders
    • Rotary into Linear w. screw

Incremental (A) and absolute (B) optical encoding disks.

Image by MIT OpenCourseWare.

(L) Incremental and (R) optical encoding disks.

Table:

<table>
<thead>
<tr>
<th>Interface</th>
<th>CANopen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution/Revolution</td>
<td>16 Bit = 65,536 steps</td>
</tr>
<tr>
<td>Revolutions</td>
<td>up to 14 Bit = 16,384</td>
</tr>
<tr>
<td>Code</td>
<td>Binary</td>
</tr>
<tr>
<td>Housing Diameter</td>
<td>58 mm</td>
</tr>
<tr>
<td>Shaft</td>
<td>Full shaft 6 or 10 mm ø / hollow shaft 15 mm ø</td>
</tr>
</tbody>
</table>

Courtesy of FABRA Inc. Used with permission.
Quadrature Encoders Determine Direction

2 photodetectors  
Holes at 90° and different r

2 emitters  
Rotating Disk

One Hole  
Rotating Disk

2 holes and 1 dual optical sensor

Emitters  
Photodetectors

1 hole and 2 single optical sensors

One sensor measures “I” and the other measures “Q”
-> Direction determined by whether I leads Q in time or vice-versa

Can be spaced more closely, for rapid direction determination
Linear Encoders

Optical encoders
- Track micro marks
- 100 nm accuracy!
- Film encoders are in cheap printers

Screen shot of the webpage for Heidenhain Linear Encoders—sealed linear encoders and exposed linear encoders, removed due to copyright restrictions. See: [Heidenhain](#).
Magneto-Acoustic Linear Encoders

- 1 mil per sample, 9 kHz updates
- Must measure T too!
- MTS Sensors
Pressure

• Displacement into pressure
  – E.g., $F = -kx$, and $P = F/A$ (force per area)

• Strain into Force
  – Strain is defined by $s = \Delta L/L$

• Piezoresistivity

![Diagram showing expansion and compression](image-url)
Membrane Switch

- Commercial – can be printed and snap-assembled
  - Made by ALPS among others (switch floor too)
  - Typically polled in row-column fashion (e.g., drive columns, read rows)

A membrane switch being used as a tactile sensor.
How a MIDI Keyboard Works

- **Velocity**
  - Measure time difference between key transitions

- **Aftertouch**
  - FSR underneath keys
    - FSRs were developed for this purpose (Interlink)
  - Poly aftertouch has FSR under each key
  - Mono aftertouch has FSR under key bank
The Buchla Thunder

Thunder 2 Tracks multipoint finger position optically using reflective back of mylar drumhead.

Thunder 1 used capacitance.

US Patent 5,913,260 - June 15, 1999 Donald F. Buchla
System and method for detecting deformation of a membrane
Optical Pressure Sensors

Figure 3: Camera view of membrane: (a) undeformed (b) in contact with an object.

- Pressure Profile of deformable dot-matrix fingertip (Hristu, Ferrier & Brockett)

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GelForce (U. Tokyo – Kamiyama et al)

See: [YouTube]

Dual layers resolve both normal and shear forces
– *Derive pressure vector*

Courtesy of TachiLab. Used with permission.
The Carbon Microphone – Sonic FSR

1878 – 1929

1628 N-1 Type Carbon Microphone

Microphone Characteristics

A. Minimum Sensitivity @ 1 kHz with 85 mA(DC) Applied Current: 38 dBmV
B. Impedance Range: 15-60 ohms
Conductive Foam

Competitive conductive foam
LT conductive foam
Wrapped FOF
Competitive conductive foam

Image by MIT OpenCourseWare.

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Metalized

Standard (3D!)
Resistive (conductive) Elastomers

Early Z-Tiles from the University of Limerick

- Carbon or silver-loaded silicone rubber
- Dynamic range limits, hysteresis, longevity…
- Commercial conductive rubber from:
  - “Zoflex” from Xilor, inc. (rfmicrolink.com)

Force Sensitive Resistors

- Composite structure
  - Top, ink, electrodes
    - Flat, but can be fragile to shear force (delamination) and sensitive to bend

Image by MIT OpenCourseWare.
Conductive Polymers and FSR’s

- Microphotograph, showing conductive ink and metalization from Interlink FSR

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FSR Characteristics

- 3-4 decades of sensitivity, 0.01 - 100 PSI, hundreds of Ω to 10 Meg Ω
  - Depending on device & Manufacturer
  - “---” is part-part repeatability bound
    - Typically ±15% - ±25% for Interlink
  - Sensitive to temperature, humidity...

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FSR Interface Circuits

• Voltage Divider
  – Very nonlinear; switch characteristic
  – Only buffer needed

• Current Mode
  – Smoother range but (Less headroom)
  – Transimpedance amp

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The FSR Potentiometer

Can also inject voltage into W and have transimpedance amplifiers at A and B
Position is: \((V_A - V_B)/(V_A + V_B)\)
and Force becomes: \(V_A + V_B\)

Oscillator

Ratiometric? From Rob Poor?
The FlexiForce (from TekScan)

Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity (Error)</td>
<td>&lt; ±5%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>&lt; ±2.5% F.S.</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>&lt; 4.5% F.S.</td>
</tr>
<tr>
<td>Drift</td>
<td>&lt; 3%/ Logarithmic Time</td>
</tr>
<tr>
<td>Rise Time</td>
<td>&lt; 20 µsec</td>
</tr>
</tbody>
</table>

Typical Response

Force Ranges

<table>
<thead>
<tr>
<th>Force (lbs)</th>
<th>(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 lb.</td>
<td>(4.4 N)</td>
</tr>
<tr>
<td>25 lb.</td>
<td>(110 N)</td>
</tr>
<tr>
<td>100 lb.</td>
<td>(440 N)</td>
</tr>
<tr>
<td>500 lb.</td>
<td>(2200 N)</td>
</tr>
<tr>
<td>1000 lb.</td>
<td>(4400 N)</td>
</tr>
</tbody>
</table>

Courtesy of TekScan. Used with permission.
## Tekscan Specs

### Table 1. Specifications of Representative Tactile Sensors

<table>
<thead>
<tr>
<th></th>
<th>Human Skin [i]</th>
<th>Fingerprint Imaging Sensor [vii]</th>
<th>Smart Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (mm)</td>
<td>2</td>
<td>0.1</td>
<td>0.1-10</td>
</tr>
<tr>
<td>Sensor Area (mm²)</td>
<td>25x25</td>
<td>13x20</td>
<td>10²–10⁷</td>
</tr>
<tr>
<td>Number of Sensels</td>
<td>10²</td>
<td>~10⁴</td>
<td>10²–10⁶</td>
</tr>
<tr>
<td>Sensel Force Range (N)</td>
<td>0.4-10</td>
<td>switch</td>
<td>0.05-100</td>
</tr>
<tr>
<td>Linearity</td>
<td>Moderate</td>
<td>-</td>
<td>High</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Low</td>
<td>-</td>
<td>Very Low</td>
</tr>
<tr>
<td>Compliance</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Bandwidth (Hz)</td>
<td>100</td>
<td>~10</td>
<td>100</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>-20 to 60</td>
<td>-10 to 45</td>
<td>-40 to 100</td>
</tr>
</tbody>
</table>

Robustness?

Courtesy of TekScan. Used with permission.
They do chair seats and beds too...

Car driving over force imaging plate

Courtesy of Hong Tan. Used with permission.

Hong Tan, Purdue

They do chair seats and beds too...

Ken Perlin/NYU make transparent “interpolating” FSRs
QTC Pressure Sensors

- Made by Peratech in the UK
- Quantum Tunneling Composites
  - Metal-filled polymers, no direct conductive path
    - Current flows via quantum tunneling (AC readout w. capacitance?)
    - More tunneling (hence current) with more pressure
    - No zero-point deadband, smoother response, more durability (maybe)

**Specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>QSRC025050</th>
<th>QSRC025130</th>
<th>QSSC025400</th>
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<tbody>
<tr>
<td>Dimensions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form Factor</td>
<td>Circular</td>
<td>Circular</td>
<td>Square</td>
</tr>
<tr>
<td>Active Area</td>
<td>5mm</td>
<td>13mm</td>
<td>40mm</td>
</tr>
<tr>
<td>Lead Length</td>
<td>35mm</td>
<td>35mm</td>
<td>35mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>1mm</td>
<td>1mm</td>
<td>1mm</td>
</tr>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand-off resistance¹</td>
<td>10⁸ ohms</td>
<td>10⁸ ohms</td>
<td>10⁸ ohms</td>
</tr>
<tr>
<td>Force sensitivity range²</td>
<td>0 N - 100 N</td>
<td>0 N - 100 N</td>
<td>0 N - 100 N</td>
</tr>
<tr>
<td>Part-to-part force repeatability³</td>
<td>±10%</td>
<td>±10%</td>
<td>±10%</td>
</tr>
<tr>
<td>Single part force repeatability³</td>
<td>±2%</td>
<td>±2%</td>
<td>±2%</td>
</tr>
<tr>
<td>Force resolution</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Max current</td>
<td>100μA/cm²</td>
<td>100μA/cm²</td>
<td>100μA/cm²</td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-30°C to 100°C</td>
<td>-30°C to 100°C</td>
<td>-30°C to 100°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>0% - 100%</td>
<td>0% - 100%</td>
<td>0% - 100%</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt; 1M cycles at 10N</td>
<td>&gt; 1M cycles at 10N</td>
<td>&gt; 1M cycles at 10N</td>
</tr>
</tbody>
</table>

1. Unloaded, un bent
2. Dependent on mechanics
3. With repeatable actuation system

© Peratech Limited. All rights reserved. This content is excluded from our Creative Commons license. For more information, see [http://ocw.mit.edu/fairuse](http://ocw.mit.edu/fairuse).
The Flex Sensor is a unique component that changes resistance when bent. An unflexed sensor has a nominal resistance of 10,000 ohms (10 K). As the flex sensor is bent the resistance gradually increases. When the sensor is bent at 90 degrees its resistance will range between 30-40 K ohms.

The sensor measures 1/4 inch wide, 4 1/2 inches long and only .019 inches thick!

Available from the Images Co. (for PowerGlove - made by “Abrams-Gentile)

High-end versions made by Immersion for their CyberGlove
- 0.5° resolution, 1° repeatability, 0.6% max nonlinearity, 2-cm min bend radius

*These only measure bend in one dimension (expanding the FSR’s on surface)*
- Conduction saturates quickly when contracted
- Can measure bidirectional bend with 2 FSR’s back-to-back (and diff amp)

Courtesy of Images SI Inc. Used with permission.
Resolution and Calibration Tests (from Stacy Morris ‘04)

*Bend Sensor calibration*
Pin Bendy Sensor with Batteries and bend according to printed protractor

*FSR calibration*
Apply known pressure via rubber bumper with materials tester

Images removed due to copyright restrictions.
Abrams-Gentile (used) Bend Sensor Pairs into differential amp for bidirectional bend sensing

Two pairs of sensors tested
Each pair tested around 3 different pivot points
Hysteresis from tape?

Poor response (age or tape?)
Better response
A novel strain sensor was used which was developed by EMPA, Switzerland [12]. The sensor thread consists of a commercial thermoplastic elastomer (TPE) filled with 50wt-% carbon black powder and changes resistivity with length. It is fiber-shaped with a diameter of 0.3mm and has, therefore, the potential to be fully integrated into textile. In this prototype setup, the sensor was attached with a silicone film (see Fig. 2) which enables a measurement range of 100% strain. The length of the sensor was chosen to be 2cm.”

Figure 2. Sensor thread attached to the textile with a silicone film.

Figure 3. Typical response of sensor to a given strain (sensor length 2cm).

Recognizing Upper Body Postures using Textile Strain Sensors
Corinne Mattmann, Oliver Amft, Holger Harms, Gerhard Tröster, and Frank Clemens (ETH Zurich) - Proc. Of ISWC 2007

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More on fabric-compatible sensors in Bio Lecture...
Merlin Stretch Sensors…

**Merlin Stretch Sensor**

The Merlin Stretch Sensor uses the latest ‘Smart’ material technology to give a uniquely flexible sensor, that can literally take measurements bent around corners or be woven into fabric.

- Flexible sensor, bends around corners!
- Small form factor - 2mm Cord
- Economical

**What is it?**

The Stretch Sensor is a flexible cylindrical cord with spade electrical fixings at each end. The sensor behaves like a variable resistor, the more you stretch it the higher the resistance.

**How does it work?**

As the length of the Stretch Sensor alters so does it's resistance. For each centimeter of length change there is a resistance change of approximately 400 Ohms/cm.

[Graph showing the relationship between resistance and displacement]

Comercial stretchy resistive sensor

http://www.merlinrobotics.co.uk

Courtesy of Merlin Robotics. Used with permission.