sound & tactile sensing
why combine tactile & sound sensors?

- applications are very different
- but both are (usually) pressure transducers
- big difference is the frequency range
  - pressure: DC - ~1 Hz
  - tactile: ~ 0.1 Hz - ~ 1000 Hz
  - sound: ~10 Hz - ~ 10 MHz (or more)
- typical devices are electromechanical
  - similar – or the same – transducer is used as both the transmitter & the receiver
pressure is force per unit area
almost all force – or pressure – sensing technologies involve …
a mechanical deformation under load
transduction-to-electrical to measure it
the main exception is for measuring gas pressure under near-vacuum conditions
then it is typically done at a microscopic level
- cooling rate of an electrically heated filament
- ion current produced by an electron current
- drag on a magnetically-suspended rotor
these are really density measurements, translated into pressure via $P V = n R T$
reading (Fraden)

- Section 3.10, Sound
  - understand Equation 3.105
  - be happy with Table 3.3
- Section 6.1, Ultrasonic Sensors
- Section 7.6, Ultrasonic Sensors
- Chapter 9, Force, Strain, Tactile
- Chapter 10, Pressure
- Chapter 12, Acoustic
topics we will cover

- the jargon of sound measurement (briefly)
- wave packets & consequent issues
- matched filter determination of ToF
- problem: beam width & specular reflection
- survey of sonar transducers
- the “strange” behavior of piezoelectrics
- a little about ultrasonic electronics modules
- issues in quantitative ultrasonic imaging
- tactile sensors & displays
  - (if not covered in a future student lecture)
the jargon of sound measurement
sound pressure level (SPL)

- “threshold of audibility”, the minimum pressure fluctuation detected by the ear, is less than $10^{-9}$ of atmospheric pressure or about $2 \times 10^{-5}$ n/m$^2$ at 1000 Hz

- “threshold of pain”: pressure $10^5$ times greater (still less than 1/1000 of atmospheric pressure)

- because of the wide range, sound pressure measurements are made on a logarithmic (decibel) scale

- “sound pressure level” (SPL) = $20 \log(P/P_0) = 10 \log(P/P_0)^2$, where $P_0 = 2 \times 10^{-5}$ newton/meter$^2$
  
  - because energy and power scale as pressure squared
  
  - caution: pay attention to when $P =$ pressure and when $P =$ power

- SPL is proportional to the average squared amplitude
sound power (SP & PWL)

- SP = total sound power $W$ emitted by a source in all directions
  (in watts = joules/second)
- sound power level
  $PWL = 10 \log(W/W_0)$ decibels
  - where $W_0 = 10^{-12}$ watt (by definition)
  - $= 10 \log(P/P_0)^2$ decibels
  - $= 20 \log(P/P_0)$ decibels

in terms of pressure
sound intensity level (IL)

rate of energy flow across unit area

sound intensity level

\[ IL = 10 \log\left(\frac{I}{I_0}\right) \]

where \( I_0 = 10^{-12} \text{ watt/meter}^2 \)
multiple sources

- two equal sources produce a 3 dB increase in sound power level
  - because \( \log_{10}2 = 0.301029996 \)
  - \( 10 \log_{10}2 \approx 3 \)

- two equal sources produce a 3 dB increase in sound pressure level (assuming on average no interference, i.e., incoherent random phases)

- for example, when two 80 dB SPL sources add the result is an 83 dB SPL (assuming they are incoherent)
tying all these & more together ...

see http://en.wikipedia.org/wiki/Sound_energy_density

\[ E = \xi^2 \cdot \omega^2 \cdot \rho = v^2 \cdot \rho = \frac{a^2 \cdot \rho}{\omega^2} = \frac{p^2}{Z \cdot c} = \frac{I}{c} = \frac{P_{ac}}{c \cdot A} \]

where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>( \rho )</td>
<td>pascals</td>
<td>sound pressure</td>
</tr>
<tr>
<td>( f )</td>
<td>hertz</td>
<td>frequency</td>
</tr>
<tr>
<td>( \xi )</td>
<td>m, meters</td>
<td>particle displacement</td>
</tr>
<tr>
<td>( c )</td>
<td>m/s</td>
<td>speed of sound</td>
</tr>
<tr>
<td>( v )</td>
<td>m/s</td>
<td>particle velocity</td>
</tr>
<tr>
<td>( \omega = 2 \cdot \pi \cdot f )</td>
<td>radians/s</td>
<td>angular frequency</td>
</tr>
<tr>
<td>( \rho )</td>
<td>kg/m(^3)</td>
<td>density of air</td>
</tr>
<tr>
<td>( Z = c \cdot \rho )</td>
<td>N\cdot s/m(^3)</td>
<td>acoustic impedance</td>
</tr>
<tr>
<td>( a )</td>
<td>m/s(^2)</td>
<td>particle acceleration</td>
</tr>
<tr>
<td>( I )</td>
<td>W/m(^2)</td>
<td>sound intensity</td>
</tr>
<tr>
<td>( E )</td>
<td>W\cdot s/m(^3)</td>
<td>sound energy density</td>
</tr>
<tr>
<td>( P_{ac} )</td>
<td>W, watts</td>
<td>sound power or acoustic power</td>
</tr>
<tr>
<td>( A )</td>
<td>m(^2)</td>
<td>area</td>
</tr>
</tbody>
</table>
exercise

An acoustic sensor, in the absence of any signal of interest, outputs an RMS noise level of 500 μV. When an acoustic signal of interest is added, the sensor’s RMS output becomes 1300 μV. What is the signal-to-noise power ratio expressed in decibels? What would it be if the sensor’s RMS output were to become 2 V when signal of interest is added? [Note: be careful about (1) how RMS quantities add (2) the distinction between signal-to-noise and (signal+noise)-to-noise]
ranging by wave packet ToF

- emit a pulse of acoustic energy
- detect its echoes from nearby objects
- measure the time-of-flight (ToF) of each
- multiply by speed-of-sound to get ranges

issues:

- directionality: which object at which azimuth
- signal diminishes with range
  - spreading: energy density decrease \(1/z^2\)
    - all waves diminish as \(1/z^{(\text{dimensionality_of_space } - 1)}\)
  - attenuation: energy loss to heat (exponential)
    - inherent in nature of sound (but not light)
the “wave packet” concept

- a “wave packet” is a finite-duration burst of transmitted energy (acoustic, light, etc)
  - $\tau$ measures its duration
  - $t_0$ measures its mean time
  - often it is – or is approximated as – Gaussian:
    $$A(t) = A_0 \exp\left(-\frac{(t-t_0)^2}{\tau}\right) \cos(2\pi f (t-t_0))$$

![Graph of wave packet](image)
problem: range jumps

cheap systems commonly detect the time of echo amplitude crossing a threshold

threshold \sim 0.2

threshold \sim 0.1
solution: matched filter

- correlate incoming signal with its expected shape, i.e., the shape of the outgoing pulse

- but it’s not quite as easy as you would like: dispersion and differential attenuation distort the echo vs. the outgoing pulse

  - dispersion: velocity depends on frequency
    - issue for sound and for light in a medium
  
  - differential attenuation: amplitude decay per unit distance covered depends on frequency
    - this is the energy dissipation phenomena, not the universal geometrical spreading
nevertheless, here is a seat-of-the-pants picture of how matched filters work
envelopes of pulse and echo

gauss[t_, t0_, ts_] := (1/Sqrt[2 Pi] ts) Exp[-(t - t0)^2 / (2 ts^2)]

Plot[{gauss[t, t0, ts], gauss[t, t0 + tof, ts]}, {t, t0 - 3. ts, t0 + tof + 3. ts}, PlotStyle -> {Hue[.7], Hue[.0]}, PlotRange -> {0, .4}] /.
{t0 -> 25., ts -> 1., tof -> 10.}
underlying ultrasonic oscillation

Plot[\{gauss[t, t0, ts] \cos[2 \pi f (t - t0)], gauss[t, t0 + tof, ts] \cos[2 \pi f (t - (t0 + tof))]\}, \{t, t0 - 3. ts, t0 + tof + 3. ts\},
PlotStyle \rightarrow \{Hue[.7], Hue[.0]\}, PlotRange \rightarrow \{-4, .4\}] /. \{t0 \rightarrow 25., ts \rightarrow 1., tof \rightarrow 10., f \rightarrow 1.\}
pulse — guess — echo

Plot[{
  gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
  gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))],
  gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))],
  {t, t0 - 3. ts, t0 + tof + 3. ts},
  PlotStyle -> {Hue[.7], Hue[.4], Hue[.0]},
  PlotRange -> {-4, 4}] /. {t0 -> 25., ts -> 1., f -> 1, tguess -> 8., tof -> 10.}
guess * echo when error = 0. period

Plot[{{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
    gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))]},
    gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
   {t, t0 - 3. ts, t0 + tof + 3. ts},
   PlotStyle -> {Hue[.7], Hue[.0]},
   PlotRange -> {-.4, .4}] /. {t0 -> 25., ts -> 1., f -> 1, tguess -> 10., tof -> 10.}
guess * echo when error = .25 period

Plot[
{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
  gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))]
  gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
{t, t0 - 3. ts, t0 + tof + 3. ts},
PlotStyle -> {Hue[.7], Hue[.0]},
PlotRange -> {{-4, 4}} /. {t0 -> 25., ts -> 1., f -> 1., tguess -> 9.75, tof -> 10.}
guess * echo when error = .5 period

Plot[{
  gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
  gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))]
  gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))],
  {t, t0 - 3. ts, t0 + tof + 3. ts},
  PlotStyle -> {Hue[.7], Hue[.0]},
  PlotRange -> {-.4, .4}] /. {t0 -> 25., ts -> 1., f -> 1., tguess -> 9.5, tof -> 10.}
guess * echo when error = .75 period

Plot[
  {gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
   gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))]
   gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
  {t, t0 - 3. ts, t0 + tof + 3. ts},
  PlotStyle -> {Hue[.7], Hue[.0]},
  PlotRange -> {-.4, .4} /. {t0 -> 25., ts -> 1., f -> 1, tguess -> 9.25, tof -> 10.}
guess * echo when error = 1.0 period

Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
    gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))],
    gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
{t, t0 - 3. ts, t0 + tof + 3. ts},
PlotStyle -> {Hue[.7], Hue[.0]},
PlotRange -> {-.4, .4}] /. {t0 -> 25., ts -> 1., f -> 1, tguess -> 9., tof -> 10.}
integral of guess * echo over time plotted as function of guess

```math
\text{Plot}\left[\text{NIntegrate}\left[\text{gauss}[t, t_0 + \text{tgx}, ts] \cdot \cos[2 \pi f \left(t - (t_0 + \text{tgx})\right)] \cdot \text{gauss}[t, t_0 + \text{tof}, ts] \cdot \cos[2 \pi f \left(t - (t_0 + \text{tof})\right)]\right],
\{t, t_0 + \text{tgx} - 3.\ ts, t_0 + \text{tof} + 3.\ ts\}, \{\text{tgx}, \text{tof} - 3.\ ts, \text{tof} + 3.\ ts\}\right] /\left[t_0 \rightarrow 25., \ ts \rightarrow 1., \ f \rightarrow 1., \ \text{tof} \rightarrow 10.\right]
```
exercise

Describe the frequency spectrum of the wave packet used in the previous example. [hint: In general $\Delta f \Delta t \geq 1/(4\pi)$, and for a Gaussian envelope $\geq$ can be replaced by $\approx$. A wave packet that is Gaussian in time has a Gaussian frequency spectrum. Given all that, you need only to estimate its center & width.] How will *dispersion* and *differential attenuation* affect time-of-flight measured by this method?
problem: beam width

specular surfaces are visible – by specular reflection – at “non-specular” angles

walls appear as arcs in ultrasonic range images (that use co-located transmitter and receiver)
so walls appear as broken arcs:

(when using threshold detection)
since as the signal gets weaker (with angle) the apparent time-of-flight gets longer ...
survey of transducers and electronic modules for ultrasonic range sensing
Polaroid (electrostatic) transducers

3-455 - Polaroid Sonar Ranging Kit - $149.00

Now you can get the classic Polaroid sonar system in a great experimenters kit. Includes two instrument grade transducers, two drive circuits (fully assembled & tested), plus connectors, tech manual and app notes.

Build them into two robots, or use both on one machine. Easily interfaced to Basic Stamps, BOT-boards, PC parallel port, etc. Detect distances by sonar from 15 cm to 10 meters (6 inches to 33 feet!).

http://www.robotstorehk.com/sensor/sensor.html
http://www.robotstore.com/download/3-740_Sonar_Exp_instr_1.02.pdf
Polaroid-transducer systems

3-705 - Ultrasonic Owl Scanner Kit - $119.00

Give ultrasonic vision to your mobile robot. Fully assembled and tested circuit - no soldering required. Includes Polaroid transducer, housing, servo and cable. Serial interface at 9600 baud (connect to PC, Stamp, BOTBoard, etc.) Measures 0.15 to 2.70 m (0.5 to 10 feet) with 1 cm (1/2 inch) resolution. Simple commands, run in continuous or controlled modes. Includes Windows software (95/98) to display data in both linear and radial modes. Runs on 9 to 12 VDC input. A complete sonar system!
Polaroid-transducer instruments

Dimension Master Plus
Advanced Ultrasonic Tape Measure with Built-in Aiming Light and 3 Polaroid Sensors, for Ultra-Narrow Measuring Beam!

Real Estate Agents/Brokers, Contractors/Builders, Interior Designers, Remodelers & Estimators, Do-It-Yourselfers--Anyone Who Takes Interior or Room Measurements
The advanced Dimension Master Plus is the world's most accurate ultrasonic tape measure, and the only featuring TriSensor Technology, using three Polaroid sensors! The three sensors allow for an ultra-narrow (2-degree) beam for the utmost accuracy. Plus, the Dimension Master Plus features a built-in calculator with dimensional unit conversions.

Panasonic (piezoelectric) transmitters and receivers

**Panasonic Ceramic Sensor/Transducer**

Panasonic Ceramic Sensor consisting of a disc/bimorph type piezoelectric ceramic vibrator that is used as a sensor for transmitting and receiving ultrasonic in the air. Since the ultrasonic ceramic sensor has a resonance type vibrator, it is high in sensitivity and has outstanding sound pressure level. It has wide applications for burglar alarm systems, automatic door openers, flow rate detectors, and remote-control systems in TVs, home appliances, and toys etc. Sensors are not washable.

<table>
<thead>
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<th>Type</th>
<th>Class</th>
<th>Ctrl Freq. (KHz)</th>
<th>Sensitivity (dBA/mbar)</th>
<th>Sensitivity (dB = 1V/Pa)</th>
<th>Min. Band-Width (KHz)</th>
<th>Sound Pressure Level (dB)</th>
<th>Max. Input Volt. (Vrms)</th>
<th>Dimensions (mm)</th>
<th>Digi-Key Part No.</th>
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<td>-67</td>
<td>-47</td>
<td>4.0</td>
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<td>16.0</td>
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<td>-55</td>
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<td>16.0</td>
<td>12.0</td>
<td>10.0</td>
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Ultrasonic Ceramic Sensors
(Ultrasonic Ceramic Transducers)
Type U/H/S/Q

Features
- High sensitivity: -45 dB min.
- Excellent temperature and humidity durability
- Small in size
- Applicable to multi-function remote control system because of its wide bandwidth

Applications
Ultrasonic wave transmitter and receiver for:
- Remote control equipment for such as TV, air conditioner and garage door opener etc.
- Proximity switch for burglar alarm system, parking meter and automatic door opener etc.
beam "width" (angular distribution)
sensitivity vs. frequency & load

EFR RUB40K22

Characteristic Change vs. Load Resistance

![Graph showing sensitivity vs. frequency and load resistance](image)

- Sensitivity (dB)
- Frequency (kHz)
- Load Resistance (kΩ): 300 kΩ, 100 kΩ, 30 kΩ, 10 kΩ, 4.0 kΩ, 2.2 kΩ, 1.2 kΩ
frequency & output vs. drive

EFROUB40K22

Characteristic Change vs. Input Voltage

Center Frequency

Output S.P.L. (dB)

Maximum Sound Pressure Level

Input Voltage (Vrms)

Center Frequency (kHz)
received signal vs. distance

EFR RUB40K22
EFR OUB40K22

Distance vs. Reception Sensitivity

![Diagram showing received signal vs. distance with a graph depicting the relationship between reception sensitivity (mV) and distance (m). The graph shows a decreasing trend as distance increases.]

- Ein: 10 Vrms
- RL: 3.9 kΩ
- SP/MIC: Ultrasonic Ceramic Sensor
Massa 40 kHz & 75 kHz Models

Massa Products Corporation - Model E-152

### Specifications

<table>
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<th>E-152/75</th>
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<tr>
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<td>at Receiving</td>
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<td>+/-2 kHz</td>
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<td>Sensitivity</td>
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<td>Bandwidth</td>
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<td>Tuned</td>
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<tr>
<td>Untuned</td>
<td>1 kHz</td>
<td>1 kHz</td>
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<td>Transmitting Sensitivity (dB vs. 1 μbar per volt at 1 ft. untuned)</td>
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<td>+10</td>
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<tr>
<td>Receiving Sensitivity (dB vs. 1 volt/μbar)</td>
<td>-57</td>
<td>-62</td>
</tr>
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</table>
impedance & angular distribution

Note higher frequency (shorter wavelength) has narrower beam
the “strange” resonance characteristics of piezo-electric transducers
resonance characteristics

EFR RUB40K22
EFR OUB40K22

Frequency Characteristics of Resonator

![Graph showing frequency characteristics of resonance with impedance on the y-axis and frequency on the x-axis.]
impedance vs. frequency

The most common transducer used with the LM1812 is the piezo-ceramic type which is electrically similar to a quartz crystal. Piezo-ceramic transducers are resistive at only two frequencies, termed the resonant and antiresonant ($f_r$, $f_a$) frequencies. Elsewhere these transducers exhibit some reactance as shown in Figure 3.

![Figure 3: Phase and Magnitude of Transducer Impedance](image)

The LM1812 is primarily used with a single transducer performing both transmit and receive functions. In this mode, maximum echo sensitivity will occur at a frequency close to resonance.

Transducer ringing is a troublesome phenomenon of single transducer systems. After a transducer has been electrically driven in the transmit mode, some time is required for the mechanical vibrations to stop. Depending on the amount of damping, this ringing may last from 10 to 1000 cycles. This mechanical ring produces an electrical signal strong enough ($>200 \mu V_{p-p}$) to hold the detector ON, thus masking any echo signals occurring during this time.

A solution to this ring problem is to vary the receiver gain from a minimum, just after transmit, to a maximum, when the ring signal has dropped below the full-gain detection threshold. Since near-range echo signals are much stronger than ring signals, close echos will still be detected in spite of the reduced gain.

The gain is varied by attenuating the signal between pins 2 and 3 of the LM1812. Figure 4 shows such an arrangement. An externally generated 12V pulse (Figure 17) keys the transmitter and activates the attenuator. This pulse charges C to a voltage set by R8, turning the FET OFF. C slowly discharges through R, decreasing the gate voltage, which in turn decreases the attenuation of the signal passing from pin 3 to pin 2. R and C are selected so that the FET is not
sonar electronics modules
time-dependent amplification

► receiver amplifier gain is typically “ramped” approximately linearly with time after acoustic pulse emission
► this helps suppress direct coupling (i.e., not via echo) between transmitted pulse and electronic detection circuit
► but primarily it is used to compensate signal strength fall off with distance
► but you can’t do it forever … eventually you’ll just be amplifying noise
circuit layout issues to achieve isolation of transmit and receive

FIGURE 11. Component Side of Layout Showing Isolation of Receiver Input and Output
IC for sonar applications

National Semiconductor

LM1812 Ultrasonic Transceiver

General Description
The LM1812 is a general purpose ultrasonic transceiver designed for use in a variety of ranging, sensing, and communications applications. The chip contains a pulse-modulated class C transmitter, a high gain receiver, a pulse modulation detector, and noise rejection circuitry.

A single LC network defines the operating frequency for both the transmitter and receiver. The class C transmitter output drives up to 1A (12W) peak at frequencies up to 325 kHz. The externally programmed receiver gain provides a detection sensitivity of 200 μVp-p. Detection circuitry included on-chip is capable of rejecting impulse noise with external programming. The detector output sinks up to 1A.

Applications include sonar systems, non-contact ranging, and acoustical data links, in both liquid and gas ambients.

Features
- One or two-transducer operation
- Transducers interchangeable without realignment
- No external transistors
- Impulse noise rejection
- No heat sinking
- Protection circuitry included
- Detector output drives 1A peak load
- Ranges in excess of 100 feet in water, 20 feet in air
- 12W peak transmit power

Applications
- Liquid level measurement
- Sonar
- Surface profiling
- Data links
- Hydroacoustic communications
- Non-contact sensing
- Industrial process control
circuit functional details

Order Number LM1812N
See NS Package Number N18A

20090323 mws@cmu.edu 16722 sound & tactile sensing & sensors 50
TI TL851/2 hybrid analog-digital

- Designed for Use With the TL851 in Sonar Ranging Modules Like the SN28827
- Digitally Controlled Variable-Gain Variable-Bandwidth Amplifier
- Operational Frequency Range of 20 kHz to 90 kHz
- TTL-Compatible
- Operates From Power Sources of 4.5 V to 6.8 V
- Interfaces to Electrostatic or Piezoelectric Transducers
- Overall Gain Adjustable With One External Resistor

- often used with Polaroid (electrostatic) transducers as alternative to the Polaroid-supplied electronics
some issues in quantitative ultrasonic imaging
e.g., in medical imaging …

- speed of sound in “flesh and blood” is:
  - not known
  - not constant (even in one individual subject)
  - not amenable to measurement using “manufactured artifacts”

- so if precisely scaled range is needed, an “in situ” calibration method is required
“average” or “typical” values are fine:

- for qualitative visualization, pathology / diagnosis, etc
- but probably not for, e.g., custom design of wheelchair cushions
- and certainly not for, e.g., planning a micro-surgical path
problem

- image guided surgery literature seeks:
  - navigational accuracy ~ 1 mm
  - endpoint precision ~ 0.1 mm

- ignorance of precise acoustic properties of skin, fat, muscle, etc, layers makes these specifications problematic
approach

► identify elementary cases
► invent in situ calibration protocols for them:
  ◆ multiple parallel homogeneous layers
  ◆ speed of sound gradient in a single layer
  ◆ a tapered layer
► assume
  ◆ any real case is a (separable) combination of the elementary cases
  ◆ mechanically accurate scanning capability
basic ToF technique

▶ a single-sided ultrasonic thickness measurement method

◆ presumes speed of sound \( c_i \) is known

\[ c_i \text{ known} \]

measure: \( t_i \)

calculate: \( z_i = c_i t_i / 2 \)
and a differential method

presumes speed of sound $c_i$ does not change with thickness

c_i$ unknown

measure: $t_i$, $\Delta t_i$, $\Delta z_i$
calculate: $c_i$ and $z_i$

$c_i = 2 \frac{\Delta z_i}{\Delta t_i}$

$z_i = c_i \frac{t_i}{2}$
one homogeneous layer

- two (or more) oblique paths
  - overcomes the presumptions of the normal path methods
  - however, possible confusion from diffuse reflection!
  - if $i>2$ a least-squares solution will optimize accuracy
\[ \begin{align*}
\text{measure: } \{x_1, t_i\} \\
\text{calculate: } c \text{ and } z \\
c &= \sqrt{z^2 + x_i^2} \\
c &= \frac{2\sqrt{x_i^2 + z^2}}{t_i} \\
z &= \sqrt{\frac{x_2^2 \cdot t_1^2 - x_1^2 \cdot t_2^2}{t_2^2 - t_1^2}}
\end{align*} \]
several parallel homogeneous layers

- select two values of $x_1$; measure corresponding two values of $x_2$

- mainstay of geoacoustics, e.g., oil prospecting in complex rock strata
- need to assume the paths are distinguishable by, e.g., signal amplitude
parallel layers with velocity gradient

- \( \sin \theta / c = k \) holds even if \( c \) is a function of position
  - acoustic trajectory is then curved

- continuous \( c \) causes refraction but not reflection

- if \( c \) is a linear function of position (depth) then the curved path is a circular arc

- this result is a mainstay of underwater acoustics, where temperature and salinity gradients lead to speed-of-sound gradients

- three T/R separations are enough to measure \( c_0, z \), and the launch angles \( \{\theta_1, \theta_2, \theta_3\} \)
  - corresponding to the chosen \( \{x_1, x_2, x_3\} \)
measure: \{x_j, t_j\}

calculate: \(c_0, \alpha, z, \{\theta_j\}\)

note: compare with the “mirage” effect, where you have reflection that doesn’t require any reflecting surface
nonparallel layers

- acoustic time-of-flight defines an elliptical locus to which the reflecting discontinuity is tangent
- there is usually only one physically reasonable line that is tangent to two such ellipses
  - so if \( c \) is known, two \( \{x_i, t_i\} \) pairs fix the depth and angle of inclination of the reflecting plane
  - an additional pair will resolve any ambiguity
  - when \( c \) is not known in advance, an additional pair is sufficient to find both \( c \) and the correct reflecting plane
measure: \{x_i, t_i\} for \ i = 1, 2, 3

calculate: \( c \), and the line that is tangent to both ellipses

\[
\frac{x^2}{a_i^2} + \frac{z^2}{b_i^2} = 1 \quad \text{where} \quad a_i^2 = c^2 \ t_i^2 \quad \text{and} \quad b_i^2 = a_i^2 - x_i^2
\]
tactile sensors & displays
recommended reading

► classic tactile sensing articles for history:
  ◆ Nicholls & Lee (~1990)
  ◆ Leon Harmon (~1982)

► current robotics literature for latest gadgets

► articles cited

  ◆ older articles on next page
  ◆ hopefully newer articles cited in up-coming student lecture
older tactile sensing literature

- Ron Fearing: http://robotics.eecs.berkeley.edu/~ronf/tactile.html
- also: medical-tactile sensing (not covered explicitly here)
tactile sensing

simulating (sensors) and
stimulating (displays) the
human sense of touch
human skin tactile sensitivity

► at least four different kinds of sensor cells
► different spatial and frequency sensitivities
speculative specifications fingers

- “ideal stimulator” would provide 50 N/cm² peak pressure, 4 mm stroke, and 25 Hz BW (Fearing)
- skin acts like a spatial low-pass filter
  - when we handle flexible materials (fabric, paper) we sense the pressure variation across the finger tip
- fingertip mechanoreceptor bandwidth ~30 Hz
- density 70 cm⁻² (resolve ~1.2 mm between points)
- finger curvature, thermal properties, and other environmental factors seem critical to teletaction
conceptual tactile sensor array (Fearing)

and mine ~1983
current haptic interfaces and tactile displays

- virtual reality
- people with disabilities

MIT’s Phantom (now by startup SenSation)

John Hopkins University Somatosensory Labs

and mine ~1985

UC Berkeley Robotics Lab

Stimulator Pins

Guide Plate (150 pins)
tactile sensor requirements

- see the Leon Harmon articles:
  - surveyed industry, government, research people to ascertain the specs they *thought* tactile sensing for robotic assembly etc. required
  - (but how did they know??)

- “blue sky” and practical requirements:
  - skin-like sensors, hand-like actuators, low-level processing
  - practical specifications summarized in Nicholls article

- financed by Lord Corporation
  - defunct product: tactile sensor array for robotics
a solution in search of a problem?

- identification or location?
- agree with Nicholls and Lee’s conclusion that vision is well-developed and probably fundamentally better for identification ... better role for tactile is precise relative location
- difficulty & importance of slip sensing
  - literature often mentions “incipient slip”, but it is never clear what it means
  - coefficient of friction decreases once slip begins, making recovery difficult
real-world applications of tactile sensing


  “The HI-T-HAND Expert-1 assembly robot has now been completed. Its delicate tactile control is capable of inserting a shaft into a hole with a clearance of 20 micrometers, faster and more dexterously than in a human operation. It is impossible for conventional robots and automatic assembling machines to perform such operations of precision insertion. Accordingly, such operations have been left for man’s hand to perform. Now, however, the sequence controller makes it possible, without the use of a computer for robots to perform certain of these functions.”

- this is the ONLY one I know!
technologies for tactile sensing
you name it, IT’S BEEN TRIED!

- momentary switch contact
- spring + LVDT or some such analog pressure measurement
  - including MEMS techniques, e.g., strain gauges on diaphragms
- force sensitive resistor (with or without built-in mechanical threshold)
- capacitative or optical measurements of surface deformation
- liquid crystal (color &/or opacity changes with deformation)
- total internal reflection (e.g., for fingerprints)
- phonograph needle for slip/vibration *(do you know what it is?)*
- thermistors etc for temperature/thermal conductivity etc
- piezoelectric, pyroelectric (e.g., PVDF)
- etc etc etc
most commonplace, maybe most promising: “touch pad” capacitive arrays
http://www.synaptics.com/technology/cps.cfm
exception to the generalization: this is a “proximity” vs. a “pressure” sensor!

a good example of the principle that if Y (in the environment) makes X (a resistor, capacitor, etc) BAD, then a BAD design for X can be exploited to as a GOOD sensor for Y
a little philosophy:
the synergy of sensor & display development
tactile displays THEN tactile sensors?

► television and telephone: analogy
  ♦ contrived sensor is secondary to natural display
    ■ make the best speaker you can ... then optimize microphone
    ■ make the best TV display you can ... then optimize camera
    ■ (until recently ... computer-understanding changes the rules ...)

► radar and sonar: contrast
  ♦ contrived display is secondary to a trans-human sensor
    ■ raw data initially as peaks, wiggles, etc, in signal vs. time plot
    ■ human-centered displays later conceived and developed for non-experts, natural interpretation even by experts, etc
a principle?

- there is no point in making a display with more resolution than your best sensor
  - in any domain:
    - spatial, temporal, dynamic range, color, etc
  - (unless you have a virtual sensor that is better!)
- there is no point in making a sensor with more resolution than your best display
  - (though in many domains you can “zoom in”)
- so improvement cycles display ↔ sensor
piezo-resistive sensors
pressure sensitive resistors (PSR)

bulk resistance vs. contact resistance

\[ R \text{ ohms} = \frac{\rho \text{ ohm-m} \cdot l \text{ m}}{A \text{ m}^2} \]

Squeezing changes mostly \( A/l \)

\[ R \text{ ohms} = \frac{\rho \text{ ohm-m} \cdot l \text{ m}}{A \text{ m}^2} \]

Squeezing changes mostly \( A \) of end contacts
PSR magnitude

- Nicholls and Lee say few hundred to few thousand ohms is typical ...
- my experience is that common conductive foams (IC packaging etc) etc are typically 1000 - 10000 times higher ...
  - so high impedance measurement techniques must be employed
  - and time response ($\tau = RC$) can suffer
PSR noise

- no general theory (that I know)
- contact-resistance-based designs are noisy
- surface effects are noisier than volume effects
  - density of opportunities for trouble is higher
    in a space of lower dimensionality
    - a single defect is fatal in 1-dimension
- but depending on details of the particular design, under microscopic examination distinction may not be clear
  - bulk resistance change may be due to distortion \((A/l)\)
  - but it can also be due to changes in inter-grain contact
exercise

A cylindrical resistive element is compressed or stretched in a way that does not change its basically-cylindrical shape, and does not change its volume; assuming its resistivity does not change either, derive how $\Delta R/R$ (fractional change in resistance) depends on $\Delta L/L$ (fractional change in length).
piezo-electric sensors
piezo- and pyroelectric devices

► piezo- (pressure) and pyro- (heat) electricity are always coupled
► it is due to separation of electrical charges in the material’s crystalline arrangement
  ◆ electric dipoles at the molecular level (e.g., H₂O)
  ◆ high voltage poling to macroscopically align dipoles
  ◆ “electrets” made by poling various waxy mixtures
► pressure $\rightarrow$ voltage (sensor)
  voltage $\rightarrow$ deformation (actuator)
► due to leakage, effect is transient
  ◆ to stabilize, leakage is intentionally increased, making device response effectively to $dP/dt$
► high voltage + high input impedance $\rightarrow$ tiny current (hard to measure, slow to measure)
practical piezoelectric materials

► quartz (cut along particular crystal axes to maximize piezo- and minimize pyro- effects)
  ◆ effect small but very stable

► various ceramics, e.g., ZnO, PZT\(^\text{TM}\)
  ◆ deposition on micro- and mini- fabricated devices
    ■ SAW (surface acoustic wave) devices for sure
    ■ MEMS devices discussed but not sure whether implemented

► plastics: polyvinylidene difluoride (PDVF, PVF\(_2\))
  ◆ enormous quantities are reportedly used in submarine sonar transducers
    ■ yeah, so why is it so expensive?
magnitude of piezoelectric effect

- easy to get tens of volts but need high input impedance measuring instrument
- can get very high voltages (enough to spark across ~ 1 mm) in response to impact
  - buy yourself a “flintless” butane lighter
capacitive sensing
capacitive devices

- “mouse pad” or “touch pad” is now ubiquitous, reliable, stable
- same geometrical factors as resistive sensors (but remember that capacitance is defined “upside down”: \[ V = L \frac{dl}{dt} + R I + \frac{Q}{C} \])
- actual approach is to measure distortion in “stray” capacitance
- (again) see http://www.synaptics.com/technology/cps.cfm
- many geometries, including some “finger-like” curvatures

\[ V \text{ volts} = \varepsilon \text{ farad/m} \ A \ m^2 / l \ m \]
magnitude of capacitive effects

- \( \mu_0 = 4\pi \times 10^{-7} \text{ henry/m}, \ \varepsilon_0 = \frac{\mu_0}{c^2} = 8.85 \times 10^{-12} \text{ farad/m} \)
- “small capacitor” is \( \approx 100 \text{ pF} \) (\( p = \text{pico} = 10^{-12} \))
- say you want to see a 1\% change in capacitance
- say tactel is 1 mm\(^2\), dielectric constant is 10
- then to get 100 pF need \( l = 10 \varepsilon_0 A / C = 10^{-6} \text{ m} \) or \( 10^{-3} \text{ mm} \)
- and to resolve a 1\% change need to see \( 10^{-8} \text{ m} \)
  - wavelength of green light is around \( 50 \times 10^{-8} \text{ m} \)
- might use multi-layer tricks to improve this
- **but the smallness of this effect probably explains why the commercial technology exploits the “stray capacitance” effect vs. pressure-induced capacitance change**
  - however: the best vacuum/gas pressure sensors are capacitive
miscellaneous

tactile sensing schemes
magnetic and inductive effects

- many prototypes, probably no products
- inductive devices are more-or-less miniature LVDTs
- magnetic effects, e.g., magneto-resistance plausible
  - recent developments of “giant” and “colossal” magneto-resistance materials may hold promise, but no developments as yet ...
- slip sensing potential with dipoles oriented *within* surface
- Hall effect sensors may be the most plausible, as Hall effect switches are in common use in computer keyboards etc

![Hall effect diagram]

**Hall effect:**
Voltage due to deflection of current’s charge carriers
deformation of elastomers

- many mechanical, optical, and acoustic readout schemes prototyped ...
  - optical? for example, modified total internal reflection schemes (as mentioned above)
  - acoustic? Grahn @ Utah: ultrasonic measurement of compression
- typically cumbersome ... probably obsolete except as source of ideas for future MEMS implementations ...
fiber optic schemes, e.g., Schoenwald @ Rockwell
- seemed promising
- potentially “fabric”- or even “skin”-like
- but never went anywhere commercially
miscellaneous issues
“finger-like” surfaces

for surfaces with “true gaussian curvature”, little that seems ready for prime-time ...

R. Fearing, Int. J. Robotics Research, V. 9 #3, June 1990, p.3-23: Tactile Sensing Mechanisms (from his PhD thesis): “fingertip” (cylinder with hemispherical cap), with capacitive pressure sensor embedded in the cylindrical (only) part

- 8 circumferential x 8 axial electrode array in molded rubber
- capacitance measured at 100 kHz; scanned at 7 Hz
- maybe cylindrical surfaces are not so bad
  - e.g., it is useful to be able to bend planar sheets
- problems with hysteresis and creep, coupling between tactels, modelling response to fingertip loading
- paper is good example of a complete electrical/mechanical model
related area: proximity sensing

frustrated by lack of good “touch sensors”, there have been several (mostly Japanese) demonstrations of object identification by scanning a short range (~1 cm) “robot fingertip” proximity sensor.

four competitive moderate-cost commercial technologies:
- capacitive best for dielectric (insulating) materials
- inductive best for metallic (conducting) materials
- optical: simple transmitter-receiver pair, e.g., Radio Shack
- acoustic: probably for somewhat longer range

some proven but less developed and accepted ways:
- fiber optic bundles
- focus based methods (e.g., using CD-player components)
- (field emission/tunneling/discharge/ etc. are a bit far out)
  - sensitive but difficult to calibrate
MEMS tactile display development (mostly CMU)

thanks to George Lopez
MEMS actuators for tactile stimulation

- two sealed chambers sharing common membrane
- inner chamber out-of-plane force/deflection caused by electrostatic compression of outer chamber
- move towards integrated actuator and control, all “on-chip”; experiment now with CMOS membranes
MEMS tactile stimulator array concept

A 10 x 10 tactile stimulator array

- An individual MEMS-based taxel (tactile pixel)
- Stimulator off (no applied voltage)
- Stimulator on (applied voltage creates electrostatic deflection)

- Cross-sectional view
- Concentric chambers with shared, sealed volumes
- Common membrane

[Image of a 10x10 array with diagrams showing the concept of a tactile stimulator array.]
test taxel chip fabrication results

tactile stimulator test chip with 11 different inner radii

openings between inner and outer chamber volume

bottom electrode of actuator (polysilicon)

Kapton common membrane (post-fab)

upper electrode of actuator (polysilicon)
long term goal: build on flexible silicon membranes