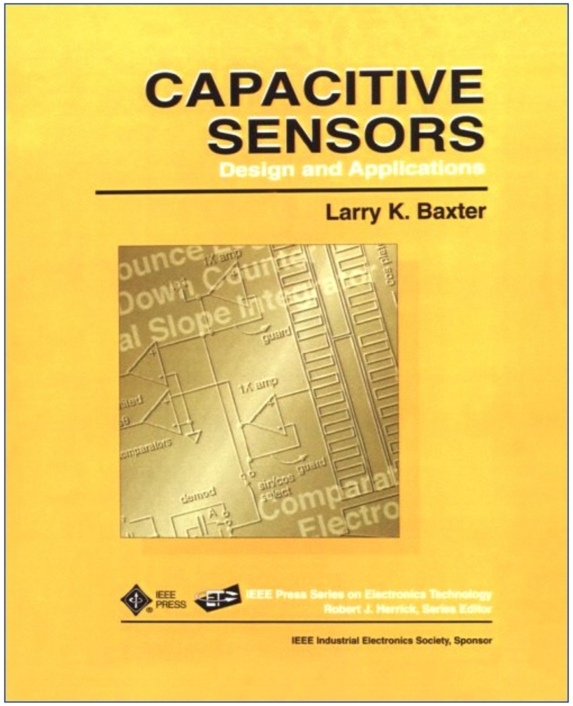
MAS836 – Sensor Technologies for Interactive Environments

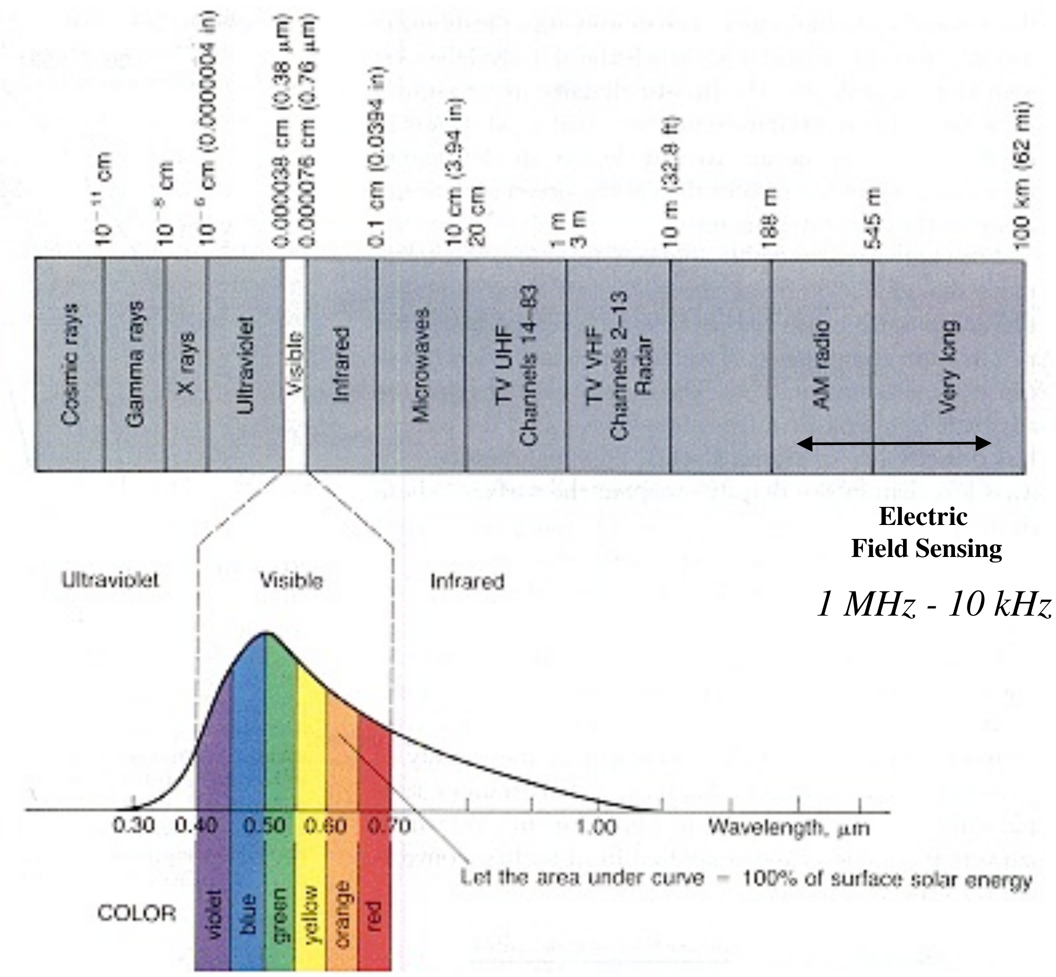
Lecture 6 – Electric Field Sensing

Good Reading…



- Larry Baxter
  - Capacitive Sensors
- See also our EFS paper:
  - Joseph A. Paradiso and Neil Gershenfeld, "Musical Applications of Electric Field Sensing," Computer Music Journal 21(2), Summer 1997, pp. 69-89.
    - http://www.media.mit.edu/resenv/pubs/papers/96_04_cmj.pdf

The Electromagnetic Spectrum

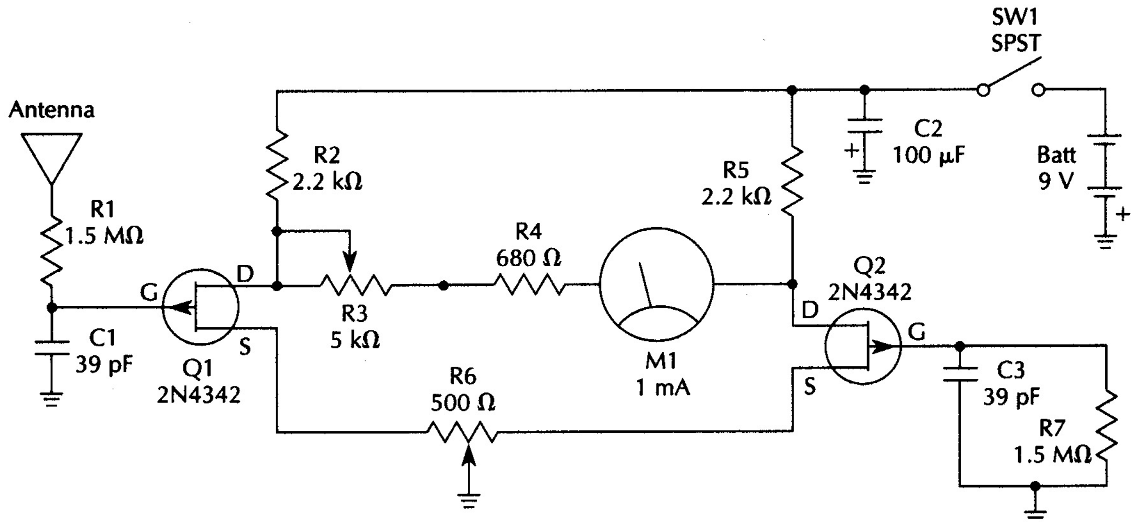


EFS (capacitive) sensing implies that $\lambda = c/f >>$ sensing range = d -> Near Field

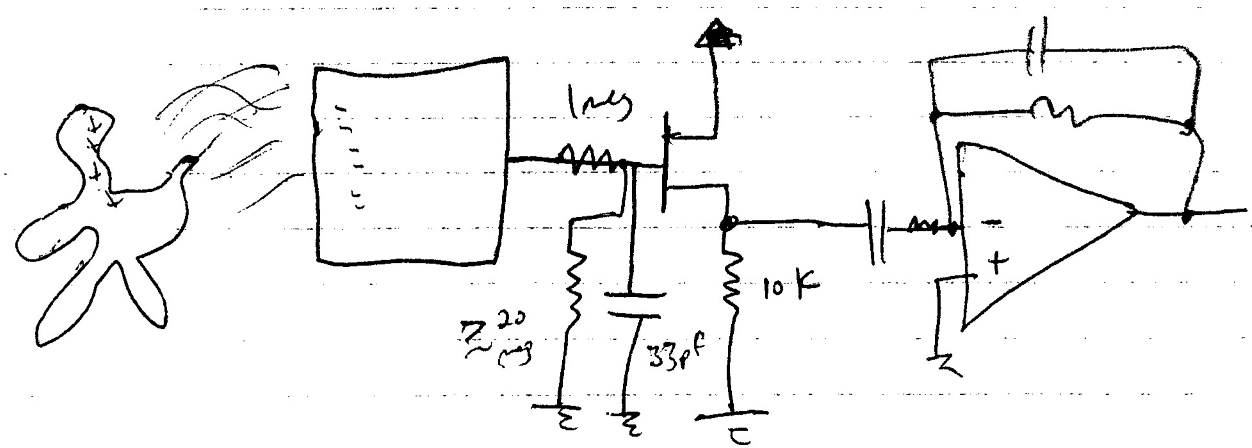
Electric Field Sensing

- Pros:
  - Cheap
  - Not affected by light, sound, etc.
  - Not “really” line-of-sight
  - Easy to do and easy to configure
    - Range scales with size and spacing of the electrodes
  - Can get extremely high resolution (e.g., angstroms) if appropriately configured and shielded
- Cons:
  - Hard to get detailed information
    - e.g., can’t (maybe) tell if you’re smiling, but can easily tell that your hand moves near a point.
    - Doesn’t deal well with ambiguity
  - Sensing field can be self-shielded
    - Can’t see through skin, metal, etc.
  - Sensitive range is limited (e.g., 1-3 meters max)
  - Nearby metal can perturb and attenuate sensitive range
  - Although synchronous filtering helps, some sensitivity to external EMI

Tribolectric (DC electrostatic) sensing

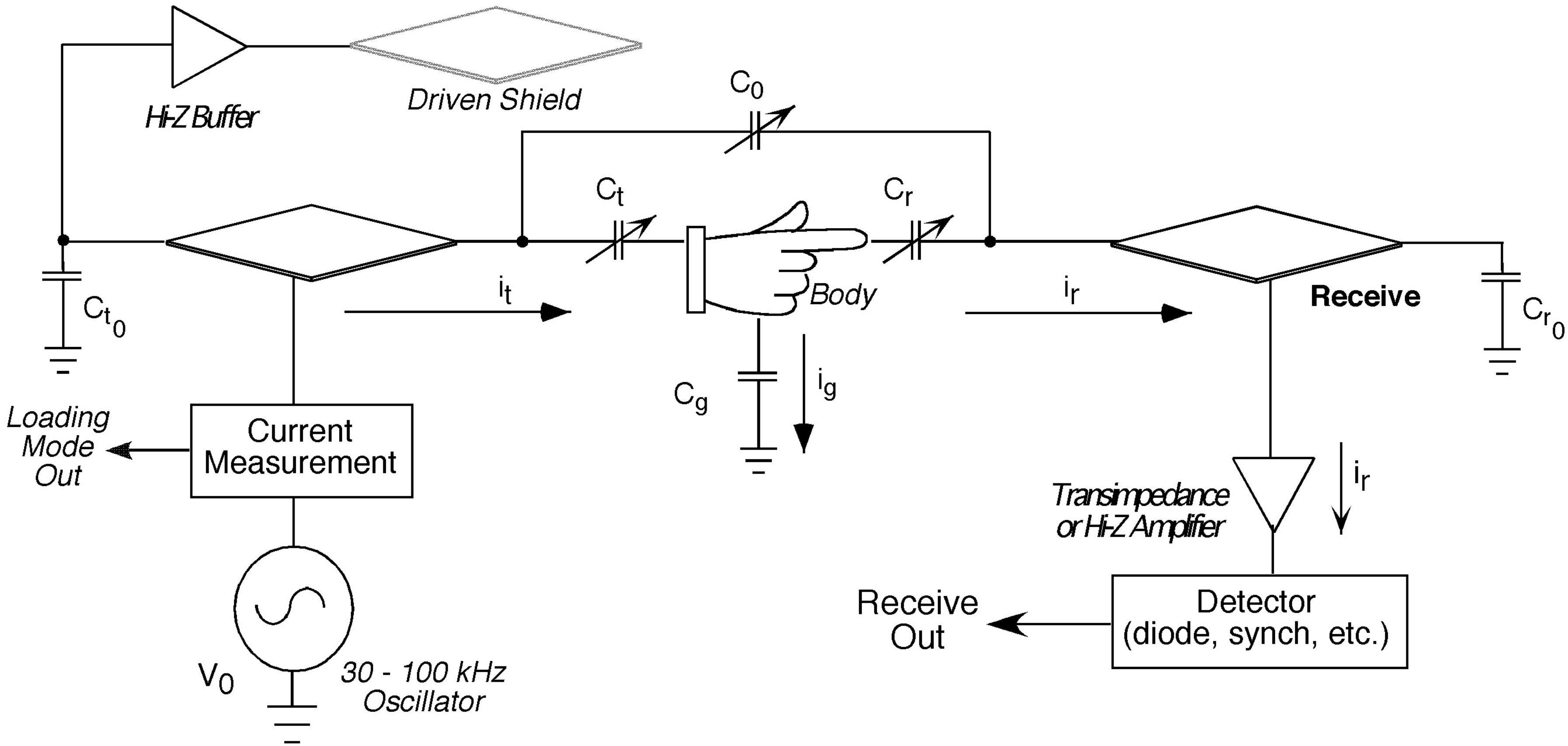


Electroscope (fr. Petrozellis)

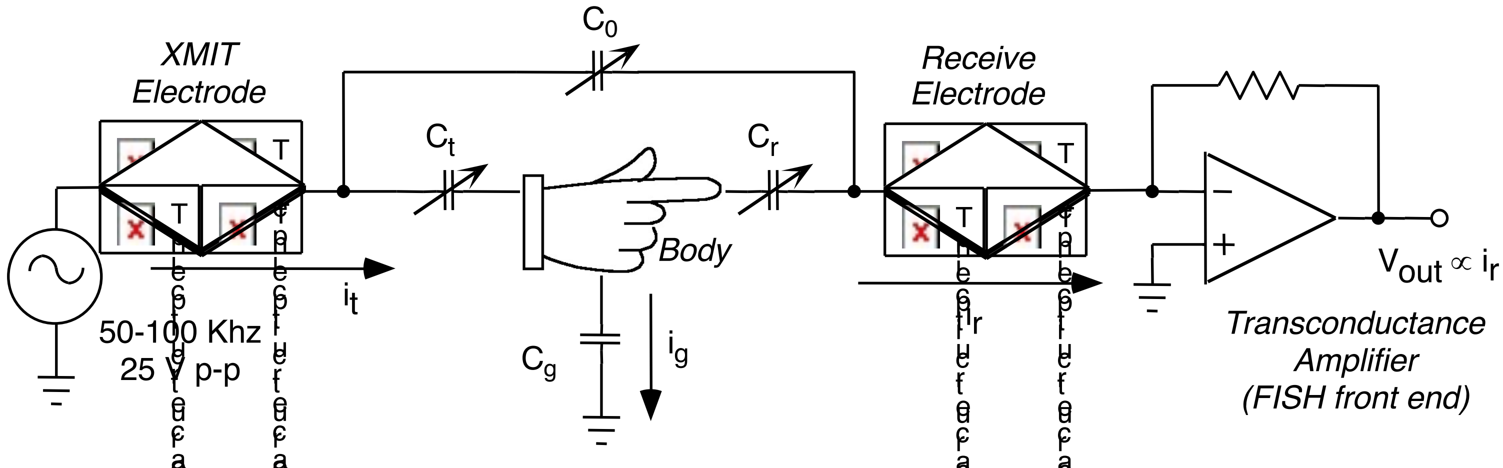


Similar - can use FET-input OpAmp too

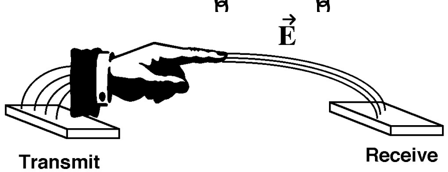
General electric field sensing model



Noncontact Gesture Sensing

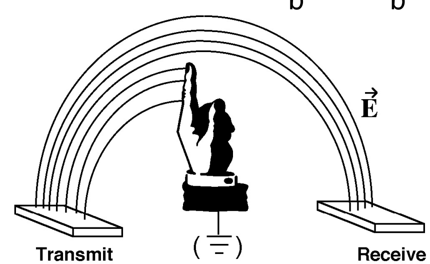


Equivalent circuit for all modes of electric field sensing



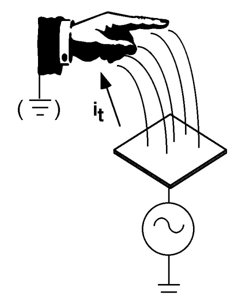
Transmit mode ($C_t >> C_g$)

- User must contact transmitter
- User uniquely tagged
- Can use multiple frequencies; multiple users
- 2-object geometry
  => Best for accurate tracking
- Industrial (short range) proximity



Shunt mode ($C_g >> C_t$)

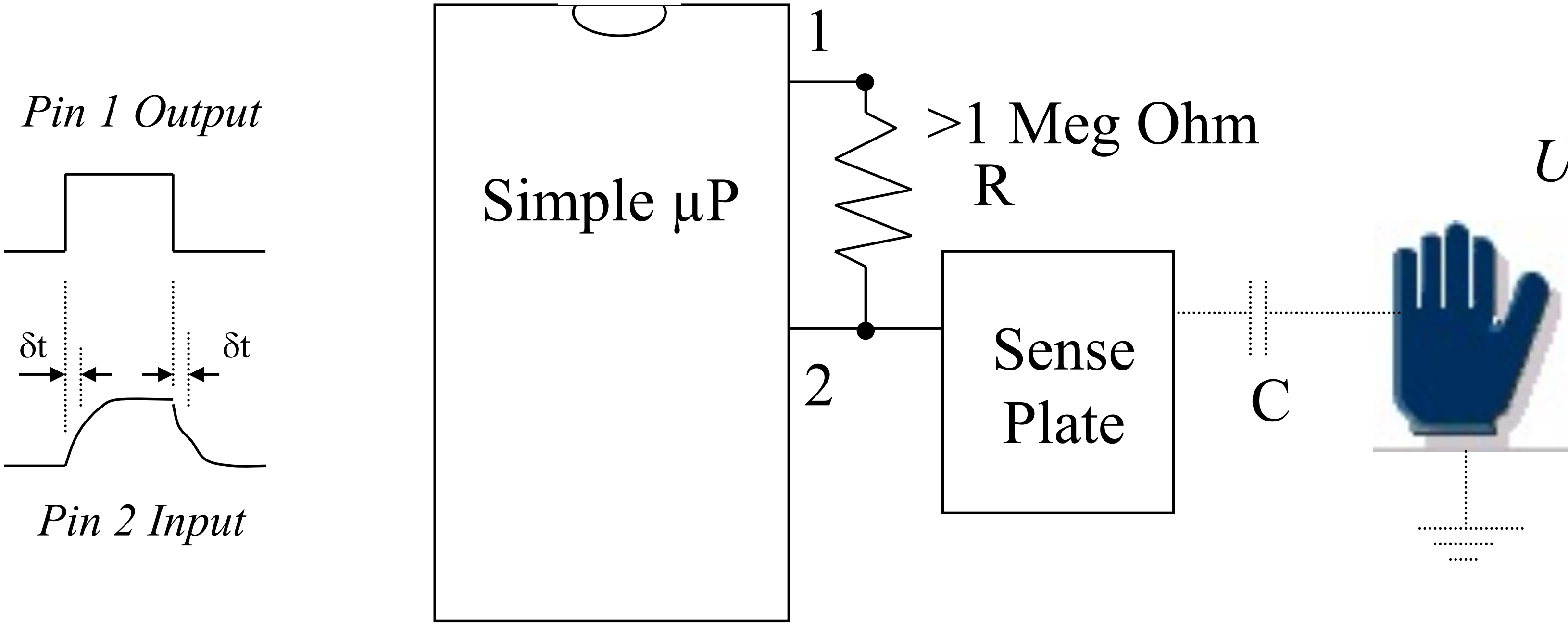
- No contact with electrode
- 3-object geometry
  => Hard to do tracking
- Can “focus” w. tomograpy
  => Add more transceivers



Loading Mode (measure I_t)

- Single Electrode
- No cable to electrode
- Couples to everything
- Hard to adjust sens. area
- Used for everything
  - Stud finders (pre MIR)
    Theremins, buttons...

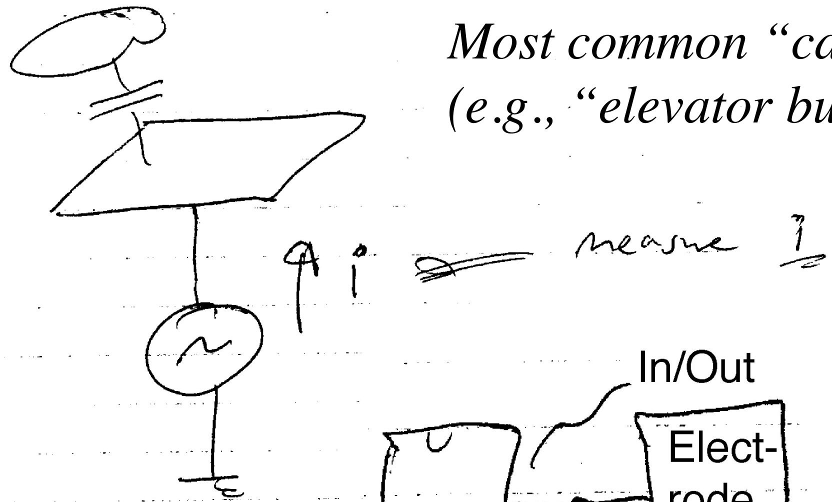
Minimal Capacitive loading circuit

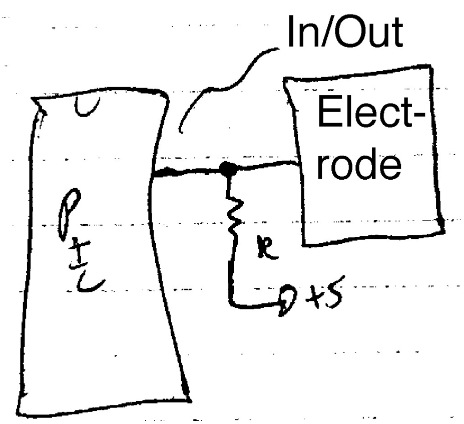


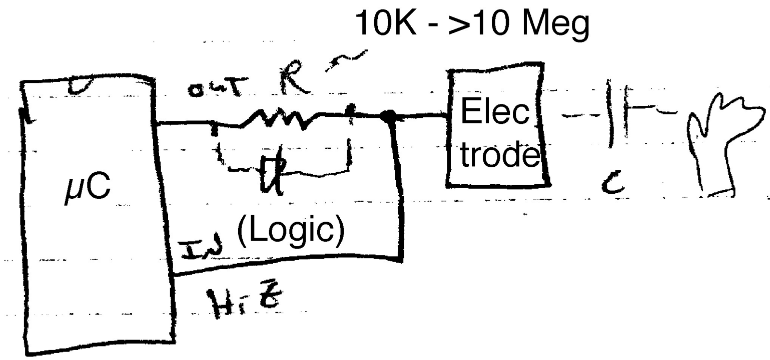
- Pin 1 is digital output, pin 2 is digital input
- Toggle state of pin 1 and measure time needed for state of pin 2 to flip
  - Time difference increases with R and C
    - Fix R, hence C is measured
- Loading mode measurement – range typically few cm

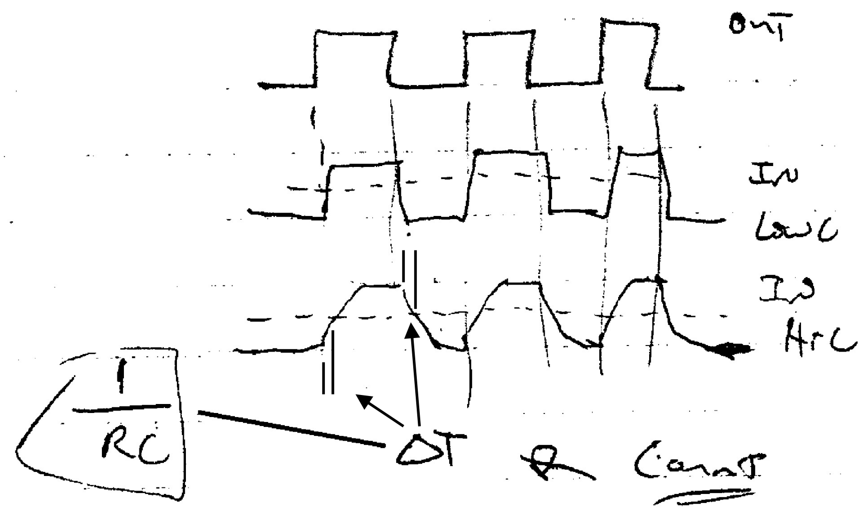
Loading Mode Sensing

Most common "capacitive" sensing (e.g., "elevator buttons")



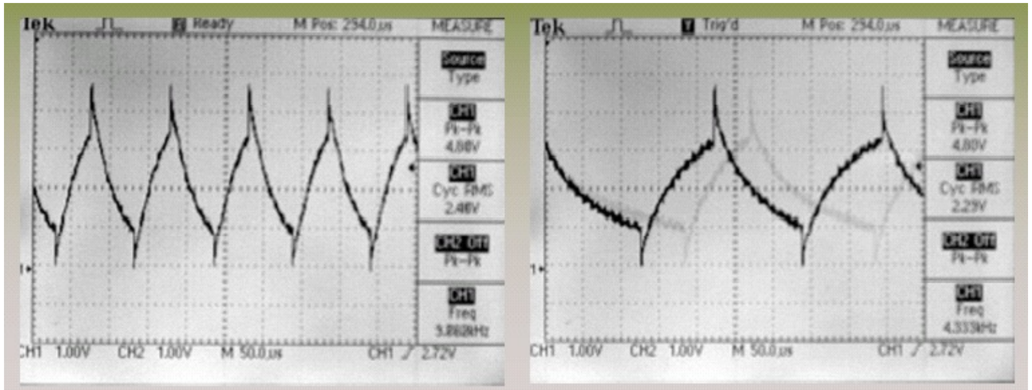




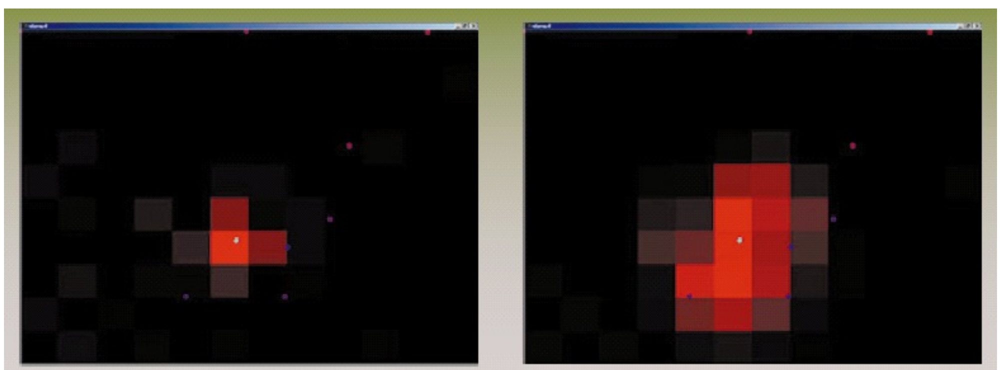


1- Set pin to output, and pull down
2- After brief wait, declare as logic input
3- Measure T until input goes to "1"

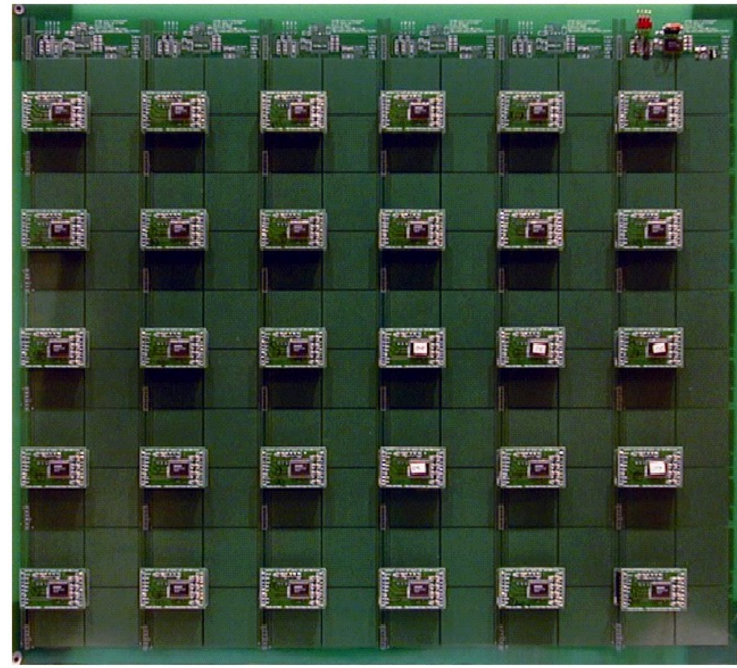
Rehmi Post's E-Field Touch Table



No hand present | Hand present



Finger | Palm

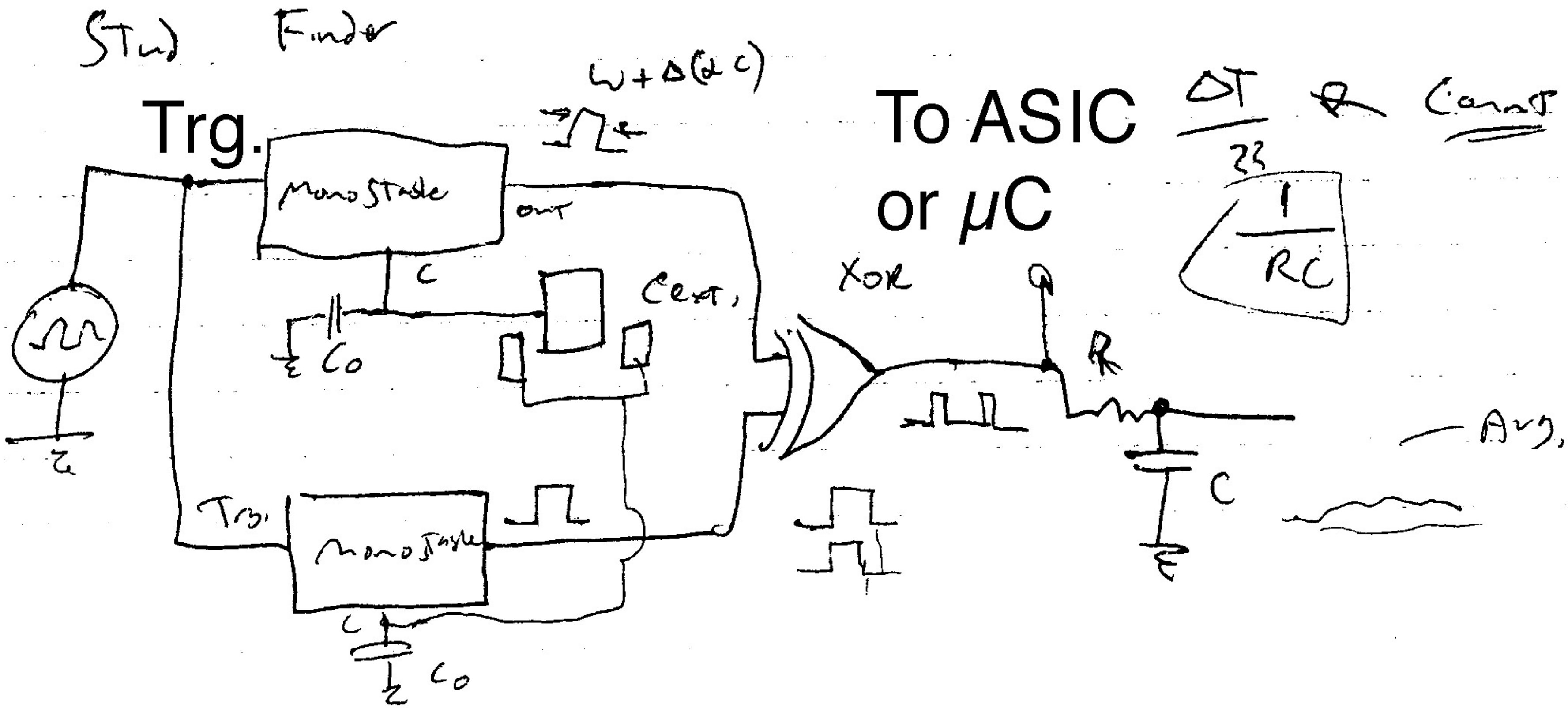


tauFish array with 30 tauFish (120 electrodes)

Loading Mode
Used at MOMA, 1999

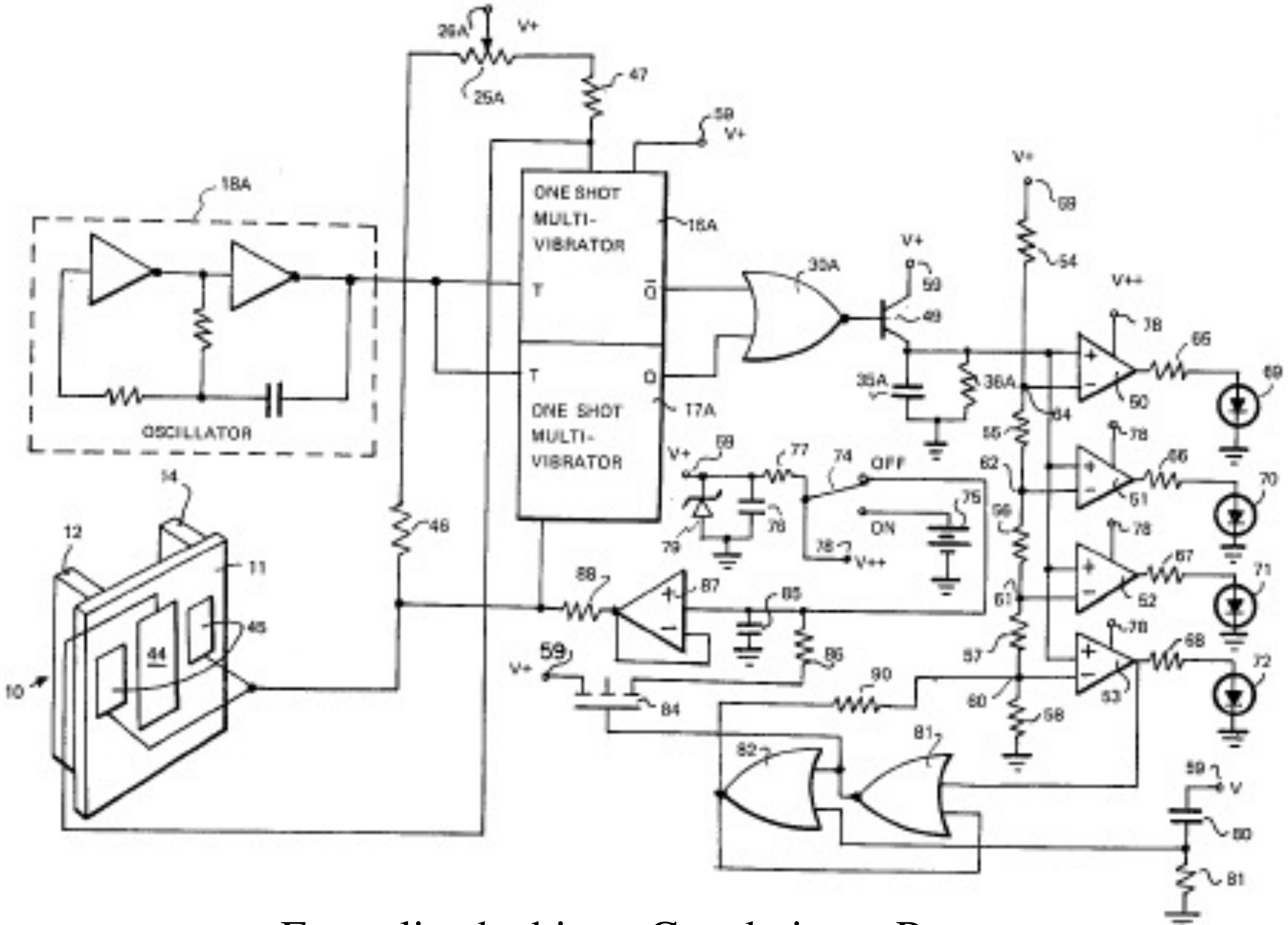
Stud Finders

The Stud Finder



- Uses dual monostables (compare against reference)
- Look for difference in period of exposed monostable
- Electrode geometry yields spatial differentiation!

Franklin & Fuller - US Pat. 4,099,118

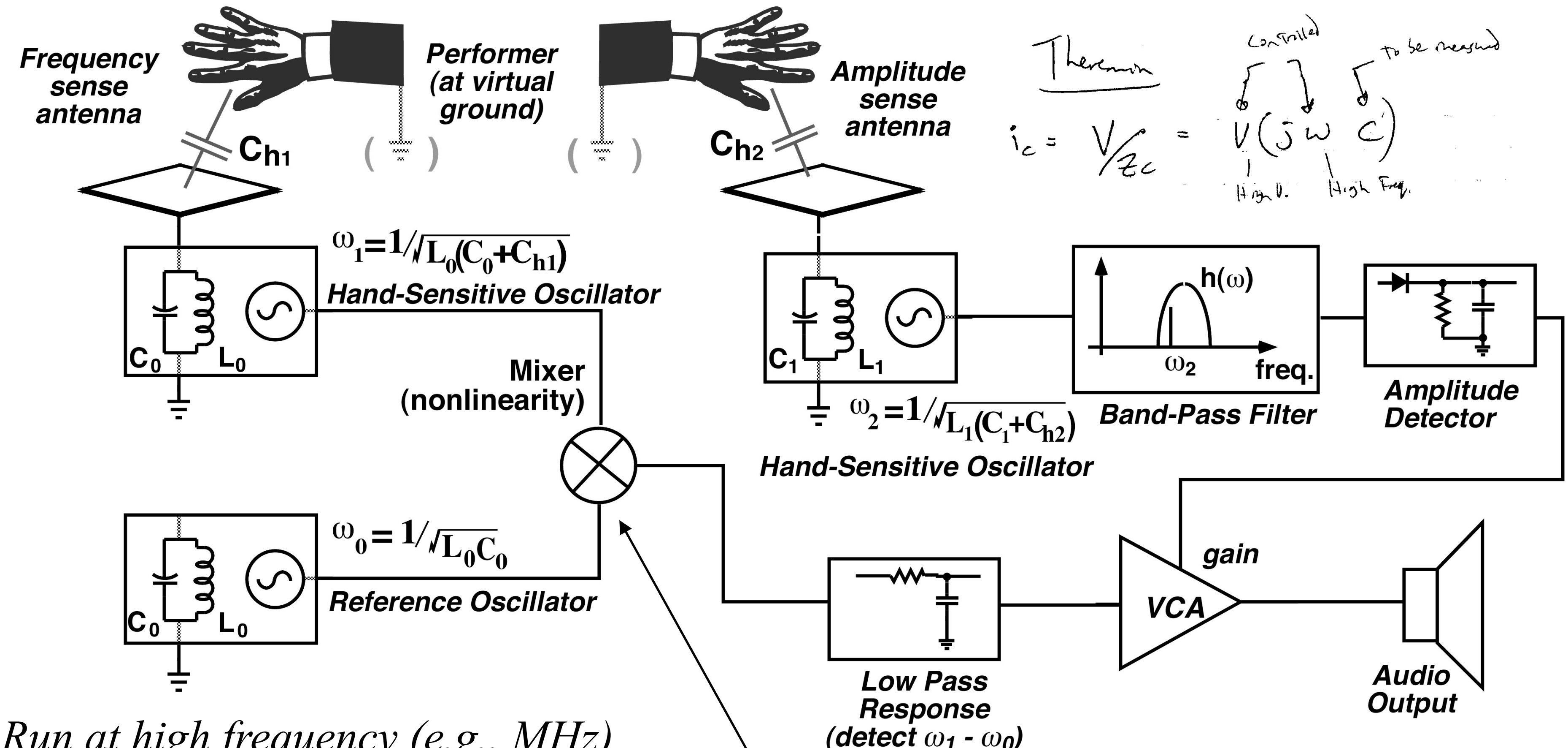


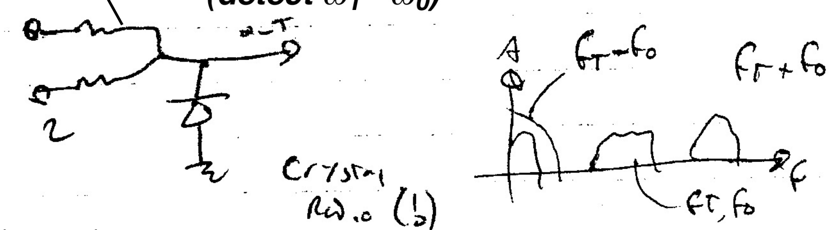
Formalized a bit… Can do in a μP

Theremin

- Capacitive sensing of users hand
- Invented by Leon Theremin in Russia circa 1917-1920
- First “successful” electronic musical instrument

The Theremin





Run at high frequency (e.g., MHz)
- Gives strong coupling
- Detect beats (20 Hz - 20 kHz)
- Need stability!!
  - Although can accommodate w. hand pos.
    - Can go ~1 ft. to a meter or several (but less stable)

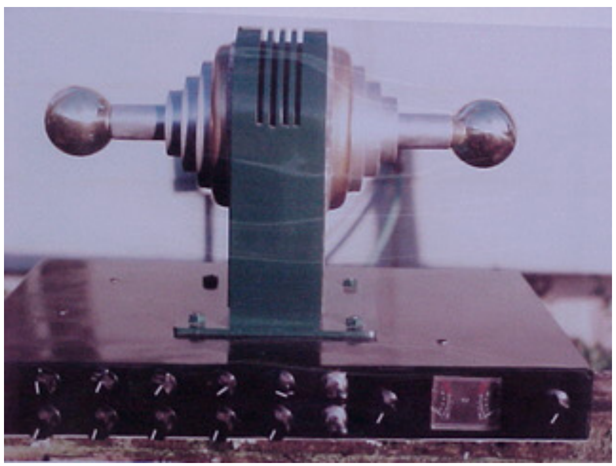
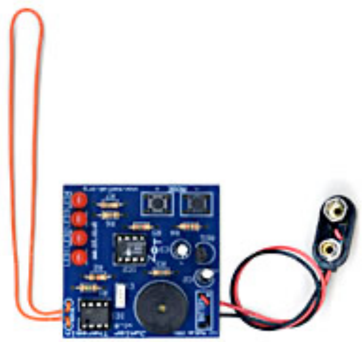
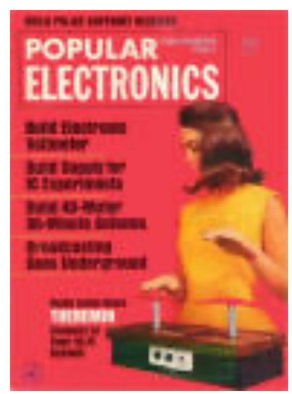
Theremin in New York, 1927 - 1938

- Made by RCA (licensed in 1929, made in the 30’s)
- Many pieces commissioned for it
- See “Theremin – an Electronic Odyssey”

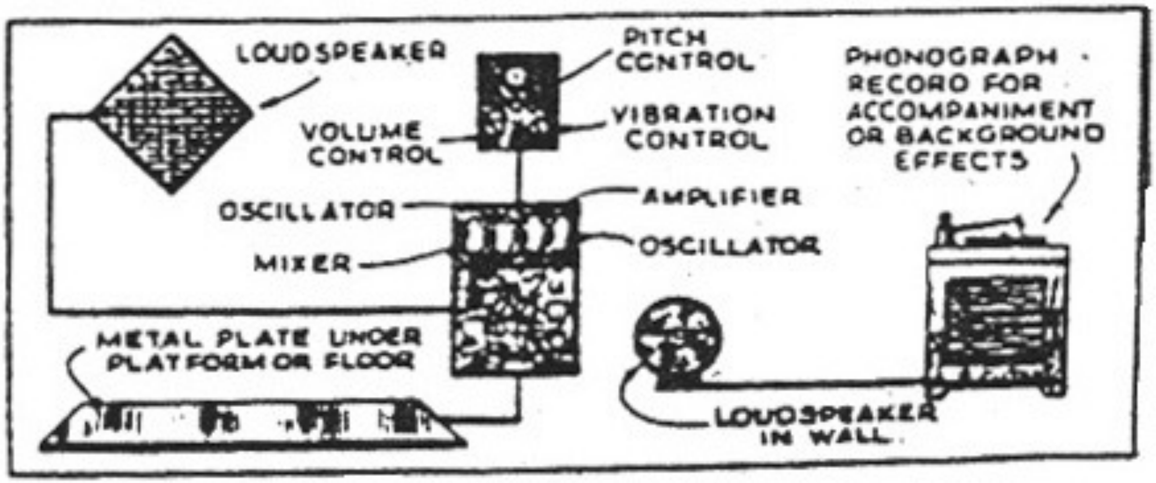
In case you don't know what a Theremin is..

Many versions today: tube-transistor-opamp-μP



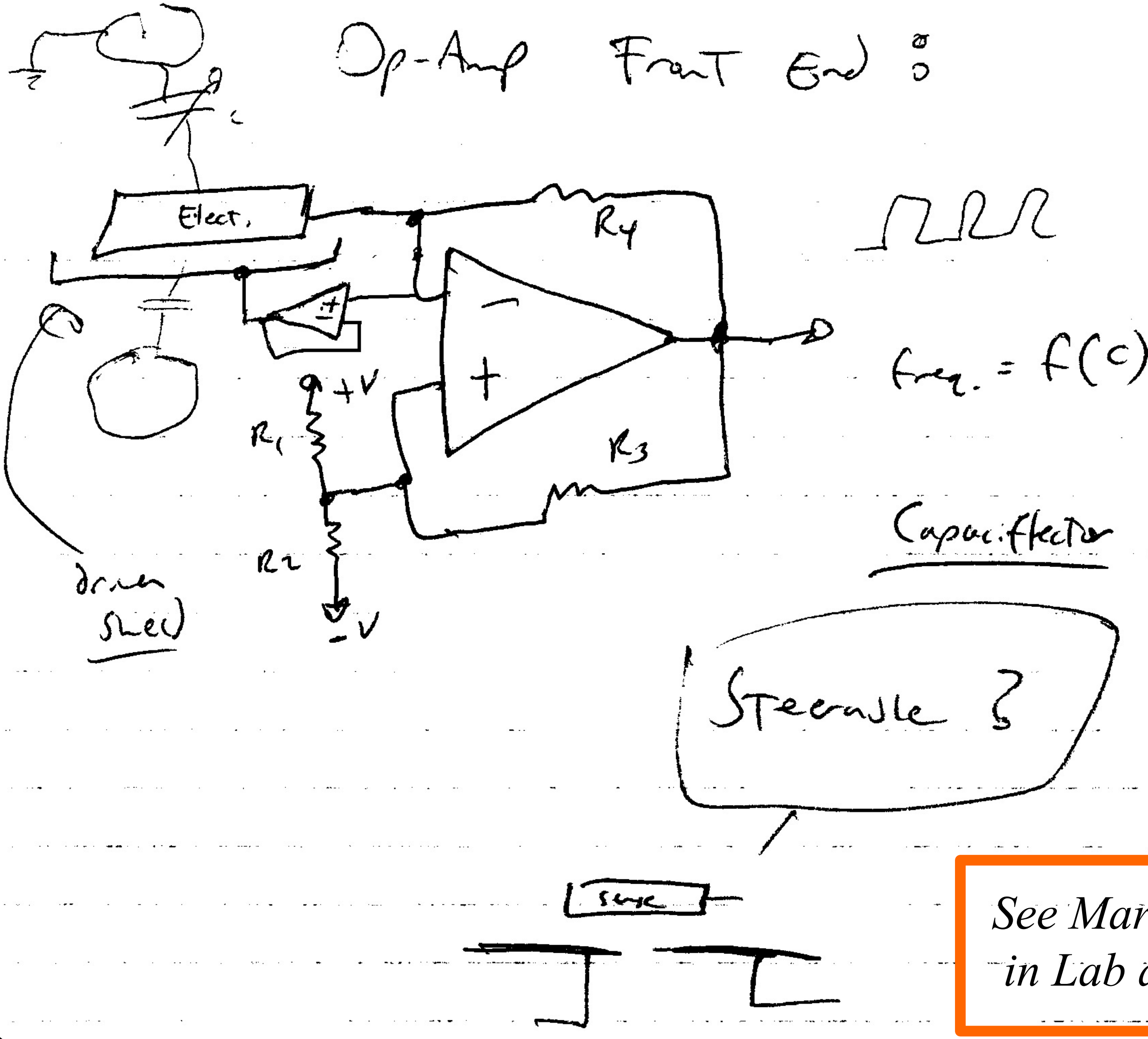




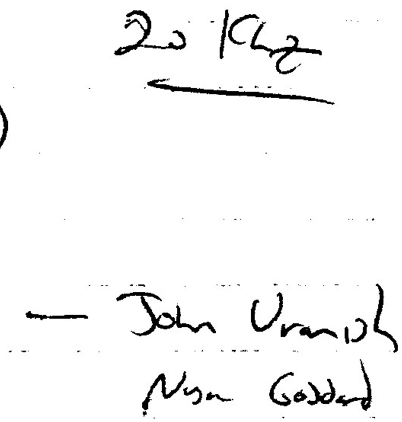
The Terpsitone



- Theremin's dance interface – early 30's

Capacitively Controlled Multivibrator

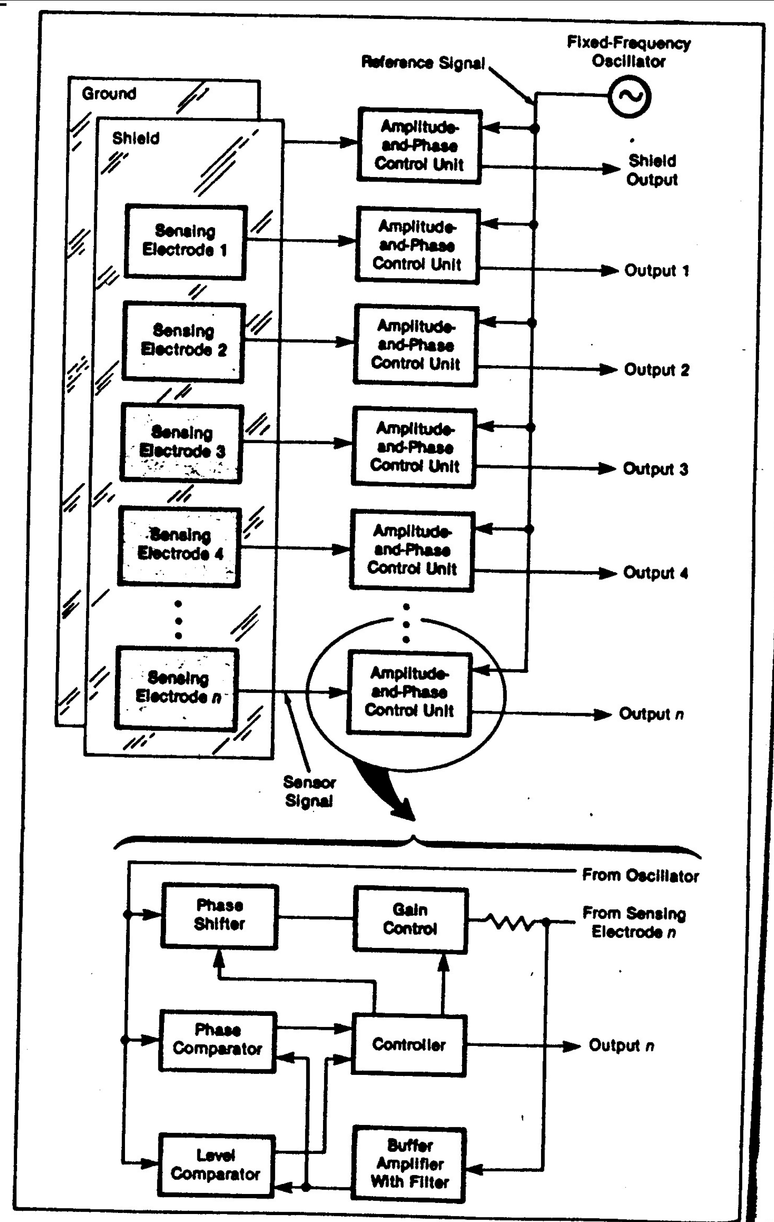




See Reading Links!

See Mark Feldmeier's circuit in Lab assignments

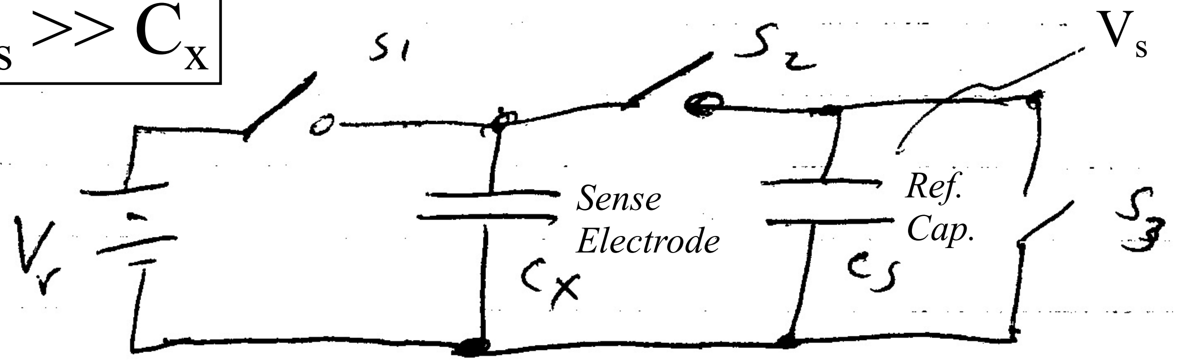
Capaciflector Camera



Vranish, et. al.
NASA Goddard

Switched Capacitor Measurements

$C_s >> C_x$



Charge Pump!

$$V_s = V_r \frac{C_x}{C_s + C_x}$$

$\Downarrow$

$C_s >> C_x \rightarrow$

$$\approx V_r \frac{C_x}{C_s}$$

$$C_x = C_s \frac{V_s}{V_r}$$

- close/open S3 – Discharge C_s
- Close S1 → Charge C_x
- open S1
- Close S2 → C_x charge goes to C_s
- Repeat N times
- ↓ measure V_{C_s}

Next Measurement

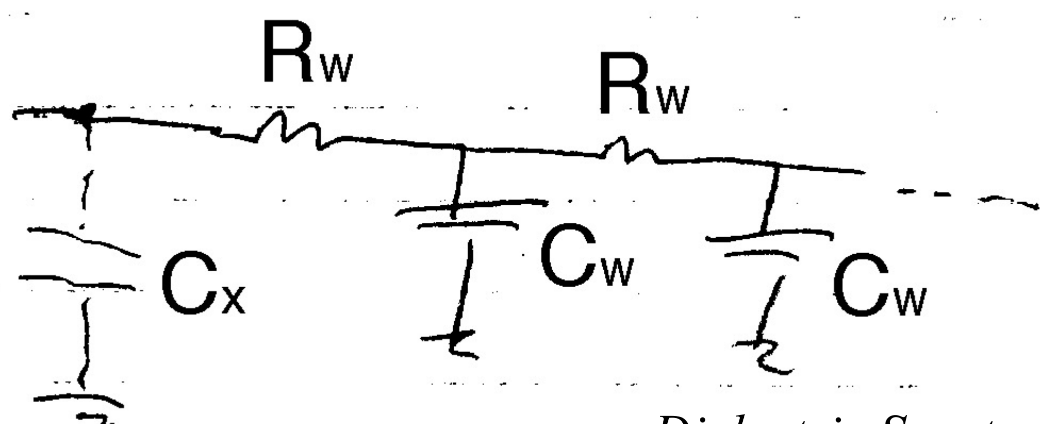
Measure V_s, infer C_x

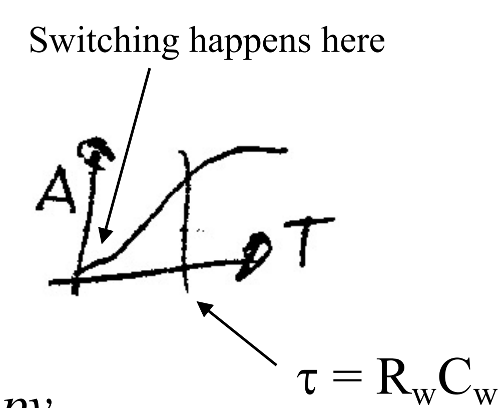
Need N here!

See: http://www.qprox.com/downloads/misc/white_paper.pdf

Charge Pump Capacitive Sensing

- Sensitive down to 0.01 pF (10 Attofarads)!
- Short switching times involved (e.g., 100 nsec)
  - Not much background at these frequencies
    - And not much time for interference to integrate
  - Repeated pulses can be intrinsically spread spectrum
    - Irregular intervals don’t correlate with artifical sources
      - Noise is intrinsically integrated out
  - Can “see” through water??
    - Water has resistance, fast pulses don’t engage intrinsic RC highpass

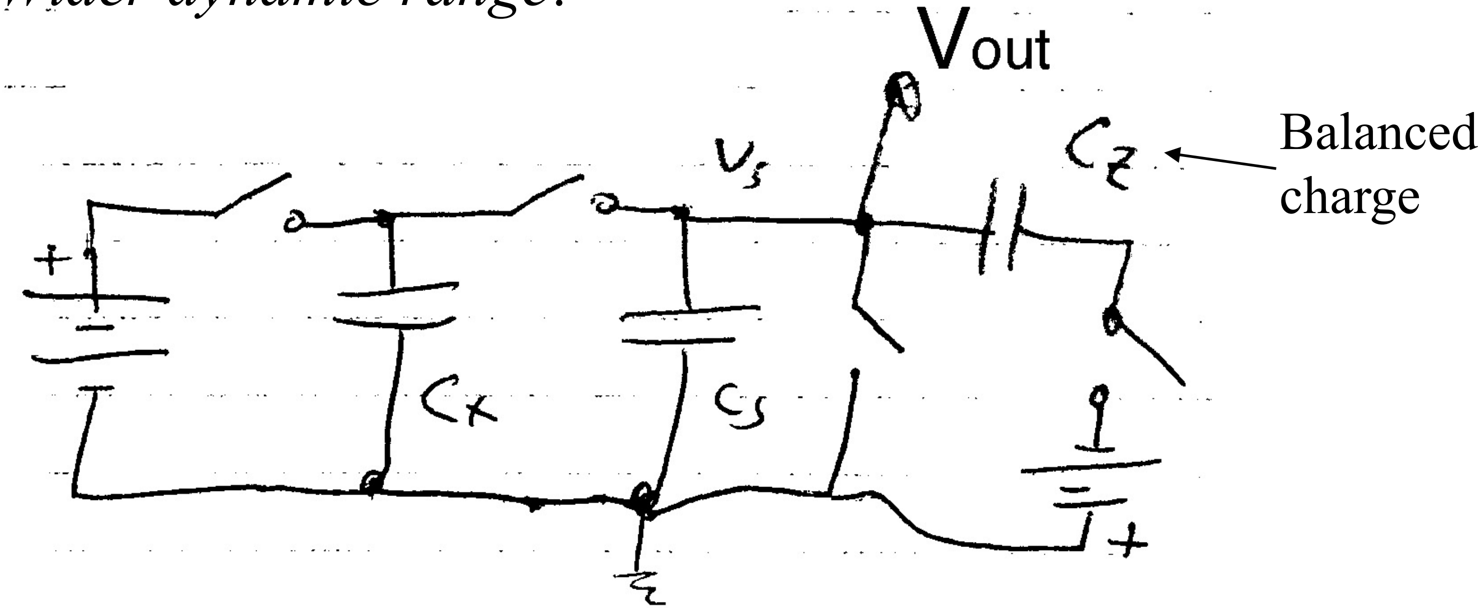




Dielectric Spectroscopy

Differential Arrangement

Wider dynamic range?



Quantum Sensor Corporation - "QT" chip series

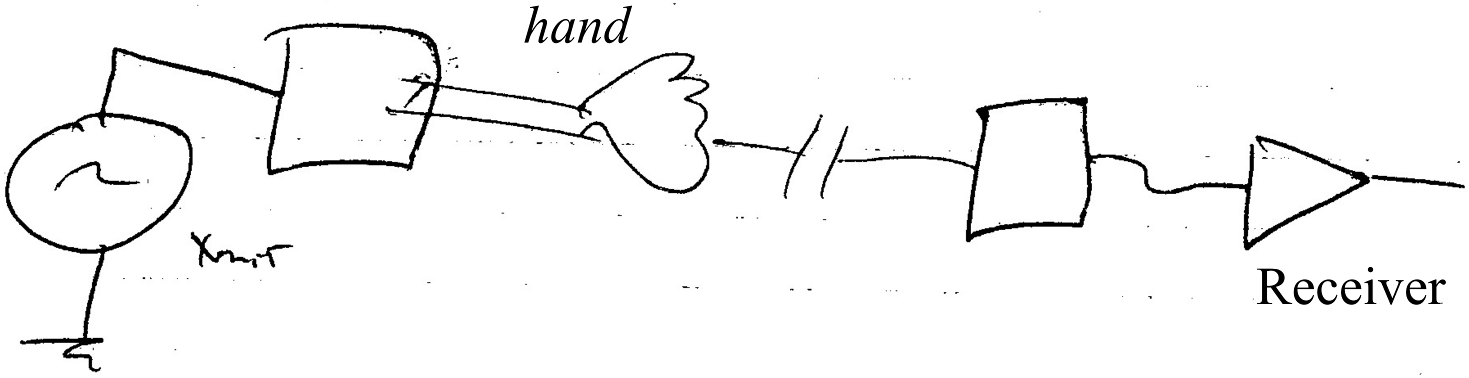
Can be done all in software by moding pins (use simple PIC, etc.)

QPROX sensors - see Sensors article for details

Transmit Mode

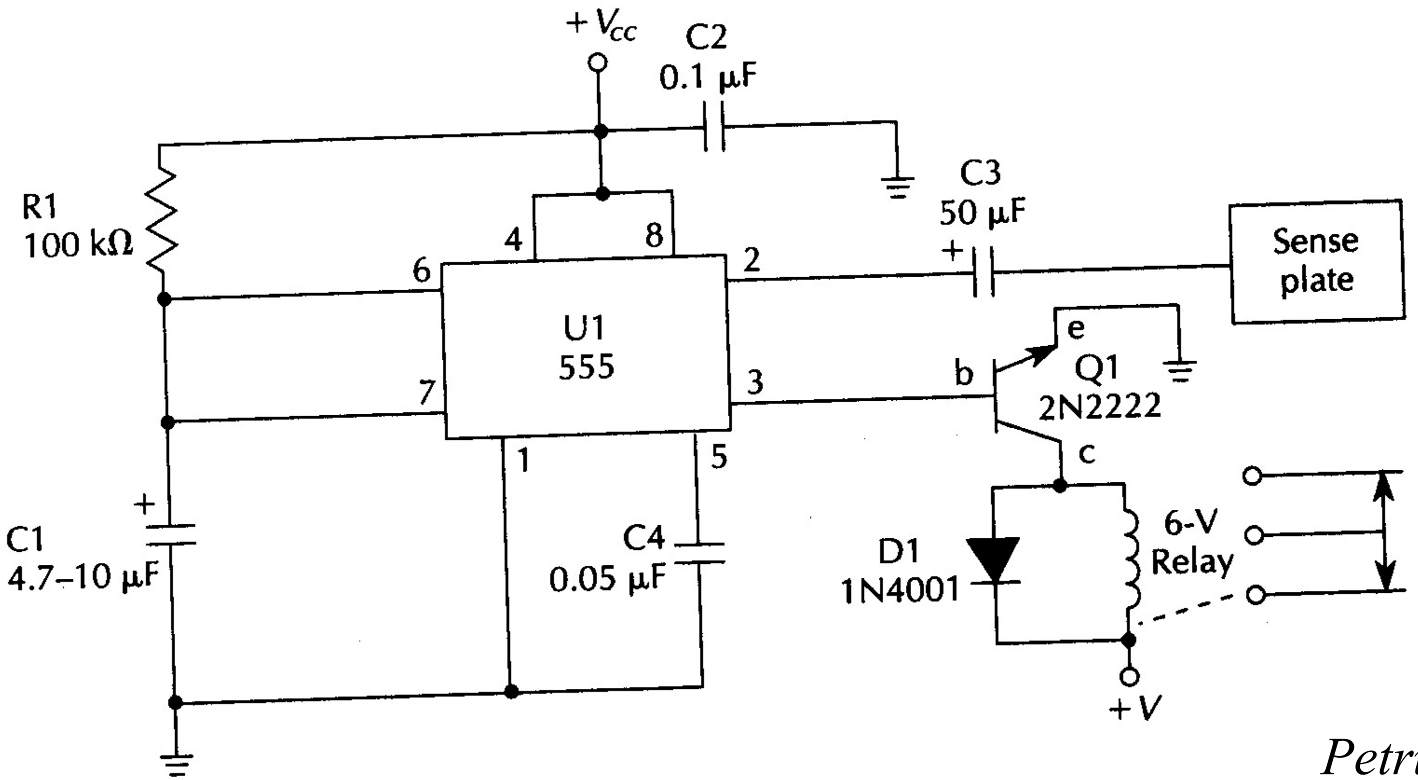
- Transmit Mode → Simplest

→ Tracking Object Tagged



2-electrode geometry

Simple Induced-Hum Touch Sensor

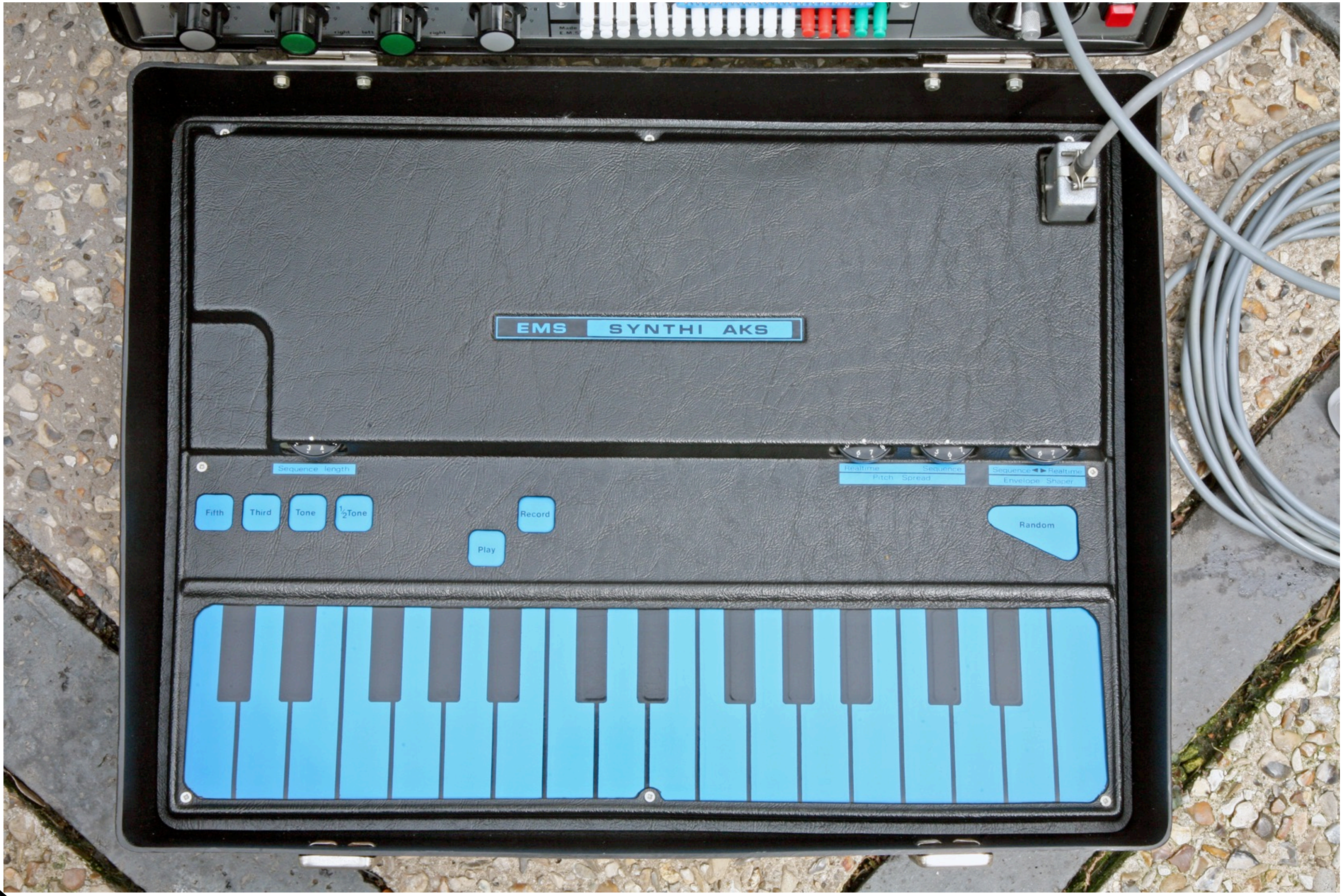


Petruzellis

Touch switch.

- 50/60 Hz pickup couples into high-Z input
  - Triggers logic high
  - Can use essentially any Hi-Z (e.g., CMOS) gate
  - Static protection??

EMS Synthi AKS used this (1972)

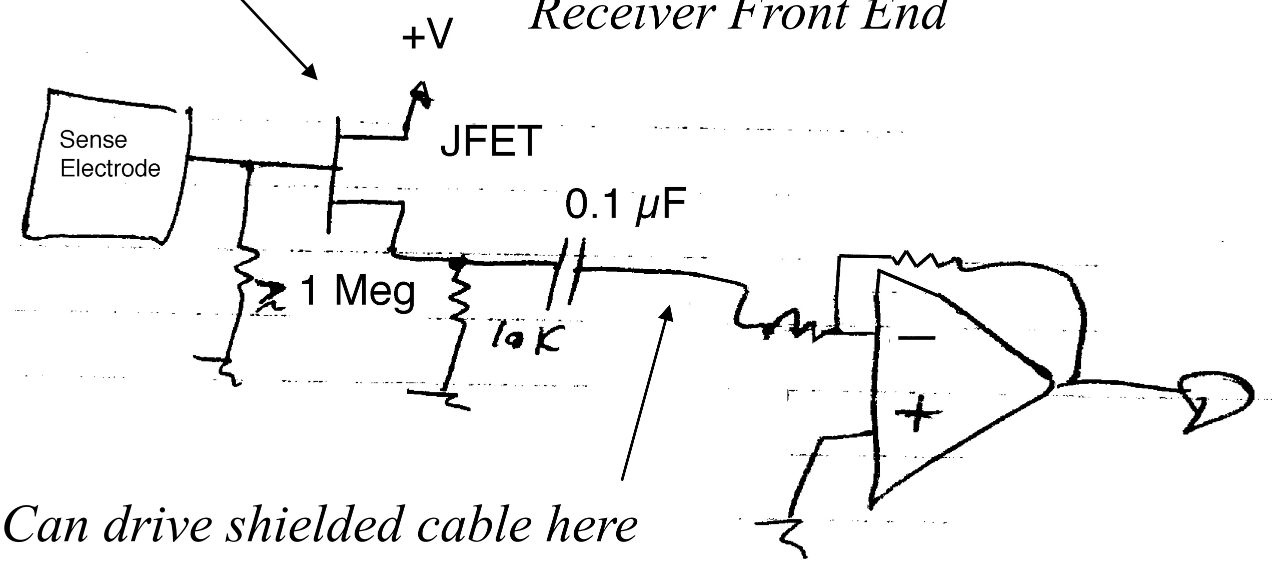


High-Impedance Front End

Simple, High Impedance
- Electrode Floats
  -> Voltage Sensor!

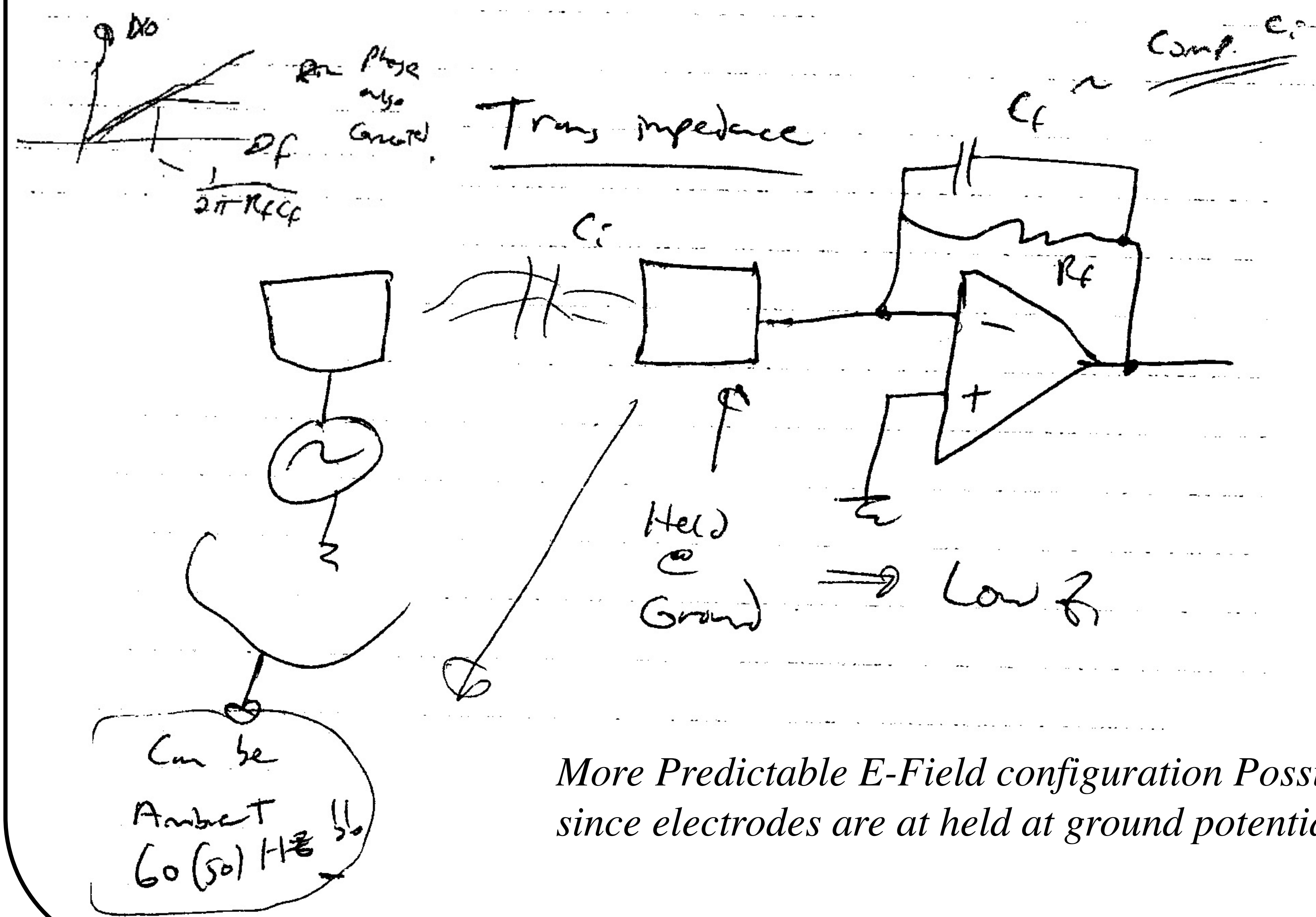
JFET can be Noninverting FET OpAmp

Receiver Front End



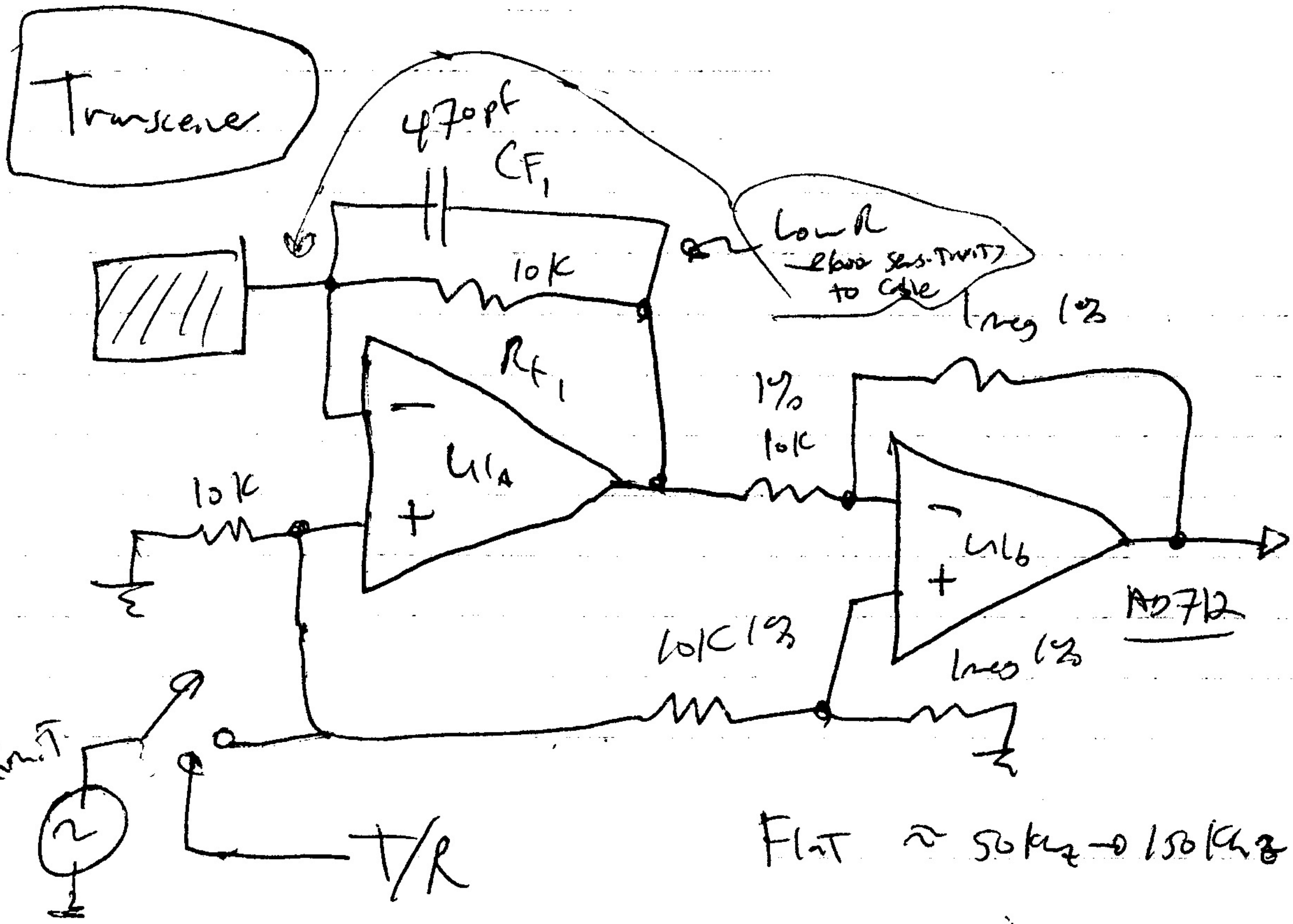
Can drive shielded cable here

Low Impedance Front End



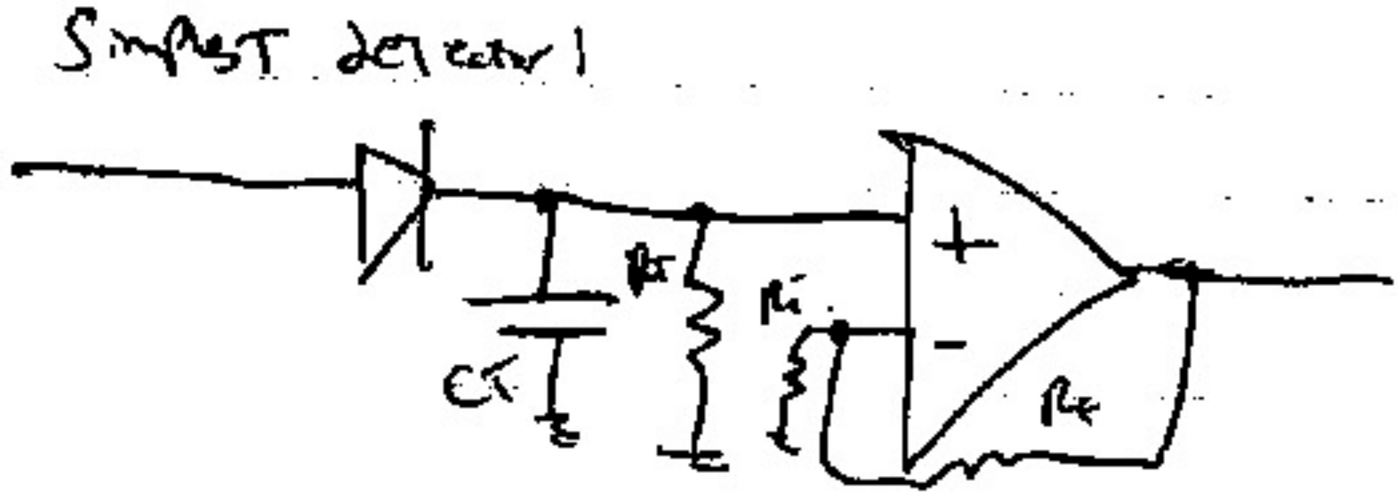
More Predictable E-Field configuration Possible, since electrodes are at held at ground potential

The Transceiver Electrode



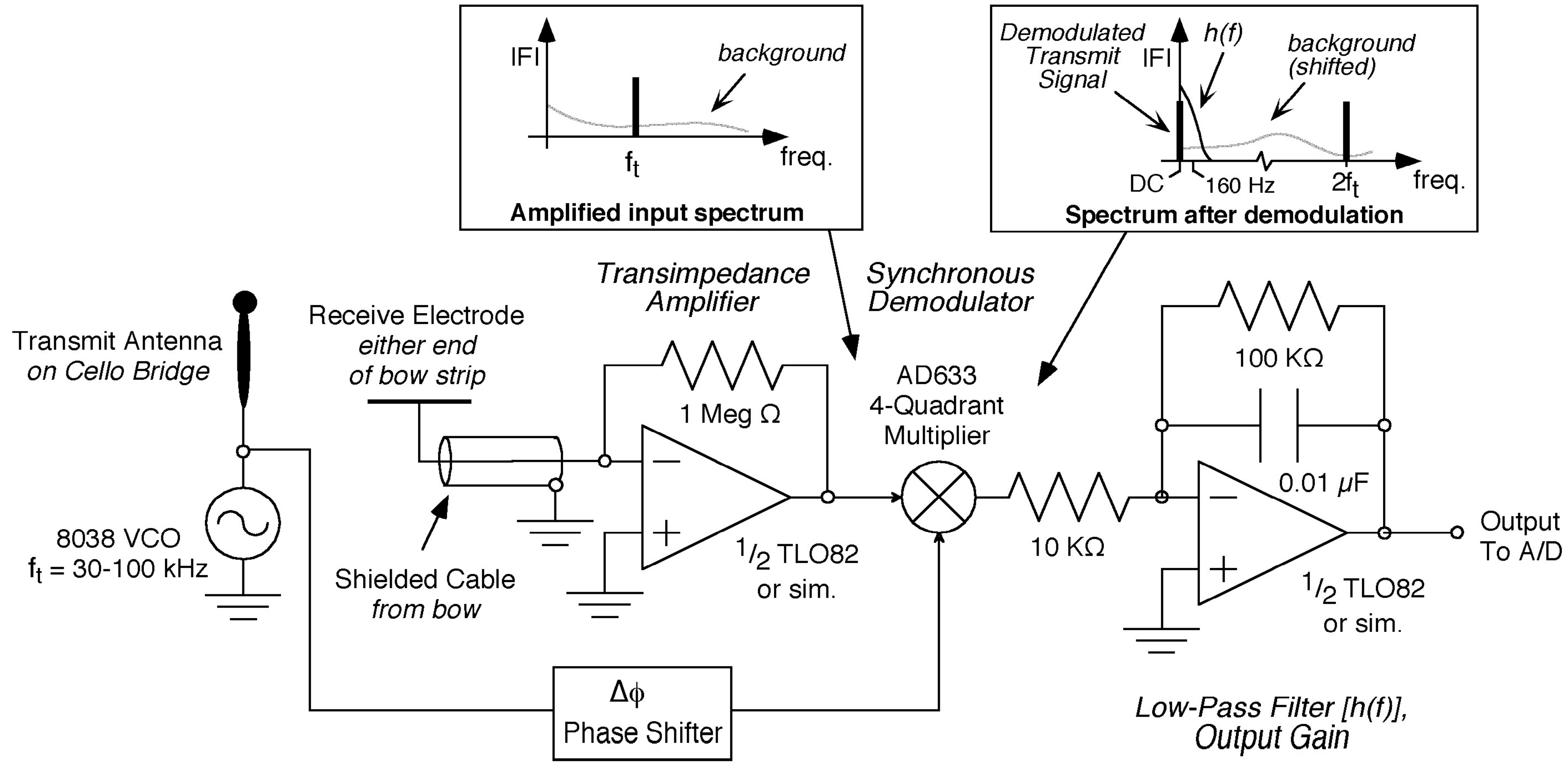
Simple Wideband Detection

Phase for Hi-Z is low - Phase for transimpedance is 90°
Phase can vary with cable loading, etc…



Wideband detector doesn't eliminate out of band noise
All spectrum is detected.

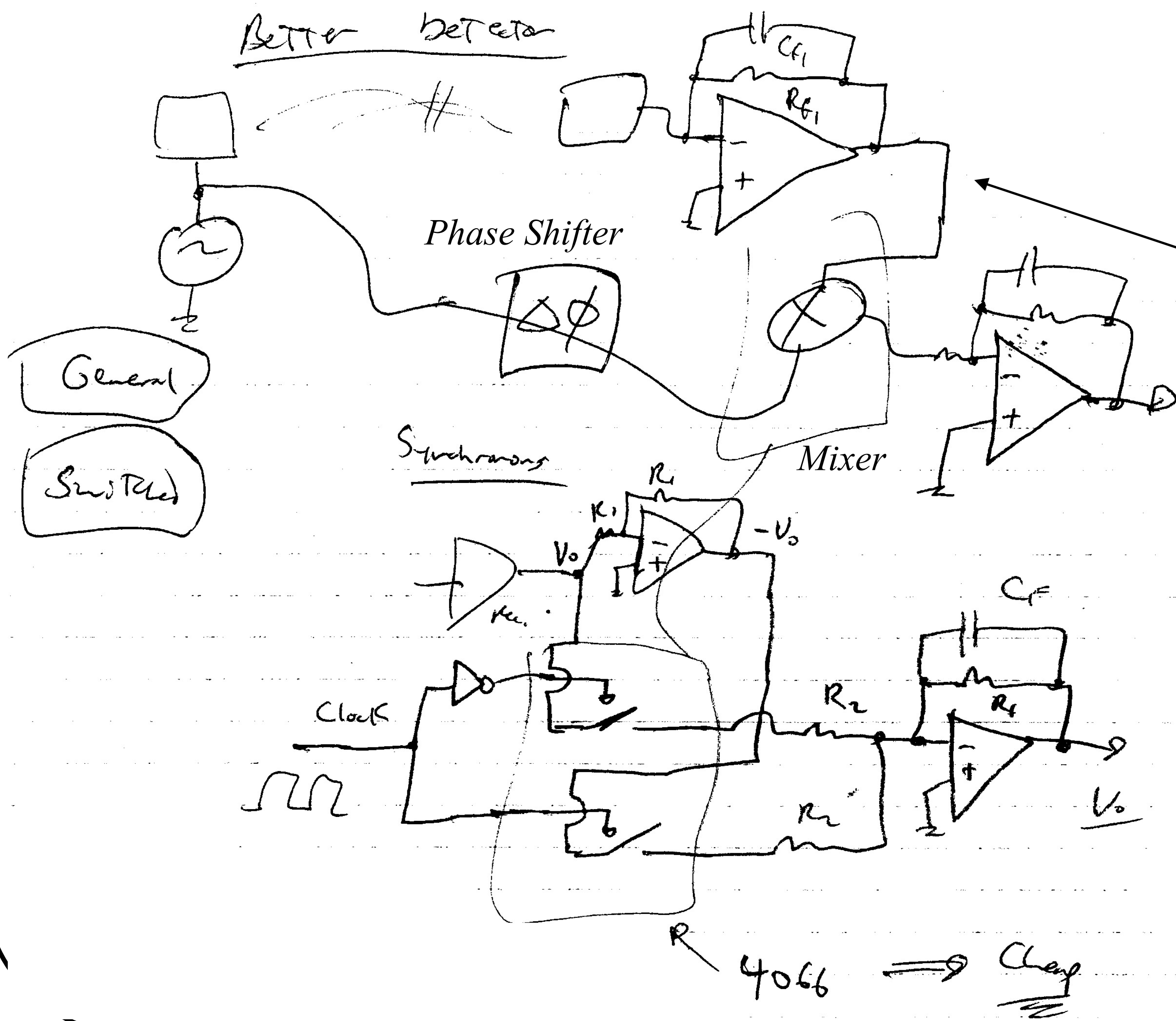
Cello Readout Channel



- **Synchronous "Lock in" amplifier looks only at the transmit frequency**
- **Demodulates to DC**
- **Very inexpensive (few $/channel)**
- **Used for GEM stretched wire R&D!**

Max Mathews (Radio Drum) - Bob Boie (Bell/BNL)

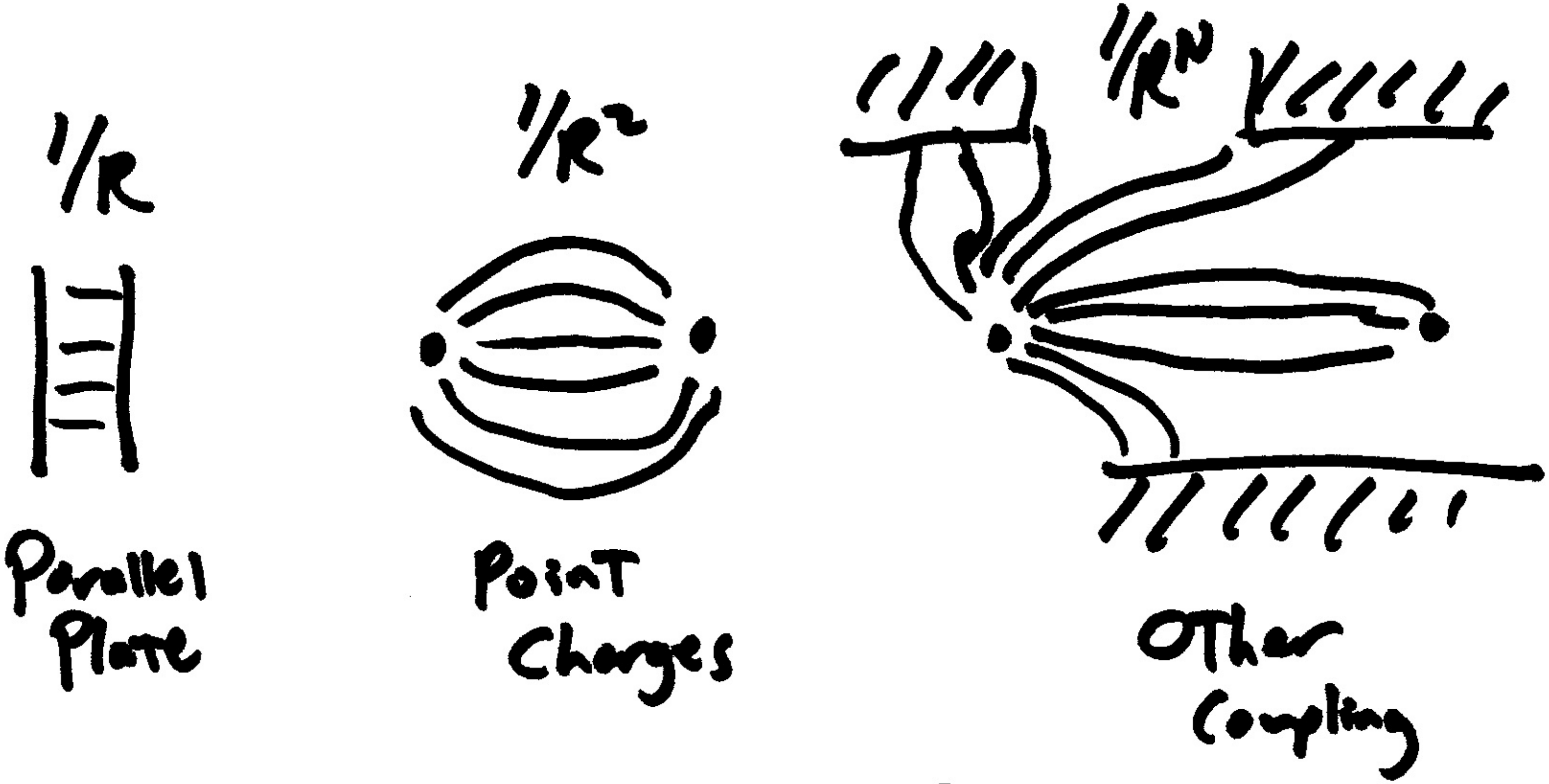
Synchronous Detection



Note: synchronous detection works only if signal stays linear (and doesn't saturate).
A bandpass filter can be inserted here to limit noise sensitivity

Mixer can be switched system as at left, or 4-quadrant multiplier like an AD633

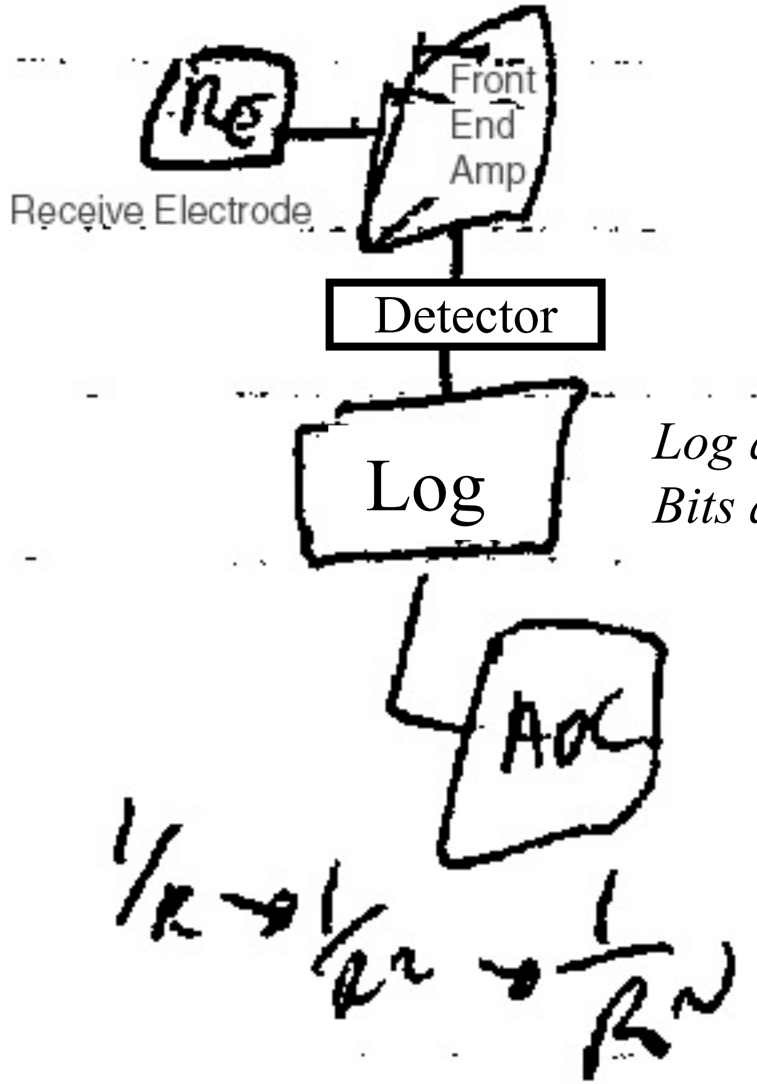
EFS Coupling Dropoff with Range



EFS Coupling $\sim e^{-R}$

Most bits are used up at very short range…

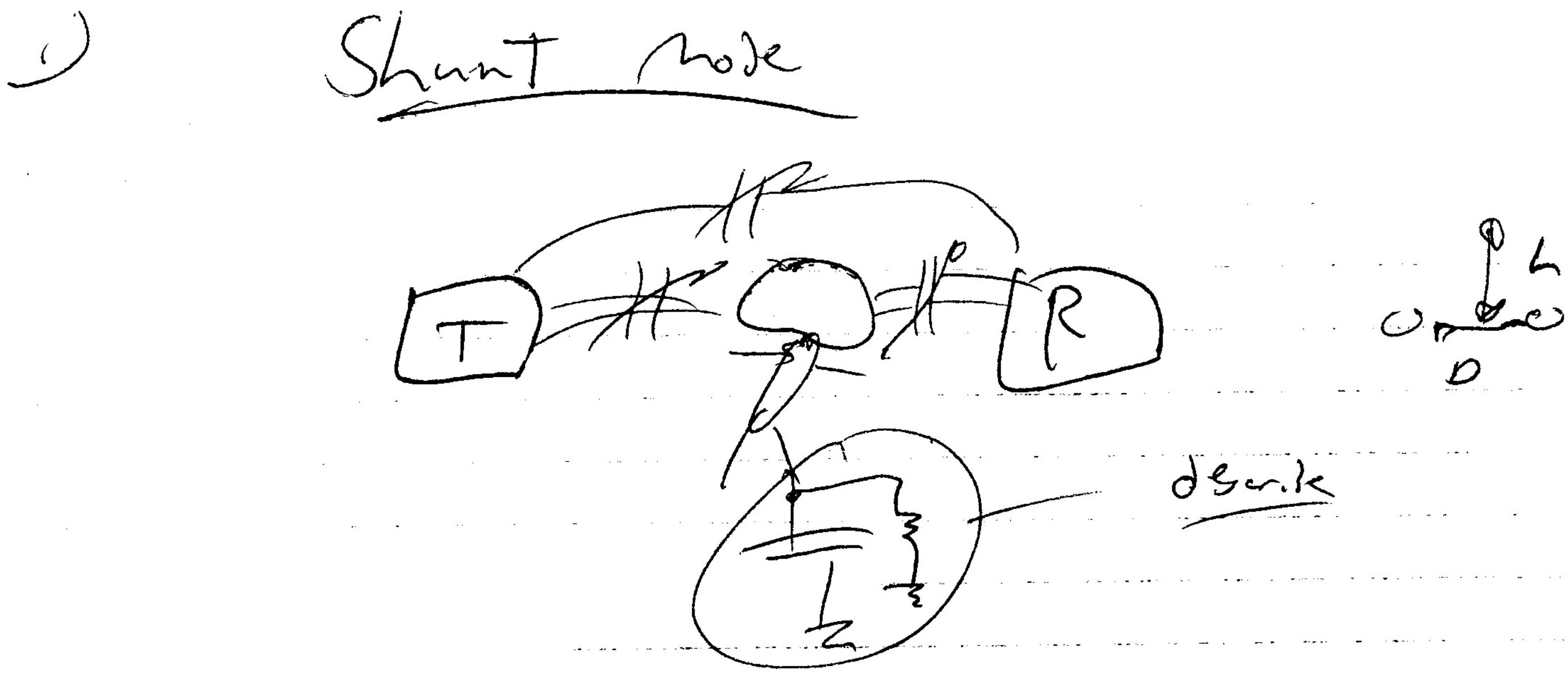
The Sensor Chair



Log amp linearizes range response
Bits are distributed linearly

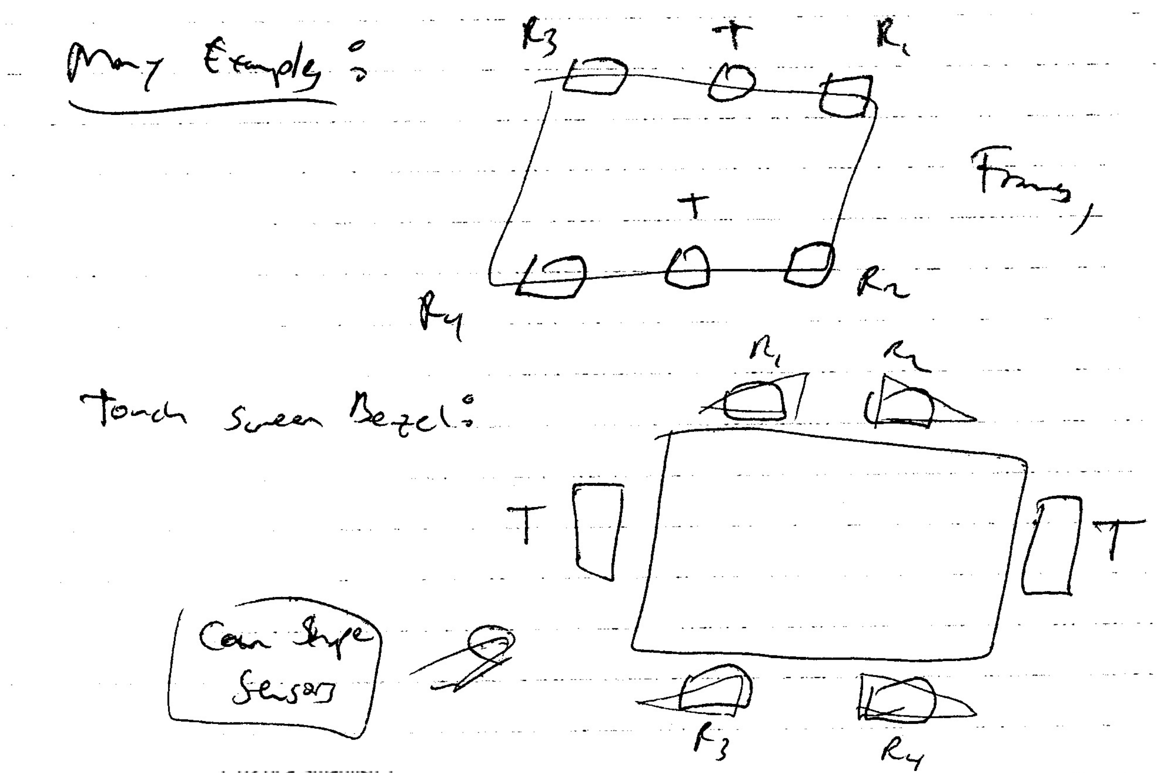
Parallel Plate to point-point to incremental flux leakage means:
Exponential falloff in received signal with range

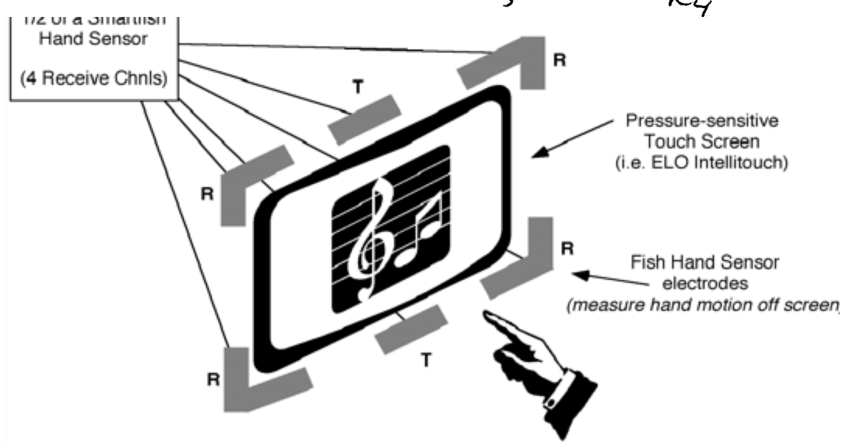
Shunt Mode



- Don’t need object strictly connected to ground
  - Ambient capacitive ground coupling usually OK
- EF ‘shadow’ cast between T and R
  - Detected signal goes down!
- Can intrinsically shape sensitive region between T & R
  - L ≈ D
- Any electrode can be T or R
  - EF tomography

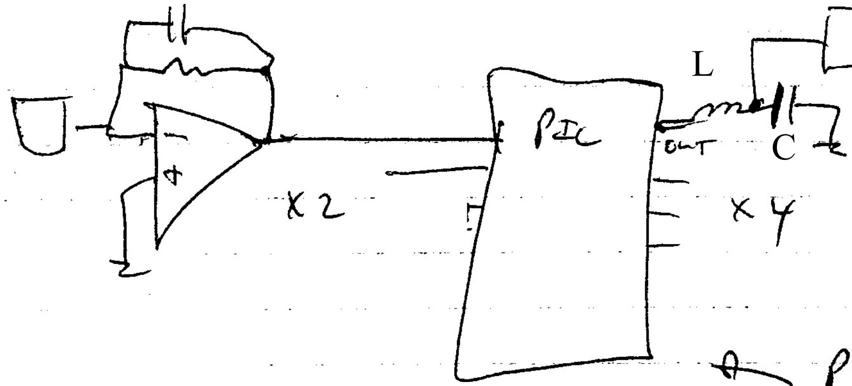
Shunt Mode Examples





The LazyFish

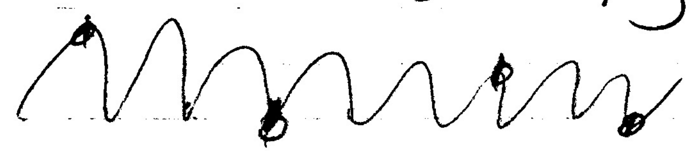
Lazy Fish ~ Josh Smith ('97--)



LC gives voltage boost

Later version used 4x Transceiver

→ PIC Rings up LC, Then does Synchronous Subsampling



— Subtracts ⊕ from ⊖ and averages

⇒ Need To smaller entire +→- dynamic range of received waveform [waste bits for smaller range of C] ~ Shunt mode!

⇒ Gain bits back by averaging ($\sqrt{N}$)

⇒ Minimal Components

⇒ Comb filter response [allows noise @ Nf_s] ⇒ Narrowband!

See: http://web.media.mit.edu/~jrs/efs.html

Technology Trajectory...

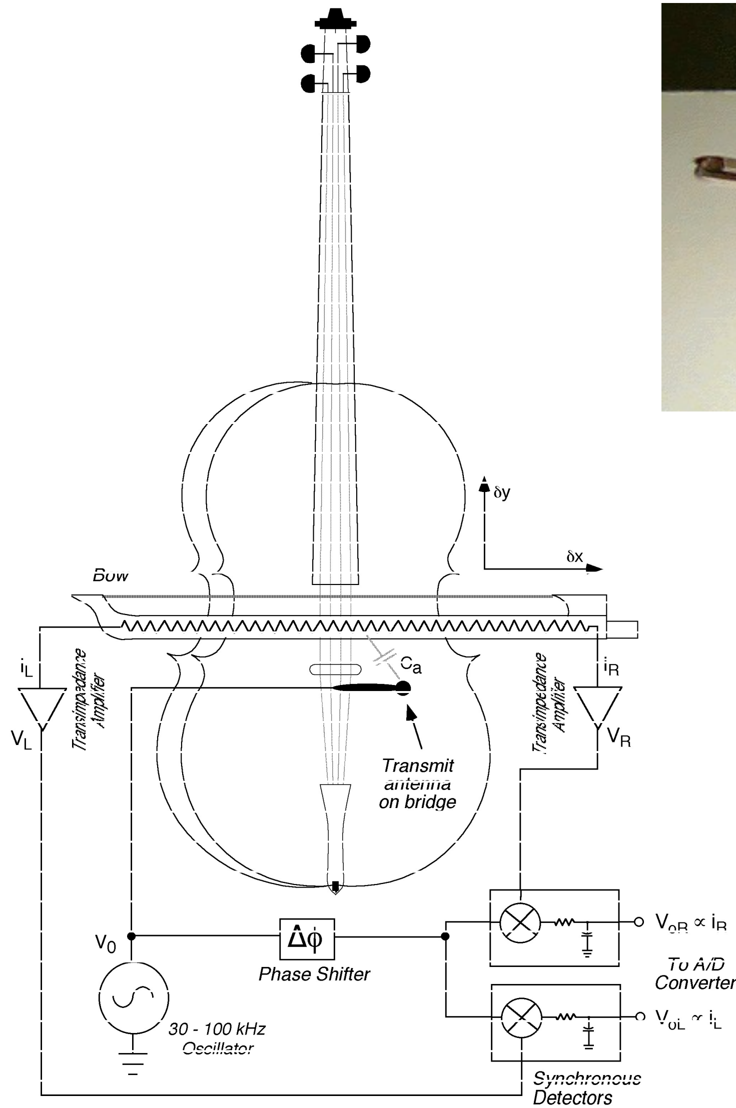
Case Study in Conceptual Drift at the MIT Media Lab…

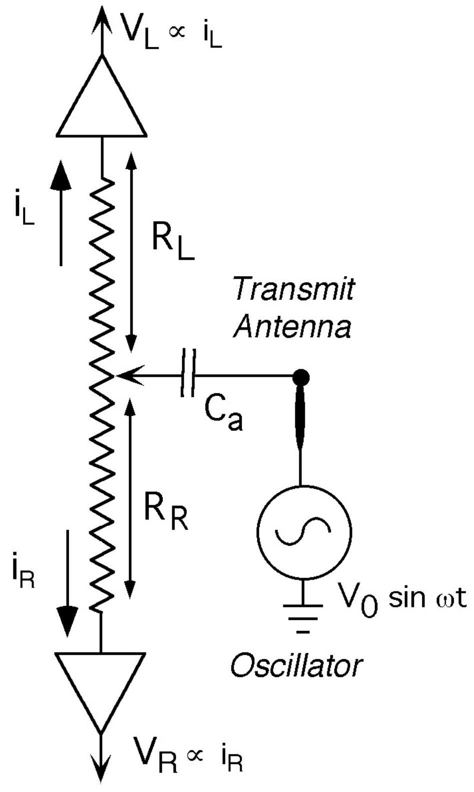
Electric Field Sensing

1991-2003

See: http://www.media.mit.edu/resenv/pubs/papers/96_04_cmj.pdf
http://www.media.mit.edu/resenv/pubs/papers/98_02_CGA_Final.pdf
http://web.media.mit.edu/~jrs/phd.pdf

Cello Bow Sensors - 1990





$f_t \cong 100$ khz

$\lambda \cong 2$ miles

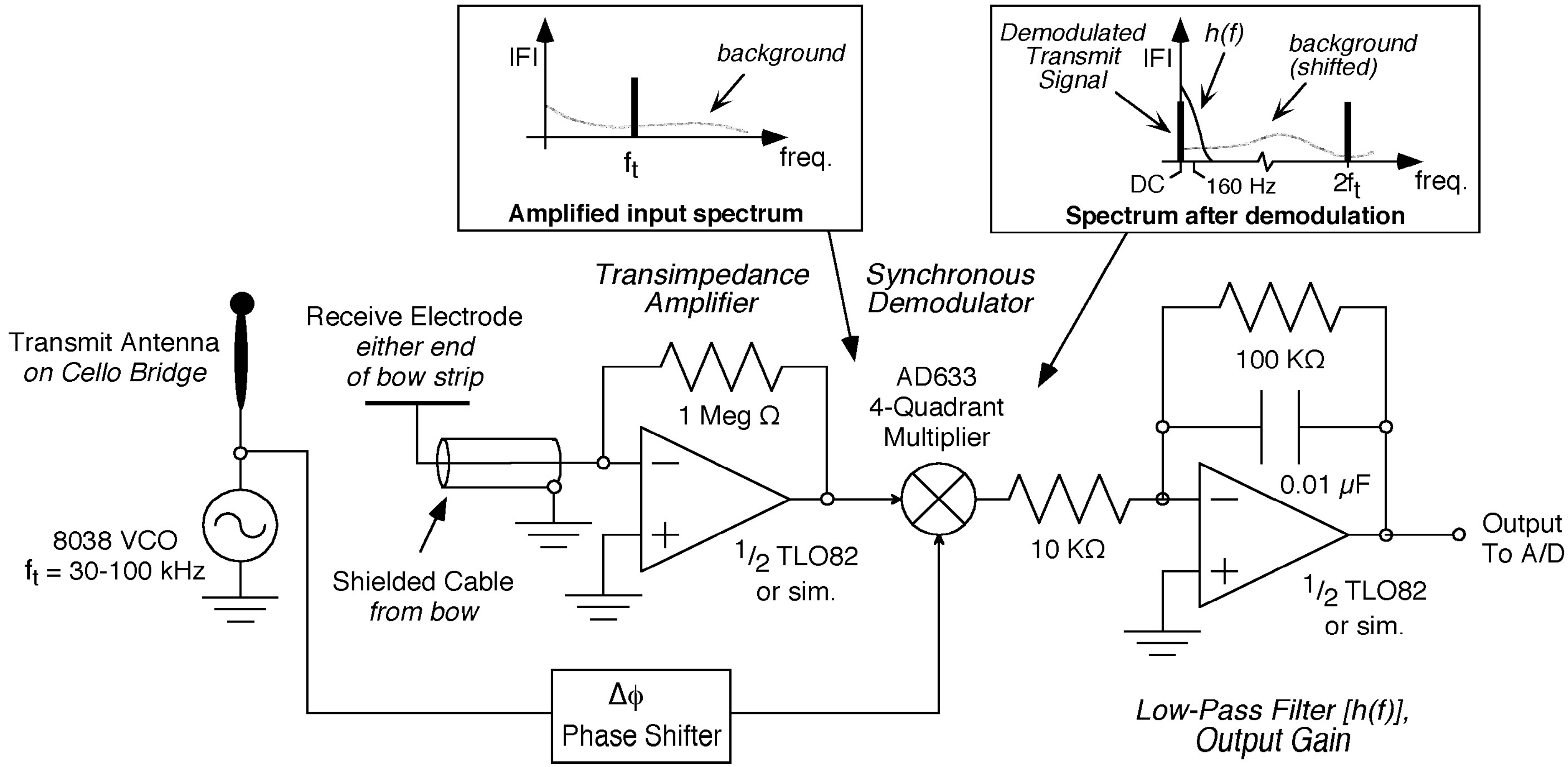
↓

Transmit antenna capacitively couples into bow electrode

$y = f(V_L + V_R)$

$x \propto V_L - V_R$

Cello Readout Channel



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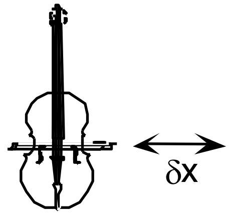
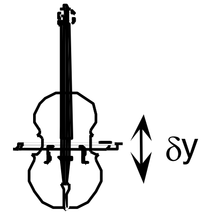
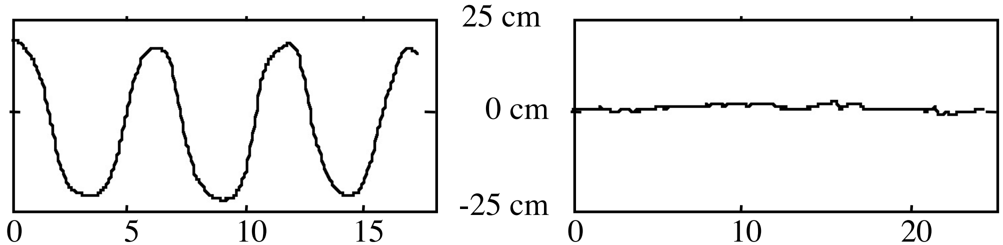
Cello Bow Position Measurements



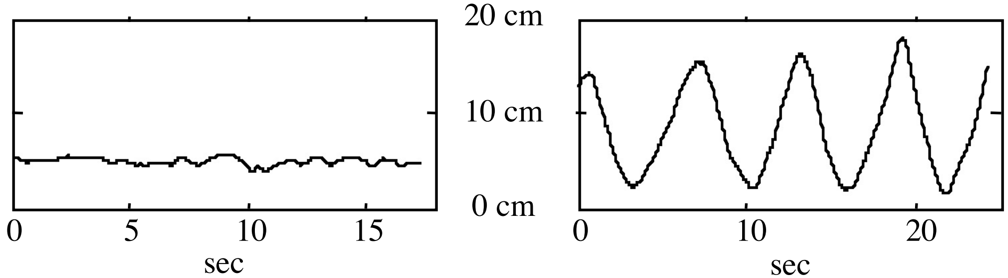
Lateral Bow Motion



Longitudinal Bow Motion



Pickup Signals; Difference over Sum (Eq. 2)

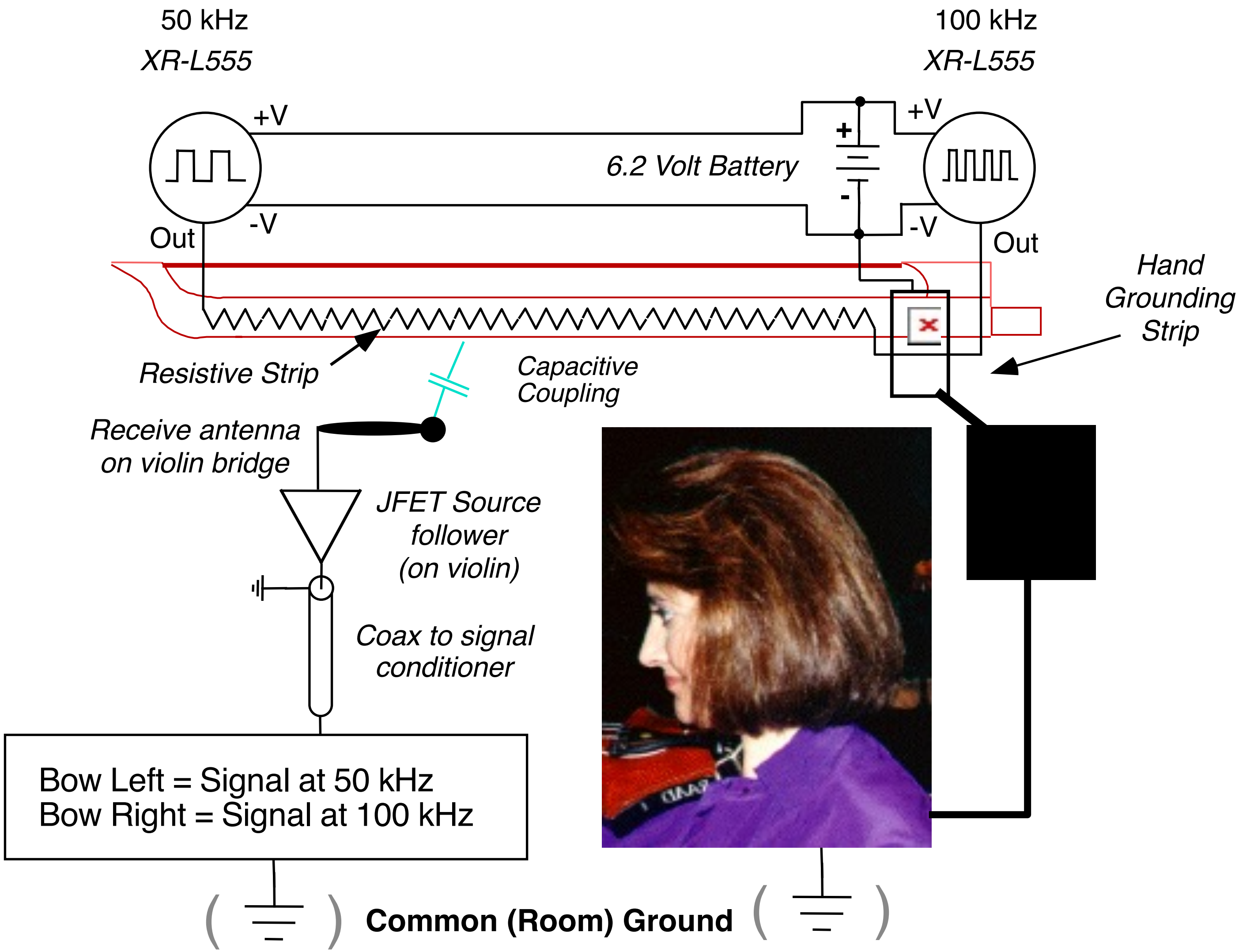


Pickup Signals; Inverse Sum (Eq. 3)

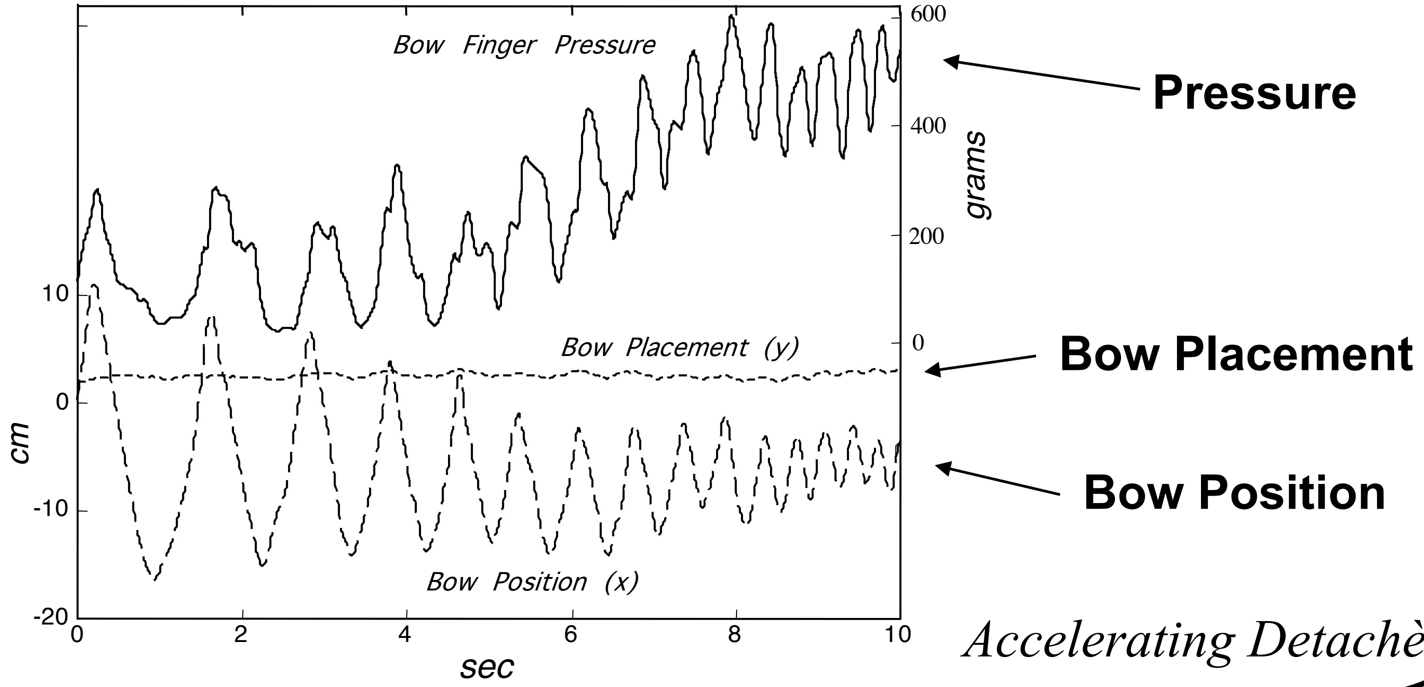
$$\frac{i_L - i_R}{i_L + i_R} = \frac{R_R - R_L}{R_R + R_L} = \frac{(R_0 + \alpha x) - (R_0 - \alpha x)}{(R_0 + \alpha x) + (R_0 - \alpha x)} = \alpha \frac{x}{R_0}$$

$$\frac{1}{i_R + i_L} = \frac{1}{V_0}\left[\frac{R_L \; R_R}{R_L + R_R} + \frac{1}{j\omega C_a}\right] \approx \frac{1}{j\omega C_a V_0} \propto \frac{y}{j\omega V_0} \quad (\textit{for small } y)$$

Wireless Violin Bow Sensors - 1993



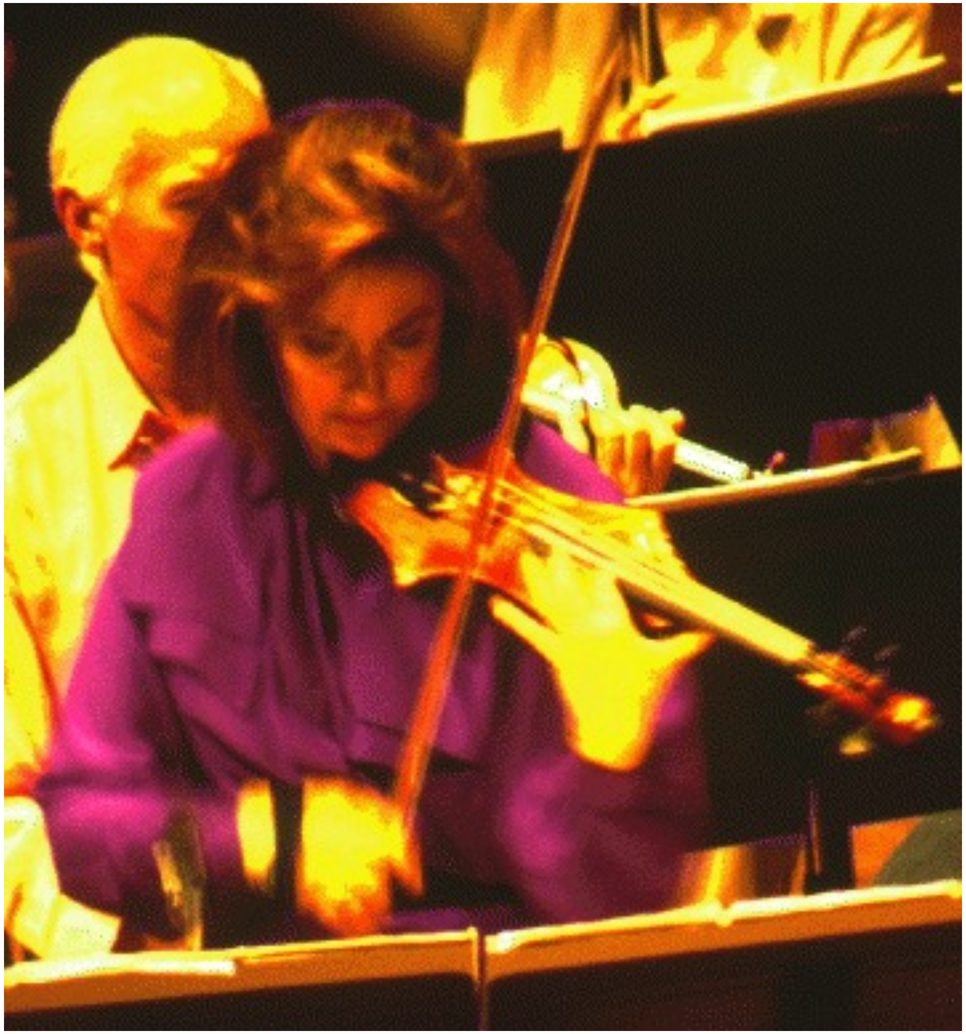
Wireless Violin Bow Performance



Accelerating Detachè

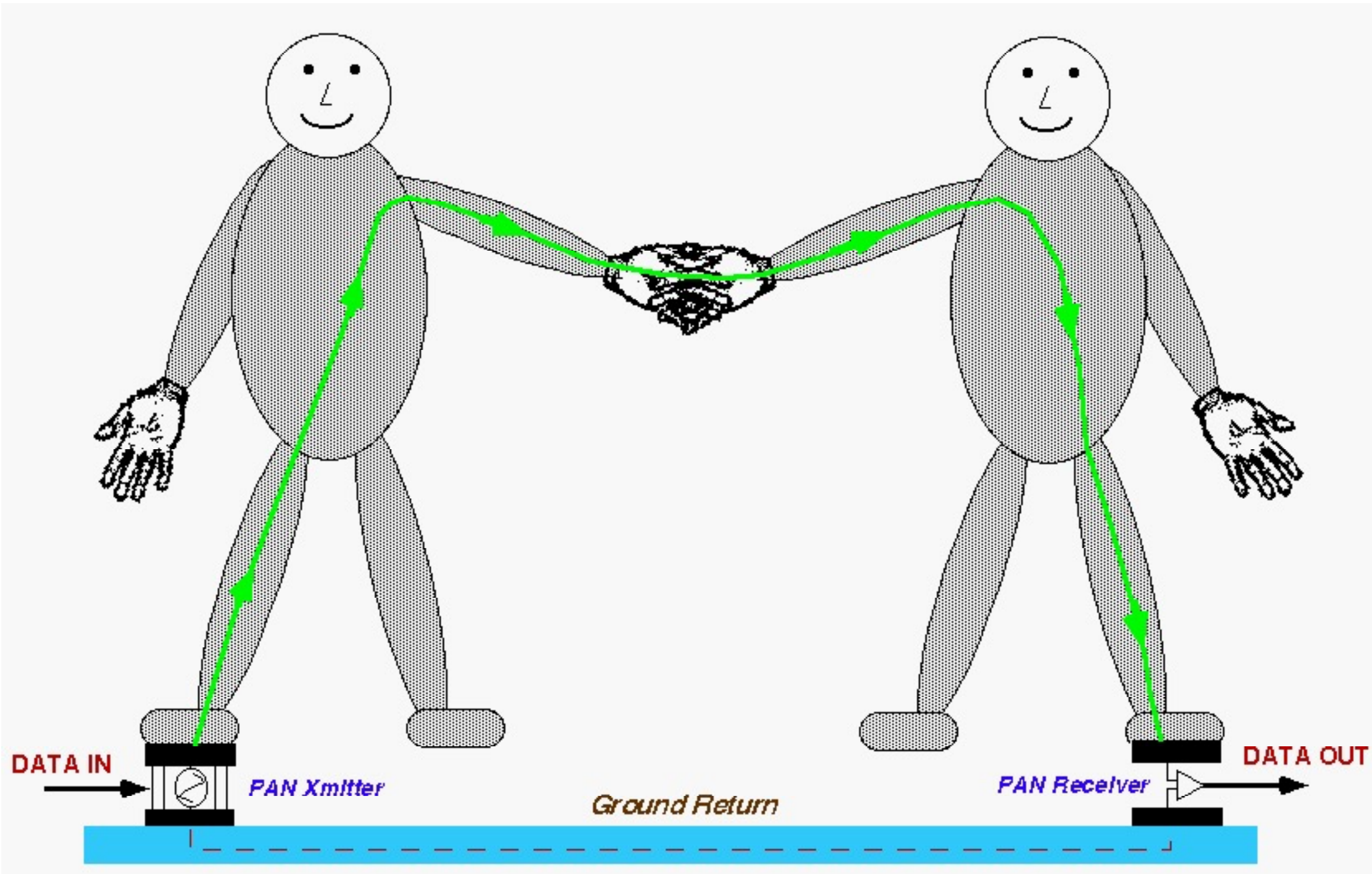
Performance Debuts

Yo-yo Ma; August 14, 1991
Tanglewood



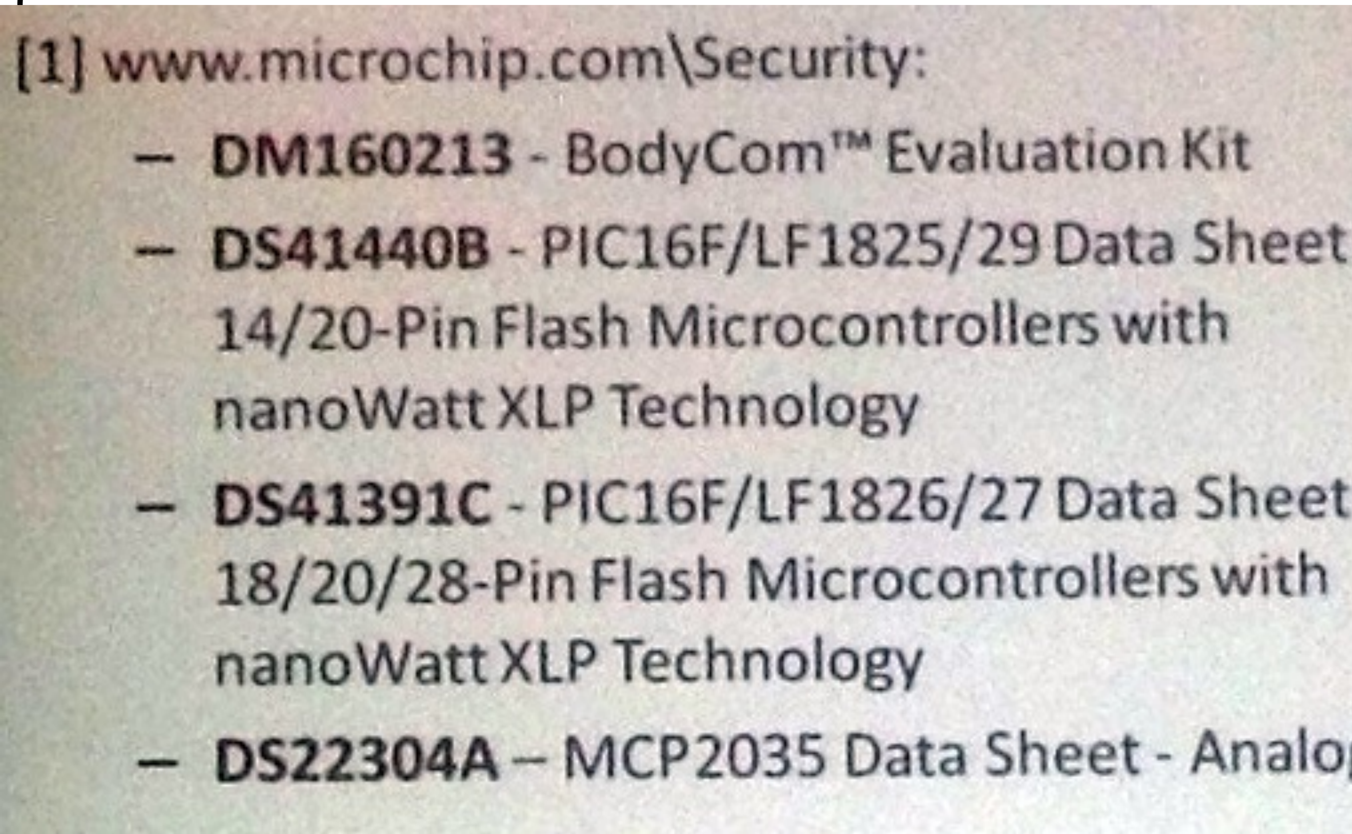
Ani Kavafian; September, 1993
St. Paul, MN

The PAN Handshake - 1995

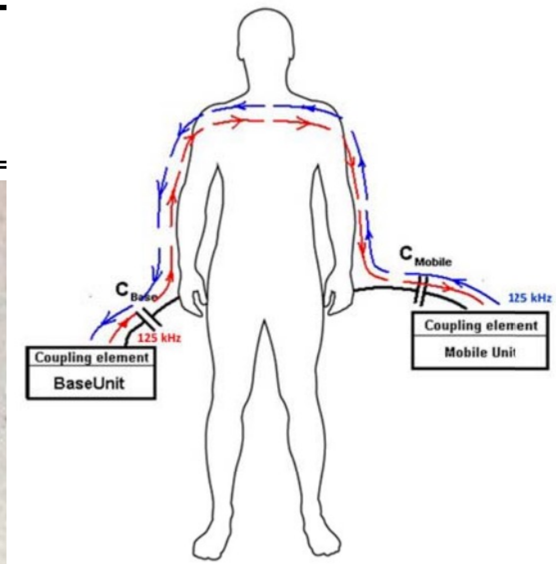


PAN Demo circa 1995

Commercial Dev Kit


[1] www.microchip.com\Security:

- **DM160213** - BodyCom™ Evaluation Kit
- **DS41440B** - PIC16F/LF1825/29 Data Sheet 14/20-Pin Flash Microcontrollers with nanoWatt XLP Technology
- **DS41391C** - PIC16F/LF1826/27 Data Sheet – 18/20/28-Pin Flash Microcontrollers with nanoWatt XLP Technology
- **DS22304A** – MCP2035 Data Sheet - Analog Front End Device



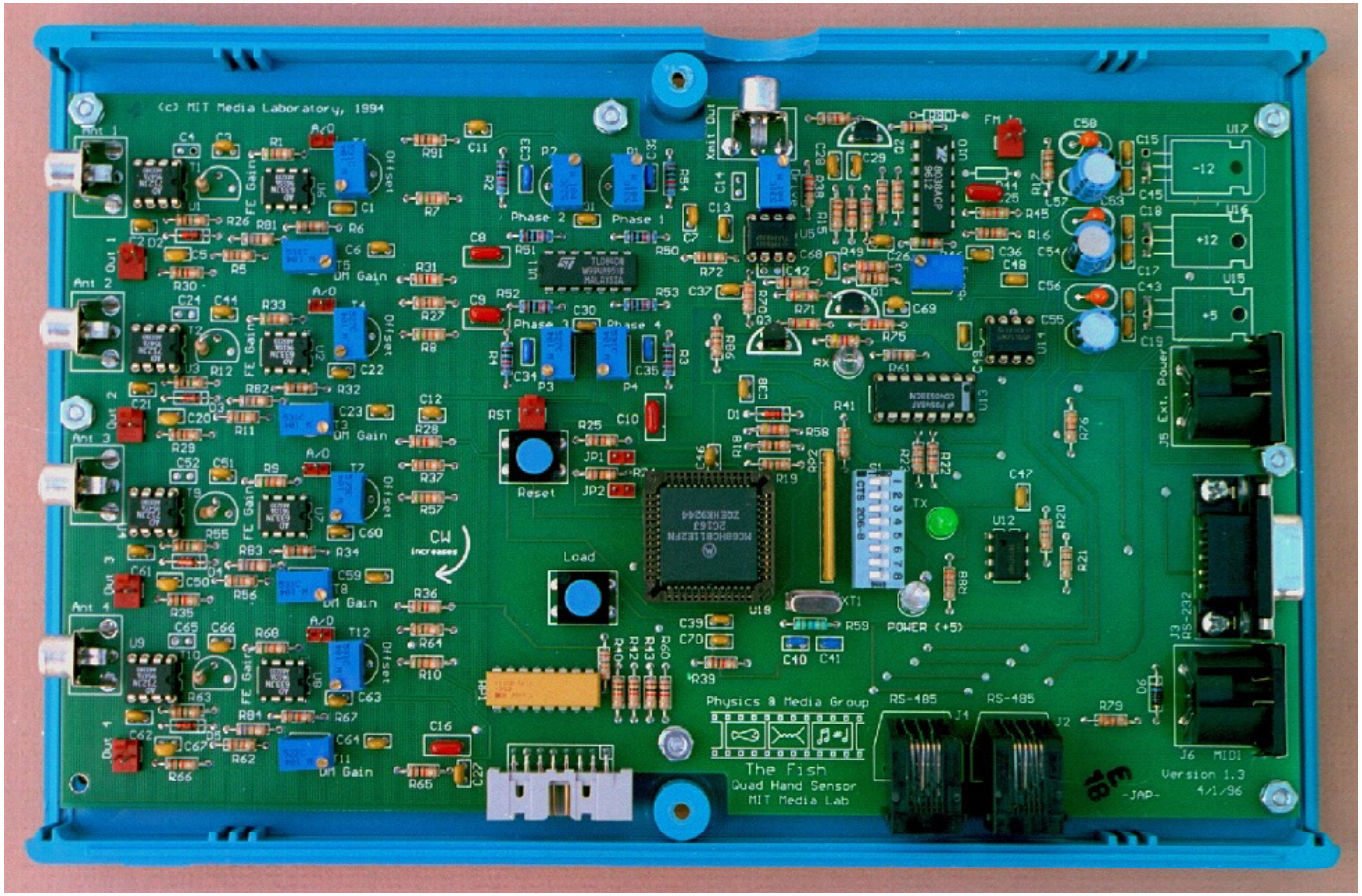
- PAN Development kit from Microchip
  - They call it 'BodyCom' - http://ww1.microchip.com/downloads/en/AppNotes/00001391C.pdf

Motorola BiStatix Tag

- Use Electric (as opposed to magnetic or RF) fields to power and read tag
  - Inexpensive (no coil needed, printed antenna)
  - Airline luggage tags, postal applications, etc.

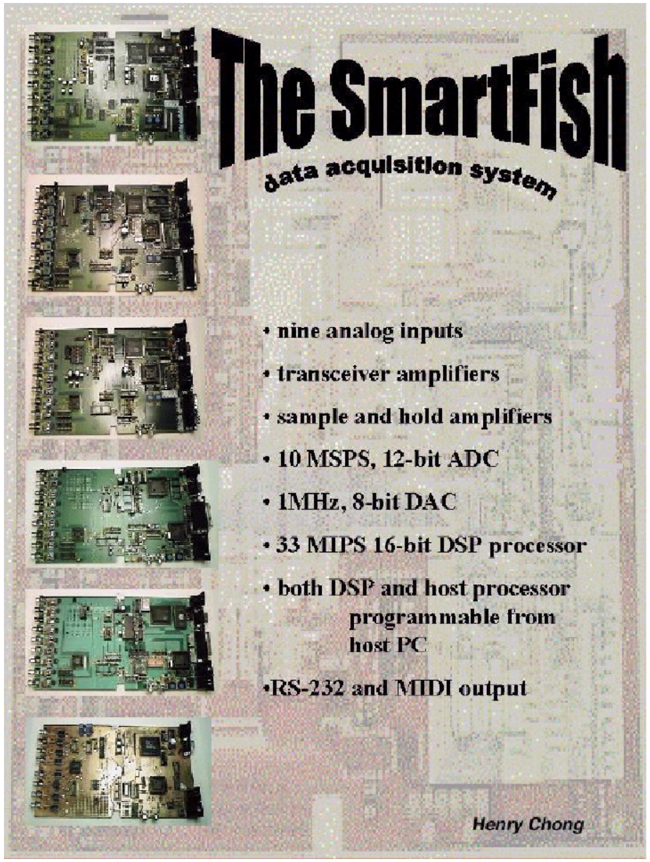
The Fish Classic

Hundreds Served!
Paradiso & Zimmerman, 1994



- 4 channels of gesture sensing (current amp & synchronous demodulation)
- Onboard VCO, 20-100 kHz
- 68HC11 CPU (digitizes 4 sensor outputs & 4 external inputs)
- RS-232, RS-485, MIDI, parallel user port

The Spawn...

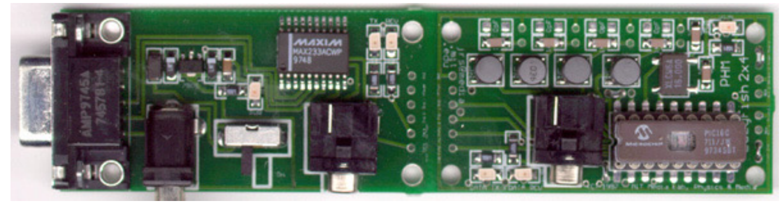


The SmartFish

Henry Chong, 1996

- 9 transceive channels
- Mhz throughput, programmable DSP
- Gobs of features, Expensive...

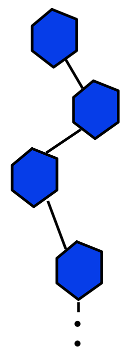
⇨ *RIP!*

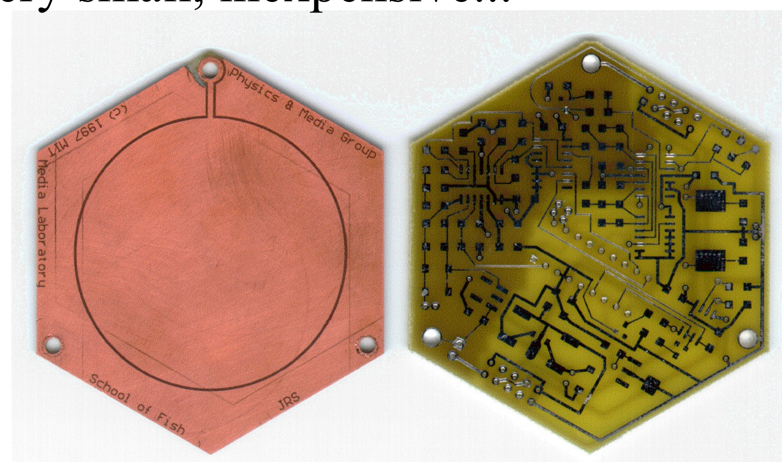


The LazyFish

Josh Smith, 1998

- 4 Transmit channels, 2 Receive
- Synchronous undersampling in PIC
- Very small, inexpensive...



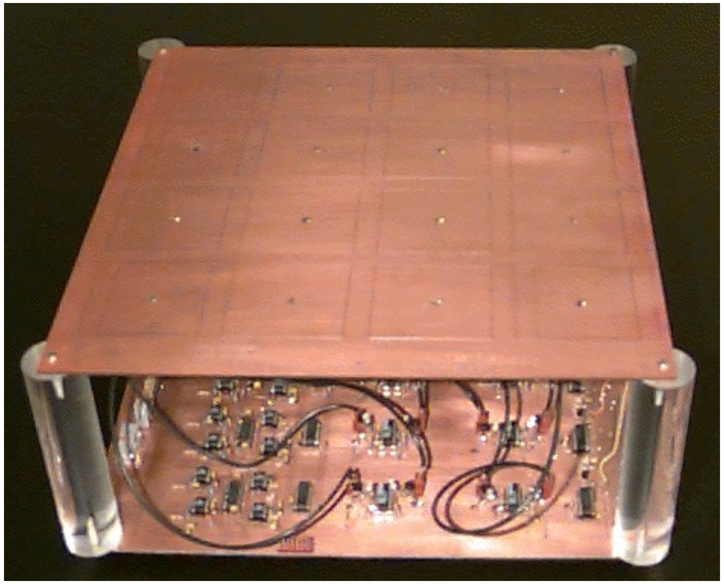


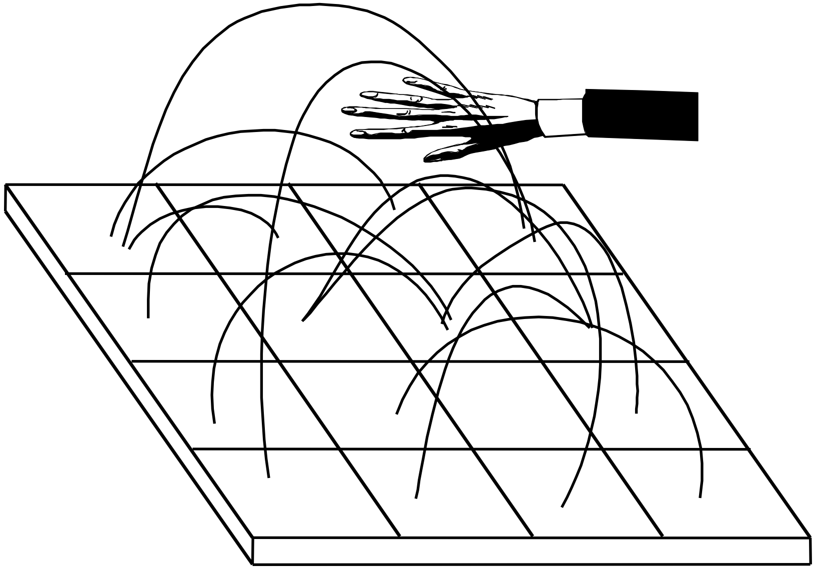
The School of Fish

Josh Smith, 1997

- Smart Electrode
- Daisy-chained RS-485 bus
- Generic topologies, “imaging”

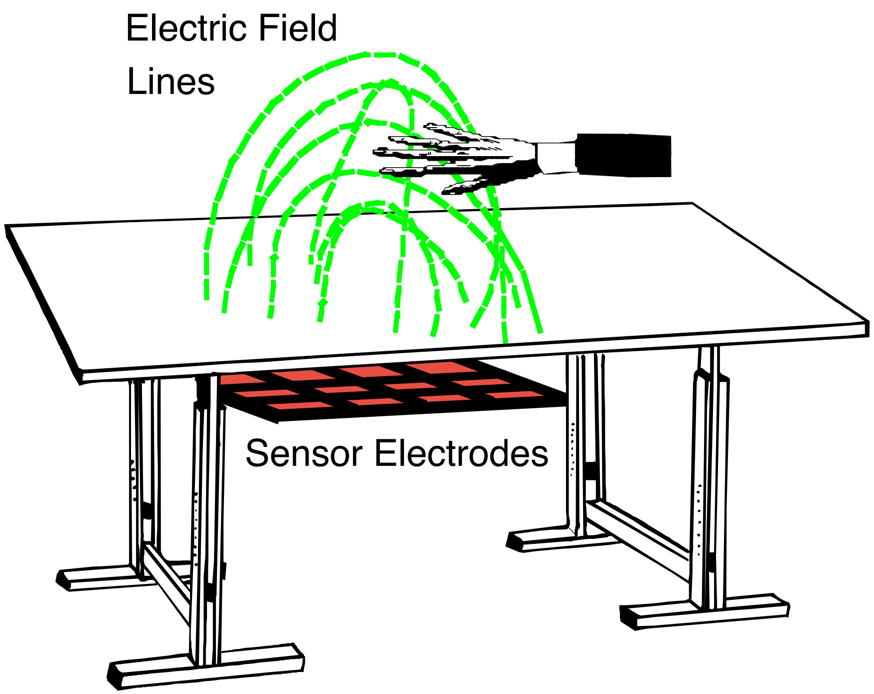
Electrostatic Tomography

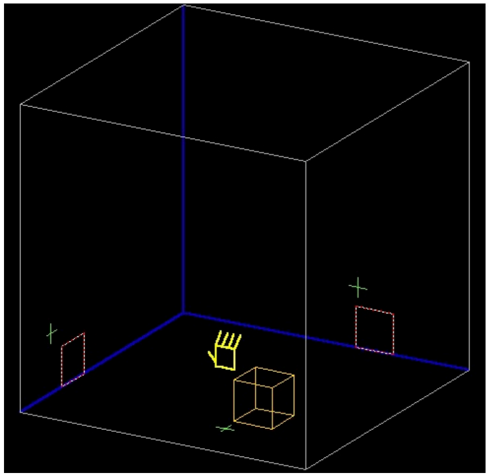




- **Have constructed an expandable array of 4 x 4 transceiver electrodes**
  - Can transmit and receive dynamically from any combination
- **Extra information enables system to begin to image**
  - Electrostatic tomography techniques now being applied (Josh Smith)
  - **Not possible through standard "loading mode" techniques**
- **(lensless focal plane array)**
- **Tables can see what's on top...**

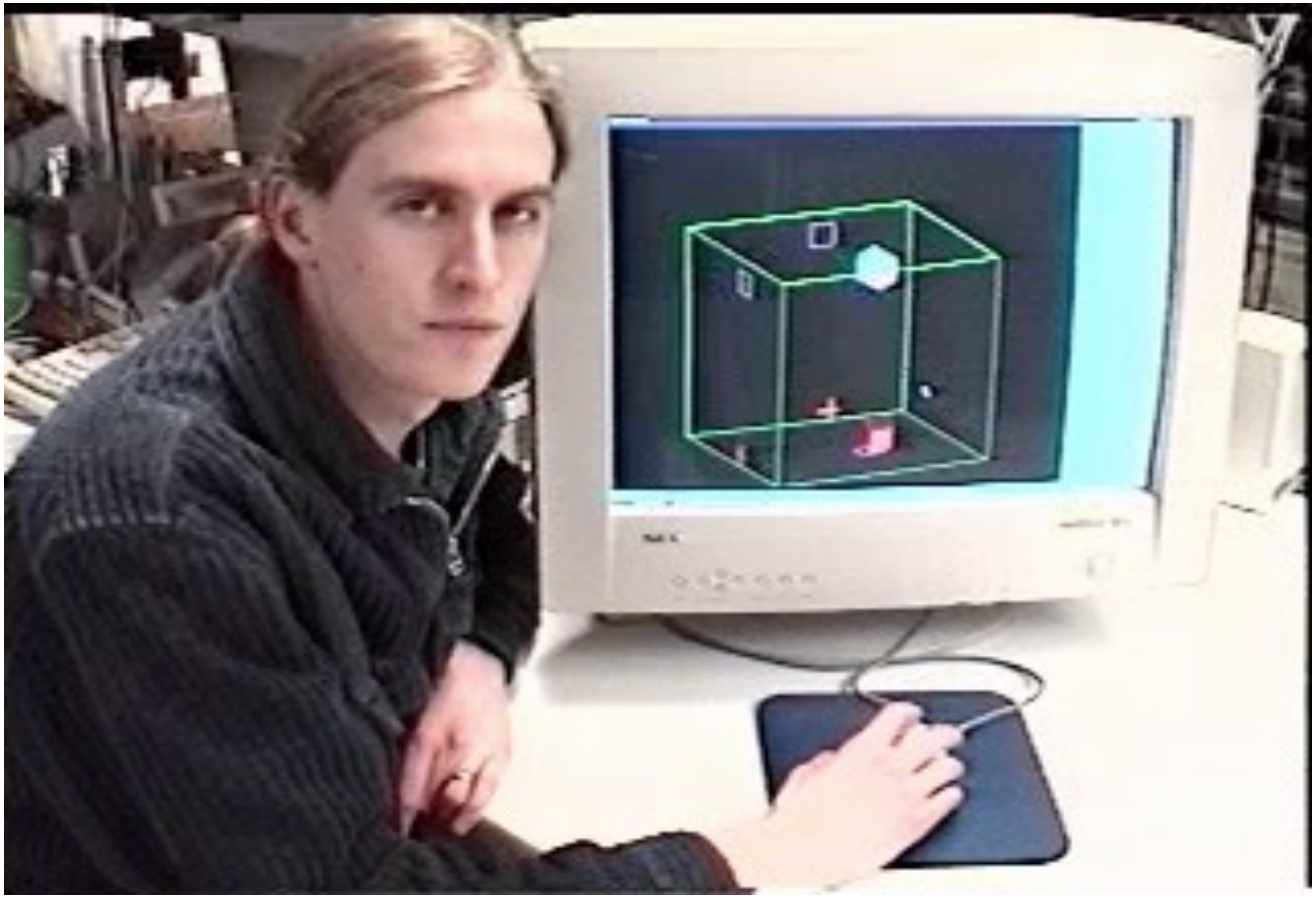
Smart Tables



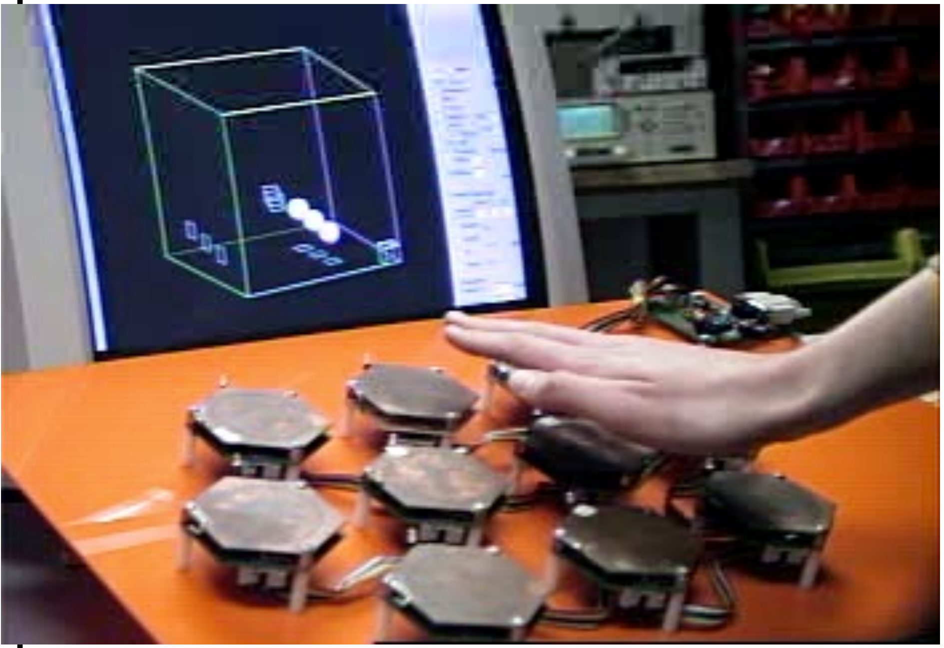


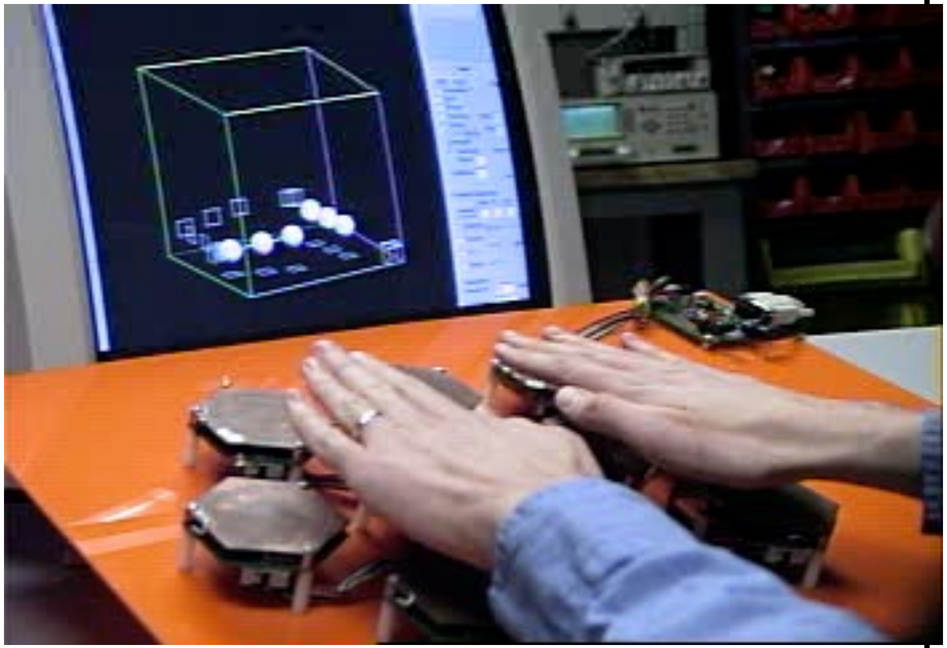
Electrodes under table can "image" above

Embedded LazyFish (JRS)



Josh Smith Tomography Demos

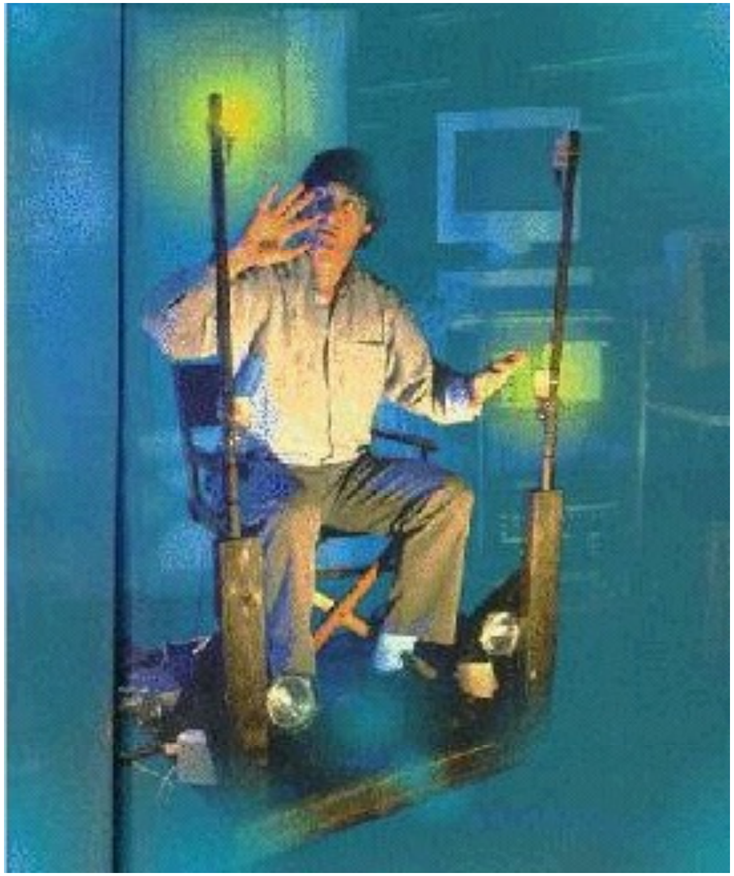


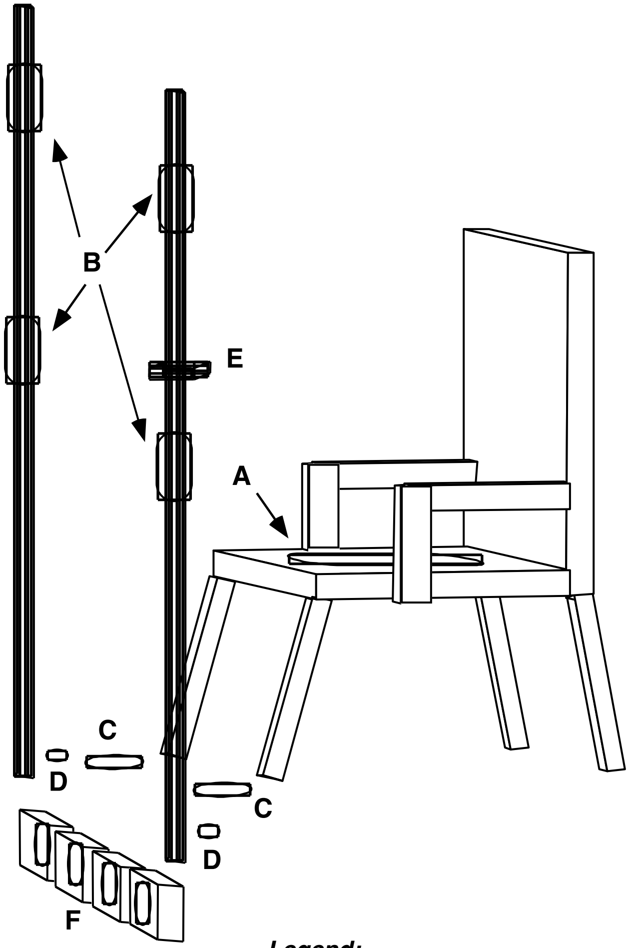


Tom White's EFS applications

- Search through watch catalog (Swatch)
- Two-handed navigation (Pin the Tail…)

The Penn and Teller Spirit Chair - 1994



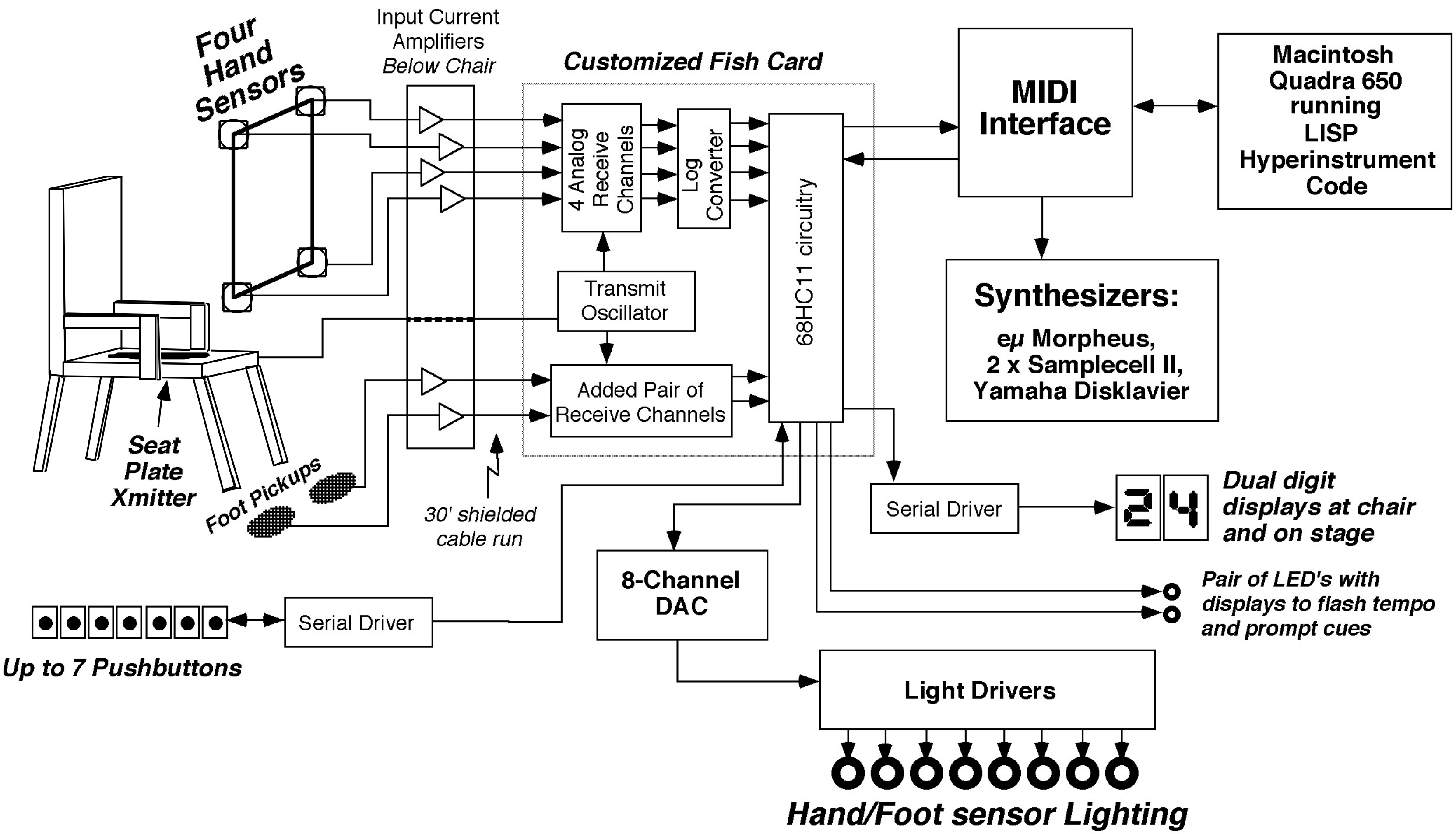


Legend:

A: Copper plate on chair top to transmit 70 kHz carrier signal
B: Four illuminated antennas to sense hand positions
C: Two antennas to detect left and right feet
D: Two pushbuttons for generating sensor-independent triggers
E: Digital display for computer to cue performer
F: Four lights under chair platform, nominally controlled by foot sensors

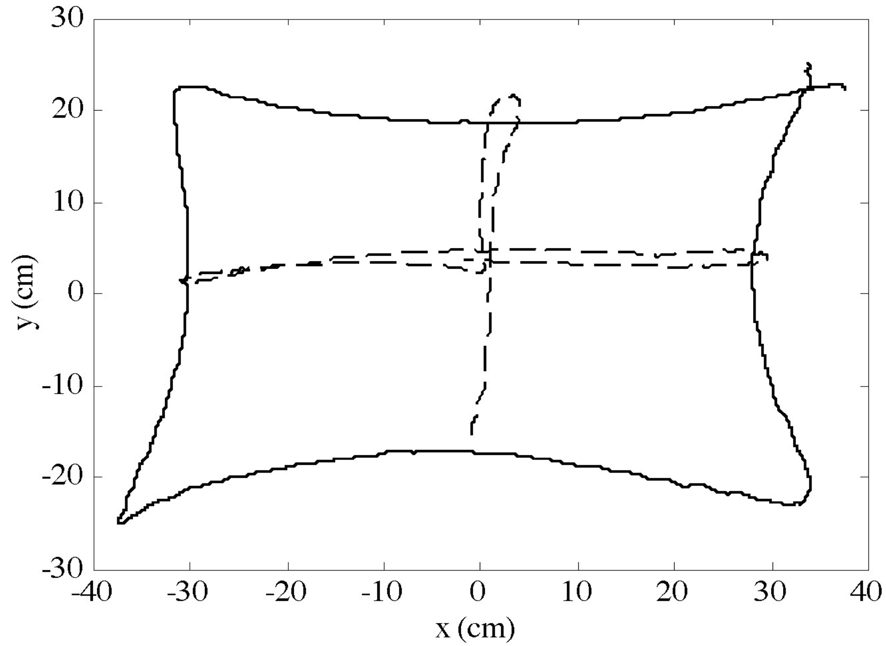
Transmit Mode

The Spirit Chair Performance System

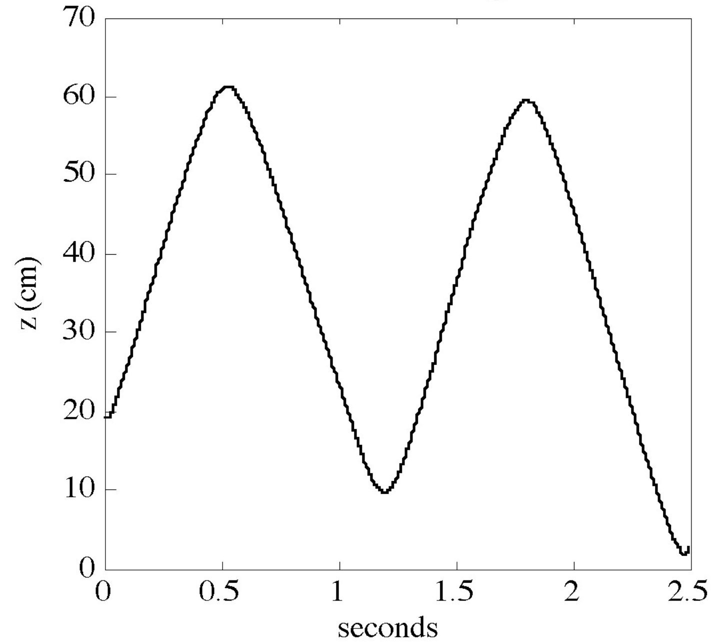


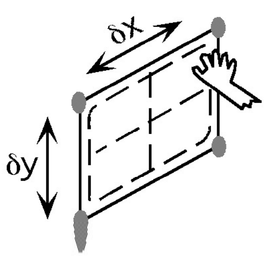
Reconstructed Hand Position

Reconstructed x,y from linear combination of sensor signals

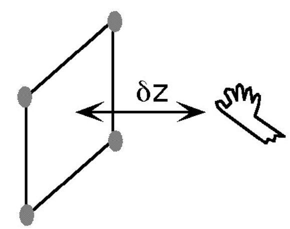


Reconstructed z from sum of all four sensor signals





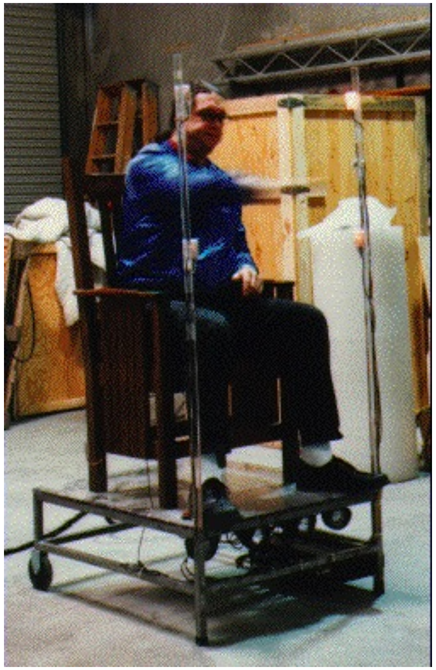
Hand motion around perimeter and through center of xy plane



Hand motion along z in and out of xy plane

- **After initial calibration (hand visits 9 points around sensing perimeter)**
- **Linear math (log amplifiers linearize proximity signals)**

MIT Crew at P&T Headquarters in Vegas; 9/94, 11/94, 12/94



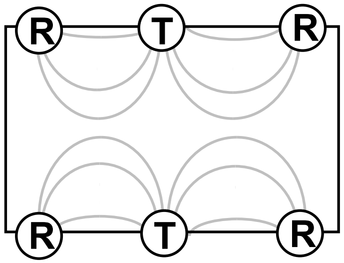
Debut at Digital Expression, Kresge Auditorium MIT

Media Medium

October, 1994

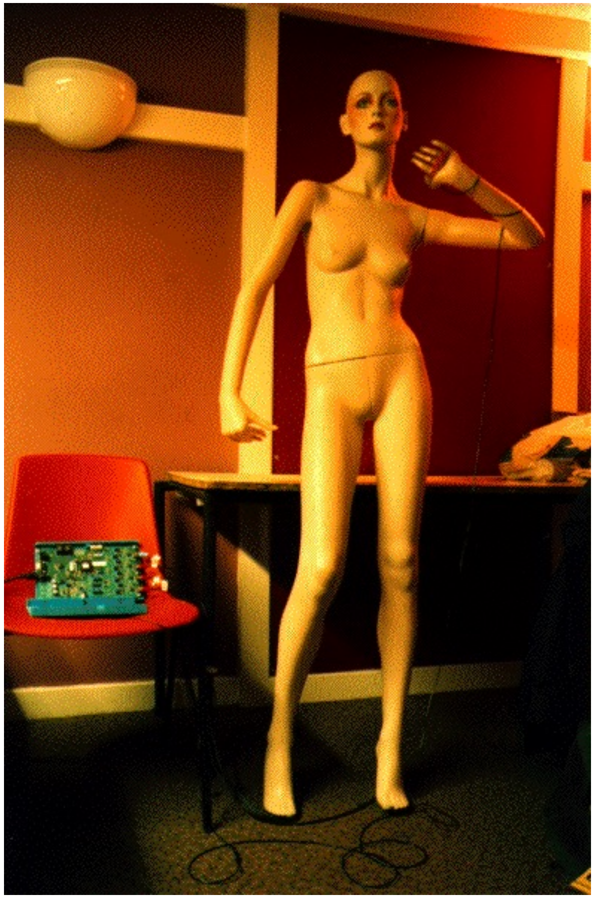
Showtime!!

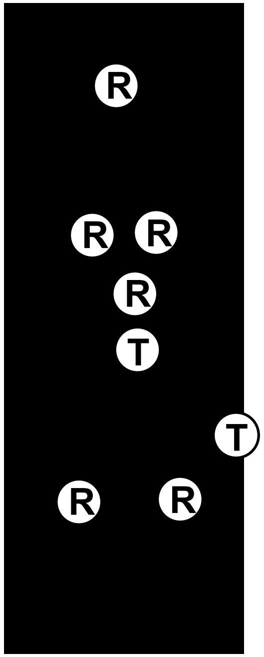
The Former Prince Wembley March '95



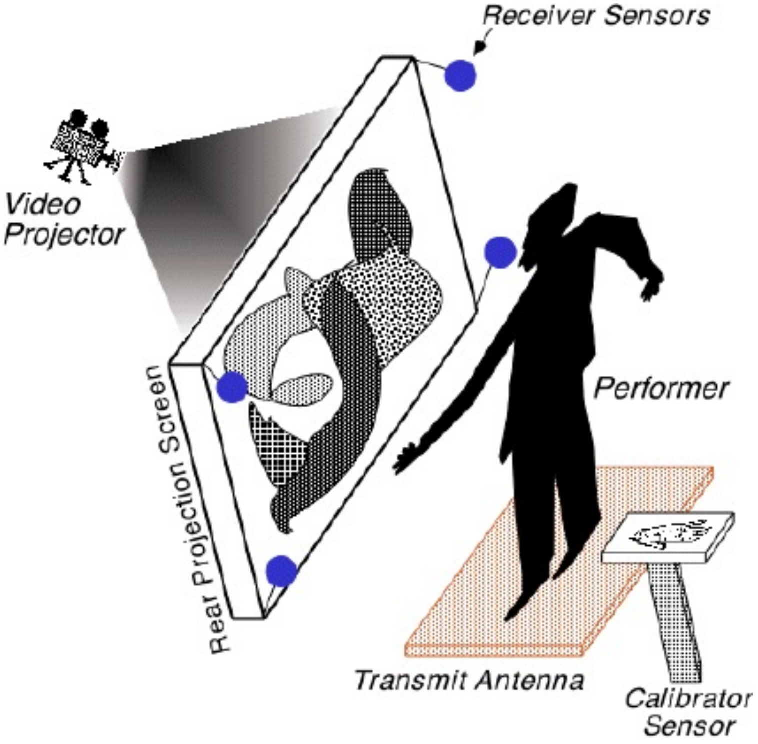
Dual shunt-mode frame

Shunt-mode Mannequin



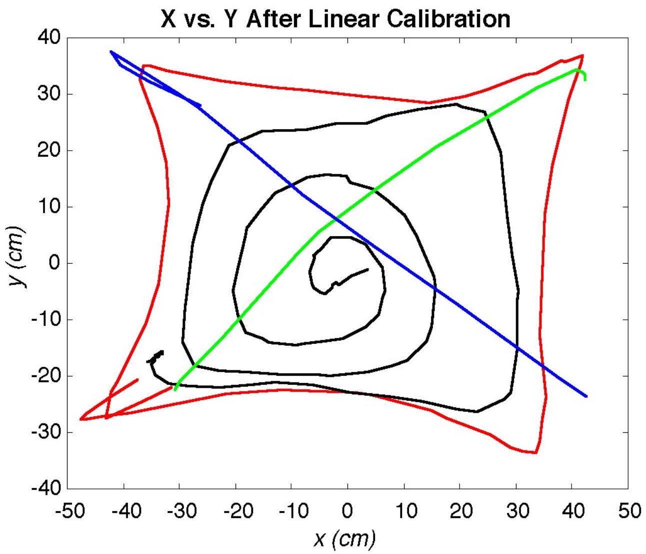


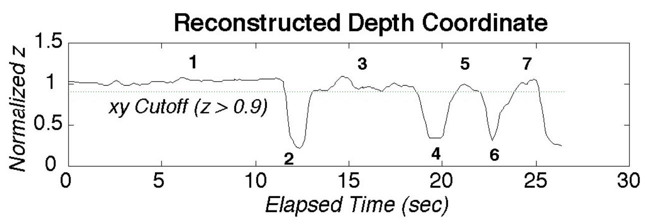
The "Gesture Wall"

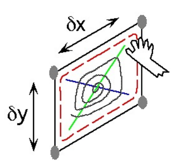


- User conducts music, graphics
- Capacitive sensing of body in front of projection screen
  - Transmit 50 kHz carrier into body through feet
  - Synchronously receive with 4 copper pickups around screen
  - Measures range to body at each pickup
  - Range measurements linear after log-amp conditioning
  - Sensitive to entire body, difficulty with both hands, calibrate shoes

Gesture Wall Performance

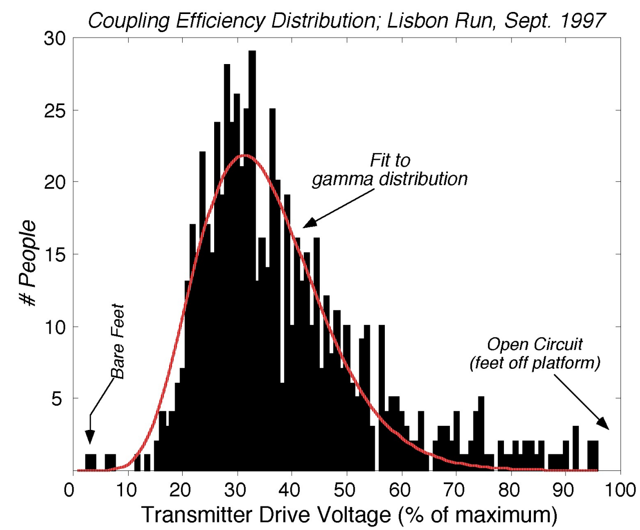






1 Hand approaches sensor plane and traces spiral
2 Hand pulled back
3 Hand approaches sensor plane and traverses perimeter
4 Hand pulled back
5 Hand traverses one diagonal
6 Hand pulled back
7 Hand traverses orthogonal diagonal

Drawing in the Air

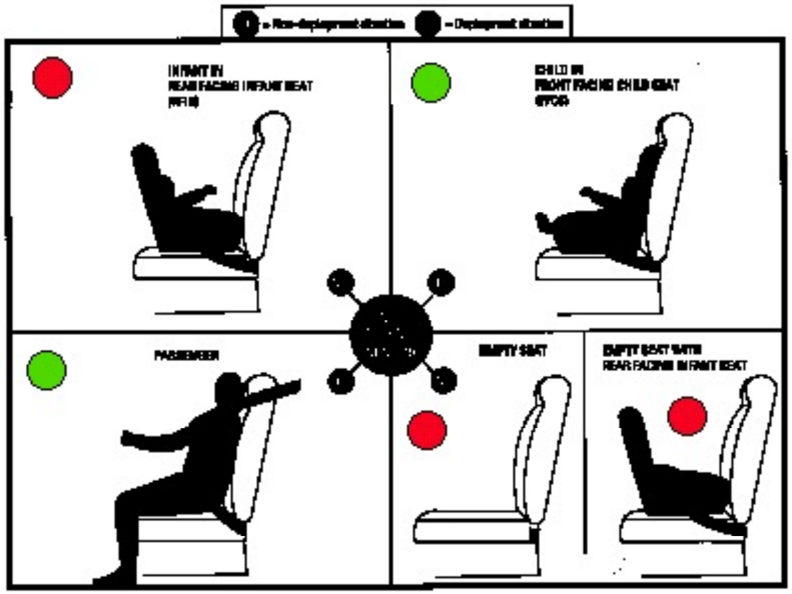


Calibrating the Feet

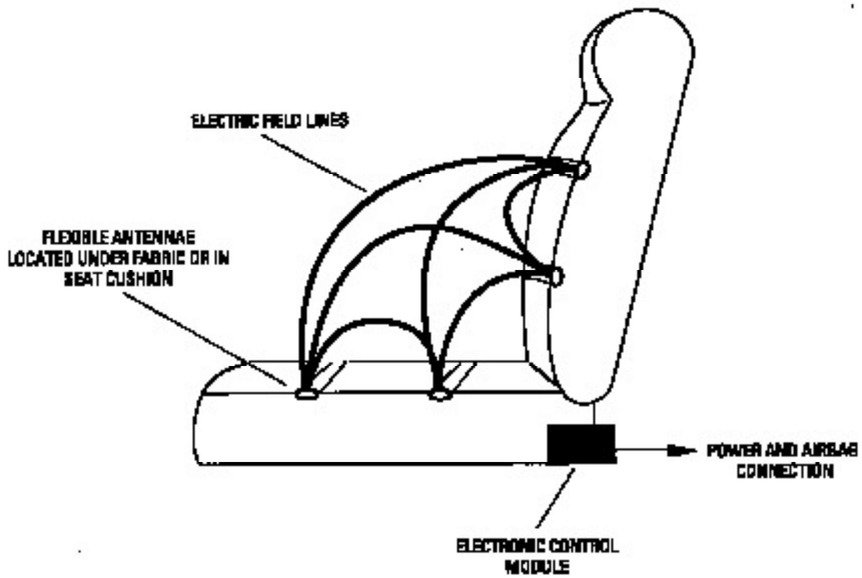
Gesture Wall Afterward...

- Nicely sensitive to bulk gesture
  - Theremin-style, but better tracking, stability
- Tracks well when feet calibrated and body back, hand forward
  - Takes "average" position when 2 hands and body close
- Still good for simple interactive music & graphics
  - Not repeatable enough for highly causal or moderately precise graphical/musical response

The NEC Smart Car Seat



When not to deploy the airbag



Electric Field Imaging from the Seat

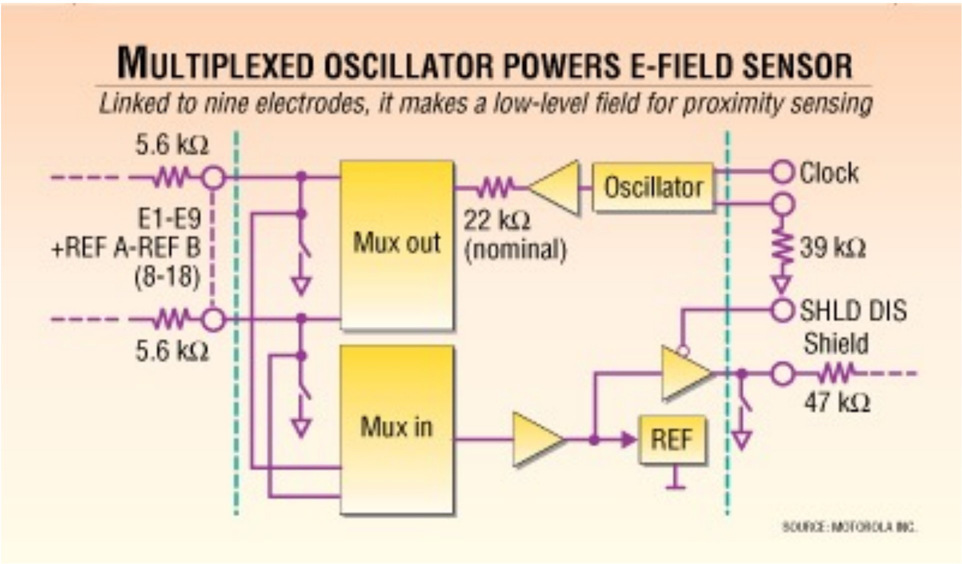
- 4 Transceiver Electrodes
  - Order 16 measurements
- Decision boundaries for deploy/not_deploy

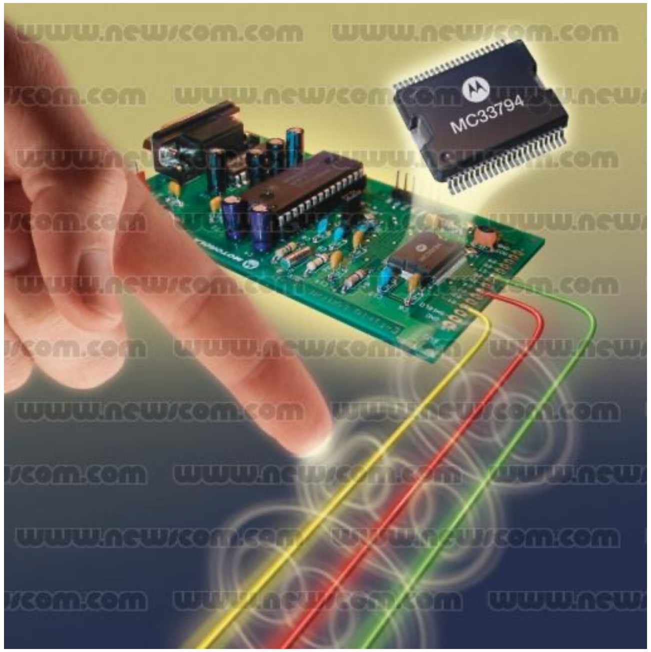
The Elesys Seat Sentry

elesys
Honda elesys Co.,Ltd.

- Honda/NEC joint venture
- Deploy decision for front and side airbags
  - All from the seat!
- Becoming a standard

The Motorola MC33794 chip

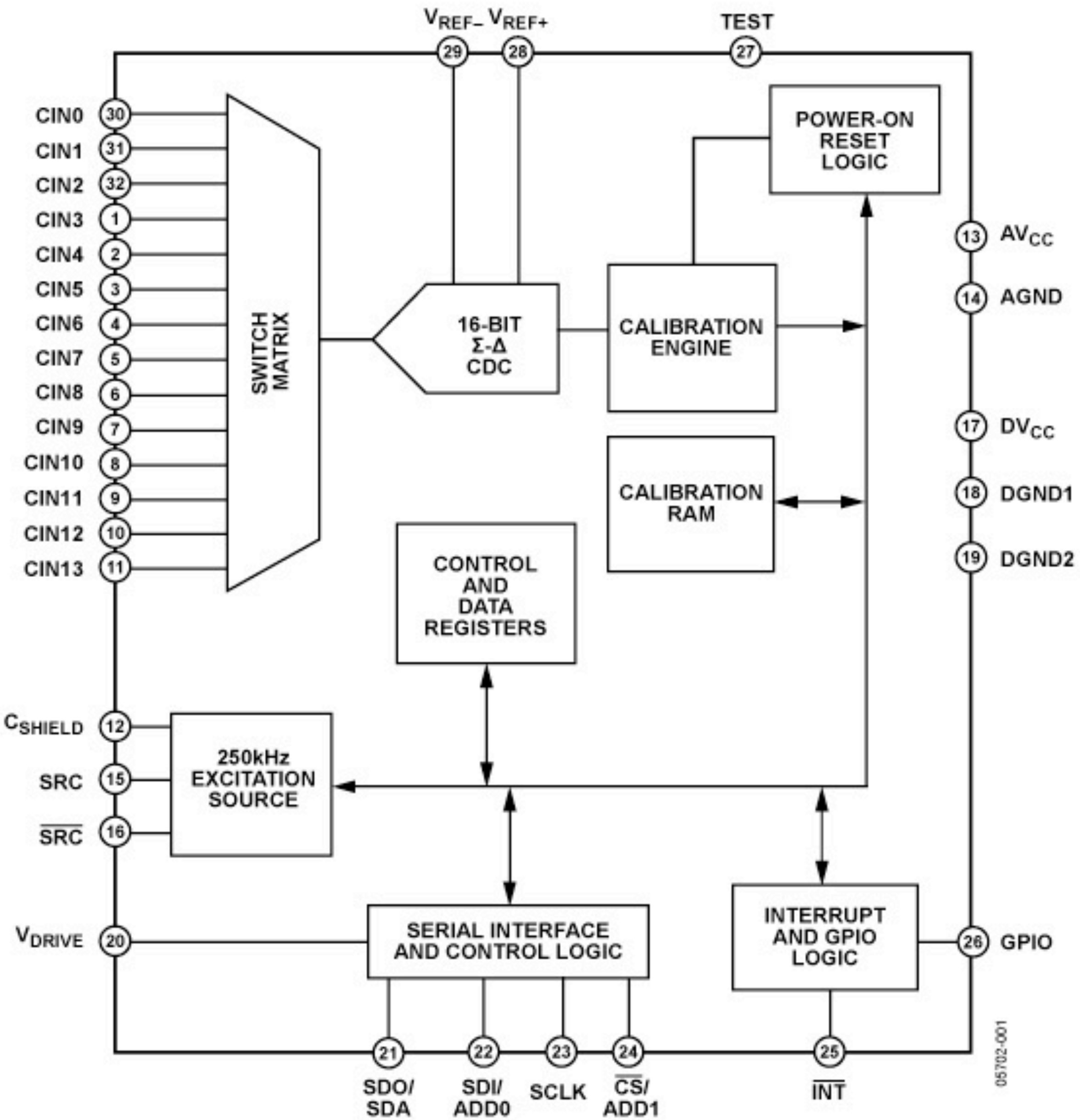




- Newly developed for SeatSentry with ML
- Leveraging into many other applications
- 9 channels

Family of capacitive sensors from AD

http://www.analog.com/en/content/0%2C2886%2C760%255F788%255F66102%2C00.html



- AD7142 (14-channel) and several others
- T/R mode
- Calibrates out external signals when sensors idle
- Low power - aimed at touch controllers and sensors (e.g., humidity)
- SPI output

Other Capacitive Sensing Chips

Hello Joe,The IC I was looking for was a chip that provides an automatic environmental noise cancellation, lots of inputs, something enables me to create a capacitives ensing matrix with one layer PCB.I started with AD7147 which provides on-chip multiplexing for up to 36 inputs.

http://www.analog.com/static/imported-files/application_notes/AN-929.pdf
http://www.analog.com/en/analog-to-digital-converters/capacitance-to-digital-converters/ad7147/products/product.html

The chip I am using now for my project is CY8C20x from Cypress. It is cheaper than the Analog device chip but as effective. The setup was easier but not asw ell-documented as the Analog Device chip

.http://www.cypress.com/?docID=25698

There is also the QTouch (such as QT100A) from Quantum which Ateml adapt and has libraries as part of their touch sensing solution (Atmel QTouch Library)

.http://www.atmel.com/Images/doc8207.pdf

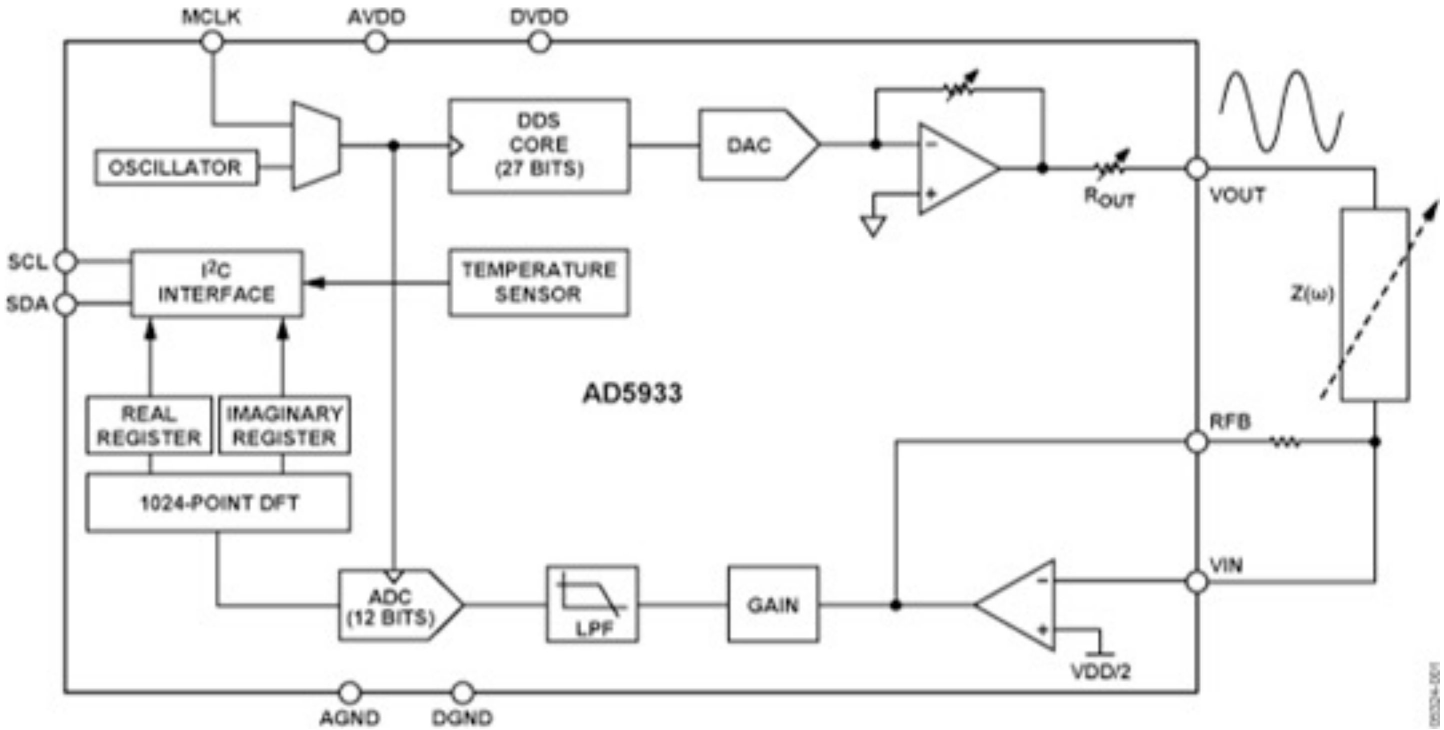
So if you are already developing your projects with an AVR 32 bits or TINYmicrocontroller, it would be a good idea to check this first.

From NanWei Gong, 3/2012

best,-nanwei

Many chips now available

- Many more IC solutions available now…
  - http://www.analog.com/en/products/rf-microwave/direct-digital-synthesis-modulators/ad5933.html



Asaf Azaria – Thumbs Up - 2015

Azaria, A., Mayton, B., and Paradiso, J.A., "Thumbs-Up: Wearable Sensing Device for Detecting Hand-to-Mouth Compulsive Habits," 9'th International Conference on Biomedical Electronics and Devices (BIODEVICES 2016).