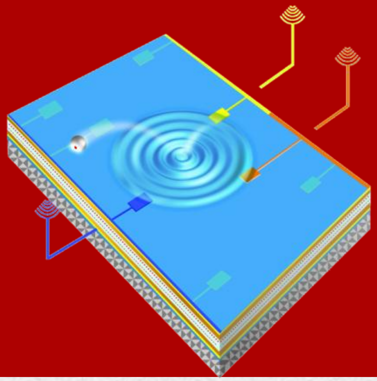
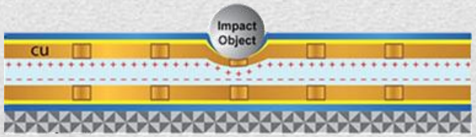
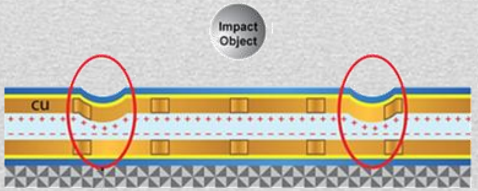
PASSIVE TACTILE SENSING

UCLA MASTERS OF ENGINEERING

DESIGN STUDY







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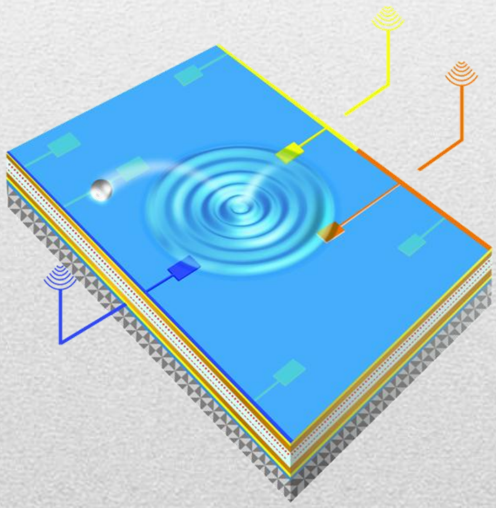
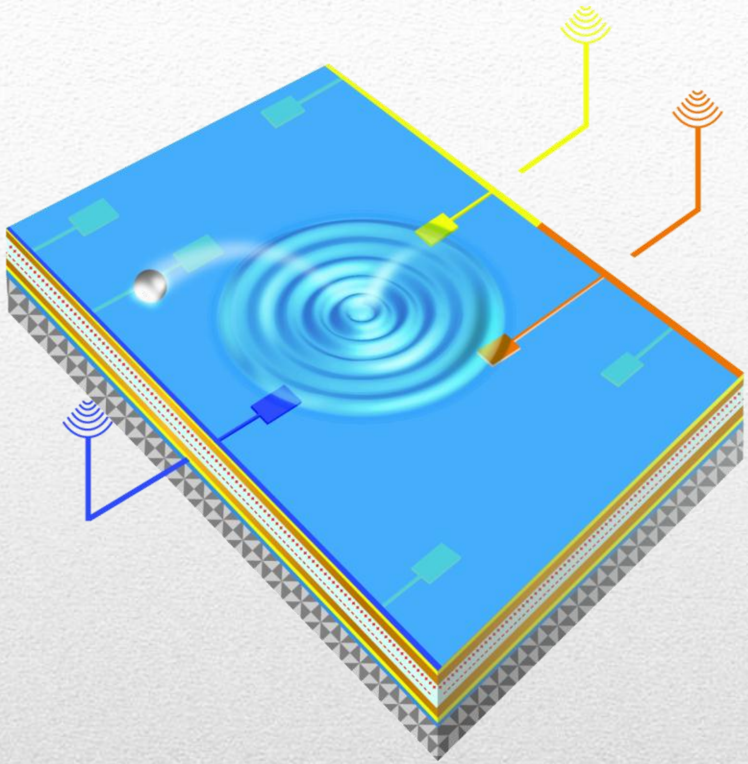
UCLA Masters of Engineering - Spring 2012

- The proposed design is a passive, wireless tactile sensor
- By using the piezoelectric effect and a carefully arranged set of parallel plate capacitors, radio-frequency chirps can be observed after an impact occurs on the sensor
- The received chirps can be triangulated to give an accurate location of impact

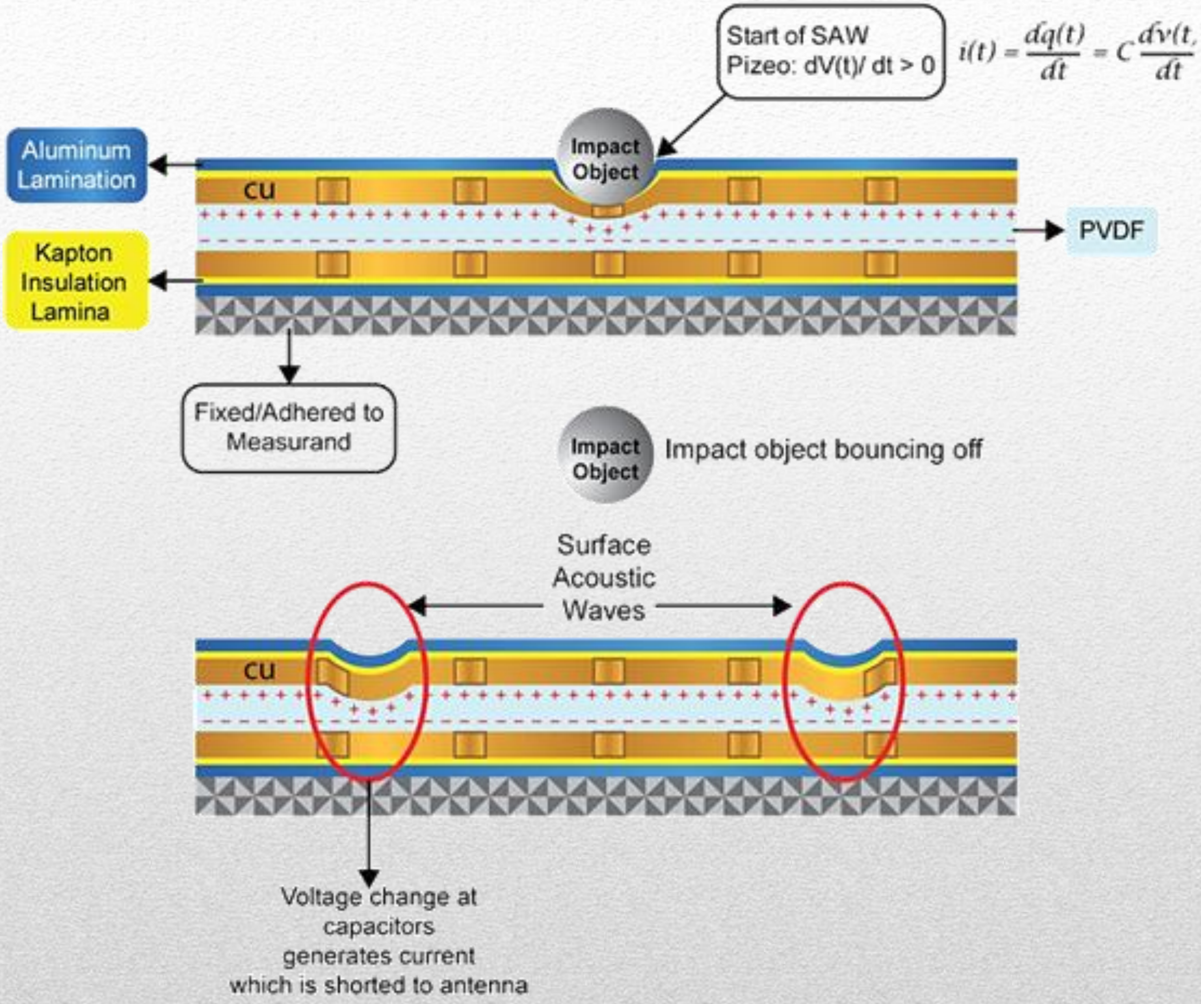


Project Overview



1. An object hits the sensor
2. SAW is produced
3. Crest of SAW activates nodes via Piezoelectric effect
4. Nodes produce wireless chirp
5. Location is resolved with Triangulation

Action View



Design Side View

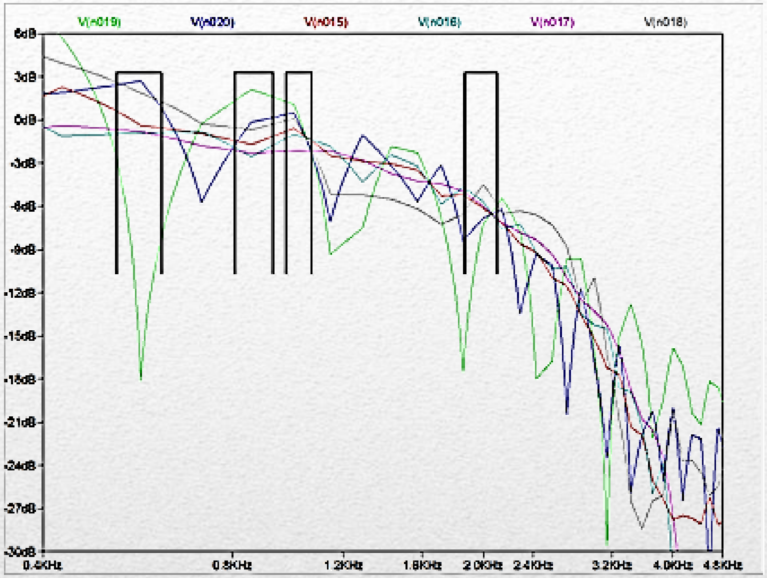
- Referring to the previous slide, “Design Side View” the proposed set of materials, in order, for this impact sensor are:

1. Aluminum top Layer
2. Kapton top Layer
3. Copper top Layer
4. Piezoelectric Polymer (PVDF) middle dielectric Layer
5. Copper bottom Layer
6. Kapton bottom Layer
7. Aluminum bottom Layer

Material Overview

- The sensor is to function as such:
  - Shape wise, it will be rectangular and extremely thin. Each layer will be on the order of a mil (thousandth of an inch)
  - The sensor will be adhered to a surface, such as an aerospace payload, where it will be exposed to the elements
  - As objects impact the sensor, a natural surface acoustic wave (SAW) will occur
  - This SAW, as it traverses across the piezoelectric polymer layer, will produce an electric field.
    - These charges will create current on the copper islands which will drain into an antenna attached to the sensor
    - The antenna will emit chirps whose center frequencies are related to the unique shapes of the capacitive island
    - $i(t) = C \frac{dv(t)}{dt}$

Functional Overview



Left figure shows a time domain view of the chirps emitting from the sensor

Right figure shows a frequency transform of these chirps – uses FFT

Chirp Representation

- A middleware receiver will be set to pick up these chirps and mark the time difference of arrival (TDOA) of each chirp.

- With proper software, the TDOA can be used to triangulate the location of impact using a two dimensional multilateration algorithm.
  - This algorithm is based on the intersection of 3 circles
  - In initial testing, the algorithm is quite fast in Matlab and will be discussed later in the presentation.

- This report will constitute the design study of the sensor itself, as well as the triangulation algorithm.

- ➢ The study of the antenna, radio frequency specification, and middleware system will be done by a fellow UCLA Masters of engineering student in a separate report.

Systems Overview

- The goal of this masters project is to study each material used, study the piezoelectric effect, study the expected voltages that could be produced, and study the algorithm which will union them all.
- I plan to utilize many resources from journals, books, and internet
- I plan to create a finite element model based on the most important assumptions of this project
- The overall goal is to build the ground work for creating a prototype in a laboratory

Report Goals

- The aluminum is set to act as a protective shield to the sensor.
  - Since the sensor is exposed to the elements, a protective layer will be necessary.
  - Damage potential will be reduced
- The aluminum layer may be able to act as a crude antenna if other antenna designs prove too cumbersome

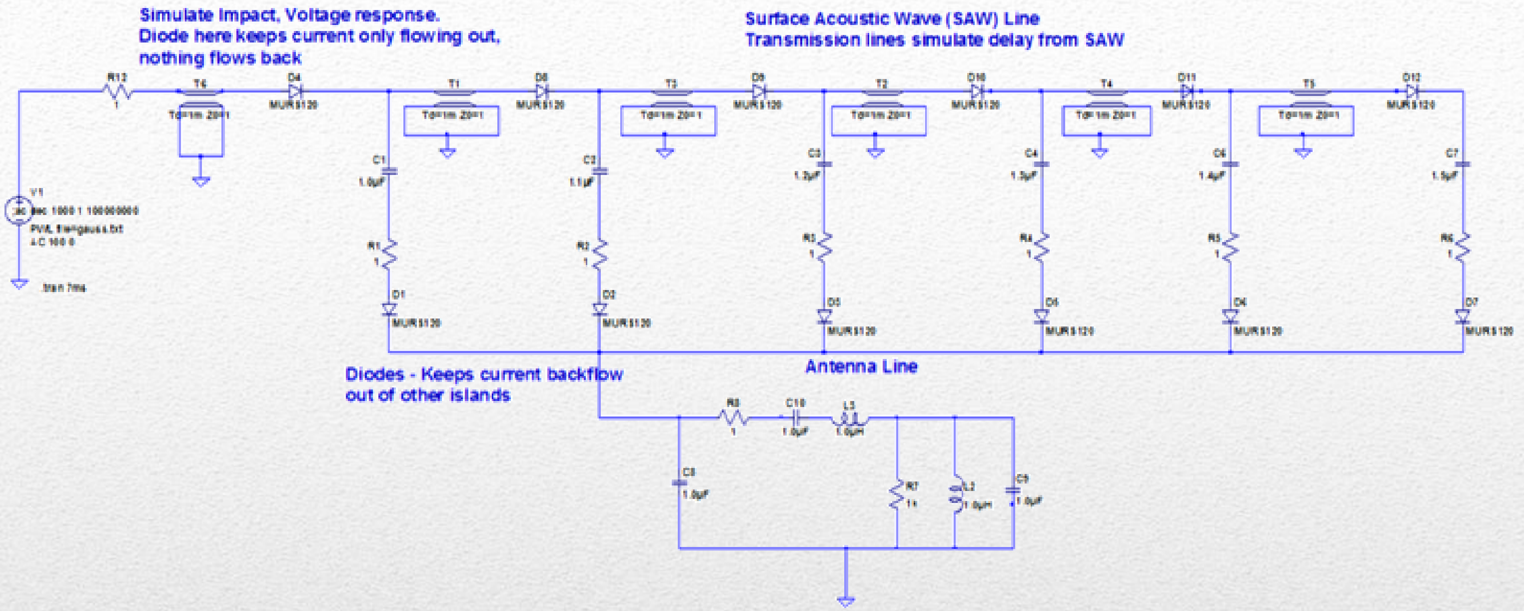
Aluminum Purpose

- Kapton is a well regarded insulator and will electrically separate the capacitive layer
  - This will be described in the proceeding slides
- Kapton may be used within the copper layers as well to reduce potential parasitic effects.
  - Again, this will be explained further in the capacitor and conductor slides.

Kapton Purpose

- Copper is one of the best conductors and is relatively low cost, thus it will serve as the top and bottom plates of the capacitors.
- Referring to Design Side View, the copper will be split into an array of islands.
  - Each island will vary slightly geometrically, thus constituting a different capacitive value.
  - Since transient current is a function of capacitance, this will inherently allow for unique chirps from each island.
- I.e., these different capacitive values will cause frequency shifts in the RF output
  - Thus allowing a detector to distinguish one capacitor from another, and hence one location from another.

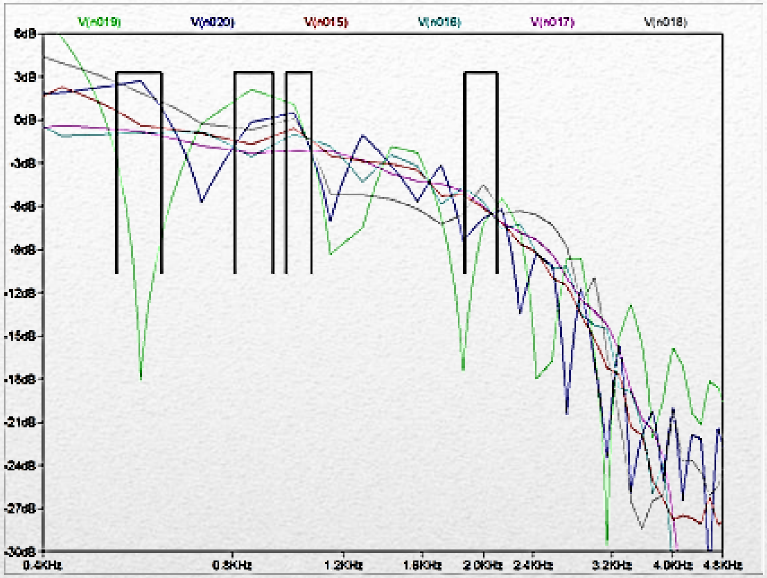
Copper & Capacitor Layer



SPICE is used to create a purely electrical simulation of the sensor in action.

Transmission lines create the delay effect, diodes ensure directionality in the current flow, and the RC-branches model the sensor's capacitive nodes.

Electrical Loads/SPICE



Same figures as slide 7

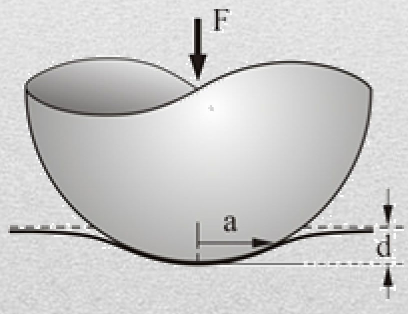
Chirp Representation

- Parasitic effects could be present if unintended conducting lines and capacitors become present.
- In the copper layer, it may be advantageous to strip all unneeded copper from the sensor and, to fill the vacancy, replace it with more Kapton.
  - Thus the copper will only form islands and conducting lines. No floating copper.
- Current may also leak to other nodes; to resolve this, implanting polymer based diodes at each capacitive island will electrically isolate each island.

Parasitic Effects

Contact Mechanics

- A study of the physical impact is conducted
- The physical impact duration is closely related to the frequency range of the sensor.
  - The quicker the actual impact takes place, the more frequency is produced
  - This will be looked at more in the Piezoelectric Effect slides
- Based on Hertzian Contact Solution



$$F = \frac{4}{3} E^{*} R^{1/2} d^{3/2}$$

$$\frac{1}{E^{*}} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

$$a = \sqrt{Rd}$$

- Multiple perspectives to study impact duration:
  - 1 – Velocity and material factor

$$T_H = 2.94\left(\frac{5}{4}\pi\rho_1\cdot\left(\frac{1}{E_1'}+\frac{1}{E_2'}\right)\right)^{2/5}\frac{R}{v_0^{1/5}}$$

  - 2 – Resonant frequency factor

$$f = \frac{n\cdot v}{4\cdot L} \qquad [1/\mathrm{s}]$$
$$v = \sqrt{E/\rho} \qquad [\mathrm{m/s}]$$
$$\Delta T \propto 1/f \qquad [\mathrm{s}]$$

  - 3 – Observational perspective
    - Analyze many impacts with a high speed camera and generate statistics

- Each method produces an impact duration on the order of 100 microseconds

Contact Mechanics

- The Piezoelectric Effect is mathematically modeled by a large coupling matrix equation which relates a material's Young's modulus, Permittivity, Piezoelectric coefficients, and input Stress.

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

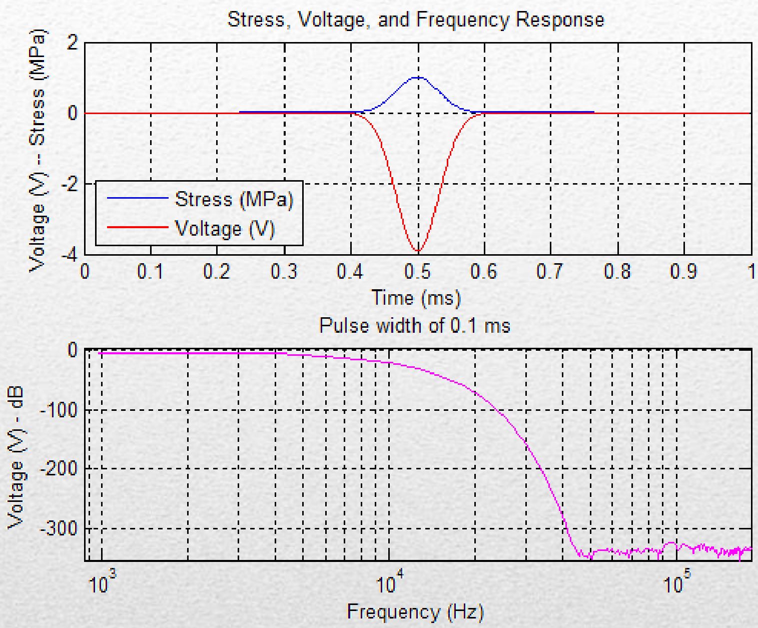
$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

- The following equation relates normal stress with voltage:

$$V(t) = \frac{d_{33}A}{C}\left[\exp\left(-\frac{t}{RC}\right) - 1\right] \cdot T_3(t) \qquad \left\{ \begin{array}{l} d_{33} = 15 \cdot 10^{-12}\ \mathrm{C/N} \\ A = 0.00129032\,\mathrm{m}^2 \\ C = 4.947 \cdot 10^{-9}\ \mathrm{F} \\ R = 1\Omega \end{array} \right\}$$

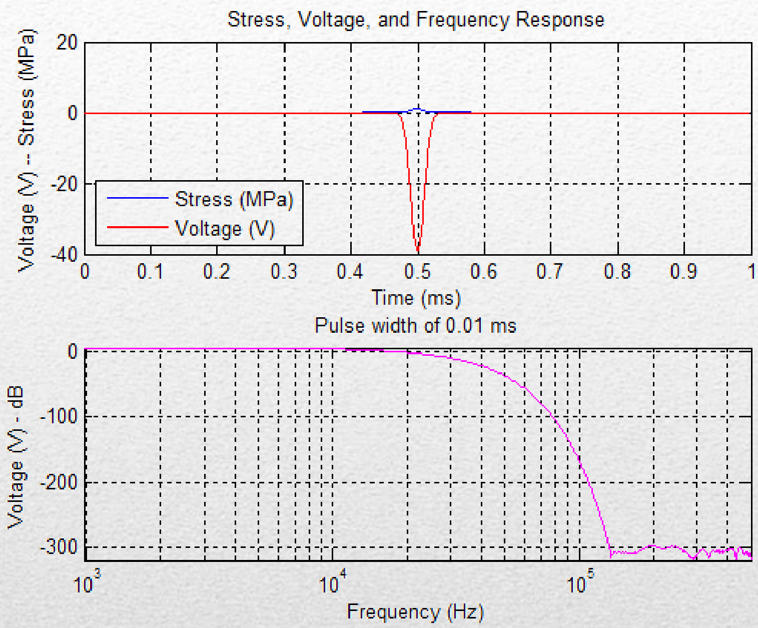
Piezoelectric Effect

- The following input stress is applied:
  - 1 MPa Gaussian
  - 0.1 ms pulse width
  - Onto a 1 mil thick PVDF
- This shows a useable bandwidth in the sub 2 kHz range

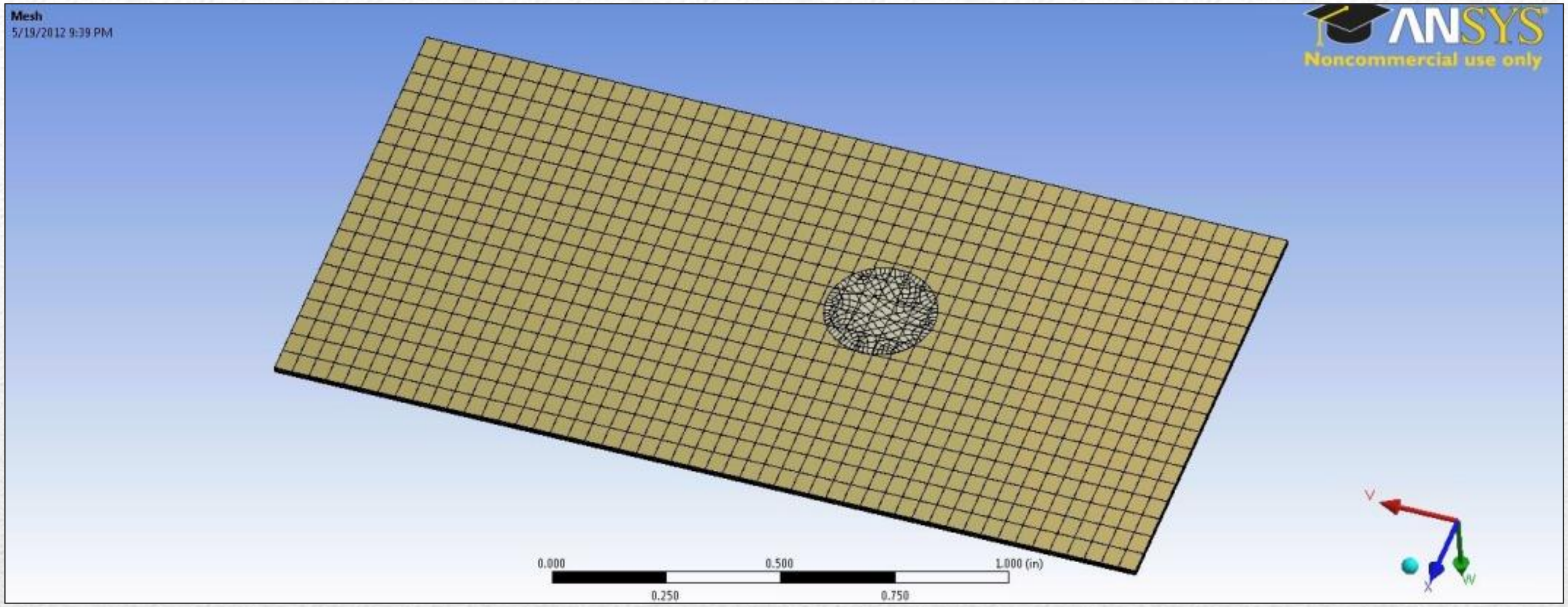


Piezoelectric Effect – Frequency Response

- The following input stress is applied:
  - 1 MPa Gaussian
  - 0.01 ms pulse width
  - Onto a 10 mil thick PVDF
- This shows a useable bandwidth in the sub 10 kHz range

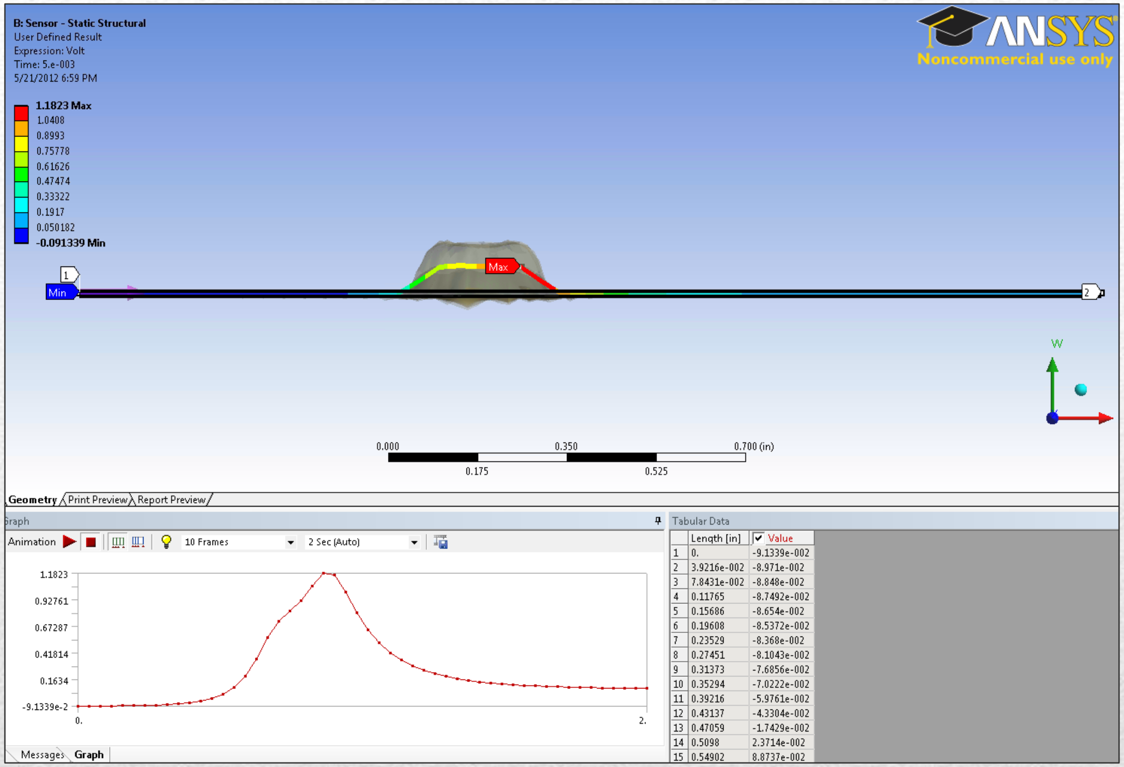


Piezoelectric Effect – Frequency Response



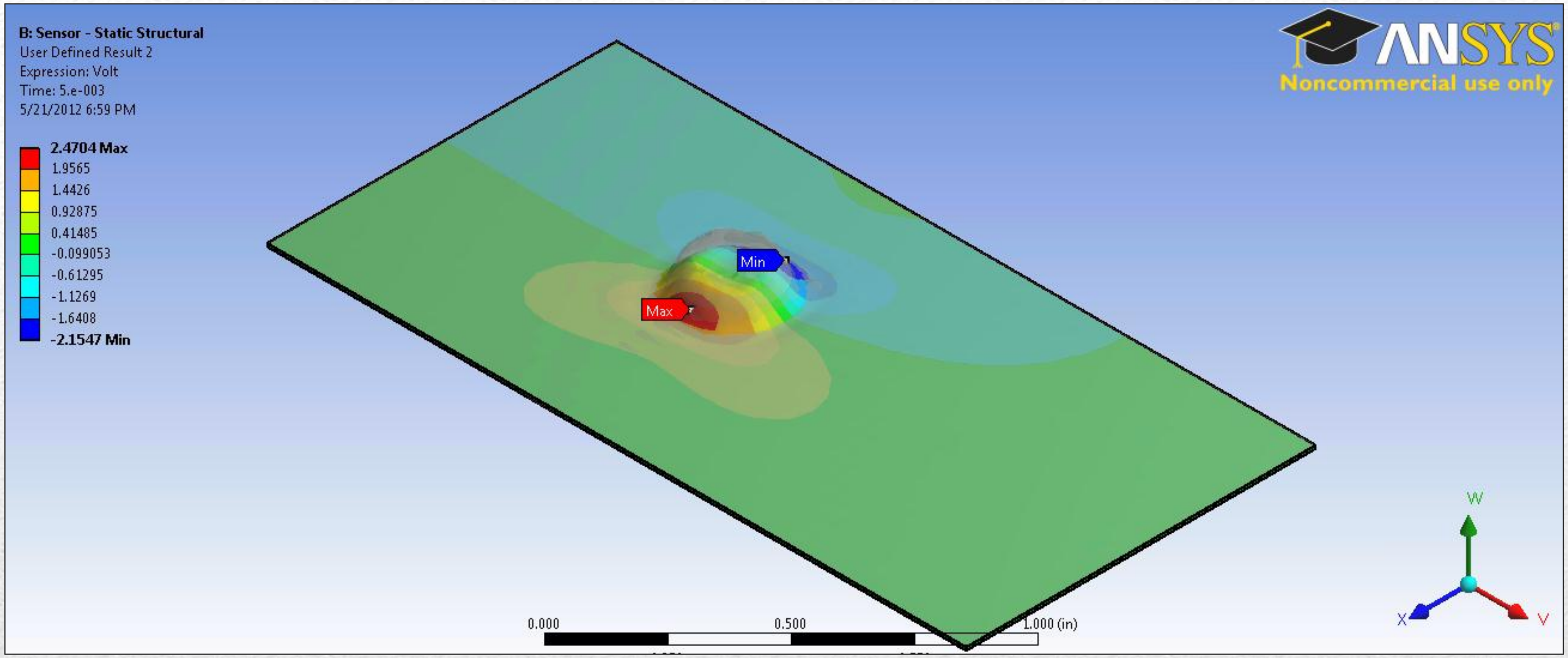
This figure shows the Finite Element Analysis (FEA) mesh. The sensor is modeled here with 7 thin layers. The circle near the middle shows the area of impact.

Finite Element Analysis



FEA confirms the expectation of a voltage drop on the sensor upon impact. This helps calibrate the design

Finite Element Analysis

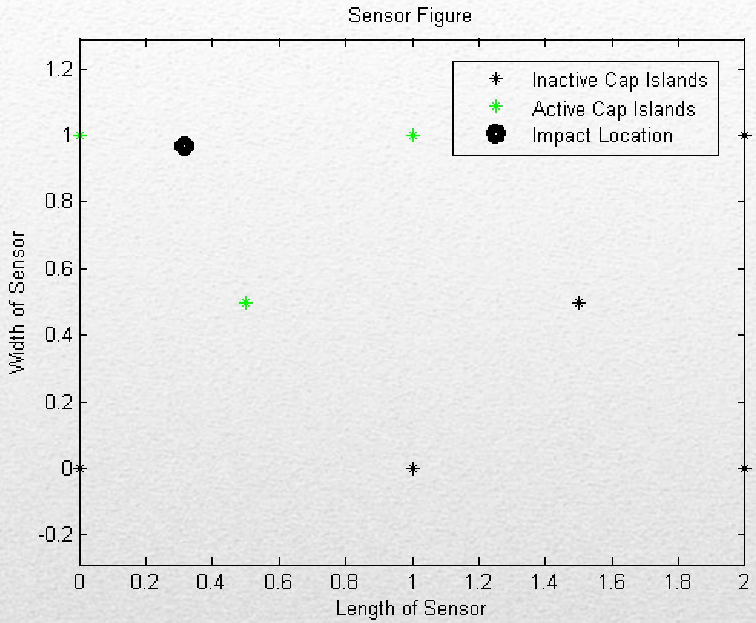


This analysis demonstrates a magnitude 2 voltage drop in initial wave crest

Finite Element Analysis

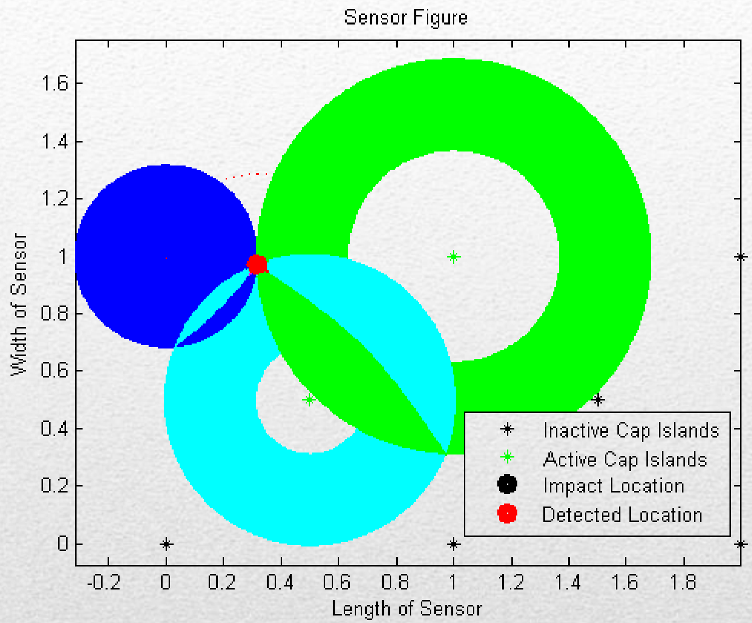
- A section of this report will be devoted to simulating the triangulation algorithm in Matlab
- The following will be demonstrated:
  - Receiving 3 signals
  - Finding the time difference of arrival (TDOA) of them
  - And knowing the origin of each signal
  - Constitutes all that is needed to determine the impact location

Triangulation Simulation



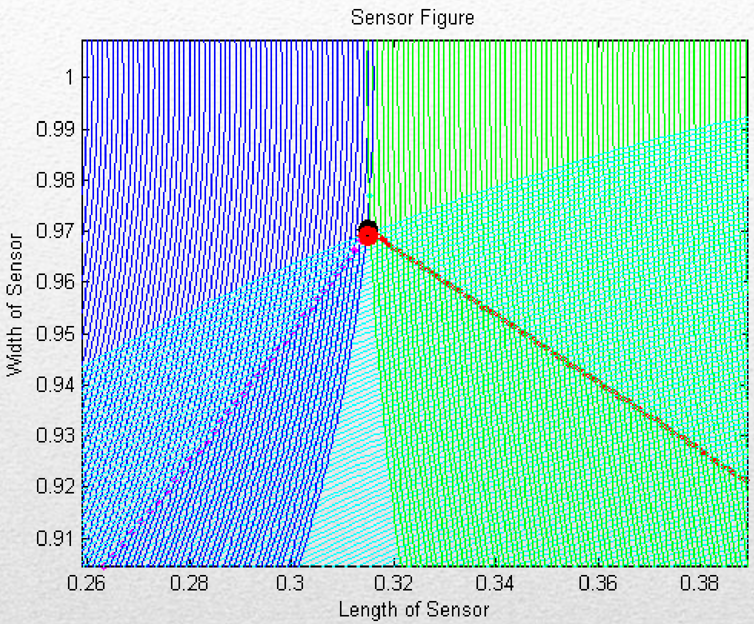
- To the left is a top view of the sensor.
  - The asterisks are the locations of capacitive islands (or nodes)
- The impact location marked by a black dot.
- Active nodes are colored green
  - Nodes are active (green) once the SAW touches them.
  - Theoretically, all nodes will activate when the SAW touches them, but only the first 3 matter for triangulation

Matlab Sensor Simulator



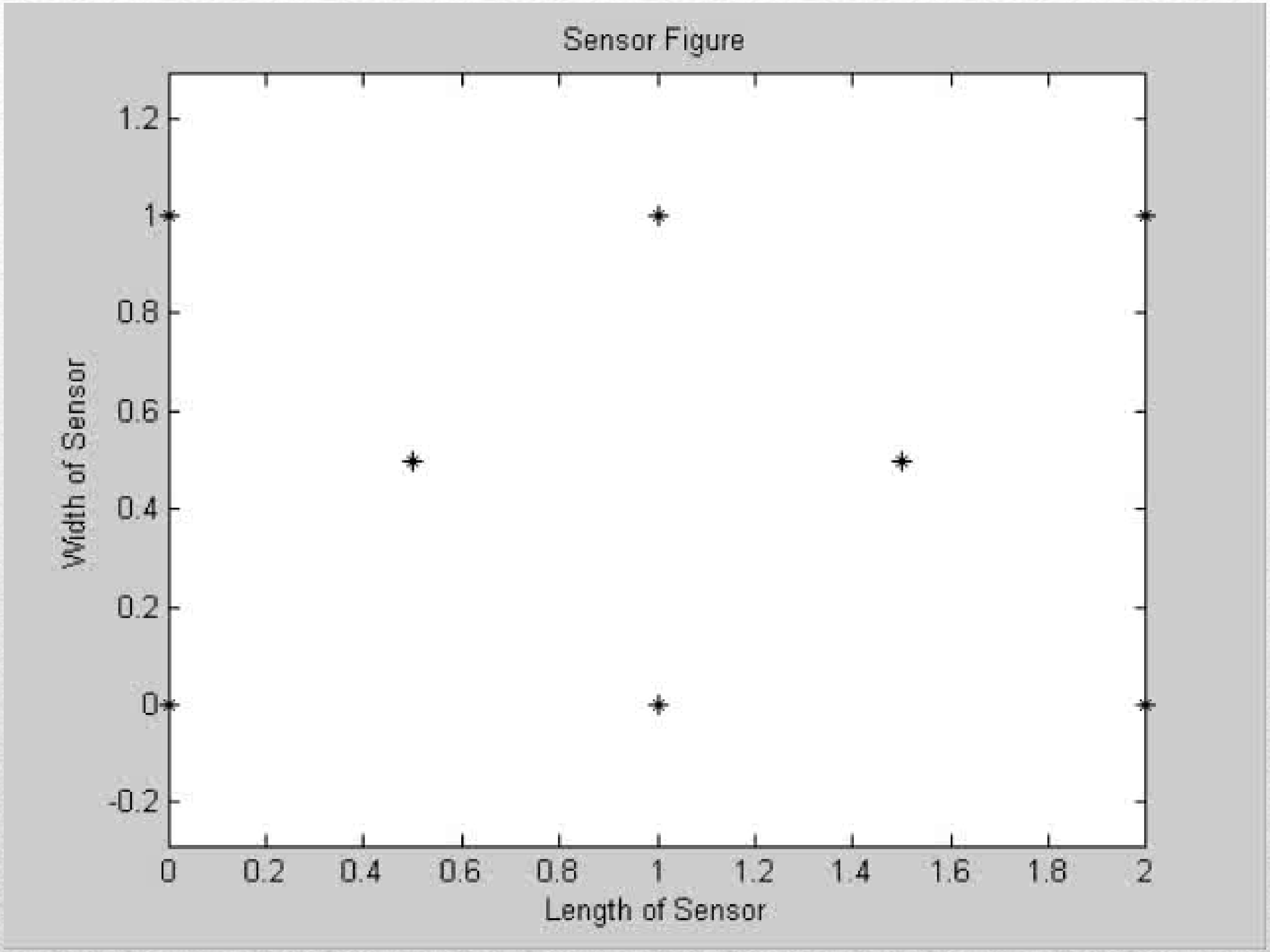
- This image is a visual representations of the triangulation algorithm
- The resolved impact location is the red dot at the intersection of the 3 circles.
    - Details of this will be explained more thoroughly in the final report

Location Resolved



- This slide shows a close up of the detected location and impact
- The delta between the actual hit and resolved location is 0.001" or 0.254 mm. Compared to its 2 sq. inch area, this is a 0.05% error.
- A Monte Carlo of 30,000 simulations showed none having an error greater than 2.83%
  - This means that, at worst, the detected impact location will be 0.0566", or 1.438 mm, from the actual impact location.

Zoomed in Location

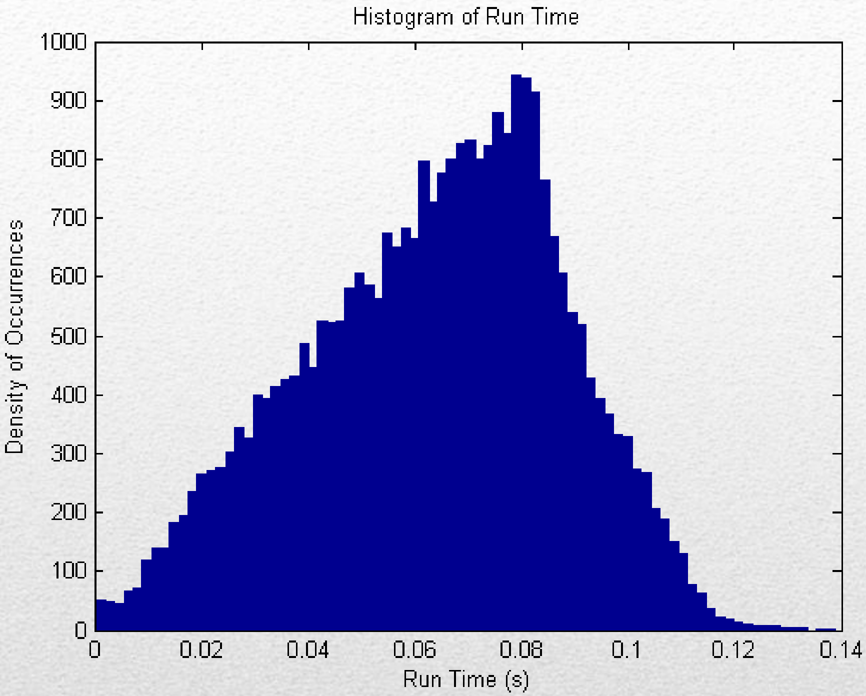


Movie: Sensor in Action

This histogram represents a set of 30,000 Monte Carlo simulations of the triangulation algorithm, reduced to 200 bins for easier viewing.

The X-axis is the amount of time it took the algorithm to determine location in seconds

```
Mean Sec  = 0.0637
Std. Dev. = 0.0242
Max Sec   = 0.3467
Min Sec   = 0.0003
```



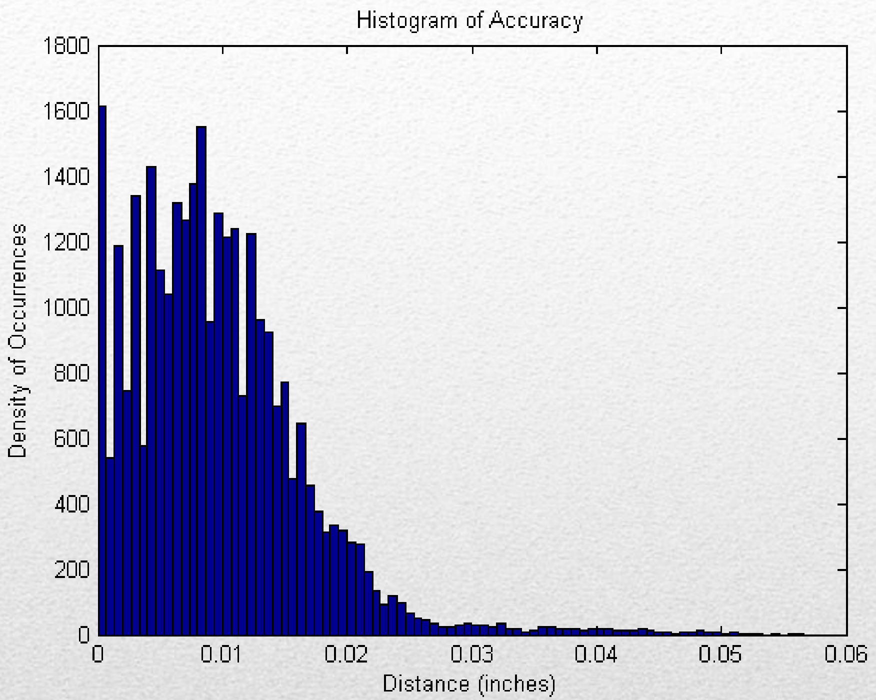
Monte Carlo Histogram – Algorithm Time

This histogram aggregates the distance between the actual hit location and the algorithm's resolved hit location.

This is based off the same 30,000 Monte Carlo and fit into 85 bins.

Of the 30,000 simulations, about 1,600 had nearly 0% error. The average error is 0.49% compared to the 2 sq. inch area.

```
Mean dist.  = 0.0097″
Std. Dev.   = 0.0070″
Max dist.   = 0.0566″
Min dist.   = 0.0000″
```



Monte Carlo Histogram – Algorithm Accuracy

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