

# Geometric Reconstruction using Acoustic Sensing

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# Overview

**Research Goal:** Use acoustic signals from a soft finger to classify geometric contact conditions

## Tasks:

- Contact position classification (tip/middle/base/no contact)
- Edge detection (contact/edge/no edge)
- Fine feature detection (paper clip present/absent)

**Method:** Extract acoustic features from broadband frequency sweeps and classify using machine learning

# Data and Features

## Dataset:

- 4 experimental batches, 650 total samples
- Soft pneumatic finger with embedded speaker/microphone
- 2-second broadband chirp signals (20Hz-20kHz)
- Controlled contact conditions

## Features Extracted:

- 38 acoustic features (spectral, temporal, frequency domain)
- 15 impulse response features (transfer function characteristics)
- Total: 53 features per sample

# Acoustic Features: Spectral (13)

- spectral\_centroid - Center of mass of spectrum
- spectral\_bandwidth - Spread around centroid
- spectral\_rolloff - 85% energy frequency
- spectral\_flux - Spectral change rate
- spectral\_flatness - Noise vs tone measure
- spectral\_contrast - Peak-to-valley differences

## Temporal Features (8):

- zero\_crossing\_rate - Signal noisiness
- rms\_energy - Signal energy
- envelope\_features - Amplitude properties

Reference: Tzanetakis & Cook (2002)

# Acoustic Features: MFCC and High-Frequency

## MFCC Features (12):

- `mfcc_0` to `mfcc_11` - Mel-scale cepstral coefficients
- Perceptually relevant spectral representation
- Capture timbre and spectral envelope

## High-Frequency Features (5):

- `ultra_high_energy_ratio` - Energy >8kHz
- `ultra_high_ratio` - High-freq to total energy
- `high_freq_content` - High-frequency measures

## Why These Features?

- Standard in audio signal processing
- Sensitive to geometric and material changes

Reference: Davis & Mermelstein (1980)

# Impulse Response Features: Magnitude (8)

- freq\_response\_centroid - Transfer function center of mass
- freq\_response\_bandwidth - Transfer function spread
- freq\_response\_skewness - Transfer function asymmetry
- freq\_response\_kurtosis - Transfer function peakedness
- resonance\_peak\_magnitude - Strongest resonance height
- resonance\_peak\_frequency - Strongest resonance frequency
- resonance\_bandwidth - Resonance peak width
- resonance\_skewness - Resonance distribution asymmetry

Reference: Oppenheim & Schafer (2010)

# Impulse Response Features: Decay and Damping (7)

- `decay_amplitude` - Amplitude decay rate
- `decay_time` - Exponential decay time constant
- `damping_ratio` - System damping measure
- `quality_factor` - Resonance sharpness (Q-factor)

## Why Impulse Response Features?

- True system characterization independent of input
- Captures physical properties: resonances, damping, stiffness
- Complements traditional acoustic features

# Dimensionality Reduction: PCA and t-SNE

## Principal Component Analysis (PCA):

- Linear technique finding maximum variance directions
- Projects high-dimensional data to lower dimensions
- Preserves global structure and distances
- Based on eigenvalue decomposition of covariance matrix

**Purpose:** Reduce 53D feature space to 2D for visualization and assess class separability

## t-Distributed Stochastic Neighbor Embedding (t-SNE):

- Nonlinear technique preserving local neighborhoods
- Converts similarities to probability distributions
- Minimizes KL divergence between distributions
- Excellent for visualizing high-dimensional clusters

# PCA and t-SNE: Class Discrimination

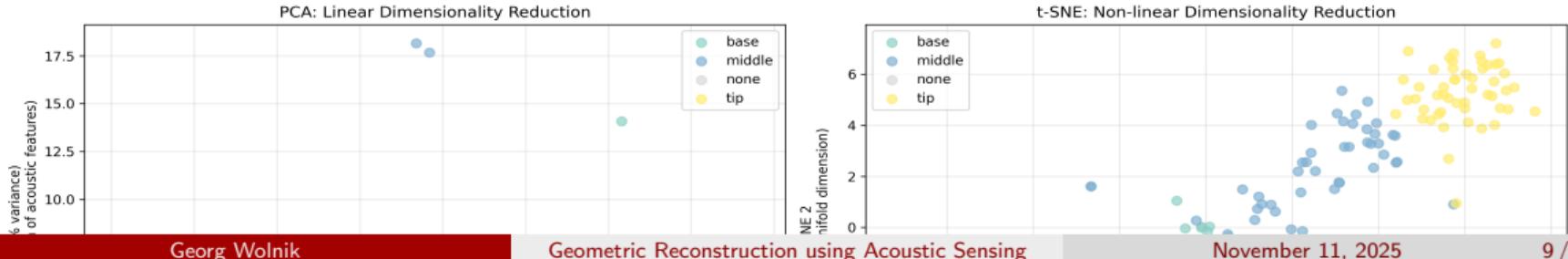
## Visualization Results:

- PCA (left): Shows linear separability of classes
- t-SNE (right): Reveals nonlinear cluster structure
- Contact position: 4 distinct clusters (tip/middle/base/no contact)
- Edge detection: 3 well-separated groups
- Paper clip detection: 2 classes with some overlap

## Key Insights:

- Clear class separation indicates discriminative features
- Nonlinear methods show tighter clusters
- Consistent performance across visualization methods

Contact Position Discrimination (Batch 2) - Method Comparison



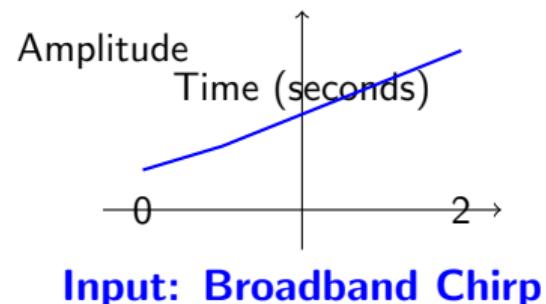
# Transfer Function: The Input Sweep

## What We Send: Broadband Chirp Signal

- Linear frequency sweep from 20Hz to 20kHz
- 2-second duration for good frequency resolution
- Known, controlled input signal
- Excites all frequencies of interest

## Signal Properties:

- Constant amplitude across frequencies
- Linear frequency increase over time
- Designed to characterize system response



**Input: Broadband Chirp**

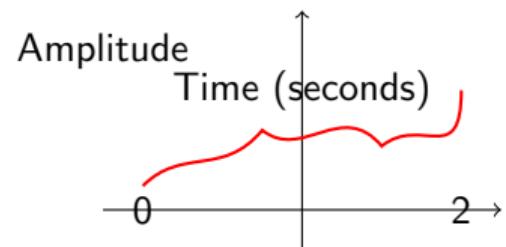
# Transfer Function: What We Receive

## What We Record: Modified Response

- Microphone captures the acoustic response
- Signal is modified by finger-object interaction
- Contains information about contact geometry
- Same duration as input signal (2 seconds)

## Key Observation:

- Different contact conditions produce different responses
- The modification reveals geometric properties
- Direct analysis of this signal gives traditional acoustic features



**Output: Modified Response**

# Transfer Function: Deconvolution Process

## Computing the Transfer Function:

### 1. Fourier Transform Both Signals:

- $X(f) = \text{FFT}[\text{input sweep}]$
- $Y(f) = \text{FFT}[\text{received response}]$

### 2. Deconvolution:

- $H(f) = Y(f) / X(f)$
- Normalize by input spectrum
- Apply windowing to reduce noise

### 3. Result:

- Transfer function  $H(f)$  shows how the system modifies each frequency
- Magnitude — $H(f)$ — reveals resonances and damping
- Phase information available but not used here

## Key Advantage

Transfer function is independent of the input signal - it characterizes the acoustic system itself

# Transfer Function: System Response Analysis

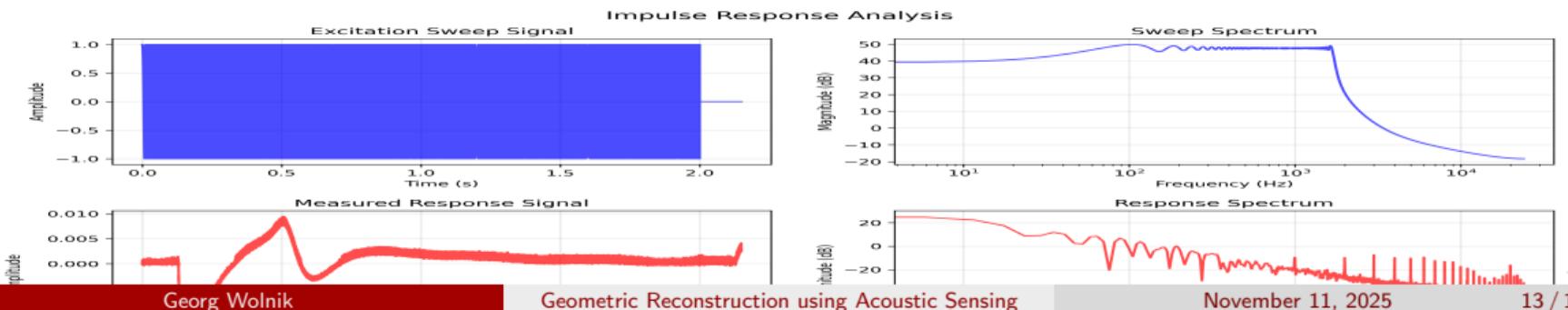
## Complete System Response Analysis:

### What It Shows:

- Input sweep spectrum (top-left)
- Response spectrum (top-right)
- System transfer function (bottom-left)
- Corresponding time-domain waveform (bottom-right)

### Key Insights:

- Transfer function reveals frequency-dependent system behavior
- Resonances and anti-resonances characterize contact geometry
- Damping properties affect peak shapes and widths



# Transfer Function: Additional Features

With Transfer Function, We Now Have Access To:

15 New Impulse Response Features:

- Resonance characteristics (frequency, magnitude, bandwidth)
- System damping properties (Q-factor, decay rates)
- Frequency response statistics (centroid, bandwidth, skewness)
- Properties independent of the specific input signal

Why This Matters:

- Traditional acoustic features depend on input signal design
- Impulse response features characterize the physical system
- Provides complementary information to acoustic features
- Enables more robust and generalizable classification

## Result

Combined acoustic (38) + impulse response (15) = 53 total features for training

# Saliency Analysis: Input and How It Works

## Input to Saliency Analysis:

- Complete dataset: 650 samples  $\times$  53 features each
- Features from all experimental batches combined
- Includes both acoustic (38) and impulse response (15) features
- Ground truth labels for contact position, edge detection, material classification

## How Saliency Analysis Works:

- Train neural network classifier on all 53 features
- For each feature, compute how much it affects the network's predictions
- Use backpropagation to calculate gradients w.r.t. input features
- Higher gradient magnitude = more important feature

## Method Details:

- TensorFlow/Keras implementation
- Multiple hidden layers for complex feature interactions
- Gradient computation across all training samples
- Statistical testing for significance (83% features significant)

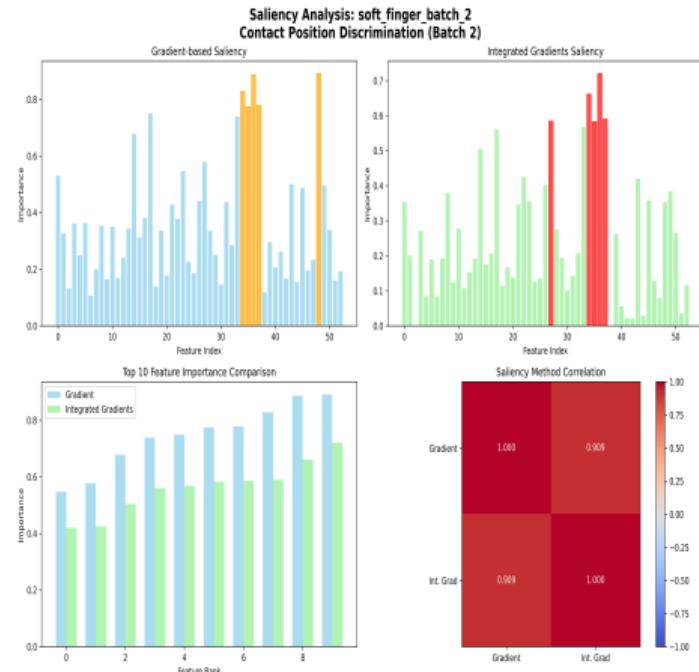
# Saliency Analysis: Results and What They Mean

## Top 6 Most Important Features:

- ① `spectral_bandwidth` - Frequency spread (acoustic)
- ② `resonance_skewness` - Resonance asymmetry (impulse)
- ③ `freq_response_centroid` - Response center (impulse)
- ④ `ultra_high_energy_ratio` - High-freq energy (acoustic)
- ⑤ `decay_amplitude` - Signal decay rate (impulse)
- ⑥ `ultra_high_ratio` - High-freq ratio (acoustic)

## Key Results:

- 3 of top 5 features are impulse response derived
- 83% of all 53 features are statistically significant
- Mixed importance between acoustic and impulse response features



# Saliency Analysis: Insights and Implications

## What These Results Tell Us:

- Impulse response features are among the most discriminative
- Acoustic features still provide crucial complementary information
- No single feature type dominates - combination is key
- Feature importance varies by classification task

## Frequency Analysis Insights:

- Multi-band spectral features provide strong separation
- Acoustic properties across frequency ranges are informative
- High frequencies contribute alongside mid-range components

## Practical Implications:

- Minimal feature sets possible (4-6 features for 95%+ accuracy)
- Real-time implementation feasible with reduced feature sets
- Feature selection can optimize computational efficiency

# Conclusions

## Main Findings:

- PCA and t-SNE show clear class separability
- Transfer function provides acoustic fingerprints
- Saliency analysis identifies key features
- High classification accuracy achieved

## Technical Validation:

- 97-100% accuracy demonstrated
- Feature importance measured
- Real-time processing feasible

## Next Steps:

- Full geometric reconstruction
- Continuous parameter regression
- Multi-finger integration

## References

-  Davis, S., & Mermelstein, P. (1980). Comparison of parametric representations for monosyllabic word recognition in continuously spoken sentences. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 28(4), 357-366.
-  Tzanetakis, G., & Cook, P. (2002). Musical genre classification of audio signals. *IEEE Transactions on Speech and Audio Processing*, 10(5), 293-302.
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