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# Acoustic Collision Detection and Localization for Robot Manipulators

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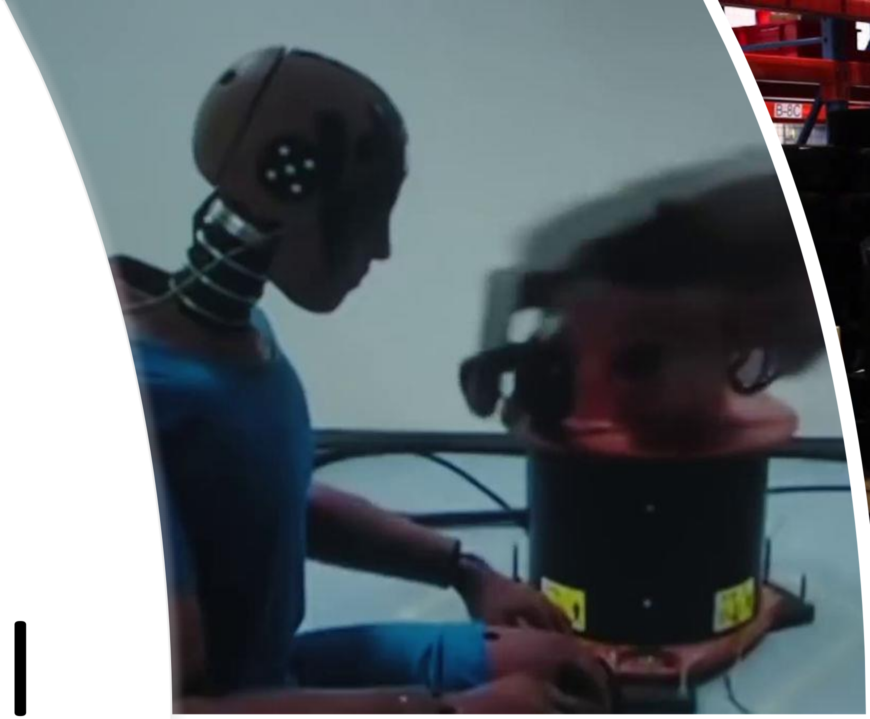
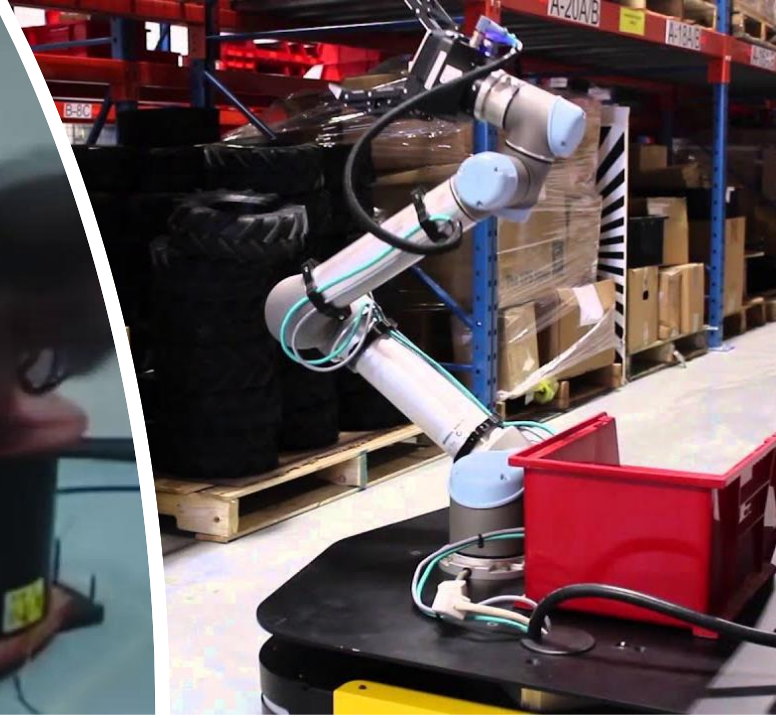
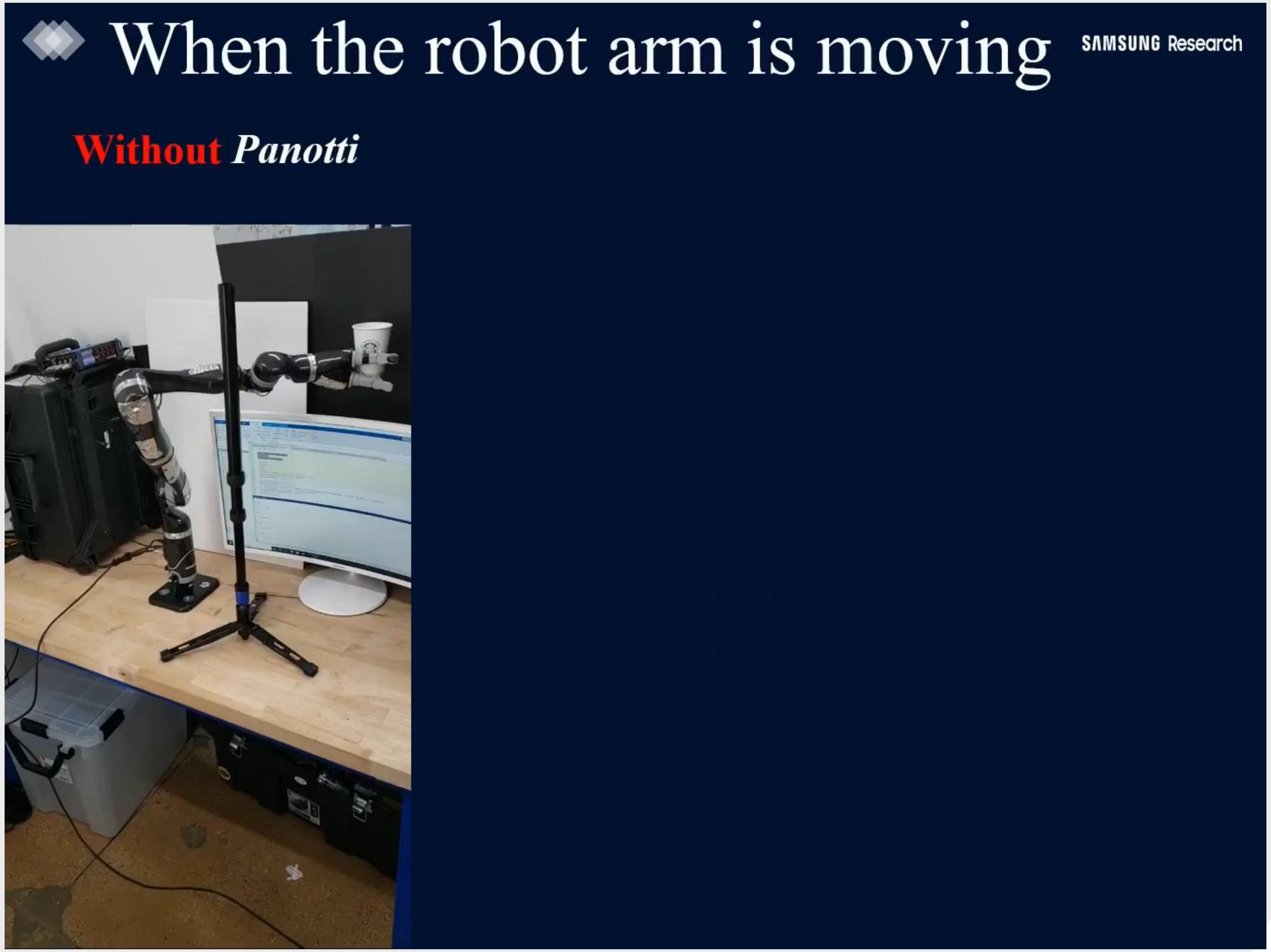
# Robot Collision Detection is Crucial





# Demo


When the robot arm is moving
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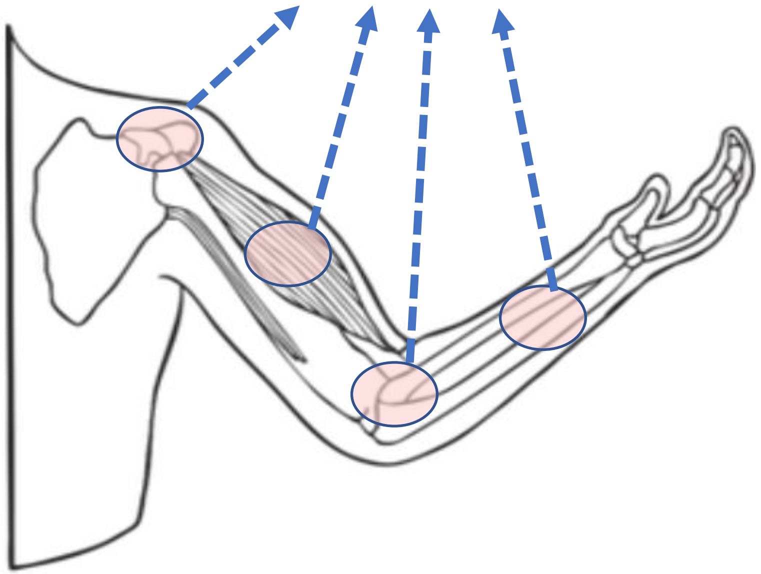
Without *Panotti*

# Existing Approaches - Intrinsic Signal

- Proprioception, e.g. motor torque, position, velocity and momentum readings coupled with inverse kinematics and dynamics
  - Require dynamic parameters
  - These parameters are noisy and subject to drifting

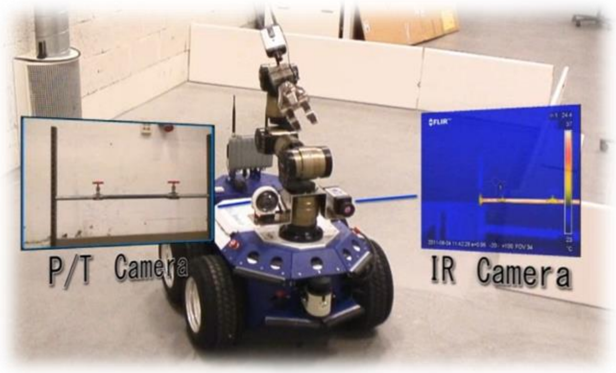
**Proprioceptive Feedback**

- Delivering information of the joint rotation with stretc
h of associated muscles/tendons



# Existing Approaches - Extrinsic Signal

- Rely on exteroceptive sensors such as cameras and tactile sensors
  - Costly
  - Difficult for maintenance
  - Occlusion issues




- We adopt low cost microphones to tackle down this problem

# Design Targets

- Collision detection
- Collision localization

# Challenges in Detection - Noise

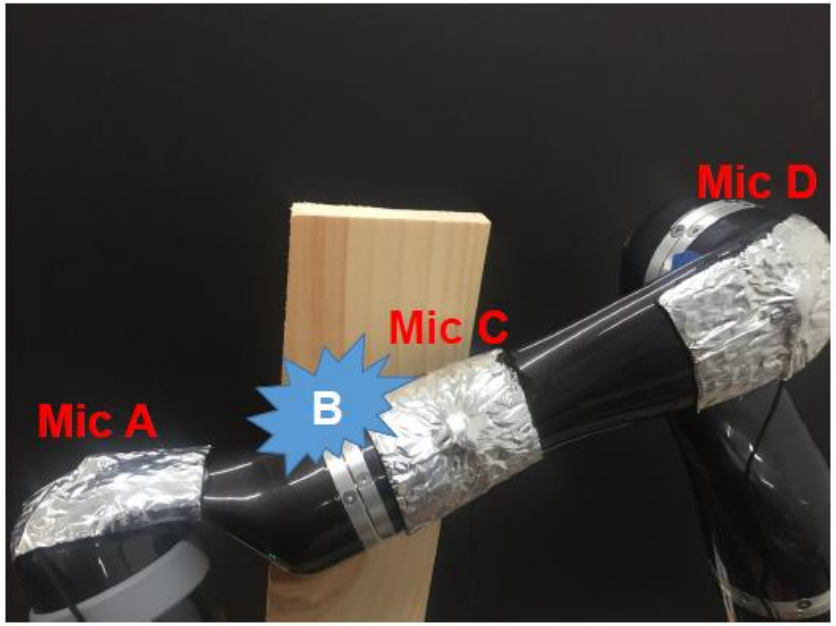
- Over the air noise

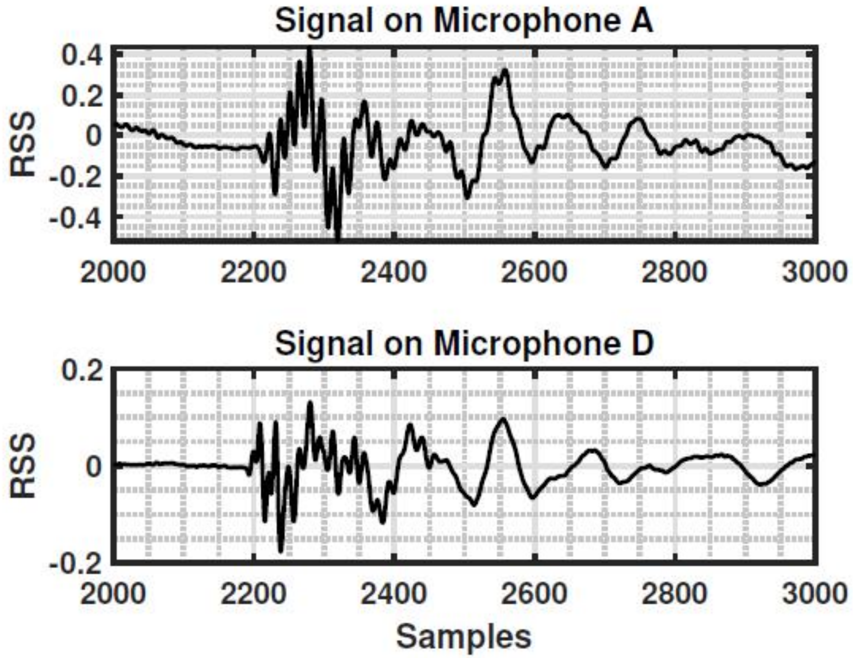
- On table/floor noise

- Motor noise

# Physics behind On-robot Collisions

- Signal are dispersive – beamforming no longer work

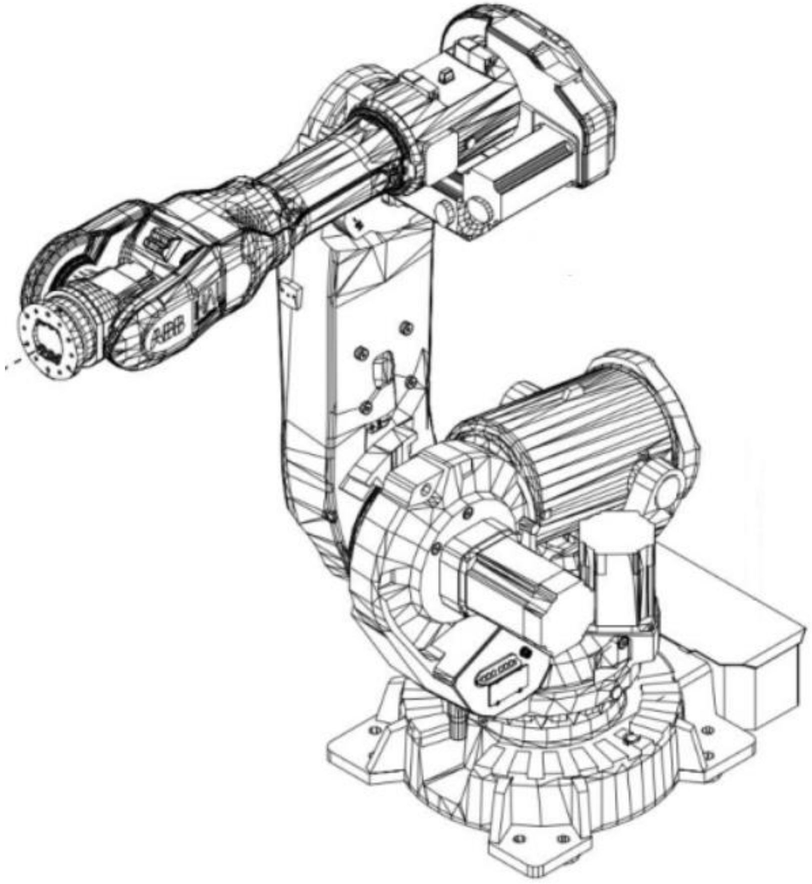


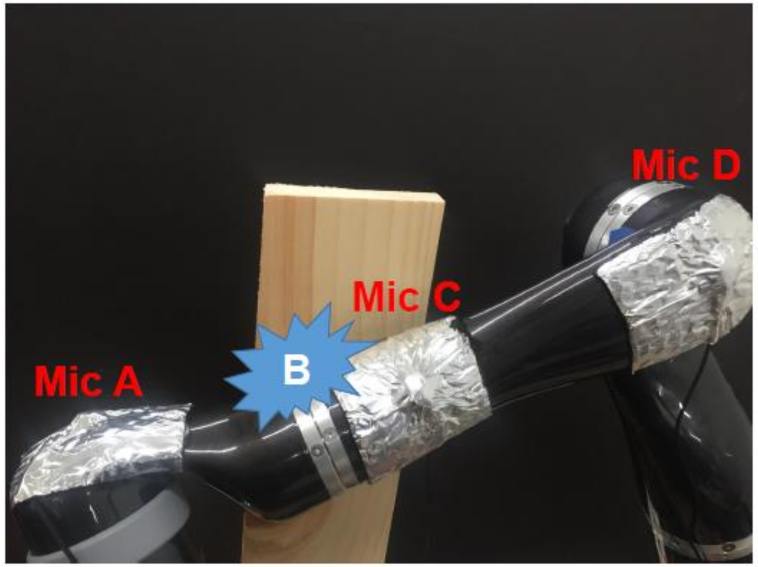




**Correlation based methods won't work well**

# Physics behind On-robot Collisions

- Structural heterogeneity – D might receive signal earlier than A





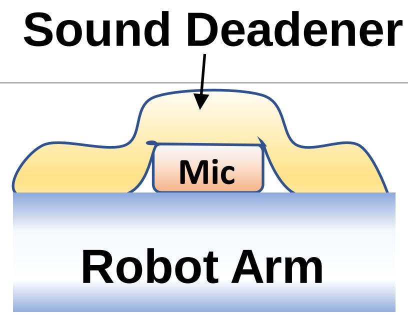
# Overview

## *Panotti* System Design

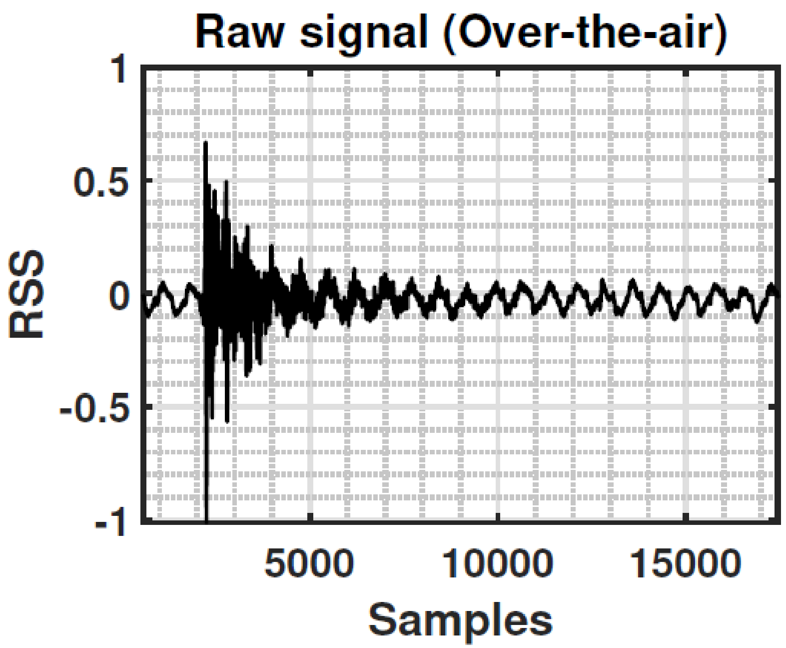
- *Panotti* system Vs. mythology
- Spectrum prorating for collision detection
- Epicenter Multilateration for Collision Localization (EMCL)
- Motor noise suppression

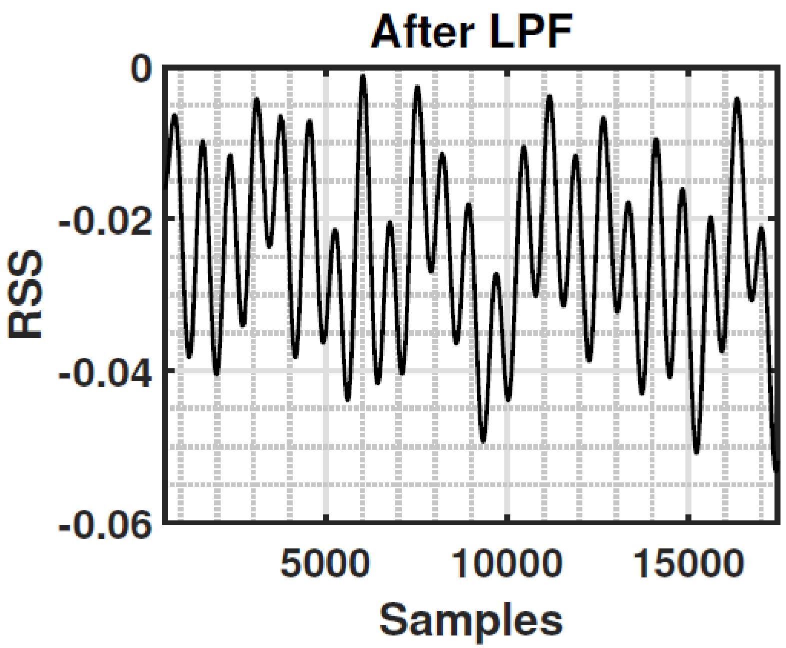
# Collision Detection






- Over the air noise
- Physical isolation
- On-robot collisions introduce micro vibrations along the robot body, which translates to significantly high amount of infrasound energy

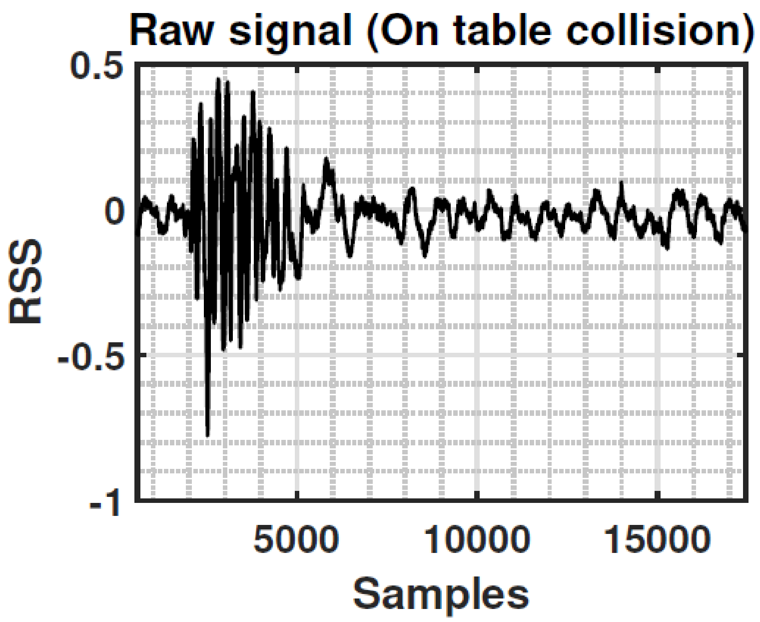


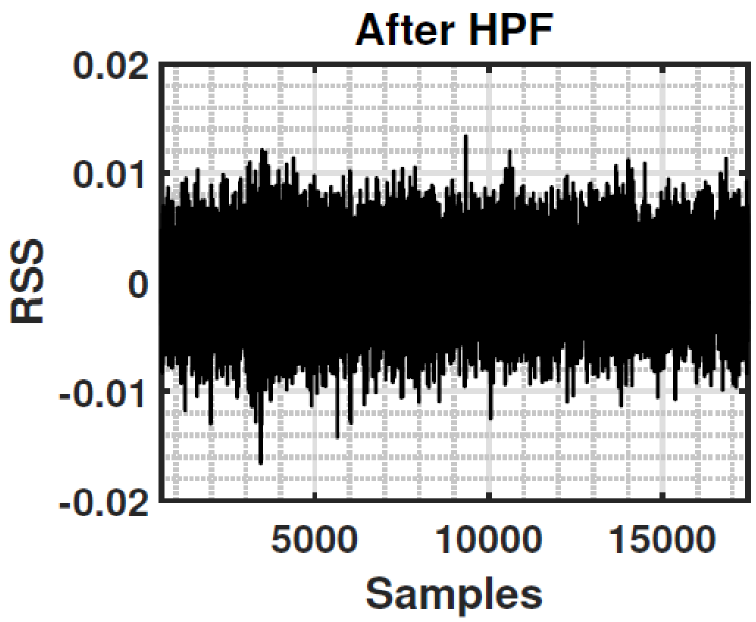




Low Pass Filter (LPF)

# Collision Detection

- On table/floor noise
- The high frequency components attenuates exponentially faster than the low frequency components
- Comparing with audio signals propagating in the air, solid materials such as wood and concrete floor absorb several magnitudes more energy in the whole spectrum



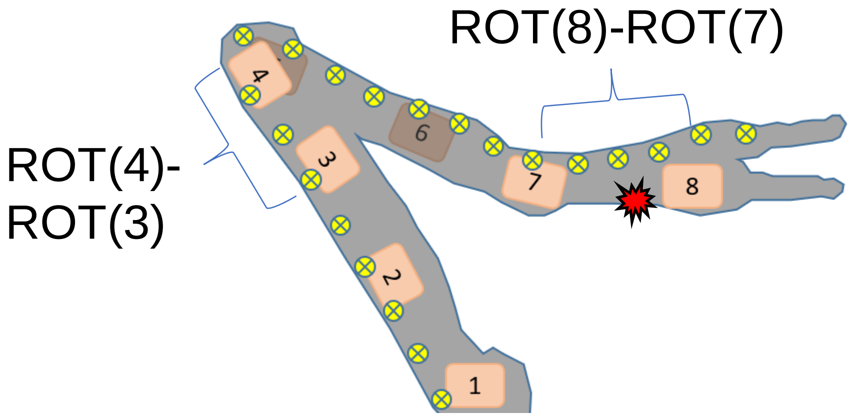

**High Pass Filter (HPF)**

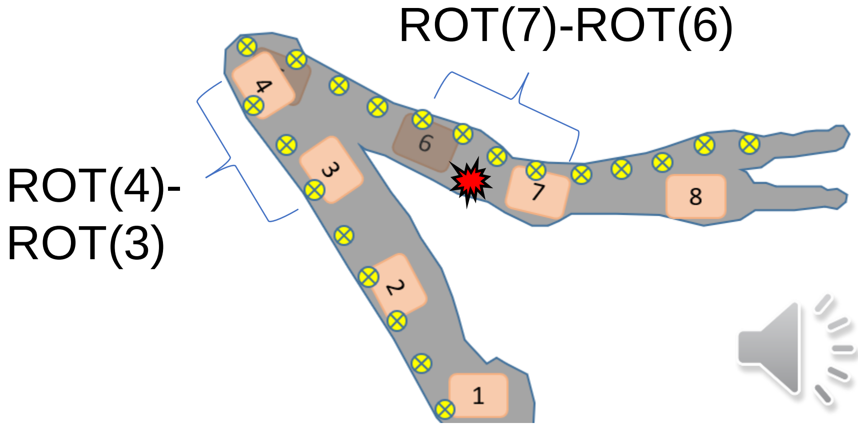
# EMCL

**N** is the number of microphones

**ROT (Relative Onset Time) :**
**ROT = [t1,t2,…,tN] - min[t1,t2,…,tN]**

- ROT(8)-ROT(7) changes when collide between 8 and 7
- ROT(7)-ROT(6) changes when collide between 7 and 6
- However, ROT(4)-ROT(3) remains the same
- Intuition: The ROT is a one-dimensional manifold in the N dimension microphone space



# EMCL - Manifold Acquisition



**M** is the number of marker location for training

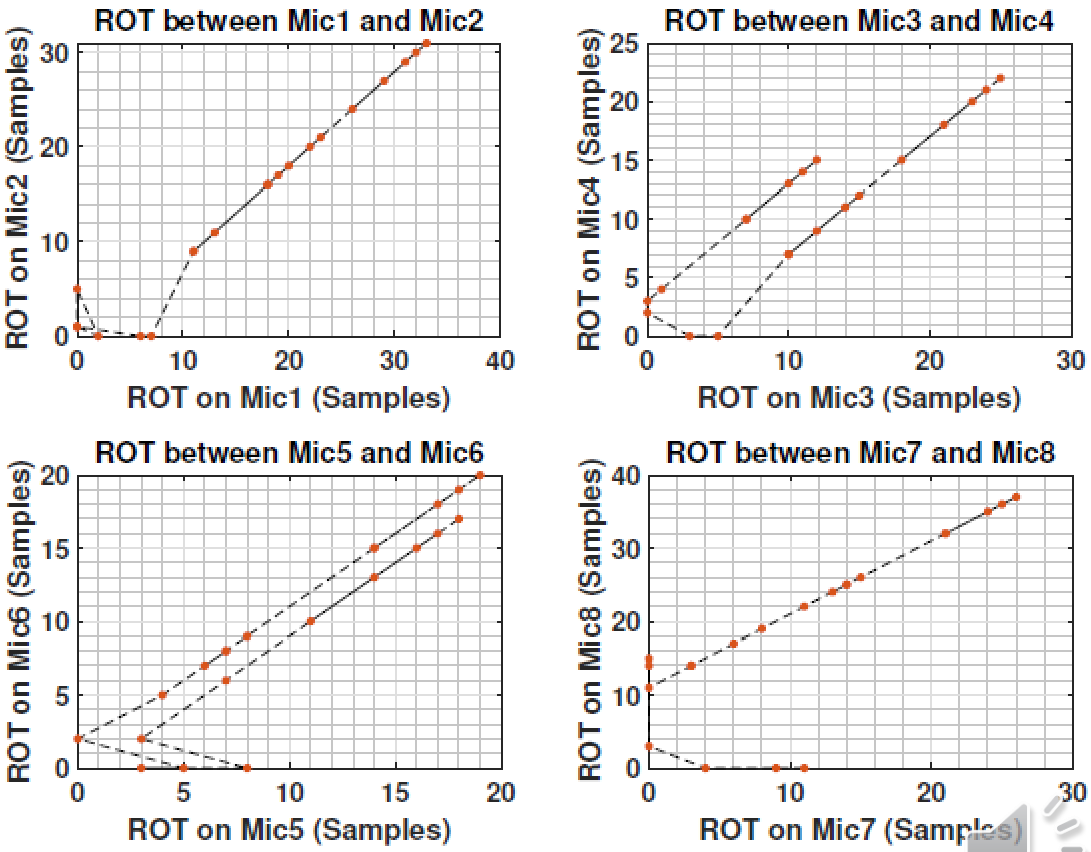
$$\mathcal{M} = [ROT_1; ROT_2; ...; ROT_M].$$

→ Hard to determine accurate onset times for the microphones far from the signal source

**Algorithm 2** Cleansing the $M \times N$ dimension manifold

**function** CLEANSING($\mathcal{M}, \Delta T$)
  $V = NULL$
  **for** i ← 1 to M **do**
    $temp = ROT_i$
    index = argmin($ROT_i$)
    **for** j ← index to 1 **do**
      **if** j≤2 **then**
        Break
      **else**
        $temp(j-2) = temp(j-1) + \Delta T(j-2)$
      **end if**
    **end for**
    **for** j ← index to N **do**
      **if** j≥N-1 **then**
        Break
      **else**
        $temp(j+2) = temp(j+1) + \Delta T(j+1)$
      **end if**
    **end for**
    $V$ = Concatenate($V, temp$)
  **end for**
  **return** $V$
**end function**

After Cleansing

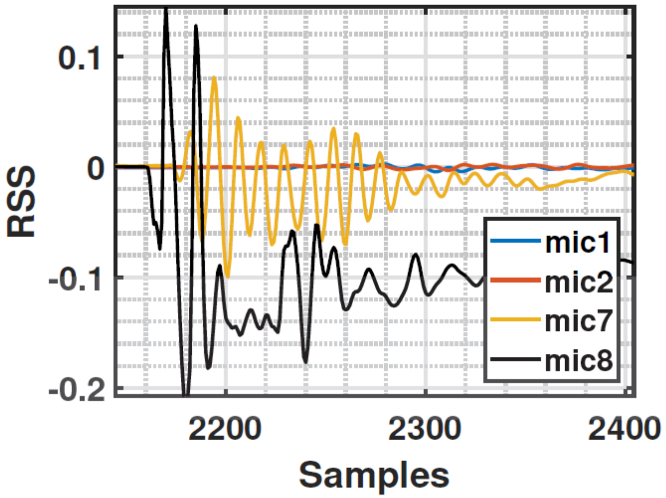


# EMCL – Incoming Collisions

- We only find the onset time of first peak $t_{ref}$ from the microphone that has the strongest signal

- Virtual onset time: $\mathcal{U} = \mathcal{M} - \mathbf{1}_N^T \otimes \mathcal{M}(i) + \mathbf{1}_M \cdot \mathbf{1}_N^T \cdot t_{ref}.$

- Scoring function, *S(i)* is the score for $i_{th}$ location: $\mathcal{S}(i) = \sum_{k=1}^{N} \mathcal{F}(\mathcal{U}_i(k))^2.$




$\otimes$: Kronecker tensor product; *M(i)* is the $i_{th}$ column in *M*; $1_N$ is a column vector of 1 with N elements

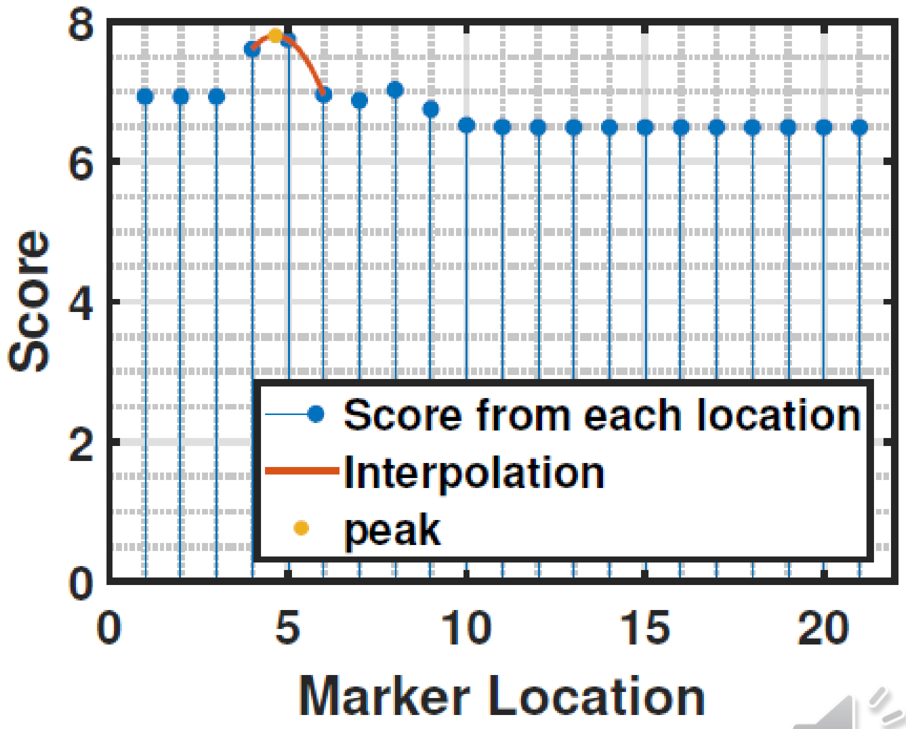
Hint: The first peak is relatively easy to find

# EMCL – Final Localization

- We choose the standard deviation within a small window as the scoring function
- Intuition: the signal starts to rise and oscillate in a faster rate if we found the right onset time

**Algorithm 3** Localization

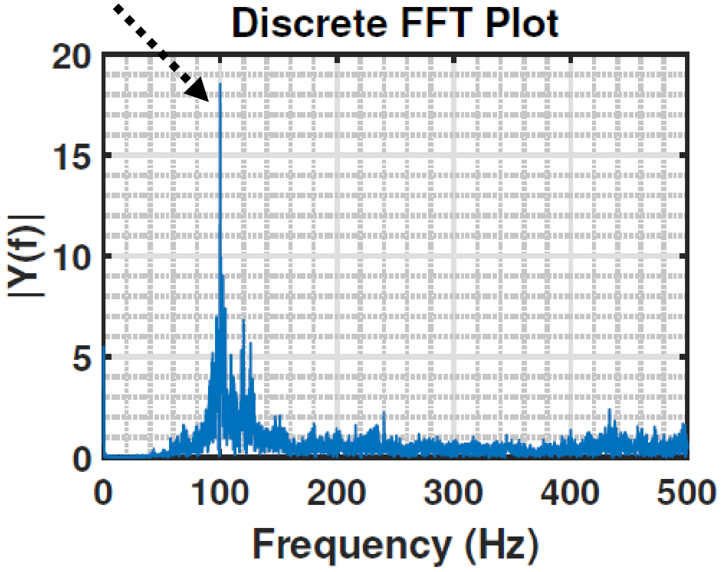
```
function LOCALIZATION(𝒮)
    k = argmax(𝒮)
    if k == 1 then
        𝒞 = QuadraticFit([S(1), S(2), S(3)])
    else
        if k == N then
            𝒞 = QuadraticFit([S(k), S(k − 1), S(k − 2)])
        end if
        𝒞 = QuadraticFit([S(k − 1), S(k), S(k + 1)])
    end if
    return argmax(𝒞)
end function
```



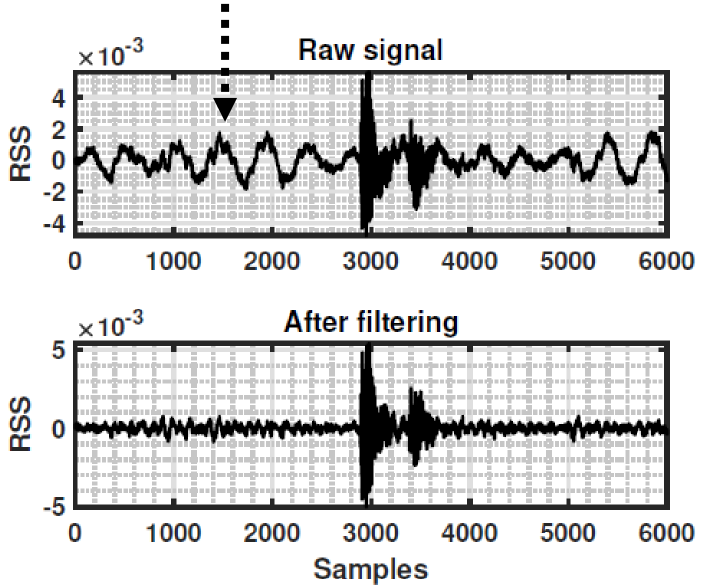
# Motor Noise Suppression

- Noise comes from the fundamental of robot motors
- One-time calibration for each robot
- Band-stop filter to remove motor noise

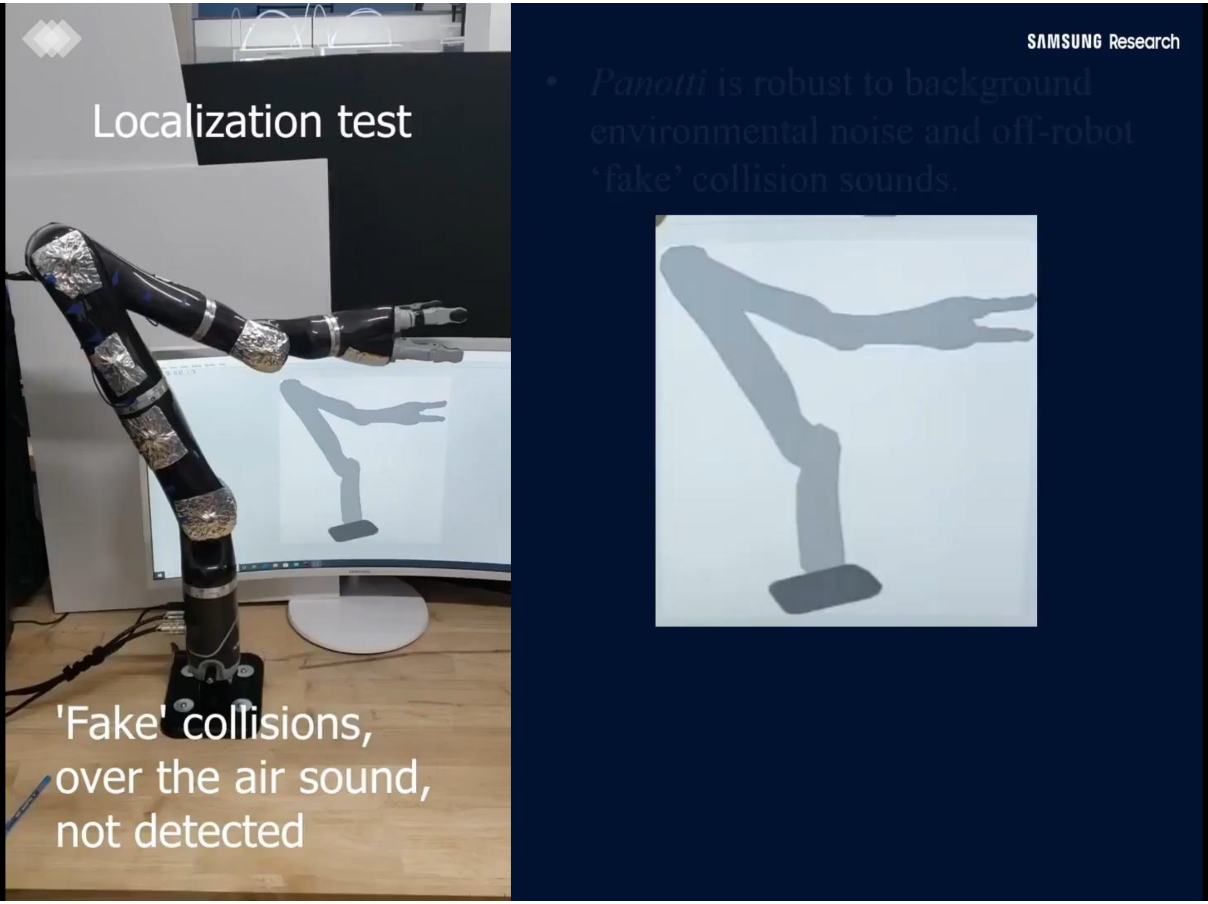
Motor fundamental




Motor noise

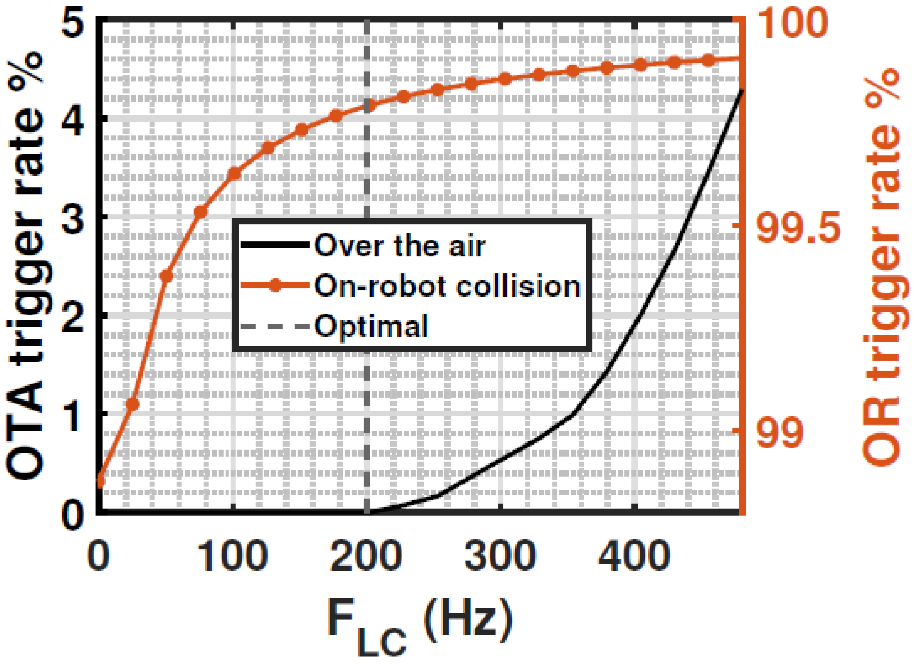


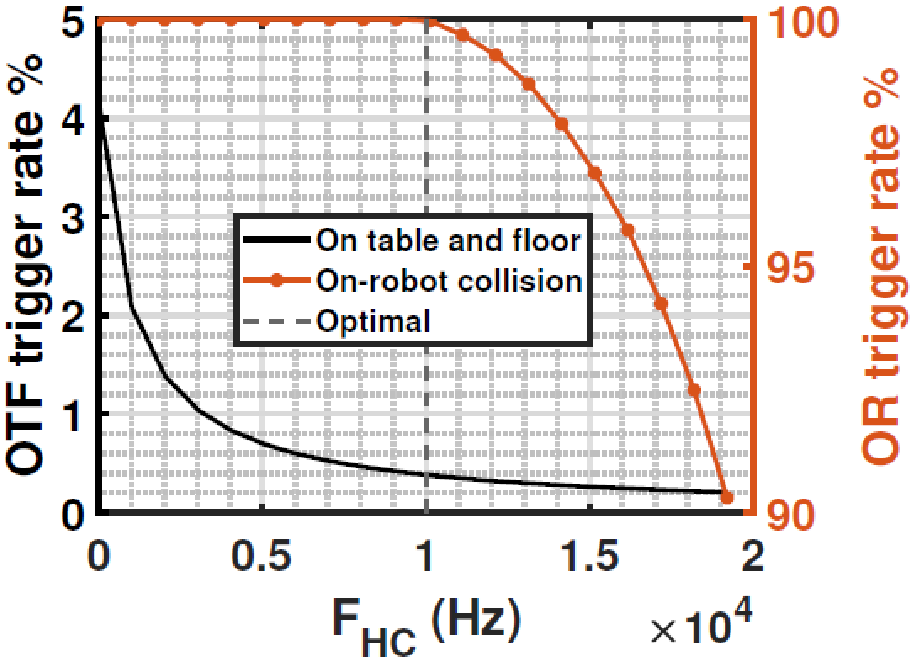
# Collision Detection and Localization Demo



# Experiment - Microbenchmark

- Determine optimal filter parameters for collision detection

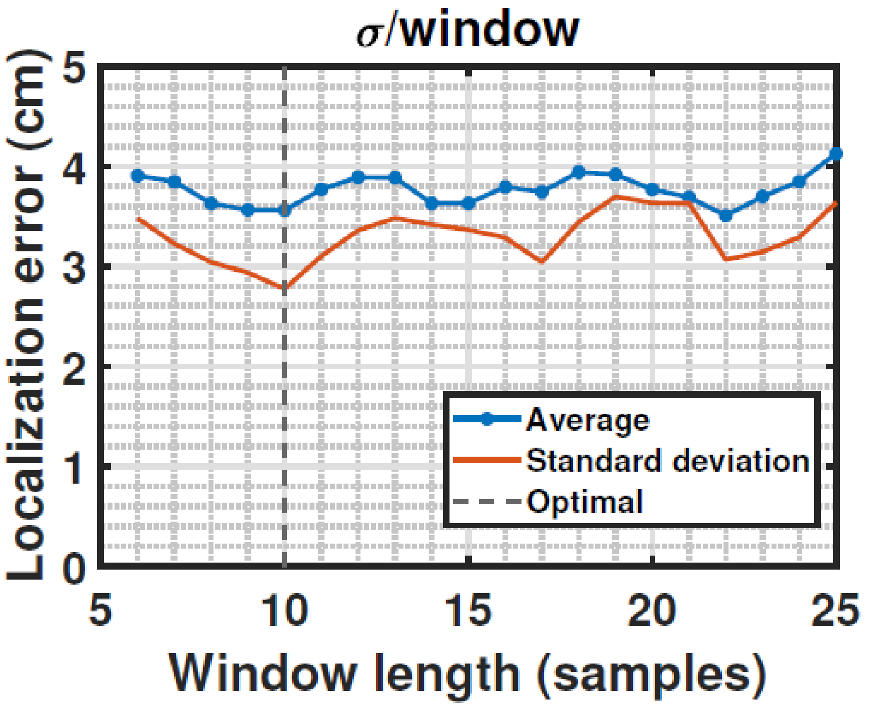


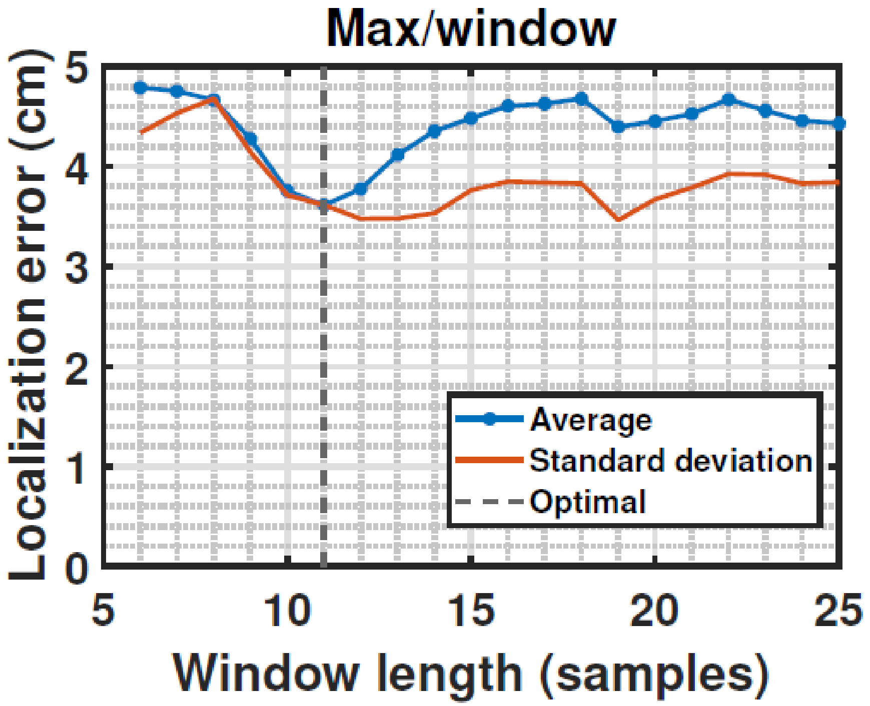

200 Hz cut off frequency for the low pass filter

10 kHz cut off frequency for the high pass filter

# Experiment - Microbenchmark




Window length when choose standard deviation as the scoring function



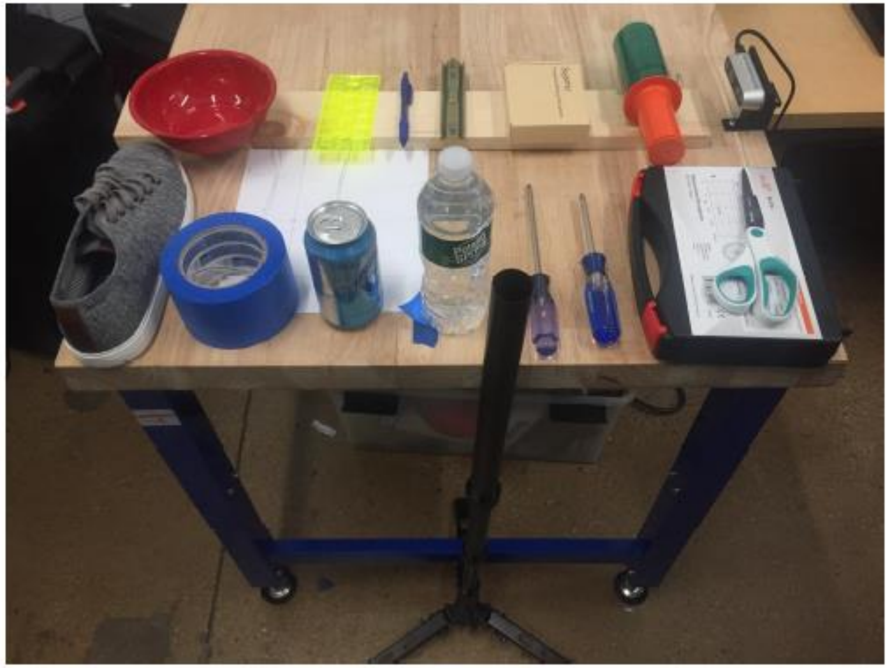

Window length when choose max strength as the scoring function

| **Scoring method** | Absolute value | Absolute value$^2$ | Max/window | Average/window | $\sigma$/window |
|---|---|---|---|---|---|
| **Average/$\sigma$** $(cm)$ | 4.38/3.87 | 4.42/3.76 | 3.87/3.12 | 4.28/3.57 | 3.47/2.79 |

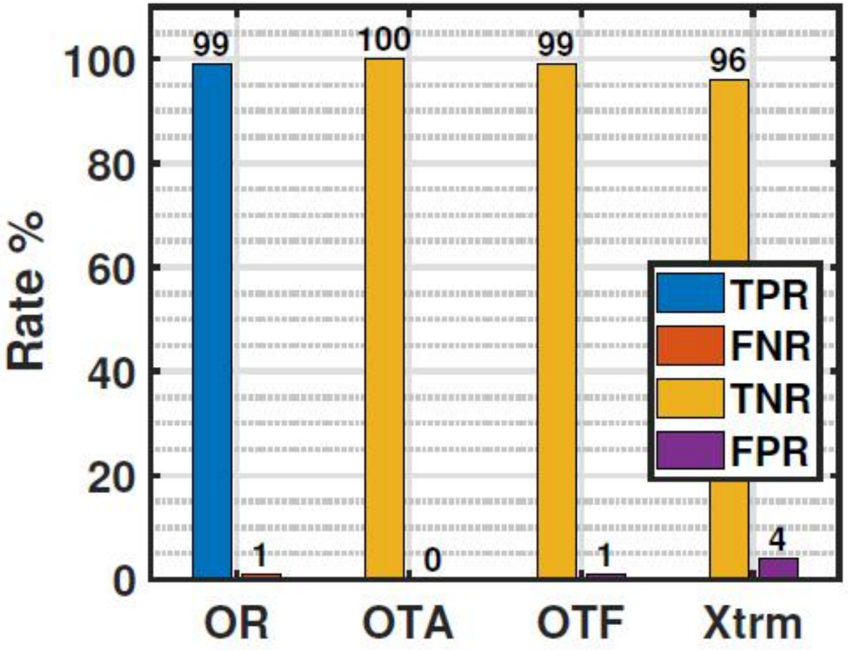
Scoring function study

# Experiment – Field Study

- Collision detection under various settings



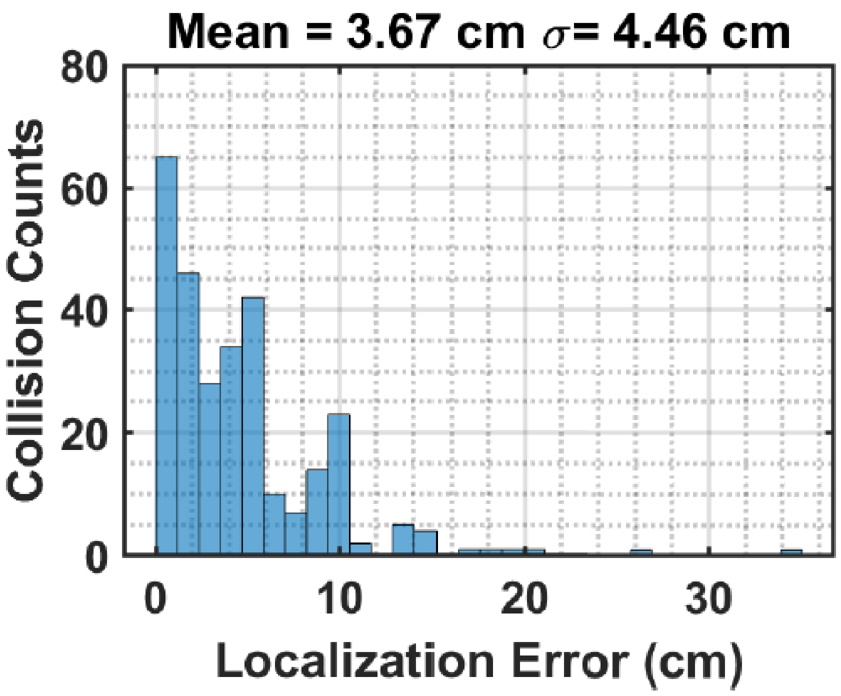
Collision objects in our experiments



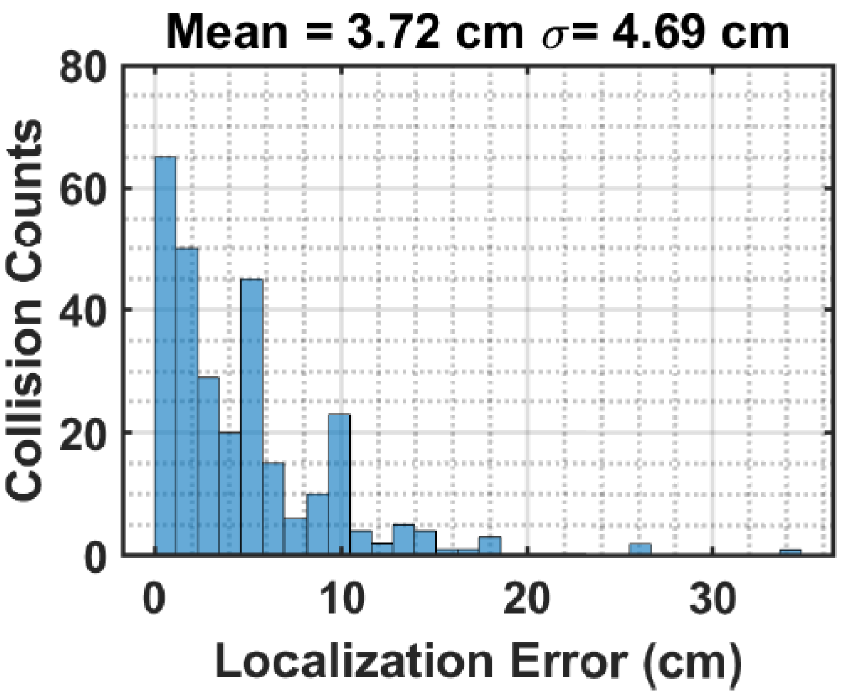

OR: on robot
OTA: over the air
OTF: on table/floor
Xtrm: extreme exp settings

TPR: True Positive rate
FNR: False Negative rate
TNR: True Negative rate
FPR: False Positive rate

- Localization accuracy when the robot arm stays static




Localization accuracy with various objects (including human)




Data with augmented motor noise

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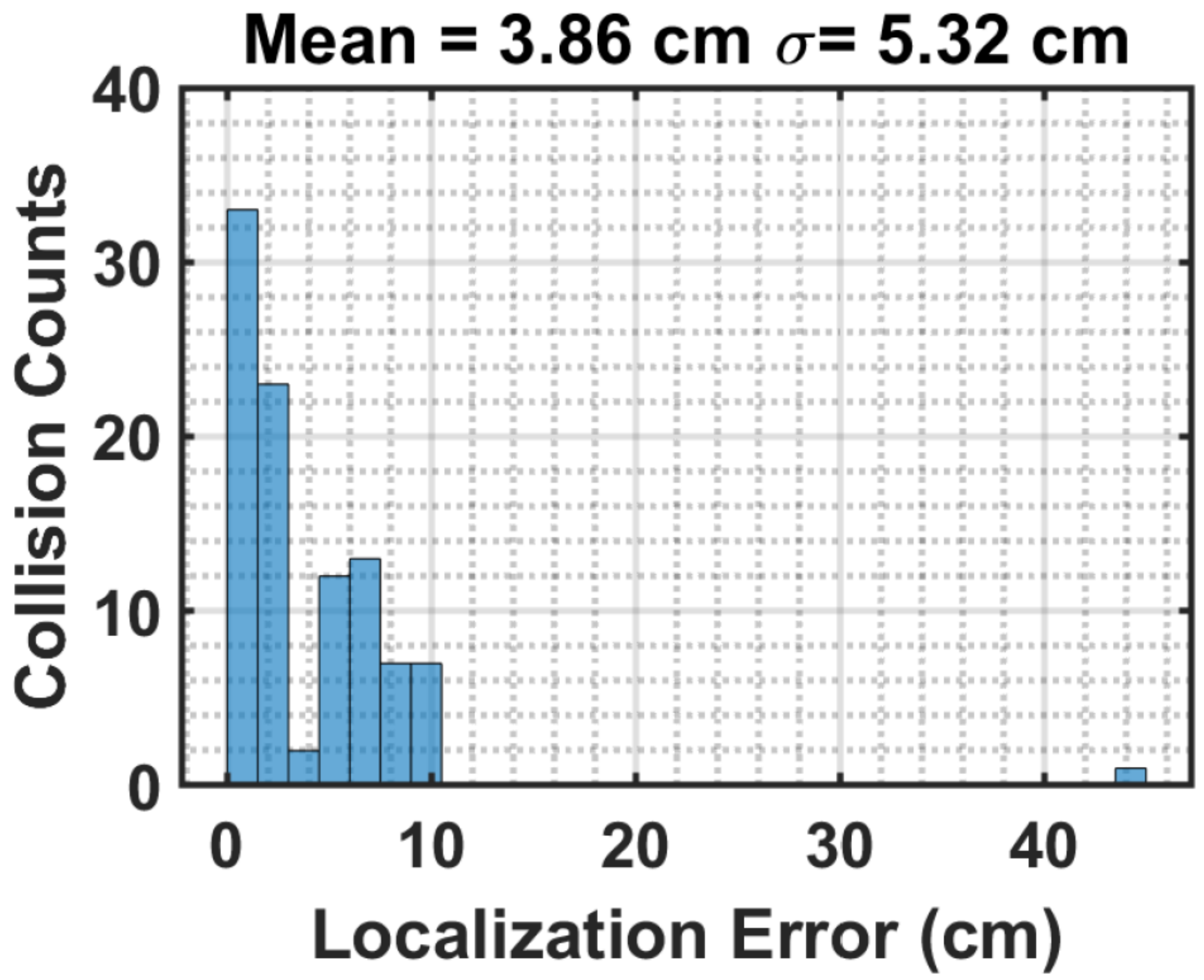
- Localization accuracy when the robot arm is moving



# Summary

- *Panotti* is the first accurate on-robot collision detection and localization system using low cost microphones
- We propose signal processing algorithms to address unique challenges for on-robot collision detection and localization
- We implement our design in an end-to-end system and did extensive evaluations of our method. The *Panotti* system is promising to be used in realworld scenarios such warehouse

# Thank You