Paper Study Report:

Device-Free Gesture Tracking Using Acoustic Signals

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Reference

- ***Device-Free Gesture Tracking Using Acoustic Signals***, Wei Wang, Alex X. Liu, Ke Sun, The 22nd Annual International Conference on Mobile Computing and Networking (October, 2016)
- https://dl.acm.org/doi/10.1145/2973750.2973764

Problem Statement

- **Try to do: software based single** object tracking on **mobile devices**

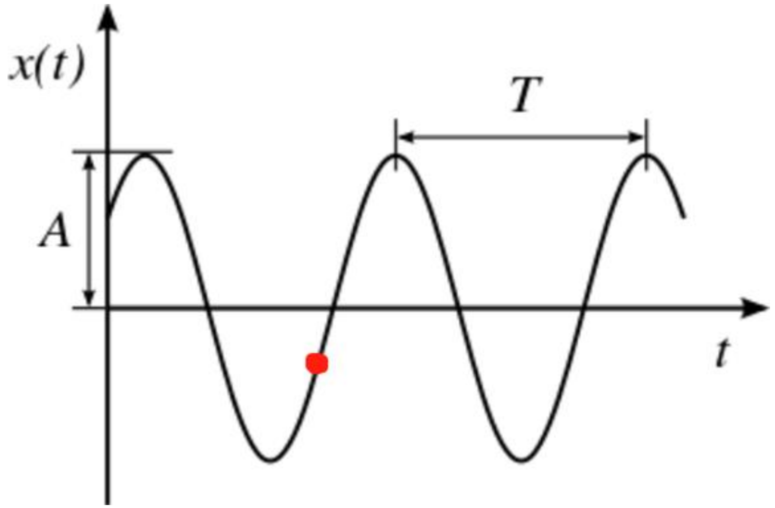
  → **acoustic signal**

- **Input**: sound signal from microphones
- **Output**: real-time object position
- **Design Goal**: high accuracy, **low latency**
- **Constraints**: low computation cost

Basic Idea

1. Use **continuous wave** to measure **phase**

- Formula: $F(t) = A \cdot cos(2\pi f t + \varphi)$



- Received sound signal in this environment

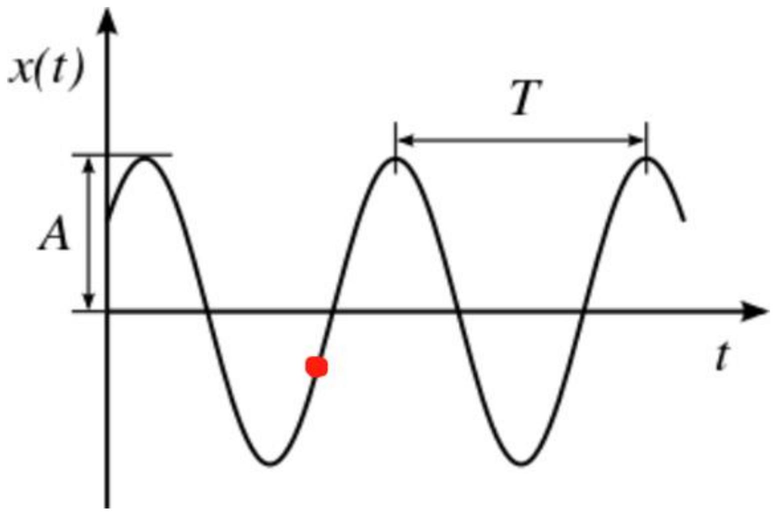
$$\boldsymbol{R_p(t) = 2A_P \cdot cos\left(2\pi f t - 2\pi f \frac{d_p(t)}{c} - \theta_p\right)}$$

$\boldsymbol{p}$: path the signal travel through, $\boldsymbol{d_p(t)}$: time-varying path length

$\boldsymbol{f}$: features of signal, **variables we can set and adjust!**

(4.3) $\boldsymbol{\theta_p}$: initial phase offset caused by hardware delay & phase inversion

Basic Idea



1. Use **continuous wave** to measure **phase**

- Formula: $\mathrm{F}(t) = A \cdot cos(2\pi f t + \varphi)$
- Received sound signal in this environment

$$\boldsymbol{R_p(t) = 2A_p \cdot cos\left(2\pi f t - 2\pi f \frac{d_p(t)}{c} - \theta_p\right)}$$

→ When $\boldsymbol{d_p(t)}$ increase by $\lambda = c/f$, $\boldsymbol{\varphi}$ decrease by 2π

→ Known: $\boldsymbol{A_p}$, $\boldsymbol{f}$ Need to get: $\Delta\varphi$ What we want: $\boldsymbol{d_p(t)}$

How?

Real World Signals

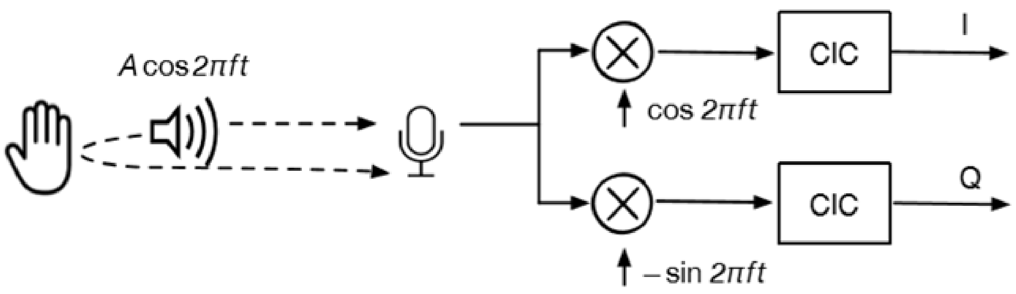
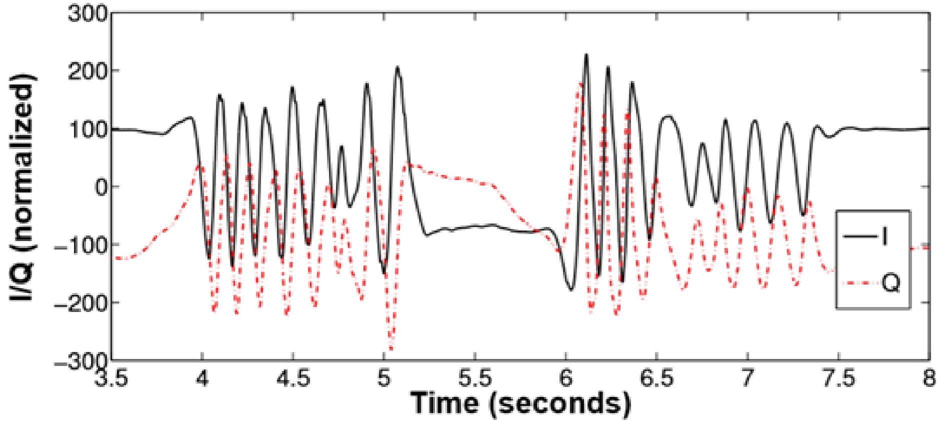


Figure 4: System structure



(a) I/Q waveforms

I: in-phase, as the real part

$$I_p(t) = A'_P cos(-2\pi f \frac{d_p(t)}{c} - \theta_p)$$

Q: quadrature, as the imaginary part

$$Q_p(t) = A'_P sin(-2\pi f \frac{d_p(t)}{c} - \theta_p)$$

→ complex baseband signal

Observe that I/Q waveforms:

static when object not moving

sinusoid when object moving

Basic Idea

2. Decompose the received signal in **vector space**

- Baseband signal (I/Q) = **static vector** + **dynamic vector**

static vector: signal reflected by static objects (walls, tables)

remain static during short time period

*note: may slightly change when object moving(especially moving fast), need to be quickly traced. Must be constant when nothing moving.

 need to extract

dynamic vector: signal reflected by moving objects

 indicate how φ change, what we need

Basic Idea

2. Deco

• Baseb

static

*no ng fast),
nee ng.

dynam

find $\boldsymbol{d_p(t)}$

⬇

find $\Delta\varphi$

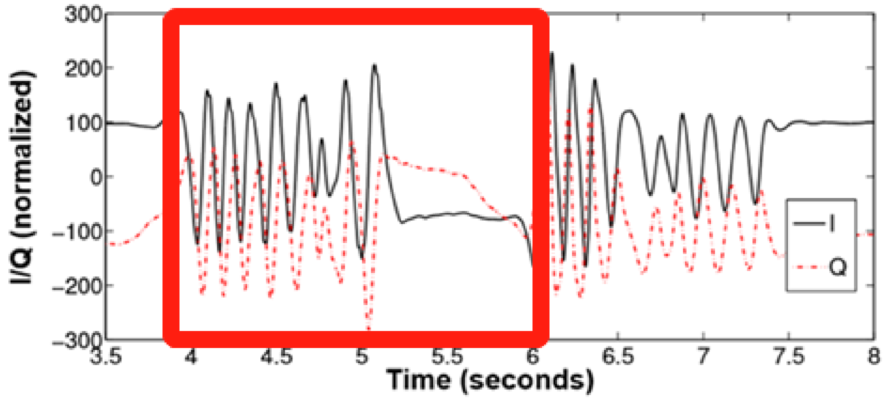
⬇

find **static & dynamic vector** in I/Q vector space

1 how to extract static vector

2 what's relation between dynamic vector & $\Delta\varphi$

① Static Vector: *Local Extreme Value Detection*



(a) I/Q waveforms

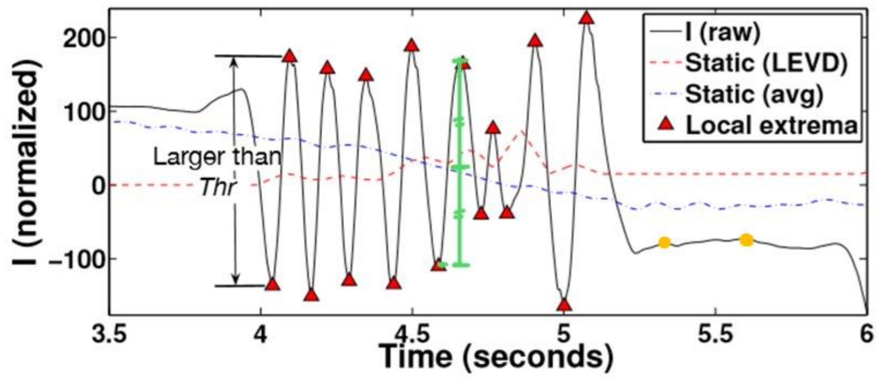


Figure 6: Local extrema based static vector estimation

- I/Q signal = static vector + dynamic vector

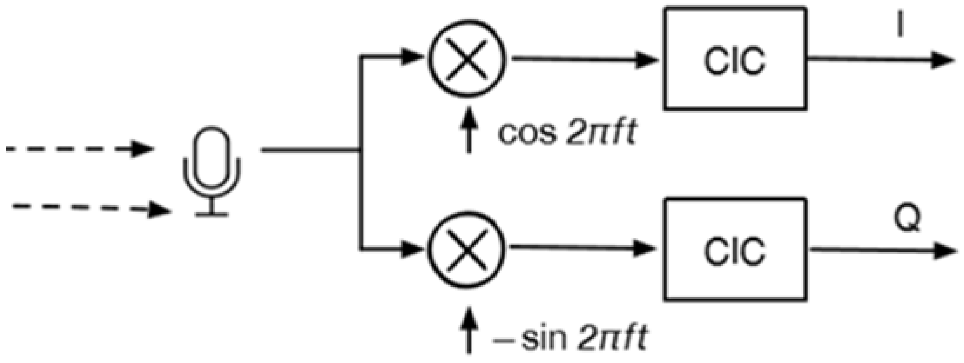
STEP 1. Pick local extremes with **large variation**, indicate movement

in this paper: $3 \times SD$ (baseband signal in a static environment)

STEP2. Take **Eestimated value of static vector** = *avg(* **nearby max & min** *)*

During 3.5-3.8s & 5.5-6s: stable (no valid extremes) ✓

$$I_p(t) = A'_P\boldsymbol{cos}(\boldsymbol{\varphi})$$



$$Q_p(t) = A'_P\boldsymbol{sin}(\boldsymbol{\varphi})$$

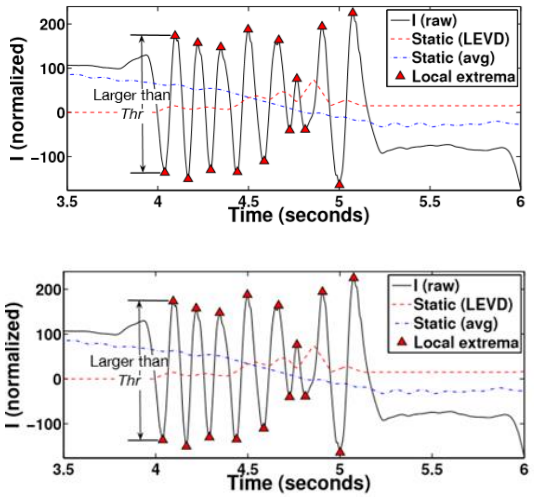
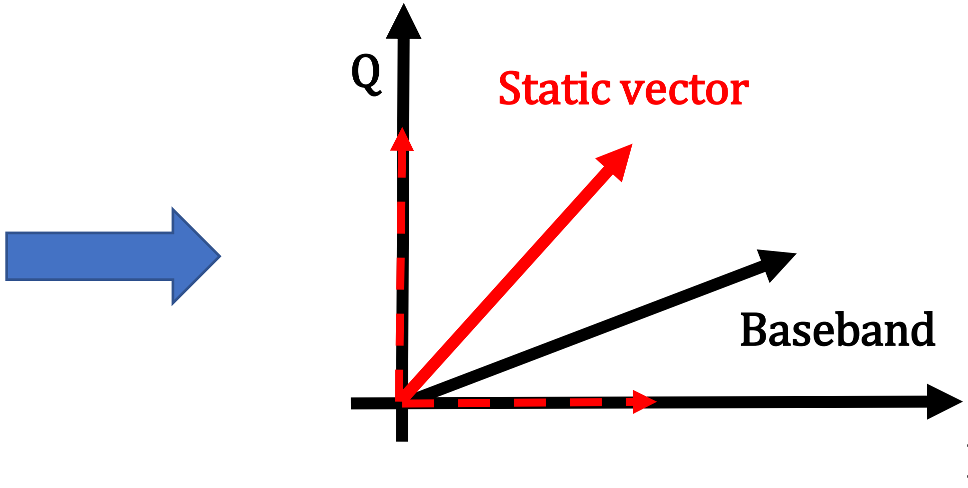


Figure 6: Local extrema based static vector estimation

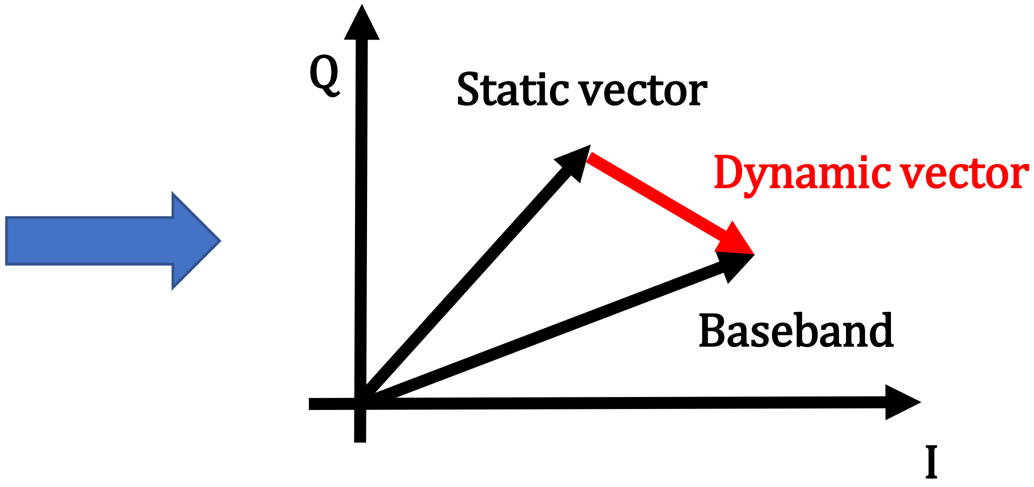
Static Vector of I

+

Static Vector of Q

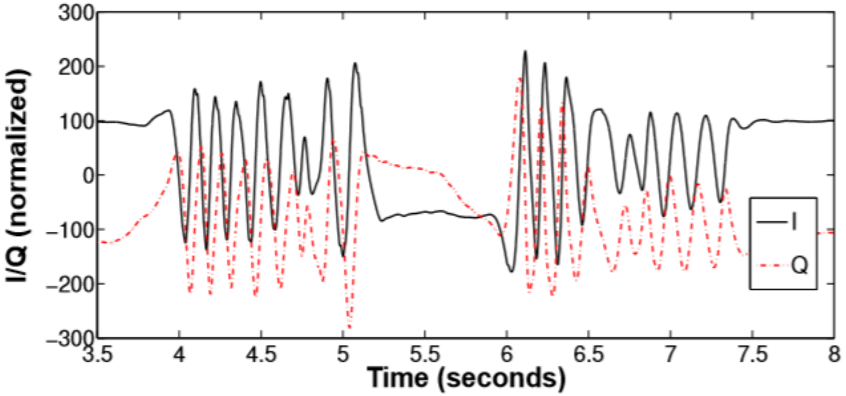


Static Vector of baseband signal

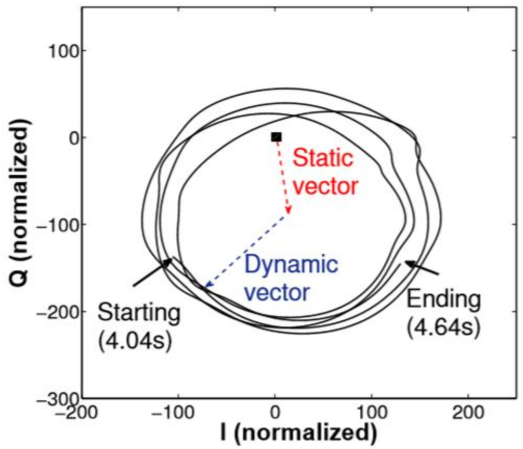


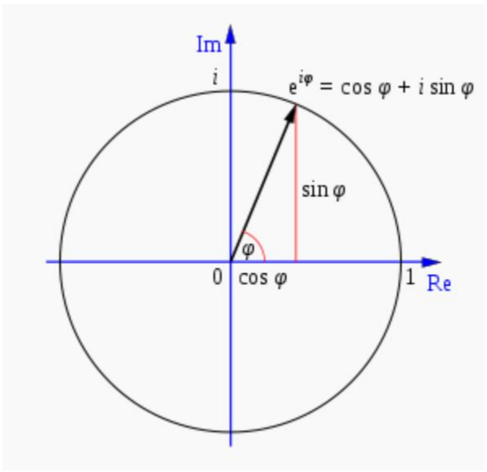
Dynamic Vector of baseband signal

② Real Word Signal - Vector Space



(a) I/Q waveforms





- Euler's formula: $B_p(t) = A'_p e^{-i\varphi} = A'_p e^{-i(2\pi f \frac{d_p(t)}{c} + \theta_p)}$ → circle
- Direction: object direction ⟺ sign of $\Delta\varphi$ ⟺ signal direction

  move closer ⟺ $d_p(t)$ ⤹ , φ ⤴ ⟺ signal move anti-clockwise

- Distance: object move $\boldsymbol{x}$ mm ⟺ $\boldsymbol{d_p(t)}$ change $\boldsymbol{2x}$ mm

  ⟺ $\boldsymbol{\varphi}$ change $\boldsymbol{2\pi \cdot 2x/\lambda}$ ⟺ signal move by $\boldsymbol{\varphi/2}$ circles

Design Goal

- High Accuracy ✓
- Low Latency ✓

Remaining Issues

- $\Delta\varphi$ indicate $\Delta d_p(t)$, not $d_p(t)$
- Initial position?

Absolute Distance

- Input: different frequencies $f_k = f_0 + k\Delta f$, k = 0, … , N − 1
- Baseband Signal **for certain path $\boldsymbol{p}$ at frequency $\boldsymbol{f_k}$**:

$$B_p(k,t) = A'_{p,k} e^{-i\left(2\pi(\boldsymbol{f_0+k\Delta f})\frac{\boldsymbol{d_p(t)}}{c}+\theta_{p,k}\right)}$$ (frequency domain)

- Apply Inverse Discrete Fourier Transform on $B_p(k,t)$

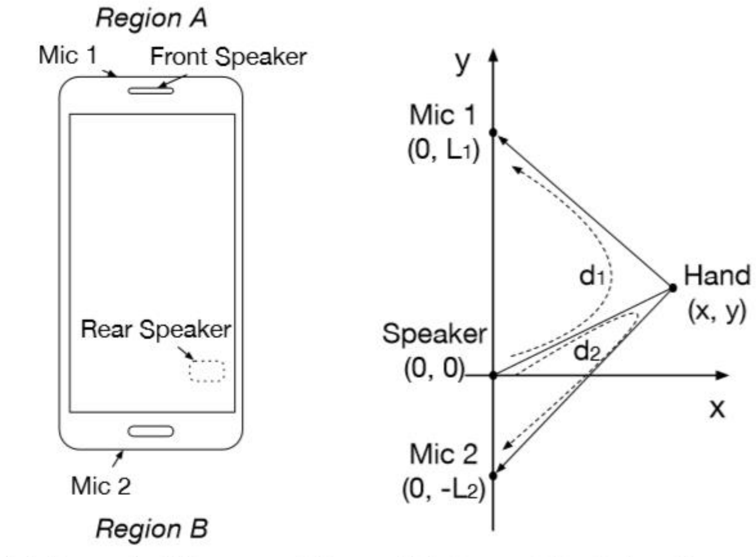
$$b_p(k,t) = \frac{1}{N}\sum_{k=0}^{N-1} B_p(k,t)e^{i2\pi kn/N}, n = 0, \ldots, N-1$$ (time domain)

→ $b_p(k,t)$ has peak at time $\hat{n} = N\boldsymbol{d_p}(\boldsymbol{t})\Delta f/c$

- Each peak corresponds to one path caused by on object
- For each k (each frequency):

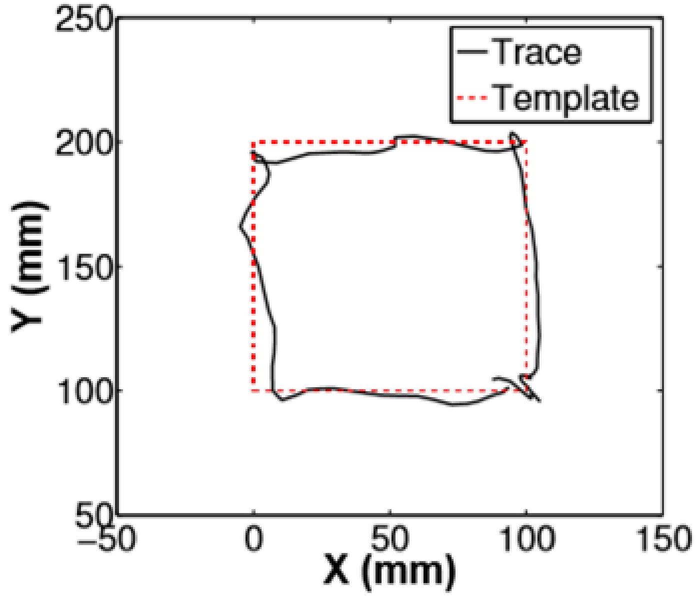
$b_p(k,t)$ peak → time point $\hat{n}$ → $\boldsymbol{d_p}(\boldsymbol{t})$ absolute distance

2D Gesture Tracking



(a) Layout of Samsung S5 (b) Geometric abstraction

Figure 9: Two dimensional tracking



(a) Drawing square

- On an ellipse
- Known: $L_1, L_2,\ \ d_1, d_2$
- Compute x, y

$$x = \frac{\sqrt{(d_1^2 - L_1^2)(d_2^2 - L_2^2)\left((L_1 + L_2)^2 - (d_1 - d_2)^2\right)}}{2(d_1 L_2 + d_2 L_1)}$$

$$y = \frac{d_2 L_1^2 - d_1 L_2^2 - d_1^2 d_2 + d_2^2 d_1}{2(d_1 L_2 + d_2 L_1)}$$

Remaining Questions

- Inverse Discrete Fourier Transform

  $B_p(k,t)$ & $b_p(k,t)$

- Object Size

- Multi Objects