Cross
Correlation

Demo

Formula with Landmark Signals

Generatin Landmark

1 STET

2. Create Landm

3. Pair Landmarks

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Synchronizing Audio Signals

via Landmark Cross Correlation

by Lea N. Possberg

Seminar: Speech Processing

November 30, 2017

Motivation

A B C B B D B D

Figure: Clustering and Synchronization (Bryan, Smaragdis, Mysore, 2012)

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Cross Correlation Function R

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

What does R do?

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Video

(https://www.youtube.com/watch?v=L6YJqhbsuFY)

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Cross Correlation Function R -Landmark Signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

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Cross Correlation Function R -Landmark Signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

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Cross Correlation Function R - Landmark Signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} L_i(\tau)^T L_j(\tau+t)$$

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Cross Correlation Function R - Landmark Signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} L_i(t)^{\mathsf{T}} L_j(\tau+t)$$

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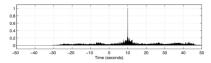
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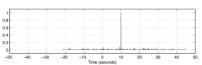
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Landmark Signals - Why?



(a) Normalized absolute time-domain cross-correlation.



(b) Normalized landmark cross-correlation.

Figure: Absolute vs. Landmark Cross Correlation (Bryan, Smaragdis, Mysore, 2012)

Cross Correlation

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Generating Landmark Signals - How?

Follow Steps 1-4

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1. Take the Short Time FT of a given audio signal





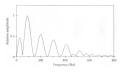


Figure: Given audio signal

Figure: Spectrum

(Images: Wagner, 2017)

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2. Identify frequency peaks and create landmark tuple





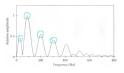


Figure: Given audio signal

Figure: Spectrum

(Images: Wagner, 2017)

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2. Identify frequency peaks and create landmark tuple

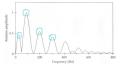


Figure: Spectrum

$$\mathsf{landmark} = (\mathsf{frequency}, \, \mathsf{timevalue}) = (\mathit{f}_1, \mathit{t}_1)$$

"time idexed frequency value"

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2. Identify frequency peaks and create landmark tuple

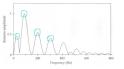


Figure: Spectrum

$$landmark = (f_1, t_1)$$

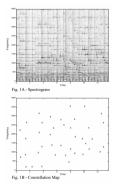


Figure: Spectrogram (Wang, 2003)

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3. Pair landmarks with nearest other landmarks

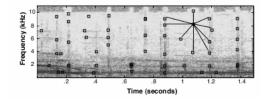


Figure: Spectrogram (Kennedy, Naaman, 2009)

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3. Pair landmarks with nearest other landmarks

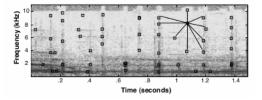


Figure: Spectrogram (Kennedy, Naaman, 2009)

landmark-pair = landmark = (frequency, frequency, timevalue)
=
$$(f_1, f_2, t_2 - t_1)$$

"time indexed landmark"

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4. Hash each landmark and create feature vector

 $hash: landmark \rightarrow integer$

$$(f_1, f_2, t_2 - t_1) \mapsto 2$$

4 Hash Landmarks

4. Hash each landmark and create feature vector

$$(f_1, f_2, t_2 - t_1) \mapsto 2$$

create feature vector:
$$\begin{pmatrix} 0 \\ 0 \\ ... \\ 0 \end{pmatrix}$$

- 4 Hash Landmarks

4. Hash each landmark and create feature vector

$$\textit{hash}: \textit{landmark} \rightarrow \textit{integer}$$

$$(f_1, f_2, t_2 - t_1) \mapsto 2$$

create feature vector:
$$\begin{pmatrix} 0 \\ 0 \\ ... \\ 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ 1 \\ ... \\ 0 \end{pmatrix} = L(t=6)$$

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4. Hash each landmark and create feature vector

 $\textit{hash}: \textit{landmark} \rightarrow \textit{integer}$

$$(f_1,f_2,t_2-t_1)\mapsto 2$$

create feature vector:
$$\begin{pmatrix} 0 \\ 0 \\ ... \\ 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ 1 \\ ... \\ 0 \end{pmatrix} = L(t=6)$$

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$$\begin{pmatrix} 0 \\ 1 \\ \dots \\ 0 \end{pmatrix} = L(t=6)$$

$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} L_i(t)^T L_j(\tau+t)$$

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$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} \underbrace{L_i(t)^T L_j(\tau+t)}$$

$$\begin{pmatrix} 0 & 1 & \dots & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \dots \\ 1 \end{pmatrix} = constant$$

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$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} \underbrace{L_i(t)^T L_j(\tau+t)}_{}$$

$$\begin{pmatrix} 0 & 1 & \dots & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \dots \\ 1 \end{pmatrix} = constant$$

"Amout of matching landmarks in both signals at one point in time"

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$$R_{L_i,L_j}(\tau) = \sum_{t=-\infty}^{\infty} L_i(t)^T L_j(\tau+t)$$

$$\begin{pmatrix} 0 & 1 & \dots & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \dots \\ 1 \end{pmatrix} = constant$$

"Amout of matching landmarks in both signals at one point in time"

"Total amount of matching landmarks for one time shift au"

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$$\hat{\tau}_{ij} = \arg\max_{\tau} R_{L_i,L_j}(\tau)$$

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Synchronizing both signals

$$\hat{\tau}_{ij} = \arg\max_{\tau} R_{L_i,L_j}(\tau)$$

"time offset to align both signals L_i and L_i "

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Complexity $(n \stackrel{.}{=} file\ length)$

• 2 loops over $t, \tau \longrightarrow \mathbf{O}(\mathbf{n}^2)$

Complexity

Complexity $(n \stackrel{\hat{}}{=} file\ length)$

• 2 loops over
$$t, \tau \longrightarrow \mathbf{O}(\mathbf{n}^2)$$

 use FFT: no need to loop over t anymore, only 1 loop over $\tau \longrightarrow \mathbf{O}(\mathbf{n} \log \mathbf{n})$

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FFT of the two signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

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FFT of the two signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

Frequency Domain: $FFT(f^*)$

FFT of signals

FFT of the two signals

$$R_{f,g}(au) = \sum_{t=-\infty}^{\infty} f^*(t)g(au+t)$$

 $FFT(f^*)$ FFT(g)Frequency Domain:

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Demo Formula with

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FFT of the two signals

$$R_{f,g}(au) = \sum_{t=-\infty}^{\infty} f^*(t)g(au+t)$$

Frequency Domain:
$$FFT(f^*) * FFT(g)$$

FFT of signals

FFT of the two signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

 $FFT(f^*) * FFT(g)$ Frequency Domain:

Time Domain: IFFT ($FFT(f^*) * FFT(g)$)

FFT of signals

FFT of the two signals

$$R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$$

Frequency Domain: $FFT(f^*) * FFT(g)$

IFFT ($FFT(f^*) * FFT(g)$) Time Domain:

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2 Reduce costs by transforming absolute signals f, g to Landmark signals L_i, L_j

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- 1 $R_{f,g}(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(\tau+t)$
- **2** Reduce costs by transforming absolute signals f, g to Landmark signals L_i, L_j
- Reduce complexity by applying the FFT to both signals before multiplying them, then apply IFFT to the result

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