Introduction to Audio Content Analysis

Module 10.2: Audio-to-Audio & Audio-to-Score Alignment

alexander lerch

Georgia Tech Center for Music Technology
College of Design

introduction

overview

Georgia Tech Center for Music Technology College of Design

corresponding textbook section

Section 10.2
Section 10.3

- **lecture content**
  - Audio-to-Audio alignment
    - use cases
    - features
    - distance measures
    - typical accuracy
  - Audio-to-Score alignment
- **learning objectives**
  - elaborate on possible use cases for audio-to-audio alignment
  - give examples for features and distance measures for alignment
  - discuss differences between audio-to-audio and audio-to-score alignment

introduction

overview

Georgia Tech Center for Music Technology College of Design

corresponding textbook section

Section 10.2
Section 10.3

- **lecture content**
  - Audio-to-Audio alignment
    - use cases
    - features
    - distance measures
    - typical accuracy
  - Audio-to-Score alignment
- **learning objectives**
  - elaborate on possible use cases for audio-to-audio alignment
  - give examples for features and distance measures for alignment
  - discuss differences between audio-to-audio and audio-to-score alignment

audio-to-audio alignment
introduction

Georgia Tech Center for Music Technology
College of Design

- **objective**
  - align two sequences of audio

- **use cases**
  - *quick browsing* for certain parts in recordings
  - *timing adjustment* (backing vocals, loops, . . .)
  - *automated dubbing*
  - *musicological analysis* (relative timing of several performances)

- **processing steps**
  - extract suitable features
  - compute distance matrix
  - compute alignment path

audio-to-audio alignment
introduction

Georgia Tech Center for Music Technology College of Design

- **objective**
  - align two sequences of audio
- **use cases**
  - *quick browsing* for certain parts in recordings
  - *timing adjustment* (backing vocals, loops, . . .)
  - *automated dubbing*
  - *musicological analysis* (relative timing of several performances)
- **processing steps**
  - extract suitable features
  - compute distance matrix
  - compute alignment path

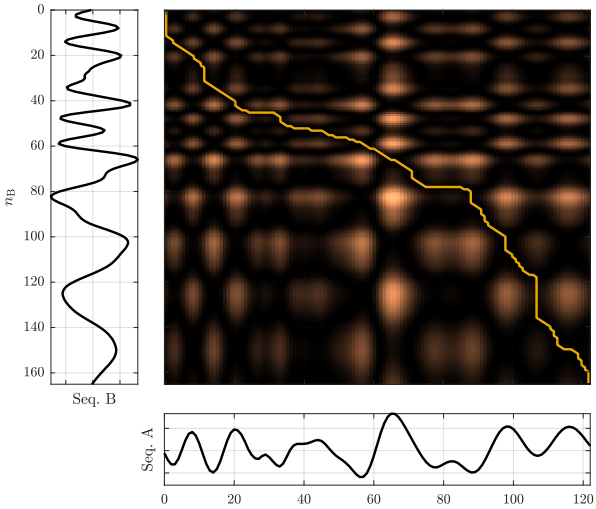
audio-to-audio alignment
introduction

- **objective**
  - align two sequences of audio
- **use cases**
  - *quick browsing* for certain parts in recordings
  - *timing adjustment* (backing vocals, loops, . . .)
  - *automated dubbing*
  - *musicological analysis* (relative timing of several performances)
- **processing steps**
  - extract suitable features
  - compute distance matrix
  - compute alignment path

audio-to-audio alignment

alignment path computation

- prerequisite:
  Module 10.1 — Dynamic Time Warping



matlab source: plotDtwPath.m

audio-to-audio alignment
features

Georgia Tech Center for Music Technology
College of Design

- **use case examples**
  - **quick browsing** — find the same part across files
    ⇒ use *pitch based* features
  - **timing adjustment** — backing vocals to lead vocals
    ⇒ use *intensity based* features
  - **automated dubbing** — same speaker several recordings
    ⇒ use *intensity based* and *timbre based* features
- **feature categories**
  - **intensity**: energy, onset probability, ...
  - **tonal**: pitch chroma, ...
  - **timbral**: MFCCs, spectral shape, ...

plot from[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment
features

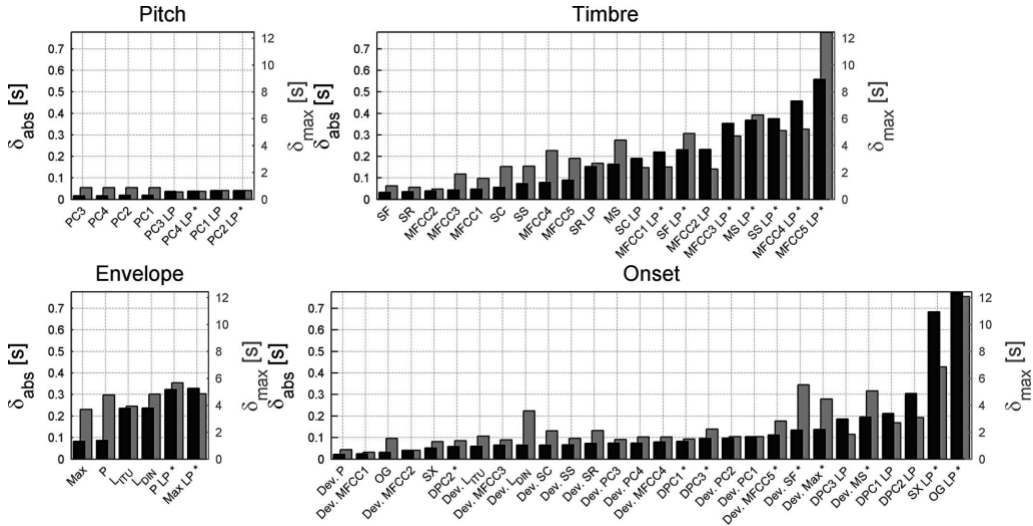
- **use case examples**
  - **quick browsing** — find the same part across files
    $\Rightarrow$ use *pitch based* features
  - **timing adjustment** — backing vocals to lead vocals
    $\Rightarrow$ use *intensity based* features
  - **automated dubbing** — same speaker several recordings
    $\Rightarrow$ use *intensity based* and *timbre based* features
- **feature categories**
  - **intensity**: energy, onset probability, ...
  - **tonal**: pitch chroma, ...
  - **timbral**: MFCCs, spectral shape, ...

plot from[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

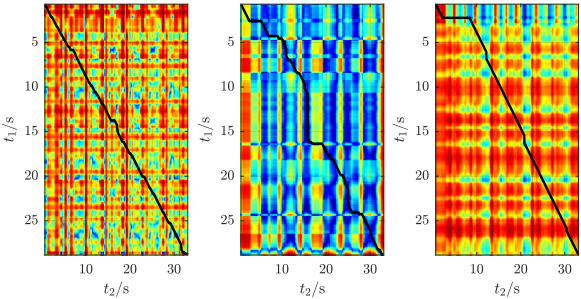
audio-to-audio alignment

features



audio-to-audio alignment

feature-dependency of results



matlab source: plotDtwFeatures.m

audio-to-audio alignment

compute distance matrix — distance measures

- typical distance measures
  - *Euclidean distance*: $d_{\mathrm{E}}(s) = \sqrt{\sum_{j=0}^{11} \left(\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right)^2}$
  - *Manhattan distance*: $d_{\mathrm{M}}(s) = \sum_{j=0}^{11} \left|\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right|$
  - *Cosine distance*: $d_{\mathrm{C}}(s) = 1 - \left(\frac{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \nu_{\mathrm{t,s}}(j)}{\sqrt{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j)^2} \sqrt{\cdot \sum_{j=0}^{11} \nu_{\mathrm{t,s}}(j)^2}} \right)$
  - *Kullback-Leibler divergence*: $d_{\mathrm{KL}}(s) = \sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \log\left(\frac{\nu_{\mathrm{e}}(j)}{\nu_{\mathrm{t,s}}(j)}\right)$
- data-driven approach: train classifier with 2-class problem[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment

compute distance matrix — distance measures

- typical distance measures
  - *Euclidean distance*: $d_{\mathrm{E}}(s) = \sqrt{\sum_{j=0}^{11} \left(\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right)^2}$
  - *Manhattan distance*: $d_{\mathrm{M}}(s) = \sum_{j=0}^{11} \left|\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right|$
  - *Cosine distance*: $d_{\mathrm{C}}(s) = 1 - \left(\frac{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \nu_{\mathrm{t,s}}(j)}{\sqrt{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j)^2} \sqrt{\cdot \sum_{j=0}^{11} \nu_{\mathrm{t,s}}(j)^2}} \right)$
  - *Kullback-Leibler divergence*: $d_{\mathrm{KL}}(s) = \sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \log\left(\frac{\nu_{\mathrm{e}}(j)}{\nu_{\mathrm{t,s}}(j)}\right)$
- data-driven approach: train classifier with 2-class problem[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment

compute distance matrix — distance measures

- typical distance measures
  - *Euclidean distance*: $d_{\mathrm{E}}(s) = \sqrt{\sum_{j=0}^{11} \left(\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right)^2}$
  - *Manhattan distance*: $d_{\mathrm{M}}(s) = \sum_{j=0}^{11} \left|\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right|$
  - *Cosine distance*: $d_{\mathrm{C}}(s) = 1 - \left(\frac{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \nu_{\mathrm{t,s}}(j)}{\sqrt{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j)^2} \sqrt{\cdot \sum_{j=0}^{11} \nu_{\mathrm{t,s}}(j)^2}} \right)$
  - *Kullback-Leibler divergence*: $d_{\mathrm{KL}}(s) = \sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \log\left(\frac{\nu_{\mathrm{e}}(j)}{\nu_{\mathrm{t,s}}(j)}\right)$
- data-driven approach: train classifier with 2-class problem[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment

compute distance matrix — distance measures

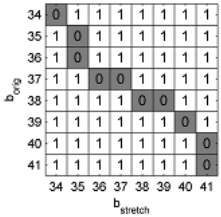
- typical distance measures
  - *Euclidean distance*: $d_{\mathrm{E}}(s) = \sqrt{\sum_{j=0}^{11} \left(\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right)^2}$
  - *Manhattan distance*: $d_{\mathrm{M}}(s) = \sum_{j=0}^{11} \left|\nu_{\mathrm{e}}(j) - \nu_{\mathrm{t,s}}(j)\right|$
  - *Cosine distance*: $d_{\mathrm{C}}(s) = 1 - \left(\frac{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \nu_{\mathrm{t,s}}(j)}{\sqrt{\sum_{j=0}^{11} \nu_{\mathrm{e}}(j)^2} \sqrt{\cdot \sum_{j=0}^{11} \nu_{\mathrm{t,s}}(j)^2}} \right)$
  - *Kullback-Leibler divergence*: $d_{\mathrm{KL}}(s) = \sum_{j=0}^{11} \nu_{\mathrm{e}}(j) \cdot \log\left(\frac{\nu_{\mathrm{e}}(j)}{\nu_{\mathrm{t,s}}(j)}\right)$
- data-driven approach: train classifier with 2-class problem[1]

[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment

compute distance matrix — distance measures

- typical distance measures
- data-driven approach: train classifier with 2-class problem[1]

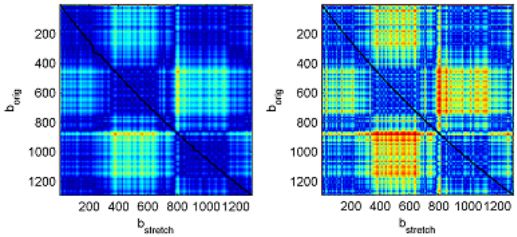


[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment

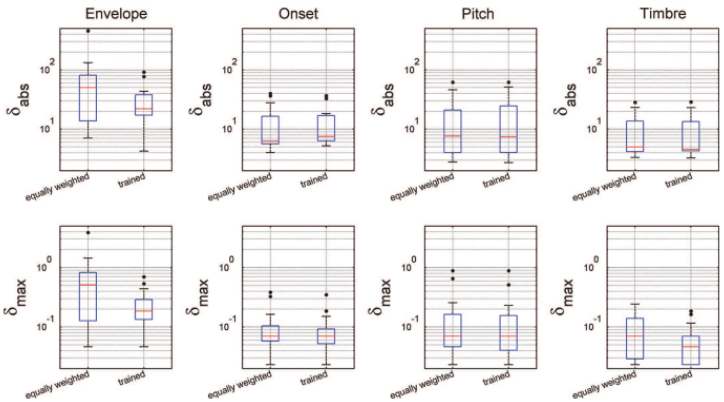
compute distance matrix — distance measures

- typical distance measures
- data-driven approach: train classifier with 2-class problem[1]



[1] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-audio alignment
typical results



originals **synced**

left: instrumental

right: a capella

[2] H. Kirchhoff and A. Lerch, "Evaluation of Features for Audio-to-Audio Alignment," *Journal of New Music Research*, vol. 40, no. 1, pp. 27–41, 2011. DOI: 10.1080/09298215.2010.529917.

audio-to-score alignment

overview

Georgia Tech Center for Music Technology College of Design

- **objective**
  - align an audio sequence with a score sequence
- **use cases**
  - score viewer
  - music education
  - retrieve matching score/audio via cost function
  - musicological analysis
- **processing steps**
  - see audio-to-audio alignment

audio-to-score alignment

overview

- **objective**
  - align an audio sequence with a score sequence
- **use cases**
  - score viewer
  - music education
  - retrieve matching score/audio via cost function
  - musicological analysis
- **processing steps**
  - see audio-to-audio alignment

audio-to-score alignment

overview

Georgia Tech Center for Music Technology College of Design

- **objective**
  - align an audio sequence with a score sequence
- **use cases**
  - score viewer
  - music education
  - retrieve matching score/audio via cost function
  - musicological analysis
- **processing steps**
  - see audio-to-audio alignment

audio-to-score alignment
challenges

- features from **different domains**
  - score contains no timbre info
  - score cannot be expected to contain no loudness info
  - score has no clear "time axis"

$\Rightarrow$ two prototypical for distance/similarity calculation

- *approach 1*: convert score into audio-like representation
  - MIDI-to-audio
  - use model synthesize
- *approach 2*: convert audio into score-like representation
  - audio-to-MIDI
  - pitch chroma
  - event-based segmentation

audio-to-score alignment
challenges

- features from **different domains**
  - score contains no timbre info
  - score cannot be expected to contain no loudness info
  - score has no clear "time axis"

$\Rightarrow$ two prototypical for distance/similarity calculation

- *approach 1*: convert score into audio-like representation
  - MIDI-to-audio
  - use model synthesize
- *approach 2*: convert audio into score-like representation
  - audio-to-MIDI
  - pitch chroma
  - event-based segmentation

alignment
evaluation

Georgia Tech Center for Music Technology
College of Design

- **goal**: compare two sequences of time stamps

- evaluation **challenges**
  - pauses/rests, and long held notes: what is the reference path?
  - noise in the begin and end of the recording
  - data not easily available
    - synthesized
    - piano sensors
    - pseudo-ground truth with time stretching
    - automatic annotation with quality assurance

alignment
evaluation

Georgia Tech Center for Music Technology
College of Design

- **goal**: compare two sequences of time stamps

- evaluation **challenges**
  - pauses/rests, and long held notes: what is the reference path?
  - noise in the begin and end of the recording
  - data not easily available
    - synthesized
    - piano sensors
    - pseudo-ground truth with time stretching
    - automatic annotation with quality assurance

alignment
evaluation metrics

- *audio-to-score*
  - missed note rate
  - misalign rate
  - piece completion
  - average absolute deviation
  - variance of deviation

- *audio-to-audio*
  - mean deviation
  - mean absolute deviation
  - maximum deviation
  - relative number of matching path points

summary
lecture content

- **audio-to-audio alignment**
  1. extract features
  2. create distance matrix with suitable distance measure
  3. use DTW to find alignment path
  4. (use time-stretching to actually align the sequences)

- **audio-to-score alignment**
  1. extract usually pitch-based features
  2. distance measure
  3. use DTW, HMM, etc to extract alignment path