Introduction to **Audio Content Analysis**

Module 9.5: Tempo Detection

alexander lerch

Georgia Tech | Center for Music Technology
College of Design

introduction

overview

corresponding textbook section

section 9.5

- **lecture content**
  - introduction to tempo detection and beat tracking
  - overview over basic approaches
  - typical challenges

- **learning objectives**
  - discuss advantages and disadvantages for different approaches to tempo detection and beat tracking
  - summarize the typical challenges of beat tracking systems

introduction

overview

corresponding textbook section

section 9.5

- **lecture content**
  - introduction to tempo detection and beat tracking
  - overview over basic approaches
  - typical challenges

- **learning objectives**
  - discuss advantages and disadvantages for different approaches to tempo detection and beat tracking
  - summarize the typical challenges of beat tracking systems

tempo detection & beat tracking

problem statement

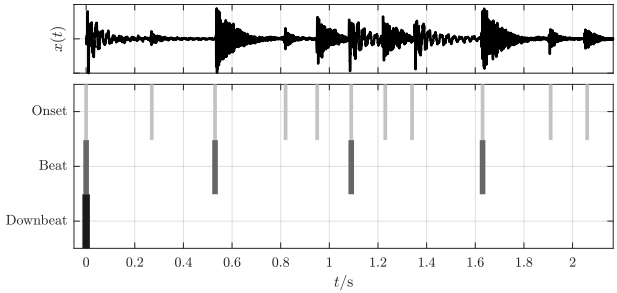
- **tempo detection**
  - detect speed of regular pulse (foot-tapping rate)
- **beat tracking**
  - detect the time instances the tempo pulses occur (beat phase)

tempo detection & beat tracking

introduction

- **objectives**
  1. find the tempo from the novelty function/onsets
  2. find the beat locations

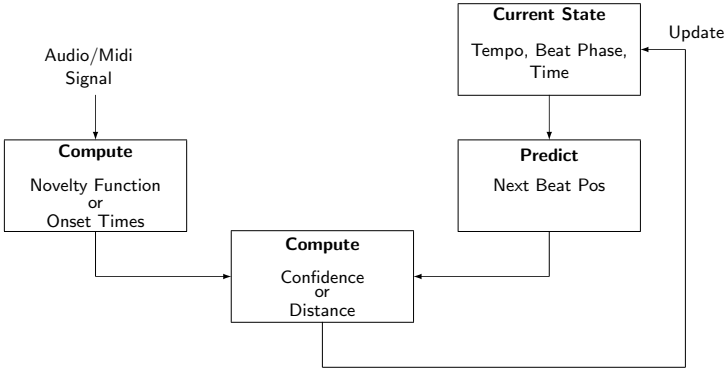
- **systematic problems**:
  1. distinguish *hierarchical levels*
     - meter
     - beat
     - subbeat/tatum
  2. detect *beats without onsets*
  3. recognize *onsets without beats*



matlab source: plotBeatGrid.m

tempo detection & beat tracking

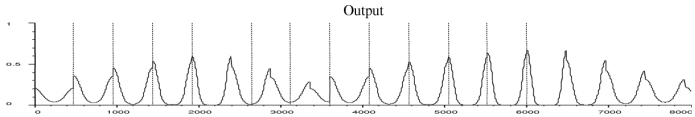
typical beat tracking system



tempo detection & beat tracking

oscillator approach

Beat tracking with an oscillator[1]



1. initialize pulse generator (tempo estimate, beat position estimate)
2. predict next beat location with pulse
3. adapt acc. to distance (predicted vs. real onset position)
   - beat period
   - beat phase
4. predict with adapted settings
5. adapt . . .

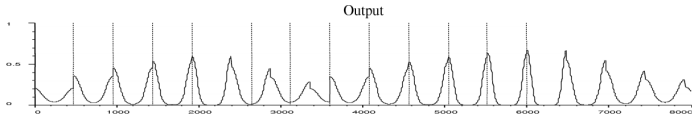
[1] E. W. Large, "Beat Tracking with a Nonlinear Oscillator," in *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI)*, Montreal, Aug. 1995.

tempo detection & beat tracking

oscillator approach

Georgia Tech Center for Music Technology College of Design

Beat tracking with an oscillator[1]



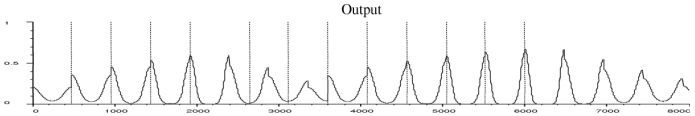
1. initialize pulse generator (tempo estimate, beat position estimate)
2. predict next beat location with pulse
3. adapt acc. to distance (predicted vs. real onset position)
   - beat period
   - beat phase
4. predict with adapted settings
5. adapt . . .

[1] E. W. Large, "Beat Tracking with a Nonlinear Oscillator," in *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI)*, Montreal, Aug. 1995.

tempo detection & beat tracking

oscillator approach

Beat tracking with an oscillator[1]



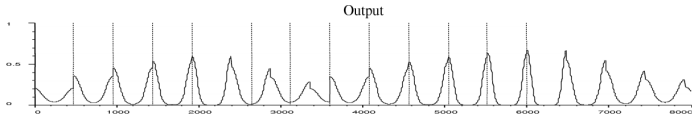
1. initialize pulse generator (tempo estimate, beat position estimate)
2. predict next beat location with pulse
3. adapt acc. to distance (predicted vs. real onset position)
   - beat period
   - beat phase
4. predict with adapted settings
5. adapt . . .

[1] E. W. Large, "Beat Tracking with a Nonlinear Oscillator," in *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI)*, Montreal, Aug. 1995.

tempo detection & beat tracking

oscillator approach

Beat tracking with an oscillator[1]



1. initialize pulse generator (tempo estimate, beat position estimate)
2. predict next beat location with pulse
3. adapt acc. to distance (predicted vs. real onset position)
   - beat period
   - beat phase
4. predict with adapted settings
5. adapt ...

[1] E. W. Large, "Beat Tracking with a Nonlinear Oscillator," in *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI)*, Montreal, Aug. 1995.

tempo detection & beat tracking

oscillator approach: initialization

How to estimate the initial tempo

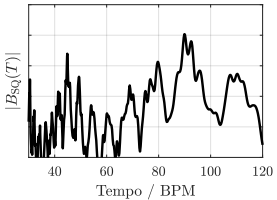
matlab source: plotBeatHistogram.m

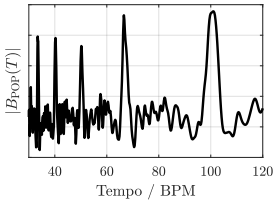
tempo detection & beat tracking

oscillator approach: initialization

How to estimate the initial tempo

- location of maximum of **ACF of novelty function**
- maximum of **IOI histogram**





- maximum of **beat spectrum/histogram**
- . . .

matlab source: plotBeatHistogram.m

tempo detection & beat tracking

multi-agent approach

1. run **multiple beat trackers** with different parameters
   - initial tempo
   - initial beat phase
   - adaptation speed
2. compute reliability/**confidence** criteria:
   - match beat and onset times
   - tempo stability
   - majority of different agents
   - ...
3. choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

multi-agent approach

1. run **multiple beat trackers** with different parameters
   - initial tempo
   - initial beat phase
   - adaptation speed
2. compute reliability/**confidence** criteria:
   - match beat and onset times
   - tempo stability
   - majority of different agents
   - ...
3. choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

multi-agent approach

1. run **multiple beat trackers** with different parameters
   - initial tempo
   - initial beat phase
   - adaptation speed
2. compute reliability/**confidence** criteria:
   - match beat and onset times
   - tempo stability
   - majority of different agents
   - ...
3. choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

multi-agent approach

1. run **multiple beat trackers** with different parameters
   - initial tempo
   - initial beat phase
   - adaptation speed
2. compute reliability/**confidence** criteria:
   - match beat and onset times
   - tempo stability
   - majority of different agents
   - ...
3. choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

multi-agent approach

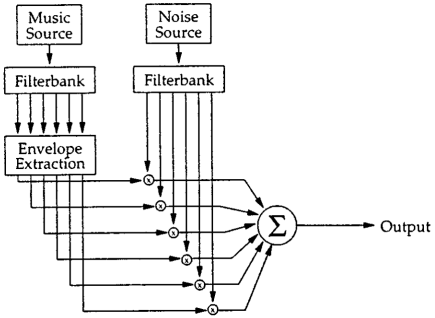
1. run **multiple beat trackers** with different parameters
   - initial tempo
   - initial beat phase
   - adaptation speed
2. compute reliability/**confidence** criteria:
   - match beat and onset times
   - tempo stability
   - majority of different agents
   - ...
3. choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

filterbank approach

Georgia Tech | Center for Music Technology College of Design

1. design **filterbank** (e.g. comb resonators spaced 1 beat)
2. compute filter output energy
3. pick maximum



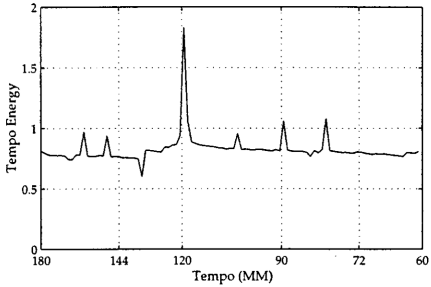
plots by Scheirer[2]

[2] E. D. Scheirer, "Tempo and beat analysis of acoustic musical signals," *Journal of the Acoustical Society of America (JASA)*, vol. 103, no. 1, pp. 588–601, 1998.

tempo detection & beat tracking

filterbank approach

1. design **filterbank** (e.g. comb resonators spaced 1 beat)
2. compute filter output energy
3. pick maximum



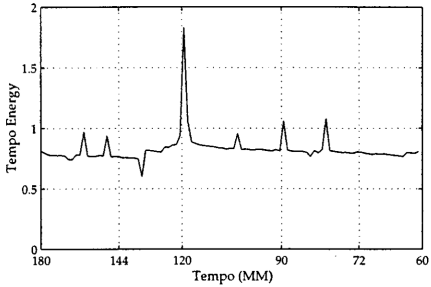
plots by Scheirer[2]

[2] E. D. Scheirer, "Tempo and beat analysis of acoustic musical signals," *Journal of the Acoustical Society of America (JASA)*, vol. 103, no. 1, pp. 588–601, 1998.

tempo detection & beat tracking

filterbank approach

1. design **filterbank** (e.g. comb resonators spaced 1 beat)
2. compute filter output energy
3. pick maximum



plots by Scheirer[2]

[2] E. D. Scheirer, "Tempo and beat analysis of acoustic musical signals," *Journal of the Acoustical Society of America (JASA)*, vol. 103, no. 1, pp. 588–601, 1998.

tempo detection & beat tracking

template-based approach

1. define set of **template pulses** in all tempi
2. compute CCF between novelty function (or its ACF) and all templates
3. choose template with highest correlation as tempo
4. choose lag with highest correlation as beat phase

tempo detection & beat tracking

typical problems

1. tempo: detection of **double/half tempo** (triple, . . .)
2. phase: detection of **off-beats**
3. tempo & phase: strongly depends on **initialization values**
4. tempo & phase: only **slow adaptation** — no sudden tempo changes

example: challenges with adaptation speed

tempo detection & beat tracking

evaluation

- evaluation of **constant tempo**
  - match within tempo range ⇒ classification metrics
- evaluation of **beat tracking**
  - ground truth can be subjective (double/half tempo, deviations)
  - each beat matched against ground truth
    - challenge 1: tolerance window definition (tempo dependent or not?)
    - challenge 2: slightly different tempo might lead to gap between metrics and perceptual severity
- **typical errors**
  - double/half tempo (sometimes also 3/2 relationships)
  - off-beat
  - problems with abrupt tempo changes

tempo detection & beat tracking

evaluation

- evaluation of **constant tempo**
  - match within tempo range $\Rightarrow$ classification metrics
- evaluation of **beat tracking**
  - ground truth can be subjective (double/half tempo, deviations)
  - each beat matched against ground truth
    - challenge 1: tolerance window definition (tempo dependent or not?)
    - challenge 2: slightly different tempo might lead to gap between metrics and perceptual severity
- **typical errors**
  - double/half tempo (sometimes also 3/2 relationships)
  - off-beat
  - problems with abrupt tempo changes

tempo detection & beat tracking

evaluation

- evaluation of **constant tempo**
  - match within tempo range $\Rightarrow$ classification metrics
- evaluation of **beat tracking**
  - ground truth can be subjective (double/half tempo, deviations)
  - each beat matched against ground truth
    - challenge 1: tolerance window definition (tempo dependent or not?)
    - challenge 2: slightly different tempo might lead to gap between metrics and perceptual severity
- **typical errors**
  - double/half tempo (sometimes also 3/2 relationships)
  - off-beat
  - problems with abrupt tempo changes

summary
lecture content

- **tempo analysis**
  - similar to pitch detection on a different scale
    - periodicity analysis of novelty function
    - time or spectral domain
- **typical approaches**
  - oscillator
  - histogram/beat spectrum
  - template correlation
- **main challenges**
  - double/half tempo
  - adaptation to sudden tempo changes