Beat Tracking based on Multiple-agent Architecture

— A Real-time Beat Tracking System for Audio Signals —

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1. Introduction

□ Application of Multiple-agent Architecture

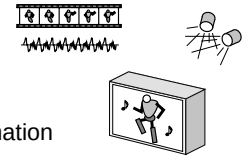
- **Application to beat tracking for musical audio signals**
  - Understand real-world audio signals
  - Need to handle various ambiguous situations
- **Advantages**
  - Interpret input signals in various ways
  - Multiple agents can examine multiple hypotheses according to different strategies
- **Main contribution**
  - Multiple-agent architecture is actually useful for a practical real-world application

□ What is Beat Tracking?

- **Track quarter notes**
  just as people keep time to music by foot-tapping

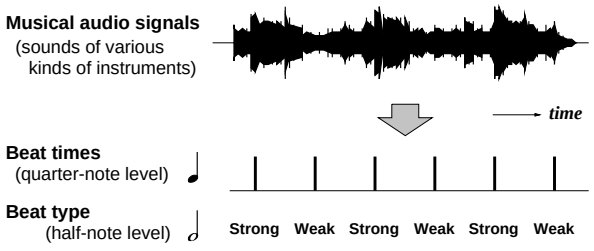
□ Why is Acoustic Beat-tracking Important?

- **Computational model of human music perception**
  - Basic unit of the temporal structure of music
- **Useful in various applications**
  - Video/Audio editing systems
  - Stage lighting control
  - Music-synchronized CG animation



□ Beat Tracking Problem

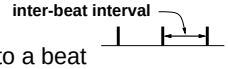
- **Organize music into almost regularly spaced beats**



- **Assumptions** Time signature : $\frac{4}{4}$
  Tempo : 61-120 M.M. almost constant

□ Issues in Tracking Musical Beats

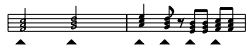
- **Peak-finding with a threshold is not sufficient**
  Many energy peaks are not directly related to beats
- **Multiple interpretations of beats are possible**
  No specific sound directly indicates the beat position
- **Ambiguous situations**
  Several events may correspond to a beat
  Different inter-beat intervals seem plausible



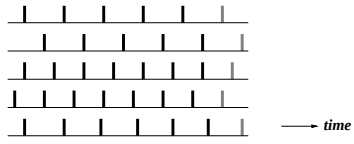
- **Context-dependent decisions using musical knowledge**
  Whether a beat is strong or weak
  Which is the best interpretation

□ Our Solutions

- **Detect multiple tracking cues**
  Onset times in several frequency ranges
  Chord change possibility



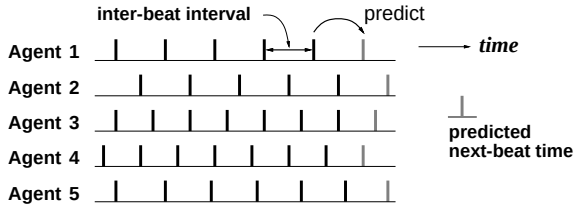
- **Maintain multiple hypotheses**
  Each corresponds to a hypothetical interpretation



2. Multiple-agent Architecture

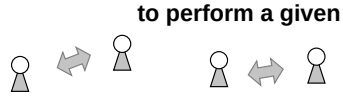
□ Multiple Agents Examine Multiple Hypotheses

- **Agents track beats according to different strategies**
- **Each maintains a beat-position hypothesis:**
  Next beat time Beat type Inter-beat interval



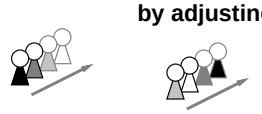
□ Definition of "Agent"

1. **The agent interacts with other agents to perform a given task**



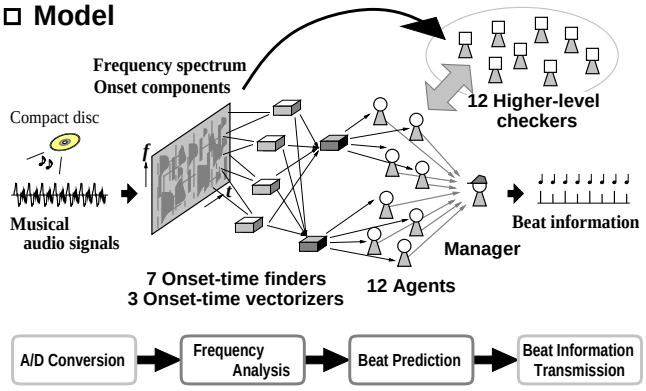
2. **The agent evaluates its own behavior on the basis of the input**

3. **The agent adapts to the input by adjusting its own behavior**



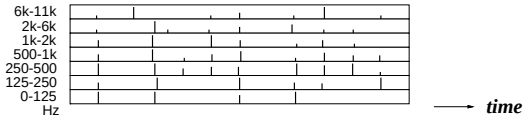
3. System Description (for music without drum-sounds)

Model



Make a Hypothesis

Onset-time vector (Result of Frequency Analysis)



Autocorrelation ⇨ Inter-beat interval
Cross-correlation ⇨ Prediction field
Chord changes ⇨ Beat type

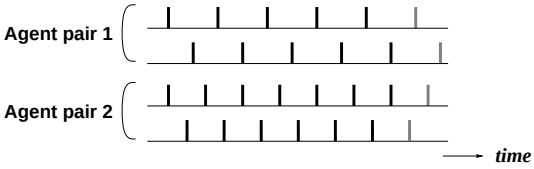
Agent-generated hypothesis

Interaction

1. Each agent interacts with another agent to perform the beat-tracking task

- **12 agents are grouped into 6 pairs**

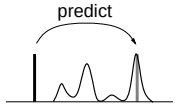
Paired agents predict next beat times cooperatively
examine the same inter-beat interval



- **Compensate for one of typical tracking errors**

Interaction

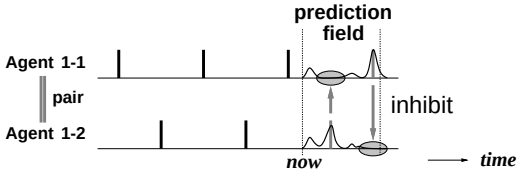
- **Interaction through prediction field**



Expectancy curve:
when the next beat is expected to occur

Height of each local peak:
the next beat-position possibility

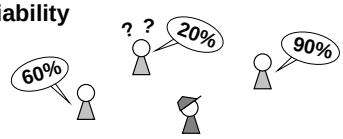
Paired agents inhibit each other's field



Evaluation

2. Each agent evaluates its own hypothesis according to the input acoustic signals

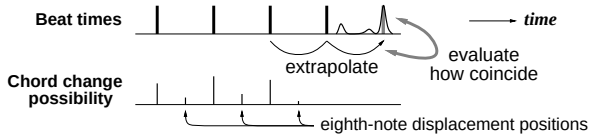
- **Reliability of the hypothesis**
  Quantitative result of the self-evaluation
- **Evaluate using musical knowledge**
- **Manager decides which is the best hypothesis according to the reliability**



Evaluation

- **Two kinds of musical knowledge**

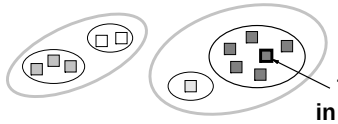
1. **Sounds are likely to occur on beats**
   Correct beat times tend to coincide with onset times
2. **Chords are more likely to change on beats than on other positions between two successive correct beats**



Evaluation

- **Manager**

1. **Classify all hypotheses into groups**
   according to beat time and inter-beat interval
2. **Calculate overall reliability of each group**
3. **Select the dominant group**
4. **Repeat three times while narrowing the allowable margin of beat times**



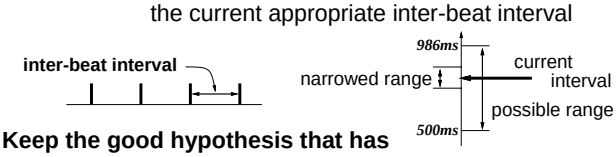
the reliable hypothesis in the most dominant group

Adaptation

3. Each agent adapts to the current input by adjusting its own strategy parameter

- **The reliability becomes high enough**
  ⇨ Tune a parameter to narrow the range of possible inter-beat intervals

Examine only a neighborhood of the current appropriate inter-beat interval



- **Keep the good hypothesis that has the inter-beat interval appropriate to the input**

4. Experimental Results

Conditions (Implemented on AP1000)

- **Audio signals without drum-sounds from CDs**
- **40 popular songs performed by 28 artists**
- **Tempo: 62-116 M.M. roughly constant**

Results

- **Correctly tracked beats in 34 out of 40 songs**
- **Mistakes in 6 songs**

beat times were wrong (4)	very few onset times temporarily fluctuated tempo
beat type was wrong (2)	irregularity of chord changes

5. Conclusion

Summary

- **Multiple-agent architecture for beat tracking**
- **Examine multiple hypotheses in parallel**
- **Each agent is capable of**

interaction	compensate for typical error
self-evaluation	decide which is the best hypothesis
adaptation	keep the good hypothesis

- **Robust enough to handle real-world audio signals**

Future Work

- **Upgrade our beat-tracking system**

  to make use of other higher-level musical structure

- **More sophisticated interaction among agents**

- **Application of the multiple-agent architecture to other perceptual problems**