Implementation of a real-time sound source localization method for outdoor animal detection using wireless sensor networks

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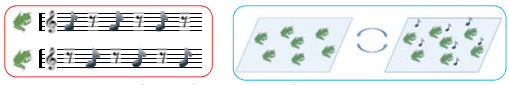
Background 1

- Biomimetics of **Japanese tree frogs**
  - Unique features
    - Anti-phase synchronization of calls in a short time scale
    - Synchronization of chorus in a long time scale



    - We are applying them to wireless communication to achieve collision avoidance and to keep connectivity
- How to make and valid a mathematical model?
  - It is important to know ***when***, ***where*** and ***which*** frogs call in an OUTDOOR environment

Implement a sound localization system for analyzing frog communication

Features of Japanese tree frog 2

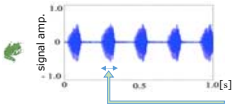
- Distribution and habitat
  - widespread in Japan
  - very active in summer (June-Aug.)
  - nocturn and prefers moisture
    - they almost live in the paddy field

Male frogs (22~45mm length) begin to call after midnight

Paddy field (about 20m x 10m) where we conducted field research

Features of Japanese tree frog 3

- Calling behavior
  - Only male frogs call, for attracting female frogs
    - they call periodically in the figure below



one bout; 0.1~0.2s

  - Calls of many frogs form a chorus
    - one chorus continues 5 min or more
    - frogs do not move away while they are calling
    - distance between calling frogs is 1m or longer

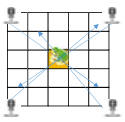
System goals and our approach 4

- Goal: satisfy system requirements
  - accurate and real-time estimation
    - <50cm error and <5m calculation time
  - easy-to-use sytem in outdoor environments
    - carrying and installation of equipments should be easy
- Approach for implementation
  - system design for ease of use:
    - each microphone is connected with a small computer (raspberry pi) and connecting each other wirelessly
    - the microphones are **located closely to each other, and identify the location of a sound source outside the microphones**
  - accurate estimation:
    - source localization method with DOA (Direction of Arrival)
    - DOA estimation with MUSIC, which is robust to a noise
  - real-time estimation:
    - reduction in the calculation time for both DOA and location estimation (in our paper)
      - **extend an existing grid-based localization method**
    - design considering communication time and calculation time
      - microphone arrays estimates DOA and send only DOA to a localization server

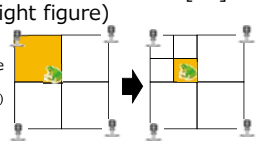
Grid-based localization method 5

- Localization method using DOA[10]
  1. Divide the observation area into $N \times N$ cells
  2. Calculate the angle cost for each cell
     - cost is defined as a square of difference between measured DOA and direction for a cell
  3. Search a cell with the minimum cost
     - Estimation result is the center of the cell
- Accuracy and computational cost are trade-off for N
- Computation reduction is also mentioned in [10] with a recursive search (right figure)

Original: $O(N^2)$



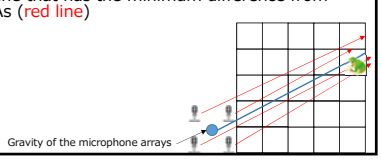
recursive search: $O(\log(N))$



[10] A. Griffin, et al., "Real-Time Localization of Multiple Audio Sources in a Wireless Acoustic Sensor Network," in Proc. EUSIPCO, 2014.

Proposal: extension of the grid-based method 6

- Problem
  - Localization for a sound source **outside microphones**
    - It is important for outdoor localization that microphone are closely placed each other to measure their accurate positions
    - The original grid-based method does not consider such a situation and its estimation accuracy might degrade
- Idea
  - Divide the cell search process of [10] into 2 step
  1. Half line search from the gravity of the microphones (blue line)
     - Search a half line that has the minimum difference from measured DOAs (red line)



Proposal: extension of the grid-based method 7

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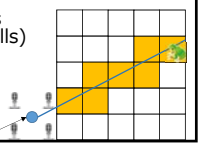
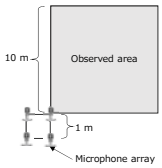
  - Divide the cell search process of [10] into 2 step
  1. Half line search from the gravity of the microphones (blue line)
     - Search a half line that has the minimum difference from measured DOAs
  2. Minimum-cost cell search from cells intersecting the half line (orange cells)
     - Computational cost is $\mathcal{O}(1)$ for step 1, $\mathcal{O}(N)$ for step 2, so totally $\mathcal{O}(N)$

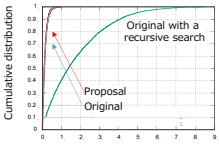


Simulation analysis 8

- Settings
  - **Observation area**: 10m x 10m
  - **Microphones**: 4 microphones are set as shown in the figure
  - **A Sound source**: randomly placed in the area
  - **DOA**: each microphone array gets DOA from the source without any error
  - **Cell fineness**: N is set to 100 and 1000
- Metrics
  - **Accuracy**: distance between estimated position and true position
  - **Calculation time**: time until the cell with minimum cost is found
- Comparison with
  - The original grid-based method without a recursive search
  - The original grid-based method with a recursive search



Simulation result 9



Calculation time

	N=100	N=1000
Original	0.039 sec	0.379 sec
Original (recursive)	0.038 sec	0.038 sec
Proposal	0.038 sec	0.038 sec

About 90% reduction

- Accuracy
  - Proposal ≈ original **without** a recursive search
  - Original with a recursive search is less accurate
- Calculation time
  - Proposal ≈ original **with** a recursive search (N=100,1000)

Implementation: Devices 10

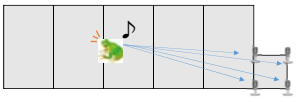
- Microphone array (Fig.)
  - 8-channel
  - Sampling frequency : 16 kHz
  - 24-bit quantization
- Wireless node
  - Raspberry Pi 3 Model B
- Localization server
  - Panasonic Let's note CF-SX1

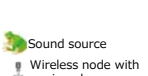
Wireless node and a microphone array

Equipment details

Item	Raspberry Pi 3 Model B	Panasonic Let's note CF-SX1
Clock frequency	1.2 GHz, 4 core	1.9 GHz, 2 core
RAM	1 GB	8 GB

Implementation: system overview 11



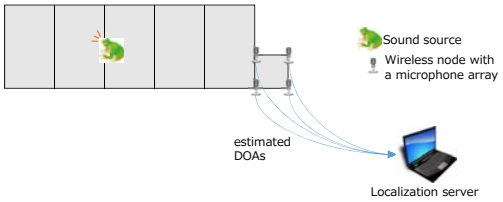


Localization server

1. **Sampling audio and estimating DOA with MUSIC[12] every 0.5 sec**
2. Sending DOA to the Localization Server wirelessly
3. Identifying the source location with our proposal

[12] R. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation," IEEE Transactions on Antennas and Propagation, vol. 34, pp. 276–280, Mar. 1986.

Implementation: system overview 12



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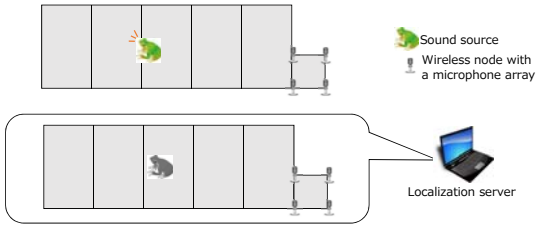

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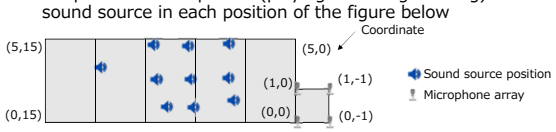
Outdoor localization experiment 14

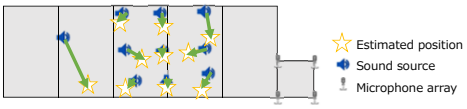
- Environment
  - Wide university ground without obstacles
- Settings
  - We placed a loud speaker (playing back frog's calling) as a sound source in each position of the figure below



  - DOA calibration is conducted before experiment using sources whose position is exactly known
  - True coordinates of the sound source are measured using a laser distance meter
  - Microphone arrays recorded 30-sec sound and output 60 DOAs for each sound source

Experiment Results 15

- Estimation accuracy
  - Average of error: 0.57 m
  - Maximum of error: 1.28 m
  - Minimum of error: 0.16 m
  - Errors are larger than those of simulation
    - DOA estimation errors affect the localization results



- Calculation time
  - DOA estimation for a 0.5-sec 8-ch sound: 0.07 sec
  - Localization : 0.1 sec

Summary and future work 16

- Summary
  - We proposed a sound-source localization method using wireless microphone-array network for outdoor environment
  - Simulation results showed that the proposed method can reduce the calculation time by 90% compared with a grid-based localization method while achieving a good accuracy
  - In the experiment, the average localization error of our localization system was 0.57 m
    - The total time required for estimating a sound-source position is 0.17 sec
- Future work
  - Improving DOA estimation
  - Determining the ideal microphone arrays position
  - Realizing the localization of multiple sound sources