Light-weight Contour Tracking in Wireless Sensor Networks

Xianjin Zhu  Rik Sarkar  Jie Gao  Joseph S. B. Mitchell

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Motivation

- **Sensor network**: sense and monitor the physical world (temperature, traffic density, pollution level, etc).
Motivation

- Time-varying 2-D signal field
- Example application scenario
  - Chemical pollution
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Motivation

- Topological features are important
- Queries:
  - Is there a safe path from B to A? C to B?
  - Is a location surrounded by chemical contaminations?
Contour tracking problem

- Track contours at a threshold of interest - below/above thresh (0/1).
- Capture their topological features as contours evolve over time
Related works

  – Track individual targets
  – Few works on tracking a continuously deforming blob or groups of targets

• **Boundary detection** [Fekete et al. 2005, Wang et al. 2006, Funke et al. 2006, Kroller et al. 2006]
  – Can be used in static scenario
  – Periodically running boundary detection in dynamic scenario is inefficient.
Our contributions

- Light-weight distributed algorithm to track time-varying contours
- Capture topological features
- Low communication cost
  - proportional to the change in the input
Outline: our approach

• Network setting & concepts
• Challenges
• Contour tracking algorithm
• Theoretical results
• Simulation results
Network setting & concepts

- Binary sensor model:
  - Color
    - BLACK: all neighbors high
    - WHITE: all neighbors low
    - GRAY: neither BLACK nor WHITE
      (mixed high and low)

- We want to track the Black boundaries.
- Robustness: resilient to outliers and ambiguity.
- Black regions and white regions are separated by gray.
- Black regions are bounded by contours of threshold.
Goal of the algorithm

• **K-gray band:**
  - a set of gray nodes at most k-hop from BLACK region

• **Contour network:** Graph to capture topological features of contours
Goal of the algorithm

- **Deformation retract:**
  - A thinner version in subspace, with same homotopy. There is a continuous deformation taking the space to the retract.
  - Contour network: skeleton of k-gray band
Challenges

- Hard to tell if a contour network is valid from local view
- Same contour topology may have multiple valid deformation retract with totally different local view
Challenges

Network setting
- Each sensor node only has local information
- Limited resources

Goal
- Naturally require distributed efficient algorithm
- Maintain graphs with identical topological information
- global property
Contour tracking algorithm

- When change occurs:
  - freeze the valid segments in the old contour graph
  - only repair the contour network where it is broken
- Automaton runs at each sensor

**RED**: a GRAY node on the contour network

![Diagram](image)
Contour Repair

• The simplest case: repair of a single contour cycle
Contour Repair

• The simplest case: repair of a single contour cycle
• Open red nodes take responsibility of repair
  – Red nodes at edge of broken contour
Contour Repair

- Which direction to send repair messages?
  - sensor nodes have no sense of orientation
- The k-hop neighbors of the closed red segments block the propagation of repair messages.
Contour Repair

- Simultaneous repair, merging and splitting
  - May encounter multiple RED nodes, which RED node to connect to?
Contour Repair

• Simultaneous repair, merging and splitting
  – May encounter multiple open RED nodes, which RED node to connect to?
  – Connect by a (non self-intersecting) spanning tree, e.g, the shortest path tree.
**Contour creation**

- Triggered at some BLACK nodes
  - have a GRAY neighbor but cannot see RED nodes in its k-hop neighborhood
- GRAY neighbors start to create a new contour
  - Select leaders within k-hop neighborhood
  - Form short chain with length > k
  - Start contour repair
Summary of algorithm

• Valid segments of contour network are still usable
• Repair only happens where the contour network is broken
• Repair connects all red nodes within an open neighborhood through a spanning tree.
• Augmented algorithm deals with small holes inside the k-gray band
Theoretical results

• **Theorem:** The contour network is a deformation retract of the k-gray band, when the system stabilizes.

• **Sketch of proof:**
  – Existing contour network is a deformation retract of the segment of k-gray band it resides in.
  – Repaired new contour network is a deformation retract of open neighborhood.
  – The boundaries align correctly.
Simulations

• Setup:
  – 4000 nodes distributed in a 500*500 field
  – Simulate dynamic changes among a sequence of stabilized states of a contour field
  – Changes happen in a random order between two stabilized states
Simulations

- Contour merge/split

Two black regions move closer. Their gray bands meet each other and (multiple) “bridges” are built up. Black regions themselves merge together.
Simulations

• Nested contours
Simulations

- Contours pass through a hole
Simulations

- Multi-level contours
  - Apply the single-level contour tracking algorithm at each level independently
Simulation

- Communication cost:
  - Proportional to number of changes
Simulations

• Video clips
Conclusions

• A light-weight distributed algorithm that captures the topological features of time-varying contours.

• The communication cost is “output-sensitive”, proportional to the amount of contour changes.

• The algorithm provides a foundation for further processing of spatial sensor data, e.g., contour compression and aggregation [Gandhi et al. 2007].
Future Works

• Explore the applications of contour tracking
  – Real-time response and emergency rescue
  – Direct vehicles to alleviate traffic jam
• Combine with our concurrent contour tree work
Thank you!

- Questions & Comments?