Modeling and Self-deployment of Distributed Mobile Sensor Networks

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Outline

- Sensor Networks
- Mobile Sensor Networks
- Modeling of Mobile Sensor Network
- Self-reconfiguration
- Cooperation and Formation Control
- Some Initial Results
- Conclusion
Sensor Networks

- Distributed Sensor Network is the network which is composed of sensors distributed in the environment.
- Enabling Technologies
  - Micro-Electro-Mechanical Systems (MEMS)
  - Wireless Communication
  - Digital Electronics
- Sensors
  - Cameras as vision sensors, Microphones as audio sensors, Ultrasonic sensors, Infra-red sensors, Temperature sensors, Humidity sensors, Force sensors, Pressure sensors, and Vibration sensors

Sensor Networks

- Capabilities
  - Information gathering
  - Information processing
  - Reliable monitoring of a variety of environments
- Sensor node
  - Sensing hardware
  - Computation/processor
  - Memory
  - Power supply
  - Transceiver/Wireless communication
Some examples of sensor networks

- Military sensor networks
  - detect enemy movements
  - the presence of hazardous material (such as poison gases or radiation, explosions, etc.)
- Environmental sensor networks
  - detect and monitor environmental changes.
- Wireless traffic sensor networks
  - monitor vehicle traffic on a highway or in a congested part of a city.
- Wireless surveillance sensor networks
  - providing security in a shopping mall, parking garage, or other facility.
- Wireless parking lot sensor networks
  - determine which spots are occupied and which spots are free.

Uses of Networked Sensors

- **Perimeter Security**
- **Complex Terrain**
- **Homeland Defense**
- **MOUT Operations**
- **Personnel Detection**
Research Thrusts

- Micro/Nano Sensor Technology
- Self-configuring wireless communication system
- Collaborative signal processing
- Sensor deployment and area coverage
- Sensor Network Security
- Mobile Sensor Network
  Sensor Actuation Coordination
- …..

Decentralized Modeling and Cooperation for Mobile Sensor Networks
Mobile Sensor Networks

- Sensing
- Communication
- Computation
- Locomotion

Sensor network tasks such as object tracking, information querying, etc. Distributed sensing, collaborative signal processing, communication and cooperation in a mobile sensor network

Fundamental Concepts

- Distributed control algorithms acting in concert with sensory information
  - Information made available at desired spatial resolution
  - Network and processing latency considerations
  - Model simplification for timely actuation
- Principles of sensor coordinated actuation
  - Integrated design: static and mobile elements
  - Multiple abstraction layers corresponding to time scales for operation
Challenges

- Integration of Sensing, Computation, Communication and Coordination of distributed nodes
- Limited transmission power and bandwidth
- Developing unified mathematical models for:
  - Task dissemination, coverage area etc.
  - Cooperation of sensor nodes according to task specifications
  - Collaborative signal processing and data fusion
  - Analysis and design for network modeling
- Coordination and relocation of sensor nodes autonomously using task specifications

Research Issues

- Sensor deployment
  - Sensor placement for target detection
- Data fusion
  - When to fuse, where to fuse, how to fuse
- Localized algorithms
  - Localized networking service
  - Localized information processing
- Network architecture
  - Ad hoc(single-hop) v/s multi-hop schemes
- Data processing paradigm
  - Client-server v/s mobile agents
Mobile Sensor Network Model

- Team of n robots
- Directed graph representation
- Each node:
  - Senses environment
  - Fuses data
  - Communicates
  - Routes
- Sensing Range
- Communication Range

Mathematical Model of Mobile Robots

- Single node dynamic model

\[
\begin{align*}
\dot{x}_i &= u_1 \cos \theta_i \\
\dot{y}_i &= u_1 \sin \theta_i \\
\dot{\theta}_i &= u_2
\end{align*}
\]

Constraint:

\[-\dot{x} \sin \theta_i + \dot{y} \sin \theta_i = 0\]
**Voronoi Diagram and Delaunay Triangulation**

- **Voronoi Diagram**
  - The partitioning of a plane with \( n \) points into \( n \) convex polygons such that each polygon contains exactly one point and every point in a given polygon is closer to its central point than to any other.

- **Centroidal Voronoi diagram**
  - A centroidal Voronoi diagram has the odd property that each generating point lies exactly on the centroid of their Voronoi region.

![Voronoi Diagram and Delaunay Triangulation Diagram](image)

**Mobile Sensor Networks**

- **Input**
- **Output**
- **Dynamics**
- **Sensing**
- **Computation**
- **Communication**
- **Coordination**

![Mobile Sensor Networks Diagram](image)
Peer-to-Peer Structure

- Distributed model of a mobile sensor network
  - The dynamic model of the mobile robot
    \[ \dot{q}_i = f_i(q_i, u) \quad q_i = \{x_i, y_i, \theta_i\} \]
  - The Voronoi region for \( p_i = \{x_i, y_i\} \)
    \[ V_i = \{ x \in \Omega \mid |x-p_i| < |x-p_j| \text{ for } j = 1, 2, \ldots, k, j \neq i \} \]
  - The edges for Delaunay tessellation \( G_i \)
- The model is a collection: \(<q_i, f_i, u_i, G_i, V_i>\)

Peer-to-Peer computing for MSN

- Peer-to-peer systems
  - Distributed system without any centralized control or hierarchical organization, nodes have identical capabilities and responsibilities, communication is asymmetric
- Technical Potential
  - can harness huge amounts of resources….
    - user PCs disk space, upstream bandwidth, CPU cycles
  - without requiring expensive hardware, bandwidth, rack space…
  - completely distributed
    - robust, less vulnerable to DoS attacks, harder to censor

Technical Challenges are decentralized control, self-organization, adaptation and scalability!
Example --- Gnutella

Coordinate Systems

- In a mobile sensor network, each mobile robot has its own coordinate system
- Local coordinate system
- Sensor network system
Node Localization and Transformation

- Transformation Matrix $T_{ij}$
- Allow 1 hop neighbors to communicate
  \[ \theta_y = \pi - (\alpha_i - \alpha_j) \]
  \[ T_{ij} = \begin{bmatrix} \cos \theta_y & -\sin \theta_y & 0 & d_{ij} \cos \alpha_j \\ \sin \theta_y & \cos \theta_y & 0 & d_{ij} \sin \alpha_j \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]
- Network kinematics model developed

Node Localization

- Key building block for sensor network kinematics
- Information processed in local coordinate system
- GPS location system for all nodes?
- Indoor operation
- High power requirement
- Distance estimation using ranging methods
- Orientation detection?
Sensor Network Kinematics

- Proposition: For any two nodes \( R_i \) and \( R_j \) in a complete directed graph \( G \), there exits a path \( R_{p1}, \cdots, R_{pm} \) which connects nodes \( R_i \) and \( R_j \). Here \( R_{p1} \in K_i \), \( R_{pm} \in K_j \) and any two adjacent nodes on the path are one-hop neighbors. To share information between nodes \( R_i \) and \( R_j \), there exists a distributed algorithm to pass information represented in the local coordinate system of sensor node \( R_i \) to sensor node \( R_j \).

Sensor Network Coverage Area

- Communication range and sensing range
Coverage Area --- Open Area

Coverage Area and Cooperation

- Use Voronoi graphs to maximize coverage
- Voronoi diagram concentric with sensing range
- Move node till max coverage is achieved
- Enlarge coverage area by moving perpendicular to the Voronoi edge ab
- Cover complete area
Centroidal Voronoi diagram

- Given a set of points \( \{ z_i \} \) \( i = 1, \ldots, k \), which is called generators, the Voronoi diagram \( \{ V_i \} \) is defined by:
  \[
  V_i = \{ x \in \Omega \mid |x-z_i| < |x-z_j| \text{ for } j = 1, 2, \ldots, k, j \neq i \}
  \]

- If \( V_i \) is the Voronoi region for \( z_i \) and \( z_i \) is the mass centroid of \( V_i \), then the tessellation is called Centroidal Voronoi Diagram.

- The centroidal Voronoi diagram for a region is not unique.

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Lloyd’s Algorithm

Lloyd’s method

0. Start with some initial set of \( K \) points \( \{ z_i \}_{i=1}^K \).

1. Construct the Voronoi tessellation \( \{ V_i \}_{i=1}^K \) of \( \Omega \) associated with the points \( \{ z_i \}_{i=1}^K \).

2. Construct the centers of mass of the Voronoi regions \( \{ V_i \}_{i=1}^K \) found in Step 1; these centroids are the new set of points \( \{ z_i \}_{i=1}^K \).

3. Go back to Step 1, or, if you are happy with what you have, quit.
Autonomous Sensor Deployment

- Construct the Voronoi tessellation $V_i$ in open space - associated with node $R_i$;
- If $V_i$ is an open set, modify $V_i$ based on the sensing range of $R_i$ to form a closed region;
- Based on the vertices of $V_i$, compute the centroid of $V_i$;
- Execute controller $u_i = k(p_i - C_{V_i})$ for certain period of time $t_i$;
- Return to step 1.
Fault Tolerant

- Initial deployment
- Lost 1 node
- Lost 2 nodes
- Lost 4 nodes

Hybrid Deployment

- Construct the Voronoi tessellation $V_i$ in open space - associated with node $R_i$;
- If $V_i$ is an open set, modify $V_i$ based on the sensing range of $R_i$ to form a closed region;
- Based on the vertices of $V_i$, compute the centroid of $V_i$;
- If $V_i \cap s_i = V_i$, no action is taken and return to step 1;
- If $V_i \cap s_i \neq V_i$, execute controller $u_i = kp(p_i-CV_i)$
  for certain period of time $t_i$;
- Return to step 1.
Hybrid Deployment

- Partial movement of node 1 and node 2
- The motion of others are not affected unless sensor network coverage is affected

Asynchronous Formation

- Algorithm:
  - Construct the Voronoi tessellation $V_i$ in open space - associated with node $R_i$;
  - If $V_i$ is an open set, modify $V_i$ based on the sensing range of $R_i$ to form a closed region;
  - Based on the vertices of $V_i$, compute the centroid of $V_i$;
  - If $R_i$ is the leading node, run the planned trajectory; else Compute and execute controller $u_i$ combining both $C_{V_i}$ and $s_i$;
  - Return to step 1.
- Problems
Asynchronous Formation

Algorithm
- Construct the Voronoi tessellation \( V_i \) in open space - associated with node \( R_i \);
- If \( V_i \) is an open set, modify \( V_i \) based on the sensing range of \( R_i \) to form a closed region;
- Based on the vertices of \( V_i \), compute the centroid of \( V_i \);
- Receive plans from a neighbors, transform it into local coordinate system, and transmit this information to other neighbors according to the flooding protocol;
- Compute and execute controller \( u_i \) combining both \( C_{V_i} \) and \( s_i \);
- Return to step 1.

Problems

Synchronous Formation

- Algorithm
- Construct the Voronoi tessellation \( V_i \) in open space - associated with node \( R_i \);
- If \( V_i \) is an open set, modify \( V_i \) based on the sensing range of \( R_i \) to form a closed region;
- Based on the vertices of \( V_i \), compute the centroid of \( V_i \);
- Receive plans from a neighbors, transform it into local coordinate system, and transmit this information to other neighbors according to the flooding protocol;
- Compute and execute controller \( u_i \) combining both \( C_{V_i} \) and \( s_i \);
- Return to step 1.

Problems
Synchronous Formation I

Synchronous Formation II
Tracking Sinusoidal Wave
Hybrid Cooperation

- Construct the Voronoi tessellation Vi in open space - associated with node Ri;
- If Vi is an open set, modify Vi based on the sensing range of Ri to form a closed region;
- Based on the vertices of Vi, compute the centroid of Vi;
- Receive plans from a neighbors, transform it into local coordinate system, and transmit this information to other neighbors according to the flooding protocol;
- Considering the goal of the mission, compute and execute controller ui combining both CVi and si;
- Return to step 1.

Hybrid Cooperation I
Conclusion and Future research

- Unified Model
- Reconfiguration, Cooperation and Formation
- Integrated Sensing, Communication, and Control
- Hybrid Perceptive Reference
- Multi-robot Target Observation