Geometry-Based Reasoning for a Large Sensor Network

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1. INTRODUCTION

In recent time, the study of wireless sensor networks (WSN) has become a rapidly developing research area. In a typical WSN scenario, a large swarm of small and inexpensive processor nodes, each with limited computing and communication resources, is distributed in some geometric region. Upon start-up, the swarm forms a decentralized and self-organizing network that surveys the region, communicating by wireless radio with limited range.

These WSN characteristics imply absence of a central control unit, limited capabilities of nodes, and limited communication between nodes. This requires developing new algorithmic ideas that combine methods of distributed computing and network protocols with traditional centralized network algorithms. The challenge is: How can we use a limited amount of strictly *local* information in order to achieve distributed knowledge of *global* network properties? As it turns out, making use of the underlying geometry is essential.

Using our toolbox SHAWN [6] for the simulation of large and complex networks, we illustrate two procedures for dealing with this challenge: one identifies the boundaries of the network; the other constructs a clustering that describes the network topology. For more technical details of the underlying algorithmic side, see our recent paper [5]. Our software is freely available at `www.swarmnet.de`.

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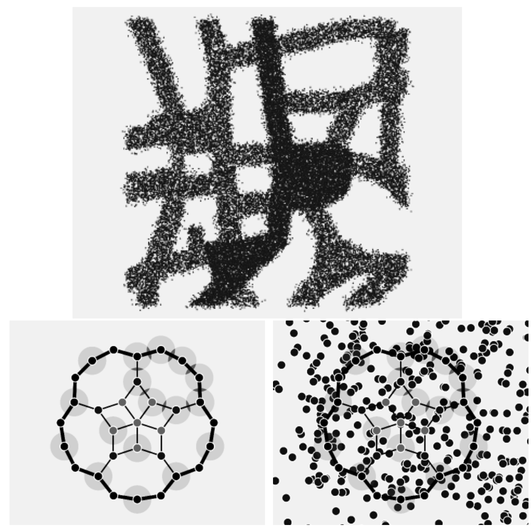

Figure 1: Top: A sensor network, obtained by scattering 60,000 nodes in a of street network. Bottom left: A flower subgraph, used for reasoning about boundary and interior of the network. Right: A flower in the context of the network shown above.

2. MODEL

A *Sensor Network* is a graph $G = (V, E)$, with an edge between any two nodes that can communicate with each other. The network is embedded in the plane by the mapping $p : V \rightarrow \mathbb{R}^2$, but positions are not available to the nodes. We assume that (G, p) is a *Unit Disk Graph*, i.e., nodes have uniform communication range. Furthermore, we assume that nodes are distributed in a specific domain $A \subset \mathbb{R}^2$, which is described by a polygon with holes; a prototypical scenario for such a domain arises by scattering nodes in a bounded street network.

3. GEOMETRY-BASED REASONING

A crucial issue in a complex environment is the extraction of a global cluster structure that reflects the network topology, based on strictly local information.

3.1 Boundary Recognition

Recognizing the network boundary is vital for detecting objects entering or leaving the monitored area or events that affect the network structure.

We first proposed the boundary recognition problem in [2], using a probabilistic setting; see [1] for a refined approach. Another approach was suggested by Funke [3, 4], which requires a particular boundary structure and sufficient density. Our method described in [5] yields deterministically provable results for any kind of boundary structure.

See Figure 1 for a geometric representation of a graph called a *flower*. Non-neighboring nodes have a minimum distance, so an independent node set requires a certain amount of space in the embedding. On the other hand, the space surrounded by a cycle is limited. This packing argument allows conclusions about the relative embedding of nodes. Applying a similar argument repeatedly, the central nodes can deduce that they lie inside of the outer cycle.

Because flowers are strictly local structures, they can be easily identified by local algorithms. In the shown example network of 60,000 sparsely connected nodes, our procedure identified 138 disjoint flowers; a single one suffices for the second stage of our algorithm.

In this second stage (cf. Figure 2), we augment flowers by adding extensions to their outer cycles, such that insideness can still be proven for all contained nodes. By repeating a local search procedure, the flowers grow to enclose more and more nodes and merge together, eventually leading to a single structure that contains most of the network.

3.2 Topology Extraction

Our second procedure addresses the topological clustering problem: To cluster the nodes in such a way that the resulting cluster shapes reflect the topology of the network; see Figure 3. By considering the hop count from the boundary, we get a shortest-path forest. Nodes that have almost the same distance to several pieces of the boundary form the medial band of the region. Nodes close to three different boundary portions form vertices of the medial band, or Voronoi vertices. After identifying a set of Voronoi vertices, we also know their distance from the boundary. This makes it easy to grow the corresponding intersection cluster to just the right size. Thus, we can identify all intersection clusters in the network. Finally, parts of the network adjacent to intersection clusters give rise to street clusters.

In the end, we have structured the network into a natural set of clusters that reflect its topology. This makes it is possible to perform complex tasks, such as tracking and guiding, based on purely local operations.

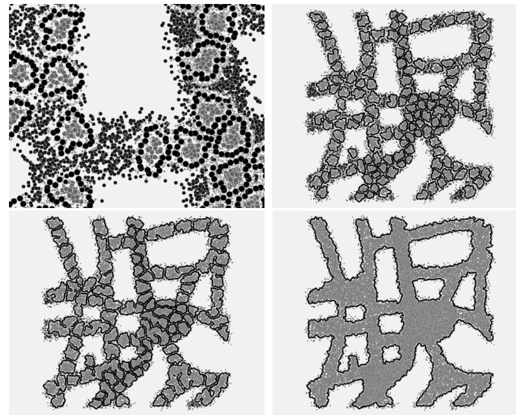

Figure 2: Top left: A set of expanding flowers in a network. Top right: A later stage of the flower expansion. Bottom left: Flowers merging together. Bottom right: The result of boundary recognition.

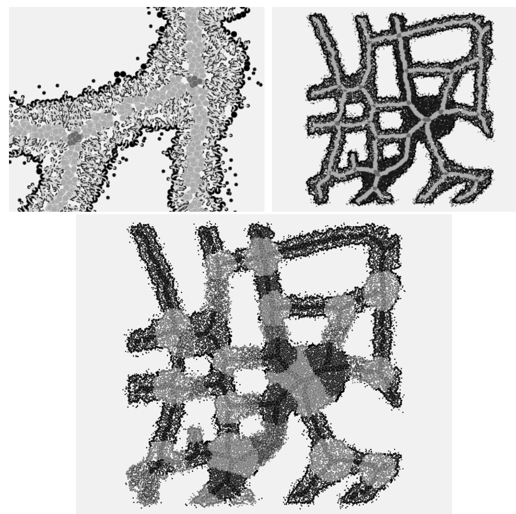

Figure 3: Top left: The shortest-path forest defines the medial band. Top right: Medial band and Voronoi vertices. Bottom: The resulting intersection and street clusters.

4. THE VIDEO

The video starts by describing sensor nodes and their deployment. Following an introduction of the algorithmic challenge, the next scene illustrates the problem of boundary recognition. Next is the concept of flowers and the way they allow local, deterministic reasoning about nodes lying in the interior of the network. Their extension by augmenting cycles is demonstrated in the following scene, leading to full-scale boundary recognition. The next part introduces the medial band and the recognition of Voronoi vertices. In the final sequence, this leads to the construction of clusters.

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