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An Online Distributed Boundary Detection and Classification Algorithm for Mobile Sensor Networks

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Abstract– We present a novel online distributed boundary detection and classification algorithm in order to improve accuracy of boundary detection and classification for mobile sensor networks. This algorithm is developed by incorporating a boundary detection algorithm and our newly proposed boundary error correction algorithm. It is a fully distributed algorithm based on the geometric approach allowing to remove boundary errors without recursive process and global synchronization. Moreover, the algorithm allows mobile nodes to identify their states corresponding to their positions in network topologies, leading to self-classification of interior and exterior boundaries of network topologies. We have demonstrated effectiveness of this algorithm in both simulation and real-world experiments and proved that the accuracy of the ratio of correctly identified nodes over the total number of nodes is 100%.

Keywords– Distributed boundary detection, Distributed boundary classification, Mobile sensor network.

1 INTRODUCTION

A mobile sensor network can be deployed for surveillance and reconnaissance, security and patrolling, and environmental monitoring in an unknown environment. Coverage area of a deployed sensor network is identified through the shape formed by the boundary nodes. In this paper, we focus on developing an online distributed boundary detection and classification algorithm enabling mobile sensor nodes to identify whether they are (inner or outer) boundary nodes of mobile sensor networks. This algorithm plays a crucial role of boundary node identification in many mobile systems, such as controlling cohesion configuration of a robotic swarm[1], monitoring dynamic obstacles in mobile sensor networks, detecting intrusion in networks[2].

In [3–10], the boundary detection algorithms were designed for sensor networks with static nodes so they do not require node locations and relative distance between nodes rather than using connectivity information in the network. In [3], the algorithm was developed for high density of static sensor networks by using a key feature of the distribution of nodes in which the nodes on the boundary have a smaller degree than the interior ones. A node can be considered as a boundary node by estimating a global distribution and a threshold degree. In [4], the deterministic boundary detection algorithm was proposed for a large-scale network of static sensors scattered in a polygonal region, e.g., a street network. The nodes only interact each other through communication without information of coordinates and geometric distances. Based on a stronger structural criterion of particular subgraph, called m-flower, interior and exterior boundaries are detected if their edges are in the flower boundary. The flower pattern was also used in [6] to detect the boundaries for both unit-disk graph and quasi-unit disk graph. In [5], a distributed boundary detection algorithm for wireless sensor networks (WSNs) was developed by exploiting special structures of the shortest paths to detect the existence of hole boundaries in the network. Another algorithm using three-hop neighbouring node information for detecting boundary around an obstacle can be found in [7]. In [8], the Localized Voronoi Polygons (LVP) was used to identify boundary nodes. If the LVP of a node is a finite number, the node is considered as an internal node, otherwise, the node is set as a boundary node. In [9], the concept of independent set from the graph theory was exploited to develop an algorithm for detecting boundaries and holes in the WSNs. The algorithm includes three main steps: each node builds an one-hop graph based on connectivity information of its neighbours; independent sets of cardinality are established, and the independent sets are connected to search for closed paths. In [10], boundary nodes are identified based on computational geometry using absolute angles of their neighbours in the local Cartesian coordinate system.

For networks of mobile sensor nodes, so-called mobile sensor networks (MSNs), the cyclic-shape algorithm [11] can be considered as the first boundary detection algorithm. This method requires local network geometry in which each node checks its missing sectors to identify whether it is a boundary node.
2 Boundary Detection

Given a mobile sensor network consisting of $N$ nodes in which each node is a mobile sensor node capable of measuring relative distance of its neighboring nodes inside its limited sensing range $r_c$ and carrying out peer-to-peer communication with nodes inside its communication range. In reality, the communication range is greater than the sensing range, so we assume that if two nodes are inside sensing range of each other, they can communicate to exchange information.

Geometric configuration of a mobile sensor network depends on spatial distribution of the nodes, which is considered in 2-dimensional space. The outer shape of the geometric configuration is defined as its boundary. Nodes on the boundary are called as boundary nodes while the others are called as interior nodes. Boundaries can be classified into exterior boundaries or interior boundaries in which a void inside the configuration is bounded by an interior boundary. Nodes inside sensing range of node $i$ are called its neighbors, $N_i$. A connectivity between nodes $i$ and $j$ is denoted by $e_{ij}$, which is positive if $j \in N_i$ or zero if $j \notin N_i$.

2.1 Boundary Detection Method

A local boundary detection algorithm presented in [11] allows node $i$ to identify itself as either a boundary node or an interior node. Node $i$ has neighbors $N_i$ sorted in a cyclic order. Each pair of two adjacent neighbors $(j, k)$ make a sector with an angle $\theta_{jk}^i$ classified into two types of sector as follows:

- **Missing Sector**: A sector $(j, k)$ is called a missing sector if nodes $i$ and $j$ are not connected, $e_{jk} = 0$, or if the angle between them is greater than or equal to $\pi$, $\theta_{jk}^i \geq \pi$. The angle $\theta_{jk}^i$ is called as missing sector angle.
- **Triangle sector**: A sector $(j, k)$ is called a triangle sector if nodes $i$ and $j$ are connected, $e_{jk} > 0$. In this case, nodes $i, j, k$ form a triangle.

A set of consecutive sectors in node $i$'s cyclic order is denoted by $P_i$. Node $i$ uses states of sectors in $P_i$ to classify itself as follows:

- **Interior node**: A node is self-labeled as an interior node if its all sectors are triangle sectors.
- **Boundary node**: A node is self-labeled as a boundary node if it has at least one missing sector. The edges on the boundary node’s missing sector are called as boundary edges.

Because a boundary is a closed-loop interconnectivity established by boundary edges in which each boundary node is connected with two neighboring ones, the algorithm to identify boundary errors is illustrated in Figure 3 and defined as follows:

**Definition 1 (Boundary error)**. A boundary node is seen as a boundary error if it is directly or indirectly connected with an interior node through boundary edges.

In other words, boundary node $i$ with a missing sector $(j,k) \in P_i$ becomes a boundary error if at least
one node of the pair \((j,k)\) or another node on the boundary indirectly connected with node \(i\) is an interior node.

The boundary errors can be removed by recursively identifying all the single-node errors and labelling them as interior nodes as described in [11]. This process requires some sort of global synchronization to periodically reset the suppressed error status on the nodes and is repeated until no existing boundary error, thus the algorithm developed in [11] is not fully distributed. Moreover, the authors claimed that the accuracy of the local boundary detection algorithm, the ratio of correctly detected nodes to the total number of nodes, reaches 86% in a static configuration in simulation. Last but not least, this algorithm has not been examined through real-world experiments.

Our motivation is to upgrade the local boundary detection algorithm to become a fully distributed algorithm, increase its accuracy of boundary detection and classification algorithm, and examine it through real-world experiments. Moreover, our algorithm in 2.2 allows boundary errors to self-correct without using the recursive process and global synchronization.

### 2.2 Boundary Error Correction

In this section, we present a boundary error correction algorithm (BEC) used to detect and remove boundary errors. It is easy to realize that a missing sector \((j,k)\) of node \(i\) is formed in a topology with at least four edges as illustrated in Figure 4. A quadrangle is established by the missing sector and a node \(g\) in \(N_{j,i} = N_j \setminus \{N_i \cup i\}\) and/or \(N_{k,i} = N_k \setminus \{N_i \cup i\}\) formed in either a closed quadrangle with four edges or an open quadrangle with more than four edges. We release a new concept as follows:

**Definition 2 (e-triangle sector).** If node \(i\)'s quadrangle is divided into triangles, node \(i\)'s missing sector formed in the quadrangle is called an e-triangle sector.

Intuitively, the quadrangle established by nodes \(i, j, k, g\) can be divided into triangles by one of three cases as follows:

- Existing node \(j\)'s triangle sector \((g,m)\) \(\in P_j\) as illustrated in Figure 6.a
- Existing node \(k\)'s triangle sector \((g,\ell)\) \(\in P_k\) as illustrated in Figure 6.b.
- Existing node \(g\)'s triangle sector \((\ell,m)\) \(\in P_g\) as illustrated in Figure 6.c.

Let \(N_{ij}\) and \(N_{ik}\) be neighbouring nodes of node \(i\) in areas \(S_{ij}\) and \(S_{ik}\), respectively, as described in Figure 5. Conditions corresponding to the scenarios to identify whether the missing sector \((j,k)\) \(\in P_i\) is an e-triangle sector or not are given as follows:

- There exists node \(m\) \(\in N_{ik}\) connected to node \(j\), \(e_{jm} = 1\), so that nodes \(j, m\) have at least one common neighbour \(g\) not in \(N_{ij}\), \(N_{j,i} \cap N_{m,i} \neq \emptyset\).

\[
\text{cond}_1 = \begin{cases} 
1 & \exists m \in N_{ik} : (e_{jm} = 1) \land (N_{j,i} \cap N_{m,i} \neq \emptyset) \\
0 & \text{Otherwise}
\end{cases}
\]  

The pair \((i, g)\) of node \(j\) contain two triangle sectors \((i, m)\) \(\in P_j\) and \((g, m)\) \(\in P_g\), so it is not a missing sector. Thus, node \(j\) is not a boundary node of the quadrangle; that is, it is an interior node.
Thus, node $j$, that is, it is an interior node. (Boundary error)

Proposition 2 (Boundary error correction). If all the nodes with e-triangle sectors are labeled as interior nodes, there does not exist any boundary error in the network. According to the proposition 1, the boundary error has an e-triangle sector. This is contradict to the assumption so the proposition is proven.

Algorithm 1: e-triangle sector detection

Input: $(j, k) \in P_i, N_i, N_k$
Output: etriangle sector

Initialization: $Cond_1 = 0, Cond_2 = 0, Cond_3 = 0$
$etriangle sector \leftarrow 0$
$[N_{ij}, N_{ik}] = Adjacent Neighbours(\theta_{ik}, \pi/2)$

for $\ell \in N_{ij}$ do
  for $m \in N_{ik}$ do
    if $(\ell, \ell) \in P_i$ and $(m, \ell) \in P_i$, so it is not a missing sector. Thus, node $k$ is not a boundary node of the quadrangle; that is, it is an interior node.

- There exists node $\ell \in N_{ij}$ connected to node $k$, $e_{ik} = 1$, so that nodes $k, \ell$ have at least one common neighbour $g$ not in $N_i, N_{i,j} \cup N_{i,k} \neq \emptyset$.

$$cond_2 = \begin{cases} 1 & \exists \ell \in N_{ij} : (e_{ik} = 1) \land (N_{i,j} \cup N_{i,k} \neq \emptyset) \\ 0 & \text{Otherwise} \end{cases}$$

The pair $(i, g)$ of node $k$ contain two triangle sectors $(i, \ell) \in P_i$ and $(m, \ell) \in P_i$, so it is not a missing sector. Thus, node $k$ is not a boundary node of the quadrangle; that is, it is an interior node.

- There exists nodes $\ell \in N_{ij}$ and $m \in N_{ik}$ connected together, $e_{ik} = 1$, so that they have at least one common neighbour $g$ not in $N_i, N_{i,j} \cup N_{i,k} \neq \emptyset$.

$$cond_3 = \begin{cases} 1 & \exists \ell \in N_{ij}, m \in N_{ik} : (e_{im} = 1) \land (N_{i,j} \cup N_{i,k} \neq \emptyset) \\ 0 & \text{Otherwise} \end{cases}$$

The pair $(j, k)$ of node $g$ contain at least two triangle sectors $(j, \ell) \in P_g$ and $(m, \ell) \in P_g$, thus it is not a missing sector. Therefore, node $g$ is not a boundary node of the quadrangle; that is, it is an interior node.

Proposition 1 (Boundary error). A boundary error appears on a boundary node if and only if it has an e-triangle sector.

Proof: If node $i$ has an e-triangle sector $(j, k) \in P_i$, it satisfies that $(cond_1 = 1) \lor (cond_2 = 1) \lor (cond_3 = 1)$. It means that one of three nodes $j, k, g$ is an interior node. According to the definition 1, node $i$ is a boundary error.

If a boundary error appears on a missing sector $(j, k) \in P_i$ formed in a quadrangle $(i, j, k, g)$, one of three nodes $j, k, g$ must be a boundary node of the quadrangle. Thus, one of pairs $(i, g)$ of node $j, (i, g)$ of node $k$, and $(\ell, m)$ of node $g$ is a boundary sector; that is, it satisfies the one of the conditions for an e-triangle sector, $(cond_1 = 1) \lor (cond_2 = 1) \lor (cond_3 = 1)$. Hence, the missing sector $(j, k) \in P_i$ is an e-triangle sector. This completes the proof.

Proposition 2 (Boundary error correction). If all the nodes with e-triangle sectors are labeled as interior nodes, there does not exist any boundary error in the network.

Proof: We use proof by contradiction. Assume that all the nodes with e-triangle sectors are labeled as interior nodes but there still exists a boundary error in the network. According to the proposition 1, the boundary error has an e-triangle sector. This is contradict to the assumption so the proposition is proven.

The core of the BEC is an e-triangle sector detection algorithm as shown in Algorithm 1. The algorithm considers a missing sector $(j, k) \in P_i$. It uses a function $Adjacent Neighbours(\theta_{ik}, \pi/2)$ to get node $i$’s neighbours $N_i$ and $N_k$ in its areas $S_i$ and $S_k$, respectively. In this algorithm, all existing edges $\{e_{im}, e_{ik}, e_{im}\}$ on $N_i$ and $N_k$ are searched and checked whether the conditions of an e-triangle sector is satisfied. If $(cond_1 = 1) \lor (cond_2 = 1) \lor (cond_3 = 1)$, it returns $etriangle sector = 1$, confirming that the missing sector $(j, k) \in P_i$ is an e-triangle sector.

This algorithm only uses sensing to identify sets $N_i$ and $P_i$, and one-hop communication between node $i$ and its neighbours $j, k, \ell, m$ to determine sets $N_j, N_k, N_m$, and $N_o$, respectively, so it is fully distributed in meaning that each node only uses local information from itself and its neighbours to classify itself as a boundary node or an interior node. The algorithm does not require global synchronization to periodically reset the suppressed error status on the nodes. Therefore, computational complexity of this algorithm is $O(N_i^2)$, but only $O(1)$ bits/node/round of communication is used to detect an e-triangle sector.

### 3 Boundary Classification

In this section, we present a boundary classification algorithm (BC) allowing a node to classify itself whether it is on an interior or exterior boundary. Figure 1 illustrates a result of this algorithm applied for a network of 100 nodes. Before presenting the algorithm, we remain the concepts of a boundary as follows:

Definition 3 (Boundary). A boundary is a closed-loop inter-connectivity containing a sequence of boundary nodes
such that each node is connected with two neighbouring ones though two boundary edges.

Figure 6. Scenarios for an e-triangle sector \((j,k) \in P_1\) where node \(i\)'s quadrangle is divided by a triangle sector: (a) \((m,g) \in P_2\); (b) \((j,g) \in P_3\); (c) \((j,g) \in P_4\).

Figure 7. Boundary classification algorithm: A node \(i = 1\) has a missing sector \((2,26)\). The message broadcasted by node \(i\) is forwarded from node 2 to node 26 via the boundary edges (green). Only boundary nodes (red) \((2,6,7,8,10,11,26)\) on the green polygon are allowed to forward the message.

Given a boundary established by \(n_b\) boundary nodes and denote \(\Theta\) as the sum of the missing sector angles on the boundary. As mentioned above, there are two typical boundaries: interior and exterior boundary.

- **Interior boundary:** An interior boundary bounds a void inside the geometric configuration of a mobile sensor network, so its missing sector angles are interior angles of the polygon established by the boundary. According to polygon theorem, the sum of the interior angles of the polygon with \(n_b\) edges equals to \((n_b - 2) \pi\). Hence, the interior boundary has property: \(\Theta = (n_b - 2) \pi\). Nodes on an interior boundary are called inner boundary nodes.

- **Exterior boundary:** An exterior boundary is outer shape of the geometric configuration, so its missing sector angles are complement of interior angles of the polygon established by the boundary. Hence, the exterior boundary has property: \(\Theta = n_b \times 2\pi - (n_b - 2) \pi = (n_b + 2) \pi\). Nodes on an exterior boundary are called outer boundary nodes.

In summary, a boundary can be classified as an interior boundary if it has \(\Theta = (n_b - 2) \pi\) or an exterior boundary if it has \(\Theta = (n_b + 2) \pi\). Any boundary node can be classified as either an inner or outer boundary node if it knows \(\Theta\) and \(n_b\). On a node, the pair \((\Theta, n_b)\) can be obtained by sending a "ping" message from a side of its missing sector to another side through a set of boundary nodes as illustrated in Figure 7. The procedure can be described as follows. In order to classify whether boundary node \(i\) with a missing sector \((j,k)\) is an inner or outer one, node \(i\) falls into active mode using multi-hop communication to gather missing sector angles \(\Theta\) and number of boundary nodes \(n_b\) on the boundary. It broadcasts a message, containing \(\Theta\) and \(n_b\) with initialization \(\Theta = \theta_i^b\) and \(n_b = 1\), respectively, for path discovery from node \(j\) to node \(k\) through the ad-hoc network of the mobile nodes. A node broadcasting the message is called a transmitter. All neighbours of a transmitter can receive the message, but a boundary node on its common boundary edge is allowed to forward the message with updated variables \(\Theta\) and \(n_b\). Updating variables is performed by adding the missing sector angle of the transmitter to \(\Theta\) and increasing \(n_b\) by one. Thank to the message forwarded to reach node \(k\), node \(i\) has possibility of identifying the sequence of boundary nodes on the path and checking the boundary classification condition by values \(\Theta\) and \(n_b\). Node \(i\) is self-labeled as an inner boundary node if \(\Theta = (n_b - 2) \pi\) or an outer boundary node if \(\Theta = (n_b + 2) \pi\), and rebroadcasts a message containing the list through the path in order to update the classification states for all boundary nodes on the list. When a boundary node has been self-labeled, it works in passive mode while the self-classification is happening on other boundary nodes. Note that, a node belongs to some difference boundaries if it has some missing sectors.

Unlike to the algorithm in [11], in our algorithm, every boundary node can be considered as a root of the boundary for self-classification when it is activated in the active mode. The boundary classification algorithm uses multi-hop communication, so it requests the communication complexity \(O(n_b)\), where \(n_b\) is number of boundary nodes on the boundary.

4 Experiments and Discussions

4.1 Simulation

Assume that each node has ability of identifying its nearest neighbours and measuring their relative
localisation within limited sensing range $r_c = 1m$. Two connected nearest neighbouring nodes can exchange information with delay communication time between them limited by $T_m$. 
We have examined the effectiveness of the BEC and BC algorithms in both static and dynamic configuration established by an ad-hoc network of sensor nodes on a flat surface in 2D model.

Firstly, the BEC and BC algorithms are investigated in a static configuration with nodes that are spatially distributed with the Gaussian random distribution as described in [15] using 100, 200, and 300 nodes. Each algorithm was simulated in 10 different scenarios with delay communication time $T_m = 0.0125s$ and $T_m = 0.125s$ corresponding to the node speed rate (RSR) between node movement and communication $RSR = 0.001$ and $RSR = 0.01$ as examined in [11].

The simulation results show that accuracy of the local boundary detection algorithm with or without BEC algorithm as illustrated in Figure 8. The median accuracy of the algorithm without BEC is 97.50%, 93.50%, and 92.83% in cases 100, 200, and 300 nodes, respectively while the accuracy reaches 100% for all the cases when the BEC algorithm was applied. Figure 9 shows the accuracy of the BC algorithm. The result confirms that the algorithm successfully classifies boundaries for all the randomized scenarios.

The running time of the local boundary detection algorithm is shown in Figures 10 and 11. Because boundary error correction using recursive algorithm depends on number of boundary errors and requires complexity of communication $O(N)$, the running time with $T_m = 0.125s$ is greater than with $T_m = 0.0125s$ and it is more time consuming in scenarios with high boundary error rate. Unlike the recursive algorithm, the BEC algorithm has complexity of communication $O(1)$ so that it only depends on the status of neighbouring nodes. The results show that the BEC algorithm is faster than the recursive algorithm when $T_m = 0.0125s$ and the boundary error rate in the network is more than 6.6% while the running time of the BEC algorithm is much lower than the one of the recursive algorithm for all scenarios having the boundary error rate not equal zero with $T_m = 0.125s$.

Secondly, the BEC and BC algorithm were examined in a dynamic configuration with 50 mobile nodes. Boundaries were detected online while the nodes was deployed to track and occupy multiple targets as described in [15]. All nodes detect and classify themselves successfully overtime without any error. Accuracy of the boundary detection algorithm over time is shown in Figure 12. The video demonstration of the simulation can be seen at this link

4.2 Experiments

In real-world experiments, we used 14 mobile robots as mobile sensor nodes to investigate the effectiveness of the online boundary detection and classification algorithm in a dynamic network. The robots are 14cm diameter disc-like differentially driven wheel platforms as in Figure 14. The sensing and communication range is set at $r_c = 1$ and the maximum velocity of the nodes is set at $0.8m/s$, similar to the simulation.

The online boundary detection and classification were measured while the robots was deployed on a flat surface to track and occupy multiple targets. We show that boundary nodes were successfully detected and classified with the accuracy 100% while the robots cooperatively tracked and occupied multiple targets as shown in Figure 13. The boundary was online created as illustrated in Figure 15 and the video demonstration can be seen at this link

5 Conclusion

We have presented the online local boundary detection and classification algorithm with error correction based on the geometric approach in 2D model. Using this algorithm, all boundary errors in a network can be removed without recursive process and global synchronization. The accuracy of this new boundary detection and classification is 100%. We validated the quality of the new boundary detection and classification algorithm in simulations of both static and dynamic network configurations, and the real-world experiments with 14 mobile robots.

References


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