A localized algorithm for bi-connectivity of connected mobile robots

Shantanu Das · Hai Liu · Amiya Nayak · Ivan Stojmenović

Published online: 6 November 2008
© Springer Science+Business Media, LLC 2008

Abstract Teams of multiple mobile robots may communicate with each-other using a wireless ad-hoc network. Fault-tolerance in communication can be achieved by making the communication network bi-connected. We present the first localized protocol for constructing a fault-tolerant bi-connected robotic network topology from a connected network, in such a way that the total movement of robots is minimized. The proposed distributed algorithm uses \( p \)-hop neighbor information to identify critical head robots that can direct two neighbors to move toward each other and bi-connect their neighborhood. Simulation results show that the total distance of movement of robots decreases significantly (e.g. about 2.5 times for networks with density 10) with our localized algorithm when compared to the existing globalized one. Proposed localized algorithm does not guarantee bi-connectivity, may partition the network, and may even stop at connected but not bi-connected stage. However, our algorithm achieved 100% success on all networks with average degrees \( \geq 10 \), and over 70% success on sparse networks with average degrees \( \geq 5 \).

Keywords Mobile sensors · Robot networks · Fault tolerance · Distributed algorithm · Localized movement control

1 Introduction

With significant advancements in robotics technology and the emergence of a large number of applications for multi-robot systems, the problem of coordinating between a group of autonomous robots has become an issue of great importance. In such robot systems, coordination between individual robots is essentially accomplished through a wireless ad hoc network. For example, coordination of robotic relay stations was studied in [5] to maintain communication between an explorer and a base station. Application of mobile robotics is vast. Potential applications include military missions, unmanned space exploration, and data collection in sensor fields. But for such applications, coordination of a robot team in pursuit of common task is essential. Existing algorithms for mobile robots coordination are suitable for robots with no or very low failure rates. However, when robots are susceptible to failures, as in many applications, it is critical for robotic networks to incorporate the ability to sustain faults and operate normally. Communication faults
in robot networks can be caused by hardware damage, energy depletion, harsh environment conditions and malicious attacks. A fault in a robot can cause stopping transmission tasks to others as well as relaying data to sink. Data sent by a robot will be lost if the receiving robot fails. So, a communication link failure on a route requires data to be re-routed. That is, in order to handle general communication faults, there should be at least two node-disjointed paths between each pair of robots in the network. A network is defined to be bi-connected if there exist two node-disjointed paths between any pair of nodes in the network, i.e., the removal of any node from the network leaves the network still connected. Therefore, bi-connectivity is the basic requirement for design of fault-tolerant networks [9].

In this paper, we focus on mobile robot networks and study movement control of robots to establish a fault-tolerant bi-connected network. The robot network is assumed to be connected, but not necessarily bi-connected. Achieving connectivity in a disconnected network is difficult due to the lack of communication between the disconnected parts. However, if the network is already connected, we can make it bi-connected (and thus fault-tolerant) by movement of selected robots. Recent work in [2] has shown that fault tolerance can be achieved through globalized robot movement control algorithm. It is a centralized algorithm that assumes one of robots or a base station has global information of the network. We focus on the localized version of movement control algorithm for building a fault-tolerant robot network. To the best of our knowledge, this is the first work on localized movement control for fault tolerance of mobile robot networks.

The rest of the paper is organized as follows. Related work is introduced in Sect. 2. We propose a localized movement control algorithm to construct bi-connected mobile robot networks in Sect. 3. Results obtained from extensive simulations are provided in Sect. 5 to show the effectiveness of our algorithm. Finally we conclude our work in Sect. 6.

2 Related work

Many topology control algorithms have been proposed to achieve network reliability in static networks [3, 4, 8, 12]. These algorithms cope with preserving fault tolerance by selecting certain links to neighbors in an already well connected network. The problem of adjusting the transmit power of nodes to create a desired topology in multiple wireless networks was studied in [10]. For static networks, two centralized algorithms were proposed to construct connected and bi-connected networks while minimizing the maximal transmission power of nodes. Two distributed heuristics were further proposed for mobile networks. The basic idea is to adaptively adjust node transmit power according to topological changes and attempt to maintain a connected topology with the minimum power. A more general case for k-vertex connectivity of wireless networks was studied in [7]. Both a centralized algorithm and a localized algorithm were proposed. Both above works assumed that nodes have uniform transmission range. That is, they focused on homogeneous networks. Topology control in heterogeneous wireless networks was discussed in [7]. Two localized algorithms were proposed. It was proved that the topologies generated by the proposed algorithms preserve bi-connectivity of networks. An extension of cone-based topology control algorithm was proposed in [1]. Each node decides its own power based on local information about relative angle of its neighbors. It showed that a fault-tolerant network topology is achievable and transmission power of each node is minimized to some extent. The proposed algorithm can be extended to 3-dimensions. All these works on topology-control construct fault-tolerant networks by adjusting transmit power of nodes. Movement of nodes is not a controllable parameter even in the works where mobile networks are considered (except in [11] where only the base station can move).

Significant amount of work has been done in coordinating teams of mobile robots or actors. However, little attention was paid to incorporate fault tolerance into these robotic networks. For example, Dynia et al. [5] studied the problem of maintaining communication between an explorer robot and base station by moving other robots along the path.

Mobile robot network can be represented as a graph, where each node is a mobile robot and each edge denotes a communication link between a pair of robots. In a connected graph, a node is called a critical node if the graph is disconnected without the node. There are no critical nodes in a bi-connected graph. So, critical nodes are important in designing movement control algorithms to achieve bi-connected networks. Jorgic et al. [6] proposed an approach for localized p-hop critical node detection. To find if a node is critical in the network, a sub-graph of p-hop neighbors of the node is considered. From this sub-graph, the node itself and all its incident edges are excluded. If this resulting sub-graph of p-hop neighbors of a node is disconnected by excluding the node, then the node is critical. Since only local topological information is used, it is specified as p-hop critical node as it may not be globally critical. However, all the globally critical nodes are always p-hop critical for any value of p. As seen in Fig. 1, the nodes A, B, and C are 2-hop critical nodes in the given network. We can also notice that nodes A and B in Fig. 1 are only 2-hop critical nodes and are not globally critical. However, node C is globally critical in the network and is also 2-hop critical. Experiments showed that over 80% of locally estimated critical nodes and links are indeed globally critical [6].

Our problem is most related to the problem discussed by Basu and Redi [2], where movement control algorithms for