Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-30 (2016) 337–342

Improving Robustness of Robotic Networks using Consensus and Wireless Signal Strength ⋆

Sidney Carvalho [*,**] **Luis Pinto** [**] **Luis Almeida** [**]
Ubirajara Moreno [*]

[*] *Department of Automation and Systems, Federal University of Santa Catarina, Brazil (e-mail: sidney.rdc@posgrad.ufsc.br)*
[**] *Instituto de Telecomunicações, University of Porto, Portugal.*

Abstract: When using multiple networked autonomous mobile robots to sense a given area online, it is of high importance to assure the network connectivity even when the robots move in the scope of their application target. In previous work we have used a topological graph property known as bi-connectivity to turn the multi-robot network robust to dropout faults while the robots were sensing a certain area or tracking a target. In this paper we continue that work by including wireless signal strength information as a measure of link quality, adapting the robots' positions to make sure each robot is connected to any other robot by at least two separate routes over time. The proposed algorithm is decentralized and based on consensus theory. We use a solution of the Traveling Salesman Problem to turn the initial arbitrary topology graph into a virtually bi-connected one. We validate our method with simulations that consider asymmetric and intermittent attenuation in the propagation model. The obtained results show that without our method the network can be disrupted while our method compensates unexpected attenuation. This work is particularly suited to networks of UAVs that sense a target area, online.

Keywords: Multi-robot networks, networked systems, topology control, consensus theory, wireless communication.

1. INTRODUCTION

With the evolution of robotic systems and reduction of their costs, the use of teams of multiple robots to solve complex tasks in a distributed way has become common, from search and rescue (Chung et al., 2011) to formation control (Lima et al., 2015; Correia and Moreno, 2015), area coverage and sensing (Bhattacharya et al., 2013), etc.

In these situations, information exchange among the robots is highly important to allow the team to achieve its global goal, supporting cooperation and coordination strategies. In turn, information exchange requires a wireless network, which is typically ad-hoc and thus exhibiting a variable topology, with the robots positions determining the number of links and paths between them (Olfati-Saber and Murray, 2004). In such scenarios, topology control is a good approach to improve certain network features, e.g., robustness to node faults, by moving the robots to adequate positions in an adequate way.

Topology control can be done in several ways. For example, Ahmadi and Stone (2006) exchange a token message among the robots to detect critical nodes in the network, i.e., those that can disconnect it when removed. When such critical nodes are detected, the robots are moved towards increasing the neighborhood of these critical ones. Conversely, Wagenpfeil et al. (2009) use potential fields to increase each robot's neighborhood making an uniform topology. A similar work is shown by Casteigts et al. (2010) presenting a concept of virtual forces that are used to build a Delaunay triangulation structure on each robot neighborhood that turns the network tolerant to robot faults by increasing the number of information paths between the robots. In Carvalho et al. (2015) we presented a solution to increase the robustness of the network with respect to robots faults or dropouts making the topology bi-connected, i.e., each robot is connected to any other robot by at least two disjunctive paths. We used a solution of the Traveling Salesman Problem to turn the initial arbitrary topology into a virtually bi-connected one and then we used a decentralized algorithm based on consensus theory to bring the robots to positions corresponding to the desired topology.

However, in Carvalho et al. (2015) we measured the actual robots positions with GPS and considered an isotropic signal propagation, which does not always apply, mainly when operating in areas with obstacles, or with heterogeneous or non-omni-directional antennas. In this paper we add two features. We consider a sensing task with sensors of circular range and we target at maximizing sensing area coverage. Then we consider the actual signal strength of the received messages and adapt the robots' positions to

---

⋆ This work was partially supported by CNPq (Brazil) through grant 207650/2015-2 and by FCT (Portugal) through grant SFRH/BD/51630/2011.

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.11.158

enforce minimum strength values and thus bi-connectivity over time, even if reducing the covered area.

Concerning the technology, we use WiFi (IEEE 802.11) in ad-hoc mode complemented with an overlay protocol, namely Reconfigurable and Adaptive Time Division Multiple Access (RA-TDMA) (Oliveira et al., 2015), which virtually eliminates collisions forcing transmissions of different robots to occur in disjoint slots.

The rest of the paper is organized as follows: in Section 2 we briefly present the background of consensus and graph theory, and wireless signal strength; in Section 3 we formulate the problem we are addressing and discuss some technical constraints; in Section 4 we show the results of numerical simulations to evaluate our method; and finally in Section 5 we present our conclusions and future work.

2. BACKGROUND

Networks of robots are usually represented as graphs $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the robot set and $\mathcal{E}$ is the link set between the robots. The algebraic shape of a graph can be defined by the adjacency matrix $A = [a_{ij}] \in \mathbb{R}^{n \times n}$, where n is the number of robots in the network, $a_{ij} > 0$ if and only if $(i, j) \in \mathcal{E}$, and $a_{ij} = 0$, otherwise.

The immediate neighborhood set of a robot i, also called 1-hop neighborhood, is defined by:

$$\mathcal{N}_i^1 = \{j \in \mathcal{V} : (i, j) \in \mathcal{E}\}.$$

However, in this work we use local information up to the 2-hop neighborhood which, for robot i, is defined by:

$$\mathcal{N}_i^2 = \{j \in \mathcal{N}_i^1; q \in \mathcal{V} \backslash \mathcal{N}_i^1 : (j, q) \in \mathcal{E}\}.$$

There are many ways to determine when two robots are neighbors. In this work we use the Euclidean distance between them. Each robot has a communication radius (r^{com}) that represents the maximum transmission distance and a coverage radius (r^{cov}) that is the maximum sensing distance for a robot (Fig. 1). The neighborhood relationship is defined as follows:

$$a_{ij} = \begin{cases} 1 & \text{if } \; d_{ij} \leq r_j^{\text{com}} \\ 0 & \text{if } \; d_{ij} > r_j^{\text{com}}, \end{cases}$$

where d_{ij} is the euclidean distance between the robots i and j. Note that each column j in the line i of the adjacency matrix represents the robots that robot i is able to receive from.

2.1 Connectivity

Connectivity is an important graph property that describes when a graph is connected or not. An important concept related to connectivity is provided by Menger's Theorem, which characterizes the connectivity of a graph in terms of the number of vertexes and edges it contains.

In our work we will consider the so-called *vertex-connectivity*, which is a variation of Menger's Theorem that expresses connectivity as a function of the number of vertexes in the graph. This property is defined as follows:

Definition 1. If there are κ distinct paths between all pairs of vertexes in a graph, then we can remove up to $\kappa - 1$ vertexes without disconnecting the graph.

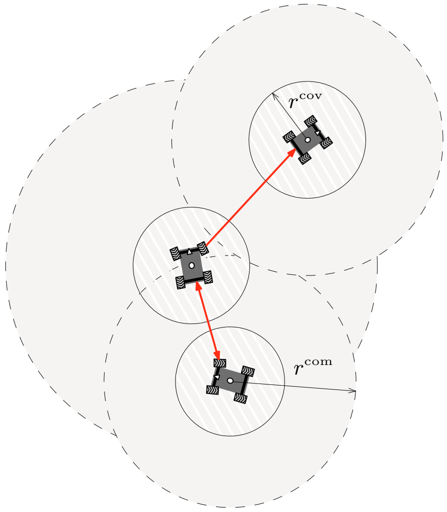

Fig. 1. Communication topology model defined by the distance between robots.

According to this definition, in order to build a topology that tolerates a robot dropout it is required to create enough redundant paths between the robots. In other words, the topology robustness degree to node dropout is directly proportional to the number of redundant paths in the corresponding graph (Fiedler, 1973). Clearly, when $\kappa = 1$ there are nodes that break the network when removed, these nodes are called *cut vertexes* or *critical nodes*. In this work we use $\kappa = 2$ as the minimum robustness degree of the network topology with respect to nodes dropout. This is called a *bi-connected* network.

2.2 Consensus

Consensus or *agreement* in mathematics is an approach to impose concordance about some information in a multi-agent system (Mesbahi and Egerstedt, 2010). A simple first order dynamic consensus algorithm can be defined for a scalar state $x_i \in \mathbb{R}$ of robot i in the following way:

$$\dot{x}_i(t) = \sum_{j=1}^{n} a_{ij}(x_j(t) - x_i(t)), \quad i = 1, \ldots, n.$$

The concordance between the robots is reached when the value of x is the same for all robots:

$$\lim_{t \to \infty} |x_i(t) - x_j(t)| = 0 \quad \forall i, j \in \{1, \ldots, n\}.$$

The minimum convergence condition to consensus is the presence of a spanning tree in the network graph (Mesbahi and Egerstedt, 2010).

2.3 Wireless Signal Strength

The Received Signal Strength Indicator (RSSI) returns the received power associated to the reception of a message and may allow determining how close a link is from disruption. However, it also allows estimating the link length (distance) as a function of propagation loss according to a propagation model. In this paper, we use the empirical model derived from the well known Log-Normal Shadow Model (Adewumi et al., 2013), which is suitable for wireless networks in free space. The RSSI-based distance model for two robots i and j is defined as follows: