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Distributed efficient localization in swarm robotics using Min–Max and Particle Swarm Optimization

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ABSTRACT

In a wireless sensors network in general, and a swarm of robots in particular, solving the localization problem consists of discovering the sensor's or robot's positions without the use of external references, such as the Global Positioning System – GPS. In this problem, the solution is performed based on distance measurements to existing reference nodes also known as anchors. These nodes have knowledge about their respective positions in the environment. Aiming at efficient yet accurate method to approach the localization problem, some bio-inspired algorithms have been explored. In this sense, targeting the accuracy of the final result rather than the efficiency of the computational process, we propose a new localization method based on Min–Max and Particle Swarm Optimization. Generally, the performance results prove the effectiveness of the proposed method for any swarm configuration. Furthermore, its efficiency is demonstrated for high connectivity swarms. Specifically, the proposed method was able to reduce the localization average error by 84%, in the worst case, considering a configuration of 10 anchors and 100 unknown nodes and by almost 100%, in the best case, considering 30 anchors and 200 unknown nodes. This proves that for high connectivity networks or swarms, the proposed method provides almost exact solution to the localization problem, which is a big shift forward in the state-of-the-art methods.

1. Introduction

Many applications of Swarm Robotic Systems (SRSs) require that a robot is able to find out its position. This position may be either absolute, *i.e.* based on a universal reference system, or relative to other robots, *i.e.* based on a local coordinate system. The robot position information is necessary, for example, to establish behaviors of self-assembly, where each robot of the swarm must be positioned within a pre-defined organization, or self-healing, where the robots reorganize themselves to reconstitute a formation that has been undone (Rubenstein, 2009). Similarly, Wireless Sensor Networks (WSNs), whose prospect of application is broader than SRSs, have attracted great attention from the industry point of view. However, in most cases, WSNs have little use when it is not possible to estimate the sensors positions (Sun & Su, 2011).

In both cases of SRSs and WSNs, the basic devices, *i.e.* robots or sensors, respectively, have common characteristics: they are of a reduced size, have access to limited energy source and must be of low cost. Thus, the straightforward solution that consists of endowing each basic device with a Global Positioning System (GPS) is often not viable.

The localization problem consists of inferring the position of a set of robots or sensors when no external reference, such as GPS, is available. Many of the localization methods depend on the ability of a node to measure its distance to some reference nodes, also known as *anchors*, whose positions are known. Common techniques for distance measurement are based on either the received signal strength (RSS), the one-way/roundtrip propagation time of a signal or the comparison of the propagation time of two signals that are known to have different propagation speeds (Lymberopoulos, Lindsey, & Savvides, 2006; Mao, Fidan, & Anderson, 2007). Typically, localization algorithms based on propagation time measurements achieve better accuracy than the RSS based algorithms (Mao et al., 2007).

As the measurement techniques presented rely on signal propagation characteristics, a threshold distance for such measurements has to be considered. In the simple case, wherein all reference nodes are within the distance measurement threshold, the measurements are direct and made in a single hop. However, in the cases where one or more reference nodes are outside this

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threshold, distance measurements are obtained indirectly using a multi-hop strategy. For this purpose, algorithms such as *Sum-dist* and *DV-hop* are used to estimate the length of the multi-hop path between the nodes (Langendoen & Reijers, 2003). Depending on the network topology, and swarm connectivity, the use of one and multi-hop can be combined. In Langendoen and Reijers (2003), a three-step approach is proposed to address the multi-hop localization:

1. Estimate the distances of each unknown node to the reference nodes.
2. Compute a rough estimation of the position of each node using the measurements obtained in step 1.
3. Refine the position estimate of each node using the position known so far and distance information informed by the neighboring nodes.

The optimization using bio-inspired techniques are often applied to the problem of localization, in the case of a single hop (de Sá, Nedjah, & Mourelle, 2014) as well as in that of multi-hop (Ekberg, 2009). In this paper, we solve the localization problem based on a multi-hop strategy. The method exploits an optimization process using the Particle Swarm Optimization (PSO) (Engelbrecht, 2005, chap. 12). The methods acts in three stages: during the first stage, the Sum-Dist (Langendoen & Reijers, 2003) is used to estimate the multi-hop distances to the reference nodes; then, during the second stage, an initial position estimate is made using the Min–Max method (Langendoen & Reijers, 2003; Savvides, Park, & Srivastava, 2002); after that, during the third stage, the refinement of the positions is performed by means of an optimization process using PSO, wherein the objective function has been precisely tailored as to guide the optimization process towards a robot localization with an acceptably low error ratio.

When compared to existing localization methods that use optimization algorithms (Carli, Panzieri, & Pascucci, 2014; Ekberg, 2009; Ekberg & Ngai, 2011; Naraghi-Pour & Rojas, 2014), the contribution of this work consists of the use of the information provided by the Min–Max method. This is done not only to assess the initial positions of the unknown nodes, but also to further refine these positions. In this novel approach, the bounds found by the Min–Max to establish the possible area for each unknown node are considered in the objective function, thus enhancing the convergence of the swarm solution to the actual position of the unknown nodes. Moreover, in contrast with some techniques presented in Section 2, it is important to emphasize that the method proposed herein solves the localization problem in a completely distributed manner. The solution is collectively found by the swarm, as opposed to a dictated solution found by a host as it is the case in most of the existing methods. The proposed distributed strategy makes the method more resilient, and requiring a relatively low number of reference nodes. It does not need any infrastructure with sensors or extra references in the environment. Furthermore, it does not require a previous survey of the environment to collect ambient's data.

Generally speaking, the performance results, presented and discussed later in this paper, prove beyond doubt that the proposed method is absolutely effective in finding an acceptable localization for any sensor network and robotic swarm configuration. Furthermore, its efficiency is demonstrated for high connectivity networks and swarms. Specifically, the proposed localization method was able to reduce the node positioning average error by 84%, considering a low connectivity configuration, and by almost 100%, considering a high connectivity case. This means that for high connectivity configurations, the proposed method was able an almost exact solution to the localization problem, which is a big shift forward when compared to existing methods.

The rest of this paper is organized as follows: First, in Section 2, some related works are presented. Later, in Section 3, we briefly describe the main steps of PSO. In Section 4, we show the proposed distributed localization method that exploits the Min–Max technique and PSO. Then, in Section 5, we report on the performance results obtained. Finally, in Section 6, we present some concluding remarks along with some possible future work.

2. Related work

The importance of the localization information to swarm robotics and wireless sensor networks systems, conjugated with the limitations in terms of hardware, cost and energy requirements that are typical of these devices, have motivated the search for more efficient yet accurate methods to solve the localization problem.

The localization methods can be organized in two classes: *range-free* and *range-based*. The former considers methods that do not need distance measurements to perform the localization process. On the other hand, the latter exploits methods that use distance measurements to estimate the node positions. Some related works are presented in Sections 2.1 and 2.2, associated with the range-free and range-based strategies, respectively.

2.1. Range-free localization

A simple range-free method, presented in Tesoriero, Tebar, Gallud, Lozano, and Penichet (2010), uses the RFID (Radio Frequency Identification) technology to locate robots in an indoor environment. In this solution, the area is divided into a grid of small cells, where passive RFID tags are installed. The robot is endowed with a passive RFID reader. As the robot moves through the mapped area, the passive RFID reader acquires the closer RFID tag, and the robot position is estimated correlating the obtained ID with a database that contains the coordinates of each RFID tag. The highlight of this solution is the simplicity and the low computational cost required to establish the robot position. On the other hand, the localization process is centralized, the robot does not have autonomy to estimate its own position, and it requires an array of RFID tag installed over all its operational environment. Another RFID based solution is presented in Calderoni, Ferrara, Franco, and Maio (2015), for indoor localization in a hospital environment. In this solution, a set of fixed passive RFID devices measures the power transmitted by an active RFID tag, and sends these measurements to a server that estimates the location of the active RFID using Random Forest classifiers. This system, intended to assess the room where the active RFID is located rather than its precise position, requires less RFID devices installed over the operational area than in Tesoriero et al. (2010).

In Yun, Lee, Chung, Kim, and Kim (2009), the authors present a solution, based on the method introduced by Bulusu, Heidemann, and Estrin (2000) and Kim and Kwon (2005), where the position of an unknown node is computed as the weighted average of the positions of all one-hop reachable reference nodes. In this case, the weight of a given reference node is determined by a Fuzzy Logic System (FLS). The input of the modeled FLS is the RSS coming from a reference node. The output of the FLS is the weight associated with the respective reference node. Simulation results showed that the FLS-based method obtained an average positioning error better than those obtained with the methods proposed by Bulusu et al. (2000) and Kim and Kwon (2005). It is worth mentioning that the number of reference nodes required by this method is relatively large, which is approximately 67% of all nodes.

In Nallanthighal and Chinta (2014), the authors propose the Improved Grid-Scan Localization Algorithm (IGSL). Firstly, based on the connectivity with a set of one-hop anchors, the unknown node