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Distributed efficient localization in swarm robotic systems using swarm intelligence algorithms

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ABSTRACT

The localization problem arises from the need of robots of a swarm robotic system (SRS), or even nodes of a wireless sensors network (WSN), to determine their positions without the use of external references, such as the Global Positioning System (GPS). In this problem, the node location may be established thanks to distance measurements to existing reference nodes, using a range-based method. Reference nodes know their respective positions in the network. In the search for efficient yet accurate methods to determine node locations, some bio-inspired algorithms have been explored. In this sense, targeting a more accurate solution of the localization problem, we propose a new multi-hop method. Two algorithms were developed considering the proposed method: one based on the Particle Swarm Optimization (PSO), and the other based on the Backtracking Search Algorithm (BSA). The method includes a new technique to assess the confidence that should be granted to a contribution received from a neighboring node, and hence incorporating it into the localization computation accordingly. The achieved performance results prove the effectiveness of the proposed method in which the BSA-based algorithm has a performance better than the PSO-based algorithm. Also, the results evince the efficiency entailed by the confidence factor assessment technique, for some network configurations. The impact of the latter is more evident when the number of reference nodes in the network is reduced. This constitutes a very big advantage with respect to state-of-the-art localization methods.

1. Introduction

Many applications of swarm robotic systems (SRSs) require that a robot is able to discover its position. This position may be either absolute, *i.e.* with respect to a universal reference system, or relative to other robots, based on a local coordinate system. The robots position information is necessary, for example, to establish behaviors of self-assembly, where each robot must be positioned within a pre-defined organization, or self-healing, where the robots reorganize themselves to reconstitute a formation that has been undone [1]. Similarly, wireless sensor networks (WSNs), whose prospect of application is broader, have attracted great attention from industry. However, in most cases, WSNs have little use when no positioning sensors are included in the nodes [2].

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

The localization problem consists of inferring the position of a set of robots or sensors when no external reference, such as GPS, is available. The methods used to solve the localization problem can be divided into two classes: range-based [1,3–7] and range-free methods [8–12]. The range-based methods depend on the ability of a node (robot or sensor) to measure its distance to reference nodes, also known as anchors, or to its neighbors. The position of reference nodes is known. On the other hand, range-free methods do not require the distance information to estimate the nodes' positions. Range-free methods are usually more economic and simpler than range-based methods, but their results are not as precise as the results achieved by the range-based methods [11].

In general, common techniques for distance measurement, on range-based localization, are based on the RSS (Received Signal Strength), TOA (Time of Arrival) and/or TDOA (Time Difference of Arrival) of two signals that are known to have different propagation

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speeds [13,14]. 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 thus, made via a single hop. However, in the cases where one or more reference nodes are outside this threshold, distance measurements are obtained indirectly using a multi-hop strategy. For this purpose, algorithms such as *Sum-dist* or *DV-hop* are used [15]. Depending on the network topology in SRSs or swarm connectivity in SRSs, the use of one and multi-hop can be combined. In [15], a three-step approach is proposed:

1. Estimate the distances of each node to the reference nodes.
2. Compute the position of each node using the measurements obtained in step 1.
3. Refine the position of each node using the positioning and distance information informed by the neighboring nodes.

The mentioned three-step approach is identified in algorithms that present skills of self-organization, robustness, and energy efficiency [15], such as the algorithms *Ad hoc positioning* [3], *N-hop multilateration* [4] and *Robust positioning* [5]. Also, this approach provides two advantages: it is possible to analyze partial results in order to have a better understanding of the combined behavior; and it is possible to further mix-and-match other alternatives for both phases, in order to obtain better performances [15].

The optimization using bio-inspired techniques are often applied to the localization problem, in the case of a single hop as well as in that of multi-hop [2,6]. This paper proposes a new method for solving the localization problem using a multi-hop strategy. Also, this paper presents two algorithms developed considering the proposed method: one based on the Particle Swarm Optimization (PSO) and the other based on the Backtracking Search Algorithm (BSA). The method acts in three stages: during the first stage, the Sum-Dist [15,5] is used to estimate the node distances to the reference nodes; then, during the second stage, an initial position estimate is made using the Min–Max method [15,5]; after that, during the third stage, the refinement of the positions is performed by means of an optimization process, using PSO or BSA, depending on the implemented algorithm. Aiming at improving the evaluation of the accuracy of inferred localizations, we propose and evaluate a new technique to establish the confidence factor, which is used to assess the importance of the contributions received from neighboring nodes.

The rest of this paper is organized as follows: First, in Section 2, we present some related works. Later, in Sections 3 and 4, we briefly describe the main steps of PSO and BSA, respectively; In Section 5, we show the proposed distributed localization method together with the novel technique to establish the confidence factor of the feedback made by the neighboring nodes; Then, in Section 6, we report and discuss on the achieved performance results. Finally, in Section 7, we present some concluding remarks along with some possible future work.

2. Related work

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

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 is presented in [8], where the RFID (Radio Frequency Identification) technology is used to locate robots in an indoor area. Basically, in this solution, the area is divided into a grid of small squared surfaces, 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 reads the RFID tag, and the robot position is estimated correlating the obtained ID with a map that contains the localization of the RFID tags.

In [9] the authors propose a method where the reference nodes periodically broadcast their coordinates, and each unknown node computes its position as the centroid, *i.e.* the arithmetic mean, of the positions of all one-hop reference nodes. In [10], the authors improve the solution proposed by [9] weighting the reference nodes according to their proximity to the unknown node. In this solution, the position of the unknown node is computed as a weighted average of the positions of all one-hop reference nodes. The performance of this method highly depends on the design of the weights. In [11], the authors developed a solution, based on the method presented by [10], where the weights of the reference nodes are computed by a Fuzzy Logic System (FLS). The input of the FLS is the RSS of a reference node. The output of the FLS is the weight of the respective reference node. The membership functions of the input of the FLS are optimized by Genetic Algorithm (GA). In the carried out simulations, the FLS-based method obtained an average positioning error better than those obtained with the methods proposed by [9,10]. The number of reference nodes required by this method is relatively large, once, in the simulations, approximately 67% of all nodes are reference nodes.

A range-free localization method that avoids the use of a large number of reference nodes is presented in [12]. The authors introduce a localization method that is based on the analysis of the fingerprint of the RSS of signals emitted by a set of heterogeneous reference nodes. The reference nodes are wireless heterogeneous devices of different technologies such as GSM (Global System for Mobile Communications), UMTS (Universal Mobile Telecommunication System) and WLAN (Wireless Local Area Network). To estimate its own position, an unknown node measures the local RSS fingerprint and compares it with a RSS fingerprint map, determining the area which best matches with the measured RSS fingerprint. The advantage of this method is that the references can be obtained from an infrastructure that commonly already exists. A drawback is that this method requires a previous survey of the RSS fingerprint of the entire zone of interest.

In general, the range-free solutions are simpler and, in some cases, require less resources, but their results are not as accurate as the range-based solutions [11].

2.2. Range-based localization

In [3], the authors introduce the *Ad hoc positioning* algorithm. This algorithm is developed to locate nodes in networks where the unknown nodes, in most cases, are not able to directly measure the distance to anchors, *i.e.* in one-hop. To deal with this constraint, the authors present three alternative multi-hop methods to obtain the distance to anchors: *DV-Hop*, *DV-Distance* and Euclidean. The DV-Hop