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Dynamic Multidimensional Scaling with anchors and height constraints for indoor localization of mobile nodes

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ABSTRACT

In distance-based localization, estimating the position of a network of wireless sensors is not an easy task. The problem increases when dealing with moving nodes and cluttered indoor environments. Many algorithms have been proposed in the literature and, among them, the Multidimensional Scaling (MDS) technique gained a lot of interest due to its resilience to flips ambiguities and easiness of use. Many variants of MDS have been proposed to overcome issues such as partial connectivity or distributed computation. In this context, it is common to place some anchors nodes to help in estimating the coordinates of the network correctly. However, instead of using the anchor's positions directly during the minimization of the MDS cost function, most approaches act on the estimated coordinates at the end of the MDS computation without fully utilizing the knowledge about anchors. In this work, the classic MDS and Dynamic MDS have been reformulated to utilize the anchor's position inside the minimization function. A set of real experiments in 3D with Ultrawide-band devices show that our approach considerably improves the accuracy of localization with respect to the usual MDS techniques.

1. Introduction

In a wireless sensor network, estimating the positions of the nodes is of primary importance in many distributed systems. In indoor environments, where the GPS is not available, distance-based localization is typically used to derive the node coordinates by measuring inter-nodes distances. Node coordinates can be estimated from distance measurements using different techniques, such as trilateration, multilateration, and Multidimensional Scaling (MDS). MDS [1,2] aims at visualizing a set of objects in an n-dimensional space. It takes as input a Dissimilarity Matrix that expresses how much two objects are dissimilar along one quality and finds a set of coordinates such that the distance between each couple of objects is proportional to the value of dissimilarity. MDS has been used for plotting sets of data in many application fields, such as economics and psychology. In the last decades, MDS has also been used for localization, where the objects are the nodes, and the dissimilarity matrix contains the inter-node distances.

Using anchor nodes in wireless sensor networks significantly improved the accuracy of localization [3]. However, in the MDS formulation the notion of anchor nodes is missing since this technique was designed for plotting generic objects with qualitative characteristics. Moreover, some limitations such as partial connectivity [4,5] and different type [6] of noise are peculiar for network localization. For this reason, many variants of MDS have been proposed in the literature. To take anchors into account, some authors proposed solutions for incorporating the known coordinates into the MDS algorithm [7]. Such variants of MDS can be distinguished into distributed and centralized approaches. In distributed solutions the computation of the algorithm is shared among the components of the network.

In centralized approaches, a common solution is to apply a roto-translation transformation after the MDS computation and superimpose the estimated coordinates over the anchors [4,5,8,9]. Biaz and Ji [7] used a different method consisting of updating the anchor's positions during the minimization procedure. However, contrarily to the current MDS versions, the positions of the anchor nodes should not be modified during the minimization. For all these cases, the coordinates of the anchors slightly change due to the minimization procedure, leading to a position error that reduces the overall accuracy of the system. Also, in the case where the anchor coordinates are modified at the end of the minimization, the output is not exact since the anchor's coordinates are not entirely used for finding the best estimation.

Fig. 1 shows a trivial example that highlights the drawbacks described above. In this example, the network is composed of three anchors and two nodes that are localized with the classical MDS and the use of a roto-translation applied to the output.

The figure exhibits that the classical MDS formulation does not benefit from the anchor information. Although the anchors'

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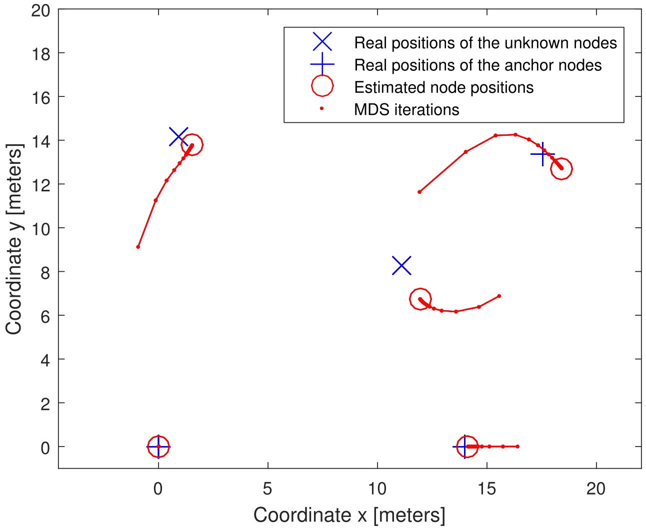

Fig. 1. Estimated coordinates computed with the classical MDS. The red dots represent the coordinates during the algorithm iterations.

positions are known, their coordinates are subject to a not required minimization. Moreover, the algorithm introduces noise on the anchors' coordinates. As shown in Fig. 1, the anchors' locations are not precisely reconstructed, even if such information is known a-priori.

A distributed version of MDS, called distributed weighted Multidimensional Scaling (dwMDS), was proposed by Costa et al. [10]. They successfully included the notion of anchors and were able to consider them in the MDS formulation since they split the computation on each node without modifying the anchor's coordinates. However, a distributed approach takes a lot of time to converge to a single agreed set of coordinates since all the network has to converge to a unique solution through wireless communication messages. For this reason, such an approach is usually suited for large static sensor networks with low computation capabilities. Instead, centralized approaches are usually preferred in small networks and in applications which consider node mobility, e.g., in the case of a small team of robots [11]. Another application case in which a centralized approach is commonly used includes indoor people tracking [3].

A previous work [12] proposes a theoretical generalization of the classical MDS algorithm, named MDS with Anchors (MDS-A), which uses the coordinates of some nodes (e.g., anchors) to improve the accuracy of the estimation. The approach presented in this paper extends the one proposed in [12] to the more general case of Dynamic Multidimensional Scaling (DMDS) – a technique used for applications that include node mobility such as indoor people tracking – by proposing Dynamic MDS with Anchors (DMDS-A) that, similarly to MDS-A, incorporates the concept of anchors in the minimization. A set of real experiments employing Ultra-wide Band (UWB) devices has been performed to validate both MDS-A and DMDS-A. Moreover, is also proposed a modification of MDS for 3D applications using the apriori knowledge of the height of the nodes. The development of such an approach has been encouraged by those applications in which nodes are attached at a fixed height (e.g., the belt of a walking person, shoes, a moving robot) and this knowledge can be used to improve the overall accuracy.

The rest of the paper is structured as follow: Section 2 provides an overview of the state of the art in MDS-based localization. Then, in Section 3 the addressed problem will be formalized. Section 4 will review the MDS and DMDS mathematical formulations. In Section 5, MDS-A, DMDS-A, and the MDS with heights constraints (MDS-Z) will be described. Experimental results will be provided and discussed in Section 6. Finally, Section 7 will state the conclusions.

2. Related work

Multidimensional Scaling (MDS) is a technique that represents a set of elements in an r-dimensional space using the similarities/dissimilarities between pairs of elements as distance information. There exist several variants of MDS such as Classical MDS, Metric MDS, Non-Metric MDS, depending on the characteristics of the distance information. The technique initially was meant for visualizing a set of objects in a 2-D (or 3-D) space. Also, a particular formulation for visualizing data with a correlation over time, called Dynamic Multidimensional Scaling (DMDS) has been proposed by Ambrosi and Hansohm [13] in 1987. In the last decade, it has been extensively used in distance-based localization for its elegant formulation, resilience to flip ambiguities, and easiness of use. However, in order to be used in practical scenarios, many variants have been proposed to overcome issues such as partial connectivity and node mobility. These techniques usually do not modify the MDS formulation but change the algorithm input (distance measurements) or adjust its output.

Many variants have been introduced in literature, and some of them used misleading acronyms that can be confused with the original approach. For example, Garimella, in his master thesis [14], proposed an MDS variation that involves the localization of "virtual" nodes apart from the original nodes. He named the proposed approach with the same name as the original DMDS. Cabero et al. [3] proposed a variant of MDS and named their approach dynamic weighted MDS (dwMDS), which is the same acronym of the well known distributed weighted MDS (dwMDS) proposed by Costa [10]. For the sake of clarity, in the rest of the paper, the name DMDS refers to the original approach proposed by Ambrosini and Hansohm [13]. All the other techniques will be defined as variants or modifications of MDS.

In Xu et al. [15], the authors use DMDS for visualizing the temporal evolution of dynamic networks. Beck and Baxley [16] proposed to use DMDS as a methodology to track nodes over time by exploiting odometry information. Among the other approaches that use MDS for tracking mobile nodes, Cabero et al. [3] proposed an extension of MDS that finds the embedding of people's trajectories by using a set of connectivity matrices through time. For this reason, they put particular attention in understanding how their approach behaves with respect to varying connectivity. Moreover, they make an extensive use of anchors conveniently fixed at the borders of a rectangle area to track the dynamic of peoples inside the hull. In Jamâa et al. [17], the authors proposed a modified version of the classical MDS approach, i.e., coordinate are computed with eigenvalues decompositions, to introduce a cooperative mobile network tracking algorithm. They changed the matrices containing the orthonormal eigenvectors and proposed two different algorithms also considering partial connectivity. In the particular context of mobile robot localization without anchors, Oliveira and Almeida [18] proposed a technique that gives confidence values to position estimates obtained by MDS at successive instants. In [19] the authors proposed a modification to MDS, which includes the notion of nodes velocities to solve the ambiguities generated by two consecutive MDS outputs. However, the approach does not use the standard SMACOF minimization being more computationally expensive.

The presented works from literature do not try to exploit the knowledge of anchor positions in the minimization but apply some filtering techniques to the MDS output. Hence, most of such extensions suffer from two drawbacks: the MDS minimization does not