NODES LOCALIZATION IN 3D WIRELESS SENSOR NETWORKS

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ABSTRACT

Advancement in wireless technologies brings new challenges in Wireless Sensor Network designing. One of the most important issues is nodes localization. Many different techniques have been proposed for solving this problem in two-dimensional (2D) network, but only a few consider three-dimensional localization. In this paper, we investigated an algorithm for three dimensional (3D) nodes localization in WSN based on multidimensional scaling (MDS) technique. Using extensive simulations we examined in details well known MDS-MAP technique regarding different network topologies, various network parameters and performance issues. The results from the simulations show that MDS-MAP produces acceptable localization error for 3D-WSN and can be a solid base for further improvements.

I. INTRODUCTION

A wireless sensor network (WSN) is a set of individual sensor nodes that obtain various measurements of different real-life occurrences. Typically, a sensor node is an autonomous distributed device that consists of three main parts [1][2]:

- sensing subsystem for data acquisition (vibration, light level, acceleration, air temperature, humidity etc.).
- processing subsystem for local data processing.
- wireless communication subsystem for data transmission (radio module).

After taking samples of physical or environmental conditions at different locations, sensors can process data or retransmit it using radio modules. The final destination of the measurements is the sink node (base station) responsible for further analyzing and for storing data in a database[3].

Following the latest developments in computer and communication technologies, everyday objects are becoming smarter, as ubiquitous connectivity and modern sensors allow them to communicate with each other. The deployment of sensors and actuators everywhere around us adds a new dimension to the world of information and communication, which enables the creation of new and enriched services widely applied in different industrial and civilian application areas, including industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications and traffic control [4][5].

The determination of the exact geographical locations of the nodes is a fundamental problem in WSN. This issue is known as nodes positioning or nodes localization. The most straightforward solution to the localization problem is to apply global positioning system (GPS) to each node. Since this is not an attractive solution in terms of cost, size and power requirements [6], there is always a need for intelligent techniques to solve this problem. Thus, an effective localization algorithm should employ all the available information from the nodes to compute their positions.

In this paper, we investigate well-known classical multidimensional scaling technique (MDS-MAP) for nodes localization in three dimensional WSN.

The rest of this paper is organized as follows. The next section refers to multidimensional scaling technique for nodes localization in 3D-WSN. The third section presents the results provided from our simulations. Finally, we conclude this paper in section four.

II. THREE DIMENSIONAL MDS

Multidimensional scaling technique has been used for many years in economics and marketing research for dimensionality reduction of the objects [7]. Using distances between each pair of objects, MDS algorithm produces 2D or 3D-points in order to visualize the objects.

There is analogy between object distances and nodes distances is WSN. Usually both represent Euclidian distances. For multidimensional objects, this distance can be easily calculated, while in WSN the distances between every pair of nodes must be somehow estimated. This is possible only for nodes that can hear each-other (nodes in close proximity which are also known as neighboring nodes).

Different techniques can be use for this purpose, but generally they can be divided into two main groups:

- based on time
  - Time of arrival (ToA)
  - Time difference of arrival (TDoA)
- based on signal
  - Received signal strength (RSS)
  - Angle of arrival (AoA)

The cheapest solution for distance estimation is RSSI, while the others usually require additional hardware.

MDS has many advantages over other techniques for nodes localization in WSN [8]. Different versions based on MDS for nodes localization in two dimensional WSN have been developed [9][10][11]. The first and the most popular algorithm proposed by Yi Shang and Wheeler Ruml [10] is MDS-MAP. Other approaches based on MDS exist, but they are complex and thus more computationally dependent [12][13]. Cluster-based MDS approaches also exist [14][15], where the wireless network is hierarchically organized and divided into clusters. These variations outperform MDS-MAP for irregular network topology (C-shape, H-shape, S-shape, etc.) and perform smaller computational complexity.

As MDS-MAP is a centralized technique, distance measurements between each pair of nodes have to be collected at the sink node, which is responsible for reconstruction of the network map. The main advantage of using MDS is its ability to generate a relative map of the network even when there are no anchor nodes (nodes with a priori known location). If there are at least four anchor nodes, MDS can estimate nodes position with very high accuracy.

Although MDS-MAP is the most explored algorithm for WSN localization, all of the algorithms in the literature based on MDS-MAP investigate and compare results only for two dimensional networks. To the extent of our knowledge, this is the first research that extensively investigates MDS-MAP algorithm for3D- WSN localization.

A. Multidimensional scaling (MDS) for 3D-WSN

MDS-MAP for 3D-WSN consists of 3 steps:

1. Calculate shortest distances between every pair of nodes (using either Dijkstra's or Floyd's all pairs shortest path algorithm). This is the distance matrix that serves as input to the multidimensional scaling in step 2.

2. Apply classical multidimensional scaling to the distance matrix. The first 3 largest eigenvalues and eigenvectors give a relative map with relative location for each node.

3. Transform the relative map into absolute map using sufficient number of anchor nodes (at least 4).

B. Finding optimal rotation and translation between corresponding 3D nodes

Generating an absolute map (step 3) of the WSN requires anchor nodes. At least four sensors' physical positions are needed in order to identify the physical positions of remaining nodes in the group in 3D case.

Let $P = \{p_1, p_{2,...,} p_N\}$ and $Q = \{q_1, q_{2,...,} q_N\}$ be two sets of corresponding nodes, where N is the number of anchor nodes in the WSN. We wish to find a transformation that optimally aligns the two sets in terms of least square errors, i.e., to minimize the sum of squares of the errors between estimated positions of the anchors from MDS map and their true positions. We seek a rotation matrix R and a translation vector t such that

$$(R,t) = \arg\min_{R,t} \sum_{i=1}^{N} \left\| (Rp_i + t) - q_i \right\|^2,$$

This transformation is also known as Euclidean or Rigid transformation, because it preserves the shape and the size.

There are many algorithms purposed in the literature that compute a rigid 3D transformation. The most explored are based on:

- Singular Value Decomposition (SVD)
- Unit Quaternion (UQ)
- Dual Quaternion (DQ)

- Orthonormal Matrices (OM)

A comparison of these four methods can be found in [16]. It is shown that the results of all these methods are similar in most cases and the difference in accuracy is almost insignificant, but the SVD is the most stable.

Finding the optimal rigid transformation with SVD can be broken down into the following steps:

1. Compute the weighted centroids of both point sets $\overline{p} = \frac{1}{N}\sum_{i=1}^{N} p_i,\ \overline{q} = \frac{1}{N}\sum_{i=1}^{N} q_i,$
2. Compute the centered vectors $p_i' := p_i - \overline{p},\ q_i' := q_i - \overline{q}$, i=1,…,N
3. Compute the 3x3 covariance matrix

   $$H = P'Q'^T,$$

   where P' and Q' are the 3xN matrices that have p_i' and q_i' as their columns, respectively.
4. Compute the singular value decomposition $H = U\Sigma V^T,$

   The rotation we are looking for is then

   $R = VU^T,$
5. Compute the optimal translation as $t = \overline{q} - R\overline{p},$

C. *Time complexity of MDS-MAP for 3D-WSN*

Time complexity of MDS-MAP is different at each step:

- In step 1, Dijkstra's or Floyd's algorithm requires $O(n^3)$ for distance matrix construction (n is the number of nodes in the network).
- In step 2, singular value decomposition in MDS has complexity of $O(n^3)$.
- In step 3, the relative map is transformed through linear transformations. Computing the rigid transformation takes $O(N)$ time for computing P and Q, while computing SVD takes only $O(3^3)$ time (since the covariance matrix H has dimension 3x3). Applying the transformation (rotation and translation) to the whole relative map takes O(n-N) time, where N is the number of anchors (N<<n).

III. Performance evaluation

The performances of the nodes localization algorithms depend on different network parameters, such as:

- network topology (random or grid-based),
- number of anchors (i.e. the anchor-to-node ratio),
- radio range (the maximum distance at which two nodes can hear each other),
- radio range error (modeled as Gaussian noise)
- density of nodes, (average number of neighbors).

Hence the location estimation error should be evaluated considering all these above mentioned parameters.

A. *Network model*

We assume a typical sensor network composed of hundreds of sensor nodes deployed randomly, across a three dimensional monitored area. The resources (CPU, battery, memory, etc) of each node are very limited. Each sensor is equipped with an omni-directional antenna, thus only the nodes within certain radio range R can communicate with each other. Further, we made the following assumptions:

- Nodes are static.
- Nodes are unaware of their location.
- The network is fully connected (there is a path between every pair of nodes).
- Nodes deployed in close proximity to each other exchange messages.
- Each node uses different signalization techniques in order to estimate the distance with its neighbors (RSSI, ToA, TDoA or AoA).

We used Matlab to simulate the network with 100 nodes randomly deployed with a uniform distribution in a cubic area (r x r x r cube where r is a unit length distance).

We consider other network properties:

- Different number of anchors (4, 6, 10 and 15) for absolute map construction. In our experiments we use SVD method for 3D rigid transformation.
- Different radio ranges R (0.35r, 0.4r, 0.45r, 0.5r and 0.55r) which lead to different average connectivity of the network.
- Radio range error (from 0 to 30% of R with step 5% of R)

Thus 140 different networks were simulated (4 x 5 x 7). The connectivity parameter and the estimation error for each scenario represent average over 30 trials. The average estimation error is normalized by the radio range R:

$$Error = \frac{\sum_{i=1}^{n} \text{distance}(pos_i^{(estimated)} - pos_i^{(true)})}{(n-N)\cdot R} \cdot 100\%$$

, where n is the number of nodes in the network, N is the number of anchor nodes, $pos_i^{(estimated)}$ is the estimated location and $pos_i^{(true)}$ is the true location of the i-th node.

B. *Experimental results of MDS-MAP for 3D-WSN*

Figure 1 and Figure 2 show examples of typical 3D networks with 100 nodes randomly deployed. Blue lines represent the distance between the absolute and the estimated position obtained with MDS-MAP algorithm. The estimation error is larger if the lines are longer. The absolute map is achieved using 15 anchors (red circles around the node).

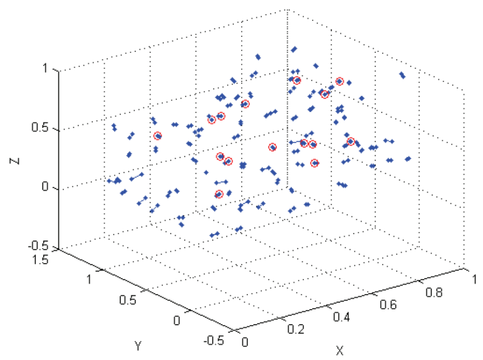

Figure 1: R=0.5r, average connectivity 25.6, range error 5% of R (estimation error 5.4148% of R).

Figure 3 and Figure 4 show the results of MDS-MAP when distance measurement between neighboring nodes is estimated with range errors of 15% of R and 30% of R respectively. The absolute map is generated using 6, 10 and 15 anchors. As expected, having more anchors improves the accuracy for all connectivity levels.

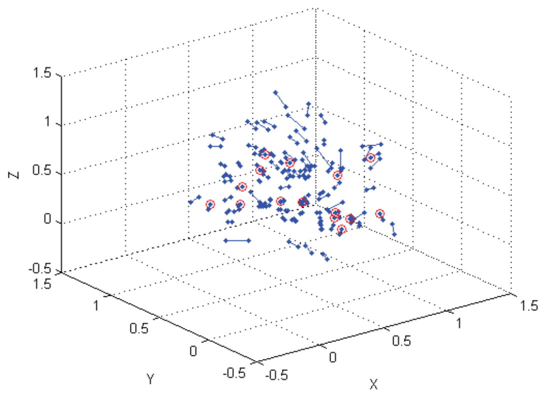

Figure 2: R=0.35r, average connectivity 11.76, range error 5% of R (estimation error 19.6493% of R).

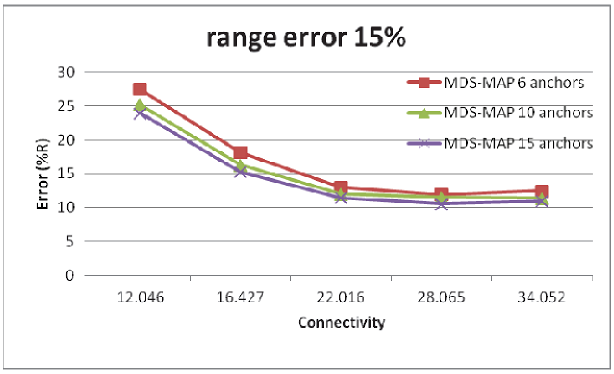

Figure 3: Average estimation error of MDS-MAP (range error 15% of R).

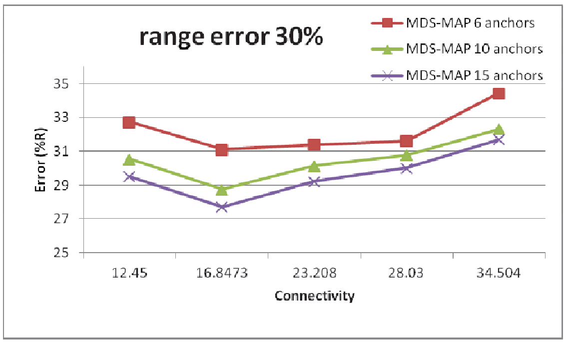

Figure 4: Average estimation error of MDS-MAP (range error 30% of R).

The comparison of average performances of MDS-MAP for different range error is given on Figure 5 and Figure 6. It can be seen that range error have smaller impact on estimation accuracy for low connectivity level compared with high connectivity levels. It also can be seen that connectivity level doesn't have much impact on estimation error for range errors above 20% of R.

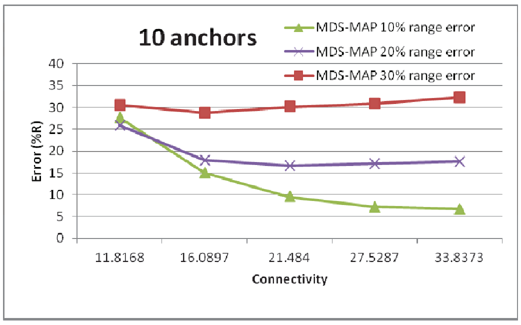

Figure 5: The effect of range error on the estimation error for 10 anchors.

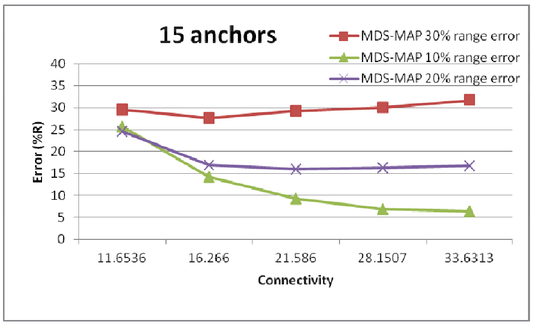

Figure 6: The effect of range error on the estimation error for 15 anchors.

IV. Conclusion

In this paper, we presented MDS-based algorithm for nodes localization in 3D-WSN. We showed that well known MDS-MAP technique for 2D localization can be adapted for three dimensional networks since it achieves acceptable accuracy.

For future work, we intend to investigate our algorithm on irregular three-dimensional network topologies. It is expected that MDS-MAP algorithms for WSN localization will not work well for such scenarios, basically because of multi-hop distance between the nodes placed on the opposite sides of each obstacle. Initial simulations that were conducted have proved this assumption. For this purpose MDS-MAP will be extended considering hierarchical network organization based on cluster formation. Cluster-based approaches developed for 2D networks in [14][15] encourage us to consider cluster-based MDS extension for 3D networks as a possible solution for networks with obstacles.

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References

[1] I.F.Akyildiz, S. Weilian, Y.Sankarasubramaniam, E.Cayirci, A Survey on Sensor Network. IEEE Communications Magazine 40, 102–114 (2002)

[2] F.L.Lewis, Wireless Sensor Networks, chapter 4 in D. J. Cook and S. K. Das, editors, Smart Environments: Technologies, Protocols, and Applications, John Wiley, New York, 2004;

[3] K. Akkaya, M. Younis, A survey of routing protocols in wireless sensor networks, Elsevier Ad Hoc Network Journal, 3(3):325–349, May 200

[4] D. Puccinelli, H. Haeggi, Wireless sensor networks: applications and challenges of ubiquitous sensing. *IEEE Circuits and Systems Magazine* 2005 (3): 19–29.

[5] B. Stojkoska, D. Davcev. "Web Interface for Habitat Monitoring Using Wireless Sensor Network." *Wireless and Mobile Communications, 2009. ICWMC'09. Fifth International Conference on*. IEEE, 2009.

[6] A. Pal. Localization Algorithms in Wireless Sensor Networks: Current Approaches and Future Challenges. In *Network Protocols and Algorithms*, 2010, Vol. 2, No. 1

[7] T. Cox and M. Cox, *Multidimensional Scaling*, Chapman & and Hall, London, 1994.

[8] B. Stojkoska, I. Ivanoska, and D. Davcev. "Wireless Sensor Networks Localization Methods: Multidimensional Scaling vs. Semidefinite Programming Approach." *ICT Innovations 2009*. Springer Berlin Heidelberg, 2010, pp. 145-155.

[9] X. Ji, H. Zha, "Sensor Positioning in Wireless Ad-hoc Sensor Networks using Multidimensional Scaling," *Proceedings of 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2004)*, March 2004.

[10] Y. Shang, W. Ruml, Y. Zhang, M. P. J. Fromherz, "Localization from mere connectivity," in *Proceedings of ACM International symposium on mobile ad hoc networking and computing*, pp. 201-212, June 2003.

[11] B. Risteska Stojkoska, V. Kirandziska, "Improved MDS-based algorithm for nodes localization in wireless sensor networks," to appear in *EUROCON, 2013.*

[12] V. Vivekanandan, V. W. Wong. Ordinal mds-based localization for wireless sensor networks. In *VTC-2006: IEEE 64th Vehicular Technology Conference*, pp. 1-5, 2006.

[13] Y. Shang, W. Ruml, "Improved mds-based localization," in *Twenty-third AnnualJoint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, pp. 2640– 2651, 2004.

[14] B. Stojkoska, D. Davcev, A. Kulakov "Cluster-based MDS Algorithm for Nodes Localization in Wireless Sensor Networks with Irregular Topologies", *Proceedings of The The Fifth ACM/IEEE International Conference,CSTST'08,* Paris, France , October, 2008, pp. 384-389.

[15] G. Yu, S. Wang “Hierarchical MDS-based Localization Algorithm for Wireless Sensor Networks”, 22nd International Conference on Advanced Information Networking and Applications, March, 2008, pp.748-754.

[16] D. W. Eggert, A. Lorusso, R. B. Fisher, “Estimating 3-D Rigid Body Transformations: A Comparison of Four Major Algorithms,” Machine Vision and Applications (1997) Vol. 9, No. 5/6, pp. 272–290.