An Application of Relative Node Positioning Using Ultra-Wideband Distance Estimates

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ABSTRACT

In this paper, application results of a relative positioning method which is based on classical Multidimensional Scaling (MDS) and Procrustes analysis are presented. The applied method has a distance-based positioning scheme and the pairwise distance estimates between nodes are obtained from roundtrip Time-of-Flight (ToF) measurements of Ultra-Wideband (UWB) signals. In the application, a UWB sensor network consisting of two types of nodes, named type A and type B, is deployed. The network is configured in such a way that each type A node can communicate with all other nodes, on the other hand, each type B node can only communicate with type A nodes. Classical MDS is applied to create local relative maps for each cluster of communications. Then, taking one of these local relative maps as a target and fitting the others to it, Procrustes analysis provides a global map displaying relative positions of all nodes.

1 INTRODUCTION

Node positioning in wireless sensor networks (WSNs) has been a crucial issue especially for monitoring, tracking and control applications in military, civilian and industrial areas. These applications include, but are not limited to, soldier surveillance on battlefield, health personnel tracking in hospitals, industrial process monitoring and control, etc. In the mentioned applications, the nodes (i.e., soldiers, personnel, equipment and material, etc.) are required to know their positions in order to fulfill their tasks. In WSNs, node positioning can be classified into two main categories: absolute and relative positioning.

In absolute positioning, a known global or local reference coordinate system is given and absolute position of each node is described with respect to this reference coordinate system. The reference coordinate system in absolute positioning is developed by using nodes, referred to as anchors, with known positions a priori. Then, by using this developed coordinate system, absolute positions of the other nodes, referred to as non-anchors or tags, are calculated. For two-dimensional networks at least three anchors, and for three-dimensional networks at least four anchors are needed. The initial position assignment of anchors can be done by placing them on positions with known coordinates, or by equipping them with the receivers of Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo, BeiDou. In most cases, however, wireless sensor nodes are randomly deployed without any prior position information, and GNSS is either not accessible or not practicable in some environments such as indoors and dense urban areas [1]. Moreover, GNSS signals have low signal power which means that even a weak jamming source can cause the GNSS receiver to fail especially in military operations areas (MOAs).

Relative positioning, on the other hand, relies only on the pairwise distance estimates between nodes to define their positions with respect to an arbitrary internal coordinate system. Relative positioning does not require any prior position information or an external infrastructure such as GNSS signals, landmarks or beacons. Finding the positions of nodes relative to each other is considered as an essential need in many applications which require autonomy and cooperation. For example, soldier-to-soldier relative positioning in MOAs is one of the key achievements for operational success.

Pairwise distance estimation techniques in WSNs make use of distance-related measurements such as Time-of-Flight (ToF), Time-Difference-of-Arrival (TDoA) and Received-Signal-Strenght-Indicator (RSSI). ToF measurement measures how long it takes for the signal to propagate, one-way or roundtrip, between nodes. One-way ToF measures the difference between the time when the source node sends a signal and the time when the target node receives it. Thus, one-way ToF requires the source and target nodes to have accurately synchronized clocks. On the other hand, roundtrip ToF measurement measures the difference between the time when a signal is sent by the source node and the time when the reply signal returned by the target node is received at the source node. Thus, for roundtrip ToF measurement, there is not any synchronization requirement since the source node uses its own clock to compute the roundtrip propagation time. This advantage makes roundtrip ToF measurement much more appealing than one-way ToF measurement. In TDoA measurement, the source node sends out a signal and this signal is received by a number of nodes with known positions, i.e., anchors. Since anchors are positioned at different distances from the source node, the signal does not reach to every anchor at the same time. These time differences can be used to estimate the position of the source node. Like in one-way ToF measurement, keeping the clocks on the anchors accurately synchronized is an essential requirement for TDoA measurement. Another measurement is based on RSSI which is a standard feature of most wireless devices. RSSI value is widely used for distance estimation because of its advantages including low-cost, flexibility, needing no extra hardware, etc. However, there are intrinsic limitations of using RSSI value as a metric for distance estimation in terms of accuracy and stability due to random fluctuations on it [2].

This paper presents application results of a relative positioning method in a two-dimensional network. The applied method is based on classical Multidimensional Scaling (MDS) and Procrustes analysis. In the application, pairwise distance estimates between Ultra-Wideband (UWB) nodes required for relative positioning are obtained via roundtrip ToF measurements. The rest of the paper is organized as follows. In Section 2, pairwise distance estimation between nodes making use of roundtrip ToF measurements of UWB signals is described. Section 3 provides the details of classical MDS and Procrustes analysis with their algorithm descriptions. In Section 4, the application setup and obtained results are presented. Finally, Section 5 concludes the paper and suggests some future improvements on the application.

2 DISTANCE ESTIMATION USING UWB SIGNALS

Several types of wireless technologies are used for distance estimation in relative positioning systems including radio-frequency (RF) technologies. UWB is one of the most promising RF technologies for relative positioning which provides a distance estimation capability much more precise than others such as Wireless Fidelity (Wi-Fi) and Bluetooth [3]. UWB allows simultaneous position and data transmission, and combines remarkable features concerning size and power consumption [4]. UWB signals are characterized by very short duration pulses with an absolute bandwidth larger than 500 MHz or a fractional bandwidth larger than 20% [5]. Large bandwidth, consequently high time resolution, of UWB signals brings many additional advantages for relative positioning such as penetration through obstacles and immunity to multipath fading [6].

In the first step of the relative positioning method applied in this paper, pairwise distances are estimated using roundtrip ToF measurements of UWB signals traveling between nodes, as depicted in Figure 2-1. In roundtrip ToF measurement, the source node sends a signal at its own local time SNt_1 to the target node and this signal is received by the target node at its local time TNt_1. After some delay, the target node sends a reply signal at its local time TNt_2 to the source node. This reply signal includes the time difference information (TNt_2-TNt_1) and arrives at the source node at its local time SNt_2. Thus, the source node is able to compute the roundtrip ToF measurement as (SNt_2-SNt_1)-(TNt_2-TNt_1). Since this calculation only needs the time difference values which are obtained from the clocks of source and target nodes separately, no synchronization requirement exists for roundtrip ToF measurement [7].

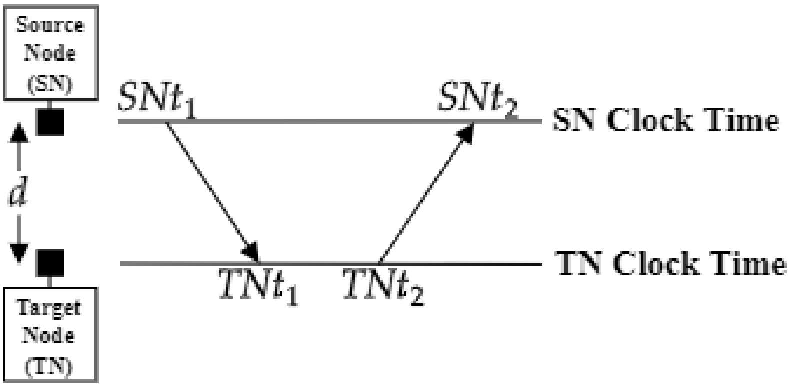

Figure 2-1: Roundtrip ToF Measurement.

Using the roundtrip ToF measurement, the distance between the source and target nodes, d, is estimated as follows:

$$d=c\times\frac{(SNt_2\text{-}SNt_1)\text{-}(TNt_2\text{-}TNt_1)}{2}$$

where c ~ 3 × 10^8 m/s is the speed of light.

3 CLASSICAL MDS AND PROCRUSTES ANALYSIS

Having obtained the distance estimates, classical MDS and Procrustes analysis will be employed to obtain the map displaying the relative positions of all nodes. In the next subsections, the details of classical MDS and Procrustes analysis are provided.

3.1 Classical MDS

Although it is originated from psychology [8], MDS is used in many areas such as politics and economics [9]. MDS is a family of different algorithms, each designed to map the original high dimensional space to a lower dimensional space. Depending on the nature of the application, several variants of MDS algorithms can be used [9]. For node positioning in wireless sensor networks, MDS algorithms have recently been used to represent the sensor nodes geometrically in lower dimensional space by using the similarity/dissimilarity information between them [10]. MDS algorithms can be grouped into two main categories: Metric and Non-metric. Classical MDS is a metric MDS algorithm which assumes the Euclidean distances among the objects as a dissimilarity information between them. Since, in this paper, pairwise Euclidean distance estimates between UWB sensor nodes are used as a dissimilarity information, the classical MDS will be utilized.

Considering a sensor network with n nodes and assuming that the pairwise distances between them d_{ij} (where $i\neq j$ and i, j=1, …, n) are fully estimated, the classical MDS algorithm [11] with the following steps can be performed to obtain relative node positioning:

Classical MDS Algorithm:

Step 1. Given the pairwise distances between nodes, d_{ij}, set up the matrix of squared distances D such that

$$D = \begin{bmatrix} 0 & d_{12}^2 & \cdots & d_{1n}^2 \\ d_{21}^2 & 0 & \cdots & d_{2n}^2 \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^2 & d_{n2}^2 & \cdots & 0 \end{bmatrix}$$

Step 2. Construct nxn centering matrix C

$$C=I-\frac{1}{n}J$$

where I and J are identity and all-ones matrices, respectively, with nxn sizes.

Step 3. Apply double centering to remove the means from each rows and columns of D and to obtain symmetric positive semi-definite matrix N with the size nxn

$$N=-\frac{1}{2}CDC$$

Step 4. Determine the m largest eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_m$ and corresponding eigenvectors $\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_m$ of N where m is the number of dimensions identified by the sensor network structure. For example, m=2 for two-dimensional networks and m=3 for three-dimensional networks.

Step 5. Finally, the relative positions of n sensor nodes are derived from the mxn coordinate matrix X

$$X=\Lambda^{1/2}E^T$$

where $\Lambda^{1/2} = \text{diag}\,(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \ldots, \sqrt{\lambda_m})$, E is the matrix of corresponding m eigenvectors of N, and the superscript ^{T} denotes the transpose of a matrix.

3.2 Procrustes Analysis

Procrustes analysis refers to the technique of matching one representation to another and producing a measure for this matching. This particular technique is named after an innkeeper from Greek mythology who made his guests fit the size of an iron bed by stretching them on a rack if they were too short or by chopping off their extremities if they were too long. According to Greek mythology, this innkeeper earned the nickname Procrustes meaning "the stretcher".

Procrustes analysis attempts to find the rigid motions (i.e., reflection, rotation and translation) and the isotropic dilation needed to best match one representation to the other [9]. In the simplest case, both representations have the same dimensionality and the same number of points with a one-to-one correspondence, which are called similar representations. Similar representations can be brought to a complete match by rigid motions and dilation. In more complicated cases, on the other hand, representations with different dimensionalities or different numbers of points are considered and a measure for the matching, referred to as Procrustes statistics, is identified [12].

Suppose that a representation of n points in a q-dimensional Euclidean space with qxn coordinate matrix $\widetilde{X}$ needs to be optimally matched with another representation of the same n points in a p-dimensional Euclidean space ($p \geq q$) with pxn coordinate matrix X. It is assumed that there is an a priori one-to-one correspondence between the points of $\widetilde{X}$ and of X. Procrustes analysis algorithm [9] with the following steps can be performed to obtain the rigid motions, dilation, and a measure for matching $\widetilde{X}$ with X:

Procrustes Analysis Algorithm:

Step 1. Place p-q rows of zeros at the bottom of $\tilde{X}$ so that both representations are in p-dimensional Euclidean space.

Step 2. Calculate $\vec{\mu}_X$ and $\vec{\mu}_{\tilde{X}}$ which are the mean vectors, also called centroids, of X and $\tilde{X}$, respectively.

Step 3. For the representations of X and $\tilde{X}$, subtract the mean vectors $\vec{\mu}_X$ and $\vec{\mu}_{\tilde{X}}$ from each of the respective coordinates of points, and obtain $\underline{X}$ and $\underline{\tilde{X}}$ with centroids at the origin.

Step 4. Find the rotation matrix

$$R=(\underline{\tilde{X}}\,\underline{X}^T\underline{X}\,\underline{\tilde{X}}^T)^{1/2}(\underline{X}\,\underline{\tilde{X}}^T)^{-1}$$

Step 5. Find the dilation

$$\rho=\frac{tr((\underline{\tilde{X}}\,\underline{X}^T\underline{X}\,\underline{\tilde{X}}^T)^{1/2})}{tr(\underline{\tilde{X}}\,\underline{\tilde{X}}^T)}$$

where tr denotes the sum of elements on the main diagonal of a matrix.

Step 6. Find the translation vector

$$\vec{b}=\vec{\mu}_X-\rho R^T\vec{\mu}_{\tilde{X}}$$

Step 7. Find the Procrustes statistics which is a measure of matching

$$M^2=1-\frac{tr((\underline{\tilde{X}}\,\underline{X}^T\underline{X}\,\underline{\tilde{X}}^T)^{1/2})^2}{tr(\underline{\tilde{X}}\,\underline{\tilde{X}}^T)tr(\underline{X}\,\underline{X}^T)}$$

Step 8. Finally, the transformed coordinates of $\tilde{X}$ is obtained as $\rho R^T\tilde{X}+\vec{b}$.

4 APPLICATION

In the next subsections, the structure of the deployed network, main features of the application setup and obtained relative positioning results are given.

4.1 Deployed Network Structure

UWB sensor network deployed in this application includes two types of nodes as depicted in Figure 4-1: type A and type B. There are three type A nodes, labeled as A_1, A_2, A_3 and eight type B nodes, labeled as B_1, B_2, …, B_8. The network is configured in such a way that each type A node is able to communicate with all other nodes. On the other hand, each type B node is able to communicate only with type A nodes.

In the application, classical MDS will be utilized to create local relative maps for each cluster of communications including three type A nodes and one type B node in two-dimensional Euclidean space. Then, by referring the common representations of type A nodes and merging these local maps via Procrustes analysis, a global map displaying relative positions of all nodes will be created.

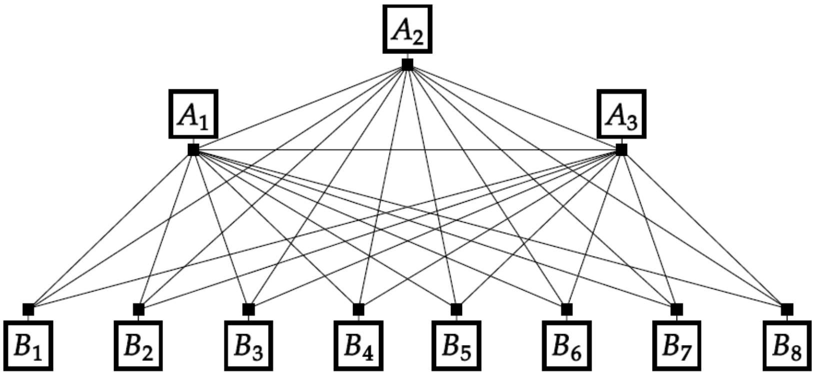

Figure 4-1: Structure of the Deployed Network.

The following symmetric squared distance matrices D_k (k=1, …, 8) are constructed for each cluster using UWB distance estimates

$$D_k=\begin{bmatrix} 0 & d^2_{A_1A_2} & d^2_{A_1A_3} & d^2_{A_1B_k} \\ d^2_{A_2A_1} & 0 & d^2_{A_2A_3} & d^2_{A_2B_k} \\ d^2_{A_3A_1} & d^2_{A_3A_2} & 0 & d^2_{A_3B_k} \\ d^2_{B_kA_1} & d^2_{B_kA_2} & d^2_{B_kA_3} & 0 \end{bmatrix}$$

As can be seen, the 3x3 square submatrix of D_k indicates the squared pairwise distance estimates among type A nodes, and is common for each D_k. On the other hand, the last row and column of D_k are used to specify the squared pairwise distance estimates from the k^{th} type B node to the each type A node. Having constructed D_k, classical MDS algorithm provides respective 2x4 coordinate matrices X_k (k=1, …, 8) for each cluster of communications including A_1, A_2, A_3 and B_k.

At this point, it should be noted that the first three columns of each X_k refer to the relative coordinates of type A nodes in each cluster, hence there is a one-to-one correspondence among X_k for type A nodes. This correspondence defines similar representations and enables us to obtain the rigid motions and dilations for matching these representations completely. For this aim, Procrustes analysis described in the previous section is utilized as follows. The relative coordinates of type A nodes in the first MDS representation X_1 is chosen as the target representation. Then, rigid motions and dilations are obtained using the similar representations of type A nodes in the other coordinate matrices X_2, …, X_8 to match them completely with the target representation. Once the rigid motions and dilations are calculated, the coordinates of the remaining type B nodes (i.e., B_2, …, B_8) are mapped onto the reference MDS representation X_1. Thus, a global map displaying the relative positions of all nodes is created.

4.2 Setup

EVB1000 modules, developed by Decawave [13] and depicted in Figure 4-2, have been used as UWB nodes in the application. Application setup in an indoor facility with the area of 10.2 x 4.2 m^2 is shown in Figure 4-3. Each EVB1000 module utilizes roundtrip ToF measurement for distance estimation and consists of a DW1000 radio transceiver compliant with the IEEE 802.15.4.-2011 UWB standard, a STM32F105RCT6 microcontroller, and an omnidirectional antenna. In the application, the default values of 4 GHz central frequency and 110 kbps data rate settings have been chosen. EVB1000 modules have been configured as type A (shown by circles in Figure 4-3) and type B (shown by triangles in Figure 4-3) nodes in order to realize the deployed network structure described in the previous subsection. All available pairwise distance estimations are transmitted to the node A_1 which is connected to a personal computer through a USB port. Then this information is fed to the applied method implemented by MATLAB.

Figure 4-2: EVB1000 Module Used as a UWB Node.

Figure 4-3: Application Setup.

4.3 Results

In the application, UWB sensor nodes are placed on positions such that the actual pairwise distances among them are as given in Table 4-1 (written in green color). These actual pairwise distance values are used as ground truth in the application and they are estimated via UWB signals. The obtained estimates are depicted in Table 4-1 (written in blue color). It should be noted that since type B nodes are not able to communicate among themselves, pairwise distances between type B nodes cannot be estimated and this lack of information about the network is shown in Table 4-1 by ---.

Using the estimated pairwise distances (written in blue color), classical MDS provides local relative maps for each cluster as shown in Figure 4-4. Choosing the relative coordinates in the first cluster as the target representation and fitting the others to it, Procrustes analysis enables us to obtain the global map displaying the relative coordinates of all nodes as depicted in Figure 4-5. Regarding the relative coordinates of all nodes from the global map that the applied method provides, the pairwise distances among all nodes can be calculated as given in Table 4-1 (written in red color). As can be seen from Table 4-1, the applied method which utilizes classical MDS and Procrustes analysis also offers the pairwise distances among type B nodes which cannot be estimated via UWB signals.

Table 4-1: Pairwise Distances between Nodes (in meters).

Actual
UWB Estimates
MDS + Procrustes

Nodes	**A_1**	**A_2**	**A_3**	**B_1**	**B_2**	**B_3**	**B_4**	**B_5**	**B_6**	**B_7**	**B_8**
A_1	0	10.48 10.71 10.71	6.27 6.47 6.46	9.08 9.15 9.15	7.89 8.03 8.01	5.91 6.06 5.99	3.80 3.92 3.88	3.06 3.21 3.12	2.55 2.69 2.57	6.63 6.76 6.76	5.43 5.62 5.57
A_2	10.48 10.71 10.71	0	5.94 6.21 6.21	3.80 3.96 3.93	2.68 2.86 2.83	4.80 5.01 4.91	7.52 7.73 7.72	7.42 7.62 7.60	8.42 8.63 8.61	4.69 4.87 4.88	5.13 5.33 5.29
A_3	6.27 6.47 6.46	5.94 6.21 6.21	0	3.06 3.13 3.04	3.50 3.63 3.61	4.24 4.40 4.40	2.47 2.65 2.58	3.84 4.00 3.96	5.53 5.74 5.75	1.34 1.35 1.43	2.47 2.59 2.49
B_1	9.08 9.15 9.15	3.80 3.96 3.93	3.06 3.13 3.04	0	2.68 --- 2.59	5.09 --- 5.03	5.40 --- 5.40	6.27 --- 6.23	7.80 --- 7.84	2.47 --- 2.40	4.03 --- 3.87
B_2	7.89 8.03 8.01	2.68 2.86 2.83	3.50 3.63 3.61	2.68 --- 2.59	0	2.68 --- 2.72	4.84 --- 4.89	4.84 --- 4.89	6.03 --- 6.14	2.16 --- 2.19	2.47 --- 2.48
B_3	5.91 6.06 5.99	4.80 5.01 4.91	4.24 4.40 4.40	5.09 --- 5.03	2.68 --- 2.72	0	4.03 --- 4.05	3.00 --- 3.04	3.65 --- 3.71	3.23 --- 3.28	1.80 --- 1.94
B_4	3.80 3.92 3.88	7.52 7.73 7.72	2.47 2.65 2.58	5.40 --- 5.40	4.84 --- 4.89	4.03 --- 4.05	0	1.90 --- 1.88	3.50 --- 3.57	3.06 --- 3.11	2.55 --- 2.52
B_5	3.06 3.21 3.12	7.42 7.62 7.60	3.84 4.00 3.93	6.27 --- 6.23	4.84 --- 4.89	3.00 --- 3.04	1.90 --- 1.88	0	1.70 --- 1.79	3.80 --- 3.84	2.40 --- 2.48
B_6	2.55 2.69 2.57	8.42 8.63 8.61	5.53 5.74 5.75	7.80 --- 7.84	6.03 --- 6.14	3.65 --- 3.71	3.50 --- 3.57	1.70 --- 1.79	0	5.37 --- 5.49	3.80 --- 3.97
B_7	6.63 6.76 6.76	4.69 4.87 4.88	1.34 1.35 1.43	2.47 --- 2.40	2.16 --- 2.19	3.23 --- 3.28	3.06 --- 3.11	3.80 --- 3.84	5.37 --- 5.49	0	1.70 --- 1.61
B_8	5.43 5.62 5.57	5.13 5.33 5.29	2.47 2.59 2.49	4.03 --- 3.87	2.47 --- 2.48	1.80 --- 1.94	2.55 --- 2.52	2.40 --- 2.48	3.80 --- 3.97	1.70 --- 1.61	0

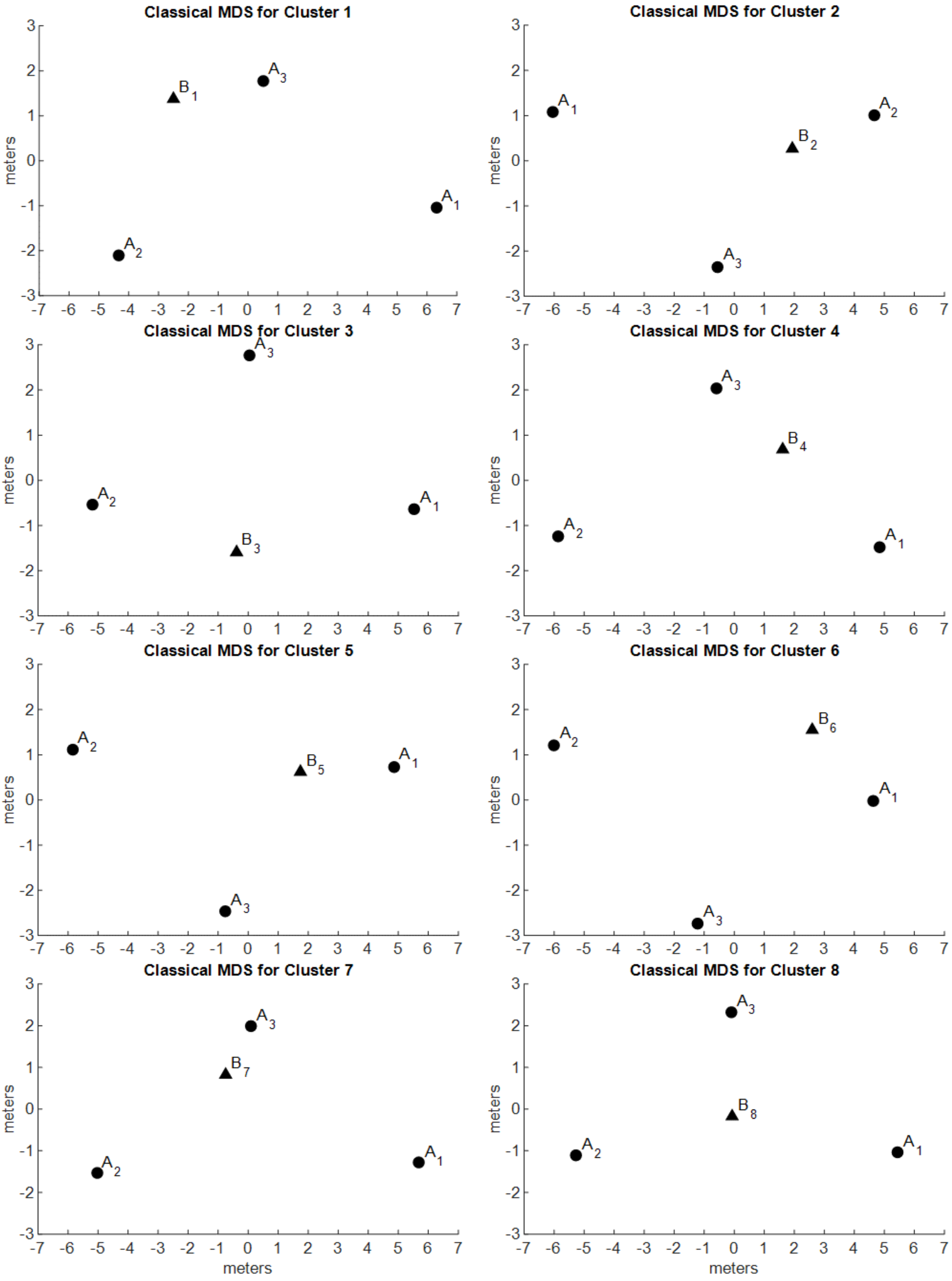

Figure 4-4: Local Relative Maps for each Cluster.

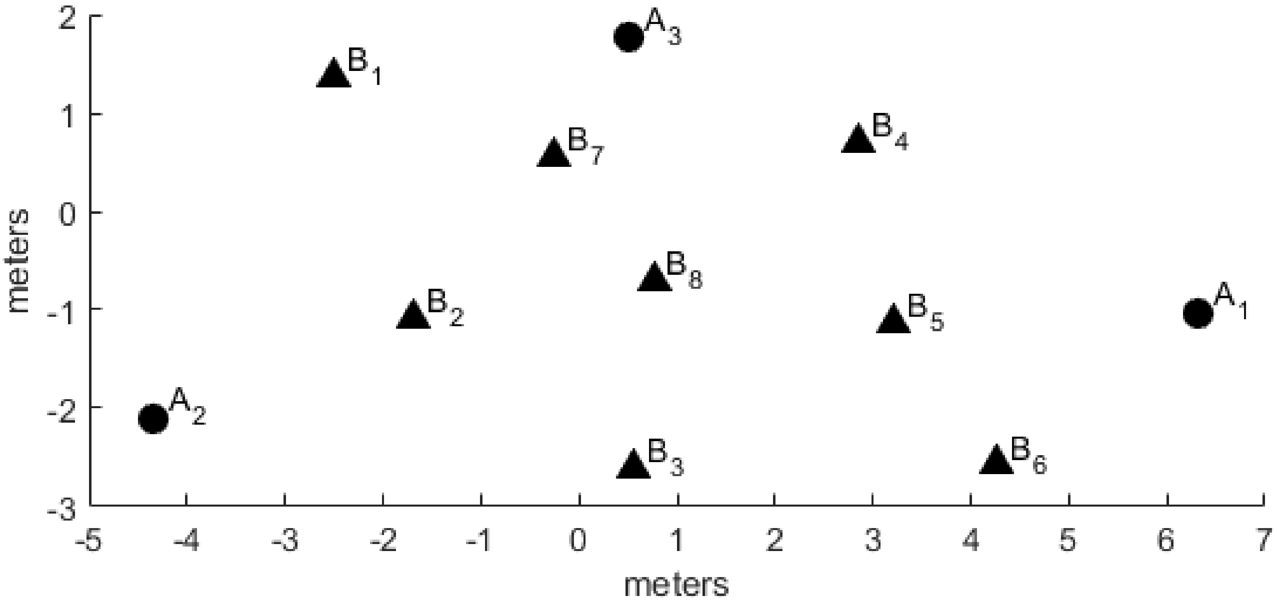

Figure 4-5: Global Map Displaying the Relative Positions of All Nodes.

5 CONCLUSIONS AND FUTURE WORK

In this paper, application results of a relative positioning method in two-dimensional network is presented. Application results show that the method provides an ability to build relative local maps of fully-connected subnetworks and then to merge them together by using their common nodes to obtain a relative global map of the entire network. Thus, the method offers an opportunity to obtain the pairwise distances among unconnected nodes which cannot be estimated via UWB signals. As illustrated in the application, pairwise distances among unconnected type B nodes can be provided by the method. Besides, the obtained global relative coordinates yield a good fit to the actual pairwise distances among the nodes used as ground truth.

Authors believe that the applied method can be effectively used for tracking the soldiers' relative positions in GNSS degraded/denied operational environments. For future work, the method will be studied for three-dimensional networks. In addition, experiments related to time complexity, power consumption and other costs of the method for real-time applications will be done.

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