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ORIGINAL ARTICLE

Network localization procedures for experimental evaluation of mobile spatial coordinate measuring system (MScMS)

Luca Mastrogiacomo · D. Maisano

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Abstract Large scale metrology refers to dimensional measurement of objects or features of perhaps a ten of meters or more in size. Alternatively, large scale metrology could be said to apply to any dimensional measurement where the metrology instrument has to be brought to the object rather than vice versa. Recent approaches seem to turn their attention towards distributed metrology systems made of multiple components with small dimensions spread around the measuring area. In general, these components are able to form a wireless network of sensors that allows rapid dimensional measurements to be performed in relation to large-size objects, with typical dimensions of several decametres. The portability, flexibility, and ease of installation of wireless sensor networks (WSNs) make these systems attractive for many industries manufacturing large scale products. This paper proposes different WSN localization procedures designed for the mobile spatial coordinate measuring system, a distributed metrology system developed at the industrial metrology and quality laboratory of DISPEA—Politecnico di Torino.

Keywords Localization algorithms · Mobile metrology system · Wireless sensor networks · Dimensional measurements · MScMS

1 Introduction

Flexibility and ease of use are becoming more and more key factors in the design and development of new products and technologies. On the other hand, quality standards are permeating all production sectors claiming more and more demanding accuracy specifications.

In the last decades, many solutions for the large scale metrology problem have been proposed. Classical centralized metrology systems are generally stand-alone units able to provide geometrical features of an object to be measured. Latest advances in large scale metrology are recently proposing distributed solutions in which a series of metrology stations share the measurement task. A distributed system is composed of a network of measuring stations that cooperatively work to collect information for determining coordinates of the object's geometry. In general, the individual stations associated with a distributed system may not be able to measure coordinates separately [1]. The coming of such new metrology approach is the result of a continuous effort toward light scalable technologies able to cover flexible working spaces [2]. Beside the well-known technique of photogrammetry which uses the information of distributed cameras to localize multiple points, nowadays, there are other distributed metrology systems using different technologies such as laser, infrared sensors, or ultrasound transceivers [2–5]. All these distributed systems rely on two possible working principles:

- Trilateration which uses the known positions of three or more reference points, and the measured distance between the point to be localized and each reference point.
- Triangulation which uses the known positions of two or more reference points, and the relative angles between the point to be localized and each reference point.

Whatever the working principle may be, the position of the metrology stations is a necessary information for all the

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L. Mastrogiacomo (✉) · D. Maisano
Politecnico di Torino, DISPEA,
Turin, Italy
e-mail: luca.mastrogiacomo@polito.it

distributed systems to work. This information is normally achieved during the set-up phase, sometimes called bundle adjustment phase. To be convenient, this phase should be fast and automated.

This paper focuses on the problem of the mobile spatial coordinate measuring system (MScMS) network localization. MScMS is a large metrology system based on an ultrasound (US) wireless sensor network [2]. It is made up of three basic parts: the network devices, distributed around the working area; a mobile probe, and a PC connected via radio to the mobile probe and the network devices. Each wireless network device is able to communicate and estimate its distance to its neighbors [6]. All distance information is stored in a distance matrix which is the input of the network localization problem.

The aim of the paper is to present some new procedures to face the MScMS network localization problem. All the procedures rely on the use of an artifact with known geometry which embeds a sufficient number of network devices and can be easily moved within the measuring volume. The procedures are compared considering the network features they can deal with, the computational workload they require and their major advantages and drawbacks. The localized position of the network devices has been compared to the nominal devices position achieved using a laser tracker (whose nominal accuracy is greater than the MScMS accuracy).

This paper is organized into five sections. Section 2 provides a general overview of the main existing network localization algorithms. Section 3 briefly describes MScMS architecture and working principle. In Section 4, three network localization strategies are presented and analyzed discussing their critical aspect. Finally, Section 5 shows the results of the experimental comparison between the proposed procedures.

2 Literature review

Dramatic advances in integrated circuits and radio technologies have made possible the use of large WSNs for many applications. Node localization has been the topic of active research and a number of systems have been proposed over the past few years. Many of these fall into one of three classes or a combination of them.

The first class includes range-free algorithms, which assume that there is no distance information available at each node [7, 8]. They try to use the basic proximity information available at each node, i.e. which nodes are nearby. In general, range-free algorithm are not accurate (coarse-grained) and are easily prone to errors.

The second class employs a number of specialized nodes (*anchor* nodes) that a priori know their positions [9–11]. The rest of the nodes try to estimate their positions relative to these anchors. Usually, anchor-based algorithms proceed incrementally: an unknown node that is connected to at least three anchors estimates its position by solving a system of non-linear equations. Once a node estimates its position, it becomes an anchor node and assists other unknown nodes in estimating their position by propagating its own localization estimate through the network.

The third class of localization systems (anchor-free algorithms) tries to compute the nodes' position without the use of anchor nodes [12–14]. In this case, instead of computing absolute nodes' positions, the algorithm estimates nodes' positions relative to a coordinate system established by a reference group of nodes.

These two last classes of localization algorithms are generally more accurate (fine-grained). The drawback of anchor-based algorithms is that the accidental errors in the a priori localization of the anchor nodes may propagate on the other nodes localizations. On the other hand, anchor-free algorithms are easily affected by ambiguity in the network layout realization [15].

MScMS needs accurate and ambiguity-free sensors network localization, anchored to a reference coordinate system a priori defined. Those requirements together with the problems of communication (see Section 3.1) make most of the above cited techniques unsuitable for the purpose of MScMS network localization.

3 MScMS

MScMS is a distributed, cost effective, and scalable measuring system designed and developed at the industrial metrology and quality laboratory of DISPEA—Politecnico di Torino. MScMS has been designed to perform simple and rapid indoor dimensional measurements of large-size objects (large scale metrology).

The system (see Fig. 1) is made up of three basic parts:

- a network of wireless devices (see Fig. 2), distributed around the measuring area;
- a mobile probe for registering the coordinates of the object "touched" points; and
- a PC to store and elaborate data.

The network is composed of small electronic devices able to communicate with each other via radiofrequency (RF) and ultrasound transmitters and receivers. Two identical devices equip the mobile probe (see Fig. 1).

When communicating to each other, wireless devices exchange both RF and US messages. By evaluating the time difference of arrival (TDoA) of the two signals (RF and US), the wireless devices can easily achieve a quite

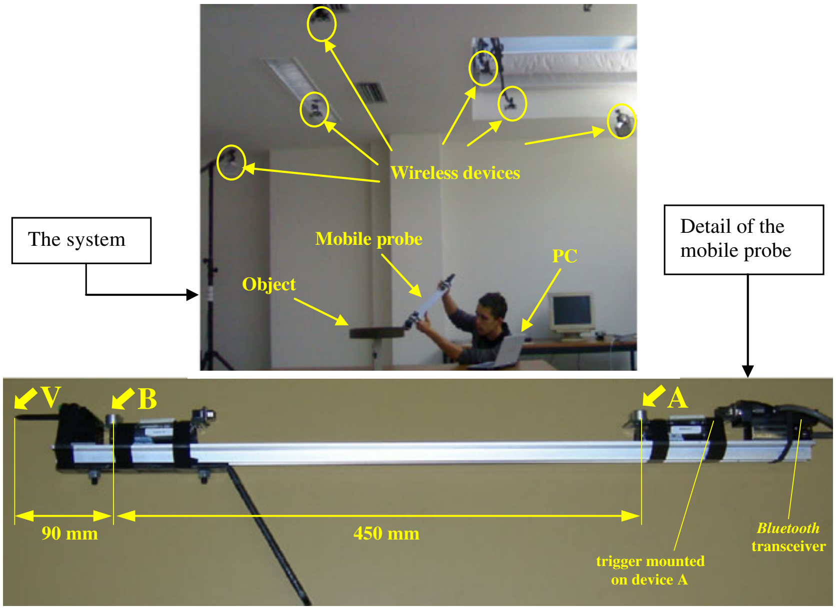

Fig. 1 MScMS. A detail of the mobile probe

accurate distance estimate. This allows each device to know the mutual distance to the other devices within its range of US propagation. Knowing the network topology, the mobile probe position is found by implementing a multilateration approach [16]. Acquired data are then available for different elaborations to determine the geometric features of the measured objects (distances, curves or surfaces).

Currently, the main drawback for MScMS is the low level of accuracy. Some preliminary accuracy tests performed on the first MScMS prototype showed that the accuracy on single point localization inside a volume of about 300 m^3 is of the order of 10 mm [2].

3.1 MScMS wireless devices

MScMS wireless devices are equipped with radiofrequency (RF at 433 MHz) and ultrasound transceivers. These devices, known as Crickets, are developed by Massachusetts Institute of Technology and manufactured by Crossbow Technology. Figure 2 shows a photo and two schematic views of MScMS wireless device. From the photo and the perspective view, it is possible to appreciate some of the components embedded on the device while the orthogonal projection quotes its dimensions.

Each device uses an Atmega 128 L microcontroller operating at 7.4 MHz, with 8 Kbytes of RAM, 128 Kbytes of flash ROM (program memory), and 4 Kbytes of EEPROM (as mostly read-only memory). Alimentation is provided by two “AA” batteries of 1.5 V [17].

The piezo-electric transducer adopted for MScMS wireless devices is a low-cost, general purpose model (Murata MA40S4R), with a relative wide bandwidth, in which the center frequency is about 40 kHz. Since ultrasound propagation is not omni-directional, each device has a limited propagation region (see Fig. 3). The direct consequence is that two devices must be one in the US propagation region of the other in order to estimate their mutual distance. As an example, consider Fig. 3: being both placed on the ceiling, devices B$_1$ and B$_2$ can easily estimate

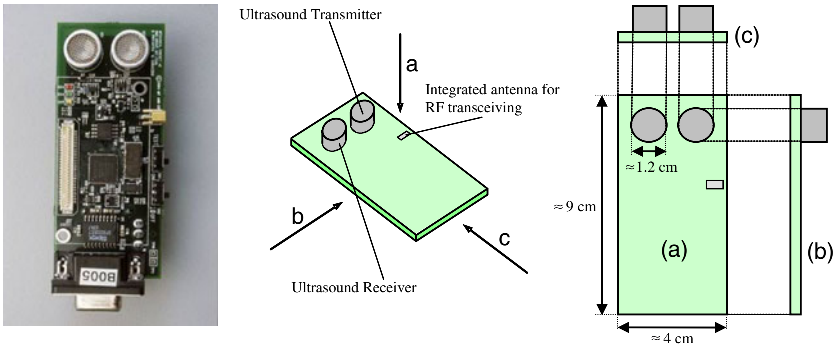

photo *perspective view* *orthogonal projection*

Fig. 2 MScMS wireless device

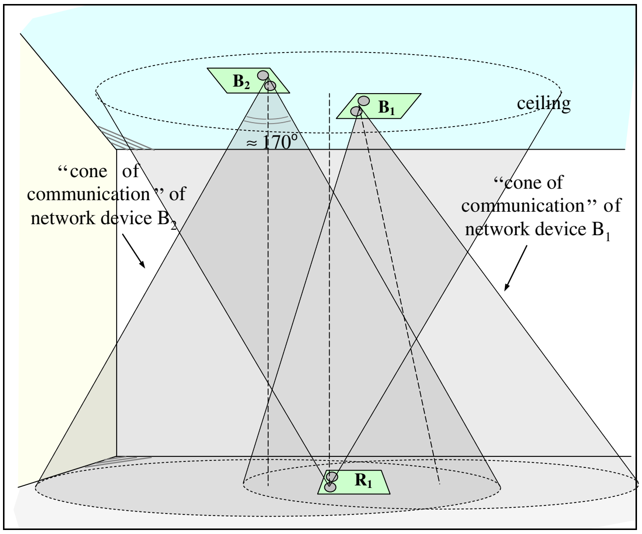

Fig. 3 Schematic representation of the device cone of communication

Fig. 4 Reference artifact prototype. In this case the number of devices embedded is three

the distance from device R_1. On the contrary, B_1 and B_2 are not able to estimate their mutual distances.

4 Localization procedures

4.1 The need for a reference artifact

As discussed in the previous sections, the inputs of every WSN localization algorithm are the mutual distances (estimates) between wireless devices. For this reason, classical localization algorithms may be ineffective with WSNs made by sensors that are able to estimate mutual distances just when devices are facing each other. Furthermore, Crickets are generally mounted parallel to each other on the ceiling to improve the working area coverage, and this condition worsens their connectivity even more.

For such kind of network, the use of a reference artifact may be a possible solution to improve network communication. A reference artifact is an object whose geometry is a design parameter (see Fig. 4) that contains three or more network devices. It can play different roles, depending on the localization strategy. By multiple repositioning of the reference artifact, it is generally possible to place it in sight of all the network devices in order to allow and ease their localization.

4.2 First Procedure

4.2.1 The logic

The key idea of this procedure is to place the reference artifact in known positions (see Fig. 5). Each time the reference artifact is moved, it is kept still for a while. During the time period in which it is not moving, the reference artifact is able to communicate and estimate the distances between the embedded and the network devices. Knowing these distances and the reference artifact position in a global reference system, the network devices can be localized in a global reference system by solving the optimization problem described in the following.

4.2.2 The algorithm

Let M be the number of wireless devices embedded in the reference artifact. As said before, the reference artifact is placed in different positions under the network devices. Let P be the number of reference artifact positioning. Since for each repositioning, the reference artifact position is supposed to be known, the reference artifact defines $M{\cdot}P$ reference points (R_i) with known coordinates ($\left(x_{R_j}, y_{R_j}, z_{R_j}\right)$, with $j=1 \ldots M{\cdot}P$). Let also $B_1 \div B_N$ be the points with unknown coordinates ($\left(x_{B_i}, y_{B_i}, z_{B_i}\right)$, with $i=1 \ldots N$) corresponding to the network devices to be localized.

During the phase of the reference artifact repositioning, the wireless devices are able to measure the distance ($\widetilde{d}_{B_iR_j}$) between the points defined by the reference artifact (R_j) and the points corresponding to the network devices (B_i).

Knowing the set of measured distances, it is possible to define a distance vector ($(d_j)_i$ with $i=1 \ldots N$ and $j=1 \ldots M{\cdot}P$) associated to each network node (B_i) as:

$$\left(d_j\right)_i = \begin{cases} \widetilde{d}_{B_iR_j} & \text{If network device } B_i \text{ is able to estimate its distance to the reference point } R_j \\ 0 & \text{otherwise} \end{cases}$$

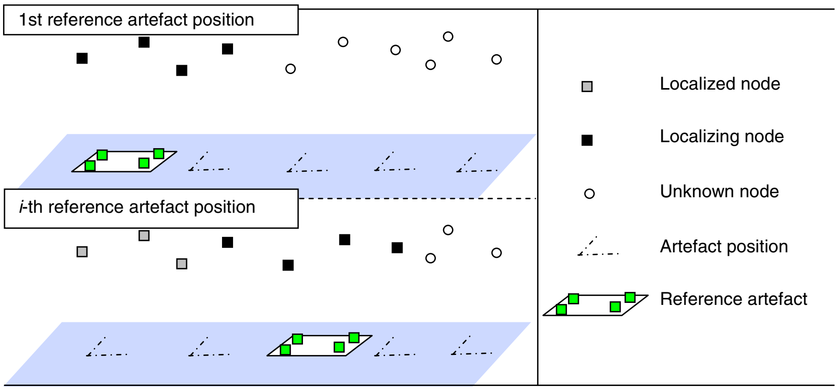

Fig. 5 Schematic representation of the first localization procedure. The multiple positioning of the reference artifact progressively localizes the network nodes

As a consequence, let's define the connection set I_i as the set of reference points to which the network device in position (B_i) is able to estimate the distance:

$$I_i = \left\{ j \in \{1,\ldots,N\} : d_j \neq 0 \right\}_i$$

The unknown position of the *i*-th network device ($B_i = (x_{B_i}, y_{B_i}, z_{B_i})$) can be found as the position that, for each $j \in I_i$, minimizes the difference between Euclidean and measured distance:

$$\left(\sqrt{\left(x_{B_i} - x_{R_j}\right)^2 + \left(y_{B_i} - y_{R_j}\right)^2 + \left(z_{B_i} - z_{R_j}\right)^2} - \widetilde{d}_{B_iR_j} \right)_{j \in I_i} \tag{1}$$

Necessary condition for a network node to be localized is to have a connection set (I_i) containing more than three elements. If number of elements of the connection set is greater than three, then the unknown position of the *i*-th network device $B_i = (x_{B_i}, y_{B_i}, z_{B_i})$ can be estimated performing the iterative minimization of the following error function (*EF*):

$$EF(B_i) = \sum_{j \in I_i} \left(\widetilde{d}_{B_iR_j} - d_{B_iR_j} \right)^2 \tag{2}$$

being:

- $d_{B_iR_j}$, the Euclidean distance between the *j*-th reference point (R_j) and the position of the *i*-th network device (B_i):

$$d_{B_iR_j} = \sqrt{\left(x_{B_i} - x_{R_i}\right)^2 + \left(y_{B_i} - y_{R_i}\right)^2 + \left(z_{B_i} - z_{R_i}\right)^2} \tag{3}$$

- $B_i = (x_{B_i}, y_{B_i}, z_{B_i})$, the position of the *i*-th network device to be localized in the localization space $\xi \subseteq \mathbb{R}^3$.
- $R_j = \left(x_{R_j}, y_{R_j}, z_{R_j}\right)$, the position of the *j*-th reference point defined by the multiple repositioning of the reference artifact.

4.2.3 Remarks

From a computational viewpoint, the algorithm is quite simple to be implemented and to run. An intuitive drawback is the need for a significant human moderation: every time the reference artifact is moved it has to be located in a global coordinate system. To perform this operation, the operator has to define a global coordinate system and manually locate the position of the reference artifact by means of external devices (laser rules, laser levels, etc.). It is obvious that the accuracy of this operation influences the accuracy of the final localization of the network devices.

4.3 Second procedure

4.3.1 The logic

The goal of the second procedure is that of getting free from the constraint of the a priori localization of the reference artifact. In this case, the artifact is not used for directly locating the network devices, but just to obtain distance information.

This localization procedure can be divided in two phases:

- First phase: the method uses multiple replacements of the reference artifact to evaluate the mutual distances between the network devices (see Fig. 6). The reference artifact is kept still in multiple positioning under the network devices as for the first procedure. Every repositioning of the reference artifact univocally defines a new local coordinate system. All network devices that are able to estimate the distances to three or more reference artifact devices, are localized in the local coordinate system by solving a non-linear problem similar to that defined in Eq 2. If two devices are localized in the same local coordinate system, then it is possible to calculate their Euclidean distance.
- Second phase: given the distances between network devices, it is possible to find their position by solving an optimization problem. The optimization searches for the global minimum of an error function whose goal is to identify the network layout that better satisfies the distances constraints.

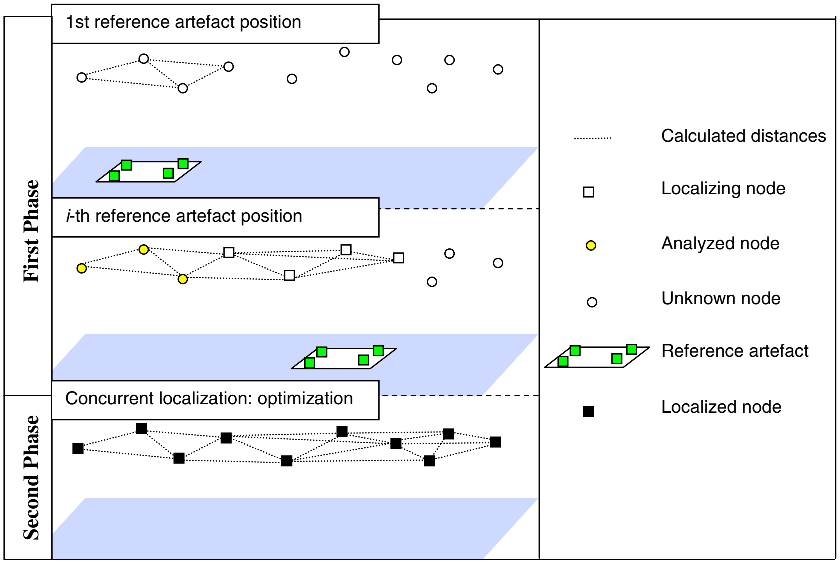

Fig. 6 First phase and second phase of the second localization strategy. Each reference artifact positioning defines a set of distances

4.3.2 The algorithm

Let N be the number of network devices involved in the localization, and $B_{ik} = \left(x_{B_{ik}}, y_{B_{ik}}, z_{B_{ik}}\right)$ and $B_{jk} = \left(x_{B_{jk}}, y_{B_{jk}}, z_{B_{jk}}\right)$ the position of two network devices localized in the same local coordinate system defined by the k-th reference artifact repositioning. Then let $\left(\widetilde{d}_{B_iB_j}\right)_k$ be their Euclidean distance calculated as

$$\left(\widetilde{d}_{B_iB_j}\right)_k = \sqrt{\left(x_{B_{ik}} - x_{B_{jk}}\right)^2 + \left(y_{B_{ik}} - y_{B_{jk}}\right)^2 + \left(z_{B_{ik}} - z_{B_{jk}}\right)^2}$$

Now, let $\widetilde{d}_{B_iB_j}$ be the average of all the Euclidean distances defined by several local coordinate systems.

Collecting all these distances derived from every repositioning of the reference artifact, it is possible to build a global distance matrix which is obviously independent of the different local coordinate systems. The resulting distance matrix is defined as:

$$D = \left(d_{ij}\right) = \begin{cases} \widetilde{d}_{B_iB_j} \;. & \text{If } B_i \text{ and } B_j \text{ can be localized in the same local coordinate system;} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

As for the first localization procedure, for each network device, it is possible to define its connection set I_i as:

$$I_i = \left\{ j \in \{1, \ldots, N\} : \widetilde{d}_{ij} \neq 0 \right\}_i$$

So far, the solution of a global optimization problem allows the concurrent localization of the network devices. The error function to be minimized is similar to that of Eq 2:

$$EF(B_1 \ldots B_N) = \sum_{i=1}^{N} \sum_{j \in I_i} \left(\widetilde{d}_{B_iB_j} - d_{B_iB_j} \right)^2 \tag{5}$$

being:

- $B_i = \left(x_{B_i}, y_{B_i}, z_{B_i}\right)$, the unknown position of point B_i in the localization space $\xi \subseteq \mathbb{R}^3$;
- $d_{B_iB_j}$, the Euclidean distance between $B_i = \left(x_{B_i}, y_{B_i}, z_{B_i}\right)$ and $B_j = \left(x_{B_j}, y_{B_j}, z_{B_j}\right)$.

The unknown optimization variables are the three spatial coordinates $\left(x_{B_i}, y_{B_i}, z_{B_i}\right)$ for $i = 1 \ldots N$. The optimization is an iterative procedure: starting from a network layout of first approximation, the algorithm iteratively refines it in order to better satisfy distances constraints. In general, the optimization convergence towards the correct layout is not a priori granted. It depends on the first approximation solution. We adopted a solution whose efficiency has already been verified. This algorithm has been proposed by Priyantha et al. and already tested on different WSNs [18].

4.3.3 Remarks

While the first localization procedure starts from the ideal condition in which each artifact repositioning is done in a known position, this procedure is free from any constraint about reference artifact positioning. On the other hand, it may be prone to some errors in case of particular network layouts with a not homogeneous node distribution.

A necessary condition for the algorithm to work is that, for each node, the distances to other four nodes must be known.

4.4 Third procedure

4.4.1 The logic

In some conditions, it is possible to overcome the main drawbacks of both the first and the second methods. While the first can be classified as an anchor-based algorithm, the second method is an anchor-free algorithm. It does not need an a priori localization of the reference artifact, thus resulting handier and more scalable. On the other hand, it may lack accuracy because it does not consider some of the available information about the local localizations.

The third method is quite similar to the second one, except for a further assumption. In practice, it is often customary to move the reference artifact on a plane, for example on the floor of the working area. This method rests on the assumption of planarity of the reference artifact support surface. The local coordinate systems resulting from the reference artifact repositioning have the same z coordinate axis.

The procedure can be summarized in two phases:

- First phase: the method uses multiple replacements of the reference artifact as for the second localization procedure. Each time the reference artifact is moved, it defines a local coordinate system. Besides storing mutual distances, during this phase also the z coordinates of each network device are saved.
- Second phase: the optimization searches for the global minimum of an error function whose goal is to identify the network layout that better satisfies distances constraints and z measurements.

4.4.2 The algorithm

As for the first and the second procedure, the reference artifact is moved under the network devices. Every repositioning of the reference artifact univocally defines a new local coordinate system. Let denote with $B_{ik} = (x_{B_{ik}}, y_{B_{ik}}, z_{B_{ik}})$ and $B_{iq} = (x_{B_{iq}}, y_{B_{iq}}, z_{B_{iq}})$ the local coordinate of the i-th network device referred to the k-th and q-th repositioning of the reference artifact, respectively. If for every repositioning of the reference artifact the defined local coordinate system has the z-axis orthogonal to the support plane, then what changes between the different local coordinate systems are just x and y coordinates. Let $\widetilde{z}_{B_i}$ be the average of all $z_{B_{ik}}$ obtained localizing the same network device (B_i) in different local coordinate systems.

Thus the localization problem can be lead to a bidimensional problem.

As for the second method, if two devices can be localized during the same reference artifact repositioning, it is possible to calculate their bidimensional Euclidean distance

$$\widetilde{d}_{B_{ik}B_{jk}} = \sqrt{\left(x_{B_{ik}} - x_{B_{jk}}\right)^2 + \left(y_{B_{ik}} - y_{B_{jk}}\right)^2}.$$

Let $\widetilde{d}_{B_iB_j}$ be the average of all the bidimensional distances between B_i and B_j defined by all the reference artifact repositioning. So far, it is possible to define a distance matrix D as in Eq 4.

The optimization of the second phase starts from a raw first approximation bidimensional layout [18] and it searches for the minimum of a different error function:

$$EF((x_1, y_1)\ldots(x_N, y_N)) = \sum_{i=1}^{N}\left[\left(\sum_{j\in I_i}\left(\widetilde{d}_{B_iB_j} - d_{B_iB_j}\right)^2\right)\right] \tag{6}$$

where:

- (x_i, y_i) are the x and y unknown coordinate of the i-th network device in the localization space $\xi \subseteq \mathbb{R}^2$;
- $d_{B_iB_j}$, the bidimensional Euclidean distance between B_i and B_j;
- N the number of devices to be localized;
- $I_i = \left\{j \in \{1, \ldots, N\} : \widetilde{d}_{ij} \neq 0\right\}_i$ the connection set of node B_i;

Once the optimization phase is concluded, the three-dimensional coordinates of each network node are $B_i = (x_{B_i}, y_{B_i}, \widetilde{z}_{B_i})$.

4.4.3 Remarks

The third method has been developed to be a compromise between the two previous methods. Assuming to know that the reference artifact is placed on a flat surface, this method handles the local calculations of the z coordinates as additional measurements.

The necessary condition for the algorithm to work is relaxed if compared to that of the second method: for each node, the distances to other three nodes must be known [19].

5 Tests and performance comparison

The three proposed localization procedures have been tested on different network topologies. The experimental trials have been run in the industrial metrology and quality laboratory of DISPEA—Politecnico di Torino. During the experimental measurements, the temperature was kept constant at about 21°C with relative humidity RH=27%. In this condition, the speed of sound value (s) was set to 343.95 m/s.

5.1 Network topologies

The experimental tests have been carried out with a number of network devices horizontally placed on the ceiling of the laboratory. In general, this kind of positioning allows a better coverage of the working area and at the same time avoids the presence of obstacles between the contact probe and the network devices.

In order to evaluate the potential sensor network effect on the localization, we considered four different network topologies fitting the same working volume (about 90 m^3):

- Low density network: eight devices placed in a 30 m^2 area (see Fig. 7a);
- Medium density network: 16 devices placed in a 30 m^2 area (see Fig. 7b);
- Medium/high density network: 20 devices placed in a 30 m^2 area (see Fig. 7c);
- High density network: 24 devices placed in a 30 m^2 area (see Fig. 7d);

For each of the four network topologies, the reference positions plotted in Fig. 7 have been measured using a laser tracker, a metrology instrument whose nominal accuracy is at least two orders of magnitude greater than the MScMS accuracy [20].

5.2 Data collection and processing

A reference artifact similar to that presented in Fig. 4, but containing five devices was used for the tests. The five devices were placed on each vertex and in the middle of a 700 mm side square. The relative positions of the devices embedded in the reference artifact were calculated using a coordinate measuring machine.

Using the laser tracker, it was possible to draw a grid of about 1,500 mm of side so as to know the position of the reference artifact in each of its repositioning. In order to completely cover the working area, the reference artifact was moved in seven different positions.

During each reference artifact positioning, a PC stored the distance estimates between the reference artifact and the network devices averaging the measurements for 30 sec (currently the Cricket working frequency is set to 1 Hz) in order to reduce the natural variability of distance measurements among Crickets (σ=5.6 mm [18]).

The same data collected by the reference artifact were used off-line as input of the three different procedures. This model allows to significantly reduce measurements variability and bias, considering the effects on time of flight measurement due to the relative position of US transceivers in terms of angle and distance.

All tests were replicated five times.

5.3 Performance comparison methodology

In order to evaluate the performances of the three proposed localization techniques, the network layouts produced by the algorithms were compared to the reference network layout given by the laser tracker. To do that, the results produced by the algorithms were roto-translated to best fit the network layout given by the laser tracker. This operation, which is just a rigid transformation, is necessary whenever there is a need to compare localizations given in different reference systems. In detail a robust least squares fitting method was used to reduce the influence of outlier points on the fitting results [21].

Finally, a further time study is provided to complete the procedures analysis.

5.4 Results: accuracy and times

To compare the nominal and the computed network layouts, we analyzed the distances between each node nominal positions and the positions obtained by the proposed procedures. If $\overrightarrow{x}_i$ is the position of the i-th network node produced by the localization procedure and $\overrightarrow{X}_i$ its nominal position, then the distances can be calculated as:

$$d_i = \left\| \overrightarrow{x}_i - \overrightarrow{X}_i \right\| = \sqrt{(x_i - X_i)^2 + (y_i - Y_i)^2 + (z_i - Z_i)^2}$$

Table 1 proposes the empirical percentiles of the distance distribution. It is possible to notice that the first method seems to work better for any density. In detail, for the low density network, it is the only working procedure: in this case the low node density results in a sparse distance matrix which is not sufficient to run the second or third localization method.

For all the other densities, the second procedure shows a great dispersion in the distance distribution. In particular, some of the nodes are localized up to more than 20 mm far from their real position. On the other hand, the output of the third procedure is a quite accurate network layout, in which the majority of the nodes are localized within a distance of 10 mm from their nominal position.

In order to uniform these results to the literature, a further analysis is given with respect to a common synthesis

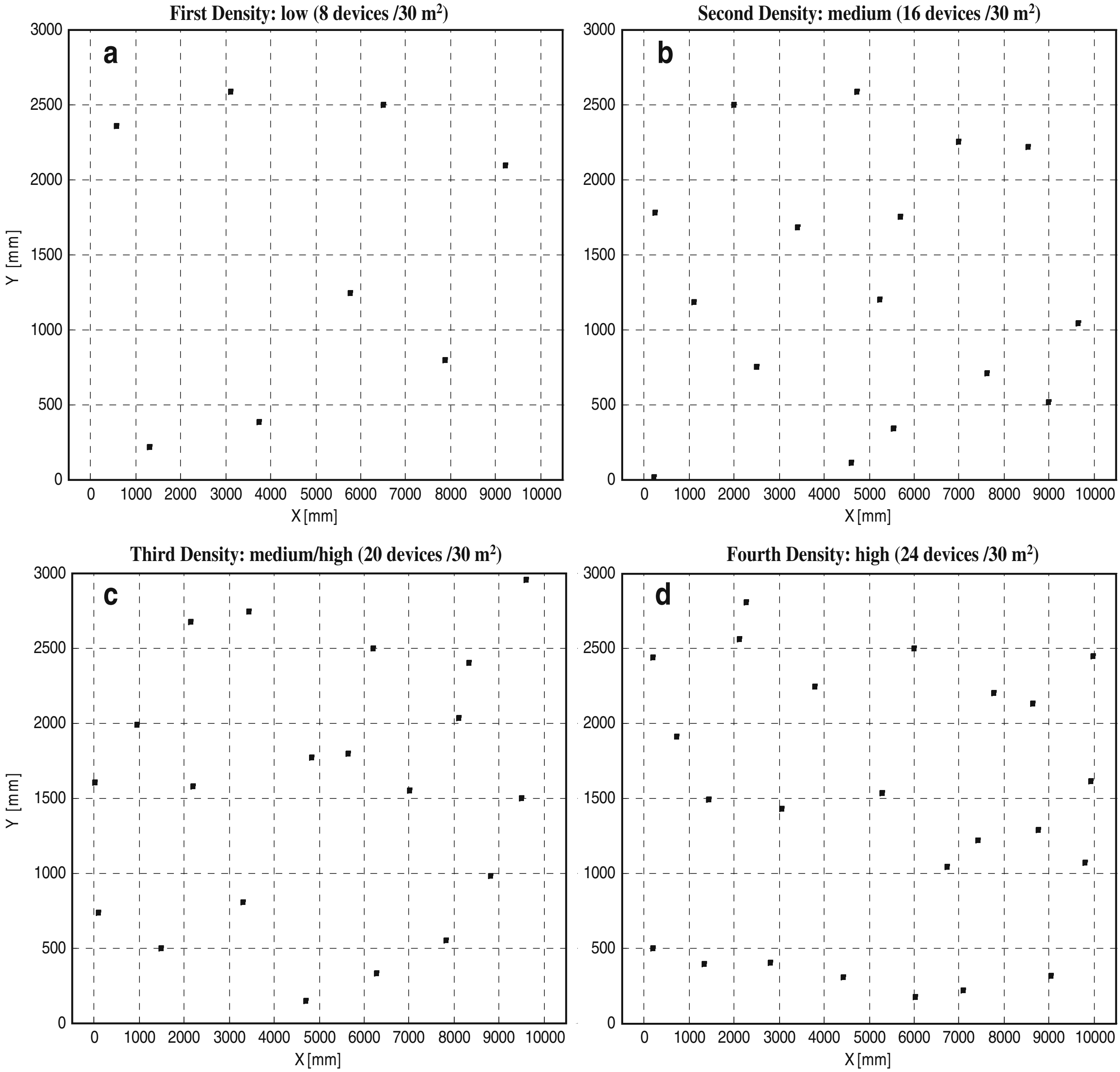

Fig. 7 The four network topologies tested

Table 1 Percentile of the of the distances between each node nominal positions and the positions obtained by the proposed procedures

Percentiles	Low density			Medium density			Medium/high density			High density		
	50%	75%	95%	50%	75%	95%	50%	75%	95%	50%	75%	95%
First Method [mm]	5.0	6.1	7.8	5.1	6.0	7.8	4.9	6.0	7.7	4.6	5.9	7.8
Second Method [mm]	n.a.	n.a.	n.a.	15.4	20.2	24.4	13.9	19.5	24.1	13.5	19.1	23.8
Third Method [mm]	n.a.	n.a.	n.a.	6.2	7.1	8.8	5.9	7.0	8.7	5.8	6.9	8.3

n.a. not applicable

Table 2 Localization error according to the error indicator defined in Eq 7

	Low density	Medium density	Medium/high density	High density
ε First method [mm]	5.1	5.2	5.0	4.7
ε Second method [mm]	n.a.	15.6	14.2	13.9
ε Third method [mm]	n.a.	6.4	6.1	6.0

n.a. not applicable

indicator [11, 15, 22]. According to the notation introduced above, the localization error can be expressed as

$$\varepsilon = \sqrt{\sum_{i=1}^{N} \frac{\left\| \vec{x}_i - \vec{X}_i \right\|^2}{N}} \tag{7}$$

where, N is the number of localized devices for each network density. Table 2 summarizes the results obtained from the experimental tests described in the previous sections. Results are consistent with the analysis given above: the second localization method shows the worse performances, while the first is the method that provides the best results according to the proposed indicator. As expected, the third procedure performances are closer to that of the first method.

In order to complete the analysis, Table 3 supplies a view of the times needed by the localization procedures. Although being qualitative, this analysis can be useful to understand the user involvement and the carrying out facility of each procedure. Last column of Table 3 provides a resumptive evaluation of the procedures' complexity in terms of user involvement and set-up complexity. The evaluation is codified on three levels: high (H), medium (M), and low (L).

The set-up time is the time needed for the procedures' arrangement. The first procedure necessitates an a priori localization of all the reference artifact positions and a manual data entry. This operation may take up to some hours depending on the size of the network. The second and the third method do not need any particular a priori setting apart from the normal software and connections start-up.

The acquisition time is the time taken by the reference artifact positioning. It is obviously dependent on the number of repositioning (seven in our experiment). For each procedure, the artifact is kept still for about 30 sec in each position. We considered an artifact handling time between each acquisition of a further 30 sec for the second and the third procedures, and 1.5 min for the first method that requires an accurate and careful positioning.

The computational time needed by the algorithm to run, is small compared to the other times. The personal computer used for this evaluation is an AMD Athlon(tm) 64 Processor 3,500+2.21 GHz with 1.98 GB RAM.

5.5 Final considerations

From the analysis of the results presented in the previous section, it emerges that the first and the third method are able to provide performances even better than the current system performances on a single point measurement [2]. In particular, among all, the first is the method that performs better, but it requires a significant user involvement as well as a further metrology instrument able to localize the artifact positions. This method may be used in particular contexts in which a large scale metrology instrument is available and can be used just once to define the reference artifact positions.

The second method, on the other hand, requires modest user involvement, being free from any constraint. The drawback is the low performance level on sensor networks not uniformly distributed, as in the tested experimental case.

Among all the examined procedures, the third method seems to be the best compromise, not needing any particular set-up, but providing a sufficient performance level. On the contrary, this procedure may be inappropriate in case the reference support surface is not sufficiently flat.

According to the results provided in Section 5.4, it is difficult to derive which is in general the better procedure. The user exigencies and the working environment play an important role in this choice. If the user has the intention to

Table 3 Time required by each localization procedure. Data are referred to our experiments

	Time			Complexity	
	Set-up	Acquisition	Computation	User involvement	Set-up complexity
First method	2 h	14 min	<10 sec	H	H
Second method	1 min	7 min	<60 sec	M	L
Third method	1 min	7 min	<30 sec	M	L

L low, *M* medium, *H* high

keep the devices still in a particular configuration for a considerable time period, then the best procedure may be the first. In this case, it can be worthwhile to spend a longer set-up time in order to achieve a higher level of accuracy. On the other hand, if the accuracy is not a key aspect, then the other two procedures can guarantee a shorter set-up time and a minor user involvement.

Even if in-line with the present system performances, the results of these methods may still be improved together with the system improvement. Currently, an empirical error correction model is under investigation in order to compensate the most important error sources in the TDoA calculation.

6 Conclusions

This paper proposes and discusses three possible procedures to the problem of MScMS network localization. All of them have been tested in the industrial metrology laboratory of DISPEA—Politecnico di Torino. The three procedures use a reference artifact placed under the network devices in order to successfully identify their positions. The use of a reference artifact embedding several network devices allows to enhance network connectivity and at the same time to collect data in static conditions that can be analyzed and processed off-line.

The first method, which assumes to know the exact position of the reference artifact in each repositioning, is the one that showed the better localization results for each of the tested network densities. On the other hand, it requires a significant human intervention in order to a priori calculate the position of the reference artifact.

The second procedure overcomes the limit of the first, not requiring any a priori knowledge about the reference artifact positioning. Although being practical and fast, this procedure provided low results on the tested network layouts.

The third procedure is a compromise between the other two. It relies on the planarity assumption of the surface on which the reference artifact is placed, without claiming any a priori knowledge about the absolute position of the reference artifact. Besides keeping the positive features of the second method, the results of this procedure were close to those of the first localization method.

Nowadays, the three proposed methods still presents an accuracy level which may be improved. This is mainly due to the use of US transceivers [23]. Regarding the future, MScMS' accuracy could be improved using more refined ranging methods based on US pulse modulation [23]. This should be obtained with not very complex modifications to the current Cricket hardware and firmware. Another possible solution to improve devices' accuracy is the use of small directivity US transducers, such as cylindrical polyvinylidene fluoride film transducers [24–26]. The distance measurement error can be also reduced by perfecting of the already existing error compensation models.

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