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THE PROBLEM OF DISTRIBUTED WIRELESS SENSORS POSITIONING IN THE MOBILE SPATIAL COORDINATE MEASURING SYSTEM (MSCMS)

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ABSTRACT

Mobile Spatial coordinate Measuring System (MScMS) is a wireless-sensor-network based system developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA – Politecnico di Torino. It has been designed to perform simple and rapid indoor dimensional measurements of medium-large size objects (large scale metrology).

It is made up of three basic parts: a “constellation” of wireless devices (Crickets), a mobile probe, and a PC to store and elaborate data. Crickets and mobile probe use ultrasound (US) transceivers in order to evaluate mutual distances.

Each US device has a communication range limited by a cone of transmission within a nominal opening angle of about 170° and a maximum distance of no more than 8 m. The mobile probe location in the working volume is obtained by a trilateration, consequently it should communicate with at least 4 constellation devices at once.

The system makes it possible to calculate the position – in terms of spatial coordinates – of the object points “touched” by the probe. Acquired data are then available for different types of elaboration (determination of distances, curves or surfaces of measured objects).

During the system set-up, the constellation Crickets (beacons) are manually placed in the working volume (we define this operation as “positioning”). After that, their coordinates are determined as much precisely as possible (this operation is said “location”).

The positioning of constellation devices is one of the most critical aspects in the system set-up. In principle, Crickets can be arranged without restrictions all around the measured object. However, the number and position of network devices are strongly related to the dimensions and shape of both the measuring volume and the measured object.

The accuracy in the location of constellation devices is fundamental for the accuracy of the coordinates of the touched points during measurement operation. It is important to assure a full coverage of the space served by network devices by a proper alignment of US transmitters. For that reason, an ad hoc software “pre-processor” has been developed in order to help the operator in positioning and locating constellation devices in the working volume, according to the measuring space and the measured object dimensional characteristics.

The aim of the paper is to introduce and describe this computer-assisted approach. Some preliminary results of experimental tests carried out on the system prototype are also presented and discussed.

1. INTRODUCTION

In many industrial fields (for example, automotive, shipbuilding and aerospace industry) dimensional measurements of large size objects should be easily and rapidly taken [1-5]. The field of large-scale metrology can be defined as the metrology of large machines and structures that is to say “the metrology of objects in which the linear dimensions range from tens to hundreds of meters” [6]. There is an increasing trend for accurate measurement of length, in particular, the 3D coordinate metrology at length scales of 5 m to 100 m has become a routine requirement in industries such as aircraft and ship construction [7].

Nowadays, the problem can be handled using many metrological systems, based on different technologies (optical, mechanical, electromagnetic etc..). These systems are more or less adequate, depending on measuring conditions, user’s experience and skill, cost, accuracy, portability etc.. In general for measuring medium-large size objects, portable systems can be preferred to fixed ones. Transferring the measuring system to the measured object place is often more practical than the vice-versa [1].

This paper analyzes the Mobile Spatial coordinate Measuring System (MScMS), which has been developed at the industrial metrology and quality engineering laboratory of DISPEA – Politecnico di Torino [8].

It is a wireless system, designed to perform dimensional measurements of medium-large size objects (for example, longerons of railway vehicles, airplane wings, fuselages etc..). These objects can hardly be measured by traditional coordinate measurement systems, such as Coordinate Measurement Machines (CMMs), because of their limited working volume [1,9]. MScMS working principle is very similar to that of well-known NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System) [10]. The main difference is that MScMS is based on ultrasound (US) technology to evaluate spatial distances, instead of radiofrequency (RF). MScMS is easily adaptable to different measuring environments and does not require complex procedures for installation, start-up or calibration [8].

The purpose of this paper is to describe the computer-assisted tool implemented in the MScMS in order to help the operator in setting up the system and carrying out the measurements according to the device technological limitations, the working volume and the dimensional characteristics of the measured object.

2. MSCMS DESCRIPTION

2.1. MScMS technological and operating features

MScMS prototype is made up of three main components (see Fig. 1) [7,8]:

- a constellation (network) of wireless devices, arranged around the working area;
- a measuring probe, communicating with constellation devices to obtain the coordinates of the touched points;
- a computing system, receiving data from the measuring probe and processing them, in order to evaluate measured object geometrical features.

Wireless devices composing the MScMS prototype − known as “Crickets” − are developed by the Massachusetts Institute of Technology (MIT) and produced by Crossbow. Being quite small, light and potentially cheap, they fit to obtain a wide range of different network configurations [11,12].

The measuring probe is a mobile system equipped with two wireless devices (*A* and *B*), a tip to touch the surface points of the measured objects and a trigger to activate data acquisition (see Fig. 2). Given the geometrical characteristics of the mobile probe, the tip coordinates can be univocally determined by means of the spatial coordinates of the two probe Crickets [7,8].

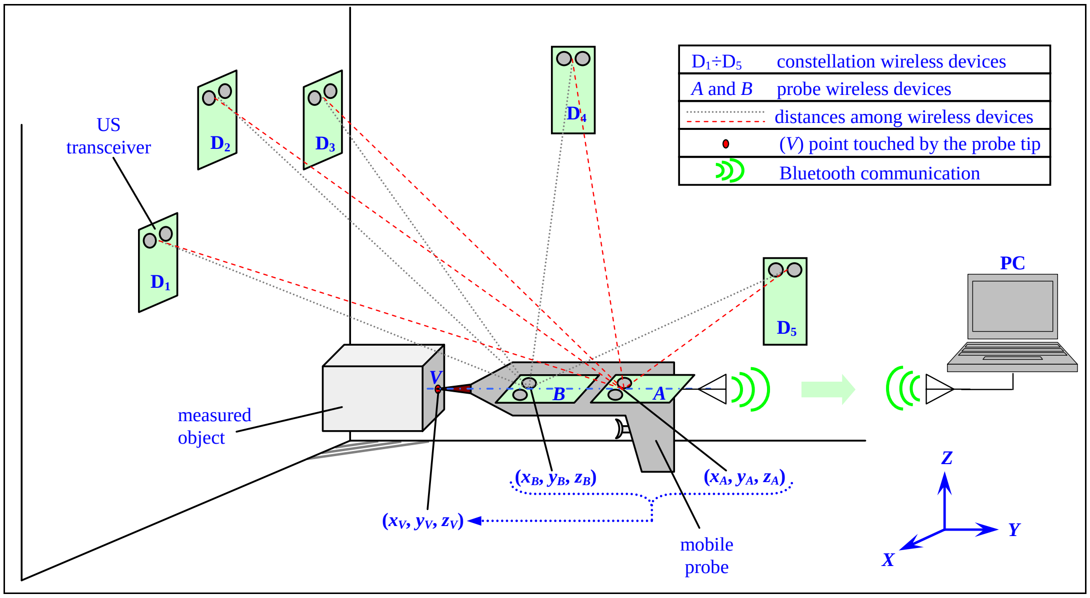

Fig. 1 – MScMS working scheme.

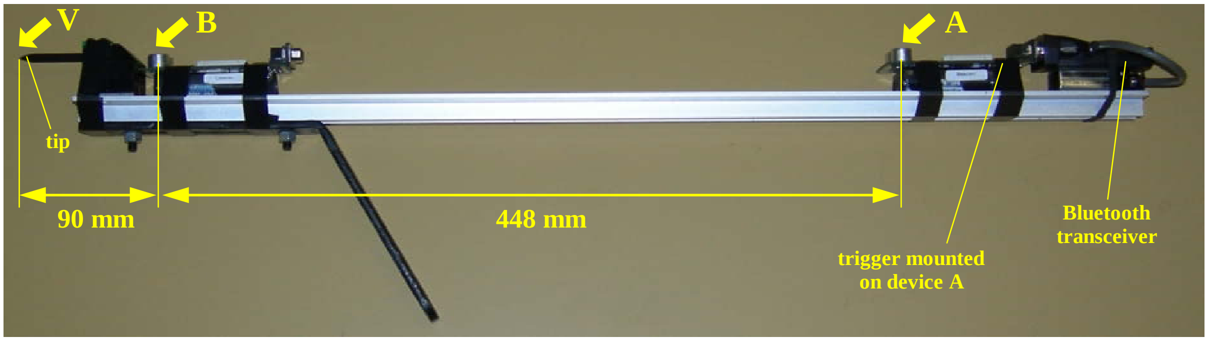

Fig. 2 – Mobile probe prototype. The distance between the two probe devices is a construction parameter defined during the probe design phase.

All the Crickets have RF and US transceivers. Transmitting signals to each other, they repeatedly communicate and calculate their mutual distances with a technique known as TDoA (Time Difference of Arrival) [13]. The RF communication makes each Cricket rapidly know the distances among other devices. A Bluetooth transmitter is connected to one of the two probe Crickets to send this distance information to the PC, which is equipped with an ad hoc software.

In practical terms, measurements consist of three phases:

- the mobile probe is used to touch the desired points from the part surface (Fig. 1);
- the trigger is pulled and data are sent via Bluetooth to the PC;
- the Cartesian coordinates of the points are calculated by software using specific algorithms, that eventually identify the geometrical features of the measured object [8]. This phase can be divided in three steps.
  - Spatial location of each probe Cricket, is achieved using a trilateration technique. To uniquely determine the relative location of a point on a 3D space, at least 4 reference points are needed [14-17]. Actually, each mobile probe Cricket locates itself using the measured distance from a minimum of 4 constellation Crickets, with a priori known locations. All information needed for the location is sent to a PC, for a centralized computing.
  - As shown in Fig. 2 , since the probe tip (*V*) lies on the same line of devices *A* and *B*, the location of the point touched by the probe tip can be univocally determined knowing the coordinates of points $A \equiv (x_A, y_A, z_A)$ and $B \equiv (x_B, y_B, z_B)$ and the probe geometrical features (distances d_{V-B} and d_{B-A}).
  - Likewise CMMs, MScMS makes it possible to determine the geometrical features of objects (circumferences, cylinders, plans, cones, spheres, etc.), on the basis of a set of measured surface points gathered from the mobile-probe, using classical optimization algorithms [18].

Before starting measurements, the location of constellation Crickets has to be determined. This phase should be fast and automated as much as possible to prevent any conflict with the system adaptability to different working places. In order to minimize human involvement, a method for a semiautomatic location has been implemented. It is important to remark that accuracy in the location of constellation nodes is fundamental for accuracy for the next mobile probe location [19].

2.2. Spatial location of probe devices: the mass-spring algorithm

Constellation devices (Crickets) operate as reference points (beacons) for the mobile probe. Spatial location of probe devices is made up by a specific procedure using a "trilateration" technique [8,20,21].

In general, a trilateration problem can be formulated as follows. Given a set of N nodes with known coordinates (x_i, y_i, z_i, where $i = 1 \ldots N$) and a set of measured distances d_{M_i} from a generic point $P \equiv (x_P, y_P, z_P)$, the following system of non-linear equations needs to be solved to calculate the unknown coordinates (x_P, y_P, z_P) of P:

$$\begin{bmatrix} (x_1-x_P)^2+(y_1-y_P)^2+(z_1-z_P)^2 \\ (x_2-x_P)^2+(y_2-y_P)^2+(z_2-z_P)^2 \\ \vdots \\ (x_N-x_P)^2+(y_N-y_P)^2+(z_N-z_P)^2 \end{bmatrix} = \begin{bmatrix} d_{M_1}^2 \\ d_{M_2}^2 \\ \vdots \\ d_{M_N}^2 \end{bmatrix} \qquad (1)$$

If this trilateration problem is over defined (4 or more reference points are available), it can be solved using a least-mean squares approach [22]. The position of each unknown node can be estimated by performing the iterative minimization of the following Error Function [8]:

$$EF(\vec{x}_P) \equiv \frac{\sum_{i=1}^{N} (d_{Ci} - d_{Mi})^2}{N} \qquad (2)$$

being:

N, the number of a-priori known reference points (vectors $\vec{x}_i = (x_i, y_i, z_i)$, $i = 1...N$);

$\vec{x}_P = (x_P, y_P, z_P)$, the point P unknown coordinates in the location space $\xi \subseteq \Re^3$;

d_{M_i}, the measured distances between the *i*-th reference point and P;

d_{C_i}, the Euclidean distance between the *i*-th reference point and P:

$$d_{C_i} = \sqrt{(x_P - x_i)^2 + (y_P - y_i)^2 + (z_P - z_i)^2} \qquad (3)$$

The problem of finding a minimum for the function $EF(\vec{x}_P)$ can be seen as the problem of finding the point of equilibrium for a mass-spring system (lowest potential energy) in which a unitary mass is associated to each network node [14,23].

Being based upon US technology, MScMS is sensible to many influencing factors. US signals may be diffracted and reflected by obstacles interposed between two devices, external uncontrolled events (key jingling, neon blinking, etc...) can become undesirable US wave sources, manual positioning procedures can give incomplete “coverage” of the measuring volume and even locating algorithms can lead to non-acceptable solutions. These and other potential causes of accidental measurement errors must be kept under control to assure a proper level of accuracy.

With the aim of protecting the system from these external influencing factors, MScMS implements a statistical test for on-line diagnostics of measurements based on error function [24]. For every localised point P an acceptance threshold is defined: if $EF(\vec{x}_P)$ is below (or equal to) this threshold, the location result is accepted; if $EF(\vec{x}_P)$ exceeds it, the location is considered unreliable, hence it is rejected and the operator is asked to perform another measurement, or – if needed – to enhance the beacon constellation.

2.3. Semi-automatic location of the constellation

Once the constellation Crickets (beacons) are positioned in the working volume (we define this operation as “positioning”), it is necessary to determine their coordinates as much precisely as possible (this operation is said “location”).

To locate Cricket devices, a semi-automatic method has been implemented.

The used technique consists in touching different reference points within the measuring area. Special artifacts can be used instead of reference points. It is reliable to select points that are easily reachable and easy to be manually located in a reference coordinate system. For example, points laying on objects with a simple and known geometry (like parallelepiped vertexes). Spatial coordinates (x_i, y_i, z_i) of the distributed constellation devices are the unknown parameters of the problem. Location of each constellation device is incrementally performed using a trilateration [15]. The acquisition procedure is driven by an ad hoc software routine. Calculations are automatically performed by the central PC.

A similar approach is also implemented for estimating the spatial orientation of Cricket transceivers. This information is essential for assessing the working volume “coverage”.

3. POSITIONING OF CONSTELLATION DEVICES

In principle, Crickets should be positioned without restrictions all around the measured object. However, the number and position of network devices are strongly related to the dimensions and shape both of the measuring volume and of the measured object, as well as the technological features (transmission cone and connectivity range) of the Cricket devices.

The factors of influence in constellation device positioning can be classified into two categories:

- “endogenous” constraints: related to system technology;
- “exogenous” constraints: related to environmental factors.

3.1. “Endogenous” constraints

Trilateration is the approach used for locating the two probe Crickets. That means both of them must be connected with at least 4 constellation beacons at the same time [15-17, 25]. As a consequence, every region of the measuring space must be “covered” by at least 4 beacons.

This condition, due to the system working principle, is strictly correlated to other technical constraints:

- transceiver “misalignment angle” (γ),
- maximum distance of communication (“communication range”, h),
- battery charge level,
- US transceiver geometrical features.

The full coverage of a location served by a Cricket beacon is conditioned by the reciprocal alignment and distance of the ultrasonic transmitters and receivers.

Figure 3 shows the radiation pattern of the ultrasonic transmitter of a Cricket. This is shown in (r, ϑ) polar coordinates, where r is the signal strength in dB and ϑ is the tilt angle from the front of the ultrasonic transmitter.

The radiation pattern shows that the direction in which the ultrasound transmitter has the maximum signal strength is 0°, while the signal strength drops to 1% (-20 dB) of the maximum value at about ±85° away from the 0° direction.

This determines a cone of transmission characterized by an opening angle of 170°. Assuming that the receiver has the same reception cone of 170°, it must be oriented so that the transmitter is included inside this cone.

Signal attenuation is also related to the distance from the transmitter. When this distance exceeds a fixed limit, the signal strength becomes so low that it is not possible to detect it correctly. We observed that, along the direction in which the ultrasound transmitter faces, this limit is about 8 m. It decreases to 4 m at ±45° away from the 0° direction.

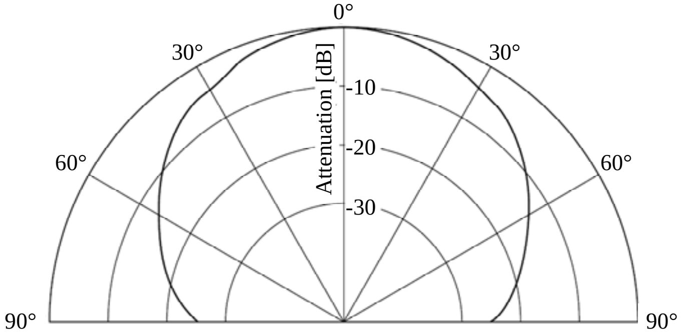

Fig. 3 – The radiation pattern (r,ϑ) of the Cricket ultrasonic transducer over signal orientation (ϑ). Signal strength drops along direction that are away from the normal direction to the transducer surface.

In general, we observed that the strength of the signal caught by the receiver strongly depends on the reciprocal position and orientation of transmitter and receiver.

For that reason, in order to identify a real communication volume in which a complete coverage is guaranteed, we conventionally define a conical portion of space ("communication cone") with the vertex coinciding with the center of the transmitter, and a "communication range" (h) and a "misalignment angle" (γ) defined as follows (see Fig. 4).

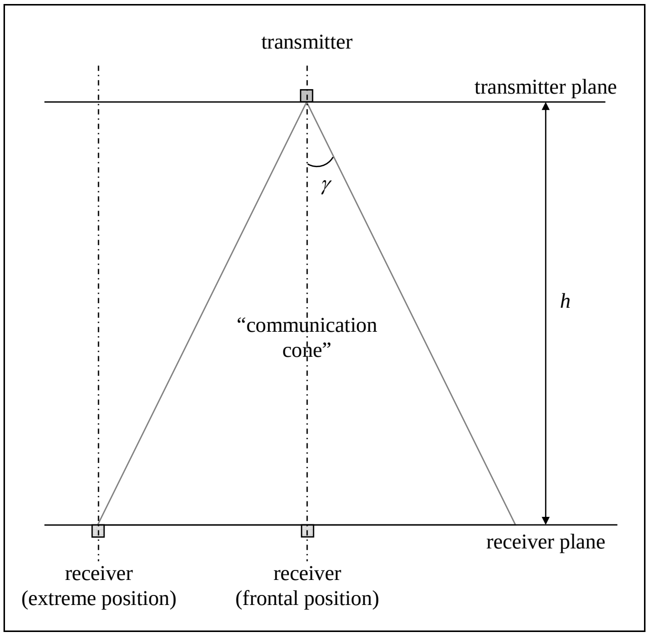

Fig. 4 – Scheme of the "communication cone" in which the US connectivity between transmitter and receiver is guaranteed.

Transmitter and receiver are positioned in two parallel planes, facing each other. The distance between these two planes is the "communication range" (h). The "misalignment angle" (γ) is defined by the maximum angle (in relation to the direction in which the transmitter faces) under which the communication between transmitter and receiver is maintained when the receiver is moved in any direction over the plane it lies without changing its initial orientation.

A series of preliminary tests carried out on a sample of Cricket devices produced the results reported in Tab. 1 (see Fig. 5).

h [m]	γ [°]
0.20	70
0.50	63
1.00	56
2.00	46
3.00	35
4.00	28
5.00	22
6.00	17
6.50	10

Tab. 1 – Results of preliminary tests conducted on a sample of Cricket devices in order to evaluate "misalignment angle" (γ) versus "communication range" (h).

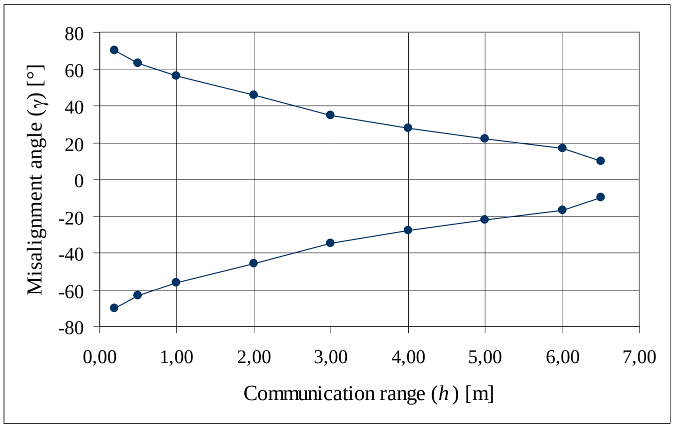

Fig. 5 – "Misalignment angle" (γ) versus "communication range" (h). Graph of data reported in Tab. 1.

In general, a practical solution to resolve the connectivity problem is mounting the network devices on the ceiling or at the top of the measuring area, as shown in Fig. 6, orienting the probe Crickets upwards as much as possible.

In this condition, we can assume as "maximum communication range" (h_{MAX}) the distance between the ceiling and the floor of the laboratory (or the reference plane at the maximum distance from the ceiling at which we are planning to work). The corresponding “misalignment angle” (see Tab. 1) is called “minimum misalignment angle” (γ_{MIN}).

We also experimentally observed that transducer battery charge level can be a parameter conditioning distance measurement. However, a significant effect appears only when the charge level is very low (close to run-down), usually batteries are replaced before this happens.

The last constraints we consider are related to the probe geometry (see Fig. 2). The distance between the two devices mounted on it, and the tip length are two basic elements for determining the extension of the connectivity areas for a given measured object (see Fig. 6). The constellation must ensure the full coverage of the areas where the probe devices are positioned during measuring operation. This condition is not required for the tip. This results in an evident advantage when measuring complex surfaces, characterized by hollows or shady areas. In these cases special tips with particular geometry can be used in order to touch hidden points [1].

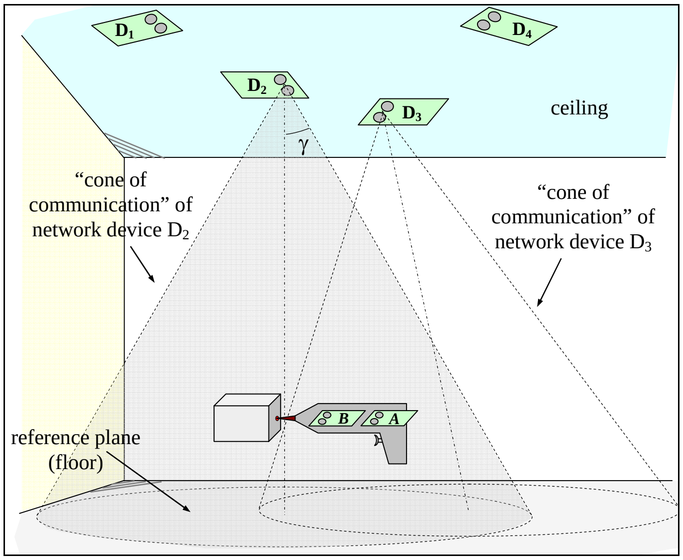

Fig. 6 – Representation scheme of the overlapping of the "communication cones" of US sensors when constellation devices are positioned on the ceiling.

3.2. “Exogenous” constraints

Many other constraints conditioning the constellation set up and the measurement procedure depend on environmental factors. Among these we consider:

- the dimension and shape of the laboratory in which the measurement are performed,
- the dimension and shape of the measured object,
- the aim of the measurement.

Due to its network structure, MScMS works correctly also in laboratories with non-convex planimetry. Usually, beacons devices are placed on the ceiling, and – if needed – on the walls and the floor of the building. In this way, in absence of interposed obstacles, the whole working volume can be covered. In specific cases, in order to “floodlight” also shady areas, special trestles can be used as supports for beacons positioned inside the working volume.

The dimension and shape of the measured object are important elements in determining:

- the minimum working distance (h_{MIN}) between constellation beacons and probe devices: the more the measured object is high, the more this distance is reduced;
- the presence of shady areas due to signal hiding,
- the presence of shady areas due to hollows or complex geometries (concave surfaces, marked cambers, discontinuities, etc.).

All these aspects influence the beacon positioning (ceiling, walls, trestles, etc.), their number and the probe geometry (tip length, tip geometry, etc.). In the following we suppose to work with a probe having a fixed geometry (see Fig. 2), and measure objects characterized by reasonably smooth surfaces (for example, airplane wings, fuselages, ship hull, etc.).

The aim of the measurement is also determinant in the constellation positioning. If the goal is to reproduce the geometry of a given object (such as, for example, in reverse-engineering), the whole object surface must be scanned. Hence the probe should be able to measure a high quantity of points uniformly distributed all over this surface. On the contrary, if the goal is to control only some specific geometrical features, a limited number of points must be covered.

3.3. MScMS sizing (beacon density)

Summing up the working hypotheses described in the previous sections, the beacon constellation should be planned in agreement with the following assumption:

- positioning of beacons on the ceiling of the laboratory,
- fixing the “maximum communication range” (h_{MAX}) and the corresponding “minimum misalignment angle” (γ_{MIN}) (see Tab. 1),
- upwards orientation of the probe Crickets,
- “floodlighting” only of zones where probe Crickets will be positioned during the measurement (according to the piece shape, the probe geometry and the measurement strategy).

Under these conditions, we may introduce the concept of beacon “density”. It is defined as the number of constellation devices we should place per unit of surface on the ceiling, in order to correctly “floodlight” a given region of an horizontal plane positioned at a distance h from the ceiling (see Fig. 7).

For beacon positioning a square mesh grid is adopted [26,27]. The covered area is determined by the intersection of the horizontal plane and the cones generated by the constellation device. Each cone intersecting the plane generates a circle on it (see Figs. 7 and 8).

The extension of the covered area is a function of the distance from the ceiling h .

The more this distance is large the more the covered area is wide and the number of overlapping communication cones is high (see Fig. 7).

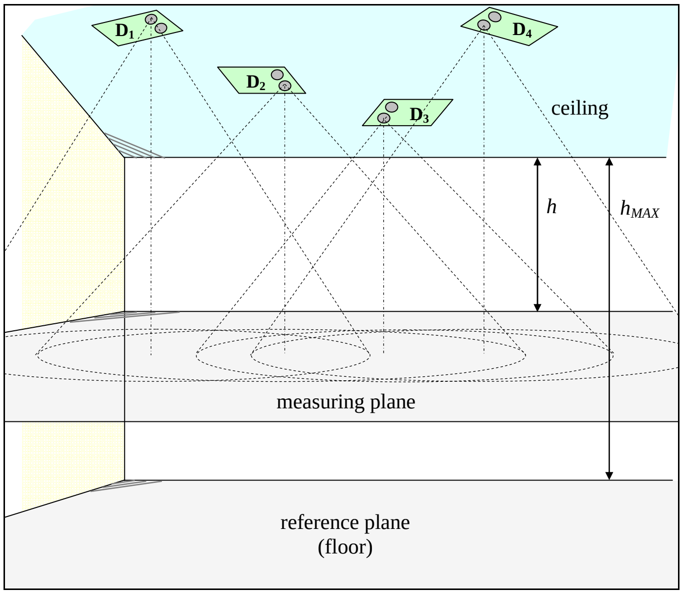

Fig. 7 – Schematic representation of the concept of beacon "density".

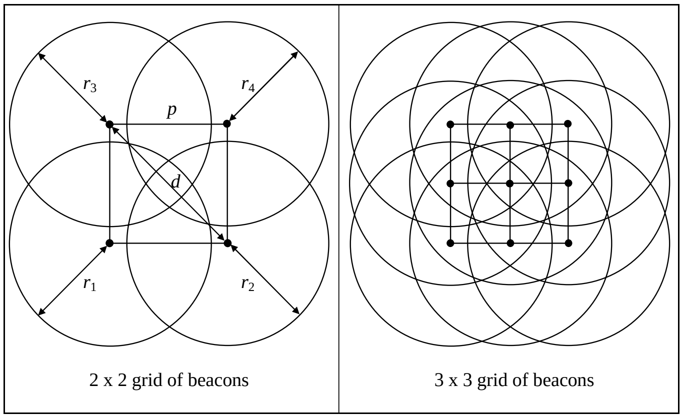

Fig. 8 – Covered areas versus beacon "density" at a given distance h from the ceiling.

If we refer to Fig. 8, we observe that a circle centred on a corner of the mesh overlaps the opposite corner if the following condition is verified:

$$d \le r_h \qquad (4)$$

Where r_h is the radius of the circle (on the plane at a distance h from the ceiling), and d is the diagonal of the square mesh of the beacon grid.

If we define as p (pitch) the minimum distance between two nodes (beacons) of the grid, the diagonal of the mesh is given by:

$$d = \sqrt{2} \cdot p \qquad (5)$$

and, considering that all the circles generated on the plane have the same extension ($r_h = r_1 = r_2 = r_3 = r_4 = \ldots$), for all the nodes of the mesh, Eq. (4) can be rewritten as follows:

$$\sqrt{2} \cdot p \le r_h \qquad (6)$$

Knowing the "misalignment angle" (γ) corresponding to distance h, on the bases of simple geometrical considerations (see Fig. 4), we can obtain the following relationship between the grid pitch and the distance from the ceiling:

$$\sqrt{2} \cdot p \le h \cdot tg(\gamma) \qquad (7)$$

which can be rewritten as follows:

$$p \le \frac{1}{\sqrt{2}} \cdot h \cdot tg(\gamma) \qquad (8)$$

Hence, if a given area positioned on a plane at a distance h from the ceiling must be covered by at least 4 beacons at the same time, we must plan a square mesh grid (see Fig. 8) with a maximum pitch size defined by Eq. (8).

According to this conclusion, if the measuring volume ranges from a minimum distance h_{MIN} to a maximum distance h_{MAX}, a suitable value of p can be estimated by the following conservative procedure:

- definition of the "maximum communication range" h_{MAX},
- individuation of the corresponding "minimum misalignment angle" γ_{MIN} (see Tab. 1),
- definition of the minimum distance h_{MIN},
- definition of the maximum pitch size p_{MAX} by applying Eq. (8) to these parameters:

$$p_{MAX} = \frac{1}{\sqrt{2}} \cdot h_{MIN} \cdot tg(\gamma_{MIN}) \qquad (9)$$

Due to the behaviour of γ versus h (see Fig. 5), the complete coverage of the given volume is guaranteed.

For example, if we are working in a range of 2÷4 m from the ceiling, we should assume $h_{MIN} = 2$ m, $h_{MAX} = 4$ m, and the corresponding $\gamma_{MIN} = 28°$ (see Tab. 1). By applying Eq. (9), we obtain a maximum pitch $p_{MAX} = 0.75$ m. That means that the square grid patch should not be greater than 0.75 m.

4. SOFTWARE-ASSISTED PROCEDURE FOR BEACON POSITIONING

In order to help the operator in positioning constellation devices in the working volume according to the measuring conditions, MScMs implements a software tool ("pre-processor") based on a step-by-step semiautomatic procedure. Similar approaches are proposed for different contexts by Bulusu et al. [27].

This procedure is based on an incremental approach which entails a first definition of the beacon grid starting from the geometrical features of the measuring volume and the measured object, as well as the measuring strategy. The obtained constellation can be enriched in order to "floodlight" the shady zones that might remain. This operation is conducted by the operator through an apposite graphical interface. The obtained configuration is tested by a measurement simulation routine. If needed, once the constellation is positioned it can be further enriched during both the calibration/location operations and the measurement process.

In detail, the whole procedure can be subdivided into two phases:

- constellation positioning,
- constellation enhancement.

4.1. Constellation positioning

This first phase consists in the grid design and beacon positioning. It is characterized by the following steps:

Step 1: The operator inserts the input parameters:
  - laboratory geometry,
  - object geometry,
  - laboratory parameterization (definition of the coordinates reference system),
  - object position in the parameterized space,
  - measurement strategy (zone to be measured on the object surface).

Step 2: The software evaluates beacon density and, starting from a node (origin) defined by the operator, defines the coordinates of the other grid nodes. This procedure can be complemented by specific algorithms for creating special meshes, enriching or reducing grid nodes [26-28].

Step 3: The software outlines the shady zones.

Step 4: The operator (using software simulation) enriches the constellation introducing additional beacons in the measuring space (position and orientation are defined).

Step 5: The software outlines the remaining shady zones. If they do not hinder the measurement strategy, the designed configuration is accepted.

Step 6: The operator places beacons into the established positions in the measuring space. This operation can be carried out with moderate precision. External devices (laser rules, laser levels, etc.) are often used for roughly verifying beacon coordinates and orientation.

4.2. Constellation enhancement

After the first phase, the operator proceeds with the implementation of the semi-automatic location procedure (see Section 2.3). At this point, the system is ready for measurement.

The second phase is applied every time an enrichment or extension of the constellation is required (this can occur during both the location and measurement processes).

It consists in the following steps:

Step 1: During the measuring operations, the operator notices that a given zone is not correctly covered. MScMS diagnostic software warns of the absence of connectivity (less then 4 beacons are detected), or the presence of signal corruption (error function $EF(\vec{x}_P)$ test).

Step 2: The operator introduces additional beacons in the measuring space (position and orientation are defined).

Step 3: The software drives the operator during the procedure of location of the additional beacon(s).

Step 4: Specific algorithms for increasing beacon density can be automatically implemented in order to reduce the location error ($EF(\vec{x}_P)$ diagnostics), or for decreasing it in zones where the measurement are not performed [26-28].

5. PRELIMINARY EXPERIMENTAL REULTS

A preliminary prototype of MScMS has been set-up and tested at the Industrial Metrology and Quality Engineering Laboratory of DISPEA – Politecnico di Torino, with the purpose of verifying system feasibility and performances.

A set of "covering tests" have been performed in order to validate the positioning procedure.

In a working volume of about 55 m^3 (width = 4,00 m, length = 6,00 m, height = 2,30 m) three runs have been conducted with different positioning parameters. During each run, the full coverage has been verified for different sets of point randomly distributed on the border and inside the working volume (see Fig. 9).

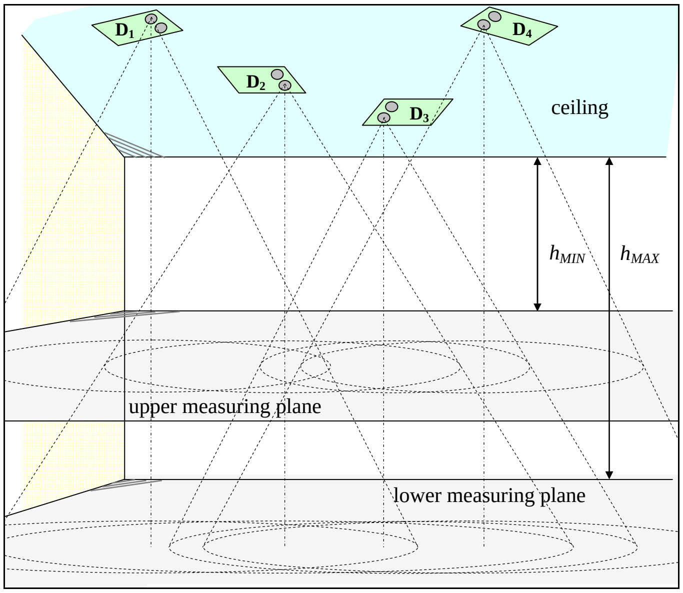

Fig. 9 – Schematic representation of the working volume for the “covering test”.

Test parameters are reported in Tab. 2. p is the pitch actually used, A is the covered area, n_B is the number of testing points on the border of the measuring volume, and n_V is the number of testing points inside the measuring volume.

	1st run	2nd run	3rd run
h_{MIN} [m]	0.80	1.30	1.80
h_{MAX} [m]	2.00	2.30	2.30
γ_{MIN} [°]	46	43	46
p_{MAX} [m]	0.59	0.86	1.19
p [m]	0.50	0.85	1.20
A [m^2]	4 x 4	4 x 4	4 x 5
n_B	27	27	27
n_V	27	27	27

Tab. 2 – “Covering test” parameters.

Tests have shown full coverage of the points on the volume borders (with, at least, 4 beacons at the same time, in the extreme zones) and inside it (with more than 5 beacons at the same time, for each point). A specific “stability test” has shown that the level of coverage is stable over time in the whole working volume.

Owing to the fact that the procedure for calculation of p_{MAX} is conservative, we observed that the covering is guaranteed also for values of h smaller than h_{MIN}. For all the three runs, we verified that, in certain zones, the effective value of h_{MIN} could be even reduced by about 0.30 m.

A series of preliminary repeatability and reproducibility tests confirms the potentiality of the system [7, 29, 30]. However, they show that much work still has to be done in order to reduce noise and location effects, which are the main causes of inaccuracy [7].

As shown, the most critical aspects of the whole measuring system are due to US sensors. With the aim of improving system accuracy the future work will be directed to [8]:

- the reduction of physical dimensions of US transceivers,
- the optimization of transceiver electronics (for example, use of amplitude threshold detection at receivers),
- the limitation of noises affecting US signals,
- the control of the environmental conditions affecting sound propagation [31].

Furthermore, specific algorithms for automatic construction of the network constellation will be studied and tested in order to reduce the location error (i.e. the $EF(\vec{x}_P)$) and, as a consequence, the measurement uncertainty, during both the constellation locating phase and the measuring phase.

6. CONCLUSIONS

MScMS measuring system can be considered as complementary to CMMs. It is portable, not expensive, and suitable for measuring large-size objects (uneasy on conventional CMMs).

MScMS is adaptable to different working environments, and does not require long installation or start-up times. Before performing measurements, constellation devices must be positioned around the measuring area according the working volume and measured object dimensional characteristics, as well as the measuring strategy. After that they can be rapidly located using a semi-automatic procedure supported by MScMS software.

The accuracy in the location of constellation devices is fundamental for the accuracy during measurement process.

It is important to assure a full coverage of the space served by network devices by a proper alignment of US transmitters. For that reason, the system is supported by an ad hoc software to drive user through positioning and locating constellation devices in the working volume, according to the measuring space and measured object dimensional characteristics.

The approach implemented by this software is based on general considerations. It can be applied to other similar systems, such as, for example, i-GPS, Hi-Ball, etc... [32,33].

Today, MScMS Achilles’ heel is represented by its low accuracy, due to the use of ultrasound transceivers (non punctiform dimension, speed of sound dependence on temperature etc..). As research perspectives, all factors affecting system precision will be analyzed and improved in detail, in order to reduce their effect.

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