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ORIGINAL ARTICLE

Mobile spatial coordinate measuring system (MScMS) and CMMs: a structured comparison

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Abstract In many branches of industry, most of manufacturing efforts are directed toward producing objects of specific forms and dimensions. Dimensional measurement is an important part of the production cycle, to check products compliance with specifications. For this, many substantial improvements in the existing technologies have been made, and new measuring systems have been introduced. This paper briefly introduces a recent measuring system—*mobile spatial coordinate measuring system* (MScMS)—which is suitable for performing dimensional measurements of large-size objects (dimension on the order of tens of meters). MScMS, thanks to its distributed wireless sensor network nature, is portable and can be easily arranged around the measured object. Furthermore, it does not require complex setup operations before being ready to perform measurements. After describing how the system works, we will compare it with well-tested and widespread instruments such as traditional coordinate measuring machines (CMMs), showing analogies and differences. The comparison is structured on the basis of different criteria, which are analyzed in detail in the first part of the paper. Although being able to perform similar measurements, CMMs and MScMS are different in technological features. CMMs are able to achieve higher level of accuracy, while MScMS is more flexible, cheap, and can be important to simplify the current measuring practices within large-scale industrial metrology. It can be concluded that these systems can easily coexist, as each system is suitable for specific applications.

Keywords Mobile measuring system · Dimensional metrology · Large-scale metrology · Wireless sensor network · Coordinate measuring machine (CMM)

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1 Introduction

This paper arises from the research activity developed at the industrial metrology and quality engineering laboratory of Department of Production Systems and Business Economics—Politecnico di Torino, on a new system prototype for dimensional measurement called *mobile spatial coordinate measuring system* (MScMS) [8]. MScMS determines dimensional features of large-size objects and has been designed to overcome some limits shown by other widespread measuring systems used nowadays, such as *coordinate measuring machines* (CMMs), theodolites/tacheometers, photogrammetry equipments, global positioning system (GPS)-based systems, and laser-trackers [2, 22].

Basing on a distributed sensor networks structure, MScMS can accomplish rapid dimensional measurements in a wide range of indoor operating environments. It consists of distributed wireless devices communicating with each other through radiofrequency (RF) and ultrasound (US) transceivers. This frame makes the system easy to handle and to move and gives the possibility of placing its components freely around the workpiece. Wireless devices known as "Crickets" are developed by the Massachusetts Institute of Technology. Being quite small, light, and potentially cheap (if mass produced), they fit to obtain a wide range of different network configurations [21, 1].

These features make the new system suitable for particular types of measurement, which cannot be carried out, for example, by conventional CMMs. Typical is the case of large-size objects that are unable to be transferred to the measuring system area (because of their dimensions or other logistical constraints) and thus require the measuring system to be moved to them. This aspect will be emphasized below.

The goal of this paper is comparing MScMS with well-tested and popular instruments such as classical CMMs. MScMS and classical CMMs have many common aspects. For both the systems, measurements are taken touching few points on the objects surface with a probe tip. Furthermore, points are defined on a Cartesian coordinate system and then coordinates are processed by specific algorithms, to determine geometrical features, angles, other objects shapes etc. On the other hand, MScMS and CMMs have many different characteristics: their physical structure, size, cost, etc. This comparison will be carried out according to a structured set of evaluation criteria.

The article is organized in five sections. Section 2 focuses on the new paradigm of the distributed measuring systems within large-scale metrology. Section 3 provides a brief introduction to the MScMS technological features and *modus operandi*. Section 4 refers to CMMs main characteristics. Section 5 illustrates the criteria for comparing MScMS and classical CMMs. Section 6 shows the results of this comparison. Finally, the future direction of the research activity is outlined.

2 The new paradigm of the distributed measuring systems

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” [23]. There is an increasing trend for accurate measurement of length, in particular, the 3D coordinate metrology at length scales of 5 to 100 m has become a routine requirement in industries such as aircraft and ship construction. There have been significant advances across a broad range of technologies, including laser interferometery, absolute distance metrology, very high density charge-coupled device cameras, and so on. In this paper, for the purpose of discussion, we can classify the measurement systems into *centralized* and *distributed* systems. In the case of centralized instruments, measurements may independently arise by a single stand-alone unit, which is a centralized complete system (i.e., a CMM, a laser scanner or a laser tracker), while distributed instruments are made of two or more distributed units (like MScMS). In general, distributed measurement systems, due to their nature, are portable and can be easily transferred around the area where the measurand is. Furthermore, compared to centralized systems, distributed systems may cover larger measuring areas, with no need for repositioning the instrumentation devices around the measured object [12].

MScMS is a modular, measuring system for large volume objects. Even if, at present time, MScMS is still a prototype and needs to be further developed, the system enables factory-wide location of multiple objects, applicable in manufacturing and assembly. Mainly, it can be used by aerospace manufacturers, but can also be adopted by automotive and industrial manufacturers both for positioning and tracking applications. As MScMS main components are a number of wireless devices distributed around the measuring area, this not rigidly connected frame makes the system easy to handle and to move and gives the possibility of placing its components freely around the workpiece, adapting to the environment and not requiring particular facilities. Consequently, MScMS is suitable for particular types of measurement that cannot be carried out by traditional frame instruments, like conventional CMMs, which are bulky and cannot be moved. The introduction of distributed measuring systems will probably have important effects on simplifying the current measuring practices within large-scale industrial metrology [15]. This tendency is confirmed by other recent distributed measuring systems based on laser and optical technology: the indoor GPS and the portable CMM [25, 28, 29].

3 MScMS technological and management features

The MScMS prototype is constituted by three main components:

- 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 *control and computing system*, able to receive and process data obtained by the measuring probe, to evaluate objects geometrical features.

The measuring probe is a mobile system constituted by two wireless devices (A and B) identical to the constellation devices placed around the working area, a tip (V) to touch the points on the surface of the measured objects and a trigger (see Fig. 1). The probe tip lies on the same line of wireless devices A and B, and the probe geometry is a priori known. In particular, as distances $d_{A\text{–}V}$ and $d_{A\text{–}B}$ are used for the probe location (described in Section 5.3), they were accurately calibrated using a CMM.

All the MScMS wireless devices (Crickets) have RF and US transceivers, which enable the communication. Crickets repeatedly calculate their mutual distances with a technique

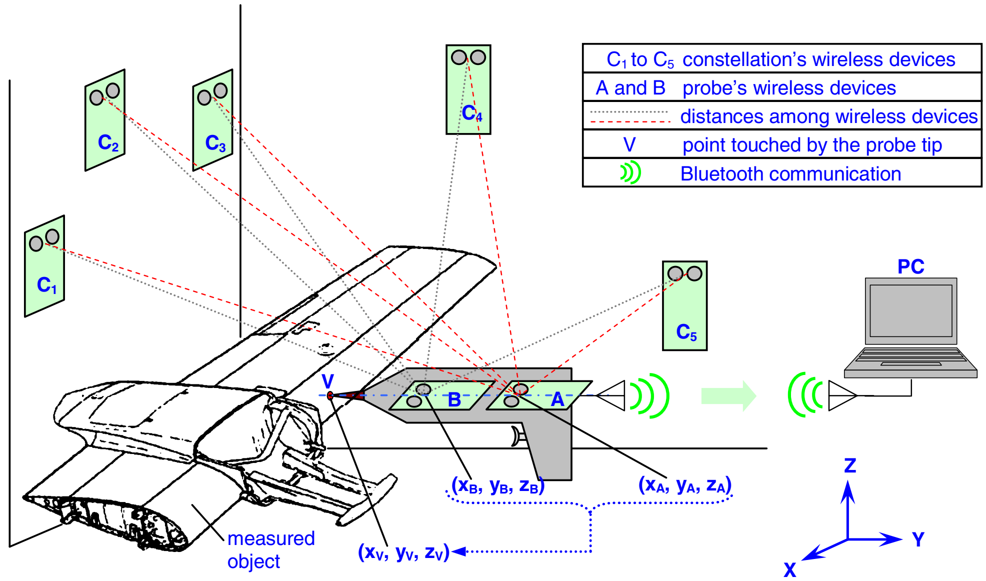

Fig. 1 MScMS representation scheme

known as TDoA (*time difference of arrival*) [11]. The RF communication makes each Cricket rapidly know the distances among other devices. A *bluetooth* transmitter with communication range up to 100 m is connected to one of the two probe's Crickets, so as to send these distances to a personal (PC) equipped with an ad hoc software.

In practical terms, measurements consist of three phases: (1) The mobile probe is used to touch the points of interest on the workpiece (see Fig. 2); (2) the trigger is pulled, and data are sent via *bluetooth* to a PC; (3) the software calculates the Cartesian coordinates of the touched points (the procedure is explained in Sections 5.3), and by specific, algorithms identifies the geometrical features of the measured object [8, 17].

As mentioned above, due to its distributed components nature, MScMS is similar to another recent measuring instrument: the indoor GPS. The two systems have a constellation of distributed devices acting as reference points for the location of a wireless measuring probe. On the other hand, MScMS and indoor GPS have many different characteristics, such as technology, measuring principle, cost, and metrological performances, which affect several factors within the systems, including system presetting, startup, and measurement execution. All these aspects are discussed in detail in [15, 16].

4 CMMs main characteristics

The CMMs are complex mechanical devices to determine the coordinates of the points touched by an electromechanical probe. CMMs can be controlled either manually or by computer numerical control (CNC) systems; they are available in a wide range of sizes and designs, offering a

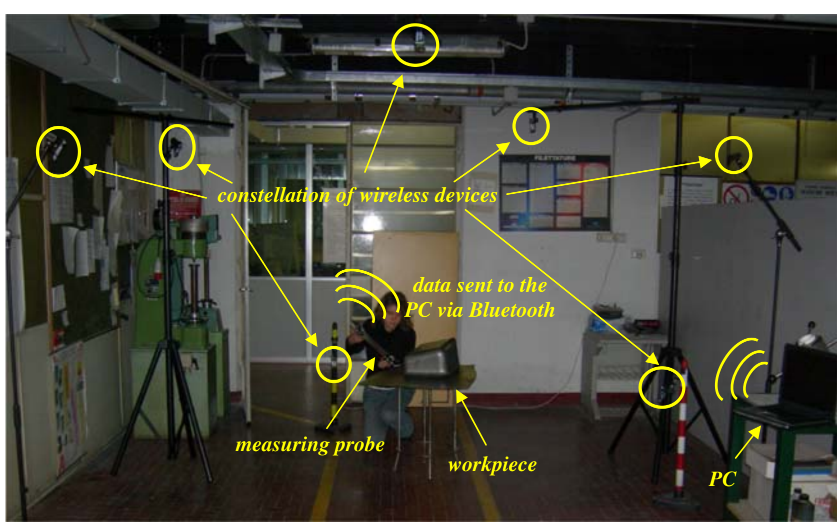

Fig. 2 Practical application of MScMS

variety of different probe technologies. CMMs consist of three basic components (Fig. 3):

- The *machine body*: three carriages move the probe along the *X*, *Y*, and *Z* Cartesian coordinate axes;
- A *measuring probe*: to touch the surface points of a workpiece;
- A *control and computing system*: to calculate the Cartesian coordinates of the points and evaluate the shape/features of the workpiece's surface.

CMMs are widely used in many industrial sectors to perform product control. The reason why they are so widespread is their reliability and accuracy [4]. CMMs software makes it possible to perform complex types of measurement (surface construction, intersections, projections). In spite of their diffusion, these machines cannot accomplish every kind of measurement because of their physical structure. With a few rare exceptions (*gantry* or *horizontal harm* CMMs, which are—anyway—expensive and bulky), CMMs cannot measure large-size objects, due to their limited measuring volume.

Table 1 Comparison criteria

Criteria for comparing MScMS and CMMs	
Portability	
Working volume	Size
	Geometry
Probe location technique	
Setup	Installation
	Start-up
	Calibration and verification
Metrological performances	Uncertainty sources
	Dimensional measurement
	Other kinds of measurements
Measurements system diagnostics	Online
	Off-line
Ease of use	Automation
	Software user interface
Flexibility	Kinds of measurement
	Geometric relations
	Concurrent measurements
Cost	Purchasing
	Maintenance
System management	Set up phase
	Measuring phase

5 Comparison criteria

The MScMS prototype has been designed to be portable, with the aim of measuring large-size objects and minimizing manual activities. In the following paragraph, MScMS and CMMs will be compared according to the set of criteria/requirements listed in Table 1.

Fig. 3 A typical CMM

In the following paragraphs, the previous criteria are individually analyzed to perform specific comparisons between MScMS and classical CMMs.

5.1 Portability

MScMS is composed by distributed and lightweight wireless devices, which are easily portable and installable in the area around the measured object. They can be fixed to the ceiling or mounted on standard supports and tripods (see Fig. 2).

While the MScMS components can be moved to different operating environments, traditional CMMs are embedded in a precise working area. Once installed, CMMs have to be permanently used there. To be moved, they need to be disassembled, re-assembled, re-installed and re-started up, spending a lot of time and with much effort.

5.2 Working volume

(Working volume) size The MScMS technology introduces an important difference in the typologies of measurements: It is suitable for dimensional measurement of large-size objects (for example, longerons of railway vehicles, airplane wings, fuselages, etc.). The big difference from traditional CMMs is that MScMS structure is not rigidly connected. It is made of separate components (wireless sensor devices) that should be easily moved and arranged

around the measuring area depending on the exigency (see Fig. 2). MScMS is *scalable* (or modular), as the number of constellation devices can be increased depending on the measurement volume to be covered, without compromising network communication and slowing down measurement activities.

On the contrary, CMMs are rigid and bulky systems in which the dimensions range can reach tens of meters. There is a great variety of CMMs, their working volume size can go up to hundreds of cubic meters. As discussed in the following sections, performances and costs are strongly influenced by CMMs dimensions [20].

(Working volume) geometry All the points within the working volume may be uniformly measured, with no discontinuities. The communication range of the MScMS RF transceivers is almost omnidirectional and up to 25 m, while US sensors communication range is limited by "cones of visions" with an opening angle of about 170° and a range of not more than 10 m (see Fig. 4). Signal strength outside the cones drops to 1% of the maximum value [21]. Therefore, it is important to provide a full coverage to the area served by constellation devices by proper orientating the US transmitters toward the measuring area. An increase of the working volume coverage can be obtained by increasing the number of network devices. In general, the most practical solution is mounting the network devices at the top of the measuring area (i.e., on the ceiling), as shown in Fig. 4.

We note that, for locating the MScMS mobile probe by trilateration, it must communicate with four network devices at least [24]. On the basis of empirical tests, we determined that a good coverage of an indoor working volume (about 4 m high) is achieved using about one network device per square meter, considering a plant layout.

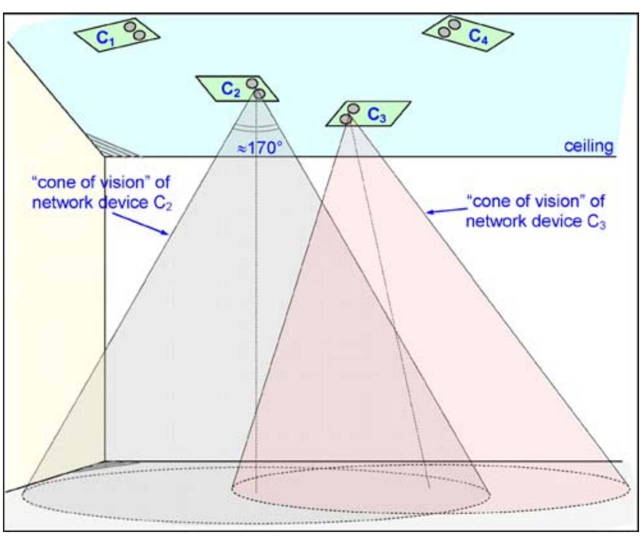

Fig. 4 Representation scheme of the US sensors "cone of vision"

MScMS may work in a non-convex working volume, that is to say, a volume which does not contain the entire line segment joining any pair of its points (e.g., A and B in Fig. 5). MScMS, due to its distributed nature, easily fit different types of indoor working environments, even with inside obstacles.

Considering CMMs, there are not discontinuities in the measuring volume, as all the points within this area can be reached by the electromechanical probe.

Although there are CMMs with large working volumes (i.e., *horizontal-arm* and *gantry* CMMs), the presence of obstacles in the proximity of the measured object is not allowed, as they may collide with the moving carriages. Considering this aspect, MScMS is more flexible than CMMs.

5.3 Probe location technique

Like CMMs, MScMS makes it possible to determine the shape/geometry 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 [2]. The following paragraph explains how the Cartesian coordinates of the points touched by the probe are obtained for MScMS and CMMs.

5.3.1 MScMS

Regarding MScMS, the position of the wireless probe tip is determined through the following steps:

1. The spatial location of each of the two probe's Crickets (A and B in Fig. 1) is achieved by solving a trilateration problem by a least-mean squares approach using a set of measured distances from four or more reference points with known position [24, 3]. The reference position of the constellation Crickets is established during the system setup phase (see Section 5.4);
2. As shown in Fig. 1, the probe tip (V) lies on the same line of wireless devices A and B, so the coordinates of the point V can be univocally calculated using the spatial coordinates of Crickets A (x_A, y_A, z_A) and B (x_B, y_B, z_B) and distances d_{A-V} and d_{A-B}, which are a priori known as they depend on the probe geometry [8];

5.3.2 Coordinate measuring machine

For CMMs, the Cartesian coordinates of the probe is obtained directly from the scale readings along the three coordinate axes (*X*, *Y*, and *Z*).

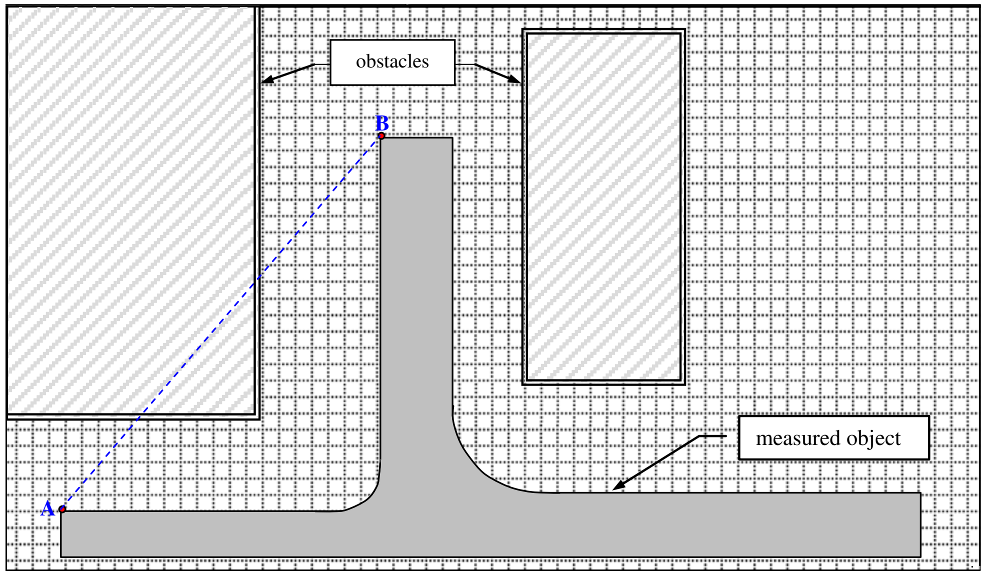

Fig. 5 Representation scheme of the concept of non-convex working volume (plant view)

5.4 Set Up

Installation Before starting measurements, the MScMS constellation Crickets are placed around the measuring area, so that the region of interest is completely covered with overlap of at least four devices [9]. Next, they have to be localized because measurements are possible only if the position of the constellation Crickets is known. To reduce manual operations, a procedure for a semiautomatic localization has been implemented [18, 19, 7]. In this procedure, a reference artifact equipped with some Cricket devices is placed in different positions within the measuring area. For each of these artifact placements, mutual distances between constellation Crickets and artifact Crickets are collected. Then, all this information is sent to the PC and used so as to locate the whole constellation by an ad hoc bundle adjustment algorithm [17, 8]. It is important to note that reducing the position uncertainty in the localization of constellation nodes is fundamental for reducing the uncertainty in the next mobile probe location.

Of course, CMMs do not require such a network location procedure, due to the different technology. However, CMMs installation requires a great effort because the system—made of different components—has to be carried and assembled into the working place by highly skilled technicians.

Start-up MScMS should be started up to activate the communication between the PC and the system and for selecting the mobile probe type. Probe qualification makes it possible to know the probe geometrical characteristics, necessary to determine the coordinates of the points touched by the probe's tip [8].

In addition, CMMs should be started up for activating the communication between the PC and the control system and for selecting the mobile probe type.

5.4.1 Calibration and verification

Calibration: *operation establishing the relation between quantity values provided by measurement standards and the corresponding indications of a measuring system, carried out under specified conditions and including evaluation of measurement uncertainty* [14].

In general, calibration defines a rule which converts the values output by the instrument's sensors to values that can be related to the appropriate standard units. Importantly, to these calibrated values, it is required to assign uncertainties that reliably take into account the uncertainties of all quantities that have an influence.

For MScMS, calibration is an operation that can be performed every time the system is started up, to test system integrity, and to set those parameters on which measurements depend (temperature, humidity, etc.). This operation does not need a sophisticated instrumentation, and it is carried out by measuring a standard reference artifact, with a priori known geometry.

Obviously, this calibration procedure is not valid for CMMs because of their different technology and, in particular, their rigid structure. CMMs calibration cannot be accomplished directly by the user, but requires a more complex procedure defined by international standards [13]. In particular, CMMs calibration consists in a sequence of manual activities that must be carried out once or twice a year and requires highly qualified operators and complex and highly accurate instruments like laser interferometers.

Verification: *confirmation through examination of a given item and provision of objective evidence that it fulfils specified requirements* [14].

Another activity to make MScMS suitable for the measurement is the system verification (block 11 in Fig. 7). It should be periodically performed to verify and adjust the measuring scale adopted (for example, the US speed changes with air temperature and humidity). This operation is performed by the use of a standard reference artifact [13].

CMMs verification is done using some standard reference artifacts or repeatedly measuring the same points to evaluate possible measurements drifts. Different approaches have been proposed in this direction [5]. Whenever a CMM does not fulfill specified requirements, highly qualified operators have to intervene.

5.5 Metrological performances

Uncertainty sources The technology employed is responsible for MScMS's large uncertainty compared to CMMs [8]. MScMS measurement uncertainty may change depending on many different factors related to the use of US transceivers, such as temperature, humidity, air turbulence, transducer geometry, transducer bandwidth, and US signal detection method [3]. Furthermore, US signals may be diffracted and reflected by obstacles interposed between two devices. However, most of these negative aspects can be effectively corrected/limited by the implementation of compensation/correction models [6, 3].

Furthermore, CMMs performances may change depending on many factors like machine dimensions and stiffness, climatic conditions (temperature and humidity), or speed of contact between the probe and the workpiece. Nevertheless, CMMs uncertainty is some order of magnitude smaller than MScMS.

5.6 Dimensional measurement

5.6.1 Mobile spatial coordinate measuring system

To give an idea of MScMS prototype performances, two tests have been carried out:

1. *Repeatability test*: A single point within the working volume is measured repeatedly about 50 times, leaving the mobile probe in a fixed position. The test is repeated measuring at least 20 different points in different areas of the working volume. For each point, the standard deviations (σ_x, σ_y, σ_z) related to the registered Cartesian coordinates (x, y, z) is calculated.
2. *Reproducibility test*: This test is similar to the previous one, but the mobile-probe orientation is changed before each measurement—with the aim of approaching each point from a different direction. Furthermore, the different measurements are performed under different conditions (i.e., by different operators and in different intervals of time).
3. *Distance error test*: This test is performed using a reference artifact consisting of a bar with known length. The nominal length of the bar (around 3 m) is calibrated using a laser interferometer, which is at least four orders of magnitude more accurate than MScMS. The bar length is measured 20 times for ten different positions/orientations within the working volume. The standard deviation related to the distance residuals (σ_D), that is to say the differences between nominal distance and distances measured with MScMS are calculated.

Results of these preliminary tests are reported in Table 2.

5.6.2 Coordinate measuring machine

To provide an example of CMMs standard performance, Table 3 reports the maximum permitted error (MPE) on distance measurements related to a DEA™ machine [27]. In general, the MPE grows up with the dimension of the CMM.

Other kinds of measurements While CMMs have been designed with the purpose of performing only dimensional measurement, MScMS can carry out other kinds of measurements. Actually, Cricket devices may be equipped with other sensor boards. This gives the possibility to associate single position measurements with other kinds of measurements, such as light intensity, temperature, acceleration, magnetic field, pressure, humidity, or noise pollution. Accuracy of these kinds of measurements depends on embedded sensors utilized [26].

5.7 Measurements system diagnostics

Online measurements diagnostics As said before, MScMS is sensitive to external factors, such as environmental conditions (temperature, humidity, and presence of obstacles among distributed devices). MScMS software provides some diagnostic tools to control the measurements

Table 2 Results of the MScMS preliminary tests (with reference to single sampling measurements)

Test	Repeatability			Reproducibility			Distance error
Mean standard deviation (mm)	σ_x 4.8	σ_y 5.1	σ_z 3.5	σ_x 7.3	σ_y 7.8	σ_z 4.1	σ_D 8.0

Table 3 Performance of a standard CMM [27]

Standard CMM performance			
Stroke *x* (mm)	Stroke *y* (mm)	Stroke *z* (mm)	MPE-E for ISO 10360/2 (μm)
500	700	500	From 1.5+L/333

activities and assist in the detection of abnormal functioning. Firstly, it gives the opportunity of watching the data exchanged among the wireless devices. Secondly, it allows a graphic display of the probe's range of vision, that is to say the set of network devices it can communicate with (see Fig. 6). This helps the operator to check whether the probe is in the optimal position to perform a specific measurement (i.e., if it communicates with at least four constellation devices). Furthermore, we implemented another diagnostic tool for filtering "wrong" distances among Cricket devices, such as US reflection, diffraction, or other measuring accidents [17, 6].

On the other hand, CMMs do not offer online diagnostics for single measurement but only for shape measurements: If the reconstructed shape does not reasonably fit the measured points, then an error is reported. This kind of diagnostics is only possible when there is a significant measurements redundancy (for example, five or more points to reconstruct a sphere or four or more points to reconstruct a circumference). Similar diagnostic tools can be implemented for MScMS.

Off-line measurements diagnostics Both CMMs and MScMS can provide very similar off-line diagnostic tools. These diagnostics are based on the concept of measurement replication: If variability is higher than expected, measurements are considered not reliable [6]. During a measurement cycle, some known points are repeatedly touched by the probe at regular intervals. With reference to these points measurement, if variability results higher than natural expected variability of the instrument, the measurement cycle stops, because this means that CMMs performance is deteriorating. As a consequence, whenever a stop occurs, the operator has to investigate about its reason. Although being performed during the measurement cycle, these diagnostics cannot be considered as online, as they are performed after measurements.

5.8 Ease of use

Automation MScMS and traditional CMMs are equipped with software packages that automate data processing. Specifically considering measurements, the two systems are very different. Due to its technology, MScMS operates only manually: The user brings the mobile probe to the object to touch a set of points on its surface. This is an important difference from CMMs, which are typically controlled by CNC. CMMs software makes it possible to create routines to automatically perform the same measurements on identical objects. This implies a large reduction of time and costs when the number of (identical) objects to be measured is large. By means of a self-learning tool, the user

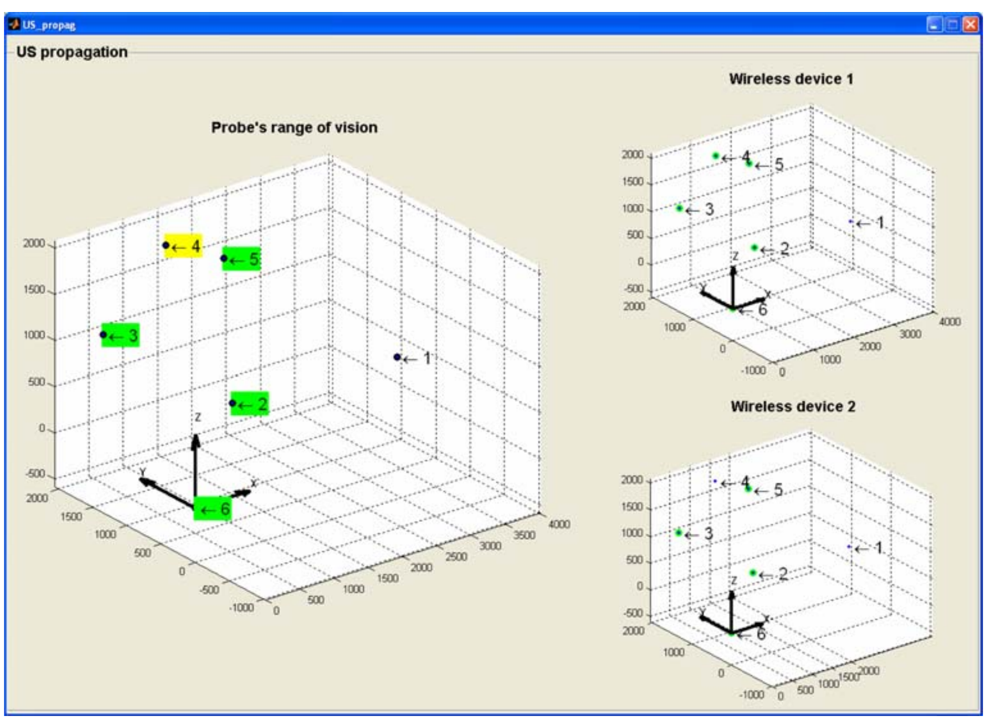

Fig. 6 Graphic representation of the probe range of vision

can also choose to manually measure the first object allowing the system to learn the measurement patch to be repeated.

The MScMS software does not provide the same facility, due to the manual nature of measurements.

Software user interface Both devices (CMMs and MScMS) provide a software user interface. Their functions are based on a similar structure, with the aim of guiding the user through the various activities. Table 4 summarizes the results of a comparison between the MScMS and CMMs software user interfaces.

As for CMMs, MScMS software has been developed to help operators by:

- leading them through the start-up and measuring activities;
- providing tools and functions that simplify their work;
- displaying the results in a clear and complete way.

The software structure is modular (see Fig. 7). Each module is associated to a specific activity (system start-up, dimensional measurements, results displaying). Modules are linked together by different operational paths.

Each path represents a sequence of screenshots. The great advantage of a modular structure is that it can be progressively extended according to the measuring system enhancement.

Figures 8, 9, 10, 11, and 12 show some screenshots of MScMS user interface.

5.9 Flexibility

Kinds of measurement Considering flexibility as the ability of performing different types of measurements, MScMS distinguishes itself from classical CMMs. As described above, MScMS offers the possibility of simultaneously performing different measurements (light, acoustic noise, pressure, temperature, acceleration, magnetic field, and humidity). This kind of measurement cannot be achieved with a classical CMM.

Geometric relations Considering flexibility as the ability of performing different types of geometric measurements, the software functions offered by MScMS are very similar to those offered by classical CMMs:

a. *Single shape measurement* (block 12 in Fig. 7). In this case, the measured workpiece's feature corresponds to a precise geometric shape (circle, plan, cylinder, etc.);
b. *Relationships among different shapes*. The measured feature arises from a relationship between two or more different parts of the object's shape, like distances,

Table 4 Comparison between the MScMS and CMMs software packages

Stage	Activities	Software tools	
		MScMS	CMMs
System startup	System initialization	Semiautomatic procedure to open the bluetooth connection	Semiautomatic procedure to start up the measuring machine
System presetting	Probe qualification	(Manual) definition of the probe's geometrical features	Semiautomatic procedure for the probe qualification
	Network localization	Semiautomatic procedure guided by visual instructions Display and memorization of the localized network layout	–
Dimensional measurement	Choice of the measuring activity	Single shape measurement. Relationships among different shapes (distances, intersections or angles)	Idem
	Measurement target	Selection of the shape (or relationship) to measure	Idem
	Measurement execution	Measurement setting and execution	Idem
	Audio–visual signals	Warning signals Display of the probe's communication range and network connectivity	Warning signals
	Output display	Numerical and graphical display of the measured points 2D and 3D charts Numerical and graphical display of the object's features Measurements system diagnostics	Idem

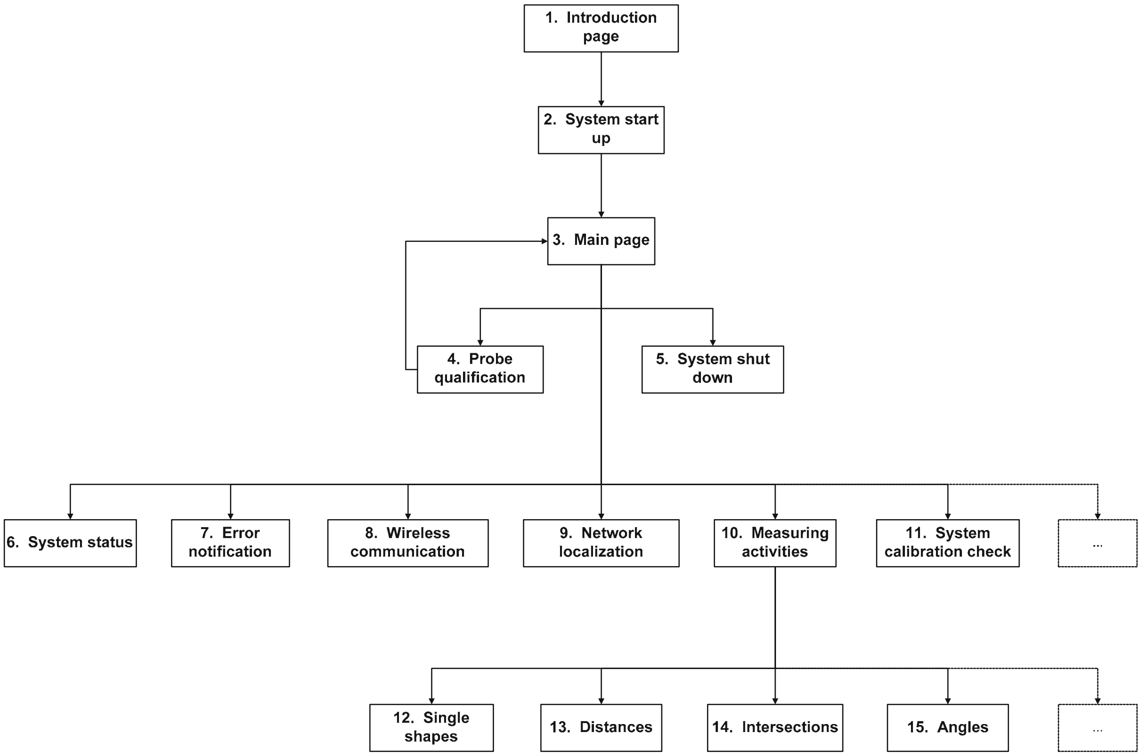

Fig. 7 MScMS software architecture

intersections, or angles between curves/surfaces (blocks 13 to 15 in Fig. 7).

Concurrent measurements A significant peculiarity of MScMS is given by the flexibility of the Cricket devices. They are light, small, and cheap and have an embedded processor to perform easy computations. For this distributed computational capacity, MScMS can simultaneously support two or more probes, to execute concurrent measurements in different parts of the network. It is so possible to

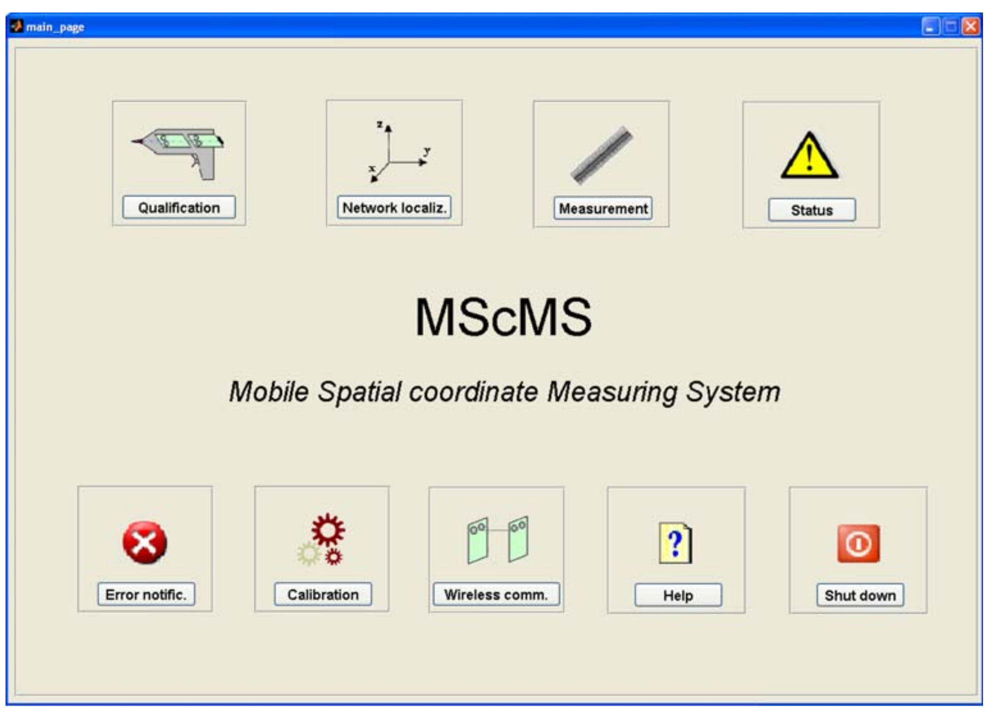

Fig. 8 The system's main menu screenshot

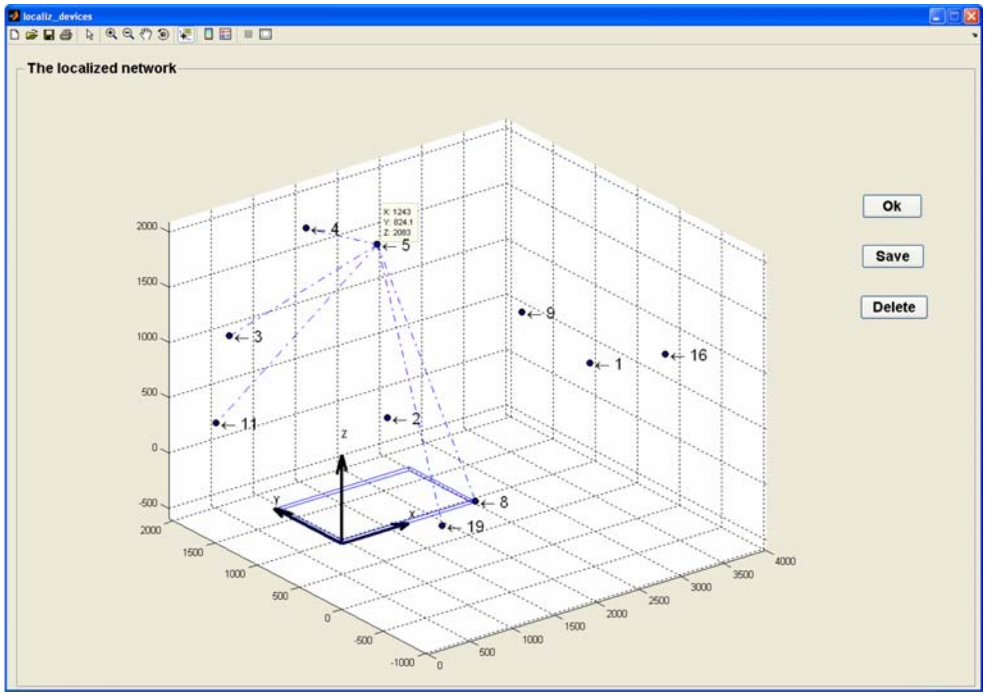

Fig. 9 The localized wireless network devices

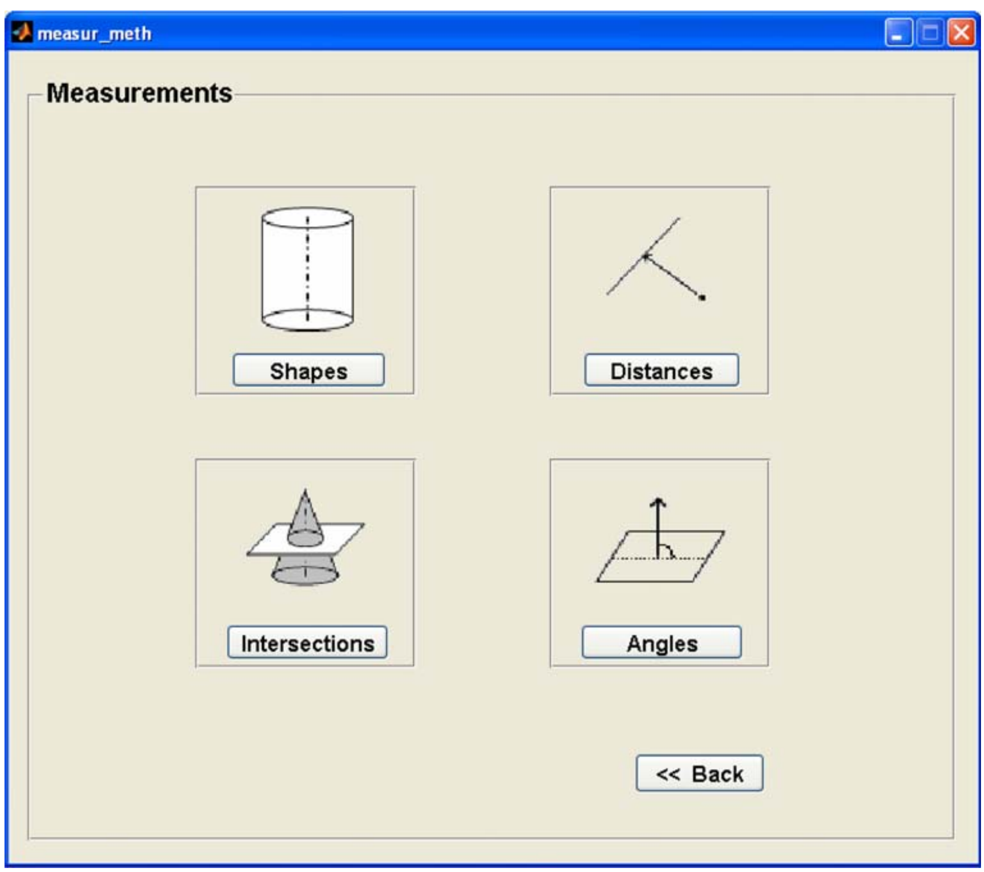

Fig. 10 Choice of the measuring activities

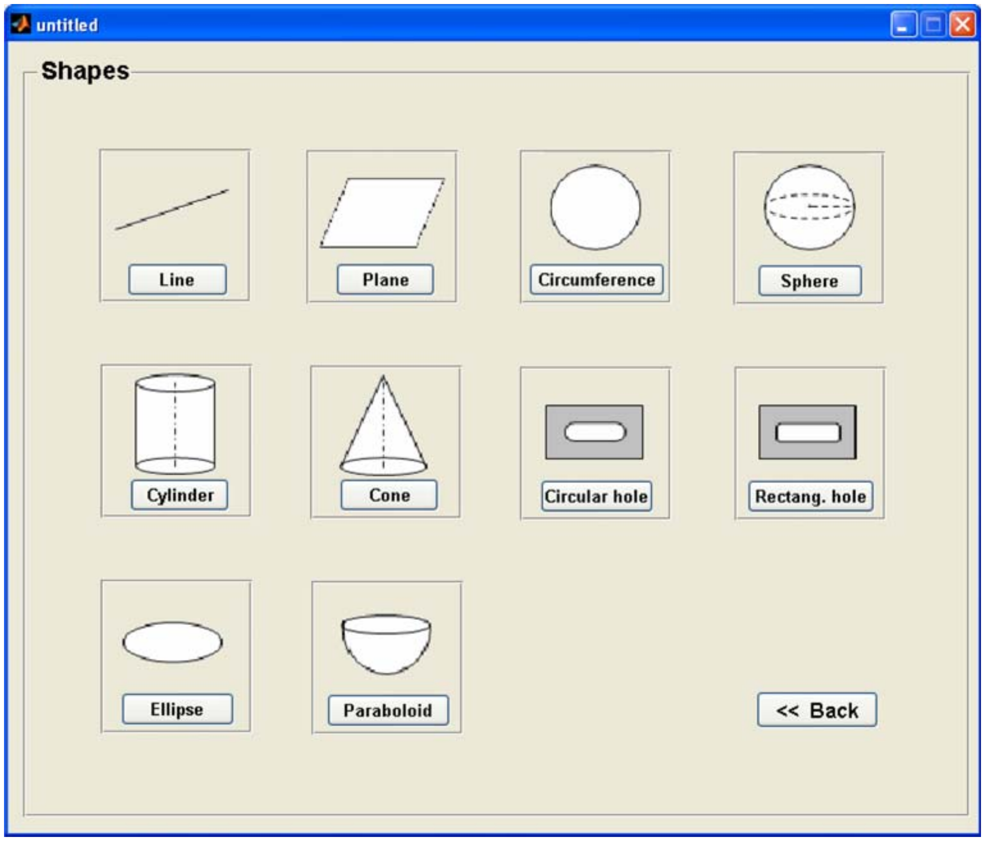

Fig. 11 Single shape measurement

perform simultaneous measurements on a single object or even on different objects, improving the system sample rate.

CMMs are not able to simultaneously perform more than one measurement at a time.

5.10 Cost

Purchasing Cost is a point in favor of MScMS. Its components (Cricket devices, supports/booms, adapters…) have an individual cost of the order of some tens of euros; system overall cost is in the order of some thousands of euros. On the other hand, the cost of classical CMMs—even the most economical and simple—is one or two orders of magnitude higher.

Maintenance The MScMS system does not need a really complicated maintenance. Maintenance costs are low, as the system does not require the intervention of highly qualified operators. Activities of calibration and verification can be easily carried out by the user.

CMM maintenance is much more complicated. As CMMs need to assure different levels of accuracy, maintaining the system requires well-prepared operators. Typically, maintenance contracts cost about 3,000 euros per year, for a single CMM.

5.11 System management

From a system management point of view, the two measuring systems' major implications concern two phases: set-up and measuring.

Set up phase Before performing measurements, both systems need to be set up. Regarding MScMS, the operator has the possibility of placing the constellation devices freely around the workpiece. He should only take care of using a proper number of constellation devices and setting their orientation to cover the measuring area (see the Section 5.2). After this, a semi-automatic localization procedure can be performed to locate the constellation devices (procedure described in Section 5.4). On the other hand, the set-up procedure for CMMs is much more complex and requires highly skilled technicians and complex instruments (i.e., laser interferometer).

Service phase For both systems, the measuring phase is rather user friendly. Regarding MScMS, the system makes it possible to modify the measuring volume depending on the exigency (e.g., when the workpiece is moved or replaced with a different one), simply adding or moving some of the constellation devices. Of course, every time the position of one or more constellation devices is changed,

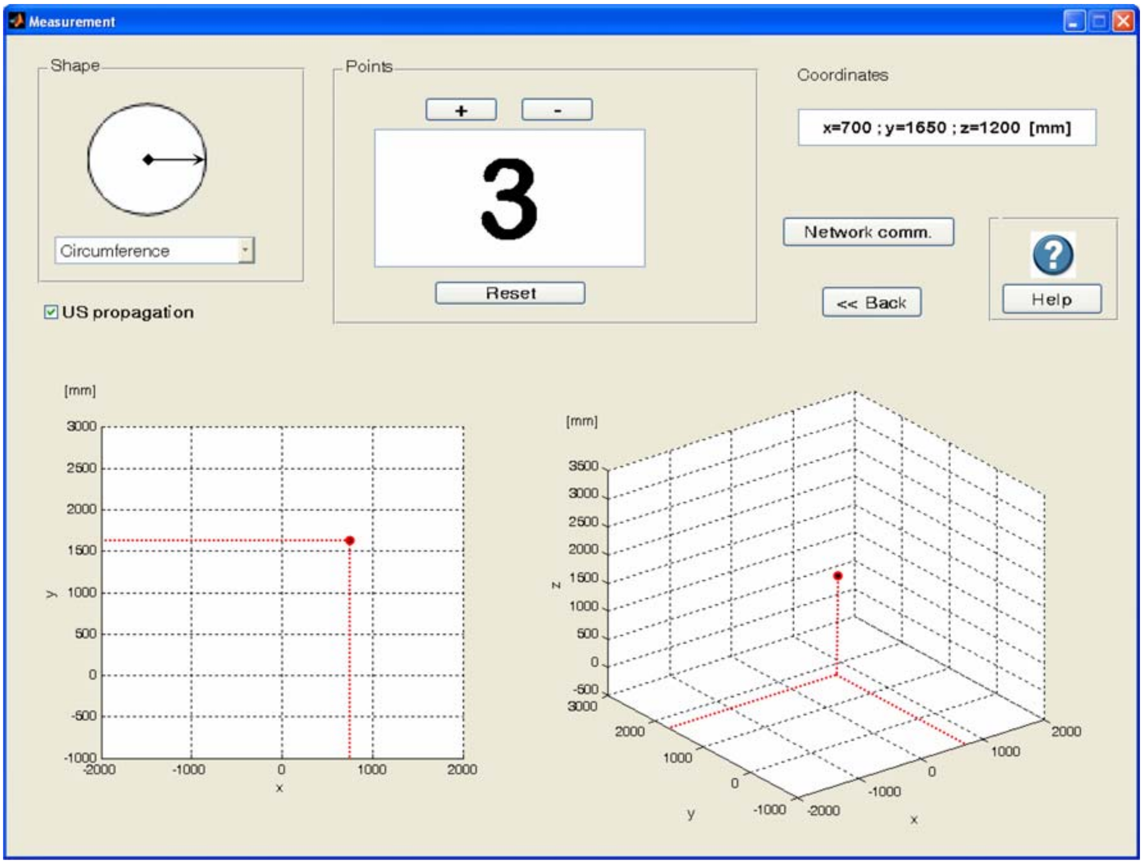

Fig. 12 Measuring page related to the circumference shape

the set-up phase should be performed again. On the contrary, CMMs are rigid systems in which the working volume size is fixed.

6 Conclusions

This paper has presented MScMS, a new system for measuring large-size objects comparing it to CMMs, the most commonly used devices for objects dimensional measurements.

MScMS and classical CMMs are similar considering measurement activities; however, due to their different technological features, they have many differences (for example, system presetting, start-up, measurement execution, etc.). In our opinion, they can easily coexist, as each system has some peculiar technological features that make it suitable for specific uses. The lower accuracy of MScMS makes it difficult to compete with CMMs when it comes to measuring off-the-shelf small-size objects. However, MScMS becomes competitive in the dimensional evaluation of large-size workpieces, where it is often required to move the machine to the place where the object is. Furthermore, wireless sensor network technology enhances MScMS with the facility of performing different kinds of measurement (temperature, light, pressure, noise, etc.).

MScMS is lightweight, easily adaptable to different working environments, and does not require long installation or start-up times. Before performing measurements, constellation devices are freely distributed around the area of work and semi-automatically located in few minutes. System is supported by an ad hoc software created in MatLab environment to drive users through measurements and data off-line elaborations. We reckon that the introduction of this and other measuring systems based on distributed components may have important effects on simplifying the current measuring practices within large-scale industrial metrology.

Today, MScMS Achilles' heel is represented by low accuracy, due to the use of US transceivers. Regarding the future, all the factors affecting system accuracy will be analyzed in detail, to improve its performance without necessitating very complex modifications to the current Cricket hardware/firmware. For example, improvements could be obtained by modifying the current Cricket US transducers, using more refined US ranging method or implementing proper compensation/correction techniques. In spite of the possible future improvements, it will be very hard to close the gap between MscMS and CMMs metrological performances, because of the US technology intrinsic limits. Nevertheless, MScMS covers an area (large-scale metrology) in which CMMs are absolutely expensive and not practical; thus, it is likely to be preferred to them for some specific applications.

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