A comparison of two distributed large-volume measurement systems: the mobile spatial co-ordinate measuring system and the indoor global positioning system

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Abstract: Advances in the area of industrial metrology have generated new technologies that are capable of measuring components with complex geometry and large dimensions. However, no standard or best-practice guides are available for the majority of such systems. Therefore, these new systems require appropriate testing and verification in order for the users to understand their full potential prior to their deployment in a real manufacturing environment. This is a crucial stage, especially when more than one system can be used for a specific measurement task. In this paper, two relatively new large-volume measurement systems, the mobile spatial co-ordinate measuring system (MScMS) and the indoor global positioning system (iGPS), are reviewed. These two systems utilize different technologies: the MScMS is based on ultrasound and radiofrequency signal transmission and the iGPS uses laser technology. Both systems have components with small dimensions that are distributed around the measuring area to form a network of sensors allowing rapid dimensional measurements to be performed in relation to large-size objects, with typical dimensions of several decametres. The portability, reconfigurability, and ease of installation make these systems attractive for many industries that manufacture large-scale products. In this paper, the major technical aspects of the two systems are briefly described and compared. Initial results of the tests performed to establish the repeatability and reproducibility of these systems are also presented.

Keywords: dimensional measurement, large-scale metrology, mobile measuring system, distance measurements, indoor GPS, metrological performance

1 INTRODUCTION

Metrology, the science of dimensional measurement, is an integral part of all manufacturing industries, regardless of the scale of their products. The conventional applications of measurement are the inspection of finished components, control of manufacturing and assembly processes, and verification of jigs and fixtures. The capabilities of new measurement systems and the improvement of their relevant control systems and computer programs have opened up new application areas for metrology. Examples of these are metrology for assisting the manufacturing and assembly processes, continued jig and fixture monitoring, and tracking of production systems and elements within a factory.

Large-volume metrology deals with the measurement of large machines and structures, in which the linear dimensions range from tens to hundreds of metres [**1**]. There is an increasing trend for accurate measurement of length; in particular, three-dimensional co-ordinate metrology at scales from 5 to 100 m has become a routine requirement in industries such as aircraft and ship construction. Recent advances across a broad range of technologies have led to some innovative measurement solutions such as laser interferometry (IFM), the absolute distance meter (ADM), and very high-density charge

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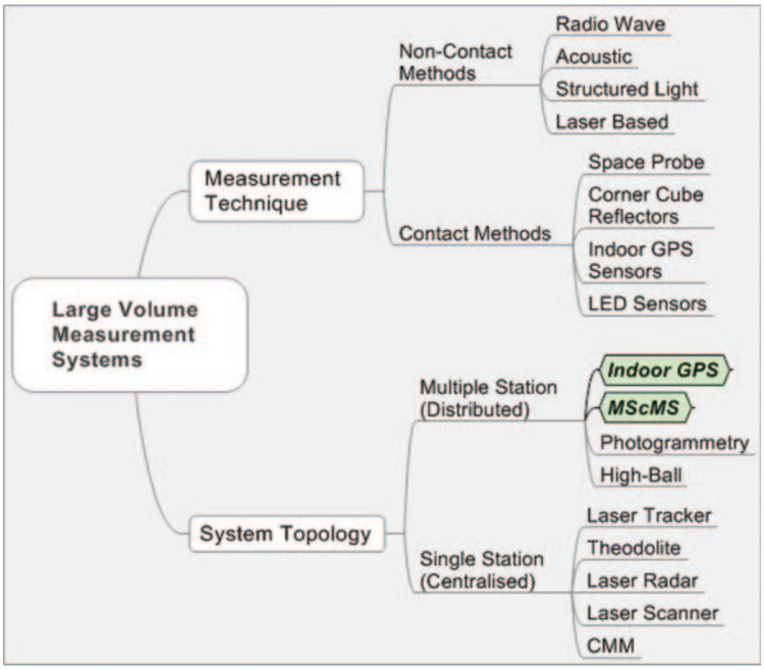

Fig. 1 Classification of large-volume measuring systems

coupled device (CCD) cameras that were previously difficult or impossible to implement [**2**]. The measurement systems digitize a component by contact or non-contact techniques, depending on their technology, which makes them more suitable for specific applications. Figure 1 shows a classification scheme of large-volume measurement systems for various applications. In this paper, the measurement systems are classified into *centralized* and *distributed* systems. A centralized system (e.g. a laser tracker) is essentially a stand-alone unit that can work independently to digitize the spatial co-ordinates of a point on the object surface. In some cases, a number of centralized systems can be simultaneously used with the aim of improving measurement accuracy. On the other hand, a distributed system needs a series of measuring stations that work co-operatively to collect information for determining co-ordinates of a point from the object's geometry. In general, the individual stations associated with a distributed system cannot measure the co-ordinates of a point independently. The co-ordinates of the desired points can be captured by combining the measurement information from different stations.

Owing to their topology and the light weight of each of their peripheral devices, distributed measurement systems are portable and can easily be transferred to the measurand.

This paper introduces and compares two recent measurement systems for large-volume objects: the mobile spatial co-ordinate measuring system (MScMS) and the indoor global positioning system (iGPS). The MScMS is a new prototype system for dimensional measurement, developed at the Industrial Metrology and Quality Laboratory of DISPEA – Politecnico di Torino [**3**]. Based on a distributed sensor network structure, the MScMS can accomplish rapid dimensional measurements of large-size objects, in a wide range of indoor operating environments. It consists of distributed wireless devices that communicate with each other through radiofrequency (RF) and ultrasound (US) transceivers.

The iGPS is a modular, large-volume tracking system enabling factory-wide localization of objects with metrological accuracy, applicable in manufacturing and assembly environments. The system components of iGPS are a number of transmitters, a control centre, sensors, and receivers [**4**]. The transmitters use laser and infrared light to determine the relative angles from the transmitters to the sensors. The sensors, used for measuring the workpiece, have photodiodes inside their modules that can sense the transmitted laser and infrared light signals (Fig. 3).

The other distributed contact measurement system shown in Fig. 1 is the 3rd Tech HiBall, a system composed of a number of infrared LEDs, arranged around the measuring area, which can be viewed by an optical sensor probe measuring the object surface [**5**]. The probe is able to locate itself, measuring the angles from the LEDs and performing a triangulation. This type of distributed system can potentially be considered as a faster and easier solution for the system operators compared with conventional CMMs, theodolites, or laser trackers.

The distributed nature of the MScMS and the iGPS eases the handling, provides scalability for the coverage of the measuring area, and makes them suitable for particular large-scale types of measurement. For instance, some large-size objects cannot be transferred to the measurement systems owing to their dimensions or other logistical constraints. Therefore, the measurement system has to be frequently deployed *in situ*. The two systems have many common aspects as follows.

1. Measurements are taken by touching the required points on the object's surface with a probe that is equipped with double sensors. Points are defined on a Cartesian co-ordinate system.
2. The co-ordinates are then processed by specific algorithms, in order to determine geometric features (curves, surfaces, distances, angles, etc.). The measured features are then used to extract the desired dimensional information such as feature positions and angles between two features.
3. Both of the systems have a constellation of transmitters distributed around the measuring area. These devices act as reference points, essential for the location of the probe. Information on the location of the transmitters is normally obtained in an initial *set-up* phase.
4. The signal is transferred through a wireless network of sensors enhancing mobility and scalability. Similarly to a satellite-based GPS, a one-way signal path is created from the transmitters to each sensor. This approach allows an unlimited number of sensors continuously and independently to calculate positional data.

On the other hand, the MScMS and the iGPS have many different characteristics, such as the technology used, the measuring principle, the cost, and metrological performance.

In the remainder of this paper, a more in-depth comparison between the above systems, considering the most important features, is carried out according to a set of criteria. The paper is organized in four remaining sections. Section 2 provides a brief introduction to the MScMS technological features and modus operandi. Section 3 is a short introduction to the iGPS. Section 4 presents a comparison between the two systems, including an initial evaluation of the metrological performance of the two systems and the identification of their most important operating factors. Finally, the conclusions and future directions of this research are given in section 5.

2 MScMS TECHNOLOGICAL AND OPERATING FEATURES

The first MScMS prototype, developed at the Industrial Metrology and Quality Laboratory of DISPEA – Politecnico di Torino, comprises three main components [**3**]:

(a) a constellation (network) of wireless devices arranged around the working area;
(b) a measuring probe communicating with the constellation devices to obtain the co-ordinates of the points touched;
(c) a computing system receiving data sent by the measuring probe and processing them in order to evaluate the object's geometrical features.

The wireless devices comprising the MScMS prototype – known as 'crickets' – have been developed by the Massachusetts Institute of Technology (MIT) and produced by Crossbow. Being quite small, light, and potentially cheap, they are fit to obtain a wide range of different network configurations [**6**, **7**]. As shown in Fig. 2, the measuring probe is a mobile system that contains two wireless devices (identical to the constellation devices placed around the working area), a tip to touch the points on the surface of the measured objects, and a trigger.

All the crickets have RF and US transceivers transmitting signals to each other. They constantly communicate and calculate their mutual distances by measuring the time-of-flight (TOF) of the US signal [**8**]. The RF communication allows each cricket rapidly to know the distances to the other devices. A bluetooth transmitter is connected to one of the two crickets of the probe to send the distance information to the PC, which is equipped with *ad hoc* software.

In practical terms, measurements consist of three phases.

1. The mobile probe is used to touch the desired points on the part's surface (Fig. 2).
2. The trigger is pulled to take the measurement and send data to the PC via bluetooth.
3. The Cartesian co-ordinates of the points are calculated by software using specific algorithms that eventually identify the geometrical features of the measurand [**9**].

The last phase can be divided into three steps as follows.

1. The spatial location of each probe's cricket is achieved using a trilateration technique. In general, a trilateration problem can be formulated as equation (1). This can be solved by a given set of n nodes (constellation devices) with known co-ordinates (x_i, y_i, z_i, with $i = 1, 2, \ldots, n$) and a set of

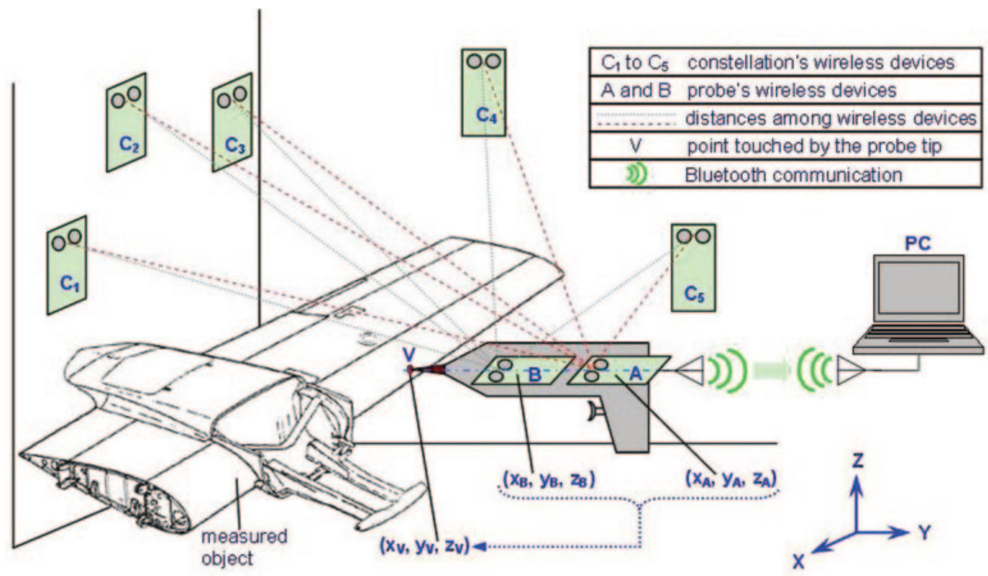

Fig. 2 MScMS representation scheme [**3**]

measured distances M_i, to calculate the unknown position of a generic point P (u, v, w)

$$\begin{bmatrix} (x_1-u)^2+(y_1-v)^2+(z_1-w)^2 \\ (x_2-u)^2+(y_2-v)^2+(z_2-w)^2 \\ \vdots \\ (x_n-u)^2+(y_n-v)^2+(z_n-w)^2 \end{bmatrix} = \begin{bmatrix} M_1^2 \\ M_2^2 \\ \vdots \\ M_n^2 \end{bmatrix} \quad (1)$$

The trilateration problem can be solved using a least-mean-square approach whenever four or more reference points are known [**10–12**]. Each mobile probe cricket locates itself using the measured distance from a minimum of four constellation crickets, with *a priori* known locations. All information needed for the location is sent to a PC for centralized computing.

2. As shown in Fig. 2, since the probe tip (V) lies on the same line as devices A and B, the co-ordinates of point V can be calculated as

$$\begin{cases} x_V = x_A + (x_B - x_A)\cdot \dfrac{d_{A-V}}{d_{A-B}} \\ y_V = y_A + (y_B - y_A)\cdot \dfrac{d_{A-V}}{d_{A-B}} \\ z_V = z_A + (z_B - z_A)\cdot \dfrac{d_{A-V}}{d_{A-B}} \end{cases} \quad (2)$$

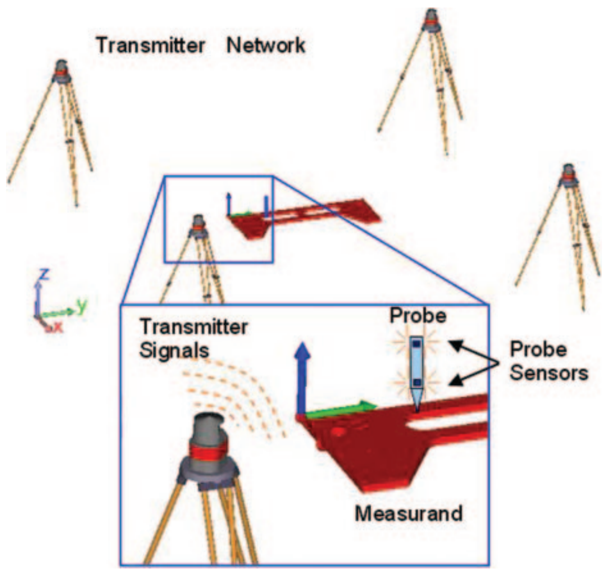

Fig. 3 iGPS representation scheme

Equation (2) unambiguously locates the point V, using the spatial co-ordinates 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 (see Fig. 3) [**3**]. The previous model is based on the assumption that the US sensors (A and B) and probe tip (V) are punctiform geometric elements. In practice, the model is inevitably approximated because sensors A and B have non-punctiform dimensions. To minimize the uncertainty of point P position, the following condition should be satisfied: $d_{A-V} \ll d_{A-B}$ [**13**].

3. The MScMS can determine the shape or geometry of objects (circumferences, cylinders, planes, cones, spheres, etc.) on the basis of a set of measured surface points gathered from the mobile probe using classical optimization algorithms [**14**].

Before the start of measurement, the locations of constellation crickets have to be determined. This phase should be fast and automated to enhance the system's adaptability to different working environments. In order to minimize manual operations, a method for a semi-automatic localization, using a calibrated artefact, has been implemented [**15**]. It is worth mentioning that the positional accuracy of the constellation nodes is fundamental for the positional accuracy of the mobile probe [**16**].

3 iGPS TECHNOLOGY AND OPERATING FEATURES

Typically, the system components of the iGPS are: three or more transmitters, a control centre, and a number of wireless sensors. The transmitters operate as reference points (with known position) continually generating three signals: two infrared laser fanned beams rotating in the head of the transmitter and an infrared LED strobe [**17**]. The sensors are passive elements that can be placed on the surface of the measurand to receive the transmitters' signals.

iGPS is a *scalable* and modular system since the number of transmitters and sensors can be increased according to the requirements of the measurement environment. Such characteristics, however, do not compromise the network's communication or slow down the set-up activities and measurements [**17**].

Before the start of measurement, the locations of transmitters have to be determined. This phase should be fast and automated to enhance industrial deployment of the system.

During measurement, the position (x, y, z) of each sensor is calculated. Each transmitter presents two measurement values to each sensor: the horizontal (azimuth, φ) and the vertical (elevation, θ) angles. Sensors can calculate their position whenever they are located in the line of sight of two or more transmitters. The principle used is triangulation [**18**]. In addition to the azimuth and elevation angles from the transmitter to the sensor, more information is needed to calculate a sensor's position, which is the relative position and orientation of the transmitters.

Similarly to the MScMS, the transmitters make a *constellation* of reference points that are located through a system set-up process. The relative position and orientation of the transmitters are determined using an advanced set-up algorithm, which is known as bundle adjustment [**11**]. In this algorithm, the angular information of each transmitter with respect to the other transmitters in the network is calculated by measuring a few points between the transmitters. Then the absolute co-ordinates of the transmitters are calculated by defining a scale, which is the absolute distance between two known points such as the length of a reference bar. The scaling factor can be improved by using larger reference lengths later on in the process. The iGPS provides a relatively rapid and semi-automated localization procedure requiring relatively few manual measurements [**12**].

Once the set-up has been completed, the measurements can be performed using a portable handheld measurement probe, known as the vector bar (Vbar). This probe is equipped with two sensors that should be carried by an operator in order to measure the co-ordinates of the points touched by the probe tip. For thermal stability, the portable probe is mainly made of composite material. The procedure for calculating the co-ordinates of the point touched by the probe tip is similar to the one implemented by the MScMS system.

1. The spatial location of each sensor is achieved using a triangulation technique. The unknown position of a generic point P (u, v, w) is given by least-squares solution of equations (3) [**19**], which needs a given set of n nodes (transmitters) with known co-ordinates (x_i, y_i, z_i, with $i = 1, 2, \ldots, n$) and a corresponding set of azimuth (φ_i) and elevation (θ_i) angles

$$\mathbf{P} = (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\boldsymbol{b}$$

where

$$\mathbf{P} = \begin{bmatrix} u \\ v \\ w \end{bmatrix},$$

$$\mathbf{A} = \begin{bmatrix} -\sin\varphi_1 \cdot \cos\theta_1, & -\sin\varphi_1 \cdot \sin\theta_1, & \cos\varphi_1 \\ -\sin\varphi_2 \cdot \cos\theta_2, & -\sin\varphi_2 \cdot \sin\theta_2, & \cos\varphi_2 \\ & \vdots & \\ -\sin\varphi_i \cdot \cos\theta_i, & -\sin\varphi_i \cdot \sin\theta_i, & \cos\varphi_i \end{bmatrix},$$

$$\boldsymbol{b} = \begin{bmatrix} (-\sin\varphi_1 \cdot \cos\theta_1) \cdot x_1 + (-\sin\varphi_1 \cdot \sin\theta_1) \cdot y_1 \\ + \cos\varphi_1 \cdot z_1 \\ (-\sin\varphi_2 \cdot \cos\theta_2) \cdot x_2 + (-\sin\varphi_2 \cdot \sin\theta_2) \cdot y_2 \\ + \cos\varphi_2 \cdot z_2 \\ \vdots \\ (-\sin\varphi_i \cdot \cos\theta_i) \cdot x_i + (-\sin\varphi_i \cdot \sin\theta_i) \cdot y_i \\ + \cos\varphi_i \cdot z_i \end{bmatrix} \quad (3)$$

For unique determination of the relative location of a point in three-dimensional space, at least two transmitters are needed [**11**, **12**]. All information needed for location calculation is sent to a computer for processing.

2. In a similar way to the MScMS, the location of a point touched by the probe tip can be calculated by equation (2) using the obtained co-ordinates of points A (x_A, y_A, z_A) and B (x_B, y_B, z_B), which are in effect the centre-points of the sensors, and the geometrical features of the probe (distances d_{A-V} and d_{A-B}).

For the experimental work described in this paper, an iGPS system equipped with four transmitters was used.

4 SYSTEM COMPARISON

In this section, the MScMS and the iGPS systems are compared, and some of the most important similarities and differences between the two systems are discussed. A summary of the comparison is given in Table 1. In the following paragraphs, some of the items are individually analysed in order to emphasize the most interesting similarities and differences between the two systems.

4.1 Number of constellation devices

For both the MScMS and the iGPS, the number of constellation devices is strictly related to their communication range and the measurement volume. In the case of the MScMS, some tests show that the coverage of an indoor working volume is achievable using about one network device per square metre, depending on the workshop layout [**3**]. Comparatively, since the communication range of the transmitters of the iGPS is much larger, the transmitters' density within the measuring volume does not have to be as high (approximately one device per 100 m^2).

Furthermore, it is important to note that the number of constellation devices 'seen' by the sensors has a strong influence on the positioning accuracy. This particular aspect was studied through exploratory tests combined with simulation.

With regard to the iGPS, 30 points, with *a priori* known positions, were measured (repeating the measurement 150 times per point), while the number of iGPS transmitters for the desired points was deliberately changed from 2 to 4 transmitters [**20**]. The co-ordinate positional errors (residuals) were determined by considering the difference between the 'true' co-ordinate position and the co-ordinate position of the points, as calculated by triangulation.

Table 1 Comparison of results between the MScMS and the iGPS

Technical feature	MScMS	iGPS
Measured variables	Distances among constellation devices and probe sensors	Two angles among each couple of sensor and transmitter
Localization technique during measurements	Trilateration	Triangulation
Transmitter's communication range	About 6–8 m	Up to 40 m
Approximate number of constellation devices	1 per m^2	1 per 100 m^2
Sample rate	About three points per second	About 30 points per second
Sensitivity to environmental conditions	Temperature, humidity, vibrations	Temperature, light, vibrations, reflection
Localization of constellation devices	Semi-automated procedure	Semi-automated procedure
System diagnostics	Diagnostic function to filter wrong measurements and to correct parameters	Use of fixed sensors to determine whether measurement system is going out of tolerance
System calibration check	Automatic calculation of the speed of sound during measurements	Real-time adjustments of scale
Metrological performance	Repeatability $\sigma \approx 5$ mm Reproducibility $\sigma \approx 8$ mm	Repeatability $\sigma \approx 0.06$ mm Reproducibility $\sigma \approx 0.16$ mm
Working volume size	Scalable	Scalable
Estimated cost for a typical system	€10k	€150k for typical system with four transmitters

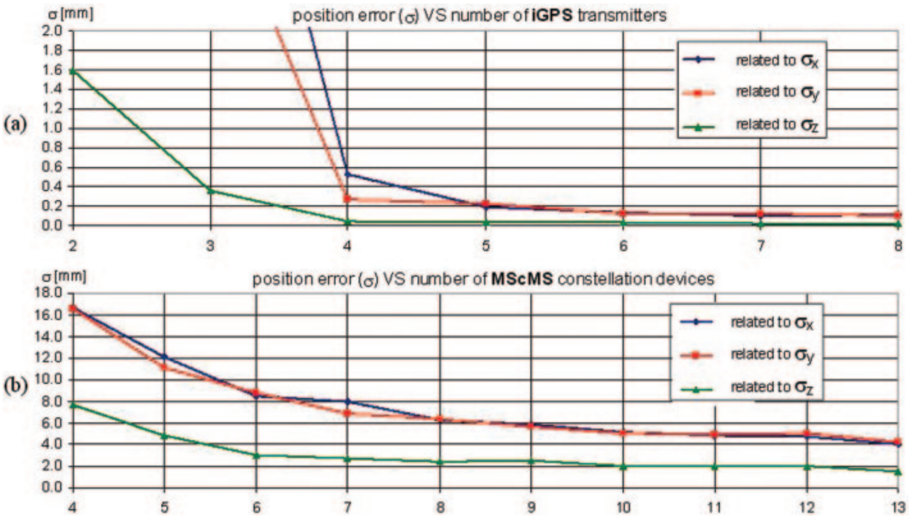

Fig. 4 Influence of the number of transmitters on the position error for the iGPS and the MScMS

The co-ordinate positional errors relating to all 30 points showed a normally distributed pattern.

In the simulation experiment, the effect of the number of transmitters was studied by varying the number of transmitters from 2 to 8. The result showed that, when only two transmitters were used, the uncertainty in the measured points was very high. This uncertainty decreased greatly (by a factor of 4 for the Z axis) when a third transmitter was used for measuring the same point. When a fourth transmitter was added, the improvement in the accuracy was still significant. The addition of a fifth and subsequent transmitters showed only a small and negligible improvement. This trend is shown in Fig. 4(a), in which the standard deviations (σ_x, σ_y, σ_z) relating to the co-ordinate positional errors are plotted against the number of transmitters (from 2 to 8).

The practical significance of these results is that, when using four iGPS transmitters, if the path between a transmitter and a desired sensor is accidentally blocked, the measurement quality will drop. This can happen when the line of sight between a sensor and one or more transmitters is obstructed by the operators or the features of the workpiece. Consequently, the transmitters should be optimally arranged around the measuring area in suitable positions to gain maximum coverage (e.g. near the ceiling, to minimize the obstruction in the line of sight between transmitters and sensors).

Regarding the MScMS, the same simulation experiment was performed by changing the number of constellation devices from 4 (the minimum number required for trilateration) to 13. As shown in Fig. 4(b), the results followed the same pattern, although the positional errors of the MScMS were larger than those of the iGPS. The overall conclusion for both the iGPS and the MScMS is that the number of constellation devices deployed within the mobile probe sensor range is an inverse function of the resulting positional error.

4.2 Sample rate

The point collection frequencies of the MScMS and the iGPS are different owing to the speed of the exchanged signals between the constellation devices and the probe devices. The speed of ultrasonic signals is about 340 m/s, while laser signals are considerably faster (about 300 000 km/s). Consequently, the MScMS sampling rate, which is about three points per second, is much lower than the iGPS sampling rate, which is about 30 points per second.

For distributed measurement systems such as the MScMS and the iGPS, the sampling rate is a very important aspect that affects the dynamic measurements of the systems. The iGPS and the MScMS can be used to perform either static or dynamic measurements. For example, during aircraft assembly operations, they can be very useful in dynamic measurements. However, the two systems perform best in static conditions owing to the positioning methods used.

For the iGPS, since the position of each sensor is calculated using the two angles (φ and θ) from each transmitter, the sampling rate depends on the angular speed of the transmitter rotating heads. With a rotational speed of around 3000 r/min, each transmitter is able to communicate with sensors about 50 times per second. The rotational speed of each transmitter is unique and slightly different from that of the others to distinguish each transmitter. Even though the differences between the transmitters' sampling rates are small, it is impossible to receive concurrent data from all transmitters. The inevitable difference in data streaming is in the range of a few hundredths of a second. This effect does not create any problem for static measurements; however, it will affect the dynamic measurement.

For dynamic measurements, the sensors are moving over time t. For any sensor, the position during the time period t_4–t_1, is calculated by triangulating data collected at very close but different instants [**9**]. Even if the difference consists of a few tenths of a second, it produces a location error. Therefore, the faster the sensor moves, the larger the error becomes. However, for applications such as initial positioning of large structures, where accuracy is not critical, the iGPS system can provide flexible solutions.

Regarding the MScMS, this aspect is similar but more apparent owing to the lower sampling rate. The only difference is that the position of a sensor is calculated by trilateration of the distances from the constellation devices, which are not concurrent. Therefore, the location error is larger for dynamic measurements.

In this paper, the experiments for the evaluation of the systems were performed in static conditions.

4.3 Localization of the constellation devices

Both the MScMS and the iGPS give the opportunity of freely arranging the constellation devices around the desired working area, based on workpiece dimensions and geometry. Whenever the systems are moved, i.e. when the position of the constellation devices is changed, a new localization should be performed. It is evident that this step should be completed before measurement, as it has a strong effect on the measurement accuracy. For this purpose, the MScMS and the iGPS provide two different semi-automated localization procedures, both requiring several manual measurements. These measurements should be taken in different positions within the measurement area while using a calibrated artefact equipped with four cricket transmitters [**3**]. For the iGPS, the procedure is similar, but a reference bar equipped with two sensors with *a priori* known distance should be used.

4.4 System calibration check

Another activity to make the MScMS suitable for measurement is the system calibration check. It is well known that the speed of sound changes with air conditions in terms of temperature and humidity, which can exhibit both temporal and spatial variations within large working volumes. As a consequence, the speed of sound should often be measured and updated in the calculations. In order to verify this value in real time, an optimization procedure is implemented.

A similar procedure is applied for the iGPS, using a reference bar to compensate for the effects of environmental conditions. Such effects can originate from changes in the magnetic field, reflection, and air temperature and humidity, which can, for instance, affect the laser direction. What became clear from the tests is that the absolute uncertainty of the iGPS is directly related to the quality of the scale bar measurement and its initial calibration. The procedure can be fully automated using two fixed sensors, which are tied to the extremities of an interferometric scale bar. The implementation of autocalibration minimizes downtime as the system can self-calibrate continuously and in real time.

4.5 Metrological performance

A prototype MScMS and a standard iGPS were tested for the purpose of evaluating their main metrological performance. Regarding the MScMS, 21 constellation devices were arranged around a measuring area of about 24 m^2. In the case of the iGPS, four transmitters were distributed around a measuring area of about 60 m^2. Two preliminary tests were performed.

4.5.1 Repeatability test

Repeatability is defined as 'the closeness of the agreement between the results of successive measurements of the same measurand, carried out under the same conditions of measurement' [**21**, **22**]. A point within the working volume was measured repeatedly about 150 times. During these measurements, the probe was left in a fixed position, for both the MScMS and the iGPS. The test was repeated for 30 different points in different areas of the working volume. For each point, the residuals between the single measurements and their average values were calculated [**20**]. The residuals showed a normally distributed pattern. The repeatability indicator was given by the standard deviations (σ_x, σ_y, σ_z) related to each Cartesian co-ordinate residual as shown in Table 2.

4.5.2 Reproducibility test

Reproducibility is defined as 'the closeness of the agreement between the results of successive measurements of the same measurand, carried out under changed conditions of measurement' [**21**, **22**]. This test is similar to the previous one, the only difference being that the probe is repositioned in different orientations before each single point measurement. Hence, each point is approached from a different probe direction. Reproducibility gives a preliminary indication of the current accuracy of the system,

Table 2 Comparison between the MScMS and iGPS metrological performances

Mean standard deviation (mm)	Repeatability test			Reproducibility test		
	σ_x	σ_y	σ_z	σ_x	σ_y	σ_z
MScMS	4.8	5.1	3.5	7.3	7.8	4.1
iGPS	0.06	0.06	0.04	0.16	0.16	0.08

whereas repeatability gives a preliminary indication of the potential accuracy of the system [**23**]. This was based on compensating for the most important causes of systematic errors. Table 2 shows the standard deviations related to each Cartesian co-ordinate. As expected, the standard deviations for the reproducibility tests were higher than those of the repeatability tests. The results of these preliminary tests are summarized in Table 2.

In general, for both the MScMS and the iGPS, the σ_z value was lower than the σ_x and σ_y values for both repeatability and reproducibility. This was due to the geometric configuration of the constellation devices, which were mounted on tripods set more or less at the same height. Therefore, they could be considered as approximately placed on a horizontal plane (*XY*) perpendicular to the vertical (*Z*) axis [**16**].

The US transceivers, which were used to calculate the distances between sensor devices, were responsible for the low accuracy of the MScMS compared with the iGPS [**3**, **11**]. The US speed may have changed with changes in the environmental conditions, depending on time and position. Furthermore, US signals may have been diffracted and reflected by obstacles interposed between two devices. This had a negative effect on the measurement accuracy; however, it could have been limited by the use of compensation control tools [**24**].

4.6 Working volume size

The MScMS and the iGPS comprise separate, multiple devices that can be easily moved and arranged around the measuring area according to requirements. These systems are *scalable* and *modular*, since the number of constellation devices can be increased depending on the size and peculiarities of the workpiece and the measurement environment. Such characteristics, however, do not compromise the network communication or slow down the support activities such as constellation location and measurements.

4.7 System diagnostics

The MScMS software provides some diagnostic tools to control the activities and assist in the detection of abnormal functions. First, it gives the opportunity of viewing (directly from the measuring page or during network localization) the distance data exchanged among the wireless devices. Second, during measurement activities, it allows a graphic display of the probe's range of vision, which is the set of network devices with which it can communicate. This helps the operator to check whether the probe is in the optimal position to perform the measurement, for example when it communicates with at least four constellation devices.

As mentioned above, the MScMS is sensitive to external factors, such as the environmental conditions of the measuring area (temperature, humidity, presence of obstacles among distributed devices). However, wrong distance measurements, like those affected by US reflection, diffraction, or other measuring accidents among cricket devices, can be indirectly detected and rejected. For this purpose, the MScMS is equipped with an effective diagnostic test able to discriminate measurements that have good form but are at a wrong distance. This test is based on analysis of the residuals related to the error function optimized during the trilateration process [**9**, **15**].

For filtering bad measurement data due to external factors such as light, temperature, or vibrations, the iGPS also provides diagnostic controls. The reliability of measurements increases dramatically by using multiple fixed sensors which are placed at *a priori* known positions. With these sensors, the system can perform an automatic initial set-up continually to correct the measurement field and determine whether the system is conforming to the desired tolerance [**4**].

4.8 Cost

Cost is a point in favour of the MScMS, since its main components, including cricket devices, supports and booms, adapters, etc., have an individual cost of a few tens of euros. This reduces the overall cost of the system to about €10k. On the other hand, the cost of the iGPS, even for the most economical and simple configuration, is much higher (around €150k).

5 CONCLUSIONS

This paper firstly gives a brief review of two state-of-the-art, large-volume measurement systems, the MScMS and the iGPS. The two systems are compared in order to highlight the pros and cons of each system, based on initial experimental results and available information from the literature.

In terms of measurement procedure, the MScMS and the iGPS are similar as they are multitransmitter, multisensor measurement networks. However, they present many differences on account of their different technological features. The technological differences affect several factors within the systems, including system presetting, start-up, and measurement execution. It can be concluded that these systems can easily coexist, since each system is suitable for specific applications. The metrological performance of the iGPS is superior to that of the MScMS; however, the overall cost of the MScMS is more attractive in applications that do not require a high level of accuracy. It is also shown that, with the existing state of their technology, the MScMS and the iGPS may not be completely suitable for dynamic measurements. However, by predicting the direction of movement and by using error compensation methods, this limitation may be resolved, and the iGPS can potentially be utilized for rough positioning and/or slow dynamic measurements. Both of these systems are lightweight and easily adaptable to different working environments, and they can be rapidly installed and used. Prior to performing measurements, the constellation devices are freely distributed around the working area and semi-automatically located in a few minutes.

Future work will consist of trials and studies to identify the best layout for the positioning of MScMS and iGPS constellation devices and other components. Research will also be carried out to optimize the number of sensors for achieving the desired accuracies for dimensional measurement. Furthermore, the dynamic performance of the systems will be investigated in more detail.

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